

Warm Pool and East Asian monsoon during MIS-13

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Relative impact of insolation and Warm Pool surface temperature on the East Asia Summer Monsoon during the MIS-13 interglacial

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Abstract

During Marine Isotope Stage (MIS) 13, an interglacial about 500 000 years ago, the East Asian summer monsoon (EASM) was suggested exceptionally strong by different proxies in China. However, MIS-13 is a weak interglacial in marine oxygen isotope records and has relatively low CO₂ and CH₄ concentrations compared to other interglacials of the last 800 000 years. In the mean time, the sea surface temperature (SST) reconstructions show that the Western Pacific Warm Pool was relatively warm during MIS-13. Based on climate modeling experiments, this study aims at investigating whether this Warm Pool warming could explain the exceptionally strong EASM occurring during the relatively cool interglacial MIS-13. The individual contributions of insolation and of the Warm Pool SST as well as their synergism are quantified through experiments with the Hadley Centre atmosphere model, HadAM3 and using the factor separation technique. The SST over the Warm Pool region has been increased based on geological reconstructions. Our results show that the pure impact of a strong summer insolation contributes to strengthen significantly the summer precipitation in northern China but only little in southern China. The pure impact of enhanced Warm Pool SST reduces, slightly, the summer precipitation in both northern and southern China. However, the synergism between insolation and enhanced Warm Pool SST contributes to a large increase of summer precipitation in southern China but to a decrease in northern China. Therefore, the ultimate role of enhanced Warm Pool SST reinforces the impact of insolation in southern China but reduces its impact in northern China. We conclude that enhanced SST over the Warm Pool region does help to explain the strong MIS-13 EASM precipitation in southern China as recorded in proxy data, but other explanation is needed for explaining the exceptionally strong EASM in northern China.

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1 Introduction

Marine Isotope Stage (MIS) 13, an interglacial about 500 ka ago, is the coolest interglacial of the past 800 ka over Antarctica (Jouzel et al., 2007). The average CO₂ concentration is about 240 ppmv, which is low for an interglacial (Luthi et al., 2008). It also has higher marine benthic $\delta^{18}\text{O}$ values than other interglacials, implying larger continental ice sheets and/or cooler deep-sea temperature. However, the paleosoil S5-1 in the loess from northern China, which corresponds to MIS-13, is the strongest developed soil of the past 800 ka, suggesting an extremely strong East Asian summer monsoon (EASM) precipitation (e.g. Kukla et al., 1990; Guo et al., 1998). This strong EASM was confirmed by the lake sediments from the Tibet Plateau (Chen et al., 1999) and by the paleo red soils from southern China (Yin and Guo, 2006). It appears also as strong as the other interglacials in the stalagmites records from western China (Cheng et al., 2012). These terrestrial reconstructions are in line with maritime summer monsoon proxy (Wei et al., 2007) and sea surface salinity reconstruction (Shyu et al., 2001) in the South China Sea. A strong EASM occurring during a relatively cool interglacial MIS-13 was pointed out by Yin and Guo (2008) as a seeming paradox.

In order to understand this seeming paradox, several modelling studies have investigated the impacts of insolation and ice sheets on the MIS-13 EASM. Using the LOVECLIM model (an Earth system model of intermediate complexity), Yin et al. (2008, 2009) found that strong summer insolation in the Northern Hemisphere (NH) contributes to intensify the EASM during MIS-13 as compared to today, but insolation alone does not make the MIS-13 EASM exceptionally strong as compared to other interglacials. Unexpectedly, they also found that a small Eurasian ice sheet reinforces additionally the EASM through a topographically induced wave train, which might explain the exceptional EASM during MIS-13. These findings have been confirmed by more complex general circulation models including an atmosphere-only model ARPEGE (Sundaram et al., 2012; Muri et al., 2012) and an atmosphere-ocean coupled model HadCM3 (Muri et al., 2013). However, it is still unclear if there was

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influence on East Asia summer monsoon variability. According to Zhao et al. (2000), if the Warm Pool temperature increases, the subtropical high extends further westward in the northwest Pacific Ocean and its ridge is displaced further southward, resulting in a change of the precipitation pattern in China. This leads actually to less rainfall in northern China and more rainfall in southern China. Moreover Zhou et al. (2009) explored the impacts of higher and lower pool SST on the East Asia summer monsoon rainfall for the present-day using five different AGCMs. Their results suggest that the SST changes in the Warm Pool influence the Walker circulation, with a subsequent reduction of convection in the tropical central and eastern Pacific, which in turn forces an ENSO/Gill-type response that modulates the WPSH.

