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Did droughts contribute to the political dynamics of Majapahit? A preliminary hydroclimatological analysis

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ABSTRACT

Majapahit was the largest Hindu-Buddhist empire that ruled the Indonesian archipelago from the late 13th to mid-16th centuries CE. Only now there is still a lot of history surrounding the Majapahit era that has yet to be revealed. One is about how environmental factors influenced the political dynamics at that time. This study tries to discuss the influence of hydroclimate regimes using the Paleo Hydrodynamics Data Assimilation (PHYDA) product on the political history of Majapahit during the dry season, which occurs during the boreal summer. We conducted a spatial analysis of the area of drought by taking data from the Palmer Drought Severity Index (PDSI) in the Maritime Continent (MC) for six crucial episodes in the history of Majapahit, namely during the reign of Jayanegara (1309 - 1328 CE), which was marked by various political instability, the golden age of Majapahit (1309 - 1328 CE). 1350 - 1389 CE), the time of the Paregreg civil war (1405 - 1406 CE), the great famine event (ca. 1426 CE), the *candrasengkala* event (1478 CE), and in 1527 CE, which was marked by the complete conquest of Majapahit by the sultanate Demak. The results show statistically significant differences in most of these six episodes (except during the heyday of Majapahit) against the reference period, which is the average PDSI over the entire Majapahit era (1293 - 1527 CE). In addition, we also conducted a temporal analysis linking PDSI with shifts in the West Pacific Inter Tropical Convergence Zone (WP ITCZ) and El Niño Southern Oscillation (ENSO) represented by Niño 3.4 Sea Surface Temperature (SST). This temporal analysis results show a positive correlation between WP ITCZ - PDSI, a negative correlation between Niño 3.4 SST - PDSI and a negative correlation between ITCZ - Niño 3.4 SST. All of these correlations are statistically significant. So the probable cause of dry/wet conditions in MC during the Majapahit era was triggered by a meridional ITCZ shift which triggered different ENSO phases through Bjerknes feedback. This preliminary study has implications as opening the way to understand the influence of environmental factors on political conditions in the Majapahit era in more detail.

INTRODUCTION

Majapahit (1293 - 1597 Common Era (CE)) was the largest thalassocracy empire in the history of the Indonesian archipelago (Noorduyn, 1978; Muljana, 2005; Djafar, 2009; Rahardjo et al., 2011) (Figure 1). In addition, Majapahit can also be said to be one of the kingdoms that held power for the longest time throughout the classical Hindu-Buddhist period in the Indonesian archipelago (Djafar, 2009; Rahardjo et al., 2011). Although Majapahit was a monarchical kingdom with a centralized government, the pattern of its government was not far from the patronage of its vassal states, commonly known as the mandala concept (Wolters, 1999), which was often applied to kingdoms in the classical Hindu-Buddhist period in

Southeast Asia. This pattern of power often causes political instability. According to the old Javanese eulogy *Nagarakretagama* (Coedes, 1975), its power spanned Java, Sumatra, the Malay Peninsula, and Kalimantan to eastern Indonesia, although historians still debate its territory (Lombard, 1969; Ricklefs, 2008; Ricklefs et al., 2010).

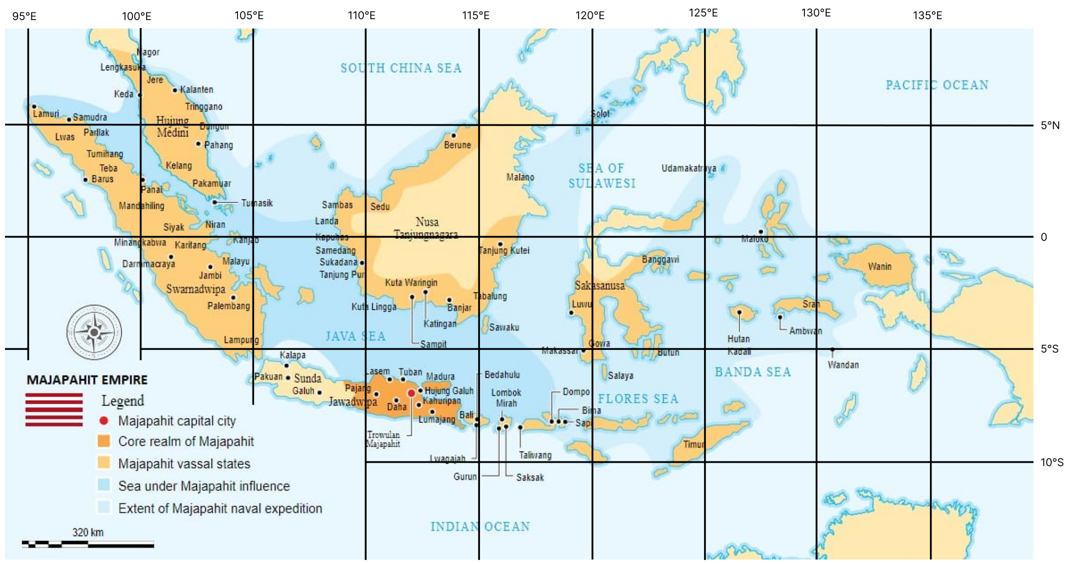

Figure 1. Mandala's influence of Majapahit power in the Indonesian archipelago at its heyday in Hayam Wuruk (1350 - 1389 CE) reign (modification from Cribb (2013)).

Unraveling the history of Majapahit, from its collapse to the emergence of Islamic sultanates in Java, makes us discover various important astonishing events. Political intrigue, war strategies, territorial expansion, and cultural battles are important events that have indirectly formed a new civilization in the Indonesian archipelago. Majapahit's cultural heritage can be seen in architecture and the political, social, cultural, and economic realms (Noorduyn, 1978; Lombard, 1969). Majapahit's power, which extended to the entire Indonesian archipelago, shaped Indonesian culture. In the political realm, when the Indonesian archipelago was reunited with the Republic of Indonesia, the idea of the legacy of Majapahit emerged in the concept of national leadership. Like the Indonesia motto, *Bhineka Tunggal Ika* (unity in diversity), it is none other than a pearl of wisdom composed by Mpu Tantular, a Majapahit poet in the 14th century CE (Djoened and Poesponegoro, 2008). Since Islam occupied the archipelago, the Hindu-Buddhist kingdoms seemed to have lost their political power. Islam sultanates then succeeded in becoming important political players. According to Ricklefs et al. (2010), Majapahit occupies a very important position in the archipelago's historical dynamics. Majapahit has brought the fragrance of the archipelago's earth to various parts of the world, especially the Southeast Asian region. Majapahit splendor and military strength under the leadership of Hayam Wuruk, as a king, and Gajah Mada, as a prime minister, made Majapahit respected by foreign nations.

