

Decadal Variations of the East Asian Summer Monsoon Forced by the 11-Year Insolation Cycle

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ABSTRACT

Statistical evidence suggests that solar activity may affect the atmospheric circulation over East Asia (EA), but the way in which the 11-yr solar radiation cycle affects the East Asian summer monsoon (EASM) remains unexplained. Based on one control experiment and four solar-only forcing experiments performed during the Community Earth System Model–Last Millennium Ensemble (CESM–LME) model project, we explore the potential impacts of the 11-yr solar cycle on EASM variability and the physical processes through which solar forcing influences EASM decadal variability. The model results show that the warm season [May–September (MJJAS)] mean precipitation over EA exhibits significant decadal variation with a “northern wet–southern dry” pattern during peak years in the strong 11-yr solar cycle epoch (AD 900–1285), which is in contrast to the absence of decadal signals during the weak 11-yr solar cycle epoch (AD 1400–1535). For the four-member ensemble averaged solar-only forcing experiment, the summer mean precipitation over northern EA is significantly correlated with the solar forcing ($r = 0.414$, $n = 68$, $p < 0.05$) on a decadal time scale during the strong cycle epoch, whereas there is no statistical link between the EASM and solar activity during the weak cycle epoch ($r = 0.002$, $n = 24$). A strong, 11-yr solar cycle is also shown to excite an anomalous sea surface temperature (SST) pattern that resembles a cool Pacific decadal oscillation (PDO) phase, which has a significant 11-yr periodicity. The associated anomalous North Pacific anticyclone dominates the entire extratropical North Pacific and enhances the southerly monsoon over EA, which results in abundant rainfall over northern EA. We argue that the 11-yr solar cycle affects the EASM decadal variation through excitation of a coupled decadal mode in the Asia–North Pacific region.

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1. Introduction

Solar radiation is the ultimate energy source for Earth systems. The change in solar radiation intensity caused by solar variability has a significant impact on climate change (Huo and Xiao 2016; Xiao and Huo 2016). The possibility that the solar activity may affect Earth's climate system was discussed as early as 1801 (Herschel 1801). Subsequently, numerous studies have indicated statistical correlations between climate change and solar activity (Laut and Gundermann 1999; Van Loon and Shea 2000; Van Loon and Meehl 2008; Haigh 2003; Tung and Camp 2008; Gray et al. 2010). Meanwhile, efforts have been devoted to studying the mechanism about the influences of solar activity on the climate system (Gray et al. 2001; Gray 2003; Matthes et al. 2006; White and Liu 2008a,b). However, most of those studies mainly focused on the influences of solar cycle variability (solar maximum minus solar minimum) on climate variability (Haigh 1996; Meehl et al. 2008, 2009) instead of on the decadal climate change. Additionally, the assessment reports of the Intergovernmental Panel on Climate Change (IPCC) suggested that more than half of global warming over the present warming period (PWP) is caused by human activity; however, the IPCC also pointed out that the effects of natural factors (e.g., volcanic eruptions and solar activity) are underestimated (IPCC 2007, 2013). The impacts of solar activity on climate change remain largely unknown.

The East Asian summer monsoon (EASM) is an important component of global monsoons. The EASM displays a complex spatial structure, which consists of the South Asian high, northwestern Pacific subtropical high, Mascarene high, Australian high, cross-equatorial flows, mei-yu fronts, etc. (Huang and Tang 1987). Different causes of EASM variations on different time scales are recognized. Modern climatologists have focused on the interannual variability of the EASM, which arises primarily from the impacts of El Niño–Southern Oscillation (ENSO) (Chang et al. 2000a,b; Wang et al. 2000) and local monsoon–ocean–land interactions (Wang et al. 2001; Xie et al. 2009; Yim et al. 2016). In contrast, paleoclimatologists have focused more on EASM variability on multidecadal, centennial, and millennial time scales by studying various proxy records and numerical simulation results, recognizing that the EASM is strongly modulated by external forcings, especially solar radiation (Wang et al. 2008a; Liu et al. 2009; Man et al. 2012). Numerous studies have revealed that the north–south dipolar structure of summer rainfall over eastern China is associated with EASM decadal variability (Zhou et al. 2009; Liu et al. 2014; Zhang and Zhou 2015). Unfortunately, the mechanism that

produces decadal variability in the EASM remains largely controversial (Li et al. 2010; Zhu et al. 2012).

Statistical evidence suggests that solar activity might have significant effects on the atmospheric circulation over East Asia (EA). Using low-pass-filtered Chinese dryness/wetness indices, Currie (1995) found a statistically significant signal of solar influence on annual precipitation in central and northern China. The large decadal to millennial variability of the East Asian monsoon climate may have been forced by the solar activity during the Last Glacial Maximum (Wu et al. 2006). The periodicity of the Asian monsoon precipitation was found to be similar to that of solar activity on decadal to centennial time scales (Wang et al. 2005; Tan et al. 2008). Zhao et al. (2012) determined that the solar variability seems to dominate the long-period (>8 yr) variation in summer precipitation in China by using monthly high-resolution data. There is no doubt that the solar activity has a significant influence on the EASM; however, there is no broadly accepted explanation for how the solar activity affects the EASM.

