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Key Points:
- Anticorrelations are found in EASM and EAWM variations from multidecadal to millennial timescales during the Holocene.
- The negative EASM-EAWM relation is likely caused by the AMOC.

Supporting Information:
- Supporting Information S1

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Abstract The East Asian summer monsoon and winter monsoon (EASM and EAWM) are two important components of the East Asian monsoon system. However, the relationship between the two components during the Holocene remains debated in the observation. Here, we use a set of simulations in CCSM3 to investigate the EASM-EAWM relation across different timescales during the Holocene. It is shown that the intensities of EASM and EAWM are positively correlated at orbital timescale but negatively correlated from millennial down to multidecadal timescales. The positive correlation at orbital timescales is forced by the seasonal insolation forcing, while the negative correlation at millennial and shorter timescales is caused mainly by the internal variability of the Atlantic Meridional Overturning Circulation (AMOC) and the subsequent teleconnection to East Asia via land-sea thermal contrast.

Plain Language Summary The East Asian summer monsoon (EASM) and East Asian winter monsoon (EAWM) are important factors that affect regional climate. However, it has remained controversial whether EASM and EAWM vary in-phase or out of phase in the Holocene. Our simulations show that EASM correlates with EAWM positively at orbital timescale due to the seasonal precessional forcing but negatively correlated from multidecadal to millennial timescales because of the impact of the Atlantic Meridional Overturning Circulation (AMOC).

1. Introduction

The East Asian monsoon system contains two important components: the East Asian summer monsoon (EASM) with warm and wet southerly winds and the East Asian winter monsoon (EAWM) with cold and dry northerly winds (Ha et al., 2012). Most previous works have studied EASM and EAWM separately. Recently, however, more attention has been paid to the relationship between the intensities of EASM and EAWM in present-day climate variability (Chen et al., 2013; Feng & Chen, 2014; Li et al., 2011; Wang & Wu, 2012; Yan et al., 2011) and past climate changes (Chen et al., 2013; Feng & Chen, 2014; Ge et al., 2017; Kang et al., 2018; Li et al., 2011; Steinke et al., 2011; Wang et al., 2012; Wang & Wu, 2012; Wen et al., 2016; Yan et al., 2011; Yancheva et al., 2007; Zhang & Lu, 2007).

For the present climate variability, there seems to be a quasi-biennial oscillation between EASM and EAWM (Li et al., 2011): a stronger EASM tends to be followed by a stronger EASM, and then a weaker EAWM, a weaker EASM summer, and eventually a stronger EAWM. Here, a strong EASM is accompanied by strengthened southerly winds over eastern China and above normal precipitation over northern China, and a strong EAWM is accompanied by strengthened northerly winds and strong cooling over East Asia. However, the EASM-EAWM relation seems to be inconclusive at longer timescales (Li et al., 2011; Wen et al., 2016), particularly at decadal and longer timescales during the Holocene (last 10,000 years), i.e., whether they are positively correlated or negatively correlated. Here, a positively correlated EASM-EAWM means that they both strengthened or weakened, while a negatively correlated EASM-EAWM means that when one of them gets strengthened/weakened, the other gets weakened/strengthened. The records of magnetic properties and
the titanium content of the sediments from Lake Huguang Maar in coastal southeastern China over the past 16 kyr suggested that a stronger EAWM was associated with a weaker EASM at millennial timescale; i.e., they were negatively correlated (Yancheva et al., 2007). However, historical climate records showed that cold winters (i.e., strong EAWM) were associated with wet summers (i.e., strong EASM) during AD 700–900, indicating a positive correlation between EASM and EAWM during that period at centennial timescale (Zhang & Lu, 2007). The EAWM proxy derived from the zonal sea surface temperature difference in the southern South China Sea (SCS) and the temperature difference between alkenone and P. obliquiloculata in the northern SCS seemed to exhibit a negative correlation with the intensity of EASM during the last deglaciation at orbital timescale but a positive correlation with EASM during the early Holocene at millennial timescale (Steinke et al., 2011). The Holocene EASM and EAWM reconstructed from peat records over the eastern Tibetan Plateau, however, showed two variability modes, i.e., a negative correlation during the early Holocene, a positive correlation during the middle Holocene, and a negative correlation again during the late Holocene (Yu et al., 2006). The sediment core on the northern SCS continental shelf revealed that EASM and EAWM were negatively correlated during the cooling periods around 7500, 4800, 4200, 3200, and 300 BP, but positively correlated during the warm periods around 7100, 3700, and 2100 BP (Ge et al., 2017). These different relationships of EASM–EAWM in the Holocene are likely caused by, at least partly, the limited time resolution of the proxy records, and more importantly, the different timescales of the variability.

