Meteorological Factors Influencing Coastal Flooding in Semarang, Central Java, Indonesia, on 23 May 2022

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Meteorological Factors Influencing Coastal Flooding in Semarang, Central Java, Indonesia, on 23 May 2022

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Abstract It has been well established that coastal flooding is caused by heavy rains, storm surges, and high tidal waves that potentially lead to tremendous damage. Using brightness temperature (TBB) data from the Himawari satellite and ocean surface wind data from ERA5, we have investigated meteorological factors influencing strong wind and increased seawater level over the northern coast of Semarang which caused the coastal flood on 23 May 2022. Our results indicated that there are two potential meteorological factors that contribute to the coastal flooding during that period. Firstly, the formation of MCS over the ocean on the northern coast of Semarang led to heavy rain over the coast and strong-surface wind speed that potentially enhances ocean tidal waves toward Semarang. Secondly, the unusually strong-surface easterly winds cause the increase in seawater level through the Ekman pumping mechanism. As for the latter, the strong easterly wind stress led to strong Ekman transport to the south of the flow (i.e., to the northern coast of Java), causing a large net transport of seawater toward this region as a result of a balance between Coriolis and turbulent (wind) drag forces. Our results provided a new perspective on the factors influencing the increased seawater level intruding into Semarang during the coastal flooding on 23 May 2022.

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1 Introduction

Semarang is one of the big cities in Indonesia and is located on the northern coast of Java Island. Semarang city is an urban area and has a specific problem related to the coastal environment, and it has been reported that the coastal area is a subside relative to the mean sea level [1]. The condition that the topography is under the sea level rise, due to the effects of land subsidence, makes Semarang vulnerable to coastal floods [2–8].

On 23 May 2022, Semarang experienced a tidal flood disaster that caused the breaking of the coastal embankment in the Tanjung Emas Area. The Semarang City Disaster Mitigation Agency (BPBD) on Tuesday announced that the breaking of the coastal embankment causes seawater to flood the land with inundations of 40 cm to 1.5 m. Moreover, Tanjung Emas Maritime Meteorological Station Semarang BMKG recorded the height of the tide before the embankment broke at 15.00 WIB (08Z) reaching 2 m [9]. It is also recorded by BPBD that the coastal flooding had affected 1255 households [10]. The Semarang tidal flood during this day occurred in the phase of the moon perbani (neap tides), so the influence on the tides was not as high as in the phase of the full moon (spring tides) [11]. The existence of a storm that occurred at 02.00 WIB early in the morning in the Java Sea and the presence of persistent winds since a few days earlier are suspected to be one of the triggers for the Semarang tidal flood [11].

In this paper, the factors that affect strong winds and sea level increases that caused coastal floods on 23 May 2022, on the northern coast of Semarang, will be investigated using satellite and reanalysis data. The detail of the data and method that are employed for this study is written in Sect. 2. Then, the results and the discussion are described in Sect. 3. Furthermore, this is followed by the conclusions and future works in Sect. 4.

2 Data and Methods

The fifth-generation reanalysis data from The European Center for Medium-Range Weather Forecasting (ECMWF ERA5) [12] was used in this study. Data used from ERA5 is Mean Sea Level Pressure (MSLP), u and v components of wind at 10 m, 925 hPa wind, and Sea Surface Temperature (SST). The Global Satellite Mapping of Precipitation (GSMaP) gauge-corrected version-7 standard precipitation product was used to investigate the presence of rain that occurs in the Java Sea [13]. The spatial resolution of the GSMaP data is 0.01×0.01 degrees, and the temporal resolution is 1 h (https://sharaku.eorc.jaxa.jp).

In addition, the presence of the Mesoscale Convective System (MCS) was identified using Temperature Black Body (TBB) from Band-13 (IR) of Himawari-8 satellite, using the "Grab 'em, Tag 'em, Graph 'em" (GTG) algorithm [14]. Criteria for the MCS phase are described in Table 1.

Table 1 Criteria for MCS phase

Physical characteristics	Criteria
BT(10.4)	243 K
Size	10,000 km^2
Duration	Size and temperature definition must be met for a period of 3 h
Initiation	Size and temperature definition are first satisfied
Termination	Size and temperature definition are no longer satisfied
Mature	Minimum mean of cloud temperature definition must be met

The GTG method has been widely used in analyzing the role of MCS in Indonesia, for example, in the case of heavy rains in Jakarta in January 2013 [15], Semarang [16], and New Capital City Nusantara of Indonesia [17].

In addition, Ekman transport and pumping velocity were also calculated which were derived from wind stress at an altitude of 10 m.

