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Key Points:

- It is dynamically possible to have much higher precipitation when summer insolation is high in the East Asian monsoon region
- Fully accounting for ocean circulation is important in simulating East Asian monsoon change
- East Asian monsoon intensity probably increases with increasing northern hemispheric insolation

Supporting Information:

- Supporting Information S1

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The Response of East Asian Monsoon to the Precessional Cycle: A New Study Using the Geophysical Fluid Dynamics Laboratory Model

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Abstract Speleothem oxygen isotopes have been shown to exhibit a close relationship with summer insolation in the Northern Hemisphere, leading to the hypothesis that East Asian monsoon intensity is proportional to the summer insolation. This hypothesis, however, has been questioned because previous climate model simulations have been unable to simulate the observed large variation in precipitation or the precipitation isotope values, about a half of the variation in the entire modern tropical regions, in response to the insolation change due to the precession cycle. Here we show new results, using the fully coupled Geophysical Fluid Dynamics Laboratory model, that it is dynamically possible to have much higher precipitation during the high summer insolation period compared with the low summer insolation period in the East Asian monsoon region. We conclude that past East Asian monsoon intensity probably increased with increasing northern hemispheric insolation, given a large change in speleothem oxygen isotopes.

Plain Language Summary Speleothems from calcite caves draw attention because precise dating is possible using the U-Th method, opening up a unique chance of studying the past hydrological cycle. The isotopic composition of Chinese caves shows a remarkably coherent pattern following the summer solar radiative flux in the Northern Hemisphere, particularly responding to the precessional cycle, leading to the hypothesis that East Asian monsoon intensity is proportional to the summer insolation. However, because climate models were not able to simulate the direct precipitation response following the insolation over the East Asian monsoon region or the isotope variation, this interpretation of the speleothem data has been challenged. Our new results show that it is dynamically possible to have much higher precipitation (more than 100% increase locally) during the high summer insolation period compared with the low summer insolation period in the East Asian monsoon region, but unlike previous studies, our simulations use a fully coupled ocean model, emphasizing the importance of including the ocean dynamics in studying climate response.

1. Introduction

The isotopic composition of Chinese caves shows a remarkably coherent pattern following the summer insolation (solar radiative flux) in the Northern Hemisphere (NH), particularly responding to the precessional cycle. Among all modes of variation, precession gives the largest seasonal variation of insolation, especially for large orbital eccentricities. Monsoons are seasonal by their nature, and a high correlation between insolation and speleothem $\delta^{18}\text{O}$ provides a possible link between insolation and the hydrological cycle in East Asia. Speleothem $\delta^{18}\text{O}$ in the Southern Hemisphere (Cruz et al., 2006), where the effect of orbital precession is opposite, is anticorrelated with the NH $\delta^{18}\text{O}$, supporting the hypothesis that $\delta^{18}\text{O}$ is related to the change in the seasonal insolation.

The amount effect links $\delta^{18}\text{O}$ and precipitation amount: As precipitation increases, precipitation $\delta^{18}\text{O}$ decreases in tropical islands and monsoon regions (Rozanski et al., 1993). The amount effect results from H_2^{18}O having a lower saturation vapor pressure than H_2^{16}O , which implies that the ratio of $^{18}\text{O}/^{16}\text{O}$ decreases as an air parcel goes through the condensation process, with selective condensation preference for the heavier isotopes, similar to the distillation process of petroleum. As a result, ambient $\delta^{18}\text{O}$ of atmospheric vapor is much lower than $\delta^{18}\text{O}$ of vapor resulting from evaporation of ocean water (Lee et al., 2007). $\delta^{18}\text{O}$ of vapor is particularly low when there is a lot of distillation, (e.g., strong convective regions or polar regions). In regions where evaporation exceeds precipitation, $\delta^{18}\text{O}$ of vapor is closer to the

equilibrium expected from evaporation of the oceanic value. In the convective regions where water vapor is a result of transport convergence from other regions, $\delta^{18}\text{O}$ tends to be lower than the equilibrium value. The whole variation in the tropical oceanic and coastal regions is about 8‰ (Dansgaard, 1964; Rozanski et al., 1993).

