International Journal of Remote Sensing and Earth Sciences Vol. 16 No. 2 December 2019: 59-72

TENDENCY FOR CLIMATE-VARIABILITY-DRIVEN RISE IN SEA LEVEL DETECTED IN THE ALTIMETER ERA IN THE MARINE WATERS OF ACEH, INDONESIA

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Received: 15 January 2019; Revised: 13 February 2020; Approved: 20 February 2020

Abstract. Long-term sea level rise (SLR) leads to increasing frequency in overtopping events resulting from polar ice liquefaction triggered by rising global temperatures. Aceh province is directly bordered by the Indian Ocean, and is subject to the influence of ocean–atmosphere interactions which have a role in triggering temperature and sea level anomalies. Elevated sea level is possibly caused by temperature-induced water mass redistributions. This study aimed to prove that the Indian Ocean Dipole (IOD) and El-Nino–Southern Oscillation (ENSO) had an influence on sea level change in Aceh waters over the six years 2009–2015. Sea level anomaly (SLA) was identified using Jason-2 satellite data for the 2009–2015 period, to enable the mathematical prediction of SLR rate for further years. We found that SLR was approximately 0.0095 mm/year with an upward trend during the six years of observation. Overall, negative mode of IOD and positive phase of ENSO tend to trigger anomalies of sea level at certain times, and have a stronger influence on increasing SLA and sea surface temperature anomaly (SSTA) which takes place in a ‘see-saw’ fashion. Over the period of observation, the strongest evidence of IOD-correlated SLA, ENSO-correlated SLA and SSTA-correlated SLA were identified in second transitional seasons, with more than 50% of R^2 value. The upward trend in SLA is influenced by climatic factors that successively control ocean–atmosphere interactions in Aceh’s marine waters.

Keywords: *Sea level rise, altimeter, Aceh waters, Indian Ocean Dipole, sea level anomaly*

1 INTRODUCTION

Climate change is one of the natural phenomena controlling all aspects of life on earth (Urban, 2005), with the most extreme impacts being on sea temperature and sea level (Agnew, 2017). Sea level rises gradually, and periodical changes can be observed through surface elevation changes (Hay, Morrow, Kopp, & Mitrovica, 2015). Recent sea level rise (SLR) has the potential to increase overtopping frequency on land; as a result, many vulnerable coastal areas have suffered frequent tidal flooding, generating new areas of water on land as well as coastline changes (Lovelock et al., 2015).

Coastal areas are most prone to such events because they are intensely influenced by both land and sea, with pressures from both being likely to be reflected in coastal characteristics. Current issues are the number of tidal flooding events triggered by sea level rise and the land subsidence being suffered by large cities (Wang, Gao, Xu, & Yu, 2012). The main factors inducing sea level rise are global warming and the greenhouse effect (Wuriatmo, 2011) as related to global sea temperature rise (Gregory et al., 2013). Increase in ocean temperature will induce polar ice liquefaction which eventually yields increased global sea levels (Hansen et al., 2016). A prediction

http://dx.doi.org/10.30536/j.ijreses.2019.v16.a3091

published by Jevrejeva et al. (2012) predicted that between 2100 and 2500, global sea level will rise by 4.39 meters to a total rise of 5.49 meters at peak elevation. Another study stated that the trend in sea level rise caused by sea temperature rise is approximately 1 mm/year (Church et al., 2011).

Indonesia is a strategic region in terms of SLR because it is located between two oceans and two continents. The most prone coastal areas of Indonesia are the western part of Sumatra and the northern coast of Java, which are directly influenced by SLA induced by ocean–atmosphere interactions from the Indian and Pacific oceans. Because of the intense control of physical conditions along the coastline caused by climatic factors, sea temperature and probably sea level will be affected by climate anomaly. In the Indian Ocean, the tendency for climate anomaly results from the ocean–atmosphere interactions known as the Indian Ocean Dipole (IOD). These interactions result in high pressure in the eastern part of the Indian Ocean (including western Sumatra and southern Java) in which air mass moves westward. This air mass transfer pushes water mass at its front and lifts water mass to the surface. As a result, sea temperature to the south of Java and the west of Sumatra fall dramatically while the opposite condition occurs in eastern Africa, a condition known as the positive mode of IOD (Kailaku, 2009; Yamagata et al., 2002). In contrast, when warmer water and greater precipitation occurred in the eastern Indian Ocean while in the west, cooler and drier conditions take place, negative mode of IOD occurred (Wisha, Al Tanto, and Ilham, 2017; Wisha & Khoirunnisa, 2017). In some cases, the co-occurrence of positive IOD and an El-Nino Modoki will result in anomalous warming and surplus rainfall over the equatorial Northwest Pacific and the South China Sea. Meanwhile, in the northern part of Sumatra, the influence of positive IOD–El-Nino Modoki tends to be lowering in sea level and temperature anomaly (Pradhan et al., 2011). Thus, the pressure of IOD will impact strongly on this region.

