Potential impacts of enhanced tropical cyclone activity on the El Niño–Southern Oscillation and East Asian monsoon in the mid-Piacenzian warm period

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ABSTRACT

Tropical cyclones (TCs) not only passively respond to climate change, but also play an important role in vertical mixing of the upper ocean and in driving oceanic heat transport. Using a fully coupled climate model, the authors investigate the potential effect of TC-induced vertical mixing on the El Niño–Southern Oscillation (ENSO) and East Asian monsoon in the mid-Piacenzian, during which global TCs are estimated to have been stronger. Sensitivity experiments indicate that the TC-induced oceanic mixing over global storm basins leads to additional warming over the eastern tropical Pacific and a deeper thermocline in the mid-Piacenzian, whereas it dampens the interannual variability of ENSO. Regarding the East Asian monsoon circulations, low-level (850 hPa) summer and winter winds are intensified in response to enhanced vertical mixing, with a southward/westward shift of the western North Pacific high and westerly jet in summer and a deepened East Asian trough in winter. These climatic features are largely reproduced in the experiment with enhanced vertical mixing only over the central-eastern North Pacific. These results may shed light on TC feedbacks associated with vertical mixing and advance our understanding on mid-Piacenzian climate.

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1. Introduction

The mid-Piacenzian, spanning from ~3.264 to 3.025 Ma, is the most recent interval in Earth’s history, on the geological time scale, with sustained warmth (Dowsett et al. 2010). The atmospheric CO₂ concentration in the mid-Piacenzian (~400 ppmv) was close to the anthropogenically forced CO₂ levels observed in recent years (Seki et al. 2010; Haywood, Dowsett, and Dolan 2016). Geological evidence and model simulations indicate an increase in global mean temperature by ~2–4°C in the mid-Piacenzian relative to the pre-industrial period (Haywood et al. 2013). Driven by the higher temperature, the polar ice sheets were greatly retreated in the mid-Piacenzian (Cook et al. 2013; Dolan et al. 2015; Naish et al. 2009), leading to a rise in global mean sea-level by ~10–40 m (Raymo et al. 2011; Rohling et al. 2014; Rovere et al. 2014). The major terrestrial biomes exhibited a poleward expansion in the northern high latitudes, and the extent of arid and desert areas was reduced (Salzmann et al. 2008); the Loess Plateau may have experienced intensified aridity (Ji et al. 2017).

In addition to changes in the mean state, extreme events, such as tropical cyclones (TCs), also experienced remarkable variations in the mid-Piacenzian. Using an ultra-high resolution (~25 km) climate model, Yan et al. (2016) suggested that global TCs tended to be stronger and more powerful in the mid-Piacenzian. Notably, TCs not only passively vary with climate, but also play an important role in the vertical mixing of the upper ocean and in driving oceanic poleward heat transport (Emanuel 2001). An observational-based study indicated that TCs may account for approximately 15% of peak ocean heat transport (Sriver and Huber 2007). Further modeling studies have confirmed the role of TCs in heat transport and suggest that TCs could significantly modulate
oceanic and atmospheric circulations by strengthening the upper ocean vertical mixing (Jansen and Ferrari 2009; Korty, Emanuel, and Scott 2008; Manucharyan, Brierley, and Fedorov 2011; Srver et al. 2010).

The enhanced TC activity in the mid-Piacenzian potentially allowed more intensive TC–ocean interactions via the intensified upper ocean mixing, leading to changes in sea surface temperatures (SSTs). Thus, it is very interesting to investigate how SSTs may have responded to changes in TC behavior in the mid-Piacenzian. Climate models generally underestimate the reconstructed west–east temperature gradient across the Pacific in the mid-Piacenzian (Dowsett et al. 2013). This model–data mismatch has been discussed for a long time, but not fully resolved (Haywood, Dowsett, and Dolan 2016). Notably, it is argued that TC-induced vertical mixing may have contributed to the ‘permanent El Niño’ in the early Pliocene, hence reducing the aforementioned model–data inconsistency (Fedorov, Brierley, and Emanuel 2010). However, it remains unclear whether this might also have been the case in the mid-Piacenzian, as changes in TC activity differ greatly between the two periods, which is closely linked with the differences in the reconstructed SSTs (Fedorov, Brierley, and Emanuel 2010; Yan et al. 2016). Meanwhile, TC-induced oceanic changes could in turn affect atmospheric circulations, such as the East Asian monsoon, which has not yet been examined. Additionally, existing modeling studies targeting the climatic effect of TCs are largely based on the present-day boundary conditions. Given the higher climate sensitivity of the mid-Piacenzian relative to the present day (Pagani et al. 2010), it is meaningful to further examine TC feedbacks using the mid-Piacenzian boundary conditions.

