The study of MJO impact on wave height and wind speed in Indonesian Seas

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Abstract. Indonesia is passed by an atmospheric phenomenon, called the Madden-Julian Oscillation (MJO), which has an impact on the wave height in the Indonesian Seas. The significant wave height is simulated using WAVEWATCH-III (WW3) numerical model in Indonesian region (90⁰E-150⁰E, 20⁰N-20⁰S) forced by surface winds from Cross-Calibrated Multi-Platform (CCMP), Navy Global Environmental Model (NAVGEM), and Navy Operational Global Atmospheric Prediction System (NOGAPS). This simulation is concentrated on MJO phase 3, 4, and 5 which passed through Indonesia and its adjacent waters that occurred in particular time between 1990-2015. In this study, the impact of MJO was analyzed during every monsoon season. In addition, wind speed analysis was carried out to further enrich the analysis of the MJO impact. The simulation result shows that MJO exerts the highest impact during phase 5 and DJF, which contributes to the increase of wind speed (WS) and significant wave height (SWH) in Indonesian inner seas by 6 m/s and 30 cm, respectively, and in southern Lesser Sunda Island by 8 m/s and 1.2 m, respectively. MJO can also contribute to decreasing of the WS and SWH, when it occurred during DJF and MAM phase 3, and JJA phase 4. There is no noticeable change of WS and SWH during SON.

1. Introduction
Madden-Julian Oscillation (MJO) is a planetary-scale eastward propagation of convection and precipitation zone along the equator with 40-50 days of oscillation period (Madden and Julian, 1972). The enhanced convection is mainly caused by a formation of low-pressure area associated with high sea surface temperature (SST) that starts around east of Africa. It propagates with average speed of 5 m/s from western Indian Ocean to the eastern Pacific Ocean, bringing with it a number of impacts on some areas such as weather, climate, and ocean condition. Zhang (2005; 2013), in his study, briefly summarized that MJO has influences on precipitation, sea surface temperature, tropical cyclone activities, flood, Indonesian forest fires, and even global and lightning electromagnetic field. Among the various influences brought by MJO, SST is one of the notable impact on the ocean condition along the equator. The change in SST will influence the wind condition and furthermore, will also have an effect on wave condition. Duwaliser et al (2013) on his study using 6 years (2008-2013) of National Oceanic and Atmospheric Administration (NOAA) WAVEWATCH-III hindcast data forced by National Centers for Environmental Prediction (NCEP) wind data, found that MJO, depending on its phase, may cause
both positive and negative anomaly globally. Moreover, As studied by Marshall et al (2015), MJO is able to cause a large fetch (~10,000 km) over a period of weeks. Using WAVEWATCH-III wave hindcast model from Centre for Australian Weather and Climate Research (CAWCR) forced by Climate Forecast System Reanalysis (CFSR) 10-m wind data for 1979-2009 period, this study by Marshall et al (2015) also found that MJO have different impact, both positive and negative, on wind speed (WS) globally ranging from 1-5 m/s, and on significant wave height (SWH) ranging from 20-50 cm based on its phase and location. In addition, Marshall et al (2015) also found that MJO can cause an increase in wave period, indicating that the wave generation is more influenced by remote wind forcing caused by MJO rather than by swell. This result furthermore shows that the wind anomalies caused by MJO is able to cause both positive and negative anomalies on SWH condition.

This purpose of this paper is to further expand the study about MJO effect on wave, especially within the Indonesian Archipelago where MJO propagate through regularly. To meet this goal, the study will focus mainly on region adjacent to Indonesia’s waters to investigate how MJO affects the wind and wave condition around Indonesia. Only MJO phase 3, 4, 5 that happened between 1991-2015 will be included in this study as they occurred near Indonesia, with phase 3 occurring west of Indonesia, phase 4 adjacent to Java and Lesser Sunda Islands, and phase 5 east Indonesia. MJO occurrence in every season (DJF, 1st transitional period of monsoon, JJA, and 2nd transitional period of monsoon) will be considered. The time of occurrence has been chosen to not coincide with the event of El-Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) to exclude their effect on winds and wave condition around Indonesia. It is also well-known that MJO tends to be more active in the ENSO-neutral event compared to one with ENSO occurrence. This approach will allow us understand how the phase and season play an important role on the effect of MJO on WS and SWH around Indonesian regions, without interference from ENSO and IOD, the most dominant interannual phenomena in the region.

