

# Global Patterns of Increasing Interannual Variability of Surface Air Temperature throughout the Holocene

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**ABSTRACT:** We examine the interannual variability of surface air temperature throughout the Holocene and the associated mechanisms by using our new set of Holocene transient simulations spanning from 11.5 ka before present to the preindustrial period. The interannual variability of annual, winter, and summer temperature increases with a linear trend of 0.005°, 0.007°, and 0.005°C ka<sup>-1</sup> globally since 11.5 ka, respectively. The temperature variability evolution can be explained by the orbital forcing in most regions, with an additional impact from the retreat of ice sheets over North America and Europe but, overall, little effect from the change in atmospheric greenhouse gas concentrations. In response to the insolation change from the early to late Holocene, primarily due to the precession, variations in energy balance components contribute to the enhanced temperature variability by a global mean of 8%–10%. Specifically, surface net heat flux and radiation flux at the top of atmosphere generally play dominant roles, while atmospheric energy convergence minus storage partially offsets them at the global scale. Regionally, cloud effects and sea surface temperature variability are important in low latitudes, while sea ice changes are the main factors in mid- to high-latitude oceans. Due to the seasonal contrast in insolation, various responses of global surface mean temperature and its meridional gradient, sea ice fraction, total cloud, and surface soil moisture result in the seasonal difference in temperature variability change, particularly in the Arctic Ocean and northern continents. The simulated temperature variability change throughout the Holocene is qualitatively consistent with most of the available proxy data, although uncertainties still exist on both sides.

**SIGNIFICANCE STATEMENT:** The purpose of this article is to investigate the year-to-year variability of surface air temperature throughout the Holocene from a global perspective. This is important because enhanced temperature variability increases the risk of cold and warm extremes, causing more profound socioeconomic impacts than the mean state. Based on our new set of Holocene transient simulations spanning from 11.5 ka before present to 1850, the results display a globally increasing variability of annual and seasonal temperatures since 11.5 ka primarily due to the orbital forcing. Associated mechanisms, including cloud effects, sea surface temperature variability, and sea ice changes, are highlighted from an energy balance decomposition. This study deepens our understanding of the evolution and mechanism of global temperature variability under warming backgrounds.

**KEYWORDS:** Energy budget/balance; Paleoclimate; Surface temperature; Coupled models; Numerical analysis/modeling; Climate variability

## 1. Introduction

Temperature variability refers to the oscillation amplitude of temperature around its mean state at various temporal and spatial scales, which is one of the main indicators of climate, and its change can be regarded as climate stability. It is closely linked with extreme temperature events, and its impact on the environment, economy, and agriculture is more important than the mean state (Katz and Brown 1992; Mustin et al. 2013; Thornton et al. 2014; Seddon et al. 2016). Among its various time scales, temperature variability on the interannual time scale, a focus of the Climate and Ocean: Variability, Predictability and Change

(CLIVAR) project launched by the World Climate Research Programme (WCRP) (CLIVAR Scientific Steering Group 1995), is particularly noteworthy. There is scientific consensus on a global increase of surface temperature in the past few decades (Gulev et al. 2021), and the warming trend tends to continue in the future (Lee et al. 2021). However, whether the observed warming has caused the temperature to be more variable (Hansen et al. 2012) or more stable (Huntingford et al. 2013; Rhines and Huybers 2013), and, more importantly, how temperature variability will change in a warmer future (Brown et al. 2017; Bathiany et al. 2018; Olonscheck et al. 2021; Shi et al. 2024), are still controversial topics. In this context, investigating the temperature variability during past warm periods in Earth's history, especially at the interannual scale, offers a good opportunity to understand its future trend and mechanisms.

The Holocene, which began around 11.5 thousand years ago (ka), is the recent interglacial epoch in the Quaternary. The warmest interval (between about 6 and 7 ka ago) of the Holocene is

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estimated to be 0.2°–1.0°C warmer than 1850–1900 (Gulev et al. 2021). Distinct global environment variations have occurred during this period, primarily caused by insolation changes due to altered orbital parameters of the Earth, the retreat of continental ice sheets, and varied atmospheric concentrations of greenhouse gases (GHGs) (Mayewski et al. 2004). The Holocene is an important period for the development of human civilization, as well as a relatively stable period of climate change in Earth's history. The global mean surface temperature overall increases from the early Holocene (e.g., Koerner and Fisher 1990; Wang et al. 2005; Shakun et al. 2012) to the mid-Holocene (e.g., Shi et al. 1994; Kaufman et al. 2004; Wanner et al. 2008; Zhou et al. 2016). Then, the temperature has declined (Marcott et al. 2013; Kaufman et al. 2020a; Dong et al. 2022; Zhang et al. 2022) or continued to rise during the late Holocene (Liu et al. 2014; Baker et al. 2017; Liu et al. 2018; Marsicek et al. 2018) as inferred from various reconstructions or simulations, which is the so-called “Holocene temperature conundrum” that remains unresolved (Osman et al. 2021; Chen et al. 2024; Jiang et al. 2024). Superimposed on the above long-term climate trends at millennial scales are several rapid cooling events across decadal to centennial time scales (Wanner et al. 2011; Walker et al. 2012). The rapid climate change and temperature variabilities are directly related to human survival and development. For example, the Holocene climate anomalies, including temperature and hydrological changes, may have directly led to the decline of ancient world civilizations and the replacement of historical dynasties (e.g., Yan et al. 2015). Overall, the Holocene provides us an ideal platform to study how temperature variability evolves throughout the current interglacial period in response to different external forcings.

Early records of ice cores, loess, stalagmites, and marine sediments have indicated that there were large modifications in climate variability between glacial and interglacial periods, and the temperature variability during the Quaternary glacial period was notably greater than the interglacial level (Schulz et al. 2004; Jouzel et al. 2007). More recently, a network of terrestrial and marine temperature proxies displayed that the temperature variability on centennial scales reduced globally by a factor of 4 with a warming trend from the last glacial maximum to the Holocene, with even greater declining trends in mid- and high latitudes, which was explained by variations in meridional temperature gradient (Rehfeld et al. 2018). Our recent modeling studies, based on multiple climate models within the framework of the Paleoclimate Modelling Intercomparison Project phases 3 and 4 (PMIP3/4), further revealed a globally enhanced temperature variability on the interannual scale during the last glacial maximum (J. Shi et al. 2022) and a summer amplification during the last interglacial period with respect to the preindustrial period (Shi et al. 2025). Most research on the Holocene temperature variability covering at least the past 4000 years has been performed on the basis of ice core records, pollen, corals, or marine sediments across various time scales. More specifically, the surface temperature variability was inferred to be relatively small from 11.7 ka to the present at the millennial scale from the North Greenland Ice Core Project (NGRIP) record (Shao and Ditlevsen 2016), whereas it was considerably large for the past 4000 years derived from the snow

temperature of another Greenland ice core record at Greenland Ice Sheet Project 2 (GISP2) (Kobashi et al. 2011) and over the past 8000 years from multiproxy sea surface temperature (SST) records (Laepple and Huybers 2014) at decadal or longer time scales. A recent work with transient Holocene simulations from nine climate models and 120 proxy records found dominant multicentennial temperature variability during the Holocene (Askjær et al. 2022), but only with an emphasis on peak frequencies at the centennial time scale. Studies ranging from interannual to millennial time scales have suggested that both simulated and reconstructed Holocene temperature variabilities, as well as their discrepancies, generally increase with time scales, which is probably due to the marine influence (Zhu et al. 2019; Hébert et al. 2022; Laepple et al. 2023). Of note is that previous work on the Holocene temperature variability at the interannual time scale has mostly focused on the last millennium, using both simulations to examine the influence of various forcings (e.g., Otto-Bliesner et al. 2016) and reconstructions based on tree rings, corals, speleothems (e.g., Franke et al. 2013; Parsons et al. 2017; Bühler et al. 2021), or multiproxy compilations (e.g., Fernández-Donado et al. 2013; PAGES 2k Consortium 2019; Zhu et al. 2019). Overall, existing studies on the year-to-year temperature variability evolution covering the whole Holocene are rare and, in particular, lack an examination of the seasonal differences and associated mechanisms from the modeling perspective.

Therefore, here we use our new set of Holocene transient simulations, with all and single external forcings, to examine the global-scale evolution of interannual temperature variability throughout the Holocene, with emphases on the seasonal differences and the underlying mechanisms from the energy balance perspective, and to compare the simulation results with available reconstructions in a qualitative manner. This paper is structured as follows. Data, methods, and model evaluation are described in section 2. The global trend of interannual variability of temperature throughout the Holocene is displayed in section 3, followed by the associated physical mechanisms in section 4. The model–data comparison is presented in section 5, with conclusions and discussion given in the last section.

## 2. Data and methods

### a. Data

We use the monthly output data from our newly finished set of Holocene transient simulations spanning from 11.5 ka to 1850 (hereinafter HT-11.5 ka) for analysis, which were performed by a global fully coupled Community Earth System Model, version 1.2.1 (CESM1.2.1; Hurrell et al. 2013), with relatively fine resolutions. Specifically, the atmosphere and land components use a grid resolution of approximately 1.9° latitude  $\times$  2.5° longitude, while the ocean and sea ice components share a horizontal grid of approximately 1°, vertically with 26 layers in the atmosphere and 60 levels in the ocean. The HT-11.5 ka simulations include four transient experiments: three single-forcing experiments separately forced by time-evolving boundary conditions of Earth's orbital parameters (HT-ORB), GHG concentrations (HT-GHG), and ice sheets and orography (HT-ICE),

keeping the other two forcings prescribed at 11.5 ka, and one experiment with all above forcings varying with time (HT-ALL). The orbital forcing (i.e., the three orbital parameters of obliquity, eccentricity, and longitude of perihelion) follows [Berger \(1978\)](#) and is dominated throughout the Holocene by the precession. Based on it, the solar radiation distribution at the top of the atmosphere (TOA) depending on season and latitude is prescribed. The time-varying GHGs include atmospheric carbon dioxide ([Bereiter et al. 2015](#)), methane ([Loulergue et al. 2008](#)), and nitrous oxide ([Schilt et al. 2010](#)). The ice sheet extent and orography were transient following the ICE-6G\_C reconstruction ([Argus et al. 2014](#); [Peltier et al. 2015](#)), with prominent changes occurring over the Laurentide and Eurasian ice sheets. Other forcings, e.g., the land–sea distribution, dust, meltwater, volcanic forcing, and vegetation, are fixed at 1850. Altogether, each of the four experiments was transiently run from 11.5 ka to 1850 for 11 400 years (0 ka is 1950). More details about the model components, boundary conditions, and experimental design for the HT-11.5 ka simulations can be found in [Tian et al. \(2022\)](#).