Climate anomaly may affect Aceh province, which is becoming an area impacted by SLR. The climate stress is not only affecting the physical condition of Aceh waters but also the surrounding environment. Coral bleaching was reported in Aceh province and Weh Island during the negative mode of IOD supported by ENSO in 2011 (Rimba et al., 2012) and in 2016 (Wisha & Ondara, 2018). If it continues, SLR will induce coastal damage and degradation such as erosion and coastline changes (Khasanah, 2017). It is essential to determine the amalgamated influence of IOD and ENSO on Aceh province in order to prove that the SLR and tidal flooding occurring regularly is controlled by climatic factors and anomalies.

Nowadays, sophisticated long-term observation data for the sea can be obtained from satellite altimetry, and this is one of the options that can be used to observe and predict SLR locally and globally. There are 12 existing altimetry satellites, one of which is Jason-2, available since 2008. The temporal resolution of the Jason-2 satellite is approximately ten days (specifically 9.9156 days) and the distance between its orbital is separated by approximately 315 km along the equator (Wuriatmo, 2011). This method can be useful for predicting the possibility of SLR for future years. Study of SLR and its relationship with climatic factors is essential because the occurrence of sea level anomaly will tend to impact on coastal communities and settlements which may be affected by climate anomaly. Thus, this study aims to examine the trend in sea level change in

Aceh's marine waters during 2009–2015 and its relation to climatic factors.

2 MATERIALS AND METHODOLOGY

2.1 Location and data

Geographically, Aceh province is located between 01° 58' 37.2" - 06°04' 33.6" N and 94° 57' 57.6" - 98° 17' 13.2" E, with an altitude of around 125 meters above sea level. Aceh province is bordered by the Malacca Strait in the north and east, North Sumatra province in the south and the Indian Ocean in the West. This region is vulnerable to earthquakes, tsunamis and other coastal hazards because it is exactly located in the subduction zone between the Indo-Australian and Eurasian plates. Climate variability also has a role in influencing coastal conditions, such as heavy rainfall induced by Madden-Julian Oscillation (MJO) and sea temperature rise triggered by both IOD and ENSO. Those conditions are predicted to affect sea level rise, inducing tidal flooding and abrasion.

Sea level data were retrieved from the RADS (Radar Altimetry Database System) of the Jason-2 satellite from 2008 to 2015: cycles 166–202 with pass numbers of 14, 27, 90, 103, 166, and 179 (webpage: http://rads.tudelft.nl). RADS provides correction and flagging in the form of a user interface for which users do not need programming skills in order to process the RADS data, thus users of RADS can specify the option of single corrections and can flag easily. RADS data are connected to the global tidal model (Naeije et al., 2000).

2.2 Data Standardisation

The retrieved data were cropped across the study area with the boundary between 0.5° 00' 00" – 6.5° 00' 00" North and 92° 00' 00" - 98°00' 00" East included in the satellite track (Figure 2-1). Data chosen were sea level anomaly (SLA) cycles 1-55 and pass satellite data 1, 14, 27, 90, 103, 166 and 179 in which the track number showed the orbital of the satellite once it was recording, reiterated for 9.9156 days. The distance between satellite tracks is around 315 km at the equator line. The cropped data were then grouped based on the same month and year, then filtered according to the boundary of study area. In this stage, NaN data must be deleted to avoid error propagations in future steps. Meanwhile, the filtered data from each pass were merged to gain seven years of SLA.

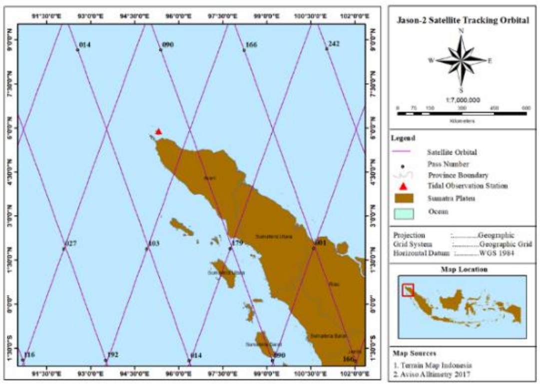

Figure 2-1: Pass Jason-2 satellite track and the tidal observation station

2.3 Methods

A month consists of three cycles. The monthly average values of SLA for every observation station were plotted in a graph to reveal the linear trend for six years. The validation of satellite data was performed using IOC sea level monitoring retrieved from *http://www.ioc-ealevelmonitoring.org/*, which the Jason-2 sea level data were compared with IOC tidal data. The sea level reference used for SLA was mean sea surface (MSS). Sea level anomaly from Jason-2 satellite altimetry data can be calculated using linear regression formula in the form of time series data as follows:

$$y = mx + c \tag{2-1}$$

where y = vertical distance; x = horizontal distance; m = gradient; c = cross section at line y

Linear regression was employed to define the velocity estimation of SLA at certain times in the form of time series, so that it can be predicted (forecasted) for other periods (Rohman, 2010). In this case, the *y* component represents SLA data (in meters), while the *x* component is an independent variable determining time, and gradient *m* is the slope of the line that represents the SLA rate.

To evaluate the influence of climatic factors on SLA, we used DMI (dipole mode index) data (retrieved from htpp://www.jamstec.go.jp). The supporting time series sea surface temperature data were retrieved from the European Centre for Medium-Range Weather Forecast (ECMWF) (http://www.ecmwf.int/en/research/climate-reanalysis/browse-reanalysis-datasets). To prove the erratic influence of ENSO, we employed the Southern Oscillation Index (SOI) (retrieved from http://www.weatherzone.com). Linear regression and correlation were employed in this study to investigate the possible impacts of ocean–atmosphere interactions. However, there is a significant correlation between DMI and SLA, therefore it is possible that the linear regression of any variable on DMI would be contaminated to some degree by this correlation (Saji & Yamagata, 2003).

On the other hand, ENSO might also have a special role in triggering sea level anomaly in Aceh waters. As an equatorial region, rainfall intensity in Indonesia is strongly driven by MJO and this might have a role in elevated sea level. To address this, we tried to correlate the real-time multivariate MJO (RMM) index retrieved from http://www.bom.gov.au/climate/mjo/ with the anomaly in sea level drawn from Jason-2 satellite data analysis. In addition, we only considered the RMM index during the peak period of SLA, to identify if MJO also has a role in elevating sea level.

3 RESULTS AND DISCUSSION

In this study, rise in sea level during the period 2009–2015 was approached from SLA data drawn from the processing of satellite altimetry data grouped in cycles. The validation of this data is shown in Figure 3-1. It can be seen that the same phase of IOC data and SLA Jason-2 data is obtained, so it can therefore be considered that the analysis is thorough and represents field conditions. For technical reasons, the validation was only applied for two annually periods of observation (2013 and 2014).