Several hypotheses exist to explain paleo-oxygen isotope variability. When Earth is closer to the Sun in the northern hemispheric summer, the oxygen isotopic ratios of cave speleothems in East Asia are lower (Cheng et al., 2006; Wang et al., 2001), leading to the hypothesis that the summer monsoon in East Asia is stronger when summer sunlight was stronger there (Cheng et al., 2006; Wang et al., 2001). By calling on the amount effect, it has been argued that much higher precipitation is the cause of the lower $\delta^{18}\text{O}$ during the period when the NH received more insolation during summer. Other caves in the pan-Asian regions show a similar trend (Battisti et al., 2014). For the Indian monsoon, most climate models show an increase of precipitation during the hotter NH summer period (Battisti et al., 2014). This explanation that East Asian speleothems record monsoon intensity, however, has been questioned because previous modeling studies show little precipitation change in East Asia following the precessional cycle (Battisti et al., 2014). Many modeling studies (Kutzbach et al., 2007; Weber & Tuenter, 2011) initiated a more detailed discussion of the nature and sensitivity to forcing of the Asian monsoon: upstream change (Z Liu et al., 2014; Pausata et al., 2011), internal climate dynamics (Caley et al., 2014; Shi et al., 2012), or precipitation seasonality (Chiang et al., 2015; Kong et al., 2017; Shi, 2016).

Although not specifically designed to study insolation change, Pausata et al. (2011) and Lee et al. (2012) suggest that $\delta^{18}\text{O}$ decreased as a result of upstream precipitation change. Liu et al. (2014) included the comparison between 6- and 1-ka runs, and they also concluded that upstream precipitation change is responsible for the $\delta^{18}\text{O}$ change. These models show the intensification of the Indian monsoon, and thus, vapor entering the East Asian monsoon has a much lower concentration of H_2^{18}O . It is possible to have low $\delta^{18}\text{O}$ without a local change of Asian precipitation. The problem with this hypothesis is that the modeled $\delta^{18}\text{O}$ change is not large enough to be able to explain the speleothem observations (Battisti et al., 2014; Liu et al., 2014).

The third hypothesis is that even if the annual mean precipitation change is negligible, $\delta^{18}\text{O}$ can vary if the seasonality of precipitation changes. $\delta^{18}\text{O}$ values are much lower during the monsoon season, and thus, a change in the seasonal pattern of precipitation toward more intense monsoon precipitation (when $\delta^{18}\text{O}$ is low) and a drier rest of the year (i.e., winter/spring when $\delta^{18}\text{O}$ is high) will lower the annual average. In East Asia, the location of jets moves northward from spring to summer, with precipitation amount being highly correlated with the location of jets. In spring jets are located south of Tibet, moves northward in June, and is just north of Tibet during the monsoon season (Schiemann et al., 2009). In late July, the jets jump farther north, coinciding with the suppressed precipitation in the East Asian monsoon region (Lin & Lu, 2008). The location of jets tends to move poleward with increasing temperature (Lu et al., 2008), and Chiang et al. (2015) argue that the jet moves northward earlier when NH summer is hotter. This shift toward earlier arrival of summer-like conditions decreases the winter/spring contribution of precipitation, which has higher $\delta^{18}\text{O}$, leading to a lower $\delta^{18}\text{O}$ during the high summer insolation period. This hypothesis has yet to be proved.

Most simulations that were used to study the link between $\delta^{18}\text{O}$ and insolation forcing in East Asia were run with slab ocean models (Battisti et al., 2014; Chiang et al., 2015). Slab ocean models are useful because it takes less time to reach equilibrium (see supporting information), and thus, it is easier to test a hypothesis with many model simulations with a different configuration. However, ocean dynamics play a significant role in understanding the climate response (e.g., Clement et al., 1996; Held et al., 2010), and X Liu et al. (2017) demonstrated that including ocean dynamics is essential in understanding tropical precipitation variability. Motivated by the fact that the magnitude of isotope ratios is not reproduced by most climate models, we analyze simulations using a new model including a fully-coupled setup, the National Oceanic and Atmospheric Administration/Geophysical Fluid Dynamics Laboratory (GFDL) General Circulation Model (Delworth et al., 2006). Previous modeling studies used the National Center for Atmospheric Research (Chiang et al., 2015; Pausata et al., 2011) or the European Centre/Hamburg (Battisti et al., 2014) models to investigate paleomonsoon. We show that the Asian monsoon precipitation increases when summer insolation is higher, indicating the important role of ocean dynamics and supporting the hypothesis that regional precipitation change can be explained by the changes to NH insolation. In section 2, we describe the model

