Sea surface temperatures in the South China Sea as a natural thermostat to the rainfall over Borneo: preliminary results

Y S Djamil1, R K Lestari2,3 and X Wang4,5

1Indonesia Institute of Sciences, Research Center for Geo-technology, Bandung, West Java, 40135, Indonesia
2Institute for Globally Distributed Open Research and Education, Kashiwa, Japan
3Ronin Institute, Montclair, NJ 07043, US
4Asian School of the Environment, Nanyang Technological University, 639798, Singapore
5Earth Observatory of Singapore, Nanyang Technological University, 639798, Singapore
Corresponding e-mail: yudh004@lipi.go.id

Abstract. Community Climate System Model version 4 (CCSM4) simulated warmer sea surface temperatures (SSTs) in the South China Sea (SCS) for the mid-Holocene scenario compared to the pre-Industrial. Previous sensitivity experiments using the atmospheric component of the CCSM4, the Community Atmospheric Model version 4 (CAM4), showed that warmer SSTs in the SCS suppresses rainfall over Borneo, which is in-contrary to the effect of the stronger insolation over the island. In this study, we show that warmer SSTs in the SCS, as simulated in the CCSM4, is responding to a weaker low-level wind impacted by the stronger convectional rainfall over Borneo due to stronger insolation. These results suggest that warmer SSTs in the SCS might act as a negative feedback which damps the effect of the stronger insolation on rainfall changes over Borneo.

1. Introduction

South China Sea (SCS) is a near-equatorial large body of water which often acts as a heat source to drive weather and climate in the equatorial Maritime Continent, especially over Borneo [17]. It has been found that sea surface temperatures (SSTs) in the SCS strongly influence several climatological features over the region, e.g., the northern migration of the Inter-tropical Convergence Zone (ITCZ) in boreal summer, and the Asian monsoon surges in boreal winter [8, 9, 10]. However, despite the dynamical importance of the SCS to the regional climate, its long-term variability and connections with the other climate components remain unclear. Present study aims to investigate preliminary results for the underline mechanisms of the long-term variability of the SCS SSTs modulated by the long-term insolation or orbital cycle, and its significance to change the regional climate.

Compared to today, tropics experienced stronger insolation in boreal summer-to-autumn during the mid-Holocene, a time period ~6000 years ago (kyr), because of a different setting of the orbital parameters [1, 7]. The response of SSTs in the SCS during the mid-Holocene remains unclear in paleo proxy studies since mixed responses were observed from locations close to each other [6, 13, 14]. On the other hand, numerical simulations of the mid-Holocene climate change using coupled-general circulation model (CGCM) could provide a possible scenario for the changing SSTs in the SCS if it performed well in simulating rainfall change over the Maritime Continent (e.g., Borneo and SCS) [4].
Such simulations have been conducted by using the Community Climate System Model version 4 (CCSM4) as part of the Paleoclimate Model Intercomparison Project Phase-5 (PMIP5) [2, 16].

Previous study showed that CCSM4 simulation for the mid-Holocene, in comparison with the pre-Industrial, produced a higher annual rainfall mainly over the large islands in the Maritime Continent (e.g., Borneo, Sumatra, and Sulawesi) [4]. These results were consistent with the speleothem-based rainfall proxy records developed from each island [3, 18, 19]. CCSM4 also showed a slight lower annual rainfall over the SCS which is consistent with the coral-based rainfall proxy data from northern SCS [15]. In term of surface temperature, CCSM4 simulated slight warmer annual SSTs in the center of SCS, which was mainly contributed by much warmer SSTs in a wider region of SCS during the boreal autumn (September, October, and November, SON) (Figure 1.a & b). These significantly warmer SSTs in the boreal autumn are not in line with a drier climate, because warmer SSTs commonly coincide with a region of a more active convection [5]. The drier climate over the SCS is shown as the implication of a stronger convection over Borneo since the strong convection ‘trapped’ moisture supplied by the southerly flux during the boreal summer-to-autumn [4]. On the other hand, the stronger convection over Borneo is shown as the net product of the impact of stronger insolation onto Borneo and warmer SSTs in the SCS [4].

*Figure 1*. Mean sea surface temperatures simulated by the CCSM4 during (a) all-year and (b) SON season for the mid-Holocene minus pre-Industrial. Dotted grids are not significant at 95% confidence level based on Welch’s t-test.

