Transient climate simulations of the Holocene (version 1) – experimental design and boundary conditions

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Abstract. The Holocene, started approximately 11.5 thousand years before present (ka), is the latest interglacial period with several rapid climate changes from decades to centuries time scales superimposed on the millennium scale mean climate trend. Climate models provide useful tools to investigate the underlying dynamic mechanisms for the climate change during this well-studied time period. Thanks to the improvements of the climate model and computational power, transient
15 simulation of the Holocene offers an opportunity to investigate the climate evolution in response to time-varying external forcings and feedbacks. Here, we present the design of a new set of transient experiments for the whole Holocene from 11.5 ka to the preindustrial period (1850 CE) (HT-11.5ka) to investigate both combined and separated effects of the main external forcing of orbital insolation, atmospheric greenhouse gas (GHG) concentrations, and ice sheets on the climate evolution over the Holocene. The HT-11.5ka simulations are performed with a relatively high-resolution version of the comprehensive
20 Earth system model CESM1.2.1 without acceleration, both fully- and singly-forced by time-varying boundary conditions of orbital configurations, atmospheric GHGs, and ice sheets. Preliminary simulation results show a slight decrease of the global annual mean surface air temperature from 11.5 ka to 7.5 ka due to both ~~decreases~~ changes in orbital insolation and GHG concentrations, with an abrupt cooling at approximate 7.5 ka, which is followed by a continuous warming until the preindustrial period mainly due to increased GHG concentrations. Both at global and zonal mean scales, ~~T~~the simulated
25 ~~cooling magnitude~~annual and seasonal temperature changes at 6 ka lie~~s~~ within the range of the 14 PMIP4 model results and ~~is close to~~are overall stronger than their ~~median~~ arithmetic mean result~~s~~ for the mid-Holocene simulations. Further analyses on the HT-11.5ka transient simulation results will be covered by follow-up studies.

1 Introduction

1.1 Climate evolution over the Holocene

30 Since the end of the Younger Dryas cooling event at ~11.5 thousand years before present (ka), the global climate has entered the Holocene period. The Holocene is the latest interglacial period in the Quaternary glacial–interglacial cycles, which has experienced strong global environmental changes mainly due to the retreat of continental ice sheets, changes in atmospheric greenhouse gas (GHG) concentrations, and variations in the seasonal insolation associated with changes in the Earth's orbital parameters and solar variability (Mayewski et al., 2004). Although previous attempts to subdivide the Holocene still remain

35 inconclusive, the Holocene can roughly be divided into three periods (Nesje and Dahl, 1993): the early Holocene with a high boreal summer insolation and a large remnant ice sheet in North America, the Holocene Hypsithermal with a continuing high boreal summer insolation but a small remnant North American ice sheet, and the late Holocene Neoglacial with a declining boreal summer insolation (Wanner and Ritz, 2011; Wanner et al., 2011; Walker et al., 2012).

The early Holocene, approximately spanning from 11.5 to 9 ka, represents the last transition from full glacial to interglacial

40 conditions, which is characterized by a warming trend ~~in the Northern Hemisphere,~~ mainly in the northern mid- and high-latitudes~~,~~ as revealed from numerous reconstructions (e.g., Koerner and Fisher, 1990; Yuan et al., 2004; Wang et al., 2005; Hald et al., 2007; Vinther et al., 2008; Brooks et al., 2012; ~~Hoelzmann et al., 2004;~~ Shakun et al., 2012; Birks, 2015). ~~Although with differences in magnitude, the early Holocene warming was consistently indicated from ice cores in Greenland (Grootes et al., 1993; Vinther et al., 2008) and the Canadian High Arctic (Koerner and Fisher, 1990), lake sediments in~~

45 ~~western and northern Europe (Brooks and Birks, 2000; Brooks et al., 2012; Birks, 2015), speleothems in China (Yuan et al., 2004; Wang et al., 2005), and marine sediments in the North Atlantic (Bond et al., 1993; Kandiano et al., 2004; Hald et al., 2007).~~ In tropical regions, the change in precipitation was more prominent during the early Holocene, among which the African Humid Period is one typical example (Gasse, 2001; Hoelzmann et al., 2004)~~. Proxy-based evidence also shows~~, in addition to a humidity climate ~~during this transition period from lake sediments~~ in the Arabian Sea~~,~~ ~~and~~ the Bay of Bengal ~~in~~

50 ~~coincidence with the stronger Asian southwest monsoon~~ (Gupta et al., 2003; Staubwasser, 2006)~~,~~ and ~~from the marine sediment off the Venezuelan coast in~~ the northern South America ~~in relation to the southward migration of the Intertropical Convergence Zone~~ (Haug et al., 2001), which was suggested to be fundamentally affected by precession (e.g., Renssen et al., 2004). ~~In contrast~~However, a drier climate was inferred from ~~the paleoenvironmental and archaeological~~ multi-evidence in the central and southern South America (Maslin and Burns, 2000; Seltzer et al., 2000; Núñez et al., 2002)~~. In addition,~~

55 ~~reconstructions from a variety of archives have shown that~~ and the westerlies-dominated North Asia ~~was markedly drier than today during the early Holocene~~, whereas the monsoon-influenced East Asia was substantially wetter but with asynchronous peak of precipitation in Northeast, Northwest, and North China (An et al., 2000; Chen et al., 2008, 2019; Zhang et al., 2011). The Holocene Hypsithermal, covering from about 9 ka to 5–6 ka, generally refers to the interval of warmth associated with the peak Holocene temperature, which is also called ~~the mid-Holocene,~~ the Holocene Thermal Maximum, the Holocene

60 Climatic Optimum, Altithermal or Megathermal (Deevey and Flint, 1957; Wanner et al., 2008; Ljungqvist, 2011). The

timing and spatial pattern of this period in different regions have long attracted the attention of researchers. ~~For example, the Holocene megathermal period was defined as 8.5–3.0 ka in China by Shi et al. (1994) according to multiple evidence from pollen, ice core, paleo lake, and paleosol data.~~ Relative to the preindustrial period, the reconstructed Holocene maximum temperature appeared during 10–8 ka in the North Atlantic and the adjacent polar regions, during 7–5 ka in northern Europe and northwestern North America, and between early and middle Holocene at the northern mid- and high-latitudes, e.g., during 8.5–3.0 ka in China (Shi et al., 1994) and to be time-transgressive across the Western Hemisphere of the Arctic (Kaufman et al., 2004), ~~during 7–5 ka in northern Europe and northwestern North America,~~ suggesting that these local warm periods were very likely not globally synchronous (Jansen et al., 2007). ~~Based on 140 sites across the Western Hemisphere of the Arctic, the Holocene Thermal Maximum was indicated to be time transgressive with an earlier start and end in western Arctic and a later start and end in the eastern part, especially in the southeastern part, due to the effect of the Laurentide ice sheet melting (Kaufman et al., 2004).~~ Different from the Northern Hemisphere, the southern mid- and high-latitudes experienced a ~~declining~~ drop of temperature during the middle and late Holocene following the early Holocene warming period (Shevenell et al., 2011). Concerning the moisture conditions, paleoenvironmental data ~~from lake level, vegetation and isotope records, and aeolian deposits~~ consistently showed that the midcontinental extra-tropics were wetter with cooler summers than today during the mid-Holocene (Harrison et al., 2015).

The late Holocene Neoglacial or Neoglaciation, lasting from about 5–6 ka to preindustrial period, is featured by an obvious increase in the number of glacial advances worldwide mainly due to decreasing solar forcing in the boreal summer (Solomina et al., 2015). The global mean surface temperature during this period displayed a consistent cooling trend as indicated from multi-proxy-based reconstructions ~~from 11 selected temperature time series~~ (Wanner et al., 2008~~), 37 terrestrial and 23 marine temperature records (~~; Ljungqvist, 2011~~), 73 globally distributed temperature records (~~; Marcott et al., 2013~~), and a global compilation of temperature time series from 679 sites (~~; Kaufman et al., 2020a, b~~) and 1302 records (~~; Zhang et al., 2022)~~. ~~This late Holocene cooling trend~~, which was suggested to be mainly due to the influence of orbital forcing together with the melting ice sheet in North America. ~~However, as pointed out by Wanner (2021), most of those studies are mainly based on marine records which have seasonal (mostly summer) biases in many cases, and boreal winter season, when solar insolation was increasing in the tropics and Southern Hemisphere, is only weakly represented by proxies. In fact, after removing the seasonal bias in the marine record located in the tropical western Pacific, the annual mean sea surface temperature was steadily increasing since about 12 ka (Bova et al., 2021).~~ In contrast, ~~T~~the late Holocene warming trend was ~~further~~ also supported by simulations (e.g., Liu et al., 2014; Liu et al., 2018) and by several reconstructions from subfossil pollen ~~at 642 sites across North America and Europe~~ (Marsicek et al., 2018) and ~~from two~~ stalagmites records ~~in the southern Ural Mountains over western continental Eurasia~~ during the winter season (Baker et al., 2017), which was mainly attributed to rising atmospheric GHGs and winter insolation. Therefore, it still remains inconclusive on whether the late Holocene was cooler or warmer. To reconcile this so called "Holocene temperature conundrum", further efforts should be taken to the improvements both in simulations, by including solar irradiance forcing, land-use changes, dust effects, and stratospheric chemistry and dynamics, and in reconstructions with higher spatial and temporal resolutions, a balanced

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distribution between marine and terrestrial and between the Northern and Southern Hemisphere data, and the representing proxies from both summer and winter seasons (Bova et al., 2021; Wanner, 2021; Zhang et al., 2022), as well as in the model–data assimilation approaches (Osman et al., 2021).

