ISSN 2354-9114 (online), ISSN 0024-9521 (print)
Indonesian Journal of Geography Vol 54, No 3 (2022): 437-441
DOI: 10.22146/ijg.75502 website: htps://jurnal.ugm.ac.id/ijg

INDONESIAN JOURNAL OF GEOGRAPHY

RESEARCH ARTICLE

First-order analyses on the role of surface wind in the long-term contraction of the Indo-Pacific warm pool

Andreas Siswandi[1], Yudha Setiawan Djamil[2], Rima Rachmayani[1], Sri Yudawati Cahyarini[2], Marfasran Hendrizan[2]
[1]Program Study of Oceanography, Faculty of Earth Sciences and Technology, Bandung Institute of Technology, Bandung, Indonesia,
[2]Research Center for Climate and Atmosphere, National Research and Innovation Agency, Bandung, Indonesia.

Received: 2022-08-07
Accepted: 2022-12-19

Keywords:
Indo-Pacific Warm Pool (IPWP); mid-Holocene; CCSM4; surface wind; sea surface temperature

Abstract Due to its high evaporation rate, the Indo-Pacific Warm Pool (IPWP) is one of the most important drivers of Indonesian weather and climate. Previous studies, based on the Sea Surface Temperature (SST) proxy records, suggest that IPWP in the mid-Holocene era (~6000 years ago) underwent a contraction (colder on its east-west perimeter and warmer on its center) compared to today's condition. In this research, the role of surface wind in contracting the IPWP was analyzed by checking the coherency between changes in SST, wind-stress magnitude, and evaporation. The Climate Community System Model version 4 (CCSM4) simulated these three physical quantities under the pre-Industrial and mid-Holocene scenarios. In these simulations, an anti-phase relation between SST and wind-stress magnitude indicates an important role for a weaker surface wind in warming the SST in the center of the IPWP (South China Sea and Banda Sea), mainly during boreal autumn. However, a weaker surface wind did not seem to have simultaneously suppressed ocean evaporation to warm the SST, as shown by the phase-lag relation in their monthly climatology. On the other hand, colder SSTs on the east-west perimeter of the IPWP (western coast of Sumatra and northern coast of Papua) are unlikely to be associated with changes in the surface wind following a weak correlation between their SST and wind-stress magnitude

Correspondent email:
andreas.siswandi.99@gmail.com

1. Introduction

The Indo-Pacific Warm Pool (IPWP) is defined as an area of water with a sea surface temperature (SST) value consistently about 2° to 5° C higher than the other equatorial waters and mostly located in the Indonesian archipelago (Yan et al., 1991). Although its area is relatively small compared to the ocean, this warm pool can influence the weather around Indonesian waters and the global sea-atmosphere climate system because of its strong atmospheric convection (Cane & Clement, 1999; Lestari & Iwasaki, 2006; de Deckker, 2016).

The IPWP condition can be traced back to the mid-Holocene era (~6000 years ago) based on studies of SST proxy records from the region. During the mid-Holocene, SST in the western and eastern border of IPWP was colder than today, as shown by their proxy from Mentawai and Muschu/Koil Island, respectively (Abram et al., 2009). Another proxy taken from the Makassar Strait showed that the SST in the mid-Holocene era was warmer than today (Hendrizan et al., 2017; Schröder et al., 2018). Thus, SST changes that happened throughout the IPWP from recent time to the mid-Holocene era were in the form of a "contraction". Despite the clear evidence from the SST proxy records, the underlying mechanisms of such "contraction" remain unclear. In general, modulation of large-scale SST could be driven by atmospheric forcings, such as variation in the surface wind (Small et al., 2008). Therefore, we hypothesized that the "contraction" of IPWP between today and the mid-Holocene was primarily caused by changes in the surface wind over the oceanic region in the Maritime Continent.

With around 6000 years of the time difference, there are several changes in the climate condition between the mid-Holocene and modern-day as a response to the insolation difference between both eras (Figure 1) (Indermühle et al., 1999, Laskar et al., 2004). In the Maritime Continent, climate underwent a stronger-than-today convection activity around July to October to respond to the stronger-than-today insolation (Figure 1). During these months, stronger-than-today convection around Borneo was identified to slow down the horizontal wind speed over the South China Sea (Djamil et al., 2021). In principle, a slower surface wind will lessen the heat transfer from the sea surface to the atmosphere by suppressing evaporation, eventually generating a warmer sea surface (Chelton et al., 2004). This phenomenon can be seen in most regions of the world, especially in the Pacific Ocean waters (Seo et al., 2007). Thus, a slower surface wind could be the main cause of a warmer-than-today SST during the mid-Holocene around the center of IPWP, as shown by the SST proxy records (Hendrizan et al., 2017; Schröder et al., 2018).