Previous study also revealed the independent impact of the mid-Holocene insolation and SSTs to the mid-Holocene climate by performing two atmospheric experiments using the Community Atmospheric Model version 4 (CAM4) [4]. Each experiment simulated the mid-Holocene atmosphere either forced only by the mid-Holocene insolation (labeled as SSOLIN) or its SSTs (labeled as WSST) as a modification from the pre-Industrial setup [4]. The independent impact of each forcing is quantified by subtracting the experiments (SSOLIN and WSST) with the pre-Industrial simulation (Figure 2) [4]. The experiments showed that warmer SSTs in the SCS during boreal summer-to-autumn suppress rainfall over Borneo (WSST minus piC in Figure 2.a) [4]. However, this impact is overwhelmingly negated by the impact of stronger insolation which increases convectional rainfall over Borneo significantly (SSOLIN minus piC in Figure 2.a) [4]. Thus, the SCS SSTs act as a secondary forcing to the Borneo rainfall by inducing a much weaker convection over the ocean (WSST minus piC in Figure 2.b) [4]. The slight increase in the ocean convection damps Borneo rainfall by producing a counter flow to the large scale meridional circulation which is mainly driven
by the island convection, thus, reduces the atmospheric impact of the stronger insolation over the island [4]. On the other hand, since our atmospheric experiments were conducted using SSTs prescribed from the CCSM4, those SSTs could be influenced by the atmospheric condition through the air-sea interaction mechanisms [11]. Therefore, one ought to hypothesized that changes of the SSTs in the SCS during the mid-Holocene, among other factors, were the net product of a complex interaction between SCS and the atmospheric component.

**Figure 2.** Monthly climatology of the area averaged rainfall simulated by CAM4 over (a) Borneo (110°E to 118°E, 2°S to 5°N) and (b) SCS (110°E to 118°E, 8°N to 18°N) as shown in the top left map, for the mid-Holocene minus pre-Industrial (black), SSOLIN (pre-Industrial scenario forced by the mid-Holocene insolation) minus pre-Industrial (red), WSST (pre-Industrial scenario prescribed by the mid-Holocene SST from the CCSM4 simulation) minus pre-Industrial (magenta), and the mid-Holocene reconstruction (SSOLIN+WSST-piC) minus pre-Industrial (blue). Ranges of uncertainty are within 95% confidence level based on the student’s t distribution. Boreal summer (autumn) is highlighted with cream (light green) colour in the background. Plots are adapted from [4].

2. Impact of stronger convectional rainfall over Borneo to the SSTs in the SCS
The underline mechanisms to produce warmer SSTs in the SCS during SON in the mid-Holocene climate change simulations lie upon the direct and indirect responses of the oceanic system to the stronger insolation. Indirect responses of the SSTs to the stronger insolation, in one way, can be referred from the air-sea interaction mechanisms [11]. Correlation between SST and near-surface wind generally describes the dominant factors between these two physical quantities [12]. Negative correlation signifies atmosphere as the driver to the SSTs, where intensified wind cools the ocean surface through both evaporation and possibly increased entrainment of the upper-thermocline cold waters into the mixed layer. While positive correlation signifies ocean as the driver to the atmosphere through the heat fluxes out of the ocean.

CCSM4 simulations showed southerly wind at the low-level (850mb) over the SCS during SON is weaker in the mid-Holocene than the pre-Industrial (Figure 3.a). Djamil (2018) showed that the weakening of the low-level wind over northern Borneo and SCS is mainly due to the stronger island convection as a response to the stronger insolation. Stronger convection over Borneo is associated with a stronger moisture convergence which induces northerly moisture flux which then weakens the low-level southerly wind over north of Borneo. The weakening of low-level wind over the SCS is
encountered by the sea surface as the weakening of the wind-stress parameter. The coherency between low-level wind and oceanic wind-stress in SCS during SON for the pre-Industrial and changes in their magnitude for the mid-Holocene are properly simulated by the CCSM4 (Figure 3.a & b).

Figure 3. Climatology of the (a) low-level wind at 850 mb and (b) ocean surface wind-stress from the CCSM4 simulations for the SON season. Shaded colors are the mid-Holocene minus pre-Industrial simulations significant at 95% confidence level based on Welch’s t-test. Vectors are the climatology of the horizontal wind and the ocean surface wind-stress of the pre-Industrial simulation. Coastlines plotted in panel a (b) are the land (ocean) fraction used by the atmospheric (oceanic) component of the CCSM4 at the value of 0.5.