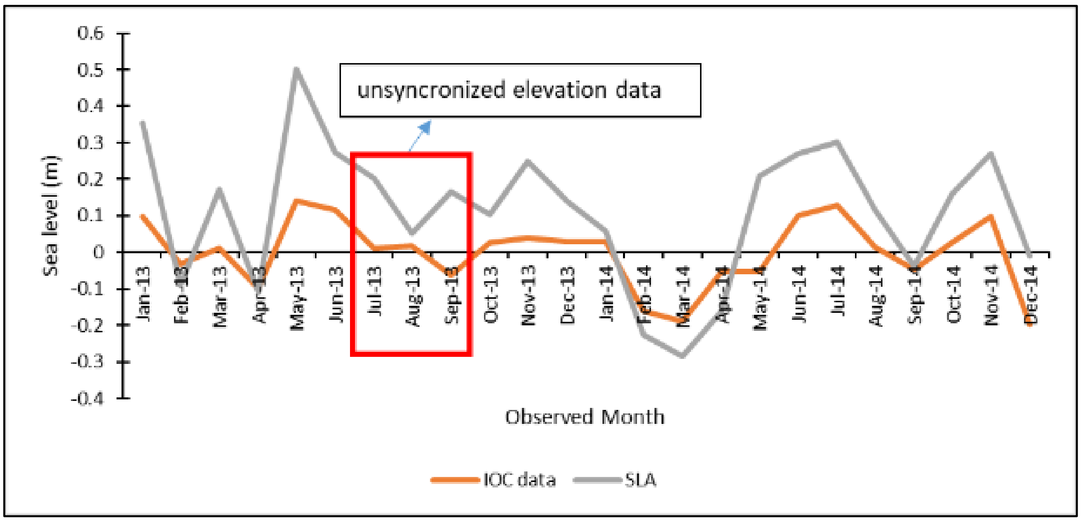

Figure 3-1: Sea level validation using IOC tidal data

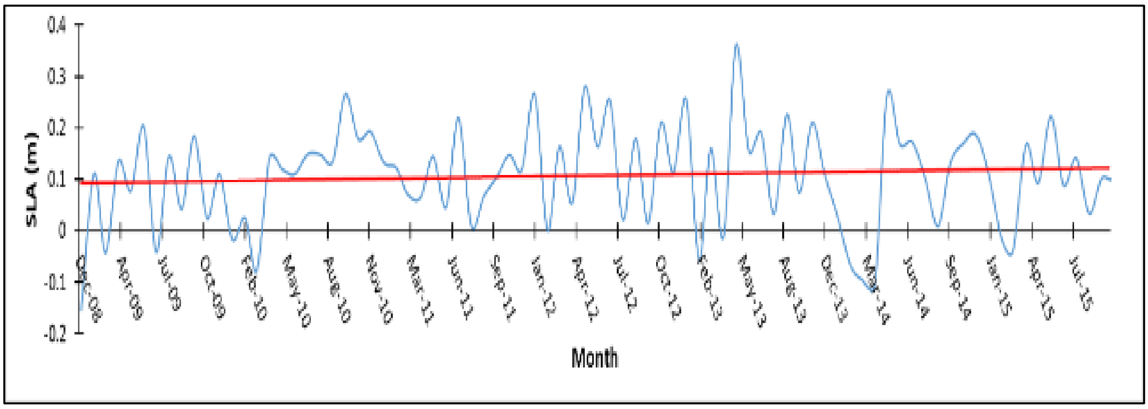

Figure 3-2: Sea level linear trend for Aceh waters 2009–2015

The same phase of sea level for SLA and IOC data was identified. An anomaly was found during July–October 2013, in which the pattern was oppositely formed (as indicated by the red square). This unsynchronized elevation of sea level ranges from 0.03–0.25 meters, and could be caused by either satellite data bias or incorrect tidal data determination. Differences in tidal frequencies may arise from errors in the model used to correct the altimetric heights as well as from local tidal deformations (Nerem et al., 2010). In addition, to deal with error data, we re-checked the compared data three times, to make sure that biased data were identified.

Figure 3-2 provides information on the linear trend of sea level anomaly during 2009–2015. The equation obtained from linear regression $y = 0.00001x - 0.3851$ (where y represents SLA and x represents time of observation) was employed to calculate sea level rise for six years and its annual changes in Aceh waters. Trend units are measured in meters and can be either negative or positive according to the analysis result (Sidabutar, Sasmito, & Amarrohman, 2016). In the actual conditions, despite rising sea level, the linear trend may be low (negative) due to the influence of climatic factors and satellite error. Overall, regional sea level rise in Aceh waters for the six-year period was 0.06 mm, with the annual average being around 0.0095 mm/year.

According to regression analysis, R^2 as the determiner coefficient is used for analyzing correlation between independent variables that influence the dependent variable. In this case, we determined the size of the influence of an observation on sea level rise in Aceh waters. The scale used is 0 to 1, whereby the higher the resulting value, the stronger the correlation between variables. The R^2 obtained of 0.0081 indicates a weak correlation between SLA and dipole mode (Montgomery, Peck, & Vining, 2012). The highest SLA value is 0.36 meters, while the lowest value is -0.15 meters (Figure 3-2).

SLA can be calculated through comparison between sea surface height obtained from satellite altimetry and MSS and its corrections (Wuriatmo, 2011). The peak anomaly was identified during April–May 2013 (first transitional season) and gradually declined during November 2013–February 2014 (northeast monsoon). This fluctuation in SLA is influenced by atmosphere–ocean interactions such as IOD and ENSO that play a role in controlling climate and weather conditions in the Indian Ocean region. These two climatic factors induce the variability of rainfall in the Indonesian archipelago. In northern Aceh waters, the influence of ENSO is more erratic (Girishkumar et al., 2015). Furthermore, the oscillations of dipole mode through the Bay of Bengal has a significant effect on reflecting temperature and sea level changes between the Asian and African continents (Aparna, McCreary, Shankar, & Vinayachandran, 2012). In contrast, as the ocean is a good heat conductor, thermal expansion occurring in the ocean is the main factor evoking global sea level changes. Antarctic polar ice, glacier liquefactions and groundwater mass intercalation have particular influence on global sea level changes (Surinati, 2013; Hartanto, Prijatna, & Nurmaulita, 2014).