Given the importance of the Warm Pool SST on the EASM and the enhanced SST in the Warm Pool region during MIS-13, one may wonder which role this Warm Pool warming plays on the EASM during MIS-13, whether it is at the origin of the exceptionally strong EASM during this interglacial, and what is its relative importance as compared to insolation. We aim at answering these questions in this study by performing sensitivity experiments with the Hadley Centre atmosphere model HadAM3. The individual impacts of Warm Pool warming and of insolation, as well as their synergism, are quantified through factor separation analysis (Stein and Alpert, 1993) (see Sect. 2 for detailed information). Although many studies have discussed about the impact of Warm Pool surface conditions on the EASM (see the paragraph above), they are mainly based on modern background climate and few deals with the past interglacials. Given the different configurations in the climate forcings (for example, NH summer occurs at aphelion at present-day but it may occur at perihelion during the past interglacials), it is worth investigating the impact of Warm Pool during the past interglacials using climate models. Moreover, factor separation analysis allows separating the pure impact of insolation and of the Warm Pool warming as well as their synergism. Therefore, this study may provide broader implications than only for MIS-13 regarding the impact of Warm Pool warming on the EASM and its synergic effect with insolation.

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The EASM system is generally described as the combination of three main components: the East Asian meiyu/baiu/changma front (a major rain-bearing system in the subtropics and mid-latitudes), the western Pacific subtropical high, and the tropical western Pacific monsoon trough, which corresponds to the western Pacific intertropical convergence zone (ITCZ). In addition, the intensity and location of subtropical westerly jet (SWJ) and tropical easterly jet (TEJ) at upper level (200 hPa), and the modulation of the Hadley and Walker circulations play a major role in the EASM rainfall variability. These EASM-associated features are analyzed here. In this study, East China monsoon region refers to the area between 105–120° E and 20–40° N (Wei and Wang, 2004; Lee et al., 2008), northern and southern China being separated by 30° N latitude. Model and experiment design are given in Sect. 2. The pure impacts of insolation and of Warm Pool SST enhancement on the EASM, their synergism as well as their combined effect are discussed in Sect. 3. Conclusion is given in the final section.

2 Model and experiment design

As our purpose is to investigate the impact of enhanced Warm Pool SST on the EASM during MIS-13, SST is prescribed in our experiments. In such a case, an atmosphere-only model instead of an atmosphere–ocean coupled model is required. The atmosphere model used here is HadAM3 (Pope et al., 2000) which was developed at the Hadley Centre for Climate Prediction and Research. It is based on the hydrostatic and primitive equations and uses an Arakawa B-grid and hybrid vertical coordinates. It has a horizontal resolution of 3.75° in longitudes and 2.5° in latitudes, with 19 vertical levels. HadAM3 has been demonstrated to perform well in the atmospheric model intercomparison project and to produce a reasonable representation of the Asian monsoon circulations and precipitation (Martin et al., 2000; Zhou et al., 2009). It has also been used in many studies on the response of East Asian monsoon to modified

forcings. For example, Liu et al. (2012) has recently used HadAM3 to investigate the impact of the changes in Tibetan Plateau thermal forcing on the EASM.

In order to quantify the impact of increased Warm Pool SST on the MIS-13 EASM and also to compare its contribution with the contribution from insolation, the factor separation technique by Stein and Alpert (1993) has been used. This method allows the identification of the individual contribution of each factor to any climatic variable as well as their synergistic effects. It has been used in many modeling studies to quantify the relative importance of specific processes or forcings and their interactions as, for example, for the Holocene (Berger, 2001; Claussen et al., 2001), the Eemian (Kubatzki et al., 2000; Crucifix and Loutre, 2002) and the last nine interglacials (Yin and Berger, 2012). In this study, it is applied to two factors, the Warm Pool SST and insolation. This requires four experiments to be made which are labeled 00, 01, 10 and 11 for any climatic variable, f . The reference experiment (f_{00}) uses the present-day insolation and the 12 month SST produced by a simulation where the atmosphere–ocean coupled model HadCM3 was driven by the MIS-13 insolation and greenhouse gas concentrations (Muri et al., 2013). In the experiment f_{10} , the insolation of MIS-13 and the reference SST are used. In the experiment f_{01} , the reference (present-day) insolation and the modified SST are used. As the Indo-Pacific Warm Pool is typically defined as the region of ocean enclosed by the 28 °C isotherm of SST (e.g. Ho et al., 1995; Fasullo and Webster, 1999) and as it appears particularly warm from March to July with highest peak in May (Zhang et al., 2009), the modified SST is obtained by adding 1 °C to the reference SST at each grid point of the Warm Pool region (where $SST \geq 28$ °C) from March to July. Based on some available studies (Zhou et al., 2009; Li et al., 1999; Zhao et al., 2000), it could be said that the EASM regional precipitation is very sensitive to changes in SST over the Warm Pool region at the seasonal and annual scales. We note that, due to lack of precise reconstruction of the Warm Pool SST during MIS-13 at these scales, this change in SST is used only as a sensitivity test. In the control experiment f_{11} , the MIS-13 insolation and the modified SST are used. Therefore, the pure impact of insolation, of increased Warm Pool SST, their synergism