Figure 4. Area averaged climatology of the (a,d) SSTs, (b,e) wind-stress magnitude, and (c,f) insolation in the SCS (110°E to 118°E, 8°N to 18°N, rectangle b in the top left map of Fig. 2) simulated by the CCSM4 for each scenario (d-f) and their differences (a-b). Ranges of uncertainty are within 95% confidence level based on student’s t distribution. Boreal summer (autumn) is highlighted with cream (light green) colour in the background.
The area of a weaker SCS wind-stress in the SON is overlapped with the warmer SSTs (Figure 1.b & Figure 3.b). Opposite changes between SSTs and wind-stress in the SCS indicate atmospheric changes as the driver to the oceanic changes. However, the peak of changes in the wind-stress climatology, which is in September, has a one-month time lead from the changes of the SST climatology, although the error-bars among the changes in the SON period are mostly overlapped (Figure 4.a & b). A closer inspection on each scenario shows that the increasing (decreasing) trend of the mid-Holocene (pre-Industrial) SST climatology along boreal summer and autumn is also coherent with the delayed (1-2 months) annual insolation rather than wind-stress (Figure 4.d-f). On the other hand, wind-stress climatology seems coherent with the SST climatology along boreal autumn in the mid-Holocene but not in the pre-Industrial simulation. In the boreal autumn, unlike the decreasing trend of the pre-Industrial SSTs, the mid-Holocene SSTs remain relatively warm in September and October following a weakened wind-stress, thus, appear as the largest changes between the two simulations (Figure 4.d-f). Therefore, warmer SST in the SCS during the mid-Holocene is likely a net product between its delayed and instantaneous responses to the stronger insolation and weaker low-level wind respectively.

3. Summary and suggestions
CCSM4 simulations under a stronger insolation showed warmer SSTs in the SCS, especially during boreal autumn. These warmer SSTs in the SCS are a possible scenario under the mid-Holocene climate since its higher rainfall over the large islands in the Maritime Continent, including Borneo, has been verified by the rainfall proxy records. Djamil (2018) suggested that warmer SSTs in the SCS during boreal autumn act as the secondary forcing to damp the increase of convectional rainfall over Borneo under stronger insolation. He had also reported weaker low level southerly wind over the SCS as an implication of stronger convection over Borneo. In return, weaker southerly wind over the SCS was supposed to increase the SSTs, which is the focus of the present study.

Weaker low-level southerly wind over the SCS during boreal autumn, which was encountered as weaker wind-stress by the sea surface, has a potential to overheat the SSTs since it shows anti-phased variability with the SCS SSTs in the mid-Holocene simulation. However, SST climatology throughout the year appears more coherent with the delayed insolation in each simulation. These results indicate a combined effect from the direct and indirect impact of the stronger insolation to the SSTs in the SCS. The impact from weaker wind-stress is an indirect response of the SSTs to the stronger insolation via higher rainfall over Borneo. Therefore, warmer SSTs in the SCS during the mid-Holocene might be the net product of the oceanic response to stronger insolation on its own region and on Borneo.

Mutual feedback between the SCS SSTs and the Borneo rainfall in orbital time-scale demonstrated a complex inter-connected long-term climate system over the Maritime Continent. We plan to carry out deeper statistical and dynamical analyses to provide more robust evidences and insights for the complex relationship between the atmospheric and oceanic parameters in modulating long-term rainfall over the Maritime Continent. Additionally, numerical experiments using either CGCM or ocean-GCM are needed to examine the underlined mechanisms including the dynamical evidence of the air-sea interaction system.

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Authors contributions
Y S Djamil acquired and analyzed CCSM4 simulations outputs from the PMIP3 online database. Y S Djamil analyzed previous numerical experiments documented in Djamil (2018). Y S Djamil wrote the manuscript, thus, acts as the main contributor. Author member: R K Lestari contributes to the discussion of the main idea and on the issue of air-sea interaction, also correction and comments on the manuscript. X Wang contributes to the discussion of the main idea, approval to access the
computational facility in the Earth Observatory of Singapore, also correction and comments on the manuscript.

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