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Mapping Climate Change Vulnerability of the Java Sea Ecosystem

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Abstract— **This present study aims to investigate climate change trends in the Java Sea and integrate these trends with the distribution of the lower trophic level of marine ecosystem parameters and the distribution of coastal ecosystems into a climate change vulnerability map using data products of wind, rainfall, sea surface temperature (SST), satellite imagery of Landsat TM and a coupled hydrodynamic-biogeochemical model output. Climate change vulnerability mapping was conducted using a Geographic Information System (GIS), with a vulnerability equation from IPCC. This study shows that the high vulnerability is located in the southern coast of Kalimantan, Jakarta Bay, Semarang waters, and Madura Strait because of riverine inputs from human activities in the land and possible future worse conditions due to the positive rainfall trends in those regions. The low vulnerability is found in the northwestern and southeastern parts of the Java Sea associated with the negative trends of rainfall and SST. In general, the moderate vulnerability covers almost the entire Java Sea. This study suggests strengthening the coastal ecosystem through protection and rehabilitation in the future to enhance adaptive capacity. In addition, the organic and inorganic riverine inputs have to minimize, related to the positive trend of rainfall in the future, particularly those regions with high vulnerability. Integration of the spatial land model, the ocean model, and climate forcing are expected to improve our understandings of climate change vulnerability, which is relevant for climate adaptation action plans.**

Keywords— **The Java Sea; climate change; vulnerability map; GIS.**

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I. INTRODUCTION

Global warming is one of the environmental issues in the world that causes global climate and environmental changes. The phenomenon is indicated by the increase in greenhouse gas emissions, especially those from burning fossil fuels. Emissions from greenhouse gases cause an increase in global surface temperature both on land and in the oceans. According to IPCC [1], the global surface temperature of the earth in the last hundred years has increased by 0.7 °C. The IPCC [1] estimates that the global surface temperature will increase by ± 2 °C and ± 4 °C by 2100.

The latest IPCC report [2] emphasizes that the impact of climate change on coastal areas is getting worse where the incidence of heavy rains will increase, including tropical cyclones with peak wind speeds. Globally, the IPCC [2] projects that extreme daily rainfall events will increase by about 7% for every 1°C of global warming. In addition, the new IPCC climate scenario [2] predicts that rainfall variability associated with ENSO will be strengthening in the second half of the 21st century. In this report, Southeast Asia regions are also threatened by the possibility of an increase in monsoon rainfall. In addition, urbanization could exacerbate the coastal cities by increasing mean and heavy precipitation and subsequently affect runoff intensity, including riverine nutrient inputs to coastal waters.

The impact of rising temperatures will cause changes in aquatic ecosystems around the world, including the Java Sea. The IPCC [2] reported that global surface and ocean temperatures were 1.09 °C and 0.88 °C higher in 2011–2020 than in 1850–1900, respectively. In addition, Iskandar *et al.* [3] reported that SST in the Indonesian seas has increased by about 0.19 ± 0.04 °C decade^{-1}, with a strong warming trend observed in the Java Sea (0.2-0.25 °C decade^{-1}). In this case, the SST trend in the Indonesian seas is more extensive than the global SST warming trend.

The impact of global warming could change the productivity and composition of marine phytoplankton communities, including the global biogeochemical cycles. A model by Thomas *et al.* [4] predicted poleward shifts in thermal niches species and a sharp decline in tropical phytoplankton diversity without an evolutionary response. Temperature and phytoplankton play a significant role in marine ecosystem dynamics as well as fishery production. Most of the primary productivity in the sea is carried out by phytoplankton, where primary productivity is the quantity of carbon fixation in the photosynthesis process. Phytoplankton converts inorganic materials into new organic compounds so that light, nutrients, CO_2, and temperature in the ocean are factors that affect primary productivity and the abundance of phytoplankton in determining ocean productivity in a region [5]–[7].