The assessment of the MJO impact is done by using output result from wave hindcast model, WAVEWATCH-III (WW3) forced with 25 years (1991-2015) of surface wind reanalysis. The method and data used in wave hindcasting will be described in Section 2. Section 3 will reveal the impact of MJO on WS and SWH around Indonesia region, and study is summarized in Section 4.

2. Materials and Method
Wave hindcast in this study is produced using WAVEWATCH-III with structured 0.125° x 0125° grid resolution over the Indonesian region (90°E-150°E, 20°N-20°S). This domain is large enough to cover South China Sea (SCS), western Pacific Ocean, and eastern Indian Ocean as to see the MJO impact on those areas as well. Cross-Calibrated Multi-Platform (CCMP) is used as the wind forcing with resolution of 0.25° x 0.25° and interval of 6 hours. As for the bathymetry, the ETOPO data with 30-arc second (0.0833°) resolution is being used with unchanged depth over time. The time of each MJO phase in this study is obtained from Australian Bureau of Meteorology website (bom.gov.au) that use RMM method and MJO diagram from Wheeler and Hendon (2014) to determine the MJO phase. The MJO phase is then compared to monthly Ocean Nino Index (ONI) data from NOAA and Indian Ocean Dipole (IOD) index from Japan Agency for Marine-Earth Science and Technology (JAMSTEC) to eliminate MJO occurrences that coincide with any ENSO and IOD event.

Rather than using composite data of MJO over years, this study will focus on one MJO occurrence on each phase and season that occur in ENSO and IOD neutral year from 1991-2015. Although there is a strong El-Niño event on 1997, ONI data from NOAA does not show any El-Niño event on March, thus, March 1997 is considered ENSO-neutral month. Moreover, the chosen MJO should satisfy the following requirements. According to study by Ramdhani (2015), only the strong MJO (index >1) is used in this study, as the strength of MJO is proportionate to the effect it caused on WS and SWH. MJO with index more than 1 indicates that the low-pressured area created is able to cause significant change in the state of wind and wave. On contrary, with index less than 1, MJO will be classified as weak or even considered inactive. Thus, giving insignificant change in the state of wind and wave. In addition to that, the MJO chosen must have a minimum duration of 5 days to be able to induce a significant anomaly (Ramdhani, 2015). With this duration, wind anomalies caused by MJO will have enough time
to create large fetch and transferring energy to the sea and create SWH higher than the normal state. The selected MJO occurrence will then be separated into 4 seasons; northeast monsoon (DJF), first monsoon’s transitional period (MAM), southwest monsoon (JJA), an second monsoon’s transitional period (SON) to observe which season gives the biggest effect on MJO’s impact. It is hoped that by adhering to these requirements, this study will provide the result of highest anomaly an MJO can cause on WS and SWH around Indonesia region on each season. MJO chosen in this study is shown in the Table 1.

![Figure 1. Three of buoy locations used in verification](image)

**Table 1.** Chosen time of MJO occurrence for each phase and season

| Phase 3 | Phase 4 | Phase 5      | No MJO         |
|---------|---------|--------------|----------------|
| DJF     | 16 – 21 January 1993 | 12 – 20 February 1997 | 3-9 February 2009 | December 2008 |
| MAM     | 4 – 10 March 1993   | 1 – 6 March 1990    | 7-13 March 1990  | March 1997    |
| JJA     | 21 – 28 June 1998   | 17 – 22 June 2007   | 10 – 15 August 2001 | August 1993 |
| SON     | 15 – 21 October 2008| 22 – 27 October 2008| 19 – 24 November 2004 | October 1990 |
Figure 2. Verification result (from left to right) for Kepulauan Seribu, Pluit, and Karawang with period of 1998-1999. $H_b$ is buoy significant wave height and $H_m$ is model significant wave height. The diagonal line indicates $y=x$.