Here, we use a fully coupled climate model to investigate the potential impacts of enhanced tropical cyclone activity on the mid-Piacenzian climate. We focus on the variations of the El Niño–Southern Oscillation (ENSO) and East Asian monsoon circulations. Such an investigation may shed light on TC feedbacks associated with vertical mixing and advance our understanding on the mid-Piacenzian climate.

2. Methods

2.1 Model description

The Community Earth System Model (CESM) is a fully coupled global climate model developed at the National Center for Atmospheric Research (Hurrell et al. 2013). CESM consists of four components: an atmospheric component, version 4 of the Community Atmosphere Model (CAM4); a land component, version 4 of the Community Land Model (CLM4); an oceanic component, version 2 of the Parallel Ocean Program (POP2); and a sea-ice component, version 4 of the Los Alamos Sea Ice Model (CICE4). In this study, CAM4 has a horizontal resolution of ~3.75° × 3.75°, with 26 vertical levels; POP2 has a nominal 3° horizontal resolution and 60 levels in the vertical direction; and CLM4 and CICE4 adopt the same horizontal resolution as CAM4 and POP2, respectively. Preliminary evaluations show that the CESM captures the observed thermocline in the equatorial Pacific well in terms of the depth and zonal gradient (not shown).

2.2 Experimental design

Following the guidelines of the Pliocene Model Intercomparison Project (PlioMIP) (Haywood et al. 2011), we design a pre-industrial experiment (PI) and a mid-Piacenzian experiment (MP). Relative to PI, the CO₂ concentration increases from 280 ppmv to 405 ppmv in MP. The topography and land cover are modified to represent the conditions of the mid-Piacenzian based on the Pliocene Research, Interpretation and Synoptic Mapping Phase 3D (PRISM3D) dataset (Dowsett et al. 2010). In brief, the topographies of the polar ice sheets were broadly 1500 m lower in the mid-Piacenzian than the present day. There was also decreased elevation over the Rocky Mountains and Andes Plateau, whereas the topography changes over Asia have been relatively complex (±1000 m). Regarding the land-cover distribution, there has been a northward expansion of boreal forests at northern high latitudes, and tundra has appeared in Greenland and Antarctica because of the retreated ice sheets. Note that we still use the present-day land–sea distribution in MP. The other boundary conditions are the same as in PI. Details concerning the application of PIRSM3D boundary conditions in CESM/CCSM4 are reported in previous studies (Yan et al. 2012; Zhang, Jiang, and Tian 2013). Next, we perform two sensitivity experiments to explore and mimic the effect of enhanced TC activity by increasing the background vertical diffusivity in the upper tropical ocean (>200 m) according to previous studies (Manucharyan, Brierley, and Fedorov 2011). In the first sensitivity experiment (MP_mix.GL), the background vertical diffusivity is ideally increased to 1.6 cm² s⁻¹ (i.e., ten times the pre-industrial value) over the tropical oceans, where TCs generally form. In the other experiment (MP_mix.CENP), increased vertical diffusivity is only applied over the central-eastern North Pacific. The amount of increased vertical diffusivity is on the same order of magnitude as the TC-induced vertical mixing observed in the present day (Srver and Huber 2007).
The two experiments are designed to (i) consider the uncertainty in the estimated mid-Piacenzian TC activity (Yan et al. 2016) and (ii) isolate the role of mixing over the central-eastern North Pacific, which is thought to be one of the key regions linking the extratropical and tropical ocean (Gu and Philander 1997). The other boundary conditions (e.g., topography and land cover) in the sensitivity experiments are identical to those in MP.

PI and MP are integrated for 1550 years and 3850 years to reach quasi-equilibrium, with the energy imbalance at the top of the atmosphere being ~0.1 and ~0.01 W m⁻², respectively. Initialized from MP, the two sensitivity experiments are then run for 500 years. We analyze the last 50 years of model outputs in each experiment. A summary of the experimental design is given in Table 1.

3. Results

CESM predicts a warmer and wetter climate in the mid-Piacenzian relative to the pre-industrial period, with an increase in global annual mean temperature and precipitation by ~2.9°C and ~5%, respectively. For the spatial distribution (Figure 1(a)), the most intense warming occurs at high latitudes of both hemispheres, and the tropics experience a moderate and uniform warming (~1–2°C). The largest variations of precipitation are in the tropical regions, with enhanced precipitation over the North Pacific and North Indian Ocean and decreased precipitation over the cold tongue and tropical Atlantic (Figure 1(b)). Broadly, precipitation is increased over land areas, except for South America. The general distribution of temperature/precipitation change is similar to the anomaly pattern found in the PlioMIP models (Haywood et al. 2013). On this basis, we use the model to examine the variations of ENSO and the East Asian monsoon and their responses to enhanced vertical mixing in detail, as reported in the following subsections.