On the contrary, an intense wind speed over the ocean surface will enhance evaporation through an intensified turbulent transfer process, which usually leads to breaking waves, from which 'spray' is formed (Bao et al., 2011). The heat loss from the ocean surface due to evaporation is transferred to the atmosphere as latent heat, eventually generating a colder ocean surface (Strahler, 2001). This mechanism could be responsible for a colder-than-today SST during the mid-Holocene in the east-west border of the IPWP, as shown by the SST proxy records (Abram et al., 2009).

Our study aims to evaluate the basic role of surface wind in changing the SST between recent times and the mid-Holocene.

The evaluation was done by conducting a first-order analysis of the relationship between changes in the surface wind (represented by wind stress) and SST in the IPWP between the two eras. Evaporation data are also analyzed in order to understand the physical processes behind this long-term sea-air interaction phenomenon. All physical quantities involved in our study are the output of the Community Climate System Model (CCSM4) simulations under the mid-Holocene and pre-Industrial scenarios. The analysis covered correlation, a comparison of their seasonal and monthly climatology, and the power spectral density of those physical quantities in some areas of interest. The methodology is detailed in the next section, followed by a section on results and discussions. Lastly, the conclusion of our study is presented in the last section.

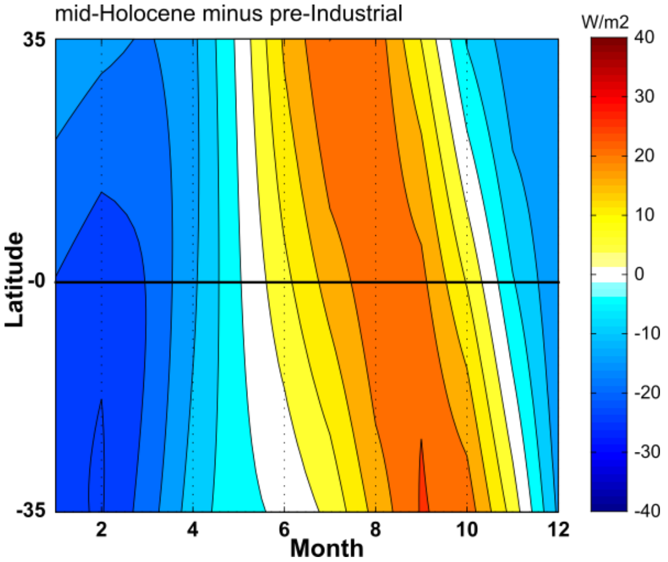

Figure 1. Monthly insolation in the IPWP area (35° S–35° N, 140° E–260° E) for mid-Holocene minus pre-Industrial based on insolation formula from Laskar et al. (2004).

2. Methods

Output from CCSM4 simulations was obtained to evaluate the role of sea-air interaction in the IPWP contraction, focusing mainly on the physical quantities associated with atmospheric forcing (SST, wind stress, and evaporation) (Rachmayani et al., 2016). CCSM4 is a coupled Global Climate Model (coupled-GCM) that has been used to simulate various climate scenarios, including pre-Industrial and mid-Holocene eras, as a part of the Paleoclimate Modelling Intercomparison Project Phase 3 (PMIP3) (Schmidt et al., 2012). CCSM4 is one of the top 12 out of 28 Global Climate Models (GCM) well-performed for simulating large-scale climate events over the region, and also one of the three GCMs with the highest spatial resolution considered suitable to be downscaled over the Indonesian Maritime Continent, or in this case, the IPWP (McSweeney et al., 2012). This CCSM4 model has a monthly temporal resolution with a spatial resolution of 0.9° x 1.25°. The differences between the two simulation scenarios besides their orbital parameters were in the time length, which was 6012 months (501 years) for the pre-Industrial and 3012 months (251 years) for the mid-Holocene (Smith et al., 2010).