Superimposed on the millennium scale mean climate trend during the above Holocene periods are several rapid cooling events on the time scales from decades to centuries (Wanner et al., 2011; Walker et al., 2012). ~~Based on ~50 globally distributed paleoclimate records, six periods of significant rapid climate changes were identified during 9–8 ka, 6–5 ka, 4.2–3.8 ka, 3.5–2.5 ka, 1.2–1.0 ka, and 0.6–0.15 ka by Mayewski et al. (2004), which generally cover the rapid cold events occurring at about 8.2 ka, 5.5 ka, 4.2 ka, 2.8 ka, 1.4 ka, and 0.4 ka ("Little Ice Age") according to studies of ice rafted debris in the North Atlantic (Bond et al., 1997; Moros et al., 2004).~~ Most of those events are characterized by cooling at northern mid- and high-latitudes, aridity at low-latitude monsoon regions, and major atmospheric circulation changes (Mayewski et al., 2004)~~. The cold events during the early Holocene before 8.2 ka~~, which were generally inferred to relate to the freshwater outbreak caused by ice melting in the North Atlantic before 8.2 ka, ~~while those during the mid- and late Holocene may mainly associate with~~ the solar variability superimposed on long-term changes in insolation during the mid- and late Holocene,~~;~~ as well as explosive volcanic eruptions and fluctuations of the thermohaline circulation ~~may also play important roles~~ (Mayewski et al., 2004; Magny et al., 2007; Wanner et al., 2011).

1.2 Transient modelling of the Holocene

Transient modelling of the Holocene offers an opportunity to examine the climate evolution in response to time-varying external forcings and feedbacks. Combined with proxy data, it is the most useful tool to comprehensively understand the causes for past complex and interrelating climate processes. Since the 1990s, the Paleoclimate Modelling Intercomparison Project (PMIP) has served to coordinate paleoclimate simulations and model–data comparisons (Joussaume and Taylor, 1995; Braconnot et al., 2007; Taylor et al., 2012), and it now enters its fourth phase (PMIP4; Kageyama et al., 2018) contributing to the current sixth phase of the Coupled Model Intercomparison Project (CMIP6; Eyring et al., 2016) and the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (IPCC, 2021). The major focuses in PMIP4 include not only equilibrium (or time-slice) simulations to investigate the impact of changes mainly in orbital forcing, e.g., during the mid-Holocene (6 ka), but also transient simulations of the last deglaciation from 21 to 9 ka with time-varying orbital forcing, GHGs, ice sheets, and other geographical changes (Ivanovic et al., 2016) and of the Holocene from 6 to 0 ka with temporal changes in orbital forcing and GHGs (Otto-Bliesner et al., 2017).

Up to now, ~~numerous~~ a dozen transient simulations covering the Holocene have been carried out using global climate models with different complexities. For example, FOAM, a fully coupled global atmosphere–ocean general circulation model with a low resolution of $4° \times 7.5°$ (latitude $\times$ longitude), was used to run a transient simulation for the past 280 ka to examine the evolutionary response of global monsoons to orbital forcing, which is accelerated by a factor of 100 (Kutzbach et al., 2008). FAMOUS (Smith et al., 2008), a low-resolution ($5° \times 7.5°$) version of the HadCM3 (Gordon et al., 2000) coupled model, was used to conduct a number of accelerated transient experiments (by a factor of 10) ~~with single and full~~

~~forcings of orbital parameters, GHGs, and ice sheets~~ for the last 120 ka to investigate the ~~physical~~ climate of ~~the atmosphere and ocean through~~ the last glacial cycle (Smith and Gregory, 2012). A set of transient simulations of the last deglaciation for the past 26 ka was performed with a low resolution (~3.75° × 3.75°) Earth system model MPI-ESM1.2 to explore differences in climate response to different underlying ice-sheet reconstructions and methods of meltwater distribution (Kapsch et al., 2020) as suggested within the PMIP4 deglaciation protocol (Ivanovic et al., 2016). The Transient Climate Evolution of the past 21 ka (TraCE-21ka; He, 2011), run with the low-resolution (~3.75° × 3.75°) National Center for Atmospheric Research (NCAR) Community Climate System Model version 3 (CCSM3), is widely used for examining the climate evolution since the last glacial maximum at global and regional scales (e.g., Liu et al., 2014; Liu et al., 2021; Wu et al., 2021). A fully coupled atmosphere–ocean–sea ice model ECBilt-CLIO, with a horizontal resolution of ~5.6° × 5.5°, was also used for transient simulations of the last deglaciation (last 21 ka) to investigate the effect of using accelerated (by a factor of 10) boundary conditions and of uncertainties in the initial state (Timm and Timmermann, 2007); additionally coupled with a vegetation model, ECBilt-CLIO-VECODE3 was performed to investigate the global characterization of the Holocene thermal maximum for the last 9 ka (Renssen et al., 2012); a later developed version LOVECLIM, additionally coupled with carbon cycle and terrestrial ice sheets (Goosse et al., 2010), was employed to examine the ~~effects of melting ice sheets and orbital forcing on the~~ early Holocene (11.5–7 ka) warming (Zhang et al., 2016), the Holocene northern temperature and hydroclimate trends (Zhang et al., 2018, 2020), and the obliquity and CO_2 effects on southern climate during the past 408 ka with an acceleration factor of 5 (Timmermann et al., 2014). ~~The three Holocene transient simulations performed with the LOVECLIM, CCSM3, and FAMOUS were compared to explore the Holocene temperature trends in the extratropical Northern Hemisphere and the spatial contrasts of the Holocene hydroclimate trend between North and East Asia (Zhang et al., 2018, 2020).~~

More concentrate on the Holocene, ~~NNU-Hol (Nanjing Normal University Holocene)~~ transient simulations for the past 12 ka, run with an acceleration factor of 10 with the low-resolution (~3.75° × 3.75°) Community Earth System Model (CESM) version 1.0.3 (CESM1.0.3), ~~successfully reconciled the temperature conundrum with~~showed a cooling trend during 5–0.15 ka by considering the volcanic forcing (Wan et al., 2020) and~~; they also showed~~ an increase trend of the northern mid-latitude precipitation during 7–0 ka in response to the orbital forcing~~, which is consistent with the reconstructions although the trend is concentrated in marine areas~~ (Sun et al., 2020). A transient simulation of the last 8 ka performed with the high-resolution (1.875° × 1.875°) MPI-ESM1.2, additionally forced by solar variability and volcanic forcing, further revealed that both ~~a~~ global warming and cooling modes coexisted during the Holocene~~, with the former mode dominating in the mid-Holocene and the latter taking over in the late Holocene, and thus shed light on the Holocene temperature conundrum~~ (Bader et al., 2020)~~. The MPI-ESM1.2 Holocene transient simulation~~, which also captured the global vegetation transitions and the time-transgressive end of the African humid period as revealed in proxy data~~, with an earlier end of the African humid period in the north/east than in the south/west due to the regionally varying dynamical controls on precipitation~~ (Dallmeyer et al., 2020, 2021). ~~A transient climate simulation of the past 9.5 ka, conducted with~~ Using a low--resolution (~3.75° × 3.75°) atmosphere–ocean–sea ice coupled model KCM with an acceleration factor of 10, a transient climate simulation of the past

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9.5 ka was conducted to examine the~~, exhibited a wave train spatial pattern and diverging trends of~~ summer precipitation across the Asian monsoon region in response to the orbital forcing (Jin et al., 2014). Two versions of the IPSL model~~, i.e., the low resolution (1.875° × 3.75°) version of IPSLCM5A LR and modified and medium resolution (1.25° × 2.5°) of IPSLCM5A-MR with a new hydrological model, a prognostic snow model, and a dynamical vegetation module,~~ were used to run the transient simulations of the last 6 ka, indicating ~~that~~ larger impacts of different model versions and experimental setups ~~have a larger impact~~ on the mean state of climate~~, e.g., the drying trend of the Indian and West African summer monsoon rainfall,~~ than on the associated interannual-to-decadal variability ~~and the vegetation climate interactions~~ (Braconnot et al., 2019a, b; Crétat et al., 2020). In addition, the four Holocene transient simulations run with MPI-ESM1.2, two versions of the IPSL model, and AWI-ESM2 (~~1.875° × 1.875°;~~ Sidorenko et al., 2019) were compared to support the orbital forcing of ENSO amplitude since the mid-Holocene (Carré et al., 2021) and ~~highlight~~ indicate the importance of the application of calendar transformation in the analysis of climate simulations when we ~~do~~ perform multi-model comparisons (Shi et al., 2021).