3.1 Response of ENSO

The simulations exhibit a uniform warming pattern (0.5–1.5°C) across the tropical Pacific in the mid-Piacenzian relative to the pre-industrial period, with stronger warming over the eastern Pacific (Figure 2(a)). The zonal SST gradient in the equatorial Pacific decreases from 4.1°C in the pre-industrial period to 3.6°C in the mid-Piacenzian (Table 2). However, the model still overestimates the reconstructed zonal SST gradient (~2°C). This model–data discrepancy is also observed in other PlioMIP climate models (Dowsett et al. 2013; Haywood et al. 2013). Taking the effect of TC-induced mixing into account, the model predicts an additional warming (0.5–2°C) over the eastern tropical Pacific, which is almost devoid of TCs (Figures 2(b) and (c)), resulting in a reduced west–east SST gradient that matches well with proxies. This warming is largely attributable to the anomalous eastward flow out of the western Pacific in the upper ocean (~50–150 m) (i.e., enhanced equatorial undercurrent), which transports warmer water to the eastern tropical Pacific (Figure 3). The thermocline, as measured by the 20°C isotherm, becomes much deeper, but with a larger west–east slope (Figure 3). Besides, surface cooling is broadly observed at the locations of mixing due to the entrainment of colder waters from the subsurface. The distribution of the SST anomaly is roughly independent of where TC-induced mixing is applied in our simulations, but the warming is more profound in the sensitivity experiment, with enhanced vertical mixing over global storm basins (MP_mix.GL) than over the central-eastern North Pacific (MP_mix.CENP).

The interannual variability of ENSO is also greatly affected by the TC-induced vertical mixing. The modeled Niño 3.4 SST shows obvious interannual variability in MP (i.e., experiencing clear El Niño and La Niña events), with a standard deviation of 1.2°C, similar to the present-day level (1.3°C) (Figure 4(a) and (b)). In contrast, the standard deviation of Niño 3.4 SST in the mid-Piacenzian is reduced considerably to 0.5–0.6°C when TC feedback is considered (Figure 4(c) and (d)). Given the higher temperature over the eastern tropical Pacific (Table 2), these results imply that TC-induced vertical mixing is favorable for an El Niño–like condition in the mid-Piacenzian, as suggested by several proxies (Wara, Ravelo, and Delaney 2005), with the central-eastern North Pacific being the key region. However, it is hotly debated whether or not the western Pacific was

### Table 1. Experimental design in this study.

| CO₂ (ppmv) | Land cover | Topography | Background vertical diffusivity (cm² s⁻¹) | Land–sea mask | Run length (years) |
|------------|------------|------------|-------------------------------------------|---------------|-------------------|
| PI         | 280        | Modern     | 0.16                                      | Modern        | 1550              |
| MP         | 405        | PRISM3D    | 0.16                                      | Modern        | 3850              |
| MP_mix.GL  | 405        | PRISM3D    | 1.6 only over the global storm basins*     | Modern        | 500               |
| MP_mix.CENP| 405        | PRISM3D    | 1.6 only over the central-eastern North Pacific† | Modern       | 500               |

*Including the Pacific and North Atlantic (10°–35°N; 110°E–20°W) and South Indian Ocean and southwestern Pacific (10°–35°S; 50°E–150°W). Vertical diffusivity is not changed over the North Indian Ocean, as TC intensity and power dissipation were lower over that region in the mid-Piacenzian (Yan et al. 2016).
† Central-eastern North Pacific (10°–30°N; 160°E–100°W)
3.2 Response of East Asian monsoon circulations

During the summer season, the model produces a southwesterly anomaly at 850 hPa over the low latitudes of East Asia in MP mix.GL relative to MP (Figure 5(a)), which can be attributed to the anomalous anticyclonic circulation arising from the warming center over southern China (Figure 5(g)). This wind anomaly is concurrent with the westward and equatorward shift of the western North Pacific high (Figure 5(c)). At the upper level (200 hPa), zonal wind is broadly enhanced south of 40°N and reduced to the north, leading to a southward migration of the subtropical westerly jet (Figure 5(e)). The southward
shift is more profound over the western North Pacific, where tropospheric temperature exhibits a meridional dipole pattern (Figure 5(g)). There features are largely reproduced in MP_mix.CENP, though regional differences still exist (Figure 5).