This research uses SST since it is an indicator for IPWP, while the magnitude of wind stress represents atmospheric forcing, i.e., surface wind. Wind stress is the shear stress quantity exerted by the wind speed on the surface of water bodies, which describes the magnitude of a force causing the deformation of the water surface. This deformation will later be a part of the evaporation process, which changes the SST (Smith, 1988). The mean values of both the SST and the wind-stress are calculated in each grid cell of the IPWP area from CCSM4 and compared to each other to see the spatial changes of both parameters. The difference in SST from the model given by this calculation will be compared with proxies from previous studies (Abram et al., 2009) to determine if the 'contraction' could be seen in the CCSM4 model. From both SST and wind-stress data, a Pearson correlation method is used to determine the score of both parameters and their change between the two scenarios. The correlation number is calculated from 300 years of monthly model data available for both scenarios. This correlation score between SST and wind stress signifies the intensity of the SST cooling mechanism by the wind stress with evaporation as a process bridging both parameters. Evaporation is used to further understand the physical mechanism by which the change of the surface wind may drive the SST (Rachmayani et al., 2019). Surface wind may drag the water particles under it along with the heat to be separated from the main water body, forming evaporation and making the ocean surface temperature colder (Small et al., 2008). The analysis will also be done in terms of monthly climatology to evaluate changes in the annual signal.

Some particular areas are then chosen for further investigation based on the correlation scores and the availability of the SST proxy records. These areas are the western coast of Sumatra, the South China Sea, the Banda Sea, and the northern coast of Papua. Changes in their climate variability were then evaluated by calculating the physical parameters' spectral analysis and monthly climatology. Power spectrum values are calculated by applying Fast Fourier Transformation (FFT) to these selected areas. The data in each area are averaged for every time step before being transformed into the frequency domain. All the calculations performed in this study used the basic mathematical package of MATLAB R2013a.

3. Results and Discussions

The annual mean of the IPWP during the mid-Holocene shows an overall colder condition than the pre-Industrial as simulated by the CCSM4, mainly around the eastern and western boundaries (Figure 2-a). These changes are consistent with the SST proxy records from the Mentawai and Muschu/Koil islands (Abram et al., 2009). On the other hand, CCSM4 simulated an unchanged annual mean of the SST around the middle part of the IPWP, which is not consistent with a warmer-than-today SST, as shown by the SST proxy records from Makassar Strait (Hendrizan et al., 2017) and Banda Sea (Spooner et al., 2005). However, warmer-than-pre-Industrial SST in the center, accompanied by colder-than-pre-Industrial SST in the borders of the IPWP, is well simulated by the CCSM4 during the SON (September, October, and November) season (Figure 2-c). During SON, the warmer-than-industrial SST occurred mainly in the South China Sea, followed by the rest of the oceanic region on the Maritime Continent, including the Banda Sea. These changes demonstrate that the warm pool contraction is dynamically possible.

From the spectrum analysis (Figure 3) in areas of interest (Figure 4), the six-month and one-year periodicity dominance can be seen in all IPWP areas for SST and wind-stress magnitude. On the western coast of Sumatra (Figure 3-a and b), South China Sea (Figures 3-c and d), and the Banda Sea (Figures 3-e and f), the annual periodicity during the pre-Industrial was stronger than in the mid-Holocene, which is contrary to the semi-annual periodicity. On the northern coast of Papua