The relationship between SST and Chlorophyll-a (Chl-a) concentrations with pelagic fish shows a different response among fish species. For example, sardine fish (Sardinella *lemuru*) and fringescalle sardine (Sardinela *fimbiarta*) show there is no direct relationship between SST and their catch per unit effort (CPUE). The response of the sardinella fishes to the concentration of Chl-a shows a positive response where an increase follows the increase in Chl-a concentration in their CPUE. The sardinella fishes are a pelagic fish species whose existence depends on the concentration of Chl-a [8].

The fisheries sector is very active in the Java Sea to support the domestic consumption of the majority of the Indonesian population, where 60% of the population lives on Java Island. On the other hand, the condition of fisheries in the Java Sea is decreasing, which is indicated by the weak ability to recover small pelagic fish resources in the waters due to overfishing [9], [10]. Overfishing is further exacerbated by decreasing water quality due to coastal water pollution [11]–[14]. Thus, planning in dealing with climate change, especially in the Java Sea, needs to be based on evidence (scientific data). For this reason, the present study aims to investigate climate change trends in the Java Sea and integrate these trends with the distribution of the lower trophic level of marine ecosystem parameters (Chl-a, nitrate, and phosphate) and the distribution of coastal ecosystems (mangroves, coral reefs, and seagrass) into a climate change vulnerability map.

II. Materials and Method

The present study was carried out using data products of wind, rainfall, SST, and Chl-a. All parameters are in monthly mean temporal resolution. Wind data was taken from the European Center of Medium Weather Forecast (www.ecmwf.int) with a spatial resolution of 1.5° x 1.5°. Precipitation (rainfall) was taken ESRL CPC Merged Analysis of Precipitation/CMAP (http://www.esrl.noaa.gov/) with a spatial resolution of 2.5° x 2.5°, SST data was taken from ICOADS, Earth System Research Laboratory (ESRL) Physical Sciences Division (PSD) NOAA (http://www.esrl.noaa.gov/). In comparison, Chl-a was taken from Global Chl-a case-1 water (CHL1) of the European Service for Ocean Colour (www.globcolour.info) with a spatial resolution of 0.25° x 0.25°. All parameters were accessed during 2010-2014 and interpolated into a spatial resolution of 2’ x 2’ for the Java Sea study area for 10 years of data analysis (1999-2008).

The present study adopts a model output developed by Koropitan and Ikeda [15] in the Java Sea. The horizontal model resolution is 2' x 2' and has 21 unequal vertical resolutions (sigma coordinate system). In particular, for vertical sigma coordinates, high resolution is applied to the surface and near-bottom layers to accommodate the friction process closer to natural conditions. The model domain includes a geographic position of 2°42' - 8°14' S and 105°42' - 114°42' E. It is a 3-dimensional coupled hydrodynamic-biogeochemical model, where the hydrodynamic model uses the Princeton Ocean Model (POM). The biogeochemical model has 8 compartments, nitrate (NO_3), ammonium (NH_4), phosphate (PO_4), phytoplankton (F), zooplankton (Z), pelagic detritus (PD), benthic detritus (BD) and dissolved inorganic carbon (DIN). This biogeochemical model accommodates riverine nutrient inputs from 21 rivers that drain into the coasts of Sumatra, Java, and Kalimantan.

Area measurements of coastal ecosystems (mangroves, coral reefs, and seagrass) around the coastal zone of the Java Sea (Fig. 1) were carried out using satellite imagery of 15 scenes from Landsat TM for each year of 1997 and 2003. The two periods of the selected year were used for comparison to analyze the coastal ecosystems changes. Image processing was started with geometry, radiometric, and atmospheric corrections, then continued with image enhancement and interpretation (such as segmentation, classification, and pattern recognition). Spatial distributions of bottom water characteristics (coral reefs, seagrass beds, sand, and rubble) were extracted from satellite images using compositing and sharpening with the standard exponential attenuation model [16]. The algorithm applies the water column correction method that is effective for constructing a thematic map of coral reefs by generating a depth-invariant bottom index using the following equation [17]:

$$Y = ln(Band1) - \frac{k_i}{k_j} ln(Band2) \quad (1)$$

Y = the bottom index; B = selected band; k_i/k_j= coefficient of attenuation.