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The intensified and northward-shifted high pressure system over the northwestern Pacific contributes to the strengthening and northward displacement of the EASM rainbelt over northern China via changes in the low level prevailing winds.

Under the impact of insolation only ($f_{10} - f_{00}$), a huge increase in JJA precipitation (2.4 mm day⁻¹) is simulated over northern China but a very small change over southern China (Fig. 2). The spatial distribution of summer precipitation anomalies (Fig. 3a) shows a significantly drier condition over Indochina and south of the Indian peninsula but wetter conditions in northern China, northeast Asia, northern India and south of Tibet. Increase in JJA precipitation over northern China and northeast Asia is due to the large warming over the NH land with an enhanced land-sea thermal contrast and a shifting of ITCZ to the north by about 8° in latitude. This is clearly indicated by the strongest rising motion at 35° N in Hadley Cell (Fig. 5a) which depends largely on land-sea thermal contrast and plays an important role on the EASM through transport of heat and moisture. Another important atmospheric feature for the East Asian summer monsoon is the East Asian jet, which is jointly controlled by extratropical dynamics and tropical heating. The changes in position and intensity of the jet core is directly associated with the meridional gradient of air temperature in the troposphere (the larger the meridional gradient, the stronger the jet). The East Asia jet displacement has a large impact on the position of the monsoon rainbelt over East Asia especially in summer (e.g. Liang and Wang, 1998). Indeed, under the impact of insolation only, the area of maximum temperature gradient shifts north due to a northward displacement of the maximum heating over the northern continents in the upper level. Figure 5a shows that the subtropical East Asian jet stream at 200 hPa, as indicated by the zonal wind averaged over the longitudes 105–120° E, is shifted northward with strong rising motions along the jet core over northern China providing more rainfall there.

For more details about ascending and descending motions over East Asia, the vertical velocity (ω) has been analyzed. The JJA vertical velocity anomaly shows a strong ascending motion occurring between 30 and 40° N from the surface to upper level (Fig. 6a) and leading to more precipitation through deep convection over northern

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China (as shown also by the meridional wind circulation in Fig. 5a). Under the impact of insolation only, the ITCZ and East Asian jet both shift northward from their mean position, while a strong low level convergence dominates the region near 35° N, all phenomena related to the rain associated to the meiyu/baiu/changma front. The enhanced land-sea thermal contrast and enhanced meridional temperature gradient during boreal summer strengthens the EASM circulation, leads to stronger southerly winds prevailing over eastern China and finally to more northward transport of water vapour (Fig. 7a) from the Arabian Sea, the Bay of Bengal and the western Pacific. Figure 7a shows that, under the impact of high NH summer insolation, the Arabian Sea and the Bay of Bengal are important sources of moisture transport to southern China, but in northern China, moisture is originated from the western Pacific.

The seasonal cycle of precipitation anomaly shows over northern China an increase from March to June with a plateau in July (2.8 mm day⁻¹ in June and in July) and a sharp decrease from August and September. This is generally in phase with seasonal changes in local surface temperature and insolation, showing the importance and direct influence of these factors on the northern EASM precipitation. Over southern China there is an abrupt increase only from April to May (2.5 mm day⁻¹) and decrease from May to June (Fig. 4a and b). This is completely independent of local insolation and temperature changes, indicating the influence of the internal feedbacks in particular from the insolation-driven seasonal SST changes on the southern EASM precipitation. Shi et al. (2012) show that the condition of the tropical Pacific SST can modulate the impact of insolation leading to different response of the EASM precipitation to insolation in northern and southern China. The general features of our insolation-induced changes in atmospheric circulations and regional precipitation patterns are in line with the results of other modeling studies (Wei and Wang, 2004; Braconnot et al., 2008), showing the robustness of the model response to modified insolation forcing.