1.3 A new set of Holocene transient experiments

Taken together, among the ~~numerous~~ above mentioned ~~sets of~~ Holocene transient simulations ~~published in the past~~, only seven of them covered the whole Holocene of past 11.5 ka, i.e., simulations with LOVECLIM for past 408 ka, FOAM for past 284 ka, FAMOUS for past 120 ka, MPI-ESM1.2 for past 26 ka, CCSM3 and ECBilt-CLIO for past 21 ka, and CESM1.0.3 for past 12 ka. They were performed with climate system models or Earth system models with intermediate complexity, all of which have relatively low spatial resolutions varying from ~5.6° × 5.5° to ~3.75° × 3.75° and/or use acceleration techniques by a factor from 5 to 100 to reduce computational resources. Note that, on the one hand~~However~~, the model resolution determines the level of detail in its representation of physical processes related with the topography, heat transport, sea ice cover, etc., which may have large effects on the Holocene climate evolution (Zhang et al., 2018). On the other hand, acceleration in transient simulations can also have a significant impact on the local climate history, for example, which will lead to damped and delayed temperature response to the boundary conditions in the North Atlantic (Timm and Timmermann, 2007). In addition, most models used for the Holocene transient simulations are fully-forced by time-varying boundary conditions of orbital configurations, GHGs, and ice sheets, some of which are additionally forced by meltwater flux, land use/land cover, solar variability, or volcanic forcing, making it difficult to isolate their relative contribution to the past climate evolution.

In this context, it is urgent to carry out a new set of unaccelerated transient experiments focusing on the whole Holocene since 11.5 ka using the comprehensive Earth system model with relatively high spatial resolutions, considering both the full-forcing and single-forcing effects of several most important boundary conditions, including the orbital parameters, GHG concentrations, and ice sheets, on the Holocene climate evolution. These set of Holocene transient simulations for the last 11.5 ka will also fill in the gap between the PMIP4 transient Core experiments for the last deglaciation from 21 to 9 ka

(Ivanovic et al., 2016) and the PMIP4 Tier 3 transient simulations for the Holocene from 6 to 0 ka (Otto-Bliesner et al.,
195   2017).

The aim of this paper is to outline the model description (in Section 2), experimental setup, and boundary conditions (in
Section 3) for the new Holocene transient climate experiments of the last 11.5 ka (henceforth HT-11.5ka for brevity), with
some preliminary results being provided in Section 4. Further analyses on these simulation results will be covered by follow-
up studies.

200   **2 Model description**

The model used to run the HT-11.5ka simulation in this study is the NCAR CESM version 1.2.1 (CESM1.2.1), which was
released on December 2013 and was a relatively new version when we started this simulation on 2016. CESM is a fully-
coupled global Earth system model that provides state-of-the-art simulations of the Earth's past, present, and future climate
states, with an earlier version 1 (CESM1) participated in the CMIP phase 5 (CMIP5; Taylor et al., 2012) and the later version
205   2 (CESM2) participated in the CMIP phase 6 (CMIP6; Eyring et al., 2016). CESM1.2.1 consists of four components and can
be coupled in different configurations. The atmospheric component we used here is the NCAR Community Atmosphere
Model version 4 (CAM4; Neale et al., 2010), also used in the CCSM version 4 (CCSM4; Gent et al., 2011), which employs a
finite volume dynamical core at a horizontal resolution of approximately $1.9° \times 2.5°$ (latitude 96 × longitude 144 grid points)
with 26 vertical layers. It contains notable improvements in the deep convection parameterization with inclusions of more
210   realistic dilution effects through an explicit representation of entrainment and sub-grid scale convective momentum
transports, in the cloud fraction parameterization with a freeze-drying process contributing to a greater consistency between
polar cloud fraction and water condensate properties, and in the radiation interface and computational scalability (Neale et al.,
2010). The land component is the Community Land Model version 4.0 (CLM4; Lawrence et al., 2011) with the carbon
nitrogen–dynamic global vegetation model turned off, which is also used in CCSM4 and run on the same horizontal grid as
215   the atmospheric component. The oceanic component is the Parallel Ocean Program version 2 (POP2; Danabasoglu et al.,
2012) based on the POP version 2.1 of the Los Alamos National Laboratory (Smith et al., 2010) as utilized in CCSM4,
which uses an approximately 1° horizontal grid with 60 vertical levels. Compared to previous model versions, the physical
improvements in POP2 include a near-surface eddy flux parameterization, an abyssal tidally mixing parameterization, an
overflow parameterization to represent the Denmark Strait, Faroe Bank Channel, Weddell Sea, and Ross Sea overflows, a
220   submesoscale mixing scheme, vertically-varying thickness and isopycnal diffusivity coefficients, and modified and generally
reduced horizontal viscosity coefficients (Hurrell et al., 2013). The sea ice component is the Los Alamos Sea Ice Model (or
referred to as the Community Ice Code) version 4.0 (CICE 4.0; Hunke and Lipscomb, 2008) with the same horizontal grid as
the ocean component. These four components are coupled by the version 7 coupler (CPL7) (Craig et al., 2012). More details
on the model are available online at https://www.cesm.ucar.edu/models/cesm1.2/ and in Hurrell et al. (2013)., and fFurther
225   information on the model performance, scalability, and throughput for different model components distinguishing between

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Input/Output, ocean and atmosphere costs, etc., are documented in the CCSM4/CESM1 special collection of the *Journal of Climate* (see http://journals.ametsoc.org/collection/CCSM4-CESM1), and additional model simulations for the past and present climates can be found, for instance, in Goldner et al. (2014), Song and Zhang (2018, 2019), and Park et al. (2019) and Song and Zhang (2018, 2019).

3 Experimental designs for the HT-11.5ka simulations

The HT-11.5ka simulations of the Holocene focus on the period from 11.5 ka to the preindustrial period (1850 CE), which will be the supplement for the PMIP4 Core simulations of the last deglaciation (version 1) spanning from 21 to 9 ka (Ivanovic et al., 2016). Note that 0 ka is 1950 CE, and 1850 CE is equivalent to 0.1 ka. All simulations spin up from the early Holocene at 11.5 ka and all boundary conditions are available from 11.5 ka to the preindustrial period. The initialization state at 11.5 ka and boundary conditions since 11.5 ka, including Earth's orbital parameters, atmospheric GHG concentrations, and ice sheets and orography, are summarized in Table 1 and described below. Boundary condition data for the HT-11.5ka transient experiments are provided on the PMIP4 wiki for the transient deglaciation (PMIP Last Deglaciation Working Group, 2016; https://pmip4.lsce.ipsl.fr/doku.php/exp_design:degla).

3.1 Early Holocene spin-up

The early Holocene spin-up experiment for the HT-11.5ka simulations is an equilibrium or time slice simulation with boundary conditions of orbital parameters, GHGs, and ice sheets prescribed at 11.5 ka (Table 1). Orbital parameters of eccentricity, obliquity, and longitude of perihelion is are set to 0.01957212, 24.17958°, and 270.2132°, respectively, with the date of vernal equinox fixed at the noon on 21 March. The solar constant is fixed to 1365 W m^{-2}, which is consistent with the preindustrial value for the PMIP phase 3 (PMIP3) and CMIP phase 5 (CMIP5) experiments but higher than the value recommended for the transient deglaciation simulation (e.g., 1361.0 ± 0.5 W m^{-2}; Mamajek et al., 2015) and the PMIP4/CMIP6 experiments (e.g., 1360.8 ± 0.5 W m^{-2}; Matthes et al., 2017; Otto-Bliesner et al., 2017). The atmospheric GHGs is are prescribed to 267.4 ppm for carbon dioxide (CO_2), 652.4 ppb for methane (CH_4), 251.1 ppb for nitrous oxide (N_2O), 0 for chlorofluorocarbons (CFCs), and the PMIP3/CMIP5 preindustrial (1850 CE) value for ozone (O_3). These values are compatible with the time-evolving boundary conditions for the HT-11.5ka simulations and consistent with the latest ice-core age model (AICC2012; Veres et al., 2013) and records (Loulergue et al., 2008; Schilt et al., 2010; Bereiter et al., 2015). Prescribed ice sheets and the associated topography use the 11.5 ka data from the ICE-6G_C (VM5a) reconstruction (henceforth ICE-6G_C; Argus et al., 2014; Peltier et al., 2015). The initial ocean condition is taken from an archived 500-yr spinup (CCSM4, 2° resolution in the atmosphere and 1° resolution in the ocean, preindustrial control, case b40.1850.track1.2deg.003). All other boundary conditions, such as the coastlines, bathymetry, vegetation and land cover, and aerosols, are prescribed at the preindustrial levels.

Forced by the above boundary conditions, the early Holocene spin-up is continuously integrated for 1500 years, with the absolute value of the trend in global mean surface air and sea surface temperatures being less than 0.05 °C and the Atlantic Meridional Overturning Circulation being stable (approximately 25.4 Sv) for the last 100 years, which means the model has reached a quasi-equilibrium state as suggested by Kageyama et al. (2018). All Holocene transient experiments start from this equilibrium state at 11.5 ka and run transiently until the preindustrial period at 1850 CE.