A multi-image sharpening method is applied to combine Band1 and Band2 based on the standard exponential attenuation model to get the maximum appearance of the bottom substrate. The depth-invariant bottom index resulted in a derived image (pseudo image) where the range of color indicates the number of classes in the aquatic substrate, such as sand, seagrass, live coral, and dead coral. The present study determined 6 classes of the bottom substrate category.

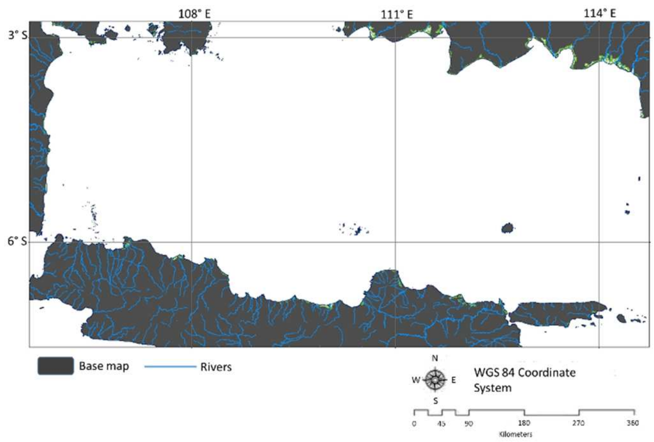

Fig. 1 Coastal zone of the Java Sea used by the present study for coastal ecosystem measurements.

Measurement of mangrove cover in the coastal areas was performed by differentiating with another land cover, made by supervised classification-based objects. Land cover data from the topographical map of Indonesia (RBI) and land cover provided by the Geospatial Information Agency-Indonesia were used as a reference for identifying mangrove forests. Supervised classification was carried out by dividing the land use type into two types: mangrove and non-mangrove. Thus, other plants and other types of closures of land were classified as non-mangrove. To minimize the error in the image classification, a radiometric correction and masking toward a body of water was applied to the satellite imagery to get the image of the mainland only. The classification-based object was carried out by grouping the objects that have spectral similarity values on some pixels. Grouping such objects are known as segmentation, which was undertaken by using the Nearest Neighbor algorithm.

Preston *et al.* [18] has adopted the principle of vulnerability mapping performed in Sydney, Australia, with some modifications for mapping climate change vulnerability in the Java Sea. By definition, the vulnerability (V) equation according to IPCC [19] is:

$$V = f(E, S, A) \quad (2)$$

Exposure (E) is the level of pressure on the climate in a specific unit analysis, representing a change over a long period or a change in climate variability, including the magnitude and frequency of extreme periods. Sensitivity (S) is the extent to which a system will be affected by or its response to a stimulus. Adaptive capacity (A) refers to the potential or ability of the system to adapt to climate change and be able to manage E/S so that it produces a good impact. So, the more extensive E or S, the greater the vulnerability, but reversely the role of A could reduce the level of vulnerability.

In this study, all parameters were uniformed in the range of values, with the thematic range of parameters being 1 – 9. This range of values was obtained by referring to the standard deviation so that the entire range of values and different units could be uniformed. Furthermore, all these parameters are combined, with the weight (percentage) of each parameter as follows:

- Exposure, consisting of climate change parameters, such as SST trend (10%), rainfall trend (5%), and wind speed trend (5%) from 1999 to 2008, as calculated from the data products,
- Sensitivity, representing the annual means of Chl-a (CHL1) (15%), dissolved inorganic nitrogen-DIN (10%), and dissolved inorganic phosphate-DIP (10%) in the Java Sea (from the model results [15]),
- Adaptive capacity, consisting of coral reef coverage (15%), mangrove (15%), and seagrass changes (15%), for 2003 conditions, as observed by Landsat TM image data.