Result of the hindcast is validated using 1 year (1998-1999) SEAWATCH buoy data from BPPT (Badan Pengkajian dan Penerapan Teknologi) in 3 locations shown in figure 1; Kepulauan Seribu, Pluit, and Karawang. All of the locations are located in shallow water area in Indonesian inner seas. Generally, the validation result from figure 2 shown that the 3 locations give good verification result with each Correlation Coefficient (CC) being 0.63, 0.52, and 0.74 from left to right, respectively. In every location, almost all of the SWH give an underestimate result, with buoy’s SWH being higher than model’s SWH, shown by dot on the picture that mainly located below the line. It is possible because the location of the buoy is in the shallow water area which does not exactly coincide with the WAVEWATCH-III native grid, resulting in a slightly lower SWH compared to the buoy. Statistical parameter here is also including bias to see the difference between model’s SWH and buoy’s SWH. All 3 locations give low bias and RMSE result, meanings that there is a small difference between the buoy’s SWH and model’s SWH, which is to be expected from the result in shallow region.
Aside from using buoy, verification is also conducted using 7 years (2009-2015) of AVISO satellite data on a larger area covering all Indonesia region. Compared to the verification using buoy data, this verification is able to show the statistical parameter spatially over the Indonesia region. However, despite being able to provide SWH data covering a wide area, AVISO satellite comes with a disadvantage of poor ability to differentiate between land and sea, resulting in unavailability of some SWH data near land and unreliable result in some of the near coastal area. In addition to that, the location of verification is chosen on every point on model that coincides with the point of AVISO to mitigate the difference in grid between model and AVISO. The result of CC, bias, and RMSE of this method is shown in Figure 3, with the white area being devoid of SWH data from AVISO. Spatial correlation gives quite satisfactory result in a large part of the model’s domain. The two data sets are most consistent around SCS with CC close to 1, followed by Indonesian inner seas, Banda Sea, and Pacific Ocean with the result ranging from 0.7 to 0.8. CC in the Indian Ocean are similar to those in the Pacific Ocean. Generally, the bias result is also quite good with result ranging from 0 m to -0.2 m around SCS, Pacific Ocean, and Indonesian inner seas, and ranging from -0.2 m in 0.2 m in Indian Ocean. The more accurate depiction of deviation between AVISO and WW3 model is provided in the spatial RMSE. In Indonesian inner seas, RMSE result is close to 0 m while in Banda Sea it is ranging from 0 m to 0.2 m, as expected of the result in a closed seas that have quite small SWH. In the oceans, however, the result is larger, 0 m to 0.6 m in Pacific Ocean and 0.3 m to 0.4 m in Indian Ocean. This large result is to be expected and proportional to the high SWH occurs in these areas.

Figure 3 Spatial statistical parameter validated using AVISO satellite data consist of (a) correlation; (b) bias; and RMSE (c).
Figure 4. Averaged wind speed anomalies of each MJO phase in DJF season

Figure 5. Averaged significant wave height anomalies of each MJO phase in DJF season
3. Results and Discussion

3.1. DJF and MAM season

As shown in figure 4, anomalies on wind speed caused by MJO in DJF season can be seen clearly on each picture. Compared to the condition of no MJO, each phase of the MJO shows quite different change. The wind speed in MJO phase 3 is seen as the lowest among the others, indicating that MJO may cause a decrease in wind speed. It may have occurred because on phase 3, MJO is located around western of Indonesia. It means, the low-pressured area in the west of Indonesia will force wind over the Java Sea to blow westward. This direction is the opposite of the northwest monsoon that blows over Indonesia region, resulting in a net decrease in the wind speed over the Java Sea. On the other hand, there is an increase of WS shown in phase 4 and 5, with phase 5 being the phase with the most impact on the WS. On phase 4, the WS seems to increase for about 2 m/s in inner seas and 5 m/s in the southern Java, raising the WS to 8 m/s from 6 m/s and to 10 m/s from 5 m/s respectively. The strongest impact shown by phase 5 increase the WS by 6 m/s (from 6 m/s to 12 m/s) in inner seas, in the southern Java and Lesser Sunda Islands by 8 m/s (from 5 m/s to 13 m/s) and in Banda Sea by 5 m/s (from 5 m/s to 10 m/s). This increase is to be expected as some of the study on MJO found that the strongest impact of MJO around Indonesia region is observed in phase 5 in DJF season (Duvaliser et al (2013); Marshall et al (2015); Ramdhani (2015)). Strongest impact on phase occurs because in this phase, the MJO-driven low-pressured areas situated in the eastern part of Indonesia, forcing the wind to blow eastward to the low-pressured area. When this happens during the northwest monsoon, MJO-forced wind will blow in the same direction with the northwest monsoon and resulted in the amplification of the wind speed and larger fetch, hence the significant increase in wind speed across inner seas and southern Java.