Ekman transport (EMT, m^{3}s^{-1} m^{-1}) is calculated using the formula used by Dieng AL [18].

$$\mathrm{EMT}_x = \frac{\tau_y}{\rho_w f}, \quad \mathrm{EMT}_y = -\frac{\tau_x}{\rho_w f} \tag{1}$$

where ρ_w is the water density (1025 kg m^{-3}), f is the Coriolis factor (1/s), and the wind stress τ (Pa) is calculated using

$$\tau_x = \rho_a \cdot C_D \cdot \sqrt{u^2 + v^2} \cdot u, \quad \tau_y = \rho_a \cdot C_D \cdot \sqrt{u^2 + v^2} \cdot v \tag{2}$$

where ρ_a is the density of air (1.25 kg m^{-3}), C_D is the coefficient of drag, and *u, v* are components of wind at 10 m above sea level.

Ekman pumping velocity (EPV, ms^{-1}) is calculated using the curl of wind stress with the equation:

$$\mathrm{EPV} = \frac{1}{\rho_w f} \nabla \times \tau \tag{3}$$

3 Result and Discussion

A breaking seawater embankment of Tanjung Emas Semarang caused a coastal flood event of up to 1.5 m on 23 May 2022 at 08Z (15 WIB). Figure 1b denotes the evolution of sea level height at Tanjung Emas Semarang from 22 May 2022 at 00Z to 24 May

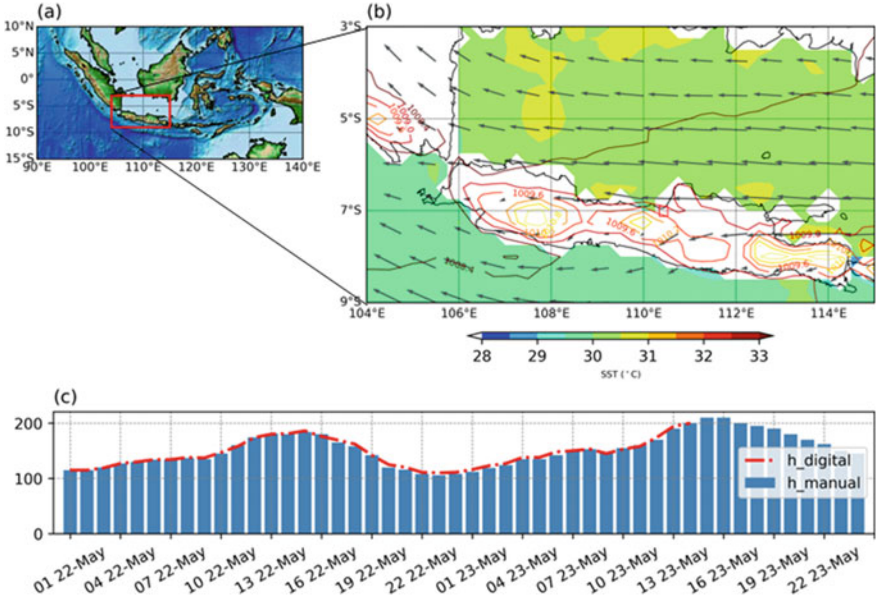

Fig. 1 Figures **a** and **b** show the geographical location of the northern coast of Java, and **c** shows a time series of sea wave heights at the time of the tidal wave on 23 May 2022

2022 at 00Z. It is worth noting that the high seawater level occurred at around 05Z–11Z on 22 and 23 May 2022 with a height between 180 and 210 cm. Specifically, the seawater level significantly increased since 23 May 2022 at 05Z and reached a peak of approximately 210 cm at 08Z and 09Z. This maximum sea level height affected the collapse of the seawater embankment and hence tidal flooding in many areas over Semarang and its surroundings. In addition, the hourly GSMaP precipitation data also shows heavy rainfall occurred in the Java Sea, next to the north of Central Java, from 22 May 2022 at 20Z till 23 May 2022 at 05Z (the GSMaP rain map is not shown here).

3.1 The MCS Evolution Ahead of Coastal Flooding

To understand the meteorological factors that modulate the increased seawater level during the coastal flooding in Semarang, we analyzed the evolution of MCS before and during the tidal flood event (see Fig. 2). A convective cloud began to develop on 22 May 2022 at 19Z in the coastal area of Central Java and was identified as the pre-MCS phase (Fig. 2a). This cloud grew rapidly (around 1 h), which showed the onset of the MCS initiation phase on 22 May 2022 at 20Z. At the same time, a rainfall of 5 mm/h occurred in the MCS areas. Then, the MCS developed to the growth stage, where the size of clouds increased further and became two cloud cells