Dynamically, since EASM and EAWM are separated half year apart, if they are related, there has to be some concurring mechanism that modulates both systems. These mechanisms, however, could be different at different timescales. For the present day, ENSO and other internal climate variability, as well as ocean-atmosphere feedbacks, may provide a link between EAWM and the subsequent EASM. For example, a strong EAWM can lead to a westerly anomaly over the western Pacific warm pool (WPWP), which triggers eastward propagation of subsurface warm water anomaly in the equatorial Kelvin wave and, in turn, excites positive sea surface temperature anomalies (SSTAs) over the eastern tropical Pacific; the excited El Nino will then force a relatively weak EASM in the following summer through atmospheric teleconnection (Chen et al., 2013; Li et al., 2011). These mechanisms, which are valid for interannual variability, however, may not be significant at longer timescales, such as decadal, centennial, even millennial, and orbital timescales. If there are indeed relationships between EASM and EAWM at those longer timescales, as suggested by the previous observations discussed above, the difference may be caused by other mechanisms. For example, in both reconstructions and model simulations, EASM and EAWM were suggested to be in-phase at orbital timescale, but out of phase at millennial timescale during the last deglaciation (Wang et al., 2012; Wen et al., 2016). The positive correlation at orbital timescale was due to the seasonal precessional forcing, while the negative correlation at millennial timescale was suggested to be caused by the North Atlantic melt water forcing via Atlantic Meridional Overturning Circulation (AMOC) and its global climate impact (Wen et al., 2016). Neither orbital nor meltwater, however, can explain the decadal to millennial EASM-EAWM relation revealed in the reconstructions during the

Figure 1. Simulated climatology of the (a) JJA mean wind850 (vector) and surface temperature (shading) and (b) DJF mean wind1000 (vector) and surface temperature (shading) during the Holocene.
Holocene, especially during the middle to late Holocene, when the meltwater forcing was absent and the orbital forcing was very smooth. This leads to our general question here: Are EASM and EAWM correlated at different timescales in the Holocene, and if yes, what are the mechanisms?

In this study, we extend the work of Wen et al. (2016) to explore the EASM-EAWM relationship from decadal to orbital timescales during the Holocene, using a transient simulation for the Holocene. The major finding is that EASM and EAWM tend to exhibit a negative correlation from multidecadal to millennial timescales, and this negative correlation is caused mainly by the AMOC variability, which is forced either externally by the melting water or internally by the climate feedback in the coupled system. In section 2, we discuss the data and analysis method. In section 3, we discuss the relationship between EASM and EAWM at different timescales. In section 4, we explore the mechanism that leads to the correlation between EASM and EAWM, with the focus on the role of the AMOC. Finally, in section 5, we summarize our results and present some further discussions.

2. Data and Methods

We will use the output of a transient global climate simulations of the last 21 kyr (TraCE-21ka) conducted in CCSM3 (Liu et al., 2009; Liu, Zhu, et al., 2014). This experiment is forced by the transient climate forcing
factors of insolation, atmospheric concentration of greenhouse gases (GHGs), melting water flux and ice sheet, and paleogeography.

The monsoon was originally proposed as a circulation system and defined based on the annual reversal of the surface wind field (Ramage, 1971). Therefore, we will also use the wind field to define two wind-based indices for EASM and EAWM. Following the previous study of Wen et al. (2016), the wind-based EASM index is defined as the regional averaged June-July-August (JJA) mean meridional wind at 850 hPa over (30–40°N, 110–120°E) (Figure 1a). The wind-based index for EAWM is defined as the regional averaged December-January-February (DJF) mean meridional wind at 1,000 hPa over (25–35°N, 115–130°E) (Figure 1b). The regressed JJA mean precipitation to the EASM index and the regressed DJF mean surface temperature to the EAWM index illustrate that the indices defined in this study can well represent the characteristics of the East Asian monsoon (Figure S1).