setup. The results, along with the discussion that emphasizes the role of ocean dynamics, are exhibited in section 3. We summarize and conclude our study in section 4.

2. Model Description

To understand how ocean dynamics influences the East Asian monsoon, we ran the GFDL Coupled Model version 2 (Delworth et al., 2006), with fully coupled atmosphere, land, sea ice, and ocean models. The GFDL Coupled Model version 2 has been widely used in the Intergovernmental Panel on Climate Change model intercomparison (Stocker et al., 2013). We performed an additional slab ocean configuration (Winton, 2003) to compare with the coupled run and demonstrate the role of ocean circulation. A slab ocean configuration provides an interaction between the atmosphere and the mixed layer of the ocean through surface exchange processes. However, horizontal and vertical ocean heat transport is prescribed, not allowing any change in ocean circulation.

For both model configurations, we performed two sets of runs: one set for June perihelion and the other set for December perihelion. The rotational axis of Earth precesses with perihelion occurring either 21 June (June perihelion case) or 21 December (December perihelion case). We used eccentricity of 0.05, which is the highest value for the past Earth, and obliquity of 23°. We note that our runs use eccentricity of 0.05, much higher than the Holocene runs of Chiang et al. (2015), but similar to that of Battisti et al. (2014). The CO₂ concentration is set to the present-day value (400 ppm). We ran for 350 years and averaged the last 50 years for the fully coupled case. For the slab ocean model, we ran for 35 years and averaged the last 10 years. The model reached quasi-equilibrium in our analysis (see the supporting information to learn more about the model equilibrium).

For the June perihelion case, insolation is much higher in the NH summer because Earth is closer to the Sun in the NH summer and much lower in the NH winter. Although annual total insolation is similar, the seasonal insolation difference between June and December perihelion cases can be up to 60 W/m² when eccentricity is set to 0.05 (Lee, 2019; Merlis et al., 2013). This change can greatly influence monsoon precipitation (Battisti et al., 2014). The response to the precessional forcing is different for land and ocean, often the opposite in the tropical region (Hsu et al., 2010), because the ocean has much higher thermal inertia.

3. Results and Discussion

3.1. The Response of the Slab Ocean Model

The slab ocean model runs exhibit a similar precipitation amount around the cave sites in East Asia (Figure 1b). In South Asia and the northern part of China, however, precipitation is much higher during the June perihelion case. Monsoon season precipitation (June–July) change is small, and the precipitation belt moves northward in summer (Figure 1d), similar to the results from Chiang et al. (2015), which also used the slab ocean configuration. Annual average precipitation is similar for the two cases, and the decrease in spring precipitation is dominant for the June perihelion case, leading to the previous hypothesis that precipitation seasonality may play a significant role in determining the isotopic composition of precipitation (Chiang et al., 2015).

The meridional movements of upper tropospheric jets are shown to be coherent with the onsets of the summer and winter monsoons in East Asia (Lin & Lu, 2008). For the June perihelion case, the latitudinal temperature gradient ($-dT/dy$) decreases due to an increased insolation in boreal summer (Figure 2d; Kong et al., 2017), leading to the northward shift and weakening of the westerlies (Figure 2f), similar to Chiang et al.'s (2015) results. Maximum wind becomes much weaker, and the peak wind location moves from 35°N to 40°N, explaining the greater increase in precipitation in the northern part of China.

3.2. The Response of the Fully Coupled Model

Fully coupled model simulations show much higher summer precipitation for the entire continental regions of South and East Asia to the north of 20°N for the June perihelion case (Figure 1a). East Asian precipitation increase in the fully coupled simulation is particularly outstanding compared with the slab ocean cases, sometimes reaching up to 100% more precipitation locally in the June perihelion than in the December perihelion.