Although, since its founding, Majapahit had experienced many ups and downs like other kingdoms or dynasties, the historical dynamics of Majapahit cannot be separated from the various political upheavals at that time. Since Raden Wijaya founded the Majapahit, there had been various rebellions, Especially during the reign of Jayanegara (1309 - 1328 CE) (Djoened and Poesponegoro, 2008; Muljana, 2005, 1976). Regardless of the various rebellions and wars that occurred from its beginning until its collapse, Majapahit is still rembered as an empire with great influence in the archipelago. Its power which was so broad and divided into 14 subordinate regions, indirectly contributes to the formation of Indonesian culture. This can be seen based on the pattern of social, political, and cultural conditions at that time.

However, at the end of Majapahit's heyday, especially after Wikramawardhana's rule (1389–1429 CE), Majapahit was overwhelmed by Paregreg civil war between the royal families (1405 - 1406 CE). This war made Majapahit lose some of its subordinate areas. In addition, the rapid spread of Islam, accompanied by the emergence of Islamic kingdoms, made Majapahit increasingly lose prestige. As a result of prolonged internal royal conflicts and the Islamization process experienced massive and systematic developments, over time, Majapahit completely collapsed. Many historians have studied and put it forward regarding the collapse of Majapahit (Noorduyn, 1978; Muljana, 2005; Djafar, 2009; Rahardjo et al., 2011). Some of them argued that the beginning of the collapse of Majapahit occurred in 1478 CE. This is based on a chronogram or *candrasengkala*, or in other words: *sirna ilang kretaning bhumi*, which means the prosperity of the earth will disappear. According to many historians, this *candrasengkala* is a depiction of the beginning of the collapse of Majapahit (Muljana, 1976; Djoened and Poesponegoro, 2008; Muljana, 2005).

Apart from differences of opinion regarding exactly when the Majapahit collapsed, the events of collapse of Majapahit were at least preceded by several important events. These events included civil wars between royal families, the loss of central power outside the area around the capital city of Majapahit, and the spread of Islam, which had grown rapidly in Malacca since the 1400s and was followed by the emergence of Islamic sultanates, which then challenged Majapahit sovereignty. When Islam entered and developed rapidly in Samudra Pasai and Malacca, many Majapahit residents who lived on the coast converted to Islam. This is because north coast of Java (*Pantura Jawa*), apart from being a meeting place for various cultures, also received less monitoring from the kingdom's center (Ricklefs, 2008). Muljana (2005) argues that many of the coastal residents who embraced Islam resulted in the growth of immigrant and Islamic villages. The existence of the new village displaced the economic lifeblood in Majapahit. The economy in coastal areas slowly shifted into the hands of immigrants. This influenced the process of the destruction of Majapahit. Along with the disappearance of Majapahit's prestige, the big cities in the coastal areas were controlled by Muslim traders. The merchants then brought new trading ports that could compete with trading ports from Majapahit.

For example, an area called Bintara, or Demak, was one of the coastal areas which was a tough competitor for the Majapahit trade port (Muljana, 1976). Many traders from various countries gathered in Demak to trade, then settled there and spread Islam in the area. During the reign of Kertabhumi (1468 - 1474 CE), Demak was led by a duke who was a Muslim, namely Raden Patah. Raden Patah was the son of Kertabhumi from a Chinese wife whom Arya Damar raised. In the future, Demak, under Raden Patah, became a fairly advanced area and was known by traders from within and outside the archipelago. In its development, the Muslims living in Demak were united by Raden Patah and succeeded in becoming a major force for the Duchy of Demak. These powers include the military, bureaucratic government, and the economy. This great power then became the capital for Demak to escape from the clutches of Majapahit. In subsequent developments, Demak, which received assistance from coastal areas such as Jepara, Surabaya, Kudus, and Banten, openly separated itself from Majapahit. In 1478 CE, Demak became an independent Islamic sultanate . Its first sultan was Raden Patah, who had the title *Sultan Akbar Al-Fattah*. For about three years, Raden Patah had made extraordinary achievements. The sultan and his followers managed to control Semarang. In 1517 CE, Demak invaded Majapahit and succeeded in severing the relationship between Majapahit and the Portuguese. In the next attack in 1527 CE, Demak succeeded in eliminating Majapahit from the Indonesian archipelago (Muljana, 2005; Ricklefs, 2008).

Apart from the effects of political turmoil and the arrival of Islam which caused the direct cause of the destruction of Majapahit, it is interesting to examine environmental causes, which may also have contributed indirectly to this event Satyana (2007). This is interesting because the territory controlled by Majapahit, namely the Indonesian archipelago, is an area that is prone to natural disasters, such as floods, landslides, volcanoes, earthquakes, and droughts regularly (Wardani and Kodoatie, 2008). Unfortunately, only a few studies have examined this topic. The only study that takes this issue seriously is a regional geological study conducted by Satyana (2007) which discusses the possible contribution of mud volcano eruptions near the capital city of Majapahit, which may have contributed to the period of the fall of this empire. Though this is necessary to reconstruct the environmental history of Majapahit from a holistic point of view.

This study attempts to answer this challenge by taking a statistical approach to drought conditions in Indonesian archipelago during the Majapahit era. These hydroclimatological parameters were chosen because it influenced the collapse and birth of various classical world civilizations (e.g. DeMenocal, 2001; Shen et al., 2007; Zhang et al., 2008; Buckley et al., 2010; Fleitmann et al., 2022). This study presents the statistical analysis of hydroclimate estimations from Paleo Hydrodynamics Data Assimilation product (PHYDA) (Steiger et al., 2018) over the Indonesian archipelago during the Majapahit reign. Considering that the Mandala of Majapahit covers almost the entire Indonesian archipelago, for this study, we took the scope of hydroclimatology area in the Southeast Asian archipelago. The Southeast Asian archipelago is better known hydroclimatologically as the Maritime Continent (MC) (Ramage, 1968). The hydroclimatological cycle in the MC, located between the tropical Indian and Pacific oceans, is regulated by the annual Asia-Australia monsoon (AAM) cycle (Aldrian and Susanto, 2003; Neale and Slingo, 2003; Chang et al., 2005; Robertson et al., 2011; Yamanaka, 2016; Yang et al., 2019). This latitudinal cycle of annual displacement of the Intertropical Convergence Zone (ITCZ) is characterized by a northwesterly movement that brings moist air from Asia to Australia during boreal winter and a southeasterly movement that brings dry air from Australia to Asia during the boreal summer. This annual cycle causes the wet season in December - January - February (DJF) and the dry season in June - July - August (JJA) over the MC (Chang et al., 2005). In addition to the annual cycle, the MC is also affected by the interannual quasi-periodic oscillation in the tropical Pacific known as the El Niño Southern Oscillation (ENSO) (Aldrian and Susanto, 2003; Robertson et al., 2011; Yoden et al., 2017). During the El Niño phase, Sea Surface Temperatures (SST) cooling anomalies occur, and the Walker circulation weakens, which results in a decrease in the convection process that occurs in the MC. Conversely, during the La Niña phase, there is an anomaly of an increase in SST and a strengthening of the Walker circulation, which increases the convection process in this region. This El Niño phase can also extend the dry season and cause drought over the MC (Hendon, 2003). Because this study only discusses the effect of droughts on the political dynamics, we limit our study to the dry season (JJA). This boreal summer periods was chosen because of the strong ENSO influence in that season (Robertson et al., 2011).