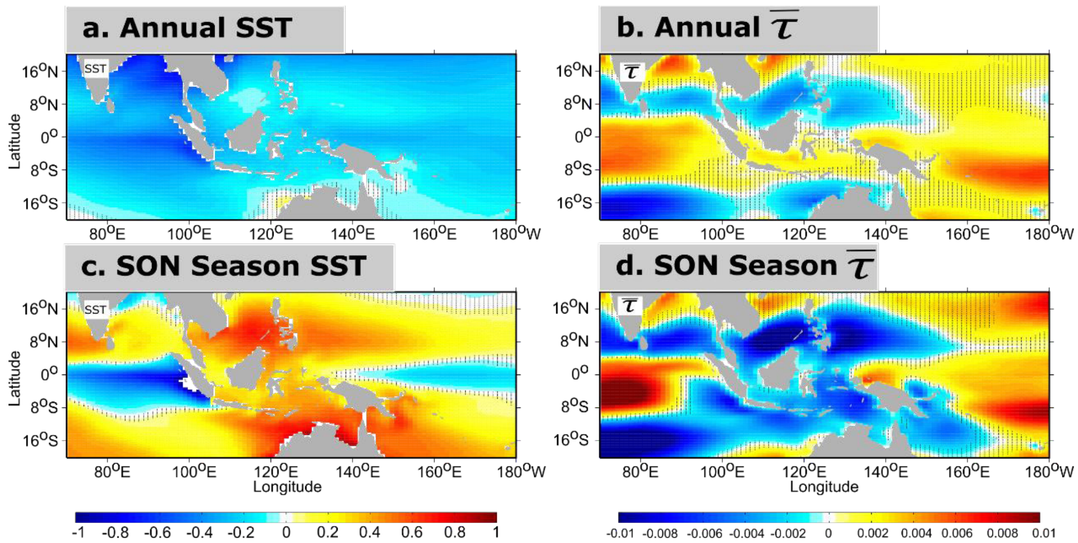

Figure 2. Mean of SST and wind-stress magnitude ($\overline{\tau}$) for the annual (a, b) and SON (c, d) as simulated by the CCSM4 for the mid-Holocene minus the pre-Industrial. Dotted areas are not significant based on a two-sample student t-test with a 95% confidence level. Land areas (grey) are outlined based on 50% land fraction data used by the CCSM4.