3.1 The influence of climatic factors on SLA

Figure 3-3 shows the phase comparison between SLA, DMI, SOI and surface temperature in Aceh waters. Overall, the variability of SLA was relatively strong which its range is averagely 0.25 meters. The strongest symptoms of SLA were observed during transitional seasons over the period of 2009–2015 whereby the higher sea level is correlated with the influence of negative dipole mode and positive SOI value. Moreover, the temperature fluctuation was in phase with SLA variability.

The lowest dipole mode was observed in May 2013, at 0.29 meters. This triggered sea level to reach its peak value of 0.36 meters at the same time. Those conditions were also in force for the reverse situation: when positive dipole mode occurred (with value of 0.944) sea level was lower (by around 0.22 meters), as identified in August 2012.

Positive mode of IOD causes higher air pressure centered in the eastern Indian Ocean, and vice versa. This induces wind to blow strongly from east to west which brings warm water mass flowing westward. As a result, greater increase in sea level values occurred in the western Indian Ocean. Annual sea temperature variability is locked to monsoon cycle phase and the peak phase of positive mode which brings about the rainy season in the southeast Indian Ocean (Du et al., 2008). During negative IOD mode, occurring in November 2010, May 2012, May 2013, September 2014, and April 2015 during transitional seasons in the western Indian Ocean, sea level tended to be higher, in accordance with the increasing of surface temperature. Furthermore, the increase of rainfall intensity due to temperature changes in the Indian Ocean strongly affects evaporation and the tendency for sea level to rise (Mulyana, 2000).

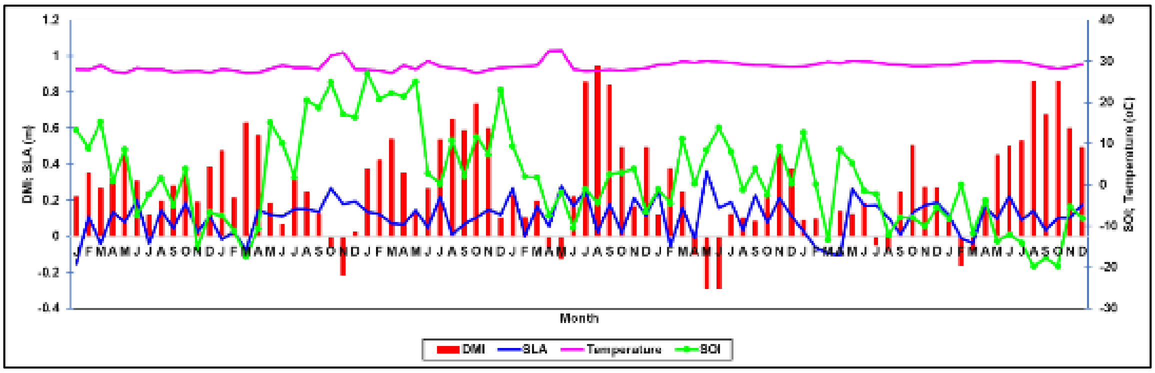

Figure 3-3: The influence of IOD and ENSO on triggering SLA and SSTA in Aceh waters