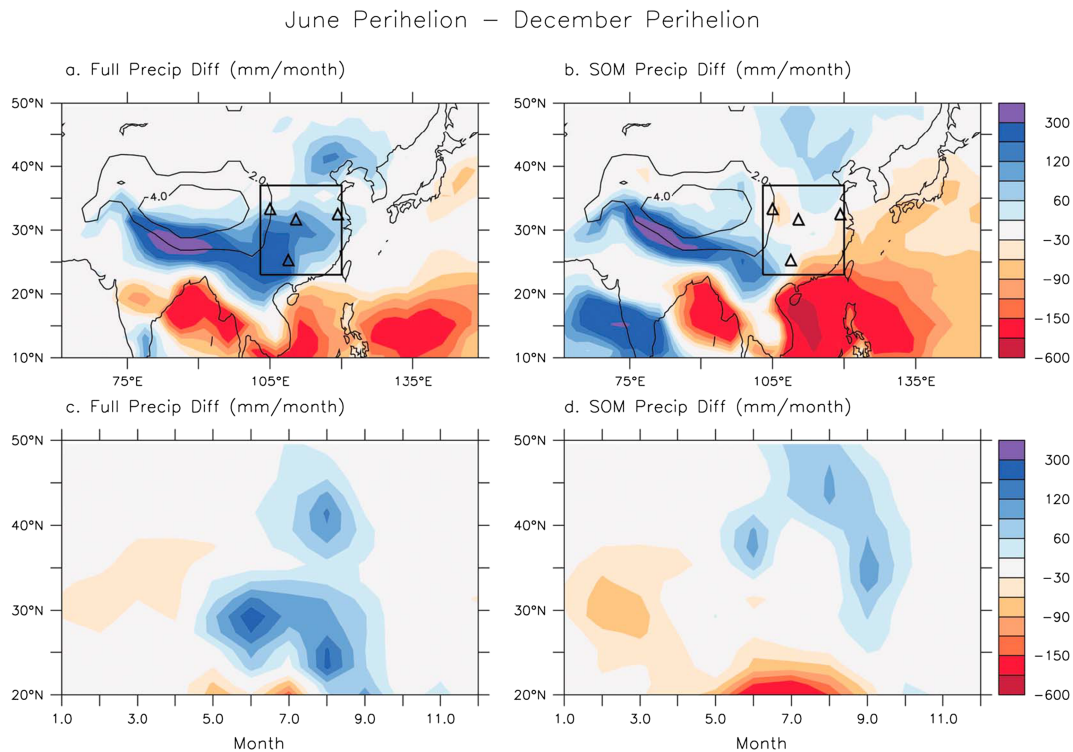


Figure 1. Summer (June-July-August) precipitation difference from June to December perihelion runs for the fully coupled (a) and the slab ocean models (b). Contour is the surface height, black triangle represents the location of the cave sites in East Asia, and the area marked with a rectangle represents the East Asian monsoon region. Latitude-time average plots for the difference in monthly precipitation from June to December perihelion runs between 105°E and 120°E for the fully coupled (c) and slab ocean models (d). SOM = slab ocean model.

For the fully coupled model, precipitation difference shows up from May and remains high until September (Figure 1c). In winter and early spring, precipitation is lower for the June perihelion case in both fully coupled and slab ocean models, probably because winter is colder in the June perihelion case. The seasonality of precipitation clearly increases in the Asian monsoon region for the fully coupled model but not much for the slab ocean model (Figures 2a and 2b). Unlike the slab ocean model runs, the latitudinal temperature gradient decrease is much smaller (the difference between the red solid and blue dashed lines is smaller in Figures 2c and 2e compared with that in Figures 2d and 2f; cf. Kong et al., 2017) and the jets very modestly change location between the two precession runs in the fully coupled model runs, along with more surface ocean cooling near Japan in the fully coupled model (Figure 3a). As the location of the jets is similar, the summer precipitation in the East Asian monsoon region increases in response to the radiative forcing in the fully coupled model, instead of the precipitation belt moving northward in conjunction with the jet migration as occurs in the slab ocean model (c.f. Merlis et al., 2013). These patterns of precipitation change in the fully coupled model may be sufficient to explain the observed $\delta^{18}\text{O}$ difference in speleothems (supporting information Text S2).