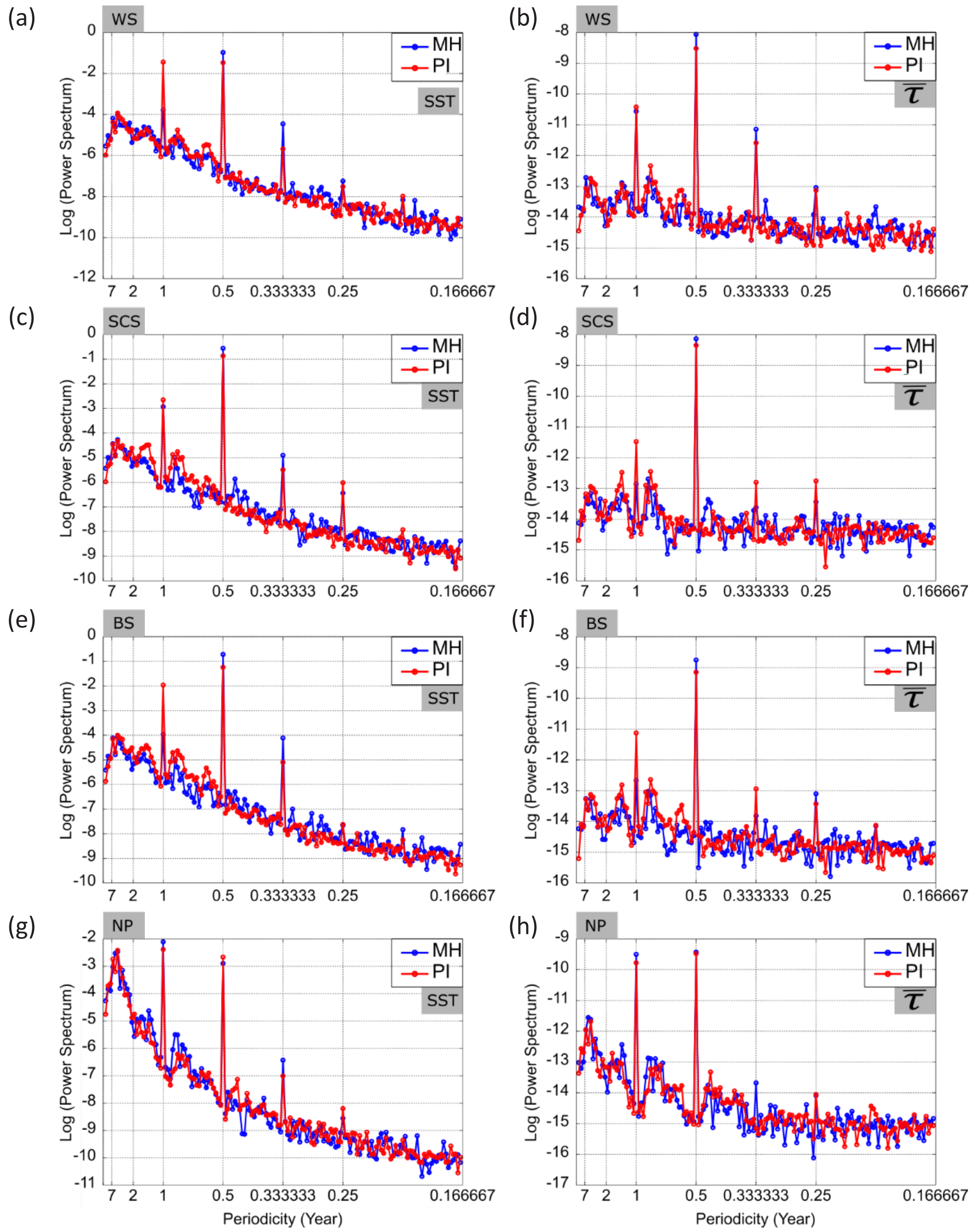

Figure 3. A power spectrum periodogram with Bartlett's method to smooth the power spectra (Bartlett, 1948) of the area-averaged SST for the mid-Holocene (blue) and pre-Industrial (red) on the western coast of Sumatra (a & b), the South China Sea (c & d), the Banda Sea (e & f), and the northern coast of Papua (g & h).

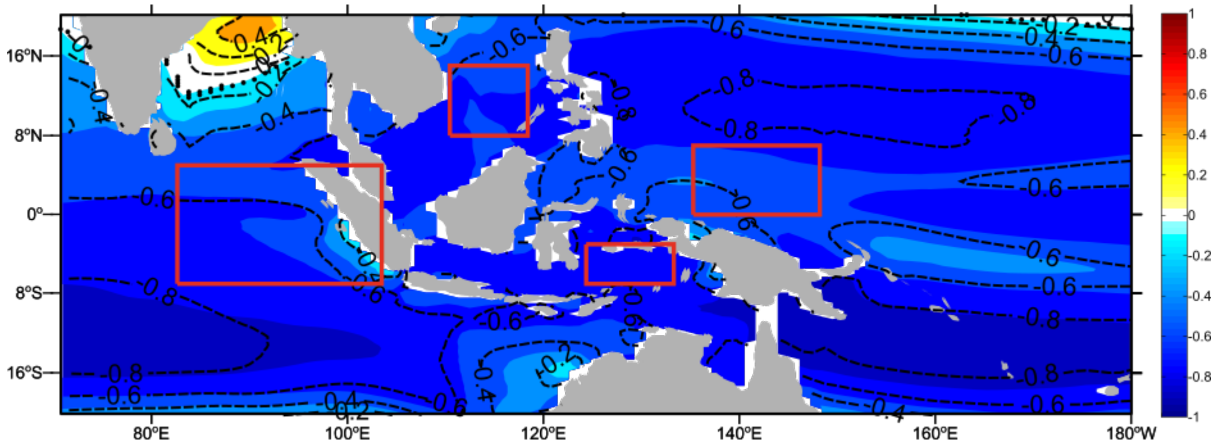

Figure 4. Correlation scores between SST and wind-stress magnitude in the IPWP as simulated by the CCSM4 for the mid-Holocene (shaded color) and pre-Industrial (striped lines), Dotted areas are not statistically significant based on t distribution statistics with a 95% confidence level. Land areas (grey) are outlined based on 50% of land fraction data used by the CCSM4. R-colored boxes are the areas of interest to be spatially averaged and further analyzed.

(Figure 3-g and h), inter-annual periodicity seems to have a similar dominance to the annual and semi-annual periodicity, suggesting that changes in these areas could not be identified from its annual climatology.