3.2 Pure contribution of Warm Pool SST on the EASM

The pure impact of enhanced Warm Pool SST ($f_{01} - f_{00}$) leads to a slight decrease in JJA precipitation in both northern and southern China (Fig. 2). The spatial distribution of the summer precipitation anomalies (Fig. 3b) shows a drier condition over India and China but a wetter one over the Warm Pool region itself and over the maritime continents. It indicates that the SST increase over the Warm Pool region only leads to an increase in local convection and precipitation, but reduces the EASM precipitation. This is in line with other modeling studies. By using two-level global circulation model, Huang and Sun (1992) showed that when the SST over tropical western Pacific Warm Pool is above normal then East Asia receives below normal rainfall in summer. Tschuck et al. (2004) also showed that a warmer western Pacific leads to anomalous north-easterlies wind over China indicating a weakened East Asian monsoon. Based on modern observational data, Lee et al. (2008) found a similar negative correlation between the Warm Pool SST and the north EASM precipitation, but a positive correlation between the Warm Pool SST and south EASM precipitation. This might be due to the different background insolation forcing and related climate between our study on MIS-13 and theirs on present-day.

Such a warmer Warm Pool reduces the land-sea thermal contrast over the NH land in summer and shifts the ITCZ to the south of 20° N (Fig. 5b). Here, the 200 hPa subtropical jet shifts southward (Fig. 5b), leading to more rainfall over East Asia south of 20° N. The remarkable decrease in the land-sea thermal contrast during boreal summer weakens the EASM circulation and generates northerly wind anomaly over eastern China, which prevents the northward transport of water vapour as shown in Fig. 7b. The vertical velocity anomaly (Fig. 6b) indicates that the ascending motion over $\sim 30^{\circ}$ N almost disappears, being changed into a weak descending motion over both northern and southern China from the surface to the upper levels revealing less convection and precipitation over the whole China. On the contrary, anomalous ascending motion

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occurs south of 20° N along with precipitation increase due to stronger local convection caused by the enhancement of the Warm Pool SST.

3.3 Synergism

Synergism can be defined as the additional contribution due to two or more factors when they act together compared to the sum of their individual contributions. It is therefore given by $(f_{11} - f_{00}) - (f_{10} - f_{00}) - (f_{01} - f_{00})$. As shown in Fig. 2, the synergism between insolation and the increase of Warm Pool SST contributes to a large increase in the summer precipitation over southern China but decrease over northern China. The corresponding spatial distribution of summer precipitation anomalies due to the synergism (Fig. 3c) shows a drier condition over northern China and northeastern Asia but a wetter over India (west coast of India and north part of Bay of Bengal) and southern China. Consistently, a strong ascending motion is seen in southern China and a weak descending motion in northern China (Fig. 6c). The strong upward motion in southern China corresponds well to the enhanced precipitation there. The EASM circulation is weakened with anomalous northerly winds over eastern China. Such an anomalous northerly surface wind is not favorable for the moisture transport up to northern China. But at the same time, the monsoon circulation over the Indian domain (land and ocean) gets intensified providing more moisture transported to southern China (Fig. 7c). In southern China, the synergism can be explained by the intensified meridional transport of water vapor inland over southern China which results from a joint effect of the insolation-induced increased southerly wind and the SST-induced increased local evaporation over the Warm Pool providing more water vapor to be transported. These two factors act together providing a better condition for precipitation increase in southern China than when one of them acts alone. In vertically integrated moisture transport, a localized cyclonic (moisture convergence) flow over East China could be associated with more precipitation in southern China and less in northern China (Fig. 7c).

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3.4 Combined effect of insolation and Warm Pool SST and their relative importance

The primary source of monsoon circulation depends largely on the surface latitudinal temperature distribution over land and the adjacent sea especially over the Asian domain. The combined effect ($f_{11} - f_{00}$) of insolation and enhanced SST over the Warm Pool region decreases the latitudinal temperature gradient at least by 0.5°C when compared to the pure insolation effect (Fig. 1d compared to Fig. 1a) due to the additional warming over the Warm Pool region. The combined effect leads to same amount of summer precipitation increase in northern and in southern China (Fig. 2). This is also shown in the spatial pattern of JJA precipitation anomaly (Fig. 3d). Figure 2 shows that the precipitation increase in northern China is only due to changes in insolation which effect is nevertheless weakened by the effect of enhanced Warm Pool SST and the synergism. However, the precipitation increase in southern China is mainly due to the synergism, the pure impacts of insolation and of the Warm Pool SST being quite small. The pure impact of enhanced Warm Pool SST has relatively small impact over the mainland of China.