Simple running mean band-pass filter is applied to differentiate the variability of EASM and EAWM at different timescales. For example, the difference between 10-year running mean and 20-year running mean is used to represent the variability at decadal timescale; the difference between 750-year running mean and 1,500-year running mean represents the variability at millennial timescale, and so on. The 3,000-year running mean is used to represent variability at orbital timescale.

### 3. EASM-EAWM Relation During the Holocene

The intensities of EASM and EAWM show clear decreasing trends during the Holocene in both the simulation (Figures 2b and 2c) and reconstructions (Huang et al., 2011; Wang et al., 2005). This indicates a positive correlation between EASM and EAWM at orbital timescale during the Holocene, which have also been found in the previous studies based on reconstructions (Wang et al., 2012) and simulations (Wen et al., 2016). It is interesting in TraCE-21ka, however, that the EASM intensity changes oppositely to EAWM at millennial to multicentennial, and even centennial timescales, indicating a significant negative correlation. This negative correlation can be seen in two examples of the variabilities of EASM and EAWM at millennial (Figure 2d) and centennial (Figure 2e) timescales.

Now, we examine systematically the correlation between the variabilities of EASM and EAWM at different timescales in the Holocene. The correlations between EASM and EAWM variabilities were calculated using different time window of band pass filter (Figure 3, black line). At the orbital timescale (window period = 3,000 years), EASM and EAMW exhibit a strong positive correlation with a correlation coefficient over 0.9, consistent with the previous works (e.g., Wen et al., 2016). As the window period decreases toward millennial (e.g., 1,000–2,000 years), the correlation turns to negative, and this negative correlation remains statistically significant all the way to multidecadal timescale (50–100 years, Figure 3, black line). A similar change of correlation is also found during the last deglaciation period (21,000–11,000 BP) when the meltwater forcing is strong (Figure S2a), and during the middle to late Holocene when the meltwater forcing is absent (Figure S2b). This significant negative correlation at millennial and shorter timescales and the positive correlation at orbital timescale for EASM-EAWM are robust and are also confirmed using the coherence analysis (Figure S3).

### 4. Mechanisms of EASM-EAWM Relations

The physical mechanism behind the positive correlation between EASM and EAWM at orbital timescale is well understood. EASM and EAWM tend to follow the seasonal insolation in summer and winter, respectively. The insolation decreases in boreal summer and increases in boreal winter (Figure 2a) and therefore forces a decrease in the land-sea thermal contrast in both summer and winter, a weakening in both EASM and EAWM, and eventually the positive correlation (Wen et al., 2016).
In comparison, the cause of the negative EASM-EAWM correlations at multidecadal to millennial timescales is not obvious. First, the negative correlation cannot be simply attributed to the external forcings of orbital parameters and GHG, because these external forcings tend to vary smoothly in the Holocene with no significant variability at multidecadal to millennial timescales (Figure 2a). The meltwater forcing has been shown to contribute to a negative EASM-EAWM correlation during the last early deglaciation, because it is one of the dominant forcings for the variability at millennial timescale (Wen et al., 2016). However, the meltwater forcing cannot be the dominant forcing for the multidecadal to millennial correlation during the Holocene when it is no longer dominant, although there may still exist relatively small injections in the reality. In our simulation work, the meltwater forcing is absent after the middle Holocene, which means the meltwater forcing is not an essential factor influencing the simulated EASM-EAWM relation during the Holocene.