3.2 Holocene transient simulations

3.2.1 Orbital parameters, solar constant, and insolation anomalies

The Earth's orbital parameters (eccentricity, obliquity, and longitude of perihelion) are time evolving through the Holocene from 11.5 ka to the preindustrial period following Berger (1978), which affect the seasonal and latitudinal distribution and magnitude of solar radiation received at the top of the atmosphere. Here, all orbital parameters are interpolated from the originally temporal resolution of 1,000 years to one year to produce continuous orbital forcings as model inputs. More specifically, the eccentricity declined through the Holocene, indicating a gradual decrease in the seasonal difference of incoming insolation since 11.5 ka. The obliquity was maximal at 9 ka, when the insolation difference was largest between low and high latitudes. The perihelion occurred close to the boreal summer solstice, autumnal equinox, and winter solstice at 11.5 ka, 6 ka, and the preindustrial period, respectively. Due to the above changes, summer (June–July–August) insolation averaged in the Northern Hemisphere slightly increased from 465 W m^{-2} at 11.5 ka to a maximum of 468 W m^{-2} at about 9.3 ka, and then continuously declined until the preindustrial period. June insolation at 60°N gradually decreased through the Holocene, whereas December insolation at 60°S increased since 11.5 ka and was maximal around 2 ka (Fig. 1a). Relative to the preindustrial period, June insolation anomalies generally increased with latitude and decreased with time, with positive maximums of ~50 W m^{-2} occurring at northern high latitudes during the early Holocene (Fig. 2).

The solar constant is fixed to 1365 W m^{-2} throughout the run, which is in line with the PMIP3 experiment set up (PMIP PI Working Group, 2010). As mentioned in Otto-Bliesner et al. (2017), this value is higher than the value for the solar constant used by the models in PMIP4 (1360.7 W m^{-2}), which will leads to a global increase of incoming solar radiation compared to the PMIP4 experiments.

3.2.2 Atmospheric GHGs

During the Holocene, CFCs is fixed at 0 and O_3 is set to the PMIP3/CMIP5 preindustrial value as the early Holocene spin-up. Other atmospheric GHGs are time evolving through the Holocene and adjusted to the AICC2012 age model (Veres et al., 2013), with CO_2 following Bereiter et al. (2015), CH_4 following Loulergue et al. (2008) and N_2O following Schilt et al. (2010). The high-resolution atmospheric CO_2 concentrations are revised EPICA Dome C (EDC; Monnin et al., 2001, 2004) and Antarctic composite ice core data built from the Law Dome (MacFarling Meure et al., 2006; Rubino et al., 2013) and West Antarctic Ice Sheet Divide (Marcott et al., 2014), which show a slight decrease trend from 11.5 to 7 ka and an increase

trend afterward (Fig. 1b). The record of atmospheric CH_4 concentrations is built from the Antarctic EDC (Loulergue et al., 2008), with a decreasing trend from the early- to mid-Holocene followed by a rising trend (Fig. 1c). The low-resolution atmospheric concentrations of N_2O derived from the Talos Dome ice core (Schilt et al., 2010) show large variabilities during the Holocene, with relatively high values around 11 ka and during 6–0 ka but low levels between 11 and 6 ka (Fig. 1d). All above GHG records are interpolated to the temporal resolution of one year to produce continuous forcings as model inputs. Note that the chronologically accurate values of CO_2, CH_4, and N_2O from the above reconstructions slightly differ from the defined 6 ka concentrations in PMIP4. The nearest measured CO_2 concentration to 6 ka is 266.7 ppm from Bereiter et al. (2015), which is higher than the 6 ka value of 264.4 ppm in PMIP4 derived from the original EDC ice core (Monnin et al., 2001, 2004) after a smoothing spline (Otto-Bliesner et al., 2017). In contrast, both the nearest measured CH_4 and N_2O concentrations of 586 ppb (Loulergue et al., 2008) and 252.4 ppb (Schilt et al., 2010) produced on the AICC2012 chronology (Veres et al., 2013) are lower than the 6 ka values of 597 ppb and 262 ppb in PMIP4 (Otto-Bliesner et al., 2017), respectively, on the original EDC1 chronology (Spahni et al., 2005).

3.2.3 Ice sheets and topography

The ice sheet extent and topography are time evolving from 11.5 ka to the preindustrial period using the ICE-6G_C reconstruction (Argus et al., 2014; Peltier et al., 2015), which is based on Glacial Isostatic Adjustment modelling and constrained by Global Positioning System measurements of vertical motion of the crust, exposure age dating of ice thicknesses, relative sea level histories, and space-based gravity data by satellite system (Peltier et al., 2015). During the Holocene, the most prominent change of ice sheets occurs in the Northern Hemisphere, especially in North America. According to the ICE-6G_C reconstruction, the North American ice sheet retreated gradually from 11.5 ka to 9 ka, with the Laurentide ice sheet holding ~12.5 m global mean sea level rise equivalent ice volume at 10 ka (Matero et al., 2020), retreated sharply from 9 ka to 7 ka, and almost disappeared after 6 ka (Fig. 3) following the data provided by Dyke (2004). The Eurasian ice sheet retreated since 11.5 ka and deglaciated after ~10 ka following Gyllencreutz et al. (2007), whereas the Greenland ice sheet was overall stable from 11.5 ka to 9 ka and slightly retreated at its marginal regions during 8–7 ka (Fig. 3). Averaged over the Northern Hemisphere, the ice area continuously declined from ~1.2×10^7 km^2 at 11.5 ka to ~0.2×10^7 km^2 during the mid-Holocene (~7–5 ka), and remained little changed since then (Fig. 1e). In contrast, there is little variation in the Southern Hemispheric ice sheets during the Holocene, with only a slight decrease in the ice extent from 11.5 ka to 10 ka around the Antarctica (Fig. 3). The orography evolves to be consistent with the ice sheet extent, with the elevation of ice sheet below 2000 m, 2500 m, and 3500 m over Eurasia, North America, and Greenland, respectively, and reaching 4000 m over Antarctica through the Holocene (Fig. 3). Besides, land surface properties are also adjusted for changes in ice extent. Where ice retreats, land surface is modified to the prescribed vegetation at the preindustrial period.

The original ICE-6G_C data set is provided at 10 arcmin (~0.17°) horizontal resolution and at intervals of 500 years through the Holocene. Both included ice extent and topography data are interpolated to the time interval of 250 years, and updated every 250 years in the transient run. Considering that coastlines, bathymetry, and land–sea distributions are little varied

during the Holocene, they are fixed as the preindustrial states in all runs. In addition, the meltwater flux change is not considered here, which is one of the options provided for the PMIP4 transient deglaciation experiments. All other forcings, such as the vegetation, land surface and dust parameters, are prescribed at the preindustrial levels.

3.2.4 Experimental setup

Four transient experiments are run in total in the HT-11.5ka simulations, one all-forcing experiment and three single-forcing experiments. The orbital parameters, atmospheric GHGs, ice sheets and topography as detailed above are synchronously evolving with time in the all-forcing experiment (hereinafter HT-ALL), while the three single-forcing experiments are forced by only one of the above forcings, with the other two forcings fixed at 11.5 ka (hereinafter HT-ORB, HT-GHG, and HT-ICE, respectively) (Table 2). All four experiments are transiently run from 11.5 ka to the preindustrial period at 1850 CE for 11400 years. Monthly output data are provided for each simulation.

4 Preliminary simulation results

On the millennium timescale, the annual global annual mean surface (2 m) air temperature (GMST) in the HT-ALL simulation slightly decreases from 11.5 ka (~13.20 °C) to 7.5 ka (~12.93 °C), with an abrupt cooling at approximate 7.5 ka, and then continuously increases until the preindustrial period (13.57 °C) (Fig. 4). The value during the preindustrial period is very close to that of 13.61 °C from the median of the 14 PMIP4 models, although with a spread among the individual models ranging from 12.59 °C in IPSL-CM6A-LR to 14.98 °C in MIROC-ES2L. At 6 ka, the GMST is approximate 13.16 °C, which resembles the value of 13.28 °C from the mid-Holocene simulation in the 14 PMIP4 model median and is within the range from 12.20 °C (IPSL-CM6A-LR) to 14.53 °C (MIROC-ES2L) in the individual model simulations. Relative to the average for 1750-1850 CE, there is a global annual mean cooling of about 0.41 °C at 6 ka in HT-ALL simulation, which lies within the range of the results from the PMIP4 models. In the 14 PMIP4 models, the mid-Holocene cooling varied from 0.18 °C in FGOALS-g3 to 0.49 °C in FGOALS-f3-L with respect to the preindustrial period, with an average of 0.33 °C for the median of all models (Fig. 5). Note that the GMST simulated by CESM1.2.1 in HT-ALL simulation is lower than that by CESM2 in the PMIP4 both for 6 ka and preindustrial simulations (13.16 vs. 13.88 °C and 13.57 vs. 14.08 °C, respectively), but the mid-Holocene cooling magnitude for the former is nearly double that of the latter (0.41 vs. 0.20 °C). The warming trend since the mid-Holocene simulated by CESM1.2.1 in our HT-11.5ka transient experiment is similar to that in the CCSM3, LOVECLIM, and FAMOUS transient simulations (Liu et al., 2014), but opposite to the cooling trend as derived from the multi-proxy reconstructions (Marcott et al., 2013; Kaufman et al., 2020a), which is the so called "Holocene temperature conundrum". The abrupt cooling at approximate 7.5 ka is also seen in the LOVECLIM transient experiment (Liu et al., 2014). In addition, the GMST evolution from early- to mid-Holocene in our CESM1.2.1 transient simulation is somewhat different from the warming trend both in reconstructions and other Holocene transient simulations (Marcott et al., 2013; Liu et al., 2014; Kaufman et al., 2020a), and the reasons for the discrepancies need for further investigations.

