Pliocene climate in Indonesia: a review

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Abstract. Pliocene climate is known as global cooling. However, some study was showing a warm condition during Pliocene. During Pliocene in the tropics, the warm condition mechanisms are still in debate, whether it occurs due to the permanent El Niño or not. Indonesia is the prominent site to study climate from past to present. Several Pliocene climate studies have resulted from records surrounding Indonesia, but not many were found from inside the Indonesian sea. Pliocene records based on Pollen analysis content in Sajau Formation, Northeast Kalimantan, shows that the presence convinces the warm wet climate condition during the late Pliocene of arboreal pollen domination. However, the causing mechanism of warm wet Pliocene climate has remained a question.

1. Introduction
Indonesia is a prominent site to study paleoclimate because of its location between two important basins, i.e., the Indian and Pacific oceans. Indonesia is also located in the active tectonic regime, namely the Pacific Ring of Fire. Climate studies from the past would consider the relation of tectonic in Indonesia. At present, the regional climate in Indonesia is influenced by monsoon [1, 2], Indonesian Throughflow (ITF) [3, 4], and global climate phenomena, e.g., Indian Ocean Dipole (IOD), El-Niño Southern Oscillation (ENSO) [5, 6, 1]. The Indonesian throughflow is an important element in circulating water mass, bringing water mass from the Pacific Ocean to the Indian Ocean, followed by distributing heat through the Indonesian archipelago [7,8]. The Indonesian seaway influences the ocean circulation will also influence the climate [9, 10]. Thus studying past climate should also pay attention to the Indonesian tectonic state. Due to the tectonically and climatically active conditions, Indonesia is an ideal location for paleoclimate study where tectonic plays a role in the ocean circulation-related to climate. Pliocene is an interesting period to study past climate variability, where Indonesia’s tectonic state is different from today [11].

Pliocene is the epoch in the geological time scale for the period between ca. 5.3 to 1.8 mya [12], known as the period for global cooling climate [13, 14]. Haywood et al. [15] divided Pliocene into three phases, i.e., the early Pliocene characterized by warm period, the short-lived warm of mid-Pliocene when the mean global temperature warmer ca. 2-3°C than preindustrial temperature [16], and the late Pliocene when the climate conditions were deteriorating. During Pliocene, the climate is generally warmer than the present [16]. Records of pollen, plant mega-fossil, and planktonic foraminifera from the western coast of America in the mid-latitude showed that the Pliocene climate
was more humid. The temperature is several degrees higher than today and less seasonality [17, 18, 19]. Stratigraphic sequence analysis from the high latitude shows that during Pliocene, significant warming in mid and high latitude for both southern or northern hemispheres has existed. However, in the low latitude, no significant changes from the current condition were observed [19]. This study presents the available Pliocene climate records from surrounding Indonesia.

Figure 1. (left) Stratigraphic column showing lithology and depositional facies of Sajau Formation [20]. (right) Stratigraphic column from the same formation, showing warm climates during Pliocene (Figure modified from [21])

2. Indonesia Pliocene climate records
There are not many Pliocene climate records from inside the Indonesian archipelago. Several studies have been done through Pliocene pollen climate interpretation. The pollen records from Mahakam delta, Kalimantan show uniformity assemblage during the Late Pliocene due to a very low
representation of the distinctive mountain vegetation in the delta sediments [22]. Thus, it is difficult for climate reconstruction. Domination of delta vegetation obscures the representation of mountainous vegetation located in the deep hinterland, which is subjected to climatic changes [22]. Another Pliocene pollen records from eastern Kalimantan show climate fluctuation in the Last Pliocene [20, 21]. Based on pollen analysis, coal seam from Sajau Formation is formed in the Late Pliocene because of the appearances of *Dacrycarpites australiensis* and *Stenochlaenidites papuanus* [20, 21], which are pollen marker for the Pliocene epoch [23, 24]. During the Late Pliocene, climate conditions alternately fluctuated from warm/wet season to cold/dry season [20, 21]. Warm/wet condition is identified based on the presence of domination of the arboreal pollen, and the non-arboreal pollen oppositely indicates for the dry season. During the Late Pliocene, this region was identified as a fluvial-delta system (Figure 1) with no influence from marine deposits, dominated by peat swamp/freshwater pollen and mangrove pollen (Figure 2), and less presence of dinoflagellates cysts [20, 21].