The JJA vertical velocity anomaly (Fig. 6d) shows two centers of ascend and deep convection. One is over northern China and is resulting from the pure impact of insolation (Fig. 6a). Another is over southern China and its position indicates that it is mostly contributed from the synergism (Fig. 6c). The heavy rainfall increase in China is closely related to these two strong upward motions. At low level, wind strength and direction during JJA also well support the moisture transport over East Asia from the Indian Ocean and the northwestern Pacific. Analysis of the spatial distribution of the total moisture transport (Fig. 7d) shows that, in southern China, the moisture transport is mainly from the Indian Ocean (especially from the Bay of Bengal). It results from the pure impact of insolation (Fig. 7a) and is reinforced by the synergism effect (Fig. 7c). In northern China, the moisture transport from the west Pacific Ocean is dominating and it is completely resulting from the pure impact of insolation. This, again, shows the

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the summer precipitation in both northern and southern China through reducing the land-sea thermal contrast. It however leads to huge precipitation increase over the Warm Pool region due to strong convection there. The synergism between insolation and enhanced Warm Pool SST contributes to a large increase of summer precipitation over southern China but to a decrease in northern China. Finally, the combined effect of insolation and enhanced Warm Pool SST leads to EASM precipitation increase in both northern and southern China.

Our model results show that the increase of EASM precipitation in northern China during MIS-13 is due to changes in insolation, and that a warmer Warm Pool largely enhances the precipitation only in southern China. Moreover, such a role of warmer Warm Pool does not happen solely through its SST increase but via its synergic effect with insolation. Therefore, a warmer Warm Pool does help to explain the exceptional MIS-13 EASM precipitation in southern China as indicated in the paleo-red soil records, but it does not help to explain it in northern China as recorded in the loess-soil sequences. As the insolation of MIS-13 has not been found exceptional as compared to other interglacials (Yin and Berger, 2012), we need to seek for other explanation for the exceptional EASM in northern China. Many terrestrial records from the Northern Hemisphere indicate quite warm land surface during MIS-13 (Guo et al., 2009). Moreover, the pollen records from marine sediment of southwest Greenland show that MIS-13 has the second largest pollen abundance (only secondary to MIS-11) among the interglacials of the last one million years, leading to the assumption that the presence of forest vegetation at least over southern Greenland and a reduced Greenland ice volume (de Vernal and Hillaire-Marcel, 2008). Therefore, the impact of a smaller Greenland ice sheet on the MIS-13 EASM might be investigated in the future to see if it can help to explain the exceptional EASM precipitation in northern China.

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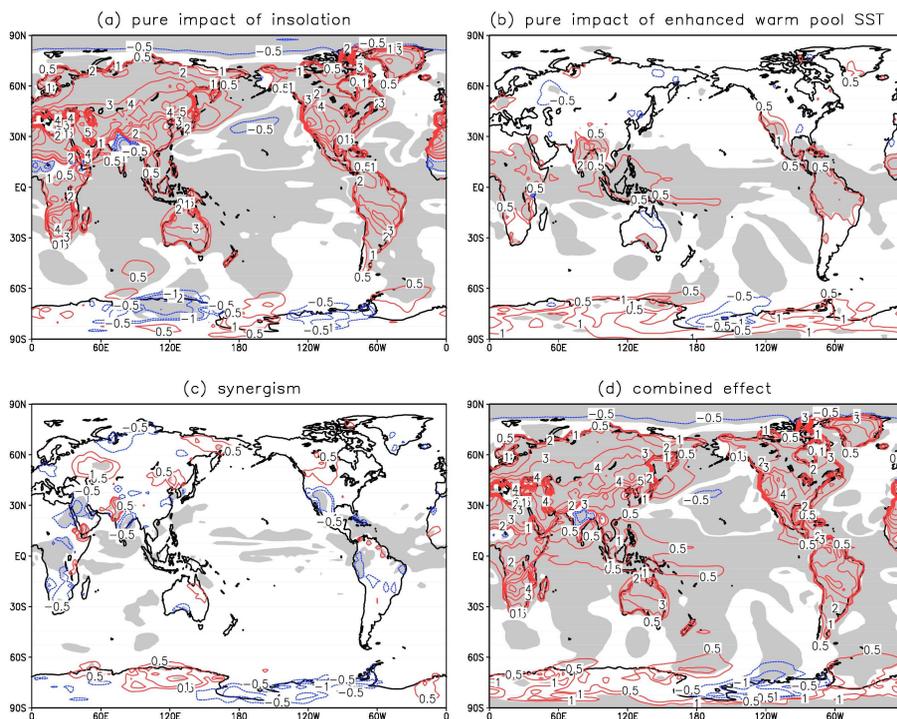


Fig. 1. Simulated summer (JJA) surface air temperature anomaly ($^{\circ}\text{C}$). **(a)** Pure impact of insolation, **(b)** pure impact of enhanced Warm Pool SST, **(c)** synergism between insolation and enhanced Warm Pool SST and **(d)** combined effect of insolation and enhanced Warm Pool SST. Areas with significance level greater than 99 % are shaded in gray.