The role of solar activity in modern climate change, particularly on the decadal time scale, is an important scientific issue. Solar activity has a significant 11-yr cycle. How does the EASM rainfall respond to this 11-yr solar cycle? If the response is significant, how does the solar forcing impact the EASM rainfall variability? In this study, we will address these questions based on the simulation results derived from one AD 850 control experiment (CTRL) and four solar-only forcing experiments [spectral solar irradiance (SSI) experiments], which were conducted by the Community Earth System Model–Last Millennium Ensemble (CESM-LME) modeling project (Otto-Bliesner et al. 2016).

2. Model, data, and methods

The CESM-LME simulation dataset provided by NCAR's Climate Change Research Section is an ensemble of fully forced and single forced simulations. The CESM1.1 uses $\sim 2^\circ$ resolution for the atmosphere and land components and $\sim 1^\circ$ resolution for the ocean and sea ice components. Before starting the CESM-LME simulations, an AD 1850 control simulation was spun up for 650 years, from which an AD 850 control simulation was branched out and run for an additional 1356 years. All CESM-LME simulations were started from year AD 850 using initial conditions derived from the AD 850 control experiment and ended in AD 2005. The only difference among each single SSI experiment is the application of small random rounding off (on the order of 10^{-14}°C) differences in the air temperature field at the start of each ensemble member (Otto-Bliesner et al. 2016).

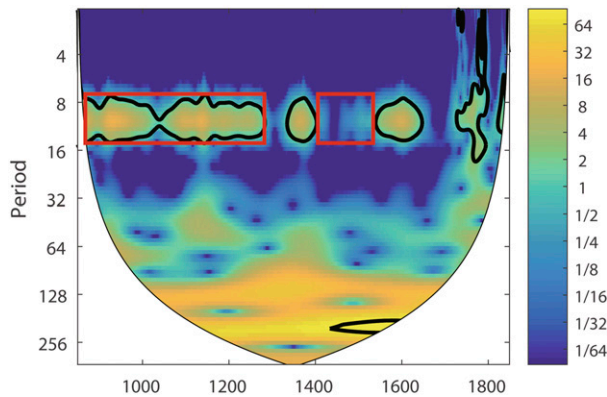


FIG. 1. Wavelet analysis of the external forcing used in the solar-only forcing experiments. The red boxes outline the two periods selected in our comparison study.

In this paper, we used the data obtained from simulations of the CTRL experiment and four solar-only forcing experiments during AD 850–1850. In the four solar-only forcing experiments, changes in the total solar irradiance (TSI) are prescribed by using the reconstructed solar forcing (Vieira et al. 2011), in which an estimated 11-yr solar cycle was imposed and the spectral solar irradiance was derived by using a linear regression of TSI at each spectral interval (Schmidt et al. 2012).

a. Decadal variability of solar forcing

From the wavelet analysis of external forcing used in the solar-only forcing experiments (Fig. 1), the solar forcing shows significant 8–16-yr solar cycles, but the intensity varies over the entire period. During four epochs (AD 900–1285, 1335–1400, 1535–1650, and 1730–1800), the insolation shows strong decadal signals, while during the other epochs (AD 1285–1335, 1400–1535, and 1650–1730; hereafter, all dates are AD), the decadal variation of insolation is generally weak. In the present study, to make results more robust, we have chosen the two longest epochs: the period of 900–1285 as an epoch with significant 8–15-yr solar cycles, and the period of 1400–1535 as an epoch without significant 8–15-yr solar cycles. Then, we compared the EASM responses to the strong and weak forcings to understand how decadal EASM variability is shaped by the 11-yr solar cycle.

b. Measure of the EASM decadal variability

The East Asian monsoon domain is defined by the regions in which the annual range (AR) of precipitation exceeds 2 mm day^{-1} , and the local summer precipitation exceeds 55% of the annual rainfall (Wang and Ding 2008), according to the Climate Prediction Center Merged

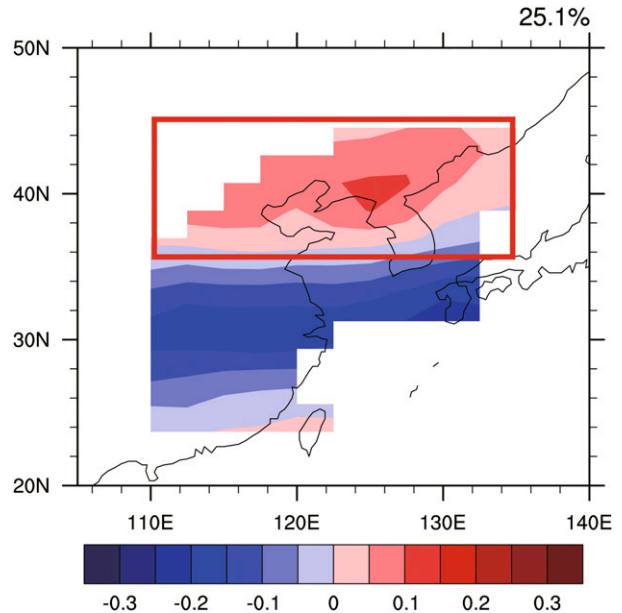


FIG. 2. The leading EOF mode of the MJJAS mean precipitation over the EA during 850–1850 after application of an 8–15-yr bandpass filter derived from ensemble averaged SSI experiments.