Next, to understand why the response of the jets is so different depending on the ocean model configuration, we examined the sea surface temperature (SST) sensitivity of the two models. A poleward shift of jets is expected with global warming (Lu et al., 2008), so one might associate warmer SSTs or warmer land surface with a poleward shift of the jets (e.g., Chiang et al., 2015). Additionally, Kaspi and Schneider (2011) show that westward radiation of large-scale atmospheric waves can influence the weather pattern in the upstream region. They demonstrate that localized heating in the ocean can result in stationary low- and high-pressure systems to its upstream and downstream regions. For the fully coupled model, localized cooling near Japan seems to induce a stationary low-pressure system in the upstream region (southwest of where cooling occurred) near the southeastern part of China and surrounding ocean where precipitation is higher compared with the slab ocean model (Figure S3).

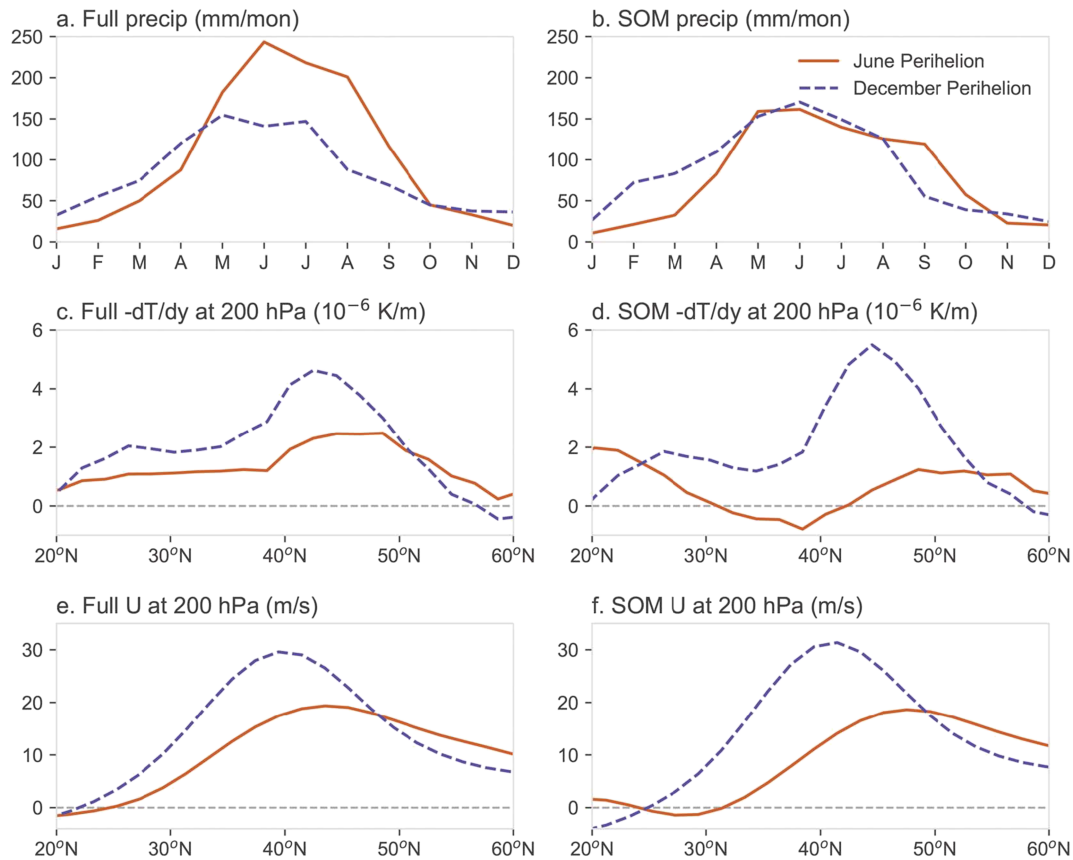


Figure 2. (a, b) Monthly mean precipitation in the East Asian monsoon region (denoted as a black rectangle in Figures 1a and 1b), (c, d) the latitudinal temperature gradient ($-dT/dy$), and (e, f) zonal wind velocity both at 200 hPa in June-July-August, averaged between 90°E and 160°E for the June perihelion (red solid line) and December perihelion (blue dashed line) cases for the fully coupled (a, c, e) and the slab ocean models (b, d, f). SOM = slab ocean model.