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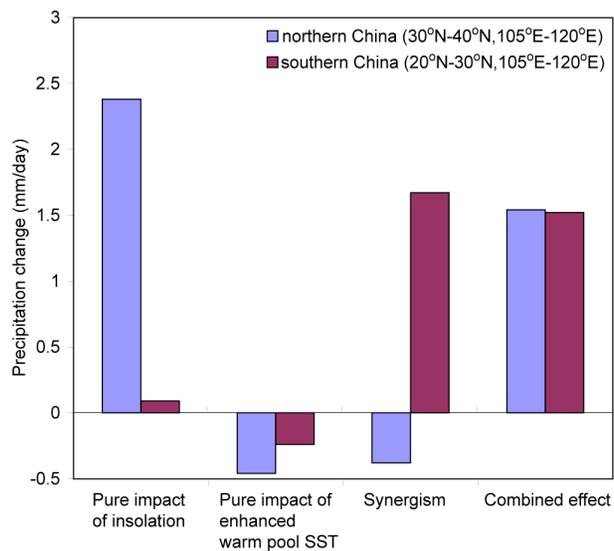


Fig. 2. Summer (JJA) precipitation change averaged over northern and southern China.

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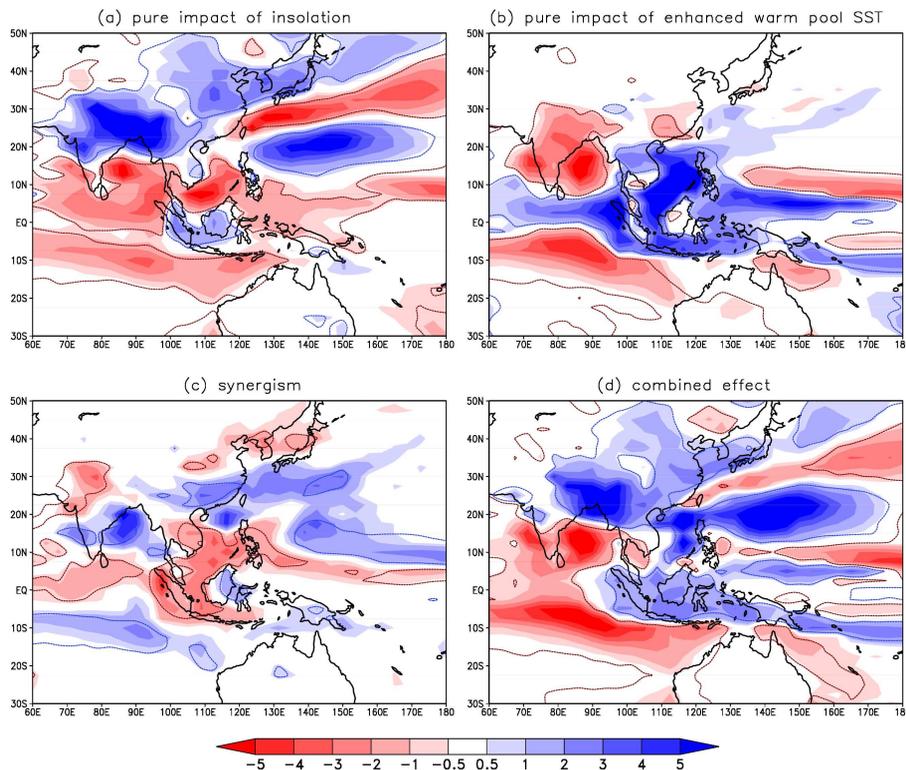


Fig. 3. Simulated summer (JJA) precipitation anomaly (mm day^{-1}). **(a)** Pure impact of insolation, **(b)** pure impact of enhanced Warm Pool SST, **(c)** synergism between insolation and enhanced Warm Pool SST and **(d)** combined effect of insolation and enhanced Warm Pool SST. Areas with significance level greater than 99 % are surrounded by contour lines.