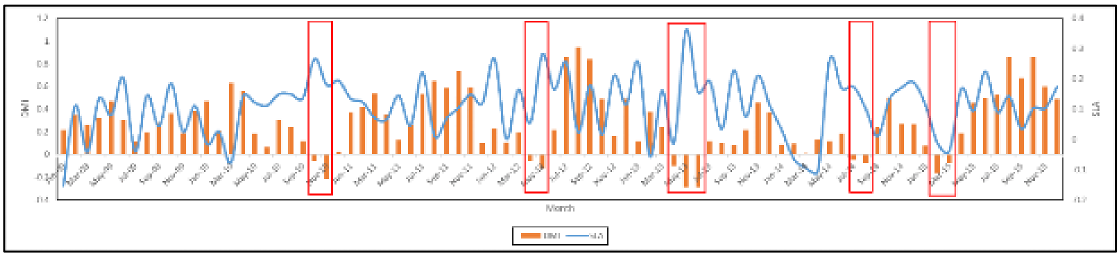

Figure 3-4: Monthly comparison between SLA and DMI

Figure 3-3 also shows that the influence of ENSO emerged erratically in Aceh waters, in which positive phases were predominant over six years, ranging from -20 up to 29. Generally, the amalgamated influence of ENSO and IOD results in the variability of surface temperature-induced anomaly in sea level. Despite stronger influence at certain phases of transitional seasons, the anomaly in sea level varied in other monsoon periods. Nevertheless, at certain periods, ENSO has a special role in bringing about a warming pool in the Indian Ocean resulting in higher evaporation and possibly impacting on sea level (Napitu, Gordon, & Pujiana, 2015). On the other hand, from data comparison as shown in Figure 3-4, we found that the influence of IOD and ENSO on triggering SLA was periodically erratic, and that the peak SLA values in 2009–2013 were most likely to reflect the influence of negative dipole mode inducing higher sea temperature and resulting in elevated SLA. In contrast, during the peak SLA phases in 2014 and 2015, the influence of ENSO was predominant in declining SLA, even though the dipole mode was negative as well. Moreover, temperature fluctuation was more likely to reflect IOD patterns ranging from 29–31°C. Thus, we can draw the conclusion that both IOD and ENSO have a consecutive role in affecting SLA and SSTA in Aceh waters. If we look in more detail, the amalgamated leverage of IOD and ENSO on Aceh waters acts like a 'see-saw' which is successively affecting anomaly in both sea level and temperature.

Figure 3-4 proves that negative dipole mode intensely induced high value of SLA (red squares) that occurred chiefly during transitional seasons. The highest SLA values were identified in October 2010, May 2012 and May 2013 with elevation of 0.28, 0.27, and 0.36 meters, respectively, and dipole mode value of -0.056, -0.122, and -0.29, respectively. According to Saji and Yamagata (2003), negative IOD events are associated with warming intensity and sea level anomalies. With regard to ENSO influence, in September 2014 and April 2015, lower values of SLA were observed (at around zero meters) when negative mode of IOD took place. This suggests that the declined sea level is most likely to reflect ENSO forcing SLA.

These conditions also trigger a consideration of whether MJO events have a role in inducing sea level change. We checked the RMM index to investigate the MJO event (Figure 3-5) during the significant periods of SLA (red squares in Figure 3-4). MJO variability is directly related to warm pool formation in the eastern Indian Ocean, such that it moves eastward in accordance with westerly winds along the equator followed by thick cumulus cloud formation. These processes cause high rainfall intensity due to warming-event-induced evaporation (Windayanti and Surinati, 2016). Because of the rise in temperature and rainfall intensity, sea level changes will probably take place.