The classification of vulnerability index refers to Preston *et al.* [18], where the index range is divided into three classes: low vulnerability index for 1-3, medium vulnerability index for 3-6, and high vulnerability index for 6-9. The weighting process (percentage) considered the climate change impact on the coastal and marine ecosystems in the Java Sea. In this case, the components of the adaptive capacity had the highest weight, especially the coastal ecosystem considering their ecological functions for marine biota. Medium weight was a component in the sensitivity, where these parameters function in primary productivity. Considering the role of the producer in the marine food chain, Chl-a, a parameter in the sensitivity, was set to be similar to the percentage of one parameter in the adaptive capacity. Furthermore, exposure has the lowest weight, considering its role as a driving force.

The mapping of climate change vulnerability was conducted using a GIS, which included three steps, 1) spatial database, 2) overlay modeling and analysis, and 3) data presentation. The spatial database was set by classifying the basic and thematic layers. The basic layers were administrative area, hydrology, and other important information such as cities, bays, straits, and river estuaries, while the thematic layers were related to coastal and marine ecosystems. All data inputs and a map product of the climate change vulnerability in the Java Sea has 2' x 2' spatial resolution.

III. Results and Discussion

A. Wind, Rainfall, and SST Trends Over the Java Sea

In general, the average wind speed for December, January, and February (DJF) or during the northwest monsoon (NWM) between 1999 to 2008 (Fig. 2) and for June, July, and August (JJA) or during the southeast monsoon (SEM) between 1999 to 2008 (Fig. 3) in the Java Sea ranged about 3.5 – 5 m s^{-1}. However, the wind speed showed a higher magnitude in the central part of the Java Sea compared to other parts in the Java Sea. Especially during SEM, the magnitude reached 5.5 – 7 ms^{-1}. The positive trend of wind speed during 1999-2008 was seen dominant around the central and eastern parts of the Java Sea, where the positive trends reached around 0.02 – 0.03 m s^{-1} $year^{-1}$ (Fig. 4). However, a negative trend was seen in the western part of the Java Sea, particularly the northern West Java and southeast of Sumatra, which reached -0.02 to -0.05 m s^{-1} $year^{-1}$. The present study also found a negative trend of wind speed in the southern coast of Java, which was similar to the study as reported by Varela *et al.* [20].

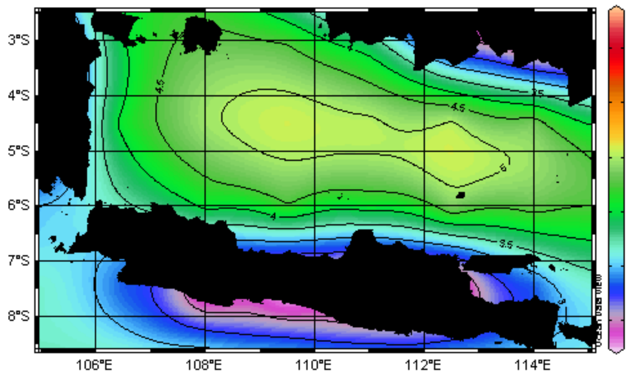

Fig. 2 Seasonal average of NWM wind speed (DJF) during 1999-2008 (ms^{-1})

In general, the seasonal average of rainfall over the Java Sea showed higher rainfall during NWM (Fig. 5) than during SEM during 1999-2008 (Fig. 6). The seasonal average of rainfall could reach 10-11 mm/day during NWM while 1-4 mm day^{-1} during SEM. The present study results are comparable with those of Hassim and Timbal [21], where the DJF average for the period 1998 – 2014 reached 12-13 mm day^{-1}, while the JJA average reached ~ 4 mm day^{-1}. The present study showed a positive trend of rainfall in the waters of South Kalimantan and the northern coast along Central and

West Java, which reaches 0.1 mm year^{-1} (Fig. 7). The positive trend corresponds with As-syakur *et al.* [22] for the exact locations, 0.06-0.18 mm year^{-1}.