To assess the performance of CESM1.2.1 in simulating the preindustrial interannual temperature variability, we use the monthly surface air temperatures from the Berkeley Earth Surface Temperature (BEST) Project ([Rohde et al. 2013a,b](#)), which are established from observations at 44 455 stations globally with a grid resolution of 1.0°. Due to the data availability, the period 1950–2000 is chosen for observation to qualitatively compare with 1800–50 for the model. Observation data are regridded to the model's horizontal resolution of  $\sim 1.9^\circ \times 2.5^\circ$  (latitude  $\times$  longitude) using an area-based interpolation algorithm.

### b. Methods

The whole Holocene of 11 400 years from the HT-11.5 ka experiments is used for analysis. Based on the annual and seasonal means of the time series, we use a 9-yr high-pass Lanczos filter ([Duchon 1979](#)) to extract the interannual signal. The temperature variability for each year is then quantified as a 101-yr sliding standard deviation based on 50 years before and after that year, which results in the loss of the first and last 50 years from the original time series. The linear trend for the time series throughout the Holocene, which is not sensitive to the size of the sliding window, and its statistical significance are examined by the Mann–Kendall test ([Kendall 1955](#); [Mondal et al. 2012](#)). The involved seasons include December–February (DJF) and June–August (JJA) without calendar adjustment, which should have small effects on our conclusions ([X. Shi et al. 2022](#)). For convenience, winter hereinafter refers to DJF in the Northern Hemisphere and JJA in the Southern Hemisphere, and summer refers to JJA in the Northern Hemisphere and DJF in the Southern Hemisphere.

To quantitatively diagnose the contribution of various factors to temperature variability during the Holocene, the energy balance method from [Räisänen \(2017\)](#) is applied. For an atmospheric column, the surface air temperature anomaly ( $\Delta T$ ) can be decomposed as

$$\Delta T = LW + SW + SURF + CONV + ERR, \quad (1)$$

where LW denotes the temperature anomaly due to the TOA upward longwave radiation, SW represents that caused by TOA net shortwave radiation, SURF that due to surface net downward heat flux, CONV that caused by horizontal energy flux convergence minus local energy storage in the atmosphere, and ERR is the residual term that is negligible (with an average absolute value less than  $10^{-3}^\circ\text{C}$ ).

SURF can be further decomposed as

$$SURF = \uparrow SW - \downarrow SW + \uparrow LW - \downarrow LW + LH + SH, \quad (2)$$

where  $\uparrow SW$  and  $\downarrow SW$  denote the upward and downward shortwave radiations,  $\uparrow LW$  and  $\downarrow LW$  denote the upward and downward longwave radiations, and LH and SH denote the upward latent and sensible heat fluxes at the surface, respectively.

Additionally, according to [Taylor et al. \(2007\)](#), SW and LW can be further divided into three components as

$$SW = SW_{\text{clear}} + SW_{\text{c-c}} + SW_{\text{p-c}}, \quad (3)$$

$$LW = LW_{\text{clear}} + LW_{\text{c-c}} + LW_{\text{p-c}}, \quad (4)$$

where the three terms on the right-hand side of both equations represent the TOA radiation flux anomaly without considering cloud effects, the contribution of cloud fraction perturbations (with all other radiation properties kept unchanged), and the differential anomalies due to the presence of clouds (with total cloud fraction remained unchanged), respectively.

Finally, following [Räisänen \(2017\)](#), we perform a standard deviation decomposition to relate the temperature variability anomaly with the atmospheric energy balance as follows:

$$SDC_i = \frac{\text{Cov}(\Delta T_i, \Delta T)}{SD(\Delta T)} = \frac{\text{Cov}(\Delta T_i, \Delta T)}{SD(\Delta T)SD_i} SD_i = r_i SD_i, \quad (5)$$

where  $\Delta T_i$  represents the term  $i$  on the right-hand side of Eq. (1),  $\text{Cov}(\Delta T_i, \Delta T)$  is the covariance between the term  $i$  and the temperature anomaly,  $r_i$  is the correlation coefficient between them,  $SD_i$  and  $SD(\Delta T)$  are their respective standard deviations, and  $SDC_i$  is the contribution of the term  $i$  to the standard deviation of temperature anomaly. According to the correlation coefficient definition, the sum of the SDCs for all energy balance terms equals the standard deviation of temperature anomaly, which is written as

$$\sum_i SDC_i = SD(\Delta T). \quad (6)$$

This method was proposed by [Räisänen \(2017\)](#) to decompose contributions of various energy balance components to interannual temperature variability changes both globally and regionally, which is convenient to apply in long-term transient simulations and reanalysis datasets ([Räisänen 2019](#)) since only two-dimensional surface and TOA model output is needed.

### c. Model evaluation

The performance of CESM1.2.1 for the climatology of interannual temperature variability during 1800–50 in the

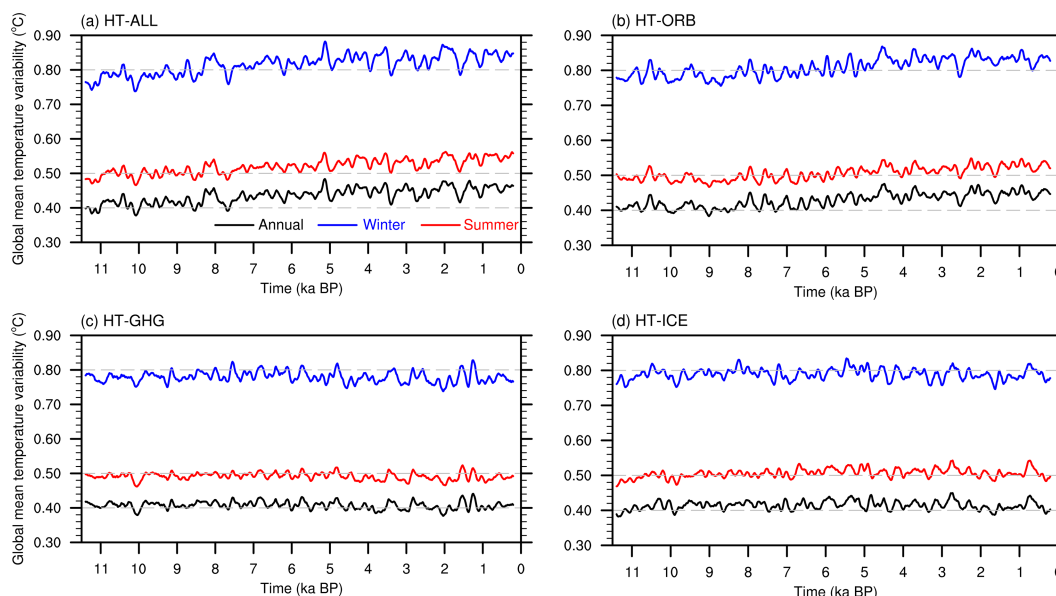


FIG. 1. Global mean SD of surface air temperature ( $^{\circ}\text{C}$ ) since 11.5 ka in the (a) HT-ALL, (b) HT-ORB, (c) HT-GHG, and (d) HT-ICE simulations. The time series is smoothed by a 101-yr running average, with black, blue, and red curves representing annual, winter, and summer means, respectively.

HT-ALL simulation is evaluated against the observation during 1950–2000. The observed geographical distribution is well reproduced by the model, showing high variabilities at mid-to high latitudes and low values in the tropics annually and seasonally, and an overall larger variability in winter than in summer (Fig. S1 in the online supplemental material). Based on the 13 824 model grid points over the globe, the spatial correlation coefficient between the simulation and observation is 0.80 for the annual mean, 0.84 in winter, and 0.63 in summer, all of which are statistically significant at the 99% confidence level using the Student's  $t$  test. However, the model generally overestimates the observed variability by a global average of  $0.07^{\circ}$ ,  $0.16^{\circ}$ , and  $0.06^{\circ}\text{C}$  for annual, winter, and summer means, respectively, particularly at high latitudes. This discrepancy could be partly caused by the different time periods used for comparisons between the model and observation. Altogether, the HT-All simulation has reasonable ability for the spatial pattern and magnitude of the climatological interannual temperature variability. In addition, the simulated annual and seasonal mean temperature changes between the mid-Holocene and preindustrial period also lie within the range of the 14 PMIP4 model results for both global and zonal means (Tian et al. 2022). This further adds our confidence in following analyses on the Holocene temperature variability that relates with the mean temperature.

### 3. Trends of interannual temperature variability throughout the Holocene

In the HT-ALL simulation, the interannual variability of surface air temperature gradually enhances over the globe since 11.5 ka (Fig. 1a). Its globally averaged value increases with a linear trend of  $0.005^{\circ}$ ,  $0.007^{\circ}$ , and  $0.005^{\circ}\text{C ka}^{-1}$  throughout the

Holocene for the annual, winter, and summer means, respectively, all of which are statistically significant at the 90% confidence level. Note that the above trend is mainly determined by the first half of the Holocene until about 5 ka on both annual and seasonal scales, with overall little trend over the last 4000–5000 years. Regionally, the annual temperature variability has increased since 11.5 ka worldwide except for parts of Eurasia, North Africa, East Antarctica, the Indian Ocean, and the Southern Ocean (SO) (Fig. 2a). The evolution in winter is similar to the annual pattern except for North Africa (Fig. 2b). Excluding the northern North America and the tropical eastern Pacific, winter trends are generally larger than the annual and summer means, especially for the decrease ( $< -0.03^{\circ}\text{C ka}^{-1}$ ) over northern Eurasia and the increase ( $> 0.04^{\circ}\text{C ka}^{-1}$ ) over the North Atlantic (NA), the Arctic, and the Southern Oceans. Prominent rising and declining trends in summer occur over North America and from North Africa to the Arabian Peninsula (NAAP), respectively (Fig. 2c). The regional trends are statistically significant at the 95% confidence level almost everywhere.