**Figure 2.** Pollen and spores found in coal layer of Sajau Formation (a) Bombacaceae (b) Sonneratia alba (c) Asteraceae (d) *Dacrycarpites australiensis* (e) Casuarinaceae (f) Blechnaceae (g) Polypodiaceae (h) *Stenochlaenidites papuanus* [21].

More recent work shows that the difference of temperature in the Pacific Ocean is about 1°C and is cooler than today [25], which signify that there is no permanent El Niño during Pliocene as what the previous study suggested [26]. In the late Pliocene, Alkenone proxy-based SST reconstruction indicates that the western Pacific warm pool was 1.3°C warmer than preindustrial and similar to the whole tropics [25]. Throughout ca 3 mya tectonic and oceanographic changes [22], the Pliocene records inside the Indonesian sea will contribute to the improving knowledge of oceanography mechanism related to the climate at that time. The recent published records from the southern part of the Indonesia archipelago [27] show that Indonesian throughflow contributed to the late Pliocene cooling in the Northern Hemisphere [27]. The Pliocene is characterized as gradual cooling and dry condition based on records from western Australia [27]. However, the mechanism of the global warming-related to El Niño during the Pliocene is remains questioned. The impact of seasonal fluctuation and interannual climate phenomena on Indonesian climate variability during the Pliocene is also unclear since there are lack of records from inside the Indonesian sea.

Therefore, Pliocene records from inside the Indonesian maritime region is required to understand more of the past climate phenomena.
3. Conclusions
Pliocene climate fluctuation in Indonesia and its mechanism related to climate phenomena such as past El Niño remains questioned due to the lack of climate data records during Pliocene from the inside Indonesian archipelago. The warm-related to El Niño phenomena during Pliocene is also questioned whether it occurs due to a permanent El Niño. Understanding more of the global warming-related to El Niño and its impact on the Indonesian climate, it is then required to generate more Pliocene records from the Indonesian maritime country.

Author Contributions
All the authors are the main contributors to this manuscript. VCA wrote the manuscript; MH supervised and reviewed the manuscript; SYC, DAU and AUN reviewed the manuscript.