DATA AND METHODS

Data

We used three hydroclimatological reconstructions mean parameters from PHYDA, as follows, annual West Pacific ITCZ index (WP ITCZ), monthly Niño 3.4 SST, and annual Palmer Drought Severity Index (PDSI) to determine drought and hydroclimatological conditions in the Majapahit region. We used PHYDA datasets because they are the best estimate of the fusion between the Community Earth System Model Last Millennium Ensemble (CESM LME) of climate model simulations (Otto-Bliesner et al., 2016) and 2,978 annually-resolved proxy series using data assimilation techniques (Bhend et al., 2012; Goosse et al., 2012; Steiger et al., 2014; Hakim et al., 2016; Franke et al., 2017; Steiger et al., 2018), which are expected to be able to describe hydroclimate conditions over the MC during the Majapahit era. Furthermore, the methodology employed in PHYDA encapsulates advancements and refinements drawn from its predecessor reanalysis product, specifically referred to as the Last Millennium Reconstruction (LMR) Steiger et al. (2018). Notably, the reconstructed PDSI outcomes within the PHYDA framework exhibit noteworthy correlations of significance not only with the LMR product but also with the Monsoon Asia Drought Atlas (MADA) over the MC Steiger et al. (2018); Roldán-Gómez et al. (2023).

We truncated the spatial data. This $2^{\circ} \times 2^{\circ}$ horizontal resolution on the Maritim Continent grids (20°S $-$ 20°N, 90° $-$ 160°E) and during the Majapahit era (1293 - 1527 CE). We divided the data analysis into two sections: spatial analysis and temporal analysis.

Spatial analysis

We conducted the spatial analysis by calculating the PDSI anomaly analysis at each stage of the political conditions in Majapahit. We calculated the drought anomalies according to six significant events in the political history of Majapahit: during the reign of Jayanegara, which was marked by many rebellions (1309 - 1328 CE), during the heyday of the Majapahit under the leadership of Hayam Wuruk (1350 - 1389 CE), during the Paregreg war (1405 - 1406 CE), in 1426 CE, which was marked by the great famine (Krom, 1926; Noorduyn, 1978), in 1478 CE, which is believed to be a significant year at the beginning of the fall of the Majapahit (*candrasengkala*) (Djoened and Poesponegoro, 2008; Djafar, 2009; Ricklefs, 2008; Ricklefs et al., 2010), and in 1527 CE which is believed to be the last year of Majapahit before being completely conquered by Demak. These anomalies were calculated by subtracting the temporal average of PDSI at each stage against the entire Majapahit era as a reference period (1293 - 1527 CE). We calculated the average from the previous year and the following year, especially concerning the events of the great famine, *candrasengkala*, and the final year of Majapahit. This was done because each of these events lasted only one year. We used the average values to mitigate the drought lag caused by the PDSI calculation, which took several months. There was concern that if we had only taken the PDSI value for each year of occurrence, we would not have been able to capture rapidly changing drought situations

(Alley, 1984). The spatial anomalies were displayed visually and compared with the existing historical literature. Calculation and visualization of these anomalies were done using the `xarray` (Hoyer and Hamman, 2017) and `Cartopy` (Met Office, 2015) libraries in the Python computing environment.

In addition to visually inspecting spatial PDSI anomalies, we also conducted the Mann-Whitney U test (Mann and Whitney, 1947) to test whether the PDSI in each grid in each of the six crucial episodes in the history of Majapahit have statistically significant differences from the PDSI in each grid throughout the reference period (1293 - 1527 CE). We employed the Mann-Whitney U test because it is a non-parametric test that does not assume that the samples in the two groups are drawn from a normal distribution (Wilks, 2011). The null hypothesis is that the sum of the rankings in the two groups does not differ. Meanwhile, for the alternative hypothesis, in the population, the sum of the rankings differs in the two groups. This test was performed by calculating the U statistics for each group (in the context of this study, the U statistics of the six critical episodes in the history of Majapahit, U_x and the reference period, U_y),

$$U_X = mn + \frac{m(m+1)}{2} - R_X \tag{1}$$

$$U_Y = mn + \frac{n(n+1)}{2} - R_Y. \tag{2}$$

Then we calculated U statistics for both of these groups,

$$U = \min(U_X, U_Y) \tag{3}$$

, where m is the number of samples drawn from population X, n is the number of samples drawn from population Y, R_X is the sum of ranks of population X, and R_Y is the sum of ranks of population Y. The p-value was calculated based on comparing the critical and U values. If the U value is less than or equal to the critical value, we reject the null hypothesis and vice versa. Because the number of PHYDA grids in the MC are large enough $(n > 20)$, the p-value was calculated based on the normal approximation using standardized test statistics (Wilks, 2011). We used the statistics module in the `SciPy` library in the Python computing environment to perform the Mann-Whitney U test (Virtanen et al., 2020).

Temporal analysis

Niño 3.4 differs from the other two, we took the annual average on this time series. Then we spatially averaged the PDSI data over the MC, so we got a single time series. We use the `xarray` library (Hoyer and Hamman, 2017) in the Python computing environment to retrieve this spatially averaged PDSI. We did not preprocess the ITCZ data because it represents the convective regime in the Indo-Pacific Warm Pool (IPWP). Finally, we made a graphical alignment (Prell et al., 1986; Lisiecki and Raymo, 2005) of these three hydroclimatic parameters using the `Pyleoclim` library (Khider et al., 2022) in the Python computing environment.

We used Pearson's correlation (Pearson and Galton, 1895) to calculate the relationship between time series: WP ITCZ - PDSI, Niño 3.4 SST - PDSI, and WP ITCZ - Niño 3.4 SST. The correlation value is determined through the following equation,

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 (y_i - \bar{y})^2}} \tag{4}$$

, where n is the length of time that Majapahit was in power (234 years), x_i and y_i are respectively the first and second time series values at time i, and $\bar{x}$ and $\bar{y}$ are the average values of the first and second time series, respectively. We used Student's t-test to determine the confidence interval. This calculation was done automatically using the `Pyleoclim` library in the Python computing environment (Khider et al., 2022).