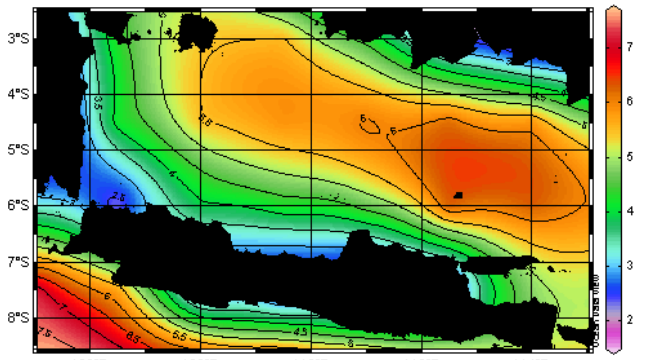

Fig. 3 Seasonal average of SEM wind speed (JJA) during 1999-2008 (ms^{-1})

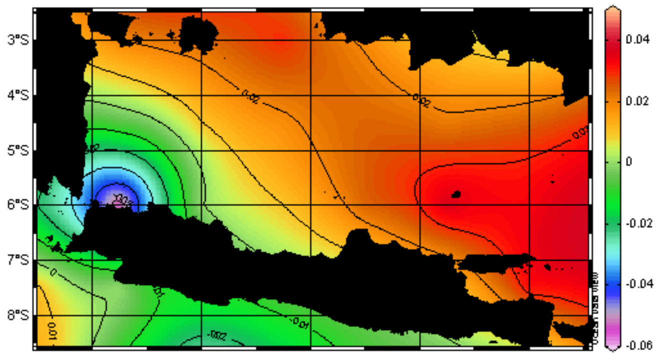

Fig. 4 Trends of wind speed in the Java Sea during 1999-2008 (m s^{-1} year^{-1})

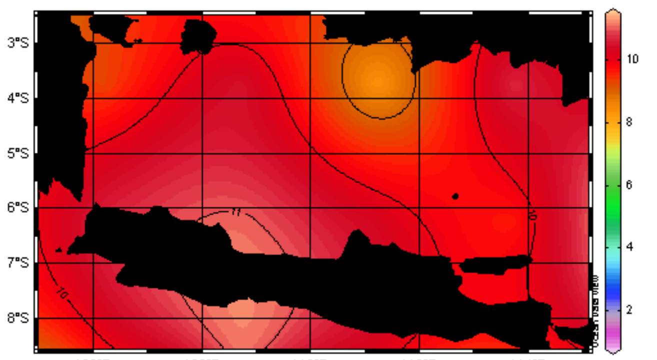

Fig. 5 Seasonal average of NWM rainfall (DJF) during 1999-2008 (mm day^{-1})

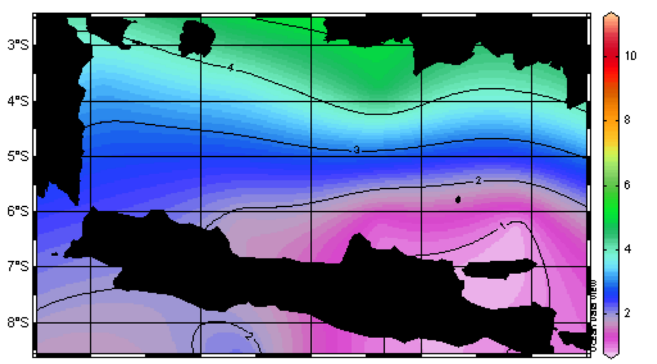

Fig. 6 Seasonal average of SEM rainfall (JJA) during 1999-2008 (mm day^{-1})

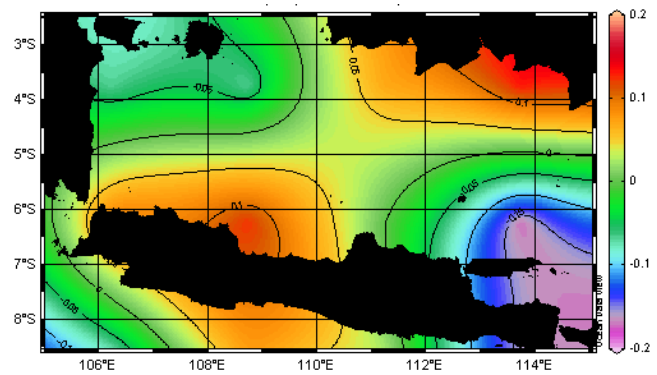

Fig. 7 Trends of rainfall in the Java Sea during 1999-2008 (mm year^{-1})