During the preindustrial period, the annual GMST of 13.57 °C in our HT-ALL simulation is very close to that of 13.62 °C from the arithmetic mean of the 14 PMIP4 models, although with a spread among the individual models ranging from 12.59 °C in IPSL-CM6A-LR to 14.98 °C in MIROC-ES2L (Table 3). At 6 ka, the annual GMST is approximate 13.16 °C, which resembles the value of 13.30 °C from the mid-Holocene simulation in the 14-PMIP4-model arithmetic mean and is

355   within the range from 12.20 °C (IPSL-CM6A-LR) to 14.53 °C (MIROC-ES2L) in the individual model simulations (Table 3). Relative to the average for 1750–1850 CE, there is a global annual mean cooling of about 0.41 °C at 6 ka in HT-ALL simulation, which lies within the range of the results from the PMIP4 models. In the 14 PMIP4 models, the mid-Holocene cooling varied from 0.18 °C in FGOALS-g3 to 0.49 °C in FGOALS-f3-L with respect to the preindustrial period, with a standard deviation of 0.11 °C among the models and an average of 0.32 °C for the arithmetic mean of all models (Fig. 5;

360   Table 3). The geographical distribution of annual mean surface air temperature change at 6 ka in our HT-ALL simulation is further compared with that from the arithmetic mean of the 14 PMIP4 models (Fig. 6). Compared to the preindustrial period, there is an annual cooling worldwide except for a slight warming in the high latitudes and over the western Europe, North Pacific, southern North America, and parts of tropical land at 6 ka in HT-ALL simulation (Fig. 6a). The annual cooling is particularly strong (> 1 °C) over northern Africa and North America, southern Asia, and part of Southern Ocean. This large-

365   scale distribution is similar to the spatial pattern of the change between the mid-Holocene and preindustrial simulations in the 14-PMIP4-model mean, although some differences exist in magnitude (Fig. 6a, b; Brierley et al., 2020). Quantitatively, the HT-ALL simulation shows an annual cooling of 0.18, 0.40, 0.61, 0.40, 0.31, and 0.20 °C at 6 ka averaged for the zonal band of 60°–90°N, 30°–60°N, 0°–30°N, 30°S–0°, 60°–30°S, and 90°–60°S, respectively. All those values are within the spread of the 14 PMIP4 models, with the largest spread over high latitudes, but are slightly stronger than the cooling in their

370   arithmetic mean by 0.05–0.14 °C, especially in the Northern Hemisphere (Fig. 7a). Due to the large seasonal changes in insolation, there are notable seasonal differences in the surface air temperature change at 6 ka, with the December–January–February (DJF) mean change dominating the annual pattern. In response to the decreased insolation in DJF, a strong cooling occurred at 6 ka over the global land regions, especially over the northern continents excluding the Greenland, and a weak cooling appeared over the global oceans except for a warming in the Arctic and Southern Ocean (Fig. 6c). In contrast, the

375   increased June–July–August (JJA) insolation at 6 ka led to a notable warming over the northern mid- and high-latitude continents, a weak warming over the northern mid- and high-latitude oceans and southern continents, and a cooling in the other regions (Fig. 6e). The seasonal difference in the spatial distribution of the surface air temperature changes at 6 ka in the HT-ALL simulation resembles that for the mid-Holocene simulations in most PMIP4 models and their arithmetic mean (Fig. 6d, f; Brierley et al., 2020). In a quantitative manner, the HT-ALL simulation shows a consistent DJF cooling of 0.68 (0.31),

380   0.95 (0.22), and 0.83 (0.43) °C averaged over the 30° zonal band of northern (southern) high-, mid-, and low-latitudes, respectively, while it displays an average warming of 0.99 and 0.50 °C over the northern high- and mid-latitudes but an average cooling varying from 0.41 to 0.66 °C over the other four zonal bands in JJA, with a global mean cooling of 0.60 for DJF and 0.17 °C for JJA (Fig. 7b, c and Table 3). All those zonal and global mean changes in seasonal temperatures are within the range of the mid-Holocene changes in the 14 PMIP4 models, which are consistent with the changes from the 14-

PMIP4-model arithmetic mean in signs but overall larger than the latter in magnitudes (Fig. 7b, c and Table 3). More specifically, both PMIP4 model spreads and differences of zonal mean changes between the HT-ALL and 14-PMIP4-model mean simulations are largest at northern high latitudes in DJF and at high latitudes in both hemispheres in JJA. As a whole, both at global and zonal mean scales, the annual and seasonal mean changes in surface air temperature at 6 ka in our HT-ALL simulation lie within the range of the 14 PMIP4 model results and are overall stronger than their arithmetic means. In particular, the annual, DJF, and JJA mean GMSTs simulated by CESM1.2.1 in the HT-ALL simulation are lower than those by CESM2 in the PMIP4 both for 6 ka and preindustrial simulations, but the mid-Holocene annual and DJF cooling magnitudes for the former (0.41 and 0.60 °C) are nearly double those of the latter (0.20 and 0.38 °C), and the JJA cooling in the former (–0.17 °C) is opposite to and four times the JJA warming in the latter (0.04 °C) (Table 3). There are also some differences, mainly in magnitudes, for the zonal mean changes in annual and seasonal temperatures at 6 ka between the two versions of CESM (Fig. 7).

Fig. 5 further displays the annual GMST evolution since 10 ka in the all-forcing and single-forcing simulations. All time series are the anomalies relative to the last 100 101 years (1750–1850 CE) of the HT-ALL simulation. In response to the orbital forcing alone, the GMST slightly decreases during the past 10 ka, with an averaged cooling of approximate 0.2 °C in HT-ORB simulation. The GMST first decreases from 10 ka to 6.5 ka and then steadily increases until now in HT-GHG simulation, which closely follows the evolution of the atmospheric concentration of CO_2 and is also modulated by that of CH_4 and N_2O. In HT-ICE simulation, the GMST increases from 10 ka to 6 ka in response to the retreat of ice sheets in the Northern Hemisphere, and then slightly decreases possibly due to the lag effect of ice sheet melting. Taken together, the weak cooling trend during the early Holocene in HT-ALL simulation is mainly driven by both decreased changes in orbital insolation and GHG concentrations, while the retreat of ice sheets plays an opposite role. On the other hand, the strong warming trend since 7.5 ka is mainly induced by increased concentrations of GHGs, which is largely resulted from that of CO_2, with a simultaneously positive contribution from the retreat of ice sheets during 7.5–6 ka and a negative contribution from the orbital insolation throughout the past 7.5 ka. It is worth mentioning that relative to the average for 1750–1850 CE in the HT-ALL experiment, the annual GMST anomalies since 10 ka in the three single-forcing experiments do not sum to the anomaly in the all-forcing experiment in our HT-11.5ka simulations (Fig. 5), which holds true for the single- and all-forcing experiments in the CCSM3, LOVECLIM, and FAMOUS transient simulations (Smith and Gregory, 2012; Liu et al., 2014) and indicates a level of nonlinearity in the climate system.

5 Summary

The Holocene presents a host of opportunities to study the climate evolution over the latest interglacial period including the mean climate trend on the millennium scale and abrupt changes on the time scales from decades to centuries. The climate model provides a useful tool to investigate the underlying dynamic mechanism for the climate change during this well-studied reconstructed time period, in particular the improvements of the model and computational power make it possible to

run transient simulations to comprehensively understand the climate evolution in response to time-varying external forcings and feedbacks. Several modelling studies have begun this work, but most of them are performed with climate system models or Earth system models with low spatial resolutions and/or acceleration techniques to reduce computational resources.

420   Therefore, we have carried out a new set of unaccelerated transient experiments covering the whole Holocene since 11.5 ka (HT-11.5ka) using a comprehensive Earth system model with relatively high spatial resolutions, considering both the full-forcing and single-forcing effects of the main boundary conditions.

The HT-11.5ka simulations are run with the NCAR CESM1.2.1 with an atmospheric resolution of approximately 1.9° × 2.5° in the horizontal and 26 layers in the vertical and an oceanic resolution of approximately 1° and 60 levels in the horizontal

425   and vertical respectively. All simulations are spin up from the early Holocene at 11.5 ka and transiently run from 11.5 ka to the preindustrial period at 1850 CE with boundary conditions of Earth's orbital parameters, atmospheric GHGs, and ice sheets and orography that have been provided on the PMIP4 wiki for the transient deglaciation (PMIP Last Deglaciation Working Group, 2016; https://pmip4.lsce.ipsl.fr/doku.php/exp_design:degla). Four transient experiments are run in total, one all-forcing experiment forced by synchronously time-evolving orbital parameters, atmospheric GHGs, and ice sheets and

430   three single-forcing experiments forced by only one of the above forcings with the other two forcings fixed at 11.5 ka. The all-forcing simulation result shows a slight decrease of the annual GMST from 11.5 ka to 7.5 ka due to both ~~decreases~~ changes in orbital insolation and GHG concentrations, with an abrupt cooling at approximate 7.5 ka, which is followed by a continuous warming until the preindustrial period mainly resulted from increased GHG concentrations. Relative to the preindustrial period, both at global and zonal mean scales, the simulated annual and seasonal mean changes~~cooling~~

435   ~~magnitude~~ in ~~the GMST~~ surface air temperature at 6 ka are ~~is close to that from the median of the 14 PMIP4 model simulations and~~ within the range of values in the ~~individual~~ 14 PMIP4 model simulations and overall stronger than those from their arithmetic mean. The late Holocene warming trend simulated by CESM1.2.1 in our all-forcing simulation is consistent with that in the CCSM3, LOVECLIM, and FAMOUS transient simulations as shown in Liu et al. (2014), but inconsistent with the reconstructed cooling trend in Marcott et al. (2013) and Kaufman et al. (2020a).