Analysis of Precipitation (CMAP; Xie and Arkin 1997). The rectangular EASM domain is 22.5° – 45° N, 110° – 135° E (Yim et al. 2014). Many different definitions have been proposed for the EASM strength (Guo 1983; Webster and Yang 1992; Shi and Zhu 1996). Wang et al. (1981) suggested that a strong EASM circulation features strong southerly winds extending northward, carrying more water vapor from the tropical Pacific and Indian Oceans to the northern EA, which results in abundant rainfall over northern EA, but the rainfall is deficient in the lower-middle reaches of the Yangtze River valley and southern EA.

The north–south dipolar structure over the EA is a characteristic of the EASM leading mode variability (Wang et al. 2008b; Zhou et al. 2009). Figure 2 shows the leading EOF mode of the decadal summer variability [May–September (MJJAS)] mean precipitation over EA, which is simulated in the ensemble mean solar-only experiments during the entire preindustrial period of 850–1850. The leading decadal mode is characterized by a dipolar pattern of precipitation with a “wet northern and dry southern” EA, including precipitation anomalies that are out of phase between the regions north and south of 35° N. To quantify the EASM decadal variability, the areal averaged precipitation anomalies over either northern or southern EA may be used. Chen et al. (2015) suggested that the EASM intensity can be directly represented by the precipitation in northern China. In this work, from a hydrological