### 4. Physical mechanisms

The global increase trend of the interannual temperature variability throughout the Holocene in the HT-ALL simulation is mostly due to the orbital forcing dominated by the precession, with overall little effect from changes in ice sheets and atmospheric GHGs (Fig. 1). In the HT-ORB simulation, both the spatial distribution and magnitude of the linear trend resemble those in the HT-ALL simulation, with a global average trend of  $0.005^{\circ}$ ,  $0.006^{\circ}$ , and  $0.004^{\circ}\text{C ka}^{-1}$  for the annual, winter, and summer means, respectively (Figs. 2d–f), which is also dominated by the trend over the first half of the Holocene



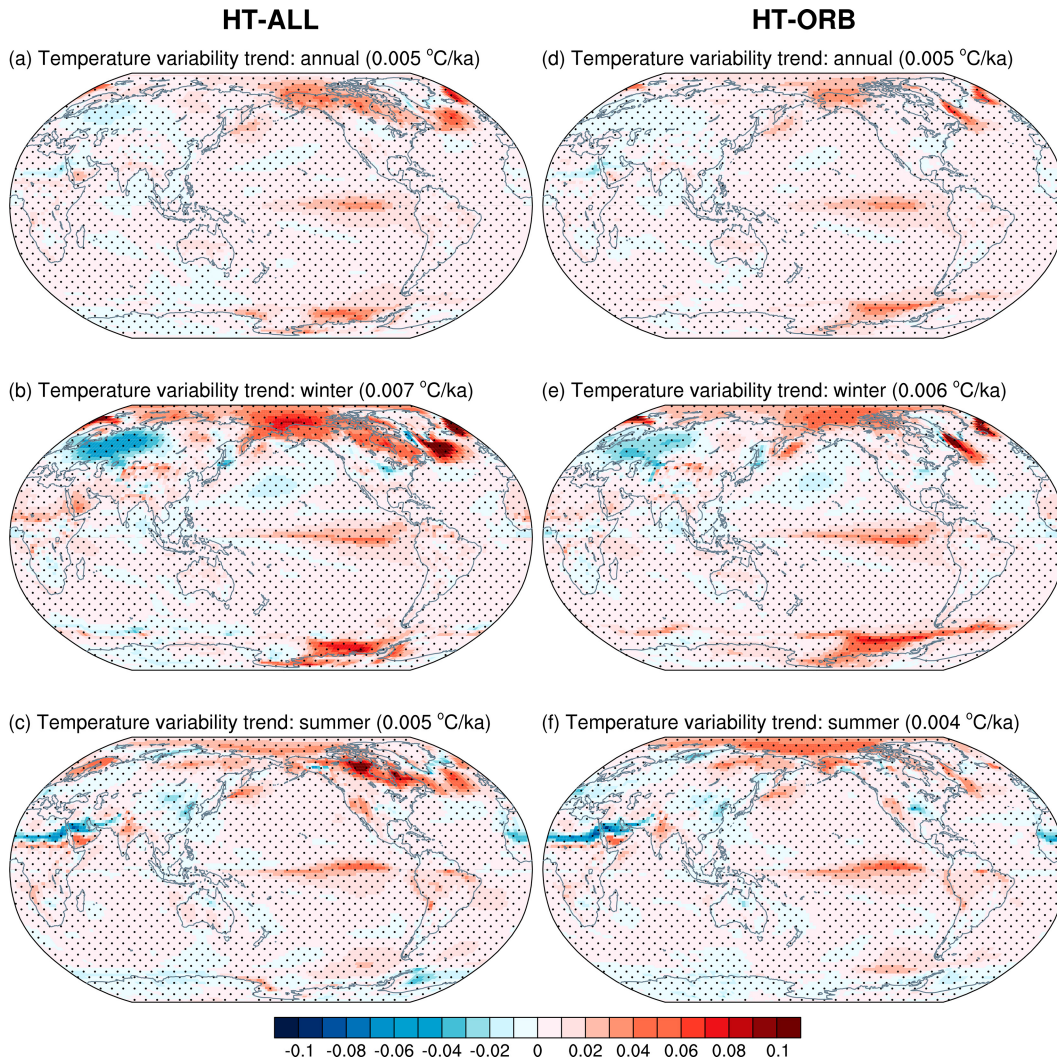


FIG. 2. Linear trend ( $^{\circ}\text{C ka}^{-1}$ ) of the interannual variability (i.e., SD) of (a),(d) annual, (b),(e) winter, and (c),(f) summer temperature since 11.5 ka in the (a)–(c) HT-ALL and (d)–(f) HT-ORB simulations. Black dots indicate the regions with statistically significant trends at the 95% confidence level. The global average trends are given in parentheses.

(Fig. 1b). Additionally, the gradual increase of the Holocene temperature variability over North America and Europe is mainly caused by the retreat of the Laurentide and Eurasian ice sheets (Dyke 2004; Gyllencreutz et al. 2007), respectively, with rising trends of less than  $0.03^{\circ}\text{C ka}^{-1}$  in winter and larger than  $0.05^{\circ}\text{C ka}^{-1}$  in summer in the HT-ICE simulation (Figs. S2e,f). The ice sheet melting, mostly occurring during the early Holocene, can affect the local temperature variability via the snow–albedo and snow–hydrological effects (Barnett et al. 1989; Yasunari et al. 1991) by modulating the surface net shortwave radiation and sensible/latent heat flux, respectively (J. Shi et al. 2022, 2024). The overall increase in atmospheric GHGs during the Holocene has no detectable impact either globally or regionally (Figs. S2a–c). We speculate that, due to its uniform distribution, GHG should have a global climate effect on the mean state and mostly result in thermodynamic changes, with limited impact on the temperature variability.

By contrast, the orbital forcing has a strong regional and seasonal pattern, which may lead to large dynamical changes and thus notable influences on the variability.

Considering that the interannual temperature variability has continuously increased from 11.5 ka to 1850 in the HT-ALL simulation, particularly from 11.5 to  $\sim 5$  ka, and the orbital forcing plays a dominant role (Figs. 1a,b), we choose two periods, i.e., the early Holocene (10–9 ka) with high northern insolation and the late Holocene (2–1 ka) with low northern insolation in summer, for further investigations. It is worth mentioning that slight variations for the choice of time periods have little influence on our primary conclusions. To connect the temperature variability change with various energy balance components in response to the orbital forcing, we calculate their contributions to the standard deviation of temperature (SDCs) for the globe, global land, and global ocean (Fig. S3) based on Eq. (1). Note that, different from the absolute value of the

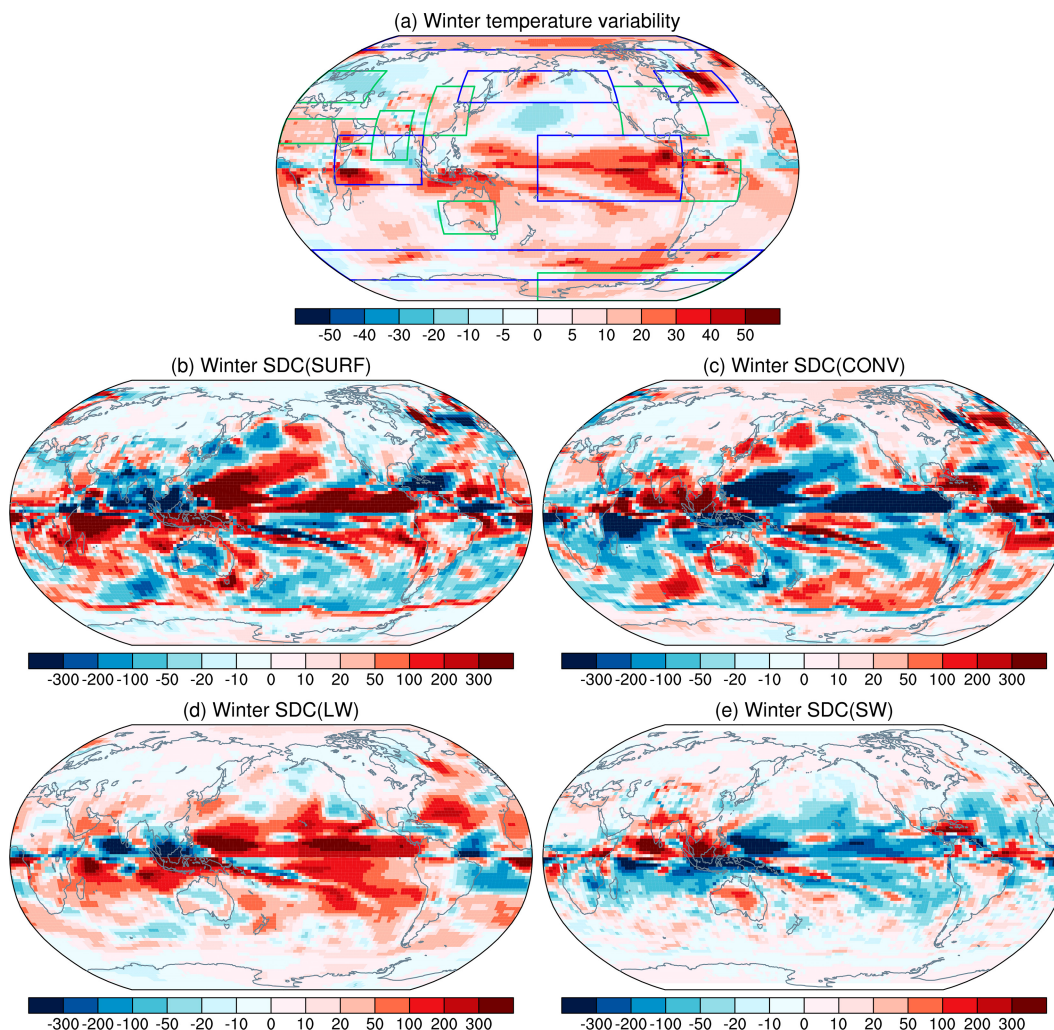


FIG. 3. Winter (a) temperature variability fractional change (%) between the late (2–1 ka) and early Holocene (10–9 ka) and the contributions (%) of the (b) surface net downward heat flux (SURF), (c) CONV, (d) TOA upward longwave radiation, and (e) TOA net shortwave radiation in the HT-ORB simulation. The green borders in (a) enclose the eight land regions, and the blue borders denote ranges of the six ocean regions as defined in Fig. 5 for a further analysis.