RESULTS AND DISCUSSION

PDSI and PDSI spatial anomalies of each PHYDA grid during the reign of Jayanegara (1308 - 1328 CE) are shown in the Figure 2 and Figure 3c, respectively. It appears during this period were negative anomalies in almost the entire PHYDA grid over the MC. This difference was further confirmed by U statistics of the two-sided Mann-Whitney test of 8235 with a p-value < 0.01. This pattern is also seen in the negative values of the spatially averaged time series of PDSI over the MC in this period (Figure 4, bottom panel). It could be stated that there was a widespread and prolonged drought over the MC region during the his reign.

After ascending the throne, Jayanegara was titled *Sri Sundarapandya Dewa Adhiswara Wikramatunggadewa*. His life story was written in several records, such as *Pararaton* and *Nagarakretagama* (Djoened and Poesponegoro, 2008). From *Pararaton*, it was known that Jayanegara had the nickname *Kala Gemet*. This nickname was pinned because the king had a personality that was not good and was considered weak as a ruler (Djoened and Poesponegoro, 2008). The reason is, during the time of Jayanegara, the Majapahit often experienced rebellions. For example, the Gajah Biru Rebellion (1314 CE), the Nambi Rebellion (1316 CE), the Semi Rebellion (1318 CE), and the Kuti Rebellion (1319 CE) (Ricklefs, 2008; Ricklefs et al., 2010). The series of rebellions occurred due to slander by Mahapati, a cunning palace official. Jayanegara's life barely survived when the Kuti Rebellion broke out because the royal capital was captured (Djoened and Poesponegoro, 2008; Muljana, 1976, 2005). Jayanegara managed to survive the series of rebellions that hit the kingdom during his reign due to Gajah Mada's role as commander of *Bhayangkara* (an elite secret service unit of Majapahit). Although after the Kuti Rebellion his government gradually improved, the disappointment of the palace officials with his attitude could not be eliminated. In 1328 CE, Jayanegara died after being stabbed by Ra Tanca, a member of *Dharmaputra* (a special group of employee loved by the king) who also acted as a royal physician (Djoened and Poesponegoro, 2008; Muljana, 1976, 2005). However, no records and historical studies that discuss drought in that period. We can only speculate if the drought may have been one of many factors in this political instability.

PDSI and PDSI spatial anomalies of each PHYDA grid during the heyday of Majapahit under Hayam Wuruk as a king and Gajah Mada as a prime minister (1350 - 1389 CE), are shown in the Figure 2 and Figure 3b, respectively. On average, during this period, there was no widespread distribution of extreme PDSI anomalies over the MC (Figure 3b). This is also evident from a relatively periodic oscillation of the spatially averaged time series of PDSI over the MC in this period (Figure 4, bottom panel). This hydroclimatological stability was also confirmed by the value of the two-sided Mann-Whitney U test on the spatial PDSI distribution (Figure 2) of 24346. Still, with a p-value > 0.01, it can be concluded that in this period, there was no statistically significant difference in PDSI compared to the reference period.

Hayam Wuruk ruled Majapahit for 39 years. He ascended the throne at a young age, when he was 16 years old, and became the fourth king to replace Tribhuwana Tunggadewi. During his leadership, Hayam Wuruk was accompanied by a prime minister named Gadjah Mada. Hayam Wuruk then married the daughter of Wijayarajasa (*Bhre Wengker*), named Sri Sudewi, with the title *Paduka Sori*. Hayam Wuruk had a daughter named Kusumawardhani, who married Wikramawardhana (the fifth king of Majapahit) (Djoened and Poesponegoro, 2008; Muljana, 1976; Ricklefs, 2008; Ricklefs et al., 2010).

During his reign, Hayam Wuruk was touted as the greatest Majapahit king. His success in bringing Majapahit to the pinnacle of glory could not have been separated from the help of Gajah Mada. When Hayam Wuruk and Gajah Mada were running the government, the entire Indonesian archipelago and even the Malacca Peninsula were flying the Majapahit banner. The *Palapa* Oath declared by Gajah Mada was carried out, with Majapahit's territory covering Sumatra, the Malay Peninsula, Kalimantan, Sulawesi, the Nusa Tenggara Islands, Maluku, Papua, Tumasik (Singapore), and parts of the Philippine Islands (Djoened and Poesponegoro, 2008; Rahardjo et al., 2011; Ricklefs, 2008; Ricklefs et al., 2010). In addition, this kingdom has relations with Campa (southern Vietnam), Cambodia, Siam (Thailand), southern Burma, Vietnam and China. Majapahit also has a formidable navy fleet under the leadership of Mpu Nala. With its military strength and strategy, Majapahit was able to create stability in its territory. Meanwhile, in the economy, Majapahit became a trade center in Southeast Asia with export commodities consisting of pepper, salt and cloth (Djoened and Poesponegoro, 2008; Rahardjo et al., 2011; Ricklefs, 2008; Ricklefs et al., 2010). Since there are no conclusive historical studies about the effect of drought on Majapahit's heyday, we can only speculate that the relatively stable hydroclimatic regime at that time may have contributed to the political and economic stability that allowed Majapahit to expand its influence.

After reaching its peak in the 14th century, Majapahit's power gradually weakened. After the death of Hayam Wuruk in 1389 CE, Majapahit entered a period of decline, one of which was the result of a conflict over the throne. Hayam Wuruk had been succeeded by the crown Princess Kusumawardhani, who had married a relative, Prince Wikramawardhana. Hayam Wuruk also had a son by his mistress, Wirabhumi, who claimed his right to the throne. Finally, the first civil war emerged, often called the Paregreg war, estimated to have occurred in 1405 - 1406 CE between Wirabhumi and Wikramawardhana (Muljana,