440   The present HT-11.5ka transient simulations for the whole Holocene, spanning from 11.5 ka to the preindustrial period, are designed to investigate both combined and separated effects of the main external forcing of orbital insolation, atmospheric GHGs, and ice sheets on the climate evolution over the Holocene, which will be the supplement for the PMIP4 transient Core experiments for the last deglaciation from 21 to 9 ka (Ivanovic et al., 2016) and the PMIP4 Tier 3 transient simulations for the Holocene from 6 to 0 ka (Otto-Bliesner et al., 2017). Although these new set of transient Holocene simulations are

445   run with a high-resolution version of the comprehensive Earth system model, the meltwater flux change, solar irradiance and volcanic forcing, land-use and vegetation changes, dust and aerosol effects, and stratospheric chemistry and dynamics are not fully considered here, which will have some effects on the results. As a first step, this study provides the detailed model description, experimental design, boundary conditions, and some preliminary results for the new set of HT-11.5ka transient simulations. Further analyses on the simulation results including the mean climate evolution and abrupt climate changes over

450   the Holocene both at global and regional scales, the underlying dynamic mechanisms, and comparisons with other transient

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simulations covering the Holocene and multi-proxy-based reconstructions, will be carried out by a series of follow-up studies.

6 Code and data availability

All boundary condition data required for running the HT-11.5ka experiments (summarized in Tables 1 and 2) can be
455 downloaded from the PMIP4 last deglaciation wiki (PMIP Last Deglaciation Working Group, 2016; https://pmip4.lsce.ipsl.fr/doku.php/exp_design:degla). The CESM1.2.1 source code is available on the CESM official website (https://svn-ccsm-models.cgd.ucar.edu/cesm1/release_tags/cesm1_2_1). The initial ocean condition for the early Holocene spin-up experiment is obtained from NCAR model case "b40.1850.track1.2deg.003" and available from the CCSM4 input data archive (https://svn-ccsm-
460 inputdata.cgd.ucar.edu/trunk/inputdata/ccsm4_init/b40.1850.track1.2deg.003/0501-01-01/). The PMIP4 model output for the mid-Holocene and preindustrial experiments can be downloaded via the Earth System Grid Federation (ESGF; https://esgf-node.llnl.gov/search/cmip6/). The GMST data from the HT-11.5ka transient simulation shown in this study can be accessed at https://zenodo.org/record/6269566#.Yhg79OhBxLo (last access: 25 February 2022) and is are archived at https://doi.org/10.5281/zenodo.6269566. Other HT-11.5ka transient simulation data are available upon reasonable request to
465 the first author and can also be reproduced with the above code and boundary condition data.

Author contributions. D. Jiang conceived the idea and designed the HT-11.5ka experiments. B. Su collected all boundary condition data for the simulations, debugged the CESM1.2.1 model, and run the early Holocene spin-up simulation. B. Su and R. Zhang collaborated to perform the all-forcing and three single-forcing transient simulations. Z. Tian wrote the manuscript, processed the output data from all simulations, and produced the figures with contributions from all authors.

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

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Table 1. Summary of model boundary conditions for the early Holocene (11.5 ka) spin-up and Holocene transient (11.5 ka to 1850 CE) experiments; see text for details. Data are available from PMIP4 last deglaciation wiki (PMIP Last Deglaciation Working Group, 2016). Boundary condition group headings are in bold.

| Experiment type	Boundary conditions	Description
Early-Holocene (11.5 ka) spin-up	**Orbital parameters**	
	Eccentricity	0.01957212
	Obliquity	24.17958°
	Perihelion–180°	270.2132°
	Date of vernal equinox	Noon on 21 March
	Solar constant	1365 W m^{-2}
	GHGs	
	Carbon dioxide (CO_2)	267.4 ppm
	Methane (CH_4)	652.4 ppb
	Nitrous oxide (N_2O)	251.1 ppb
	Chlorofluorocarbon (CFC)	0
	Ozone (O_3)	Preindustrial (1850 CE)
	Ice sheets and orography	11.5 ka data from ICE-6G_C reconstruction (Argus et al., 2014; Peltier et al., 2015)
	All others	Prescribed preindustrial (1850 CE) levels
Holocene Transient (11.5 ka to 1850 CE; HT-11.5ka)	**Orbital parameters**	All orbital parameters should be transient as per Berger (1978)
	GHGs	Adjusted to the AICC2012 chronology (Veres et al., 2013)
	Carbon dioxide (CO_2)	Transient, as per Bereiter et al. (2015)
	Methane (CH_4)	Transient, as per Loulergue et al. (2008)
	Nitrous oxide (N_2O)	Transient, as per Schilt et al. (2010)
	Ice sheets and orography	Transient with ICE-6G_C reconstruction, updated every 250 years
	All others	As per early Holocene (11.5 ka) spin-up experiment

Table 2. Boundary conditions for HT-11.5ka experiments.

	Orbital parameters	GHGs	Ice sheets	Time span
HT-ALL	Transient	Transient	Transient	11.5 ka to 1850 CE
HT-ORB	Transient	Fixed at 11.5 ka	Fixed at 11.5 ka	11.5 ka to 1850 CE
HT-GHG	Fixed at 11.5 ka	Transient	Fixed at 11.5 ka	11.5 ka to 1850 CE
HT-ICE	Fixed at 11.5 ka	Fixed at 11.5 ka	Transient	11.5 ka to 1850 CE

835 **Table 3.** Global annual, DJF, and JJA mean surface air temperatures (units: °C) for the preindustrial period, mid-Holocene, and the difference between the mid-Holocene and preindustrial periods in simulations from the 14 PMIP4 models, their arithmetic mean (MMM), and HT-ALL. In the HT-ALL simulation, the preindustrial and mid-Holocene refers to the average for 1750–1850 CE and 6 ka ± 0.05 ka, respectively.