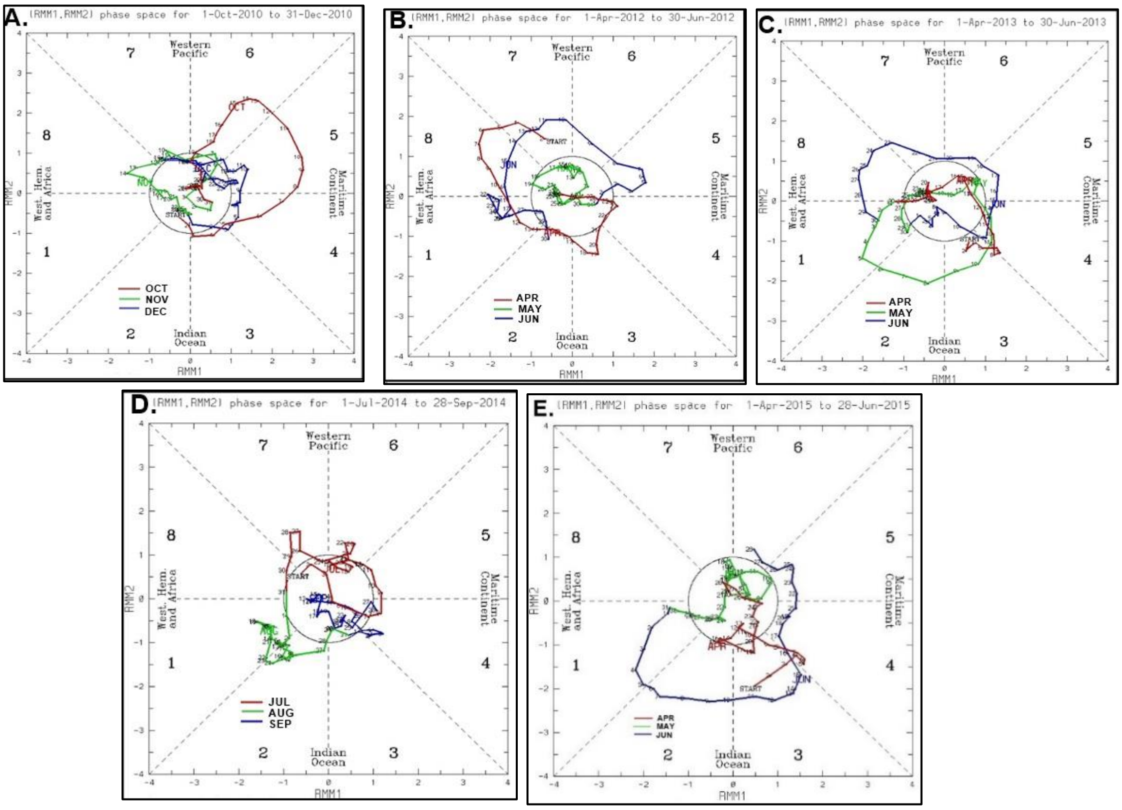

Figure 3-5: RMM index during the highest phase of sea level: A. Phase pace for October–December 2010; B. Phase space for April–June 2012; C. Phase space for April–June 2013; D. Phase space for July–September 2014; and E. Phase space for April–June 2015. (Source: http://www.bom.gov.au/climate/mjo/, modified by authors)

The MJO phase diagrams illustrate the progression of MJO as the period of significant sea level anomaly observed previously (Figure 3-5). With the exception of high SLA in May 2013, the high values of SLA which were seen in October 2010 and May 2012 were not influenced by MJO. During those two periods, the RMM index shows weak frequency of MJO in the Indian Ocean, as indicated by the index being within the center circle, meaning that it is difficult to discern MJO using the RMM method (Kim et al., 2016) (Figures 3-5A and 3-5B). Meanwhile, for the May 2013 period (Figure 3-5C), MJO showed a quite strong influence on inducing evaporation in the Indian Ocean region that will usually move in an anti-clockwise direction as MJO moves from west to east (Moum et al., 2016). While passing Indonesia seas, it is possible that the high convective evaporation resulting from the MJO event will also affect SLA in western Sumatra waters such as Aceh, where the highest SLA identified was strongly influenced by IOD-associated MJO. The weak MJO phases in the Indian Ocean are also shown in Figure 3-5D and 3-5E, reflecting the weaker influence of climatic factors on controlling water conditions in the surrounding Indian Ocean (Izumo et al., 2010).

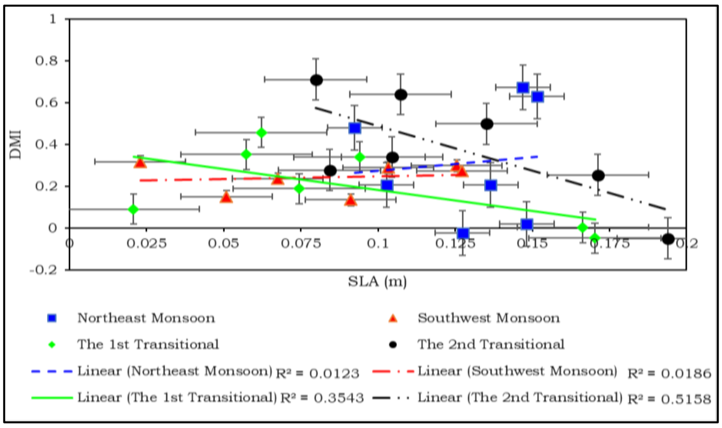

Figure 3-6: Intra-seasonal linear regression between SLA and DMI during 2009–2015

3.2 Correlation analysis of climatic factors with SLA

Figure 3-6 illustrates the seasonal linear regression of SLA and dipole mode over six years (2009–2015). Overall, during southwest and northeast monsoons, the correlation between DMI and SLA was weak, with almost zero R^2 values. Meanwhile, during transitional phases, stronger correlations were identified, at around 35 per cent and 51 per cent for the first transitional and second transitional seasons, respectively. A similar correlation is also shown by ENSO–SLA linear regression (Figure 3-7), where a sufficiently high R^2 value was determined in the second transitional season with around 70 per cent of correlative variables. The other phases seem to reflect weak tendencies of ENSO influence, with R^2 values of almost 0.1.

In contrast to the previous two correlations, the interaction variability between SSTA and SLA (Figure 3-8) was quite strong, with the exception of the southwest monsoon period, for which the R^2 value was only 7 per cent. During the two transitional phases, the interaction of SSTA-induced SLA was quite frequent, with correlation values of 0.28 and 0.53, respectively. A sufficiently strong correlation was also seen during the northeast monsoon, with R^2 value of around 40 per cent.