linear trend as shown in Fig. 2, fractional changes are displayed in Fig. S3 (also in the following Figs. 3a and 9a) for the temperature standard deviation difference between the two chosen periods. From the early to late Holocene, the interannual variability of annual, winter, and summer temperature increases by 10%, 8%, and 9% globally in the HT-ORB simulation, respectively, with overall larger increases over oceans than over land possibly due to the missing vegetation feedback. Except for global land in summer, both SURF and LW are main contributors to the annual and seasonal enhancement, with partially counteracting effects from CONV and SW. Both over land or oceans, the impact of LW is more pronounced in winter than for the annual and summer means. Since the spatial distribution and factors of winter temperature variability resemble the annual mean, the subsequent analysis will focus on orbital-induced winter changes between the late and early

Holocene and highlight the mechanisms driving seasonal differences, and regions where temperature variability changes exceed 10% will be specifically analyzed. Also note that the impacts of  $LW_{c-c}$  and  $LW_{p-c}$  or  $SW_{c-c}$  and  $SW_{p-c}$  are similar in most regions for both seasons (Figs. S4 and S5), so they will be jointly referred to as  $LW_{cloud}$  or  $SW_{cloud}$  to represent the cloud effect on TOA longwave or shortwave radiation.

In addition, thermal advection can affect the temperature variability primarily via changes in the mean meridional temperature gradient (Schneider et al. 2015; Holmes et al. 2016; Rehfeld et al. 2018), which could facilitate the generation and development of baroclinic instability (J. Shi et al. 2022) and modulate the atmospheric horizontal energy flux convergence (Räisänen 2019). Atmospheric circulation changes can also impact thermal advection and thus the temperature variability. However, there is larger uncertainty in both the direction and



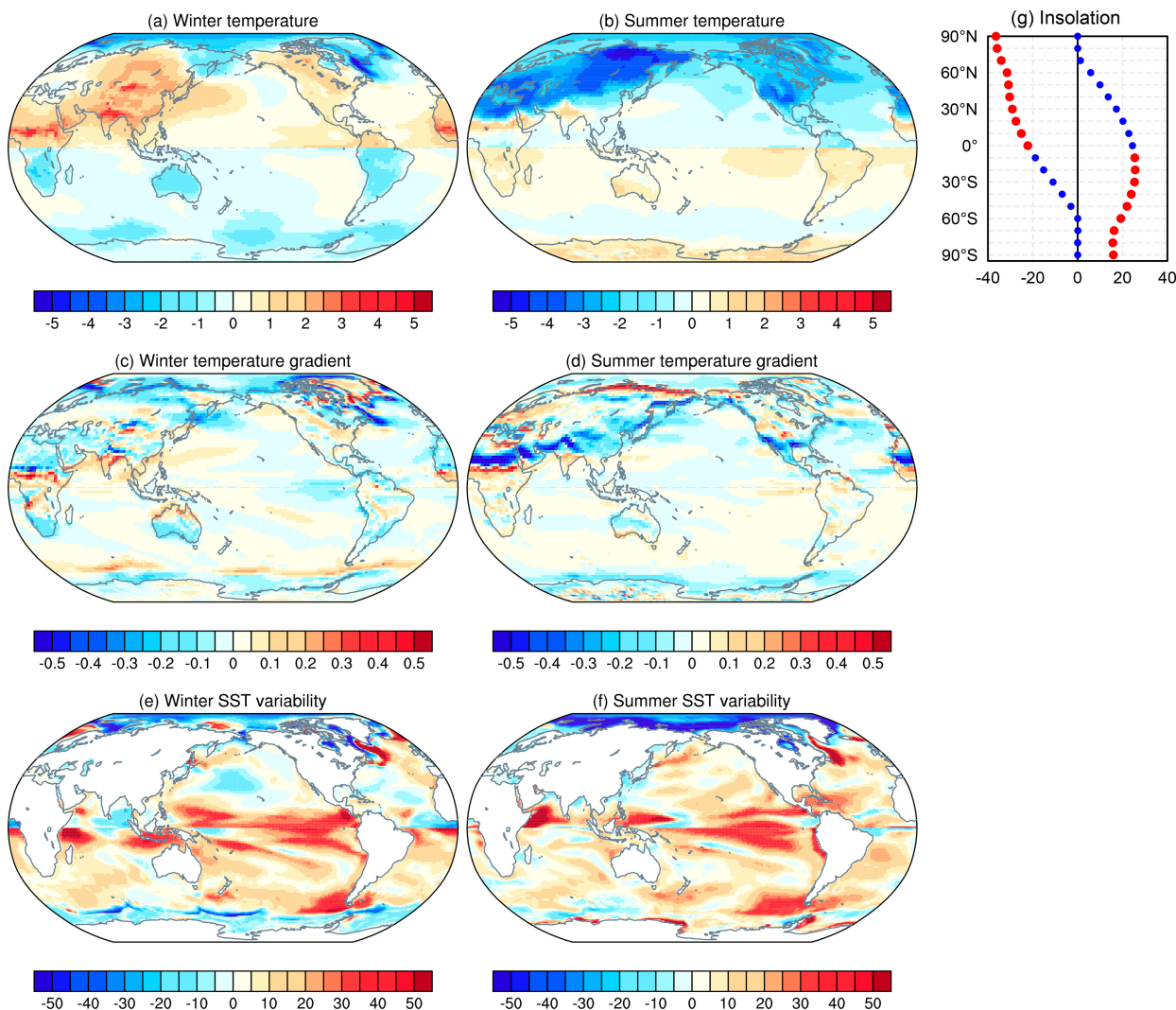


FIG. 4. Late Holocene minus early Holocene changes in (left) winter and (center) summer (top) mean surface air temperature ( $^{\circ}\text{C}$ ), (middle) meridional gradient of surface air temperature ( $10^{-2} \text{ }^{\circ}\text{C km}^{-1}$ ), (bottom) interannual variability of SST (%), and (g) insolation ( $\text{W m}^{-2}$ ; blue and red dots represent winter and summer zonal means) in the HT-ORB simulation.

cause of circulation changes than in the case of the temperature gradient (Holmes et al. 2016). Therefore, in the following sections, we will focus on the contributions of various energy balance components to the temperature standard deviation change between the late and early Holocene, with an additional role from the meridional temperature gradient in specific regions.

#### a. Mechanisms of winter temperature variability

Relative to the early Holocene, the interannual variability of winter temperature increases notably in oceans during the late Holocene, particularly over the tropical Pacific, the southern Indian Ocean, the northern North Atlantic, and the Southern Ocean by 30%–50% (Fig. 3a). In tropical oceans, the variability of surface air temperature is highly correlated with that of SST (Fig. 4e), with a positive and statistically significant spatial

correlation coefficient of 0.91 within  $30^{\circ}\text{S}$ – $30^{\circ}\text{N}$ . In the tropical east Pacific (TEP), there is an obvious increase in SST variability, consistent with an overall strengthening of El Niño–Southern Oscillation (ENSO) from the early to late Holocene (White et al. 2018; Carré et al. 2021), which is primarily attributed to the intensified Bjerknes thermocline feedback (Z. Lu et al. 2019) in relation to changes in Asian and African monsoon precipitation (Fig. S6) and the associated large-scale east–west circulation in response to the precessional forcing (Tian et al. 2017). The late-Holocene strengthened SST variability intensifies air–sea coupling and increases the variability of net surface heat flux (Fig. S7a) mainly through the effects of downward shortwave radiation, the upward longwave radiation, and the latent heat flux, contributing to the enhanced temperature variability there (Figs. 5c and 6). In contrast, CONV primarily acts to disperse heat and suppresses the air temperature variability during the