One clue of the cause of the negative correlation at millennial and shorter timescales comes from the results for the negative correlation at millennial timescale during the early deglaciation. Wen et al. (2016) suggested that during the early deglaciation, the millennial meltwater pulses injected into North Atlantic weakened the AMOC, which led to a cooling Northern Hemisphere (NH) as a part of its bipolar seesaw response. Unlike the precession, the impact of the AMOC occurs throughout the year. This cooling then weakens the EASM but strengthens the EAWM, leading to a negative correlation. In TraCE-21ka simulations,
there are indeed significant AMOC variabilities at multidecadal to millennial timescales during the Holocene (Figure S4, black line; Figure S5). These AMOC variabilities are caused largely by internal coupled ocean-atmosphere variability, although it is also partly forced by the residual meltwater forcing before the mid-Holocene (Figure S4, blue line). Interestingly, this AMOC variability is largely in phase with EASM but out of phase with EAWM (Figures 2d and 2e). This leads to a mechanism for the negative correlation as follows. A weaker (stronger) AMOC corresponds to a colder (warmer) NH (Figure S6). This cooling/warming spans from North Atlantic to East Asia, leading to the stronger cooling (warming) over the land than the adjacent ocean in boreal winter and summer, and then a stronger (weaker) land-sea thermal contrast in winter but weaker (stronger) land-sea contrast in summer, and thus stronger (weaker) EAWM northerly but weaker (stronger) EASM southerly (Figure 4). This leads to a negative correlation between EASM and EAWM.

Figures 4 and S6 give examples of the AMOC impact at centennial to millennial timescales. For the multidecadal timescale, the impact of AMOC is substantially weaker than that at millennial timescale but still significant (Figure S7). The impact of AMOC on Asian monsoonal climate at multidecadal timescale is caused by the atmospheric teleconnections and, perhaps additionally, the atmosphere-ocean interactions over the western Pacific and Indian Ocean (Gao et al., 2020; Lu et al., 2006; Wang et al., 2009). A stronger AMOC state will lead to a warmer North Atlantic, corresponding to the warm phase of the Atlantic Multidecadal Oscillation (AMO), not only in winter (DJF) but also in summer (JJA) (Figure S7). The induced tropospheric heating then generates a disturbance that propagates from Europe to East Asia (Figure S8) in the westerly jet waveguide as equivalent barotropic stationary wave train, leading to a warmer atmospheric column over land in the lower middle atmosphere in winter but middle to upper troposphere in summer (Figure S9). This response then leads to weakened land-sea thermal contrast in winter but strengthened land-sea thermal contrast in summer and thus weakens EAWM while strengthens EASM (Gao et al., 2020; Wang et al., 2009). The detailed mechanisms of this tropospheric heating in different seasons are beyond the scope of this study and will be discussed elsewhere. More investigations with more model outputs and reconstructions with high resolutions are required to further understand the mechanisms of EASM-EAWM relation at decadal and multidecadal timescales.

The role of AMOC in producing the negative EASM-EAWM correlation is confirmed in the correlation of variability across different timescales (Figure 3). It can be seen that, at millennial and shorter timescales, AMOC is always positively correlated with EASM (Figure 3, red line), but negatively correlated with EAWM (Figure 3, blue line). The positive relation between AMOC and EASM at decadal-centennial timescales is also found in the benthic microfossil proxies over the last millennium (Cheung et al., 2018). At the orbital timescale, EASM becomes negatively correlated with AMOC (Figure 3), as shown clearly in the trend of the time series, which shows a strengthening trend in AMOC but a decreasing trend in EASM (Figure 2b). This is because now EASM is forced predominantly by the summer insolation, instead of AMOC, and therefore, the apparent negative correlation does not reflect the causality.

It remains challenging to find high-resolution observations that can be used to test the correlations between EASM and EAWM in the Holocene, because of the much stringent requirement on chronology and resolution of the proxies. Nevertheless, there seems to be some evidences of a negative correlation between EASM and EAWM at millennial and centennial timescales in the loess records from southern Chinese Loess Plateau over the past 9.3 kyr (Xia et al., 2014) and 3.3 kyr (Kang et al., 2018). On the other hand, historical climate records showed that cold winters were associated with wet summers during AD 700–900, indicating a positive correlation between EASM and EAWM during that period at centennial timescale (Zhang & Lu, 2007). Much works are still needed to assess the correlations between EASM and EAWM in the observations.