![Figure 6](image_url) Figure 6. Averaged wind speed anomalies of each MJO phase in MAM season.
Figure 7. Averaged significant wave height anomalies of each MJO phase in MAM season

Figure 8. Averaged wind speed anomalies of each MJO phase in JJA season
The impact on SWH is also in accordance with the WS. In figure 5, it can be observed that there is a small decrease of SWH in phase 3 compared to No-MJO state. SWH in Java Sea is decreased by 0.1 m (from 0.5 m to 0.4 m), while the most significant decrease in this phase occurred in southern Lesser Sunda Islands with a decrease by 0.5 m (from 1.4 m to 0.9 m). Oppositely, the raise of SWH is shown by MJO phase 4 and 5 as the result of increase in WS in these phases. Wind is one of the most important wave generator in Indonesian inner seas and southern Java, thus, the stronger the wind blows over those areas, the higher the wave will be generated. Wind amplification on the event of MJO phase 5 transfers much more energy into the sea over the MJO duration, resulted in much higher wave compared to the other phase. In phase 4, the SWH is increased by 30 cm (from 0.5 m to 0.8 m) in inner seas and increased by 0.5 m in southern Java (from 1.5 m to 2 m). The most significant change in SWH can be found in phase 5, which raise the SWH in the inner seas by 1 m (from 0.5 m to 1.5 m), in southern Java by 0.7 m (from 1.5 m to 2.2 m), 0.8 m in Banda Sea (from 0.4 m to 1.2 m), and 1.2 m in southern Lesser Sunda Islands (from 1.4 m to 2.6 m). This large increases is may be due to the strong wind force created by MJO’s low-pressured area in eastern part of Indonesia.

![Figure 5](image1.png)

![Figure 6](image2.png)

![Figure 7](image3.png)

![Figure 8](image4.png)

**Figure 9.** Averaged significant wave height of each MJO phase in JJA season.

MJO event and the WS anomalies in MAM season are shown in figure 6. As the first monsoon’s transitional period, MAM has a similar wind direction to the DJF season, but with lower WS. Overall, WS and SWH anomaly on MAM season resembles that of DJF season, albeit much smaller. The most significant increase of WS is found in MJO phase 5, which yields a rise of 2 m/s over the inner seas and southern Java, and 3 m/s on Banda Sea. WS increase also occurred on phase 4 with a smaller magnitude and area coverage, 2 m/s in southern Java and 1 m/s in inner seas. On the phase 3, MJO causes a decrease in the WS over the inner seas and southern Java by 2 m/s (from 5 m/s to 3 m/s). This occurrence of increasing and decreasing WS happened because of the same mechanism as the change that happened in DJF season. Increase on MJO phase 4 and 5 occurred because of amplification in WS by the low-pressured area created by MJO in east of Indonesia, while a decrease in phase 3 happened because of wind collision caused by low-pressured area in west of Indonesia. SWH anomalies shown in figure 7 also follow the pattern of WS anomalies. The highest wave height occurrence is found in phase 5, with
an increase of 0.3 m in inner seas and 0.5 m in southern Java and Lesser Sunda Islands. MJO phase 4 does not pose significant increase in inner seas (0.2 m) but it causes 0.4 m increase of wave height in southern Java and Lesser Sunda Islands. MJO also causes the SWH to decrease in phase 3, but the change is insignificant (0.2 m over the inner seas and 0.3 m in southern Java).

3.2. JJA and SON

Being the opposite of the DJF season, JJA season has a reversed monsoon wind direction that flows from southern hemisphere to northern hemisphere across Indonesia, creating a southeastern monsoon. Low-pressured area created by MJO in this season also tends to be located farther north compared to DJF and MAM season (Wheeler and Hendon, 2004; Gotschalck, 2014), causing the change in wind speed and wave height mainly happened in northern part of Indonesia. This anomaly happens because in JJA season, the sun is located closer to the northern hemisphere (NH), resulting in NH area becomes warmer than the southern hemisphere (SH). In this season, MJO which happened mainly because of the warm SST can be easily formed in the warm NH rather than SH due to lack of sunlight heating in that area.

There is no significant change in WS except on MJO phase 5. As can be inferred from figure 8, Compared to the event of no MJO, WS during MJO phase 3 and 4 seems to only decreased in SCS, 3 m/s in phase 3 and 5 m/s in phase 4. The change is hypothesized as the effect of low-pressured area around middle and western of Indonesia caused by MJO. The low-pressured area located in southern of SCS attracts wind over the SCS to blow southward. This direction is the opposite of the southwestern monsoon that blows northward in SCS, resulting in decrease of WS over the SCS. The significant change in WS occurred on MJO phase 5 in SCS and southeastern of Philippine. Low-pressured area created by MJO in this phase is located around east of Philippines, forcing the wind over the SCS to blows eastward, as well as the wind over western and eastern Phillipine, North Maluku, and Sulu Sea to blow even stronger. It can be seen from figure 6 that the wind over the SCS in phase 5 tends to shift eastward as

Figure 10. Averaged wind speed anomalies of each MJO phase in SON season.
the result of wind forcing by low-pressured area east of Phillipine. This change is followed by an increase of WS in Sulu Sea by 2 m/s, and in both eastern and western Phillipine by 5 m/s and 3 m/s respectively. This change in WS is also followed by change in SWH, which significantly happened in MJO phase 5 that cause an increase of 0.5 m in Sulu Sea and 1 m in eastern Phillipine. Conversely, the significant decrease in wave height can be found over the SCS in phase 3 and 4, where the SWH is decreased by around 0.5 m and 0.8 m respectively.