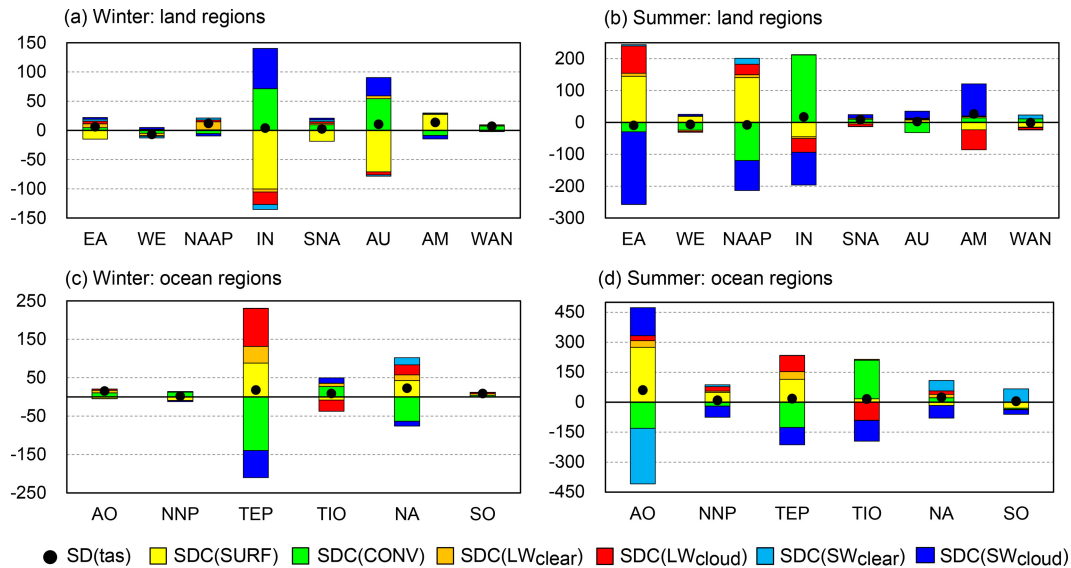


FIG. 5. Contributions (%) of the surface net downward heat flux (SURF; yellow bar), CONV (green bar),  $LW_{clear}$  (orange bar),  $LW_{cloud}$  (red bar),  $SW_{clear}$  (cyan bar), and  $SW_{cloud}$  (blue bar) to the temperature SD fractional difference (%; black dot) between the late and early Holocene for (a), (c) winter and (b), (d) summer means over (a) and (b) land and (c) and (d) ocean regions in the HT-ORB simulation. Shown are eight land regions: EA ( $20^{\circ}$ – $50^{\circ}$ N,  $100^{\circ}$ – $130^{\circ}$ E), WE ( $40^{\circ}$ – $60^{\circ}$ N,  $0^{\circ}$ – $50^{\circ}$ E), NAAP ( $15^{\circ}$ – $30^{\circ}$ N,  $0^{\circ}$ – $65^{\circ}$ E), IN ( $5^{\circ}$ – $35^{\circ}$ N,  $65^{\circ}$ – $90^{\circ}$ E), SNA ( $20^{\circ}$ – $50^{\circ}$ N,  $60^{\circ}$ – $120^{\circ}$ W), AU ( $20^{\circ}$ – $40^{\circ}$ S,  $110^{\circ}$ – $150^{\circ}$ E), AM ( $20^{\circ}$ S– $5^{\circ}$ N,  $40^{\circ}$ – $80^{\circ}$ W), and WAN ( $65^{\circ}$ – $90^{\circ}$ S,  $0^{\circ}$ – $180^{\circ}$ ). Shown are six ocean regions: AO ( $75^{\circ}$ – $90^{\circ}$ N), NNP ( $40^{\circ}$ – $60^{\circ}$ N,  $120^{\circ}$ E– $120^{\circ}$ W), TEP ( $20^{\circ}$ S– $20^{\circ}$ N,  $80^{\circ}$ – $180^{\circ}$ ), TIO ( $10^{\circ}$ S– $20^{\circ}$ N,  $40^{\circ}$ – $100^{\circ}$ E), northwestern NA ( $40^{\circ}$ – $60^{\circ}$ N,  $30^{\circ}$ – $80^{\circ}$ W), and SO ( $50^{\circ}$ – $70^{\circ}$ S).

late Holocene (Fig. 3c). Additionally, the TOA upward long-wave radiation, especially its cloud effect ( $LW_{cloud}$ ) mainly due to the increased total cloud variability (Fig. S8c), also promotes the air temperature variability, while  $SW_{cloud}$  partially offsets it (Figs. 3, 5c, 7, and 8). Similar terms (SURF and LW) intensify the air temperature variability in the southern tropical Indian Ocean (TIO) but reduce the variability of air temperature in its northern part (Figs. 3 and 6–8), primarily due to the orbital-induced changes in SST variability (Fig. 4e).

In mid- and high-latitude oceans with larger sea ice cover in the late Holocene, the winter surface air temperature variability intensifies accordingly. In the northwestern North Atlantic, due to a larger sea ice area during the late Holocene compared to the early Holocene (Fig. S9a), the reduced heat capacity increases the surface albedo, causing positive contributions of LW and  $SW_{clear}$  (Figs. 3 and 8a). Moreover, changes in sea ice and ocean circulation strengthen the net air–sea heat exchange, leading to an increased contribution of net surface heat flux (Fig. 3b) primarily through sensible and latent heat fluxes (Fig. 6). In addition, more sea ice area largely cools the local surface air, which weakens the meridional gradient of air temperature (Figs. 4a,c) and thus the thermal advection, restricting the contribution of CONV. Collectively, late-Holocene changes in surface net heat flux enhance the temperature variability in the northwestern North Atlantic, with extra contributions from LW and  $SW_{clear}$ , while CONV suppresses it by dispersing the excess energy through heat flux advection (Figs. 3 and 5c). In the midlatitudes of the North Pacific, mainly due to more sea ice north of about  $45^{\circ}$ N but less to

the south of it, CONV dominates the spatial pattern with enhanced air temperature variability in the western part but reduced variability both in the eastern part of regions north of  $40^{\circ}$ N and over regions south of  $40^{\circ}$ N, while SURF has an opposite impact (Fig. 3). In the Arctic and Southern Oceans, the increased temperature variability is jointly driven by CONV and LW due to slightly larger sea ice area from the early to late Holocene. Along the sea ice edge of the Southern Ocean with strong air–sea heat exchange, air temperature variability amplifies by changes in surface net heat flux mainly through sensible and latent heat (Figs. 3 and 6). Similar influences of sea ice changes on temperature variability have been reported in previous studies both for modern and future climates (e.g., Blackport and Kushner 2016; Collow et al. 2019; Shi et al. 2024).

The winter temperature variability varies slightly in land regions from the early to late Holocene. In India (IN) and Australia (AU), CONV and  $SW_{cloud}$  collectively promote increased standard deviation during the late Holocene, whereas the net surface heat flux largely lowers it, primarily through the impacts of the downward shortwave radiation and upward longwave radiation (Figs. 3, 5a, and 6). On one hand, the late-Holocene soil moisture reduction on the Indian subcontinent (Fig. S10a) indicates an increase in the Bowen ratio (Bowen 1926), i.e., the ratio between the sensible and latent heat flux, and hence the transition to drier surface types, leading to increased temperature variability (Bathiany et al. 2018). Moreover, the reduced soil moisture induces notable warming over India relative to the surrounding regions, which enhances the



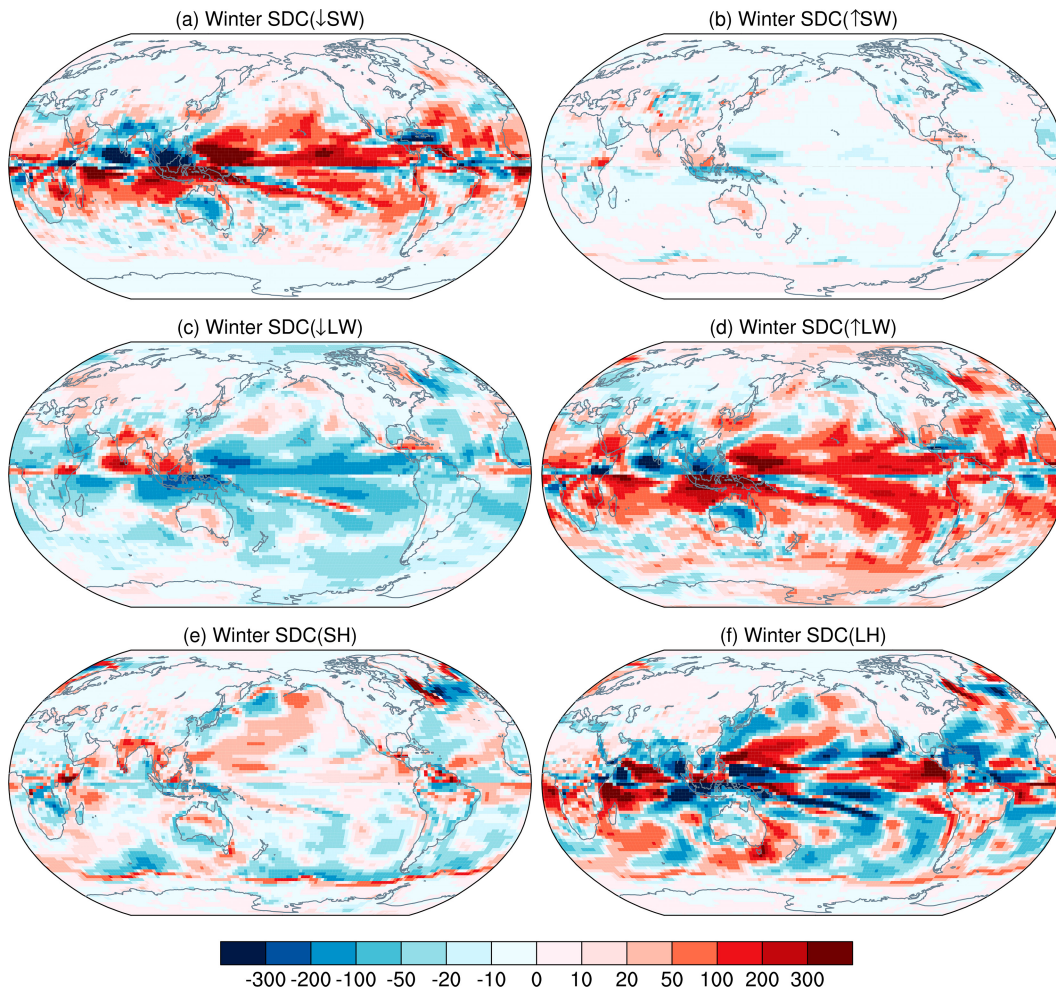


FIG. 6. Contributions (%) of the surface (a) downward ( $\downarrow$ SW) and (b) upward shortwave radiation ( $\uparrow$ SW), (c) downward ( $\downarrow$ LW) and (d) upward longwave radiation ( $\uparrow$ LW), (e) sensible heat flux (SH), and (f) latent heat flux (LH) to the winter temperature variability difference between the late and early Holocene in the HT-ORB simulation.

meridional temperature gradient and thus the effect of heat advection, causing the positive contribution of CONV (Figs. 4 and 5a and Fig. S10a). On the other hand, increases in total cloud variability, especially in Australia (Fig. S8c), promote the local temperature variability through  $SW_{cloud}$  impact, with an opposite role from  $LW_{cloud}$ . In North Africa to the Arabian Peninsula, the TOA upward longwave radiation, especially the part without considering cloud effects ( $LW_{clear}$ ), enhances the surface air temperature variability (Fig. 5a). The contribution of  $LW_{clear}$  could be associated with changes in the variability of tropospheric air temperature and water vapor (Maghrabi et al. 2019), the latter of which is connected to notable changes in the North African monsoon precipitation and its variability (Fig. S6), as a result of modified land-sea thermal contrast due to higher late-Holocene winter insolation compared to the early Holocene (Fig. 4). Net surface heat flux changes amplify the temperature variability in Amazonia (AM) mainly through the upward longwave radiation (Figs. 5a and 6). In midlatitudes of East Asia (EA) and southern North

America (SNA), net surface heat flux partially counteracts the joint effects of other energy balance components, yielding an overall slight increase in temperature variability (Fig. 5a). In west Europe (WE), the decreased temperature variability is collectively driven by CONV and  $LW_{clear}$ . CONV also dominates the slightly increased variability over West Antarctica (WAN) (Fig. 3).