For both cases, June SST is lower for the June perihelion case. Both the slab and dynamic ocean are influenced by the cooling from reduced NH insolation during the cold season (Figures 3a and 3b). For the fully coupled runs, ocean dynamics seem to produce an even stronger cooling in the North Pacific around 40°N, east of northern Japan, for the June perihelion case relative to the December perihelion case, which serves to increase latitudinal temperature gradient oppose the poleward shift in jet location in the slab ocean model under June perihelion and thus preserve the average location of the jet just north of Tibet, causing both perihelion cases with a dynamic ocean to be similar to each other. This large dynamic cooling of SSTs seems to prevent the northward shift of the jet despite the much larger insolation input into the land surface—and thus much warmer land surface temperatures (Smyth et al., 2018)—in summer for the June perihelion case.

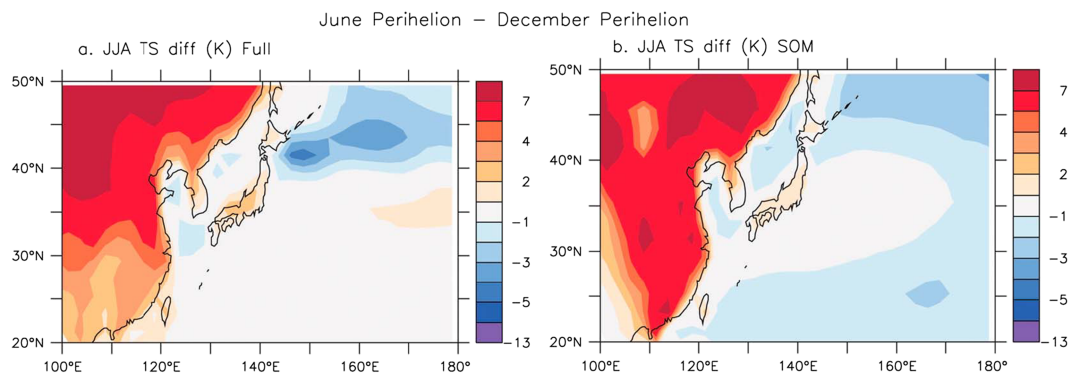


Figure 3. The surface temperature difference in JJA for the fully coupled (a) and the slab ocean models (b). JJA = June-July-August; SOM = slab ocean model.