On the other hand, a negative trend of –0.2 mm year^{-1} occurred in the eastern part of the Java Sea. A negative trend of -0.1 mm year^{-1} was also seen in the western part of the Java Sea, especially the southeastern coast of Sumatra and south of the Karimata Strait. The rainfall trend pattern in this study is similar to that reported by As-syakur *et al.* [22]. Considering the interannual variability over the Indonesian seas, Kurniadi *et al.* [23] emphasized that rainfall extremes are most robust during the dry season and weaker during the wet season due to ENSO (the El Niño-Southern Oscillation) and IOD (Indian Ocean Dipole) impacts.

The seasonal average of SST in the Java Sea showed a similar range of values during NWM (Fig. 8) and SEM (Fig. 9), which was 28-29 °C. However, the present study showed a different pattern due to the monsoonal flow pattern in the Java Sea, which is under the monsoon wind effect. The current moves from the North Natuna Sea to the Java Sea during NWM and brings a relatively cold SST, as seen entering the Java Sea (Fig. 8). On the other hand, the current reverses out of the Java Sea towards the North Natuna Sea during SEM, and the relatively cold SST due to upwelling in the southern Makassar Strait enters the Java Sea. In addition, the present study showed a positive trend of SST (0.025-0.05 °C year^{-1}) in the Java Sea during the period 1999-2008 (Fig. 10). However, particular areas in the Java Sea indicated a negative SST trend (- 0.05 °C year^{-1}), that might be affected by the SST from Karimata Strait. Kurniadi *et al.* [23] indicated a positive SST trend over the Indonesian seas, where a positive SST trend in the Java Sea reached 0.02 – 0.025 °C year^{-1}.

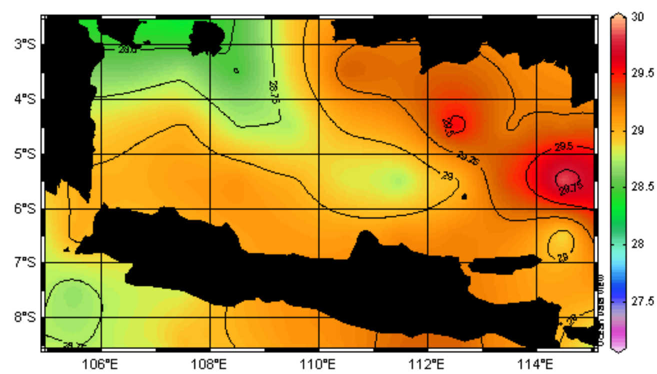

Fig. 8 Seasonal average of NWM SST (DJF) during 1999-2008 (°C day^{-1})

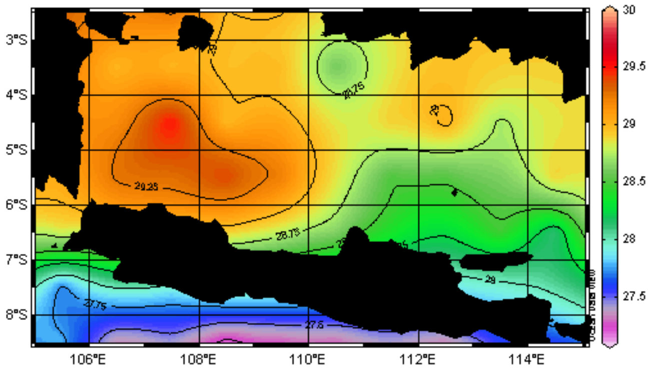

Fig. 9 Seasonal average of SEM SST (JJA) during 1999-2008 (°C day^{-1})