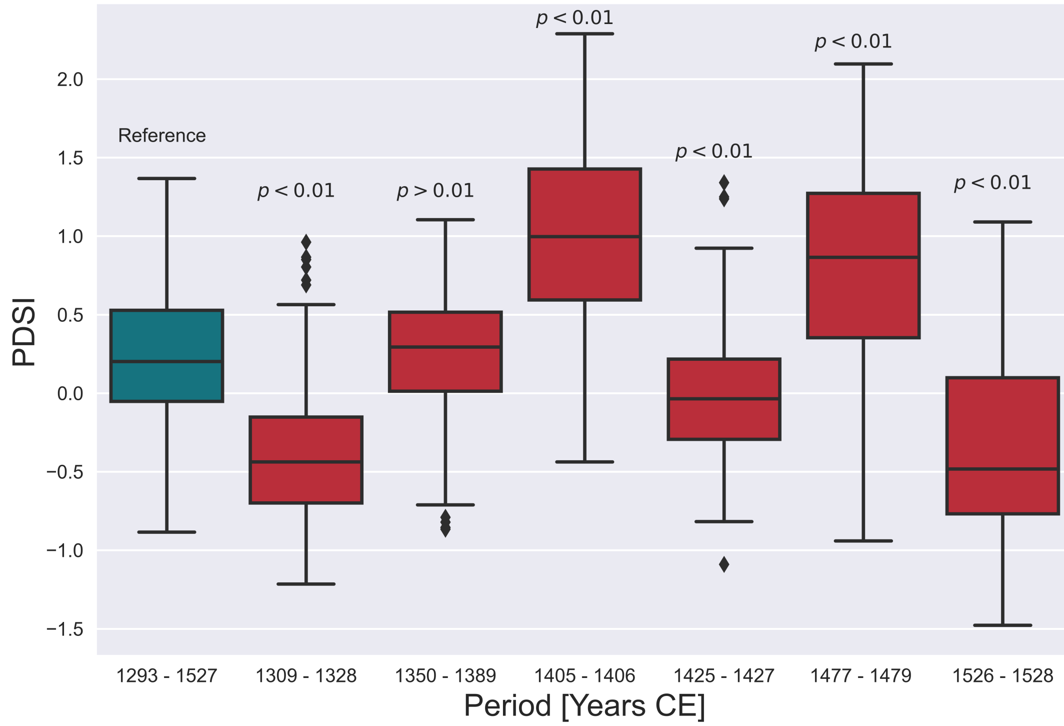

Figure 2. Boxplots depict the distribution of average PDSI values in each grid during crucial periods in Majapahit history (red) and reference periods throughout Majapahit history (blue). The center line within each box indicates the median value, while the lines at the top and bottom represent the upper and lower quartiles. Points beyond the minimum and maximum lines on the whiskers indicate extreme values.

1976, 2005; Djafar, 2009). Wikramawardhana finally won this war. This civil war weakened Majapahit's control over its conquered areas on the other side. Twenty years after this war, there was a great famine event (1426 CE) that was considered to weakened the Majapahit government's authority (Krom, 1926; Noorduyn, 1978).

During the reign of Wikramawardhana, a series of Ming Dynasty maritime expeditions led by Admiral Zheng He, a Chinese Muslim admiral, arrived in Java several times between 1405 CE to 1433 CE (Ricklefs, 2008; Ricklefs et al., 2010). Since 1430 CE, Zheng He's expedition created Chinese and Arab Muslim communities in several port cities on the north coast of Java, such as Semarang, Demak, Tuban, and Ampel (Muljana, 1976, 2005; Djoened and Poesponegoro, 2008). Islam began to have a foothold on the north coast of Java. During the middle of Majapahit's reign, Muslim traders and religious preachers started to enter the Indonesian archipelago.

PDSI and PDSI spatial anomalies of each PHYDA grid during the crucial episodes during the reign of Wikramawardhana, are shown in the Figure 2 and Figure 3, respectively. During the Paregreg War, there were relatively wet events in JJA, which can be seen in its spatial (Figure 3c) and temporal observations (Figure 4, bottom panel). The statistical significance was also confirmed by the value of the two-sided Mann-Whitney U test on the spatial PDSI distribution (Figure 2) of 39713 with a $p-$value < 0.01. Meanwhile, during the great famine event in 1426 CE, there was a drought event over the MC (Figure 3d). It was also confirmed by the Mann-Whitney U test value of 11600 for the reference period in the spatial PDSI distribution with a $p-$value < 0.01. As with other significant events in the Majapahit era, until now, research has yet to be conducted that specifically discusses droughts or floods during this period. We can only speculate that the hydroclimatic regime influenced two important events in this period.

In the late 14th and early 15th centuries, Majapahit influence throughout the archipelago began to wane. At the same time, a new trading empire based on Islam, namely the Malacca sultanate, started to emerge in the western part of the archipelago. In the western part of this empire that was beginning to collapse, Majapahit was powerless again, stemming the rise of the Malacca Sultanate, which in the mid-15th century

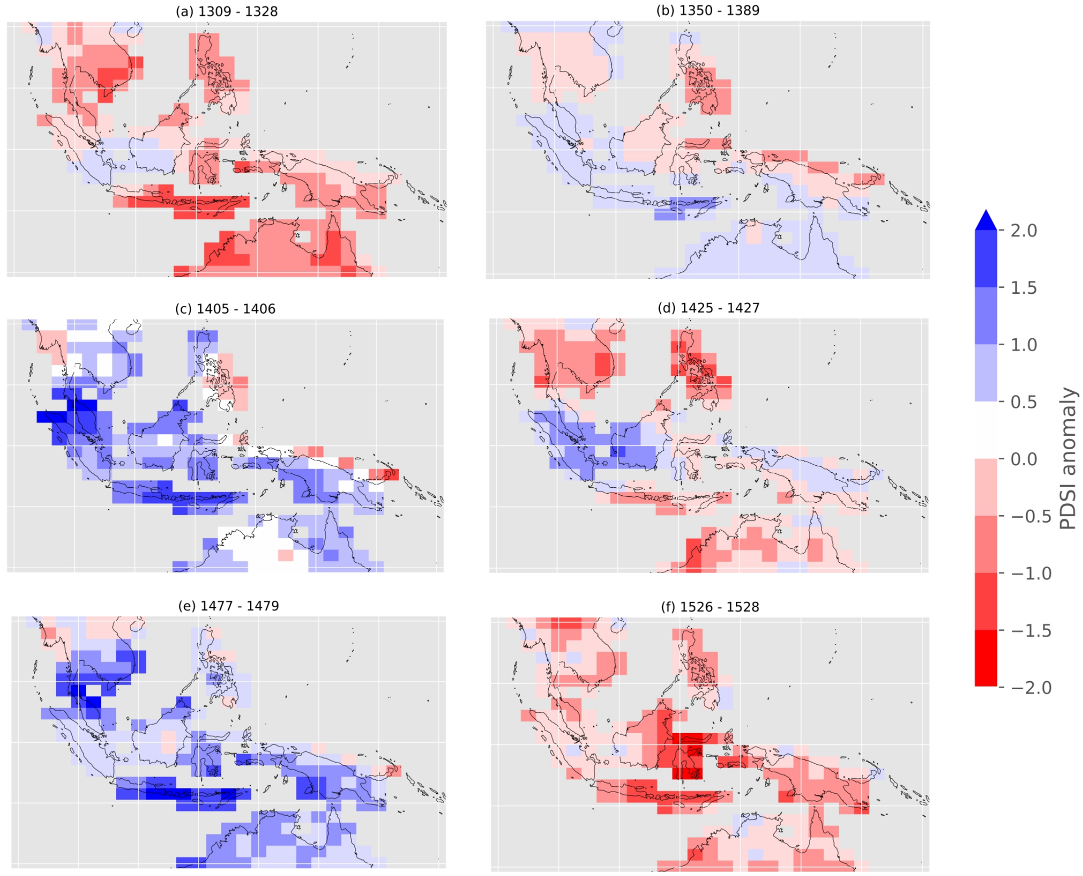

Figure 3. Spatial representation of PDSI anomalies over the MC during the six critical episodes in the history of Majapahit: (a) the reign of Jayanegara (1309 - 1328 CE), (b) the reign of Hayam Wuruk (1350 - 1389 CE), (c) Paregreg War (1405 - 1406 CE), (d) the great famine event (1427 - 1428 CE), (e) the *candrasengkala* event; which marked the beginning of the collapse of the Majapahit (1477 - 1479 CE), and (f) the final year of Majapahit (1526 - 1528 CE). All values shown refer to anomalies from the Majapahit era (1293 - 1527 CE).