Taken together, the enhanced winter temperature variability from the early to late Holocene due to the orbital forcing is primarily caused by the counteracting effects between net surface heat flux and CONV, with additional impacts from the TOA net shortwave and longwave radiation fluxes. Cloud effects and soil moisture changes are important in low latitudes, while sea ice variations are the main factors in mid- to high-latitude oceans. The underlying mechanisms relate with changes in mean surface air temperature and its meridional gradient, mean precipitation and its variability, as well as SST variability in response to higher northern but lower southern insolation during the late-Holocene winter.

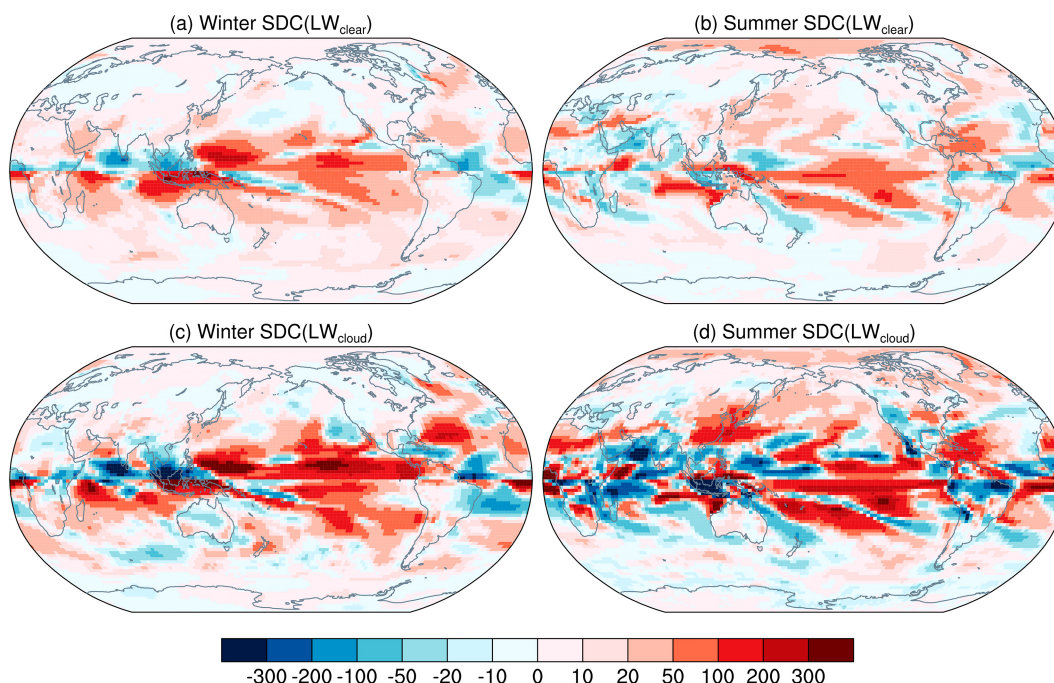


FIG. 7. Contributions (%) of (a),(b)  $LW_{clear}$  and (c),(d)  $LW_{cloud}$  to the (a) and (c) winter and (b) and (d) summer temperature variability difference between the late and early Holocene in the HT-ORB simulation.

### b. Mechanisms of summer temperature variability

Different from winter, summer temperature variability increases dramatically by an average of 61% over the Arctic Ocean (AO) from the early to late Holocene (Fig. 9a). This is primarily due to changes in net surface heat flux through the upward longwave radiation and downward shortwave radiation (Figs. 5d and 10). Additionally,  $SW_{cloud}$  and  $LW$  contribute to this increase in temperature variability mainly through enhanced total cloud variability (Fig. S8d), while CONV and  $SW_{clear}$  oppose it (Fig. 5d). The lower northern insolation during the late-Holocene summer weakens the surface warming, which facilitates larger sea ice extent and reduces the meridional temperature gradient (Fig. 4 and Fig. S9b), suppressing the convergence of energy flux and thus the contribution from CONV. Note that there are no more areas of high heat capacity from the early to late Holocene since the Arctic Ocean is frozen year-round. By contrast, the sea ice-free area near the coasts during the early Holocene summer would limit temperature variations. Correspondingly, the late Holocene increased sea ice extent and enhanced ocean circulation near the Arctic coasts intensify the air–sea heat exchange and cause positive contributions of the net surface heat flux to temperature variability. Similar terms (SURF and LW) dominate the enhanced temperature variability in the northern North Pacific (NNP) and tropical east Pacific, together with a negative contribution from CONV, except for an opposite impact of  $SW_{cloud}$  and little effect from  $SW_{clear}$  (Fig. 5d). The above impact in the northern North Pacific is primarily due to sea ice changes in response to the orbital forcing, while total cloud variations cause an overall suppression effect. In low-latitude oceans, the

summer variability of air temperature also highly correlates with that of SST, particularly in east Pacific, where the mechanisms for higher air instability in summer resemble those in winter. However, different from the tropical east Pacific, CONV predominantly amplifies the late-Holocene summer temperature variability in the tropical Indian Ocean through energy flux convergence, while the cloud effect plays a larger suppression role, particularly for  $LW_{cloud}$  (Figs. 5d, 7d, and 9). In the northwestern North Atlantic and Southern Oceans, increases in sea ice fraction enhance the air temperature variability during the late Holocene, mainly through impacts of  $SW_{clear}$  (Figs. 5d and 8). However,  $SW_{cloud}$  and net surface heat flux slightly dampen the variability primarily through the effects of total cloud and surface upward shortwave radiation, respectively (Figs. 5d and 8–10 and Fig. S8).

In land regions, the most obvious difference from winter is a remarkable reduction in summer temperature variability from North Africa to the Arabian Peninsula and over East Asia (Fig. 9a) from the early to late Holocene. This is collectively driven by impacts of  $SW_{cloud}$  and CONV, with opposite effects from net surface heat flux and  $LW_{cloud}$  (Figs. 5b and 9). In these regions, both total cloud and its variability are reduced during the late Holocene (Fig. S8), which dampen the local air temperature variability mainly through  $SW_{cloud}$  but intensify the influence of surface downward shortwave radiation on temperature (Figs. 8d and 10a). On the other hand, both decreases in summer insolation and surface soil moisture strongly weaken the local surface warming, which largely reduce the meridional temperature gradient and thus the energy flux convergence (Fig. 4 and Fig. S10b), contributing to decreased temperature variability. Moreover, the orbital-induced uneven



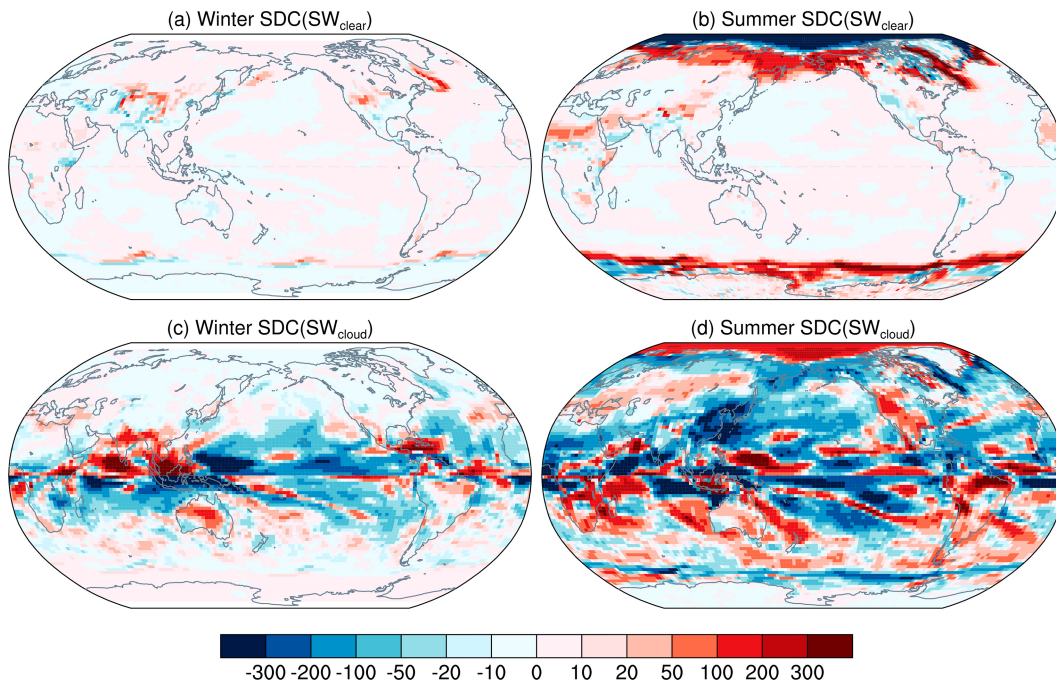


FIG. 8. Contributions (%) of (a),(b)  $SW_{clear}$  and (c),(d)  $SW_{cloud}$  to the (a) and (c) winter and (b) and (d) summer temperature variability difference between the late and early Holocene in the HT-ORB simulation.

changes in mean temperature during the late Holocene weaken the land–sea thermal contrasts (Fig. 4), suppressing the North African and Asian summer monsoon precipitation (Fig. S6b), which also dampen the local temperature variability. Compared to winter, CONV makes a larger contribution in amplifying the summer temperature variability in India due to reduced soil moisture in more areas during the late Holocene (Fig. 5 and Fig. S10), while cloud effects (both  $LW_{cloud}$  and  $SW_{cloud}$ ) partially offset it mainly caused by decreased total cloud (Fig. S8b). The late-Holocene increase in summer temperature variability over southwestern North America and Amazonia is dominated by effects of  $SW_{cloud}$  and CONV, whereas it is counteracted by  $LW_{cloud}$  and net surface heat flux mainly through downward shortwave radiation (Figs. 5 and 7–10). In comparison, the stronger summer than winter enhancement of temperature variability over those two regions is associated with different changes in monsoon precipitation and total cloud (Figs. S6 and S8). Contributions of net TOA radiation and surface heat fluxes slightly overwhelm the impact of CONV by dispersing the excess energy, leading to a weaker-than-winter increase in summer temperature variability over Australia, which can be further explained by the seasonal difference in amplitudes of precipitation and total cloud changes. Similar to winter, impacts of CONV and LW dampen the summer temperature variability over west Europe, and SURF acts to offset it in a large part primarily by latent heat flux.