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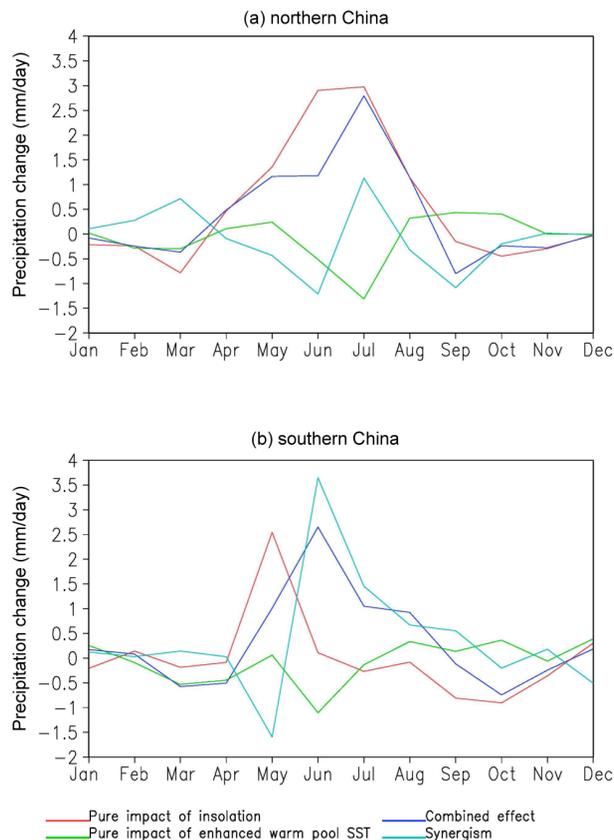


Fig. 4. Seasonal cycle of precipitation anomaly over northern **(a)** and southern **(b)** China. Contributions of insolation, of enhanced Warm Pool SST, their synergism and combined effect are given.

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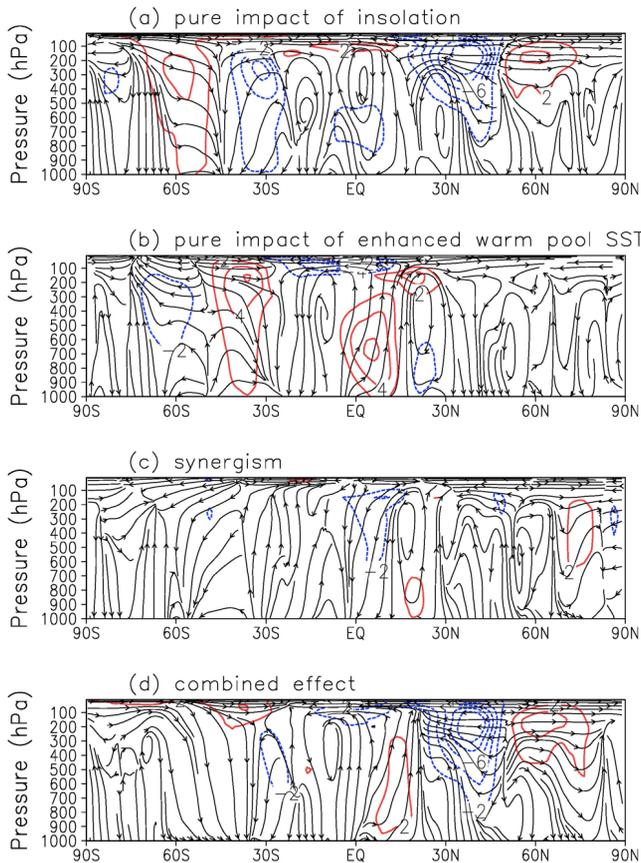


Fig. 5. JJA Hadley circulations anomaly averaged over 105–120° E. **(a)** Pure impact of insolation, **(b)** pure impact of enhanced Warm Pool SST, **(c)** synergism between insolation and enhanced Warm Pool SST and **(d)** combined effect of insolation and enhanced Warm Pool SST. Stream lines indicate meridional wind circulation and contour lines (with an interval of 2 ms^{-1}) indicate zonal wind.