began to control the strait of Malacca and spread its power to the island of Java and many preachers were sent or came voluntarily to this area for Islamization, both internal and external Islamization, one of which was Sheikh Maulana Ishaq, Sunan Giri's father, who became a preacher in Blambangan, on the north coast of East Java, at the far east (Muljana, 1976, 2005; Djoened and Poesponegoro, 2008; Ricklefs, 2008; Ricklefs et al., 2010). Meanwhile, several colonies and areas conquered by Majapahit in other regions in the archipelago, one by one, began to break away from Majapahit rule.

Not only Malacca after that but there was also the first Islamic kingdom in Java, namely Demak, which Raden Patah founded. In subsequent developments, Demak openly broke away from Majapahit. This success, of course, must be supported by the assistance of coastal areas, such as Jepara, Surabaya, Kudus and Banten. Demak became an independent Islamic sultanate; with its first king Raden Patah, the fall of Majapahit could not be separated from Demak's participation. It is because one of the causes of the collapse of Majapahit was the intervention of Demak. This event led to changes; the people of Majapahit, who were originally Hindu-Buddhist, converted to Islam, especially with the people on the north coast of Java. Second, there is a mixture of Javanese culture and Islam. The third is the shift of Hindu-Buddhist power to an Islamic power system. According to the *Kandha* text and the Islamic chronicle, written later and according to the story, the events of the capture of the capital city of Majapahit by the Muslims in 1527 CE (Muljana, 1976, 2005; Djoened and Poesponegoro, 2008; Ricklefs, 2008; Ricklefs et al., 2010).

There were two significant events during this period: the *candrasengkala* event in 1478 CE and the overall conquest of Majapahit by Demak in 1527 CE. This *candrasengkala* event was marked by an attack from another Hindu kingdom, namely the Kingdom of Kediri, with its king Girindrawarddhana Dyah Ranawijaya. At that time, the king of Majapahit was Kertabhumi. The attack resulted in the death of the Majapahit king in his palace (Djafar, 2009). The birth of the Demak sultanate also occurred in this year (Muljana, 1976, 2005; Djoened and Poesponegoro, 2008; Ricklefs, 2008; Ricklefs et al., 2010). Hydroclimatologically, during the JJA season in 1477 - 1479 CE, there was a wetter event than the reference period (Figure 3e and Figure 4). Statistically, this is also considered significant because the two-sided Mann-Whitney U test results on the spatial PDSI distribution (Figure 2) are 34699 with a $p-$value < 0.01.

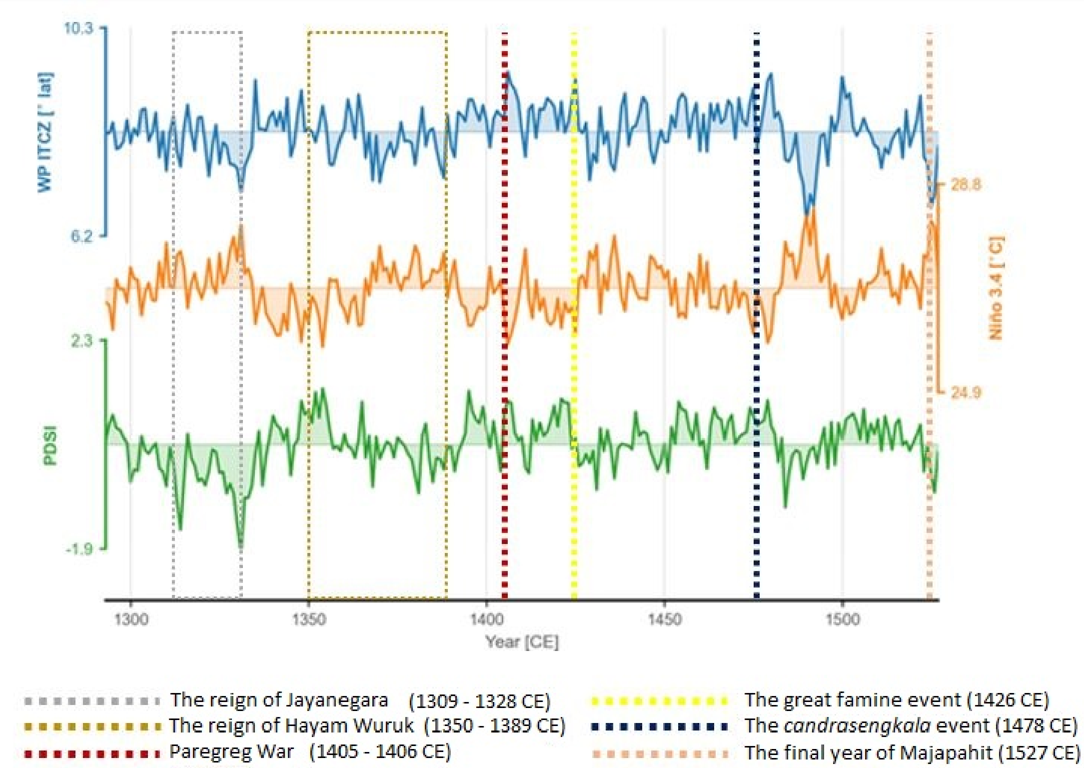

Figure 4. Hydroclimatological parameters used to identify drought during the Majapahit period from PHYDA. The top panel shows the West Pacific ITCZ in degree latitude. The middle panel shows Niño 3.4 SST (°C). The bottom panel shows the spatially averaged time series of PDSI over the MC.

In 1527, the Demak army, led by Sultan Trenggana, under the leadership of Sunan Kudus, succeeded in ultimately conquering Majapahit (Djoened and Poesponegoro, 2008; Ricklefs, 2008; Ricklefs et al., 2010). This event became the end of the existence of Majapahit. At the time of this incident, there was a drought over the MC during the boreal summer (Figure 3f and Figure 4). The difference in the spatial PDSI distribution (Figure 2) in this year against the reference period is 10453, with a $p-$value < 0.01. So, the MC drought during the Majapahit conquest by Demak was statistically significant. The hydroclimatological records of these two important events at the end of Majapahit have not been studied by historians. So we can only speculate that the hydroclimatological conditions at that time might have contributed to the end of Majapahit rule.