### 5. Conclusions and Discussions

Our analysis of TraCE-21ka simulation reveals a robust relation between EASM and EAWM in the Holocene. EASM and EAWM exhibit a positive correlation at orbital timescale but a negative correlation at millennial and shorter timescales. The negative correlation at millennial and shorter timescales is proposed to be caused by the AMOC variability, which leads to annual temperature changes in the NH, especially at upper troposphere. This temperature anomaly remains of the same sign all year around, either
warming or cooling (e.g., Figure S6), and therefore, will have the opposite effects on EASM and EAWM, inducing a negative correlation, similar to the millennial variability in the last deglaciation (Wen et al., 2016). Different from the millennial variability in the last deglaciation when AMOC variability is caused mainly by the meltwater forcing, the millennial variability in the Holocene is caused mainly by the internal variability in the coupled ocean-atmosphere system. The cause of this internal variability of the AMOC is beyond the scope of this paper and will be discussed elsewhere.

Our work provides the EASM-EAWM relationship as a function of continuous change of timescales, from multidecadal to millennial, which will give a clear view of the similarity and difference of the relationship with timescales. Note that for the multidecadal variability, the relationship is usually noisier. In this work, it is significant by applying Monte-Carlo test. However, the correlation coefficient is only about 0.1, explaining only about 1% of the relationship. We also note that the results here are derived from CCSM3 only. Although there were some simulations in some other models showing consistent results of the modulated EASM-EAWM relation by North Atlantic at multidecadal timescale (Wang et al., 2009), more works in different models are still required in the future to examine the robustness of EASM-EAWM relationships during the Holocene, especially at multidecadal timescale.

It also should be noted that the relationship between EASM and EAWM may also depend on the definitions of the indices, which themselves remain ambiguous (e.g., Wang et al., 2008; Wang & Chen, 2010). Therefore, in this study, two common definitions are additionally used and compared, i.e. the boreal summer (JJA) precipitation for EASM, and the boreal winter (DJF) surface temperature for EAWM.

Following the previous studies (Zheng et al., 2006), the area averaged DJF mean surface temperature over the whole eastern China (20–40°N, 105–120°E) is used as a temperature-based index for EAWM. The area averaged JJA mean precipitation over the North China (NC, 34–40°N, 105–120°E) is used as a NC precipitation-based index for EASM, while the South China (SC, 25–31°N, 105–120°E) JJA mean precipitation is also used as a SC-precipitation-based index for EASM.

The relationship between the wind-based EASM and the temperature-based EAWM (Figure S10) is similar to that between the wind-based EASM and the wind-based EAWM (Figure 3). This might be due to the fact that the AMOC can influence the temperature along with the wind field over Eurasia through the westerly jet waveguide and the associated circumglobal teleconnection (e.g., Figure 4); it also confirms that EAWM can be represented either by the DJF mean low level meridional wind or by the DJF mean surface temperature over the eastern China (Wang & Chen, 2010).

The NC precipitation based-EASM is also significantly negatively correlated with the wind based-EAWM at centennial timescale (Figure S11a). This is consistent with the previous works suggesting that the NC precipitation can represent the intensity of EASM; i.e., the weakened/strengthened monsoon circulation is followed by the reduced/increased precipitation in NC (Goldsmith et al., 2017; Liu, Wen, et al., 2014; Zhou et al., 2017).

For the SC precipitation-based EASM index, the relationships become complex. The SC precipitation-based EASM is correlated with the wind-based EAWM positively at decadal to centennial timescales, but negatively at multicentennial to millennial timescales, and then positively again at orbital timescale (Figure S11c). The composite analyses of the weak and strong AMOC states show that the SC summer precipitation increases in both states, in contrast to the wind field and the NC precipitation which are different between the two states (Figure S12). This suggests that the SC summer precipitation is not a good representation of the EASM intensity, because the SC precipitation in JJA is affected by not only the EASM circulation but also other factors such as tropical cyclone. In addition, the SC is signified with the “spring rain” at the beginning of its rainy season, which cannot be considered as a part of the EASM rainy season (Wang & LinHo, 2002). Additionally, the JJA precipitation over the eastern China has subtle relationship with the DJF temperature (Figures S11b and S11d).

Data Availability Statement

The original simulation data related to this paper can be downloaded from the following website:

TraCE-21ka, https://www.earthsystemgrid.org/project/trace.html.
The simulated wind data are available through Wen et al. (2016). The insolation data are calculated using the method of Huyber (2006). We plan to archive our simulation data on National Climate Data Center (NCDC) and have uploaded the insolation data and AMOC data as Supporting Information S1 for review purpose.

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