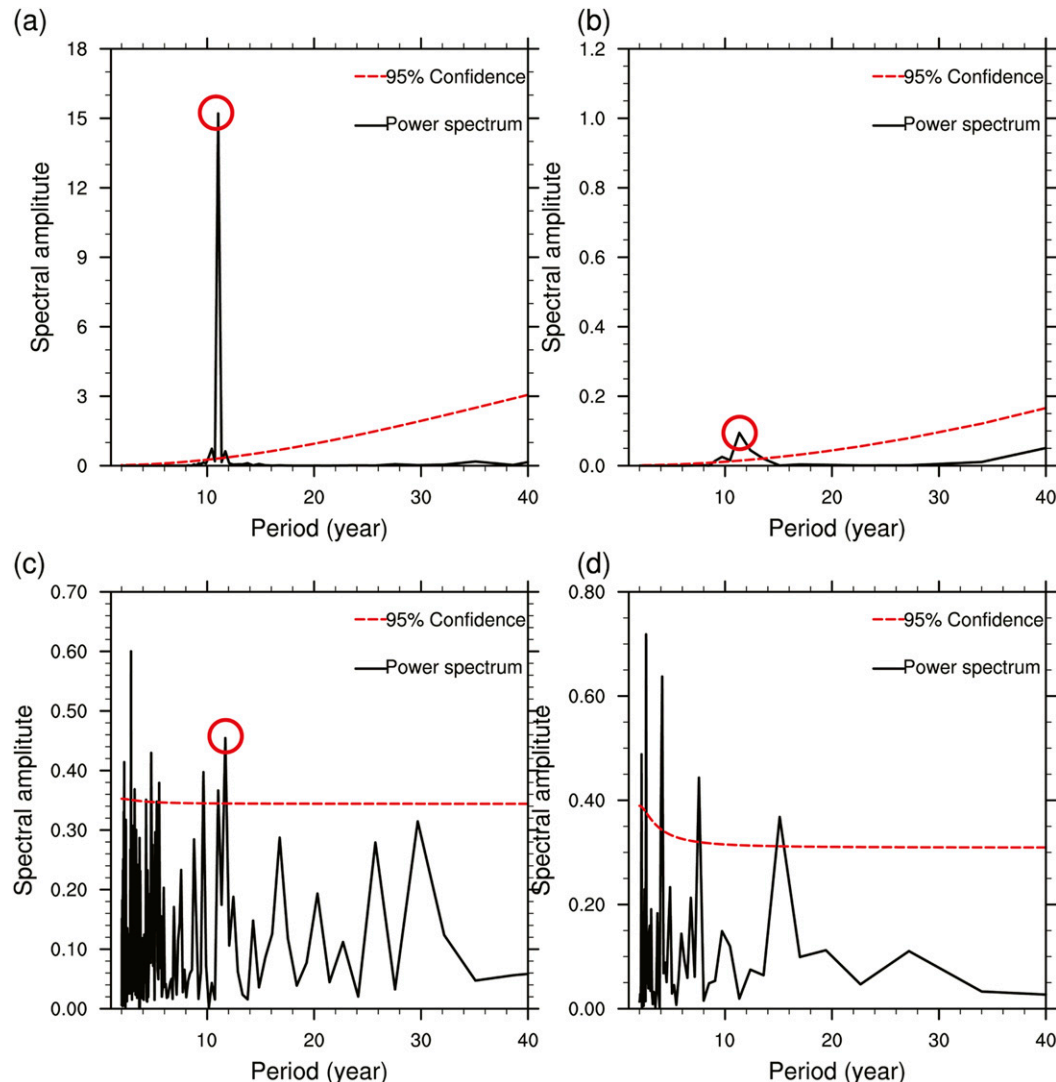


FIG. 3. Power spectrum of (a),(b) the solar forcing and (c),(d) the EASM index of ensemble averaged SSI experiments during the (a),(c) strong 11-yr solar cycle epoch (900–1285) and (b),(d) weak 11-yr solar cycle epoch (1400–1535). The red cycles are used to emphasize the 11-yr cycle.

perspective, we use the MJJAS mean precipitation over northern EA to measure the intensity of the EASM decadal variation and define an EASM index as the MJJAS averaged precipitation over the northern part of EA (35° – 45° N, 110° – 135° E).

3. Relationship between solar activity and the EASM on a decadal time scale

To investigate the EASM responses to solar activity, we first compare the power spectrum of the external forcing and EASM index during the period with a strong 11-yr solar cycle (900–1285) and the period with a weak 11-yr solar cycle (1400–1535). The 11-yr solar cycle exists in the solar forcing during both 900–1285 and

1400–1535, but the decadal signal of the EASM index over 900–1285 is much stronger than that over 1400–1535 (Figs. 3a and 3b). For convenience, we refer to the period of 900–1285 as the strong (11 yr) cycle epoch and the period of 1400–1535 as the weak (11 yr) cycle epoch. For the ensemble averaged results of four SSI experiments, although the interannual oscillation of the EASM index is significant, there is a remarkable quasi-11-yr period that occurs during the strong cycle epoch of 900–1285 (Fig. 3c), whereas the quasi-11-yr period is not obvious during the weak cycle epoch of 1400–1535 (Fig. 3d). Additionally, we have explored the EASM variation modulated by the internal climate variability, and there is no 11-yr peak presenting in the power spectrum for the entire 1000-yr CTRL experiment (Fig. 4).

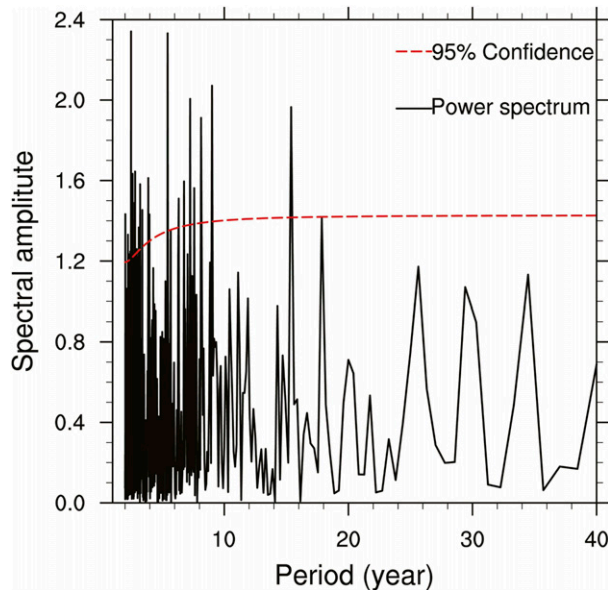


FIG. 4. Power spectrum of the EASM index of the 1000-yr CTRL experiment.

Meanwhile, the significant 11-yr period is almost not shown in each single solar-only forcing experiment during both the strong and weak 11-yr solar cycle epochs (figure omitted), which may be due to the fact that internal variability dominates each solar-only forcing experiment. It is noted that there are some challenges in detecting the forced signals in observations.

To further confirm the relationship between the EASM and solar activity on the decadal time scale, the 8–15-yr bandpass filter was applied to the external forcing and EASM index. For each single SSI experiment, the simultaneous correlation coefficients between the external solar forcing and the EASM index range from 0.038 to 0.311 during the strong cycle epoch; two of the correlation coefficients in the four SSI experiments reach the 95% confidence level. The EASM index of the four-member ensemble averaged solar-only forcing experiment is significantly correlated with the solar activity with a correlation coefficient of 0.414 (the effective sample size $n = 68$, $p < 0.05$ based on the Student's t test) during the strong cycle epoch (900–1285), whereas there is no statistical link between the EASM and solar activity during the weak cycle epoch (1400–1535) ($r = 0.002$, $n = 24$). The results shown in this section provide firm evidence that underscores the 11-yr solar cycle impact on the decadal EASM variation by using the ensemble averaged results of four solar-only forcing experiments. Therefore, in the following paragraph, our analyses are mainly based on the four-member ensemble averaged solar-only forcing experiment.