During the winter season, there is an anomalous northerly over high latitudes of East Asia in MP_mix.GL and MP_mix.CENP, relative to MP (Figure 6(a) and (b)), indicating a stronger winter monsoon. Meanwhile, geopotential height shows a negative anomaly over northern East Asia (Figure 6(c) and (d)), which leads to a strengthened East Asian trough and contributes to the anomalous northerly over that region. Besides, the subtropical westerly jet migrates southward as the zonal wind is decreased (increased) north (south) of ~40°N (Figure 6(e) and (f)). These changes in monsoon circulations are attributable to the variation in the land–sea thermal contrast, which is broadly enhanced in the sensitivity experiments relative to MP (Figure 6(g) and (h)) as wintertime tropospheric mean temperature generally shows a ‘cold land–warm ocean’ state.

To compare the effect of TC-induced vertical mixing with that of the boundary conditions (e.g., higher CO₂ concentration), we introduce an East Asian monsoon

**Figure 2.** Simulated SST anomaly (units: °C) (a) between MP and PI, (b) between MP_mix.GL and MP, and (c) between MP_mix.CENP and MP. The circles represent the sites of proxies used to suggest a reduced zonal SST gradient in the Pliocene (Wara, Ravelo, and Delaney 2005).

**Table 2.** Metrics for ENSO and the East Asian monsoon discussed in this study.

|                      | PI    | MP    | MP_mix.GL | MP_mix.CENP |
|----------------------|-------|-------|-----------|-------------|
| Zonal SST gradient (°C)* | 4.1   | 3.6   | 2.5       | 2.8         |
| Niño 3.4 SST (°C)    | 25.8  | 27.3  | 28.9      | 28.1        |
| Standard deviation of Niño 3.4 SST (°C) | 1.3   | 1.2   | 0.5       | 0.6         |
| Summer monsoon intensity (m s⁻¹)†† | 3.6   | 3.7   | 3.9       | 4.2         |
| Winter monsoon intensity (m s⁻¹)†† | 2.1   | 1.4   | 1.9       | 1.8         |

*Estimated as the regional-averaged SST anomaly between the equatorial (5°S–5°N) western Pacific (120°–160°E) and eastern Pacific (140°–80°W)
† Niño 3.4 region (5°S–5°N; 170–120°W)
†† Estimated as the regional-averaged meridional wind at 850 hPa over (20°–40°N, 105°–120°E) for the summer monsoon and (30°–50°N, 105°–120°E) for the winter monsoon.
index defined as the regionally averaged meridional wind at 850 hPa over East Asia (Jiang et al. 2013). It is shown in Table 2 that the East Asian summer monsoon is intensified in MP_mix.GL and MP_mix.CENP with respect to PI, but the change in monsoon intensity arising from enhanced vertical mixing (MP_mix.GL/MP_mix.NP minus MP) is larger than that caused by the PRISM3D boundary conditions (MP minus PI). This result indicates a dominant role of TC-induced vertical mixing in controlling the summer monsoon. In contrast, the East Asian winter monsoon is weaker in MP_mix.GL and MP_mix.NP relative to PI, though it is intensified compared to MP. This result indicates that the role of mid-Piacenzian boundary conditions overwhelms the effect of TC-induced mixing in the winter monsoon.

4. Conclusion and discussion

In this study, we report preliminary results on the role of TC-induced vertical mixing on ENSO and the East Asian monsoon in the mid-Piacenzian using a fully coupled climate model. Our simulations indicate that TC-induced mixing leads to warmer temperatures over the eastern tropical Pacific and a deeper thermocline; plus, it dampens the interannual variability of ENSO. Both the East Asian summer and winter monsoons are intensified.
in response to enhanced vertical mixing. Additionally, our results suggest that increased vertical mixing over the central-eastern North Pacific plays a comparable role in modulating ENSO and East Asian monsoon compared with larger vertical mixing over the global storm basins.