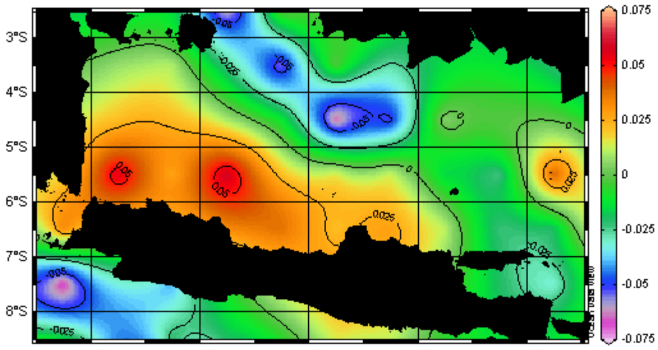

Fig. 10 Trends of SST in the Java Sea during 1999-2008 (°C year^{-1})

B. *Mapping Climate Change Vulnerability*

The coastal ecosystem changes for mangroves, coral reefs, and seagrass are presented in tabular forms because their distribution in the Java Sea is almost invisible on a map. For example, changes in mangrove coverage between 1997 and 2003 surrounding the Java Sea are presented in Table 1 based on the results of satellite data processing. The mangrove ecosystem decreased by an average of -34.6%, where the most significant change occurred on the northern coast of Java (-69%). In addition, the tabular forms for coral reef coverage decreased on average to -8.2% for Bangka Belitung Islands, Seribu Islands, Karimunjawa Islands, Kangean Island, and northern Madura Island, with the most considerable change was seen in Karimunjawa Islands (-50%). On the other hand, the distribution of seagrasses was observed only in Seribu Islands, North Jakarta, because of cloud disturbances in the satellite imagery. Changes in seagrass coverage in Seribu Islands could reach around – 9.7%.

TABLE I
REMOTELY SENSED MANGROVE COVER CHANGE (KM^2) SURROUNDING THE JAVA SEA

Coastal regions	1997	2003	Changes	Percentage of change
Southeast Sumatera	706.84	644.73	- 62.10	- 8.8%
North Java	1579.86	489.69	- 1090.18	- 69.0%
South Kalimantan	1738.00	1497.32	- 240.68	- 13.9%
Total	4024.72	2631.75	- 1392.96	- 34.6%

The results of mapping climate change vulnerability in the Java Sea are presented in Fig. 11. The high vulnerability distributes on the southern coast of Kalimantan, Jakarta Bay, Semarang waters, and Madura Strait. The high vulnerability in those regions is mainly influenced by the sensitivity parameter, characterized by riverine nutrient supply from settlements, industry, and agriculture in the land. Thus, the role of anthropogenic impact dominates this high vulnerability region, as also discussed in Koropitan and Ikeda [15]. In comparison with the previous study, the high vulnerability distribution of the present study shows overlap with the high-density distribution of the epipelagic (micronekton) biomass in the southern coast of Kalimantan, as reported by Susilo and Suniada [24]. The high-density distribution of fish biomass might be supported by high nutrient riverine inputs on the southern coast of Kalimantan. In addition, the mangrove ecosystem in this region also functions as a nursery ground and sanctuary for fish. This region also provides high organic production, which is vital for marine productivity. In other words, the organic decomposition process results in nutrient supply and primary productivity. Concerning the positive trend of rainfall in this region, the riverine inputs tend to increase in the future, bringing into eutrophication conditions. Therefore, the dissolved oxygen will decrease and consequently affects marine and fishery productivities. In addition, the mangrove cover change on the southern coast of Kalimantan is relatively significant (Table 1), with a reduction in mangrove coverage of 13.85% between 2003 and 1997. Therefore, the adaptive capacity was low in the region.