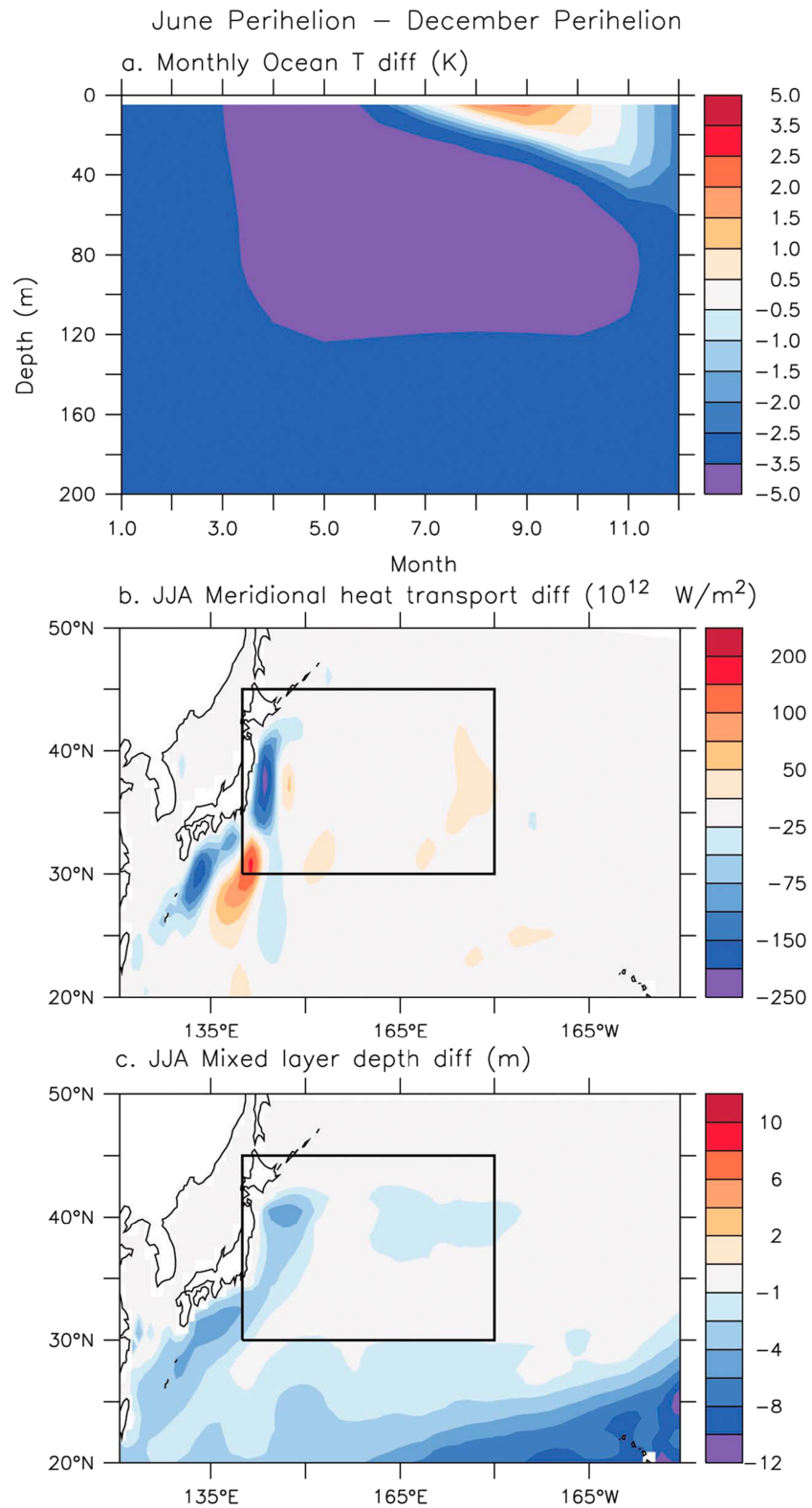


Figure 4. (a) Seasonal variation of the subsurface temperature difference between June perihelion and December perihelion runs for the fully coupled model averaged in the North Pacific (140–180°E, 30–45°N; black box in panels b and c), (b) JJA mean of vertically integrated meridional heat flux (10^{12} W), and (c) mixed layer depth (m) from June perihelion to December perihelion runs for the fully coupled model. JJA = June-July-August.

Why are the June perihelion SSTs cooler in the North Pacific compared with the December perihelion SSTs? Wintertime ocean mixed layers are deepest in the middle to high latitudes because of increased winds, waves, and cooling of the surface ocean (Bathen, 1972; Belcher et al., 2012; Kara, 2003). During the warmer seasons, the mixed layer restratifies, warming and freshening the surface water (Sprintall & Roemmich, 1999), which can leave behind subsurface temperature minima from the winter conditions (Cokelet & Stabeno, 1997; Miura et al., 2003; Ueno, 2005), which tend to constitute the watermasses that are subducted to the permanent pycnocline through the selection of the “Stommel daemon” effect (Stommel, 1979). Thus, understanding the ocean temperature difference in winter is important because the winter mixed layer affects both seasonal surface conditions and subsurface water masses (Oka et al., 2007). The June perihelion case has much warmer summer conditions but much colder winter in the NH; thus, the seasonality of the oceanic mixed layer is enhanced through the orbital change. A tendency toward stronger summertime ocean surface warming, during the season when the ocean tends to be losing heat to the atmosphere, can increase the flux out of the ocean, while restratification processes keep the SST warm, which then ends up affecting the subsurface with minimal change to SSTs (Fox-Kemper et al., 2011). As a result of these effects combined, the subsurface layer in this dynamic ocean model is overall much colder throughout the year in the North Pacific (Figure 4a), which reduces both the annual mean SST and the summertime SST of the dynamic ocean versus the slab ocean model. Furthermore, the Kuroshio current is affected in the dynamic ocean model to have much smaller energy transport near Japan because of the colder and shallower mixed layer, contributing to cooling for the June perihelion case (Figures 4b and 4c). Precipitation responses resulting from the land changes and ocean changes are therefore opposing, similar to the work of Hsu et al. (2010), who compared present and mid-Holocene climates and showed that land and ocean impacts on precipitation have opposing signatures.