The WP ITCZ in JJA (Figure 4, top panel) has a positive correlation with the spatially averaged time series of PDSI over the MC (Figure 4, bottom panel) with a value of 0.590 ($p-$value < 0.01). Meanwhile, Niño 3.4 SST has a negative correlation (Figure 4, middle panel) with the spatially averaged time series of PDSI over the MC of -0.715 ($p-$value < 0.01). Meanwhile, WP ITCZ negatively correlates with Niño 3.4 SST of -0.876 ($p-$value < 0.01). It supports the notion that the southward shift of the ITCZ weakens trade winds across the tropical Pacific which could initiate an El Niño-like response via Bjerknes feedback. In the end, this is what causes drought over the MC (Bjerknes, 1969; Pausata et al., 2020).

CONCLUDING REMARKS

This study shows that there were changes in the hydroclimatological regime over the MC in almost every important episode in the history of Majapahit. This change is also statistically significant. This change in hydroclimatological conditions may be caused by a shift in the ITCZ and the ENSO phase.

However, the coincidence of these changes cannot necessarily be said to be the cause of several events of political upheavals in Majapahit. Six things are the limitations of this study:

- This is an exaggerated simplification of the relationship between the complexity of socio-political problems during the Majapahit era and the hydroclimatological regime at that time (Haldon et al., 2018).
- Limitations on proxy records over the MC at that time certainly limited the accuracy of PHYDA in reconstructing the PDSI.
- This study is only limited to the hydroclimate conditions during the boreal summer; of course, analysis is needed in other seasons to view the hydroclimatic conditions comprehensively.
- This study is only based on the mean state of the PDSI reconstruction at PHYDA; of course, we cannot deny the standard deviation of the Ensemble Kalman filtering results from the data assimilation process that was established (Evensen, 2009).
- This study is only based on secondary historical literature, which did not record the drought at Majapahit's time. In ancient Javanese texts, there is ambiguity in the writing of natural disaster events which confuses facts and fiction (Sastrawan, 2022), so historians and philologists need particular intention and expertise to extract primary sources which are generally written in Sanskrit or ancient Javanese.
- A more in-depth study is needed on the dynamics of ITCZ - ENSO in influencing drought over the MC during the Majapahit period. It is necessary to consider that the historical events of Majapahit occurred in the shift from Medieval Climate Anomaly (MCA) (950 - 1250 CE) to Little Ice Age (1450 - 1850 CE) which made it possible for the ITCZ to shift in that period (Roldán-Gómez et al., 2022).

Apart from these six shortcomings, this study has shown a correlation between hydroclimatological conditions over the MC controlled by ENSO and ITCZ, which may play a role in the political events in Majapahit. Historical research based on primary literature, archaeological research on Majapahit heritage sites, and paleoclimate observations with high-resolution proxies in the MC are needed to reveal the role of hydroclimatological conditions in the history of Majapahit in greater depth.

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PHYDA (Steiger et al., 2018) was accessed via the NOAA/NCEI Paleoclimatology data library at the following URL: `https://www.ncei.noaa.gov/access/paleo-search/study/24230`. The Python code for producing all figures in this study is available from the GitHub repository: `https://github.com/sandyherho/majapahitDrought23`.

REFERENCES

Aldrian, E. and Susanto, R. D. (2003). Identification of three dominant rainfall regions within indonesia and their relationship to sea surface temperature. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, 23(12):1435–1452.

Alley, W. M. (1984). The Palmer drought severity index: limitations and assumptions. *Journal of Applied Meteorology and Climatology*, 23(7):1100–1109.

Bhend, J., Franke, J., Folini, D., Wild, M., and Brönnimann, S. (2012). An ensemble-based approach to climate reconstructions. *Climate of the Past*, 8(3):963–976.

Bjerknes, J. (1969). Atmospheric teleconnections from the equatorial pacific. *Monthly weather review*, 97(3):163–172.

Buckley, B., Anchukaitis, K., Penny, D., Fletcher, R., Cook, E., Sano, M., Nam, L., Wichienkeeo, A., Minh, T., and Hong, T. (2010). Climate as a contributing factor in the demise of angkor, cambodia. *Proceedings of the National Academy of Sciences of the United States of America*, 107:6748–52.

Chang, C.-P., Wang, Z., Mcbride, J., and Liu, C.-H. (2005). Annual cycle of southeast asia – maritime continent rainfall and the asymmetric monsoon transition. *Journal of Climate - J CLIMATE*, 18:287–301.

Coedes, G. (1975). *The indianized states of Southeast Asia*. University of Hawaii Press.

Cribb, R. (2013). *Historical atlas of Indonesia*. Routledge.

DeMenocal, P. B. (2001). Cultural responses to climate change during the late holocene. *Science*, 292(5517):667–673.

Djafar, H. (2009). *Masa akhir Majapahit: Girindrawardhana dan masalahnya*. Komunitas Bambu.

Djoened, M. and Poesponegoro, N. N. (2008). *Sejarah Nasional Indonesia Jilid 2: Zaman Kuno*, volume 2. Balai Pustaka (Persero), PT.

Evensen, G. (2009). *Data assimilation: the ensemble Kalman filter*, volume 2. Springer.

Fleitmann, D., Haldon, J., Bradley, R. S., Burns, S. J., Cheng, H., Edwards, R. L., Raible, C. C., Jacobson, M., and Matter, A. (2022). Droughts and societal change: The environmental context for the emergence of islam in late antique arabia. *Science*, 376(6599):1317–1321.

Franke, J., Brönnimann, S., Bhend, J., and Brugnara, Y. (2017). A monthly global paleo-reanalysis of the atmosphere from 1600 to 2005 for studying past climatic variations. *Scientific data*, 4(1):1–19.

Goosse, H., Crespin, E., Dubinkina, S., Loutre, M.-F., Mann, M. E., Renssen, H., Sallaz-Damaz, Y., and Shindell, D. (2012). The role of forcing and internal dynamics in explaining the "medieval climate anomaly". *Climate dynamics*, 39(12):2847–2866.

Hakim, G. J., Emile-Geay, J., Steig, E. J., Noone, D., Anderson, D. M., Tardif, R., Steiger, N., and Perkins, W. A. (2016). The last millennium climate reanalysis project: Framework and first results. *Journal of Geophysical Research: Atmospheres*, 121(12):6745–6764.

Haldon, J., Mordechai, L., Newfield, T. P., Chase, A. F., Izdebski, A., Guzowski, P., Labuhn, I., and Roberts, N. (2018). History meets palaeoscience: Consilience and collaboration in studying past societal responses to environmental change. *Proceedings of the National Academy of Sciences*, 115(13):3210–3218.

Hendon, H. H. (2003). Indonesian rainfall variability: Impacts of enso and local air–sea interaction. *Journal of Climate*, 16(11):1775–1790.

Hoyer, S. and Hamman, J. (2017). xarray: Nd labeled arrays and datasets in python. *Journal of Open Research Software*, 5(1).