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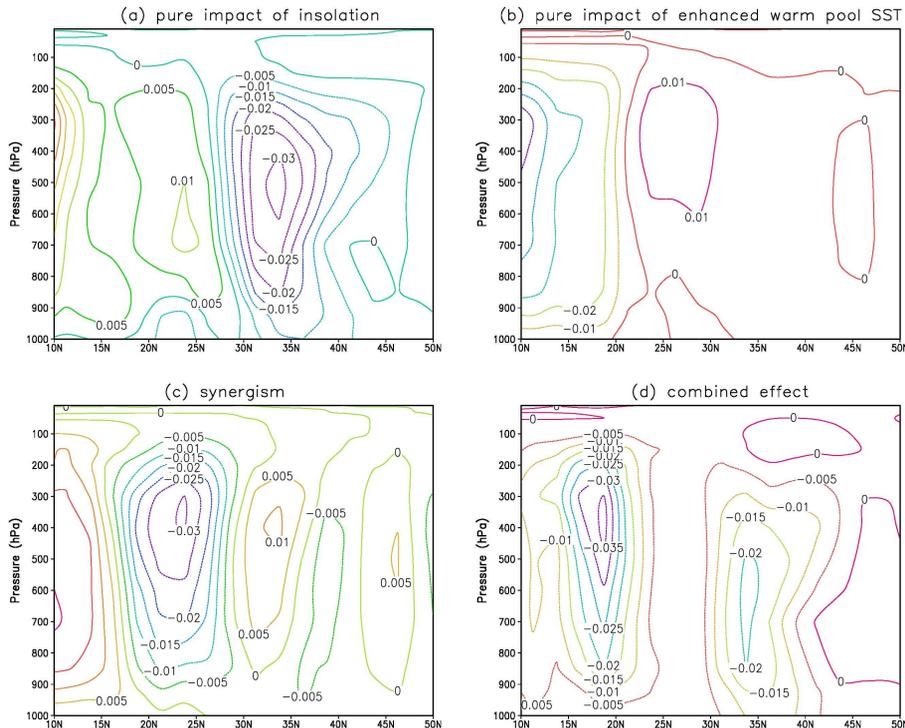


Fig. 6. JJA vertical velocity anomaly (Pa s^{-1}) averaged over 105 to 120° E. **(a)** Pure impact of insolation, **(b)** pure impact of enhanced Warm Pool SST, **(c)** synergism between insolation and enhanced Warm Pool SST and **(d)** combined effect of insolation and enhanced Warm Pool SST.

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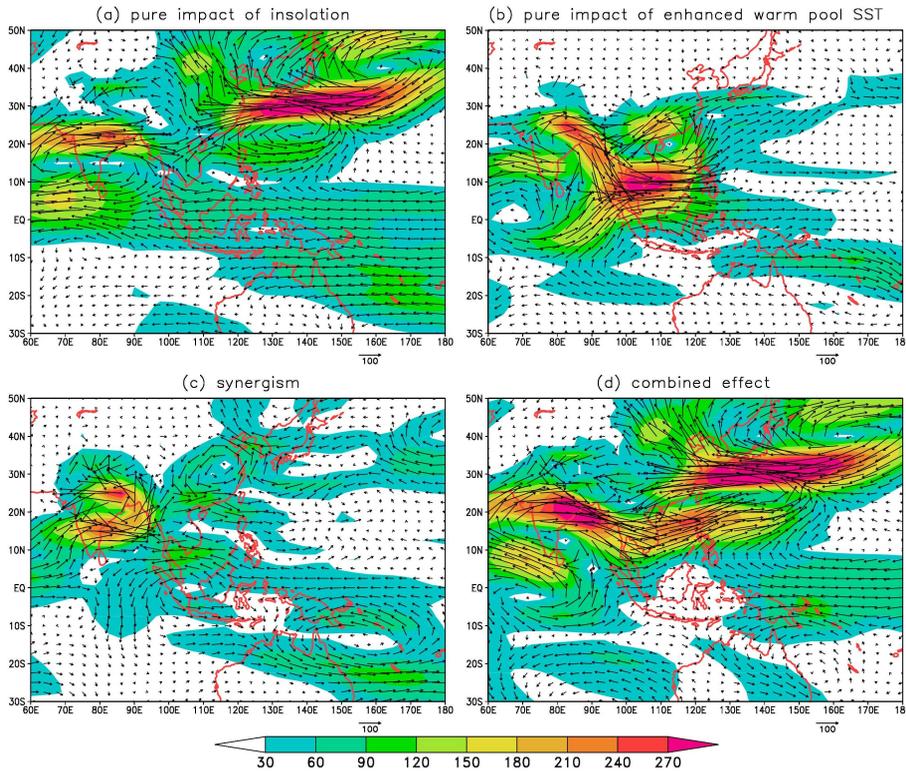


Fig. 7. JJA vertically integrated moisture transport anomaly ($\text{kgm}^{-1}\text{s}^{-1}$) in the whole troposphere. **(a)** Pure impact of insolation, **(b)** pure impact of enhanced Warm Pool SST, **(c)** synergism between insolation and enhanced Warm Pool SST and **(d)** combined effect of insolation and enhanced Warm Pool SST.

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