4. Mechanisms underlying the decadal solar variability influence on the EASM

Since abnormal changes in sea surface temperature (SST) may have a significant effect on the EASM circulation and water vapor transport (Wang et al. 2008a; Xu et al. 2016), it is meaningful to examine the SST anomalies associated with an enhanced EASM. Figure 5 shows the decadal anomalies of the MJJAS mean SST associated with the EASM index. During the strong 11-yr solar cycle epoch, the decadal variation of the EASM was associated with significant SST anomalies over the Pacific, which resembles a pan-Pacific IPO (interdecadal Pacific oscillation) (Fig. 5a). In the tropics, a strong EASM corresponds to positive SST anomalies surrounding the Maritime Continent and negative SST anomalies over the tropical eastern Pacific, which resembles a La Niña pattern. In the North Pacific poleward of 20°N, a strong EASM corresponds to a significant warming in the extratropical west-central North Pacific and a significant cooling along the west coast of North America. This North Pacific SST pattern resembles a cool phase of the Pacific decadal oscillation (PDO). On the other hand, during the weak 11-yr solar cycle epoch, the SST anomalies associated with a strong EASM show a different SST anomalous pattern (Fig. 5b). The SST anomalies in the extratropical North Pacific (poleward of 20°N) feature a tripolar pattern, which is notably different from the PDO pattern. In the tropics, the Maritime Continent warming is shifted to the equatorial western Pacific and the eastern Pacific cooling is shifted to the southeastern Pacific. The results in Fig. 5 suggest that the EASM decadal variation is specifically associated with PDO-like SST anomalies in the extratropical North Pacific.

Is the PDO pattern of SST anomalies related to the solar forcing? Those questions may be addressed by comparing the responses of the MJJAS mean SST to the solar activity during strong (Fig. 6a) and weak (Fig. 6b) cycle epochs. During the strong cycle epoch (900–1285), the overall SST pattern associated with the solar forcing is similar to the MJJAS mean SST associated with the EASM index, except over the equatorial eastern Pacific. On the other hand, during the weak cycle epoch, the impacts of solar activity on the region poleward of 20°N in the North Pacific are insignificant, although significant SST warming is observed over the equatorial western Pacific and cooling is observed over the tropical eastern North Pacific. The results shown in Fig. 6 suggest that the regions where the SST responds differently to the strong and weak 11-yr solar cycles are located poleward of 20°N in the North Pacific, and during the peak years with the strong 11-yr solar cycle can induce an SST

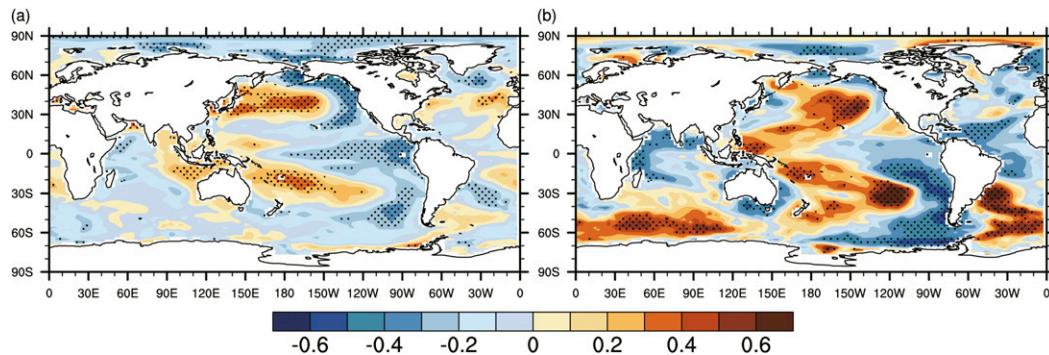


FIG. 5. Simultaneous correlation map of the MJJAS mean SST with the EASM index on the decadal time scale during the (a) strong 11-yr solar cycle epoch (900–1285) and (b) weak 11-yr solar cycle epoch (1400–1535) after the application of an 8–15-yr bandpass filter derived from ensemble averaged SSI experiments; the dotted areas are significant at the 95% confidence level.

pattern that resembles a cool PDO state. Meehl et al. (2009) suggested that the PDO-like pattern can arise from interactions of the ocean and atmosphere during the 11 peak solar years.