Khider, D., Emile-Geay, J., Zhu, F., James, A., Landers, J., Ratnakar, V., and Gil, Y. (2022). Pyleoclim: Paleoclimate timeseries analysis and visualization with python. *Paleoceanography and Paleoclimatology*, 37(10):e2022PA004509.

Krom, N. J. (1926). *Hindoe-javaansche geschiedenis*. M. Nijhoff.

Lisiecki, L. E. and Raymo, M. E. (2005). A pliocene-pleistocene stack of 57 globally distributed benthic δ18o records. *Paleoceanography*, 20(1).

Lombard, D. (1969). Jardins à java. *Arts asiatiques*, 20:135–183.

Mann, H. B. and Whitney, D. R. (1947). On a test of whether one of two random variables is stochastically larger than the other. *The annals of mathematical statistics*, pages 50–60.

Met Office (2010 - 2015). *Cartopy: a cartographic python library with a Matplotlib interface*. Exeter, Devon.

Muljana, S. (1976). *A story of Majapahit*. Singapore University Press.

Muljana, S. (2005). *Menuju Puncak Kemegahan; Sejarah Kerajaan Majapahit*. LKIS PELANGI AKSARA.

Neale, R. and Slingo, J. (2003). The Maritime Continent and its role in the global climate: A GCM study. *Journal of Climate*, 16(5):834–848.

Noorduyn, J. (1978). Majapahit in the fifteenth century. *Bijdragen tot de Taal-, Land-en Volkenkunde*, (2/3de Afl):207–274.
Otto-Bliesner, B. L., Brady, E. C., Fasullo, J., Jahn, A., Landrum, L., Stevenson, S., Rosenbloom, N., Mai, A., and Strand, G. (2016). Climate variability and change since 850 ce: An ensemble approach with the community earth system model. *Bulletin of the American Meteorological Society*, 97(5):735–754.
Pausata, F. S., Zanchettin, D., Karamperidou, C., Caballero, R., and Battisti, D. S. (2020). Itcz shift and extratropical teleconnections drive enso response to volcanic eruptions. *Science Advances*, 6(23):eaaz5006.
Pearson, K. and Galton, F. (1895). Vii. note on regression and inheritance in the case of two parents. *Proceedings of the Royal Society of London*, 58(347-352):240–242.
Prell, W. L., Imbrie, J., Martinson, D. G., Morley, J. J., Pisias, N. G., Shackleton, N. J., and Streeter, H. F. (1986). Graphic correlation of oxygen isotope stratigraphy application to the late quaternary. *Paleoceanography*, 1(2):137–162.
Rahardjo, S., Syahrie, S. P., and Rizal, J. (2011). *Peradaban Jawa: dari Mataram Kuno sampai Majapahit Akhir*. Yayasan Kertagama.
Ramage, C. S. (1968). Role of a tropical "maritime continent" in the atmospheric circulation. *Monthly Weather Review*, 96(6):365–370.
Ricklefs, M. C. (2008). *A History of Modern Indonesia since c. 1200*. Macmillan International Higher Education.
Ricklefs, M. C., Lockhart, B., Lau, A., Reyes, P., and Aung-Thwin, M. (2010). *A new history of Southeast Asia*. Macmillan International Higher Education.
Robertson, A. W., Moron, V., Qian, J.-H., Chang, C.-P., Tangang, F., Aldrian, E., Koh, T. Y., and Liew, J. (2011). The maritime continent monsoon. *The global monsoon system: research and forecast*, pages 85–98.
Roldán-Gómez, P. J., González-Rouco, J. F., Smerdon, J. E., and García-Pereira, F. (2023). Model and proxy evidence for coordinated changes in the hydroclimate of distant regions over the Last Millennium. *Climate of the Past Discussions*, 2023:1–36.
Roldán-Gómez, P., González Rouco, J. F., Melo-Aguilar, C., and Smerdon, J. (2022). The role of internal variability in itcz changes over the last millennium. *Geophysical Research Letters*, 49.
Sastrawan, W. J. (2022). Portents of power: Natural disasters throughout indonesian history. *Indonesia*, 113(1):9–30.
Satyana, A. H. (2007). Bencana geologi dalam "sandhyâkâla" jenggala dan majapahit: Hipotesis erupsi gununglumpur historis berdasarkan kitab pararaton, serat kanda, babad tanah jawi; folklor timun mas; analogi erupsi lusi; dan analisis geologi depresi kendeng-delta brantas. In *Proceedings Joint Convention Bali*, pages 1755–1315.
Shen, C., Wang, W.-C., Hao, Z., and Gong, W. (2007). Exceptional drought events over eastern china during the last five centuries. *Climatic Change*, 85(3):453–471.
Steiger, N. J., Hakim, G. J., Steig, E. J., Battisti, D. S., and Roe, G. H. (2014). Assimilation of time-averaged pseudoproxies for climate reconstruction. *Journal of Climate*, 27(1):426–441.
Steiger, N. J., Smerdon, J. E., Cook, E. R., and Cook, B. I. (2018). A reconstruction of global hydroclimate and dynamical variables over the common era. *Scientific data*, 5(1):1–15.
Virtanen, P., Gommers, R., Oliphant, T. E., Haberland, M., Reddy, T., Cournapeau, D., Burovski, E., Peterson, P., Weckesser, W., Bright, J., et al. (2020). Scipy 1.0: fundamental algorithms for scientific computing in python. *Nature methods*, 17(3):261–272.
Wardani, S. P. R. and Kodoatie, R. J. (2008). Disaster management in central java province, indonesia. In *Geotechnical engineering for disaster mitigation and rehabilitation*, pages 254–259. Springer.
Wilks, D. S. (2011). *Statistical methods in the atmospheric sciences*, volume 100. Academic press.
Wolters, O. W. (1999). *History, culture, and region in Southeast Asian perspectives*. Number 26. SEAP Publications.
Yamanaka, M. D. (2016). Physical climatology of Indonesian maritime continent: An outline to comprehend observational studies. *Atmospheric Research*, 178:231–259.
Yang, S., Zhang, T., Li, Z., and Dong, S. (2019). Climate variability over the Maritime Continent and its role in global climate variation: A review. *Journal of Meteorological Research*, 33(6):993–1015.
Yoden, S., Otsuka, S., Trilaksono, N. J., and Hadi, T. W. (2017). Recent progress in research on the maritime continent monsoon. *The Global Monsoon System: Research and Forecast*, pages 63–77.

Zhang, P., Cheng, H., Edwards, R., Chen, F., Wang, Y., Yang, X., Liu, J., Tan, M., Wang, X., Liu, J., An, C., Dai, Z., Zhou, J., Zhang, D., Jia, J., Jin, L., and Johnson, K. (2008). A test of climate, sun, and culture relationships from an 1810-year chinese cave record. *Science (New York, N.Y.)*, 322:940–2.