As a whole, the seasonal difference of temperature variability changes from the early to late Holocene is primarily driven by the seasonal contrast in insolation due to the orbital forcing, in particular the precession change. Specifically, summer

insolation decreases in the Northern but increases in the Southern Hemisphere, whereas the opposite holds for winter. Correspondingly, global surface mean temperature and its meridional gradient, sea ice fraction, total cloud, and soil moisture respond differently, leading to various changes in energy balance components and thus temperature variability. The main seasonal differences occur in the Arctic Ocean and the northern continents. During the late-Holocene summer, larger increases in sea ice extent and total cloud variability cause greater contributions of SURF and  $SW_{cloud}$ , resulting in a stronger intensification than during winter of air temperature variability in the Arctic Ocean. Due to the seasonal contrast in insolation changes from the early to late Holocene, different responses of meridional temperature gradient, monsoon precipitation, total cloud, and soil moisture lead to various contributions of SURF, CONV, and TOA radiation flux, yielding opposite changes in summer temperature variability from North Africa to the Arabian Peninsula and over East Asia as well as a larger (smaller) increase in summer variability over southwestern North America and Amazonia (Australia) compared to winter.

## 5. Temperature variability in paleo data

Since the temporal resolution of proxy data covering the whole Holocene is low, it is difficult to reconstruct the temperature variability as a year-to-year time series. Additionally, most high-resolution (near yearly) temperature records, e.g., from corals, speleothems, or tree rings, cover only the past hundreds to 2000 years (PAGES 2k Consortium 2017). Considering that the simulated temperature variability has notably increased from 11.5 to ~5 ka at the global scale (Fig. 1a),



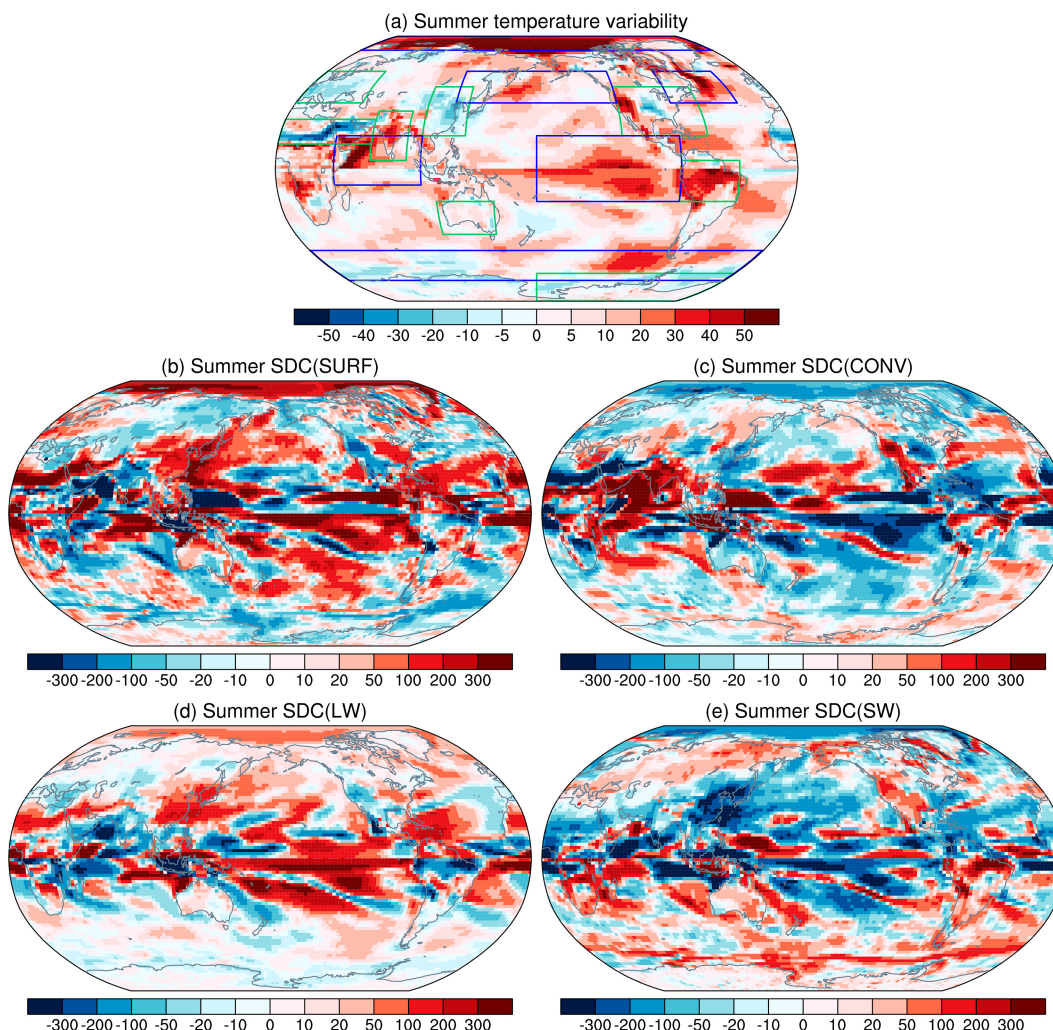


FIG. 9. As in Fig. 3, but for summer mean.

we select proxy data from the Temperature 12k database (Kaufman et al. 2020b) for annual mean temperature covering from 11.5 to 5 ka, with a median temporal resolution less than 100 years, to perform a model–data comparison. Eighty-two records, including 64 marine sediments, 9 ice cores, 6 lake sediments, 1 midden, 1 peat, and 1 speleothem at 68 sites globally, are finally chosen from the database (Table S1) to qualitatively compare with simulations across various time scales (ranging from interannual to multidecadal time scales). Here, we compute the temperature standard deviation for each record from 11.5 to 5 ka using a 1000-yr sliding window without filtering. After that, we calculate its linear trend to obtain the reconstructed temperature variability trend from 11.5 to 5 ka. Out of 82 collected proxy records, more than half (50 records) suggest a rising trend, whereas the remaining data indicate a declining value (Table S1; Fig. 11b). In comparison, 45 out of 82 records agree qualitatively with our HT-ALL simulation for the annual trend from 11.5 to 5 ka without filtering, in which 41 records consistently display increased variabilities over the western Pacific, Indian Ocean, North Atlantic, western Europe,

and North America, and four records indicate decreased values over Antarctica, East Africa, and the eastern Indian Ocean (Fig. 11c), although simulations have generally smaller amplitudes. Thirty-seven inconsistent sites are primarily found in southern Africa, north Europe, Antarctica, North America, the tropical Indian and Pacific Oceans, and North Atlantic (Fig. 11d), most of which show a declining trend in proxy data but the opposite in the model. Uncertainties in both reconstructions and simulations may lead to the discrepancy. On the one hand, Holocene temperature proxies are suggested to have seasonal biases (e.g., Bova et al. 2021) and may be mixed with additional signals (H. Lu et al. 2019). Moreover, limitations in temporal resolutions and spatial coverage, uneven distributions between terrestrial and marine records, inaccuracies in the chronological measurements, or various reconstruction methods also cause uncertainties among proxy data (Jiang et al. 2012; Kaufman et al. 2020b). For example, different trends, either in magnitudes or in signs, can be derived from proxies at nearby sites (Table S1; Fig. 11b). Even at exactly the same site, different proxies indicate both rising and

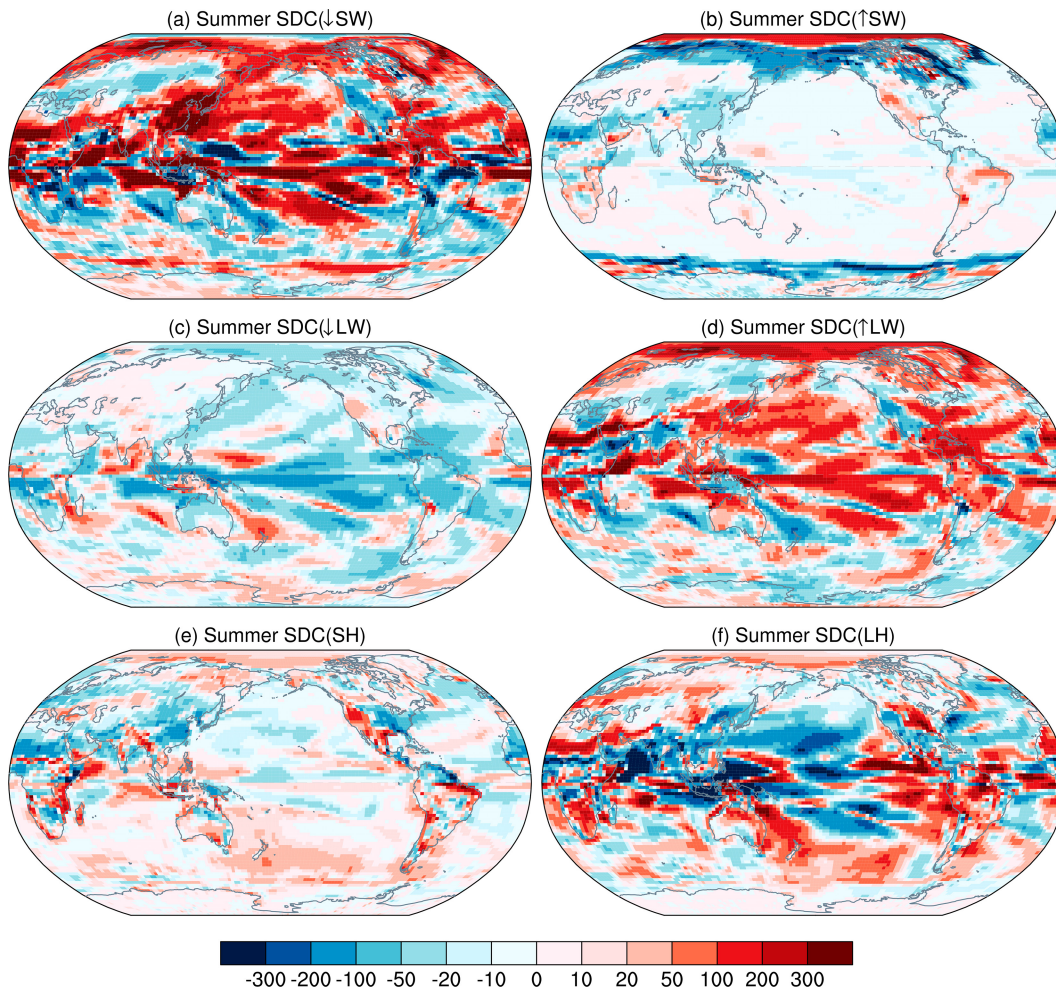


FIG. 10. As in Fig. 6, but for summer mean.