To confirm this documented solar forcing–PDO linkage in terms of spatial structure, we further examine their linkage in temporal variations. For this purpose, the PDO index is used and defined as the leading principal component of the North Pacific monthly SST variability (Mantua et al. 1997). To detect the PDO signals during the strong and weak 11-yr solar cycle epochs, a 5-yr running mean was applied prior to the EOF analysis of SST variability over the North Pacific poleward of 20°N. Spectral analyses show that during the strong 11-yr solar cycle epoch (900–1285), the PDO index has obvious decadal (11- and 19-yr cycles) energy peaks, whereas during the weak 11-yr solar cycle epoch (1400–1535) the PDO index shows a 22-yr (quasi bi-decadal) cycle (Fig. 7). Additionally, we have explored the spectral analyses of the PDO index derived from the

CTRL experiment, there are obvious decadal (18 yr) energy peaks (figure omitted). Therefore, this finding confirms that the 11-yr solar cycle can induce an 11-yr peak in the PDO pattern, and the quasi-bi-decadal (19- and 22-yr cycles) PDO peak during these two epochs could come from the internal climate variability.

To determine how the PDO can link to the EASM decadal variability during the strong 11-yr solar cycle epoch, the MJJAS mean sea level pressure (Fig. 8a) and precipitation/850-hPa winds (Fig. 8b) associated with the PDO index after the application of an 8–15-yr bandpass filter are examined. During the cool PDO phase, high pressure anomalies occur over the extratropical North Pacific (poleward of 20°N), which concurs with a large-scale North Pacific anticyclone in the lower troposphere. West of the giant North Pacific anomalous anticyclone is an Asian continental low pressure anomaly (Fig. 8a), and thus the large zonal pressure gradients between the North Pacific high and Asian low anomalies generate strong southerlies over EA

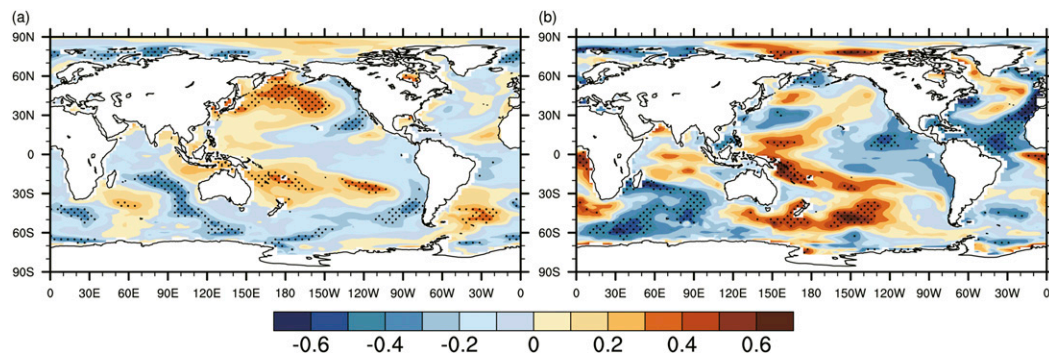


FIG. 6. Simultaneous correlation map of the MJJAS mean SST of ensemble averaged SSI experiments with external forcing on the decadal time scale during the (a) strong 11-yr solar cycle epoch (900–1285) and (b) weak 11-yr solar cycle epoch (1400–1535) after the application of an 8–15-yr bandpass filter; the dotted areas are significant at the 95% confidence level.

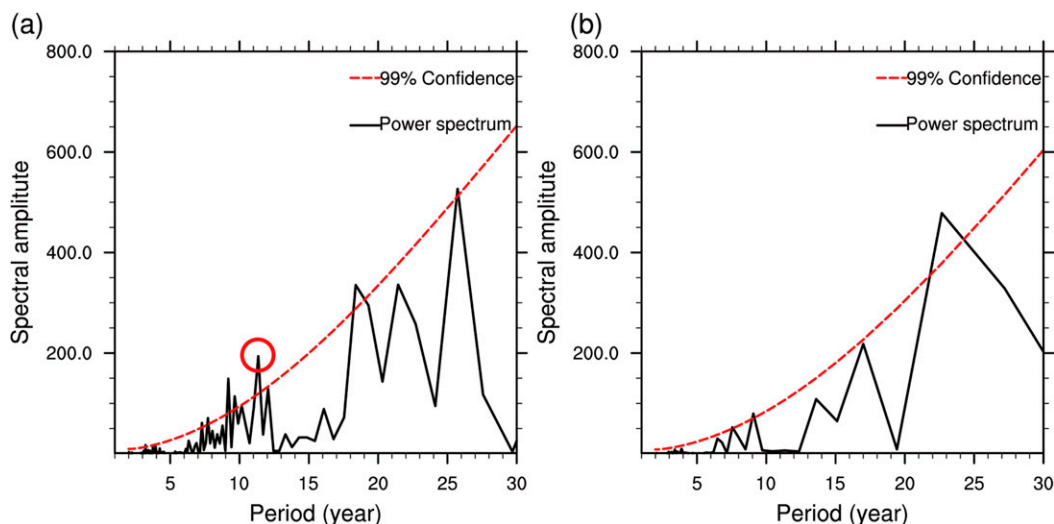


FIG. 7. Power spectrum of the PDO index of ensemble averaged SSI experiments during the (a) strong 11-yr solar cycle epoch (900–1285) and (b) weak 11-yr solar cycle epoch (1400–1535).