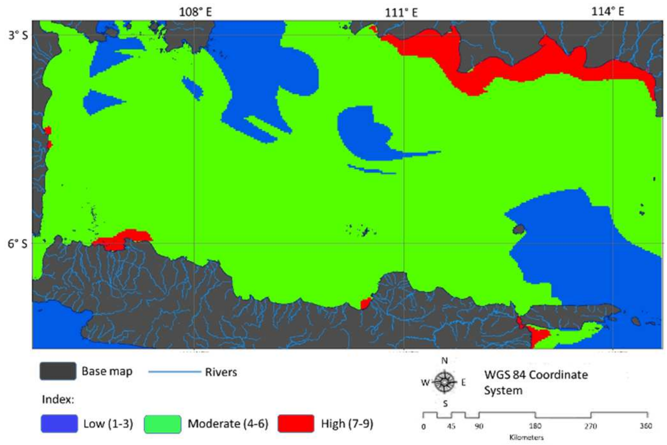

Fig. 11 Vulnerability climate change map of the Java Sea

This study shows a moderate vulnerability in almost the entire Java Sea, where the influence of the sensitivity parameter is still dominant. That means the distribution of riverine nutrient inputs is more limited in the nearshore waters. On the other hand, a low vulnerability distribution is seen in the northwestern and southeastern parts of the Java Sea, associated with climate change. The low vulnerable area represents the negative trends of rainfall and SST. Coincidentally, Wijopriono [25] reported the results of an acoustic investigation in 2002 to measure fish per unit of area. The study provided a map of the distribution of fish density distribution and highlighted its correlation with SST and seasonal (monsoonal) variability. Wijopriono [25] then concluded that the preference of pelagic fish distribution in the Java Sea is more optimal at SST less than 27 °C. The overlay of the vulnerability map and fish density distribution (the overlay map is not shown, but the fish density distribution map is clearly shown in Wijopriono [25]) indicates suitability between the low vulnerability and high fish density distribution.

Furthermore, the impact of the SST positive trend in the Java Sea has to balance with the role of the adaptive capacity parameter (coastal ecosystem), despite the coastal ecosystem distribution being limited locally and not seen on the vulnerability map of the Java Sea. Apart from being a nursery ground and sanctuary, strengthening coastal ecosystems such as mangroves also functions as a buffer area (filter) for land influences, such as retaining sediment and protecting beaches from abrasion, waves, and extreme weather (wind speed). Likewise, coral reefs provide high primary productivity for the marine ecosystem and can reduce wave energy. In addition, the seagrass ecosystem also functions as a nursery ground and provides high primary productivity for the ecosystem. Therefore, protection and rehabilitation of the coastal ecosystems are needed in enhancing the adaptive capacity actions. In addition, the impact of rainfall positive trend in the future needs to address by preparing strict land-use regulations, mainly to minimize the organic and inorganic riverine inputs.

IV. Conclusion

The present study demonstrates that a positive trend of wind speed during the period 1999-2008 covers almost the Java Sea, except the northern West Java and southeast of Sumatra, while a positive trend of rainfall covers the southern coast of Kalimantan and the north coast along Central and West Java. A positive trend of SST also covers almost the Java Sea, except a particular area influenced by the incoming low SST from the North Natuna Sea. Integration of the lower trophic level of marine ecosystem parameters and the distribution of coastal ecosystems shows a climate change vulnerability in the Java Sea, where the southern coast of Kalimantan, Jakarta Bay, Semarang waters, and Madura Strait indicates highly vulnerable areas. Meanwhile, the negative trends of rainfall and SST in the northwestern and southeastern parts of the Java Sea present low vulnerable areas. In general, the Java Sea indicates a moderately vulnerable area. In the future, strengthening coastal ecosystems (mangroves, coral reefs, and seagrass) through protection and rehabilitation will significantly enhance adaptive capacity actions. It is expected to lower the climate change vulnerability in the Java Sea ecosystem. To anticipate the positive trend of rainfall in the future, the coastal regions in the Java Sea need to minimize the organic and inorganic riverine inputs through strict land-use regulations, particularly those with high vulnerability.

A spatial land model based on GIS is required to develop a future land-use change scenario in the coastal regions along the Java Sea, including estimating riverine input scenarios for the coupled hydrodynamic-biogeochemical model of the Java Sea. On the other hand, the biogeochemical model needs to consider the thermal adaptation or temperature-dependent of the marine lower trophic ecosystem parameters (nutrients, phytoplankton, zooplankton, and detritus). Thus, integrating the land-ocean model and climate change forcing is expected to improve our understanding of climate change vulnerability, which is relevant for climate adaptation action plans.

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