Model or simulation	Preindustrial			Mid-Holocene			Difference		
	Annual	DJF	JJA	Annual	DJF	JJA	Annual	DJF	JJA
AWI-ESM-1-1-LR	12.98	11.11	14.82	12.54	10.46	14.61	−0.44	−0.65	−0.21
CESM2	14.08	12.40	15.70	13.88	12.02	15.74	−0.20	−0.38	0.04
EC-Earth3-LR	13.29	11.28	15.33	13.09	10.87	15.39	−0.20	−0.41	0.06
FGOALS-f3-L	12.94	11.05	14.87	12.45	10.42	14.58	−0.49	−0.62	−0.29
FGOALS-g3	12.77	10.80	14.72	12.59	10.45	14.84	−0.18	−0.35	0.13
GISS-E2-1-G	13.81	12.25	15.45	13.42	11.73	15.23	−0.40	−0.52	−0.22
INM-CM4-8	13.24	11.27	15.22	12.99	10.85	15.17	−0.25	−0.42	−0.05
IPSL-CM6A-LR	12.59	10.67	14.50	12.20	9.99	14.38	−0.39	−0.67	−0.12
MIROC-ES2L	14.98	13.01	17.03	14.53	12.39	16.79	−0.45	−0.62	−0.24
MPI-ESM1-2-LR	13.52	11.75	15.29	13.13	11.18	15.14	−0.39	−0.58	−0.15
MRI-ESM2-0	13.86	12.25	15.51	13.62	11.81	15.50	−0.24	−0.44	−0.003
NESM3	13.74	11.68	15.74	13.44	11.34	15.49	−0.30	−0.33	−0.25
NorESM1-F	14.43	12.66	16.26	14.10	12.08	16.19	−0.34	−0.58	−0.06
NorESM2-LM	14.45	12.83	16.05	14.21	12.32	16.11	−0.24	−0.51	0.06
MMM	13.62	11.78	15.46	13.30	11.28	15.37	−0.32	−0.51	−0.09
HT-ALL	13.57	11.85	15.38	13.16	11.25	15.21	−0.41	−0.60	−0.17
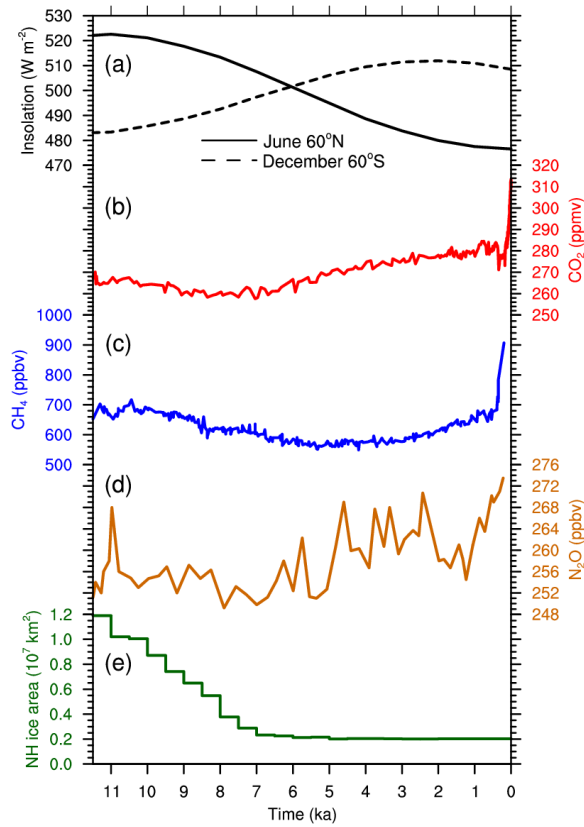
Figure 1: Temporal evolution of the external forcings in HT-11.5ka simulations since the early Holocene (11.5 ka) for (a) June insolation at 60°N (solid line) and December insolation at 60°S (dashed line) (Berger, 1978), (b) atmospheric CO_2 concentration (units: ppm) (recent composite of EPICA Dome C, Law Dome, and West Antarctic Ice Sheet Divide records, Antarctica; Bereiter et al., 2015), (c) atmospheric CH_4 concentration (EPICA Dome C, Antarctica; Loulergue et al., 2008), (d) Atmospheric N_2O concentration (Talos Dome, Antarctica; Schilt et al., 2010), and (e) area of the ice sheets in the Northern Hemisphere according to the ICE-6G_C reconstruction (Argus et al., 2014; Peltier et al., 2015).
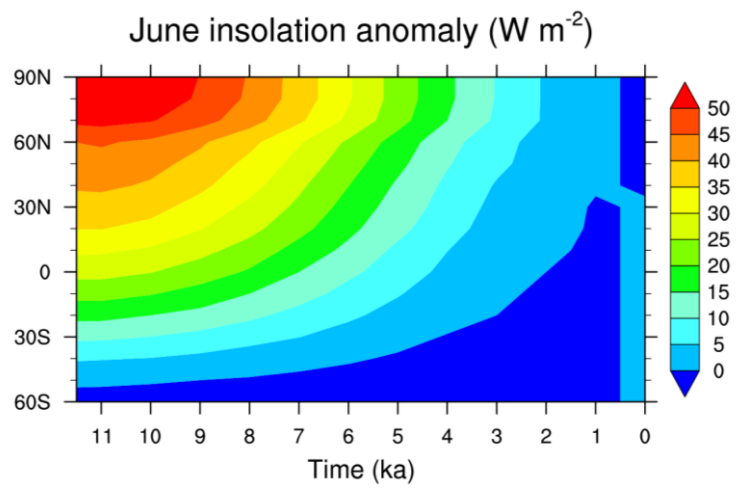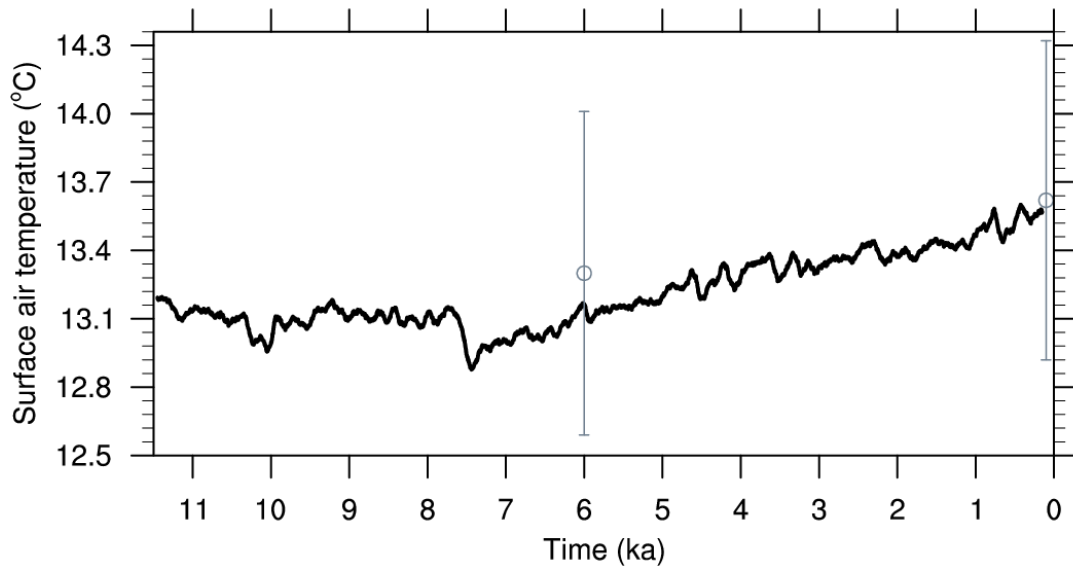
Figure 2: Latitude–time anomalies in June insolation relative to the average for the last 1000 years according to Berger (1978).
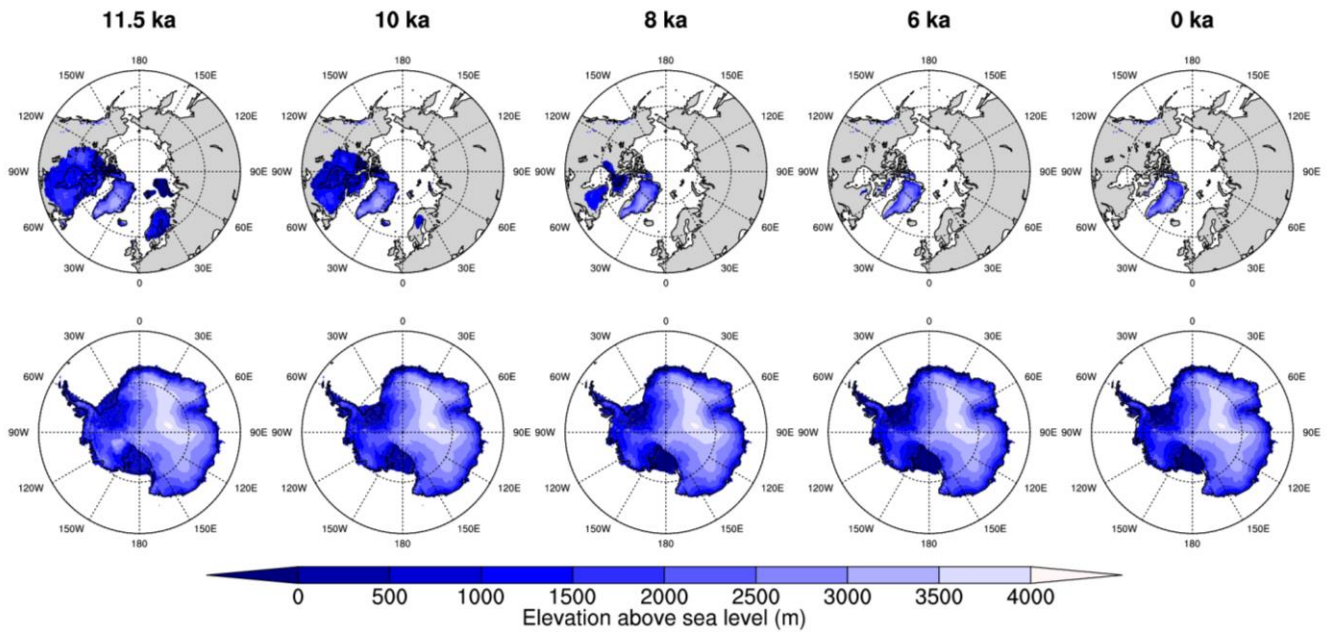
Figure 3: Northern (top) and Southern Hemisphere (bottom) ice sheet elevation at 11.5, 10, 8, 6 and 0 ka (1950 CE) for the ICE-6G_C reconstruction at 10 arcmin horizontal resolution; elevation is plotted where the fractional ice mask is more than 0.5 (Peltier et al., 2015).