4. Summary and Conclusion

Well-dated speleothems from Chinese caves show an isotopic change of up to 3–5‰, equivalent to about half of the variation in the entire tropical oceanic and coastal regions, following the precessional cycle with lower $\delta^{18}\text{O}$ during the time when the NH receives more energy. In the tropical oceanic and coastal regions, the whole ~8‰ variation in $\delta^{18}\text{O}$ has been explained by the amount effect, a decrease in precipitation $\delta^{18}\text{O}$ as the precipitation amount or intensity increases. There have been three hypotheses that explain the change in $\delta^{18}\text{O}$ in cave speleothems:

1. Precipitation change: Following the amount effect, precipitation amount, and thus the strength of East Asian monsoon, was greater when the NH was closer to the Sun in the NH (e.g., Wang et al., 2001).
2. Upstream precipitation change: Most models show a decrease in the Indian monsoon precipitation with increasing insolation. Advected water vapor would have a lower $\delta^{18}\text{O}$ value (e.g., Pausata et al., 2011).
3. Seasonality of precipitation: Even if the total precipitation change is negligible, $\delta^{18}\text{O}$ can vary if the seasonality of precipitation changes. In the June perihelion case, there was less precipitation in spring (higher $\delta^{18}\text{O}$) and maybe more precipitation in summer (lower $\delta^{18}\text{O}$) because the jets and precipitation belt would move to the north earlier (e.g., Chiang et al., 2015).

To test which hypothesis works best, we ran fully coupled climate simulations using the GFDL climate model. We used a fully coupled model, whereas most of the previous studies used a slab ocean configuration. We found a large (up to 100%) increase in precipitation in the June perihelion case in the East Asian monsoon region. In our reference slab ocean case, precipitation difference was much smaller, similar to the previous studies. Major differences between fully coupled model and slab ocean models indicate the role of the ocean circulation: The subsurface ocean is overall much colder throughout the year in the North Pacific in the June perihelion case because winter is much colder in the NH. As a result, the Kuroshio Current transports less heat to the ocean around Japan, creating a maximum in cooling in the June perihelion case. Surface ocean cooling around Japan leads to a smaller decrease of latitudinal temperature gradient and a modest shift of the jet northward in the June perihelion case for the fully coupled model compared with the slab ocean model. We note that our results could be model dependent: other fully coupled models may not exhibit a large precipitation change in response to the precessional forcing in East Asia. These results do not indicate and we do not suggest that all models will exhibit this effect but only that it is important to consider the dynamical ocean response in studies of monsoon variability.

Our results demonstrate that it is dynamically possible to have much larger precipitation in the East Asian monsoon region when the northern hemispheric summer insolation is higher. Our results also show the importance of including the ocean circulation in studying climate response. Given the large change in $\delta^{18}\text{O}$ following the precessional cycle, we speculate that there has to be a large precipitation change in addition to seasonality and upstream changes. Our results show a decrease in early spring precipitation (less high $\delta^{18}\text{O}$ precipitation) and an increase in summer precipitation (more low $\delta^{18}\text{O}$ precipitation); both would decrease $\delta^{18}\text{O}$ in precipitation. In the future work we hope to directly examine the isotopic measurements by adding stable isotopes to fully coupled climate simulations.

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