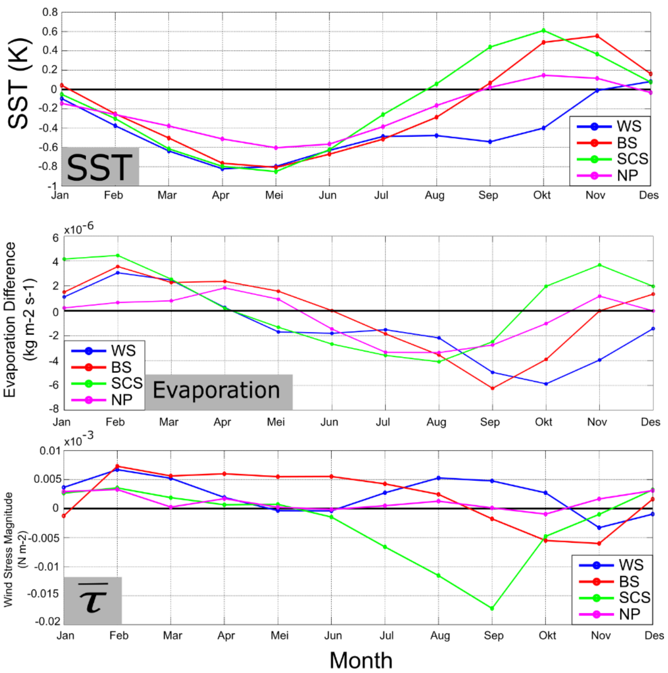

Figure 5. The climatological mean of SST (a), Evaporation (b), and wind-stress magnitude (c) for mid-Holocene minus pre-Industrial from area-averaged regions are shown in Figure 4. These regions are the western coast of Sumatra (WS: blue), the Banda Sea (BS: red), the South China Sea (SCS: green), and the northern coast of Papua (NP: purple).

CCSM4 simulated an opposite change between the annual mean of the wind-stress magnitude over IPWP and the SST, also shown in their monthly climatology (Figures 5-b and d). A higher magnitude of wind stress is shown in the western and eastern boundaries of the IPWP, while the differences are smaller in the middle part of the magnitude. The opposite condition of wind-stress magnitude from the SST indicates a strong SST response to the atmospheric forcing on the IPWP, which is shown in the negative correlation value between the two parameters all across the IPWP with some variation in the interior sea and borders of the IPWP for both scenarios. (Figure 2). SSTs show stronger responses (shown by a higher correlation value) to the wind stress in the interior sea of IPWP and weaker responses on the eastern and western borders of IPWP. Weak correlation scores in the outer parts of IPWP might be associated with changes in climate variability lasting longer than a year, such as the El Niño Southern Oscillation (ENSO) (Timmermann et al., 2018) and Indian Ocean Dipole (IOD) (Saji et al., 1999), since these waters are directly affected by those events.

In the center of IPWP (South China Sea and Banda Sea), a suppressed evaporation occurred 1-2 months ahead of a weakening of wind stress and a warming SST as shown by their climatology (Figure 5). This phase-lag relation in both locations suggests that a weaker-than-today surface wind may not simultaneously warm the SST during the mid-Holocene solely through suppressing evaporation. Despite the phase-lag relation, an instantaneous coherency between the three quantities still occurred during October in both the South China Sea and the Banda Sea. In South China, a negative difference in both evaporation and wind stress occurs earlier in the year (April –May) than in the Banda Sea (June – August). On the other hand, in both regions, a positive difference in wind-stress magnitude and evaporation is accompanied by an adverse change in SST in the first annual half (December – January) (Figures 5-a and c). This case shows that a weaker surface wind did not seem to suppress ocean evaporation in order to warm the SST simultaneously. We suspect this phenomenon could occur in the interior of IPWP because both areas (the South China Sea and Banda Sea) are directly connected to the Indonesian Throughflow (ITF), which may cause an intrusion of seawater from the Pacific Ocean, making the SST in those areas not affected by the wind-stress alone (Kida & Wijffels, 2012).

4. Conclusions

This study demonstrated that CCSM4 was able to simulate changes in the physical condition of IPWP between the pre-Industrial and mid-Holocene eras. In our research, warmer-than-today SSTs, as part of the warm pool contraction, were simulated in the internal sea of the IPWP (South China Sea and Banda Sea), mainly during SON. Our first-order analysis suggests that these warmer-than-today SSTs are likely driven by atmospheric forcing (e.g., surface wind) as an impact of a stronger-than-today insolation. However, the climatological changes of surface wind appear to be independent of the evaporation changes. This independence suggests that the underlying mechanism of such warming appears to be more complicated than just an oceanic response to a weaker surface wind that induces weaker evaporation (Small et al., 2008).

Investigation of the changes in the inter-annual periodicity of the IPWP, especially in the perimeter of the IPWP area, where colder annual SST could be more related to the changes of ENSO and IOD's activity such as frequency and intensity, should be conducted in the future to fully understand the mechanism behind the IPWP contraction. The movement of ocean currents in the interior of IPWP should also be further investigated to determine its effect on the heat distribution, especially because these regions are a direct route of the Indonesian Throughflow (ITF).