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References
[1] Aldrian E and Susanto R 2003 Identification of three dominant rainfall regions within Indonesia and their relationship to sea surface temperature Int. J. Climatol. 23 1435–52
[2] Qian J, Robertson A W and Moron V 2010 Interactions among ENSO, the Monsoon, and Diurnal Cycle in Rainfall Variability over Java, Indonesia. J. Atmos. Sci. 67 3509–24
[3] Susanto R D, Wei Z, Adi T R, Zheng Q, Fang G, Fan B, Supangat A, Agustiadi T, Li S, Trenggono M and Setiawan A 2016 Oceanography surrounding Krakatau Volcano in the Sunda Strait, Indonesia. Oceanography 29 264–72
[4] Sprintall J, Gordon A L, Wijffels S E, Feng M, Hu S, Koch-Larrouy A, Phillips H, Nugroho D, Napitu A, Pujiana K, Susanto R D, Sloyan B, Peña-Molino B, Yuan D, Riama N F, Siswanto S, Kuswardani A, Arifin Z, Wahyudi A J, Zhou H, Nagai T, Ansong J K, Bourdalle-Badié R, Chanut J, Lyard F, Arbic B K, Ramdhani A and Setiawan A 2019 Detecting Change in the Indonesian Seas Mar. Sci. 6:257
[5] Cahyarini S Y, Zinke J, Troelstra S, Suharsono, Aldrian E and Hoeksema B W 2016 Coral Sr/Ca-based sea surface temperature and air temperature variability from the inshore and offshore corals in the Seribu Islands, Indonesia Marine Pollution Bulletin 110 694-700
[6] Cahyarini S Y, Pfeiffer M, Nurhati I S, Aldrian E, Dullo W-C and Hetzinger S 2014 Twentieth century sea surface temperature and salinity variation at Timor inferred from paired coral d18O and Sr/Ca measurements J. Geophys. Res. Oceans 119 4593-04
[7] Brierley C M and Fedorov A V 2011 Tidal mixing around Indonesia and the Maritime continent: Implications for paleoclimate simulations Geophysical Research Letters 38 L24703
[8] Di Nezio P N, Timmermann A, Tierney J E, Jin F- F, Otto- Bliesner B, Rosenbloom N, Mapes B, Neale R, Ivanovic R F and Montenegro A 2016 The climate response of the Indo-Pacific warm pool to glacial sea level Paleoceanography 31 866–94
[9] Cane M A and P Molnar 2001 Closing of the Indonesian seaway as a precursor to east African aridification around 3–4 million years ago Nature 411 157-62
[10] Jochem M, Fox- Kemper B, Molnar P H and Shields C 2009 Differences in the Indonesian seaway in a coupled climate model and their relevance to Pliocene climate and El Niño Paleoceanography and Paleoeclimatology 24 PA1212
[11] Hall R 2002 Cenozoic geological and plate tectonic evolution of SE Asia and the SW Pacific: Computer-based reconstructions, model and animations Journal of Asian Earth Sciences 20 353–431
[12] Gradstein F M, Ogg J G, Smith A G, Bleeker W and Lourens L J 2004 A new geologic time scale, with special reference to Precambrian and Neogene Episodes 27 83–100
[13] Raymo M E, Lisiecki L E and Nisancioglu K H 2006 Plio-Pleistocene ice volume, Antarctic climate, and the global d18O record Science 313 492–95
[14] Lisiecki L E and Raymo M E 2007 Plio-Pleistocene climate evolution: trends and transitions in glacial cycle dynamics Quat. Sci. Rev. 26 56–69
[15] Haywood A M, Dowsett H J, Valdes P J, Lunt D J, Francis J E, and Sellwood B W 2008 Introduction. Pliocene climate, processes and problems Phil. Trans. R. Soc. A 367 3–17
[16] Jansen E. et al. 2007 Palaeoclimate. In Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change (eds S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor & H. L. Miller). Cambridge, UK: Cambridge University Press.
[17] Thompson R S 1991 Pliocene environments and climates in the western United States. Quat. Sci. Rev. 10 115–32
[18] Thompson R S and Fleming R F 1996 Middle Pliocene vegetation: reconstructions, paleoclimatic inferences, and boundary conditions for climatic modeling Mar. Micropaleontology 27 13–26
[19] Dowsett H, Barron J and Poore R 1996 Middle Pliocene sea surface temperatures: a global reconstruction Marine Micropaleontology 27 13-25
[20] Agusta V C, Hamdani A H and Winantris 2015 Pliocene pollen and spores from Sajau Coal, Berau Basin, Northeast Kalimantan, Indonesia: Environmental and Climatic Implications, International Journal of Science and Research (IJSR) ISSN (Online): 2319-7064
[21] Agusta V C 2015 Studi Lingkungan Pengendapan Batubara berdasarkan analisis Polen dan Spora Formasi Latih dan Formasi Sajau, Cekungan Berau, Kalimantan Timur. Skripsi, Universitas Padjajaran Fakultas Teknik Geologi Jurusan Teknik Geologi, Jatinangor
[22] Caratini C and Tissot C 1988 Paleogeographical evolution of the Mahakam Delta in Kalimantan, Indonesia during the Quarternary and late Pliocene Review of Palaeobotany and Palynology 55 217-28
[23] Morley R J 1978 Palynology of Tertiary and Quaternary Sediments in Southeast Asia Proceedings Indonesian Petroleum Association Sixth Annual Convention, May 1977 255-75
[24] Rahardjo A T, Polhuapessy T T, Wiyono S, Nugrahantingsih H, Lelono E B 1994 Zonasi Polen Tersier Pulau Jawa. Makalah Ikatan Ahli Geologi Indonesia, Pertemuan Ilmiah Tahunan Ke-23; Des 1994. Bandung: IAGI 77-87.
[25] Tierney J E, Haywood A M, Feng R, Bhattacharya T and Otto-Bliesner B L 2019 Pliocene warmth consistent with greenhouse gas forcing Geophysical Research Letters 46 9136–44
[26] Fedorov A, Dekens P, McCarthy M, Ravelo A, Barreiro M, Pacanowski R and Philander S 2006 The Pliocene paradox (mechanisms for a permanent El Niño) Science 312 1485–89
[27] Auer G, De Vleeschouwer D, Smith R A, Bogus K, Groeneveld J, Grunert P, et al. 2019 Timing and pacing of Indonesian Throughflow restriction and its connection to Late Pliocene climate shifts Paleoceanography and Paleoclimatology 34 635–57