In contrast to the other seasons, MJO event in SON season does not seem to have any impact on both WS and SWH over Indonesia region. The only notable change on WS occurs on MJO phase 5 in northern SCS and northern Phillipine, followed by high SWH in the same area that comes from the north. Even so, it is thought not to be the effect of MJO, but rather the effect of certain natural phenomenon occurring at that time in the higher latitude which propagates southward into the SCS. This lack of change in WS and SWH compared to the other seasons might be due to the weak nature of the WS in SON as the second monsoon transitional period, so the MJO cannot cause significant change despite having enough power to do so. The uncertainty of the wind direction in this phase is also thought to play a role in minimizing the MJO effect, depending on whether it blows upwind or downwind the low-pressured area.

4. Conclusion
The low-pressured area created by MJO in phase 3, 4, and 5 that occurred adjacent to Indonesia is able to cause anomalies in WS and eventually influencing the SWH. Increases in WS and SWH occur because the location of MJO’s low-pressured area is situated downwind of the monsoon, regardless of its season and phase. It forces the wind to blow to the low-pressured area along with the moonson and creates an amplification of the WS. MJO phase 5 on DJF season is the prime example on how MJO is able to cause significant change of WS in southern Java by 8 m/s, inner seas by 6 m/s, and Banda Sea
by 5 m/s, and cause significant change in SWH by 0.7 m in southern Java, 1 m in inner seas, 0.8 m in Banda Sea, and 1.2 m in southern Lesser Sunda Islands, respectively. On MAM, MJO phase 5 also has the same effect, but with lower value of increase, which is 2 m/s in wind speed over inner seas and southern Java, 0.3 m of wave height in inner seas, and 0.5m in Southern Lesser Sunda Islands. In lieu of increasing anomalies, MJO can also causes decreasing anomalies as occurring in MJO phase 3 on both season if its location is upwind of the monsoon. In DJF and MAM season, due to the heating in southern hemisphere, MJO tends to occur southward, resulting in WS and SWH anomalies mainly occur in inner seas, southern Java, Banda Sea, and around Lesser Sunda Straits. On the contrary, MJO tends to occur northward in JJA and SON seasons, thus creating WS and SWH anomaly in the northern part of Indonesia such as SCS, Sulu Sea, and western Pacific Ocean. The most significant impact on this season can be seen on MJO phase 5 which increases WS by 2 m/s in Sulu Sea, 3 m/s on western Philippine, and 5 m/s on eastern Philippine, followed by increase in SWH by 0.5 m in Sulu Sea and western Philippine. In SON, MJO does not seem to be creating any WS and SWH anomalies during any of its phases.

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References
[1] A G Marshall et al., Madden julian oscillation impacts on global ocean surface waves, Ocean Modelling (2015), http://dx.doi.org/10.016/j.ocemod.2015.06.002
[2] Gottschalk J, Kousky V, Higgins W and L’Heureux M 2014 MJO Summary (National Oceanic and Atmospheric Administration)
[3] Madden R A and Julian P R 1972 Description of global-scale circulation cells in the tropics with 40-50 day period. J. Atmos. Sci. 29 1109-1123.
[4] Ramdhani A 2015 Pengaruh Siklon Tropis dan Madden-Julian Oscillation (MJO) Terhadap Kejadian Gelombang Tinggi di Perairan Indonesia Bagian Dalam (Doctoral Dissertation. Institut Teknologi Bandung).
[5] Waliser D E, Wu B, Yung Y L, Guan B, Webb F and Kedar S 2013 The Impact of the MJO on Global Ocean Surface Wave Heights, Bull. Am. Meteorol. Soc. 94.
[6] Wheeler M C and Hendon H H 2004 An All-Season Real-Time Multivariate MJO Index: Development of an Index for Monitoring and Prediction, Monthly Weather Rev 132 (8), 1917-1932.
[7] Zhang C 2005 Madden-Julian Oscillation Rev. of. Geophysics. 43 (2).
[8] Zhang C 2013 Madden-Julian Oscillation: Bridging Weather and Climate Bull. Am Meteorol. Soc. 94, 1849-1870.