Acknowledgement

Kemenristek/BRIN funds this research under PROGRAM RISET DASAR KEMITRAAN year 2021, scheme WORLD CLASS RESEARCH (WCR), contract number 588a/IT1.C01/TA.00/2021.

Authors Contribution

A. Siswandi downloaded the CCSM4 simulation output, conducted the analyses, produced the figures, and wrote the manuscript. Y. S. Djamil proposed the idea, designed the analytical approach, actively joined the discussion, and revised and improved the overall content of the manuscript. Thus, A. Siswandi and Y. S. Djamil are the main contributors to this paper. Member contributing author: R. Rachmayani contributed to the initial idea, joined the discussion, and corrected the overall manuscript. S. Y. Cahyarini and M. Hendrizan provided information on the SST proxy, joined the discussion, and corrected the overall manuscript.

References

Abram, N. J., McGregor, H. v., Gagan, M. K., Hantoro, W. S., & Suwargadi, B. W. (2009). Oscillations in the southern extent of the Indo-Pacific Warm-pool during the mid-Holocene. Quaternary Science Reviews, 28(25–26), 2794–2803.

Ahrens, C. D. (2008). *Essentials of Meteorology: An Invitation to the Atmosphere*. Thomson Brooks/Cole.

Bao, J. W., Fairall, C. W., Michelson, S. A., & Bianco, L. (2011). Parameterizations of sea-spray impact on the air-sea momentum and heat fluxes. *Monthly Weather Review*, *139*(12), 3781–3797. https://doi.org/10.1175/MWR-D-11-00007.1

Bartlett, M. S. (1948). Smoothing Periodograms from Time-Series with Continuous Spectra. *Nature*, *161*(4096), 686–687.

Cane, M., & Clement, A. C. (1999). A role for the tropical pacific coupled ocean-atmosphere system on milankovitch and millennial timescales. Part II: Global impacts. In *Geophysical Monograph Series* (Vol. 112, pp. 373–383). Blackwell Publishing Ltd.

Chelton, D.B., Schlax, M.G., Freilich, M.H., Milliff, R.F., (2004). Satellite measurements reveal persistent small-scale features in ocean winds. Science 303, 978–983.

de Deckker, P. (2016). The Indo-Pacific Warm Pool: critical to world oceanography and world climate. In *Geoscience Letters* (Vol. 3, Issue 1). SpringerOpen.

Djamil, Y. S. (2018). Mid-Holocene Climate Change Over The Maritime Continent : Impact, Attribution and Mechanism. Doctoral Dissertation. Nanyang Technology University.

Hendrizan, M., Kuhnt, W., & Holbourn, A. (2017). Variability of Indonesian Throughflow and Borneo Runoff During the Last 14 kyr. *Paleoceanography*, *32*(10), 1054–1069.

Indermu, A., Stocker, T. F., Joos, F., Fischer[2], H., Smith[2], H. J., Wahlen[2], M., Deck[2], B., Mastroianni[2], D., Tschumi, J., Blunier, T., Meyer, R., & Stauffer, B. (1999). *Holocene carbon-cycle dynamics based on CO 2 trapped in ice at Taylor Dome, Antarctica*. www.nature.com

Kida, S., & Wijffels, S. (2012). The impact of the Indonesian Throughflow and tidal mixing on the summertime sea surface temperature in the western Indonesian Seas. *Journal of Geophysical Research: Oceans*, *117*(C9).

Laskar, J., Robutel, P., Joutel, F., Gastineau, M., Correia, A. C. M., & Levrard, B. (2004). A long-term numerical solution for the insolation quantities of the Earth. *Astronomy and Astrophysics*, *428*(1), 261–285.

Lestari, R.K. and Iwasaki, T., (2006). A GCM study on the roles of the seasonal marches of the SST and land-sea thermal contrast in the onset of the Asian summer monsoon. Journal of the Meteorological Society of Japan. Ser. II, 84(1), pp.69-83

McSweeney, Carol F. & Richard G. Jones. (2016). How representative is the spread of climate projections from the 5 CMIP5 GCMs used in ISI-MIP., Climate Services, Volume 1, 2016, Pages 24-29, ISSN 2405-8807.