To conclude, strong variability of SLA mostly occurred in the transitional seasons in which the influence of periodic climatic factors consecutively emerged and tended to control SSTA-induced SLA. Once again, we can consider that interaction between IOD and ENSO has a special role in determining the ocean–atmosphere interactions of Aceh waters.

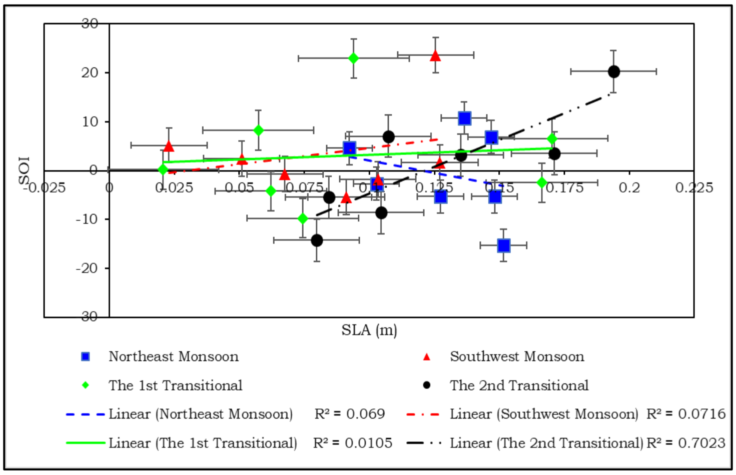

Figure 3-7: Intra-seasonal linear regression between SLA and SOI during 2009–2015

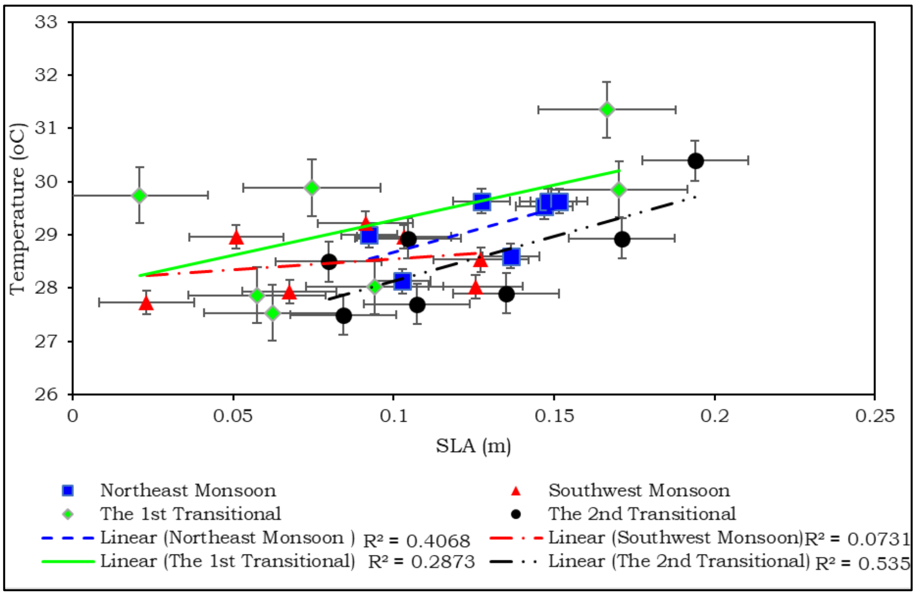

Figure 3-8: Intra-seasonal linear regression between SLA and sea temperature during 2009–2015

4 CONCLUSION

Sea level in Aceh waters shows an upward trend. In the three first years of observation, the influence of IOD was predominant, tending to increase SLA, while for the last two years of observation, SLA tended to decrease because of lower ENSO index. These interactions consecutively occur in Aceh waters in a 'see-saw' fashion. Another climatic factor that possibly has a role in triggering SLA is MJO, in that together with negative dipole mode, it induced the highest value of SLA, on May 2013. Otherwise, its influence did not appear frequently; in other words, it tends to have a weak role in triggering SLA. The strongest variability occurred during transitional phases of monsoons where the strongest correlations between IOD–SLA, ENSO–SLA, and SSTA–SLA were identified in second transitional seasons. Climatic factors have a particular role in elevated sea level in Aceh waters, the amalgamation of which will induce higher anomaly in sea level.

ACKNOWLEDGEMENT

We acknowledge the Radar Altimetry Database System (RADS) of Jason-2 satellite and the sea level monitoring of IOC for providing the sea level data used in this study. Gratitude is given to Nia Nalelul Hasanah Ridwan as the head of RICRV and to all those who have helped in the completion of this article.

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