Compared with Mg/Ca-based SSTs (Wara, Ravelo, and Delaney 2005), TC-induced mixing plays a potential role in reducing the model–data discrepancy in the zonal SST gradient over the tropical Pacific and maintaining an El Niño–like condition in the mid-Piacenzian, similar to previous findings (Fedorov, Brierley, and Emanuel 2010). Recently, it has been argued that ocean temperatures over the warm pool region were ~1–2°C higher in the mid-Piacenzian than the present day, based on TEX$_{86}$ (the tetraether index of 86 carbon atoms), as the Mg/ Ca data also incorporate the effects of salinity (O’Brien 2014; Zhang, Pagani, and Liu 2014). Thus, the model–data discrepancy may mainly result from uncertainties in the interpretation of proxies, rather than missing mechanisms in climate models. However, whether or not SSTs in the western tropical Pacific were warmer in the Pliocene is still unresolved (Fedorov et al. 2015; Ravelo et al. 2014). On the other hand, the interannual variability of ENSO is greatly dampened due to enhanced vertical mixing in our simulations, whereas geological evidence suggests clear ENSO variability in the Pliocene (Scroxton et al. 2011; Watanabe et al. 2011). Additionally, proxies suggest a stronger summer monsoon and a weaker winter monsoon over East Asia in the mid-Piacenzian (Nie, King, and Fang 2007; Nie et al. 2014; Zheng et al. 2004). However, TC-induced mixing favors a stronger winter monsoon, hence potentially driving the model to deviate from the reconstructions. These results indicate that considering the effect of TC feedback in the model is helpful in reducing the model–data discrepancy in one aspect (e.g., SSTs over eastern Pacific), but may worsen model results in another.

There are also several limitations to be considered in our simulations. We find that ENSO variability is greatly weakened in the mid-Piacenzian due to enhanced vertical

Figure 4. Time series of the winter (December–January–February) Niño3.4 SST anomaly (units: °C) relative to the long-term mean for (a) PI, (b) MP, (c) MP_mix.GL, and (d) MP_mix.CENP. SST anomalies larger and smaller than 0.5°C are shown in blue and orange, respectively.
mixing. However, the relative contributions of the zonal advective feedback and thermocline feedback remain unknown and should be studied in future work to advance our knowledge on the mechanisms behind the weakened variability. TC-induced mixing not only directly affects the large-scale thermal conditions over East Asia, but might also indirectly regulate the monsoonal circulations by modulating the ENSO variability. However, the direct and indirect role of TC-induced mixing is not differentiated in our study. For the experimental design, we mimic the role of TCs by increasing the background vertical diffusivity in the upper ocean throughout a year, as

Figure 5. Differences in (a, b) 850-hPa wind fields (units: m s\(^{-1}\)), (c, d) 500-hPa geopotential height (shading; units: gpm), (e, f) 200-hPa zonal wind (shading; units: m s\(^{-1}\); contours showing the mean zonal wind in MP), and (g, h) mean upper-tropospheric (500–200 hPa) temperature (shading; units: °C) and sea level pressure (contours; units: hPa) in summer between (a, c, e, g) MP\_mix.GL and MP and (b, d, f, h) MP\_mix.CENP and MP. Blue and green lines in (c, d) represent the explicit geopotential isolines of MP and MP\_mix. GL/MP\_mix.CENP, respectively. Areas that pass the 0.05 level of significance test are dotted.
the general pattern of climate change is largely independent on the duration of the imposed vertical mixing (Manucharyan, Brierley, and Fedorov 2011). However, in reality, TC-induced mixing is more complicated, varying with individual ocean basins in terms of season, magnitude, and depth (Sriver and Huber 2007). The idealized experimental setup here may introduce additional uncertainty into the modeled climate response (e.g., winter monsoon). Also, we adopt the modern land–sea configurations in the mid-Piacenzian experiments, so the potential role of the closure of the Panama and Indonesia seaways (e.g., Cane and Molnar 2001) is not considered.

Figure 6. Differences in (a, b) 850-hPa wind fields (units: m s\(^{-1}\)), (c, d) 500-hPa geopotential height (shading; units: gpm), (e, f) 200-hPa zonal wind (shading; units: m s\(^{-1}\)), and (g, h) mean upper-tropospheric (500–200 hPa) temperature (shading; units: °C) and sea level pressure (contours; units: hPa) in winter between (a, c, e, g) MP\_mix.GL and MP and (b, d, f, h) MP\_mix.CENP and MP. Blue and green lines in (c, d) represent the explicit geopotential isolines of MP and MP\_mix.GL/MP\_mix.CENP, respectively. Areas that pass the 0.05 level of significance test are dotted.
here, which has been shown to be important for the evolution of the East Asian monsoon (e.g., Nie et al. 2014). Besides, we perform snapshot simulations targeting ~3 Ma instead of a transient experiment during the Pliocene; and the simulated climate responses may be model-dependent given different parameterizations, dynamic schemes, and climate sensitivity in climate models. Therefore, more efforts, from both the data reconstruction and numerical modelling communities, are needed to resolve the discrepancy between simulations and reconstructions in the mid-Piacenzian. Resolving this problem is key to understanding Pliocene warmth, and is hence potentially helpful for us to project future climate changes.

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