Rachmayani, R., Prange, M., & Schulz, M. (2016). Intra-interglacial climate variability: model simulations of Marine Isotope Stages 1, 5, 11, 13, and 15. *Climate of the Past*, *12*(3), 677–695.

Rachmayani, R., Prange, M., Schulz, M., & Ningsih, N. S. (2019). Climate variability in Indonesia from 615 ka to present: First insights from low-resolution coupled model simulations. *Erde*, *150*(4), 230–240.

Saji, N. H., Goswami, B. N., Vinayachandran, P. N., & Yamagata, T. (1999). A dipole mode in the tropical Indian Ocean. *Nature*, *401*(6751), 360–363.

Seo, H., Jochum, M., Murtugudde, R., Miller, A.J., (2006). Effect of ocean mesoscale variability on the mean state of tropical Atlantic climate. Geophys. Res. Lett. 33, L09606

Schmidt, G. A., Jungclaus, J. H., Ammann, C. M., Bard, E., Braconnot, P., Crowley, T. J., Delaygue, G., Joos, F., Krivova, N. A., Muscheler, R., Otto-Bliesner, B. L., Pongratz, J., Shindell, D. T., Solanki, S. K., Steinhilber, F., & Vieira, L. E. A. (2012). Climate forcing reconstructions for use in PMIP simulations of the Last Millennium (v1.1). *Geoscientific Model Development*, *5*(1), 185–191. h

Schröder, J. F., Kuhnt, W., Holbourn, A., Beil, S., Zhang, P., Hendrizan, M., & Xu, J. (2018). Deglacial Warming and Hydroclimate Variability in the Central Indonesian Archipelago. *Paleoceanography and Paleoclimatology*, *33*(9), 974–993.

Small, R. J., deSzoeke, S. P., Xie, S. P., O'Neill, L., Seo, H., Song, Q., Cornillon, P., Spall, M., & Minobe, S. (2008). Air-sea interaction over ocean fronts and eddies. *Dynamics of Atmospheres and Oceans*, *45*(3–4), 274–319.

Smith, R., Jones, P., Briegleb, B., Bryan, F., Danabasoglu, G., Dennis, J., Dukowicz, J., Eden, C., Fox-Kemper, B., Gent, P., Hecht, M., Jayne, S., Jochum, M., Large, W., Lindsay, K., Maltrud, M., Norton, N., Peacock, S., Vertenstein, M., & Yeager, S. (2010). *The Parallel Ocean Program (POP) Reference Manual Ocean Component of the Community Climate System Model (CCSM) and Community Earth System Model (CESM) 1*.

Smith, S. D. (1988). Coefficients for sea surface wind stress, heat flux, and wind profiles as a function of wind speed and temperature. *Journal of Geophysical Research: Oceans*, *93*(C12), 15467–15472.

Spooner, M. I., Barrows, T. T., de Deckker, P., & Paterne, M. (2005). Palaeoceanography of the Banda Sea, and Late Pleistocene initiation of the Northwest Monsoon. *Global and Planetary Change*, *49*(1–2), 28–46.

Strahler, A. H. (2001). *Introducing Physical Geography*. John Wiley & Sons Incorporated.

Timmermann, A., An, S. il, Kug, J. S., Jin, F. F., Cai, W., Capotondi, A., Cobb, K., Lengaigne, M., McPhaden, M. J., Stuecker, M. F., Stein, K., Wittenberg, A. T., Yun, K. S., Bayr, T., Chen, H. C., Chikamoto, Y., Dewitte, B., Dommenget, D., Grothe, P., … Zhang, X. (2018). El Niño–Southern Oscillation complexity. In *Nature* (Vol. 559, Issue 7715, pp. 535–545). Nature Publishing Group.

Vic, C., Naveira Garabato, A. C., Green, J. A. M., Waterhouse, A. F., Zhao, Z., Melet, A., de Lavergne, C., Buijsman, M. C., & Stephenson, G. R. (2019). Deep-ocean mixing driven by small-scale internal tides. *Nature Communications*, *10*(1). h

Yan, X.-H., Ho, C.-R., Zheng, Q., & Klemas, V. (1991). Temperature and Size Variabilities of the Western Pacific Warm Pool. In *Int. J. Quantum Chem* (Vol. 255).