declining trends from the marine sediment in the Indian Ocean (site IDs 32–33, 46–47, and 73–74; [Stott et al. 2007](#); [Xu et al. 2008](#); [Mohtadi et al. 2014](#)), the Norwegian Sea (site IDs 39–40; [Risebrobakken et al. 2003](#)), and the western Pacific Ocean (site IDs 14–15; [Gibbons et al. 2014](#)). On the other hand, the current generation of CESM1 still has deficiencies in the radiation process and cloud feedback ([Gettelman et al. 2013](#); [Hurrell et al. 2013](#)). In particular, the fixed vegetation and the lack of volcanic forcing in our HT-11.5 ka simulations may affect the temperature variability during the Holocene ([Zanchettin et al. 2012](#); [Le et al. 2016](#)). Additionally, reconstructions are primarily from marine sediments with an average level of  $\sim 50$  years for the median resolution, and comparing the derived SST variability with simulated surface air temperature variability of yearly resolution will also introduce biases ([Laepple et al. 2023](#)).

## 6. Conclusions and discussion

Using our new set of transient simulations covering from 11.5 ka to the preindustrial period performed by CESM1.2.1

with relatively high resolutions, we investigate the global pattern of interannual variability of surface air temperature throughout the Holocene and associated mechanisms primarily from an energy balance perspective and qualitatively compare the simulations with available reconstructions. The primary conclusions are summarized as follows.

The new set of Holocene transient simulations can reasonably reproduce the climatological interannual temperature variability globally, with high values at mid- to high latitudes and low in the tropics, and an overall larger variability in winter than in summer. The annual variability gradually increases throughout the Holocene at the global scale, particularly over the first half of the Holocene until about 5 ka, which is largely determined by the winter evolution and primarily due to the orbital forcing. The atmospheric GHG change has overall little effect, while the retreat of ice sheets primarily explains regional variability changes over North America and Europe. In response to the insolation change from the early to late Holocene primarily due to the precession, variations in energy balance components contribute to the increased temperature variability, in which SURF and LW generally play dominant roles and CONV and



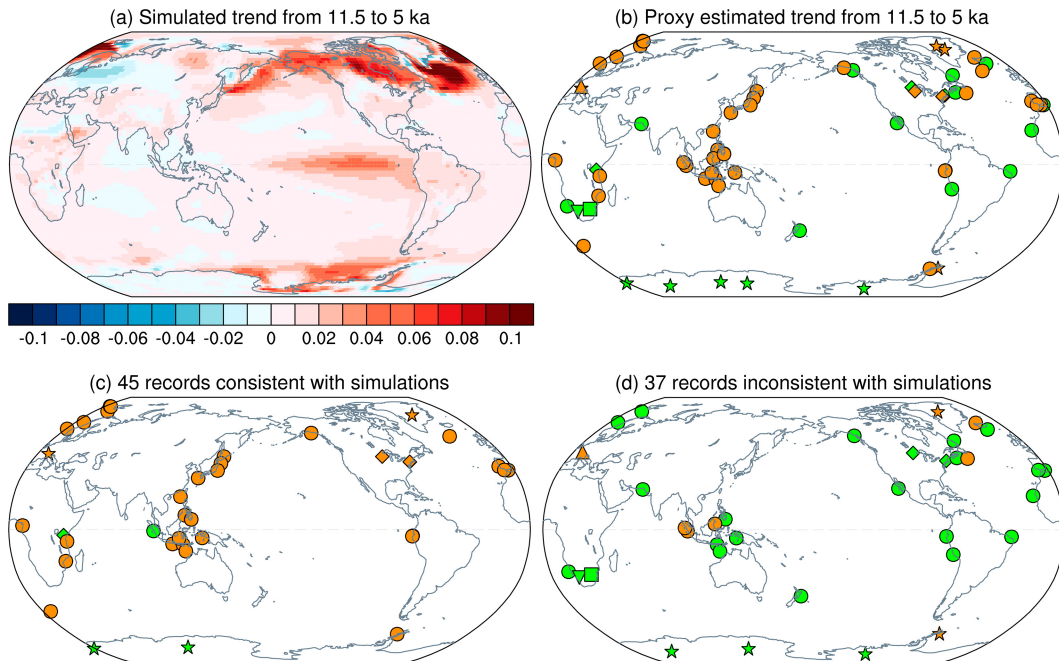


FIG. 11. Linear trends ( $^{\circ}\text{C ka}^{-1}$ ) of the SD of annual temperature (without filtering) from 11.5 to 5 ka obtained from the (a) HT-ALL simulation and (b) 82 proxy records of ice core (star), lake sediment (diamond), marine sediment (circle), midden (inverted triangle), peat (square), and speleothem (triangle). Orange and green records denote increase and decrease trends, with 45 and 37 records showing (c) consistent and (d) inconsistent trends with simulations, respectively.

SW partially offset it at the global scale. Regionally, cloud effects, changes in surface soil moisture, and SST variability are important in low latitudes, while sea ice area changes are main factors in mid- to high-latitude oceans. Due to the seasonal contrast in insolation, global surface mean temperature and its meridional gradient, sea ice fraction, total cloud, and soil moisture respond differently, leading to the seasonal difference in contributions of energy balance components to the temperature variability change, particularly in the Arctic Ocean and northern continents. Specifically, the late-Holocene summer air temperature variability increases more than winter in the Arctic Ocean, which can be explained by greater contributions of SURF and  $\text{SW}_{\text{cloud}}$  due to larger increases in sea ice extent and total cloud variability, respectively. Opposite to the slightly enhanced winter variability, the summer temperature variability is notably reduced from North Africa to the Arabian Peninsula and over East Asia, which is dominated by impacts of CONV and  $\text{SW}_{\text{cloud}}$  due to decreases in meridional temperature gradient, monsoon precipitation, and total cloud in response to reduced summer insolation during the late Holocene. Simulated annual temperature variability trends from 11.5 to 5 ka across interannual to multidecadal time scales are supported by most of the available proxy data in a qualitative manner, with uncertainties existing from both sides.

Note that the energy balance framework used for analysis in this study has been applied in explaining the interannual temperature variability change during modern period of 1980–2016 and for idealized simulations with transiently increasing carbon

dioxide (Räsänen 2017, 2019), which is thus effective and interpretable for the Holocene temperature variability evolution. Table S2 summarizes the influence factors on the standard deviation (SD) of surface air temperature anomaly from the early to late Holocene and its contribution (SDC) from each term of atmospheric energy balance as inferred from our study. In general,  $\text{SDC}(\text{SURF})$  relates with the net air–sea heat exchange, which is affected by changes in sea ice extent and SST variability.  $\text{SDC}(\text{CONV})$  tends to oppose  $\text{SDC}(\text{SURF})$  by dispersing the excess energy through heat flux advection, which is modulated by changes in meridional temperature gradient. Cloud effects on TOA longwave and shortwave radiation, i.e.,  $\text{SDC}(\text{LW}_{\text{cloud}})$  and  $\text{SDC}(\text{SW}_{\text{cloud}})$ , are determined by changes in total cloud and its variability.  $\text{SDC}(\text{SW}_{\text{clear}})$  relates with changes in surface albedo, which is associated with heat capacity changes due to sea ice variations.  $\text{SDC}(\text{LW}_{\text{clear}})$  could associate with changes in the variability of tropospheric air temperature and water vapor (Maghrabi et al. 2019) and connect with changes in mean precipitation and its variability. In addition, both enhanced meridional temperature gradient and drier land surface types (represented by reduced soil moisture) favor the increase in temperature variability in specific regions. Other potential dynamic mechanisms associated with ENSO and its teleconnections, the air–sea coupling, the freshwater flux and remnant ice sheets, and the intertropical convergence zone (e.g., Benway et al. 2006; Luan et al. 2015; Laine et al. 2016; Chen et al. 2019) require specific investigations in the future. Moreover, further comparisons between our simulations with



other available transient simulations (e.g., Jin et al. 2014; Zhang et al. 2018; Askjær et al. 2022), requiring monthly or at least yearly outputs and a coverage of the whole Holocene with calendar adjustment (X. Shi et al. 2022), need to be performed to improve the robustness of the conclusions in this study. In addition, it calls for continuous improvements in CESM model for some important physical processes, such as the cloud effect and radiation process, more reconstruction work with both high-temporal resolution and dense-spatial coverage in proxy data, as well as the development of paleoclimatic assimilation dataset based on the two sides (e.g., Erb et al. 2022), to comprehensively understand the temperature variability evolution and its mechanism throughout the Holocene.

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**Data availability statement.** The observed BEST surface air temperature data (Rohde et al. 2013a,b) can be accessed at <http://berkeleyearth.org/data/>. The HT-11.5 ka simulation data of global means of surface air temperature (Tian et al. 2022) are available in the Zenodo repository at <https://doi.org/10.5281/zenodo.6269566>, with other simulation data analyzed during the current study available from the corresponding author on reasonable request. Reconstruction data are openly available from the Temperature 12k database (Kaufman et al. 2020b) at <https://www.ncei.noaa.gov/access/paleo-search/study/27330> and publications listed in Table S1.

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