Figure 4: Global annual mean surface air temperature since 11.5 ka under the all-forcing simulation. The time series is smoothed by a 101-year moving average. The ~~red~~ grey circles at 6 ka and 0.1 ka stand for the mid-Holocene and preindustrial results simulated by the ~~median~~ arithmetic mean of the 14 PMIP4 models, with ~~red~~ grey vertical error bars representing plus and minus one standard deviation for 14 models.
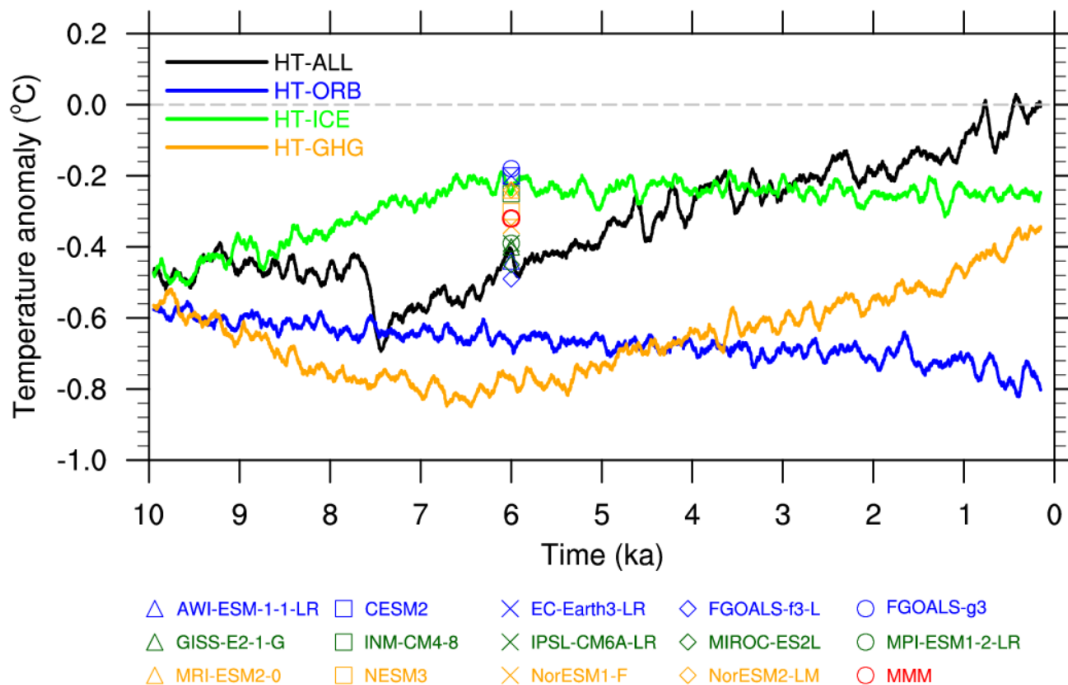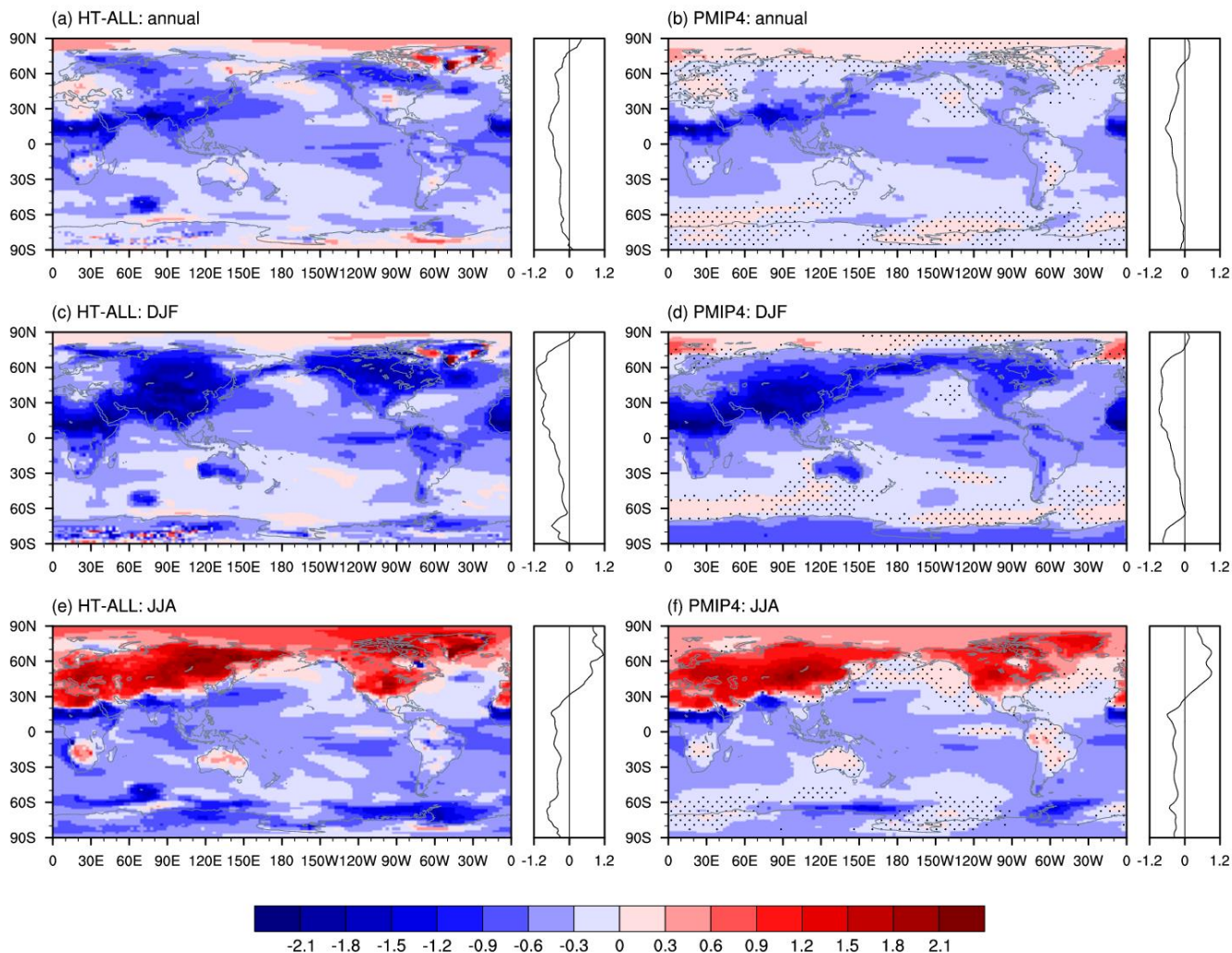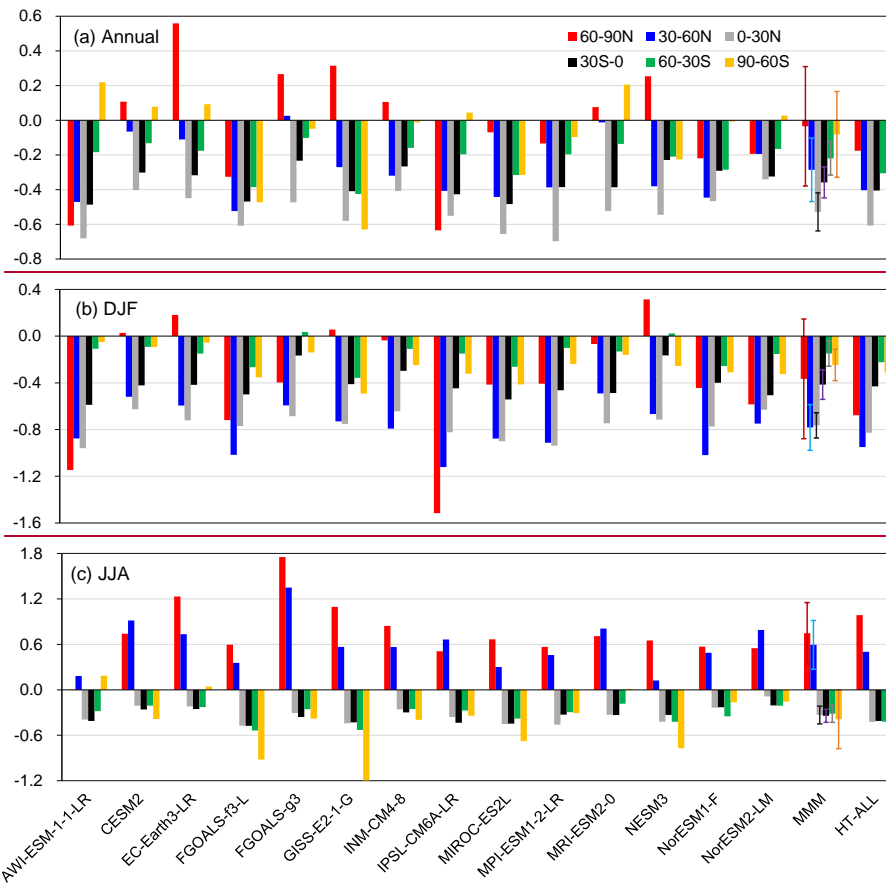
Figure 5: Global annual mean surface air temperature anomaly since 10 ka under the all-forcing (HT-ALL, black) and the single-forcing (HT-ORB, blue; HT-ICE, green; and HT-GHG, orange) simulations relative to the last ~~100~~101 years of the all-forcing simulation. All of the time series are smoothed by a 101-year moving average. The triangle, square, cross, diamond, and circle symbols at 6 ka stand for the mid-Holocene minus preindustrial results simulated by the 14 PMIP4 models and their multi-model arithmetic mean~~median~~ (MMM).

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Figure 6: Changes in (a, b) annual, (c, d) DJF, and (e, f) JJA mean surface air temperatures (units: °C) (a, c, e) between the averages for 6 ka ± 0.05 ka and the last 101 years (i.e., 1750–1850 CE) in the HT-ALL simulation and (b, d, f) between the mid-Holocene and preindustrial simulations in the arithmetic mean of the 14 PMIP4 models as listed in Figure 5. The zonal mean changes are shown on the right of each panel. The dotted areas in (b, d, f) represent less than 70% of the PMIP4 models agree with the sign of multi-model mean change.

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Figure 7: Zonal averaged changes in (a) annual, (b) DJF, and (c) JJA mean surface air temperatures (units: °C) between the mid-Holocene and preindustrial simulations in the 14 PMIP4 models and their arithmetic mean (MMM) as well as between the averages for 6 ka ± 0.05 ka and the last 101 years (i.e., 1750–1850 CE) in the HT-ALL simulation. Red, blue, grey, black, green, and orange bars represent the changes averaged over the zonal bands of 60°–90°N, 30°–60°N, 0°–30°N, 30°S–0°, 60°–30°S, and 90°–60°S, respectively. The error bar for the multi-model mean change represents plus and minus one standard deviation for the 14 PMIP4 models.