(Fig. 8b). There is a lone regional-scale east–west-oriented pressure trough at 35°N over eastern China (Fig. 8a), which corresponds to cyclonic vorticity over northern China and anticyclonic vorticity over southern China

(Fig. 8b). The cyclonic vorticity enhances the upward motion and precipitation in northern China, while the anticyclonic vorticity reduces precipitation in southern China. Thus, during a cool PDO phase, rainfall over

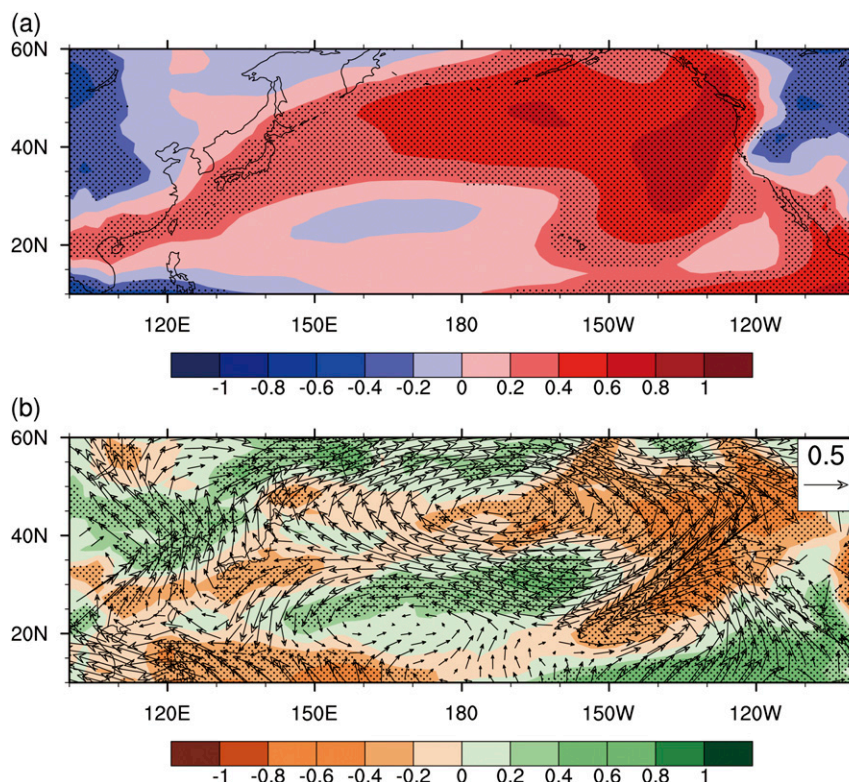


FIG. 8. Simultaneous correlation maps of (a) the MJJAS mean sea level pressure and (b) the precipitation and 850-hPa winds with respect to the PDO index during the strong 11-yr solar cycle epoch (900–1285) after the application of an 8–15-yr bandpass filter derived from ensemble averaged SSI experiments; the dotted areas are significant at the 95% confidence level.

northern China is generally abundant, whereas rain is deficient over southern China (Zhu and Yang 2003; Ma 2007; Qian and Zhou 2014; Yang et al. 2017).

In this study, we favor that during summer, the SST anomalies associated with the PDO in the extratropical North Pacific may result from the atmosphere–ocean interaction under the influence of the solar activity (Meehl et al. 2009; Liu 2012; Newman et al. 2016). The anomalous anticyclone in the extratropical North Pacific (Fig. 8b) can suppress cloudiness and increase downward solar radiation, warming the ocean beneath and resulting in positive SST anomalies in the midlatitude west-central North Pacific, which are similar to those shown in Fig. 6a. Meanwhile, the anomalous northerly on the eastern flank of the anticyclone can enhance coastal upwelling and evaporative cooling, inducing negative SST anomalies along the North American west coast. This would result in an anomaly SST pattern that is similar to a cool PDO phase (Fig. 6a). Therefore, the SST anomalies associated with the PDO may affect the atmospheric circulation and EASM, but conversely the atmospheric anomalies can produce feedback to maintain the PDO anomalies.

5. Conclusions and discussion

Solar activity shows a significant 11-yr cycle. The way in which this solar variability affects Earth's climate is an important scientific issue. Observations suggest that the multiple temporal structures of the EASM rainfall have decadal variation components. We are curious about how the EASM rainfall would respond to the 11-yr solar cycle forcing and, if the response is significant, what the mechanism is through which solar forcing can change the EASM precipitation. To address these questions, we analyzed the results derived from one control experiment and four solar-only forcing experiments, which were conducted as part of the CESM-LME modeling project.

In the four-member ensemble, solar-only forcing experiments, the model-simulated decadal variation in the EASM rainfall is dominated by a “northern wet–southern dry” pattern (Fig. 2). We found that the EASM rainfall significantly responds to the 11-yr insolation forcing. During the AD 900–1285 epoch with strong 11-yr solar cycle, the EASM index has a conspicuous peak at approximately 11 years, whereas during the insignificant forcing epoch of AD 1400–1535, the quasi-11-yr periodicity disappears (Fig. 3). The EASM index in the four-member ensemble SSI experiment is significantly correlated with the solar activity with a correlation coefficient of 0.414 ($n = 68$, $p < 0.05$) during the strong 11-yr solar cycle epoch, whereas there is no statistically significant link during the weak cycle epoch ($r = 0.002$, $n = 24$). The results here provide firm evidence

that underscores the impact of the 11-yr solar cycle on EASM decadal variation.

We show that the EASM decadal variation during the strong 11-yr solar cycle epoch is associated with SST anomalies over the Pacific that resemble a PDO-like pattern (Fig. 5a). Further, we demonstrate that during the peak years of the strong 11-yr solar cycle the anomalous SST pattern in North Pacific resembles a pattern of cool PDO phase (Fig. 6a) with a significant variance peak at 11 years (Fig. 7a). During the cool PDO phase, a large-scale anomalous anticyclone prevailing over the entire extratropical North Pacific enhances the southerlies over EA, which results in a strong EASM with abundant rainfall over northern EA. Therefore, we propose that the 11-yr solar cycle affects the EASM decadal variation through excitation of a PDO-like decadal mode that is characterized by a gigantic North Pacific anticyclone during the peak phase of the solar irradiance.

It is conceivable that during the Northern Hemisphere summer, a stronger than normal insolation associated with the 11-yr solar cycle might be able to enhance the summer climatological feature (i.e., enhance the North Pacific high and Asian continental low). This process is similar to the processes responsible for summer climate formation under a fixed solar forcing. As such, the enhanced North Pacific high (anomalous North Pacific anticyclone) can induce the PDO-like SST anomalies and an enhanced EASM through active atmosphere–ocean–land interaction in the Asian–Pacific sector. This may explain why the EASM and North Pacific Ocean have coherent decadal variability during the strong 11-yr solar cycle epoch.

In addition, the cool PDO phase during the weak 11-yr solar cycle epoch can also induce the “wet northern and dry southern” rainfall pattern over EA, but the precipitation over the EASM domain is not significantly correlated with the PDO index after the application of an 8–15-yr bandpass filter (figure omitted). While the dipolar patterns during the strong and weak 11-yr solar cycle epochs look similar, there are two notable differences. First, comparing with the epoch of weak 11-yr solar cycle, the North Pacific anticyclone in the epoch of strong 11-yr solar cycle is considerably stronger and bigger, occupying the entire North Pacific (poleward of 20°N); as a result, the southerly monsoonal flow in East Asia is much stronger and the corresponding “northern wet” region expands and the wet anomaly intensifies. This suggests that the strong 11-yr cycle has modified the spatial structure of the internal mode, the PDO, and strengthened its relationship with EASM. Second, the PDO and EASM are not significantly correlated on the decadal time scale during the weak 11-yr solar cycle epoch, whereas during the epoch of strong 11-yr solar

cycle they exhibit a significant decadal covariability. This suggests that the 11-yr solar forcing has modified the temporal evolution of PDO (by exciting a significant decadal peak) and its associated impact on EASM. In sum, the strong 11-yr solar cycle has significantly changed the spatial-temporal structure of the PDO and its relationship with EASM. We argue that PDO is the natural variability, which can be partly influenced by the external forcing; the strong 11-yr solar cycle can modulate the 11-yr PDO peak, causing the significantly abundant precipitation with 11-yr cycle over the northern part of EA.

The model results have revealed the linkages among the 11-yr solar forcing, decadal PDO-like SST anomalies, and decadal variability in EASM precipitation, while the precise process through which the 11-yr solar forcing instigates the decadal PDO and anomalous North Pacific anticyclone deserves further study.

There are two widely perceived solar influence mechanisms (Gray et al. 2010). The “top-down” mechanism regarding that the ultraviolet (UV) absorbed by stratospheric ozone indirectly influences the troposphere (Haigh 2003). Another “bottom-up” mechanism involves the coupled air–sea interaction over the relatively cloud-free subtropical ocean with incoming solar heating. The peak in the 11-yr solar cycle increases evaporation, so more moisture is carried by stronger trade winds to the convergence zones with abundant precipitation, which then generates greater equatorial ocean upwelling and lower equatorial SSTs in the eastern Pacific, resulting in the enhancement of the Hadley and Walker circulations and anomalous positive sea level pressure in the North Pacific extending to North America (Meehl et al. 2008). However, the process of the solar activity acting on the Pacific is complicated (Meehl et al. 2003, 2008); in this paper, the hypothesis regarding the top-down mechanism has not been explored.

The results of this study are based on numerical experiments performed using a single climate system model. Obviously, multimodel results should be investigated to verify this model result. The model results of this study suggest that, different from interannual variability mechanisms, the EASM decadal variation may originate from the solar forcing–excited, internally coupled mode over the North Pacific and EA. Further studies are required to verify this hypothesis.

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