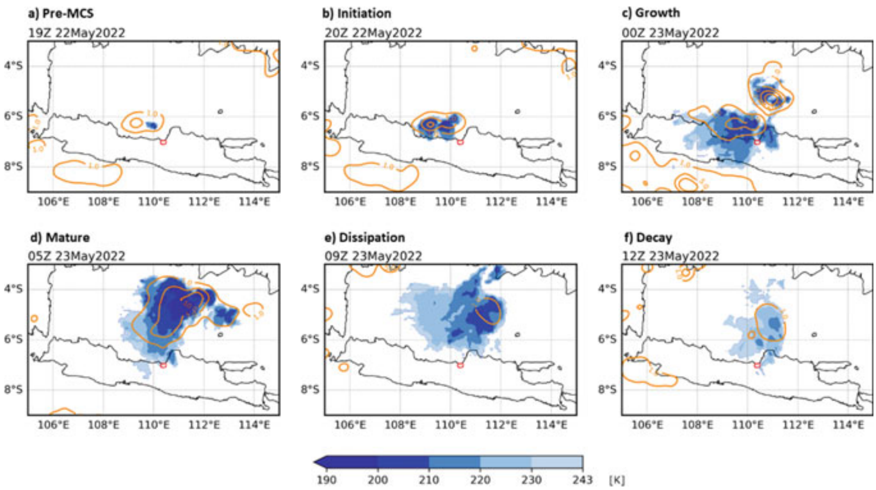

Fig. 2 Evolution of MCS (shaded) overlaid with GSMaP rain (yellow contour) in phases: **a** pre-MCS, **b** initiation, **c** growth, **d** mature, **e** dissipation, and **f** decay

to the north (Java Sea) and south area (the coastal and mainland) on 23 May 2022 at 00Z. Those MCSs propagated to the north and merged after five hours, which created a single deep MCS in the ocean. As a result, this mature stage of MCS produced heavy rainfall of 10 mm/hour over the coastal area of Central Java and the Java Sea. Thereafter, the MCS began to dissipate gradually until it reached the decay stage, which was followed by a decrease in rainfall intensity.

Overall, the evolution of MCS in the north of Semarang and surrounding areas beginning with the pre-MCS and ending with the decay stage during 12 h induced the increased storm surge over the northern coast of Java Island and hence enhanced the seawater mass due to the heavy precipitation.

3.2 Evolution of Convection and Near-Surface Easterly Wind

Figure 3 shows the evolution of convection (represented by cloud top temperature with TBB colder than 255 K), vertical velocity, and near-surface wind in each stage of MCS development as described in the previous section. A negative value of vertical velocity was identified in the coastal areas of Central Java since the pre-MCS stage. Interestingly, the highest magnitude of negative vertical velocity occurred over the ocean in the north of Semarang during the growth stage of MCS (23 May 2022 at 00Z), which is associated with the intense downward motion.

It also can be seen that persistent easterly wind was observed along the Java Sea before and during the tidal flooding event, with the magnitude varying between 7 ms^{-1} and 15 ms^{-1}. The near-surface easterly wind modulated the easterly wind

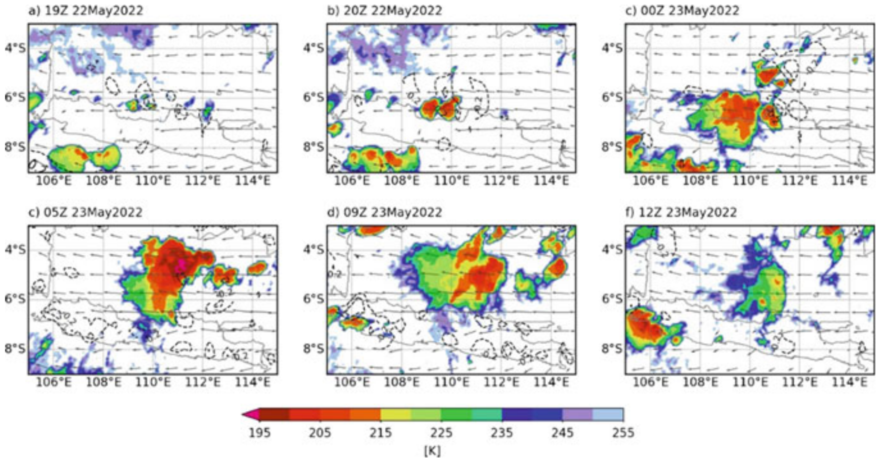

Fig. 3 Evolution of TBB (shaded), 925 hPa wind (vector), and vertical velocity (contour) associated for each phase of MCS

stress, and it induced the Ekman transport to the south areas of the northern coast of Java Island. The details of Ekman transport will be furtherly discussed in the next section.

3.3 Ekman Mass Transport (EMT) and Ekman Pumping Velocity (EPV)

Figure 4 shows the evolution of Ekman transport (EMT, vector) and Ekman pumping velocity (EPV, shaded) at 06Z (13 WIB) from 12 May 2022 to 23 May 2022. As seen in Fig. 4, on 12 May 2022, EMT is heading north, and on 14 May 2022, EMT is heading south. Several days before the tidal wave, this EMT consistently headed south toward the northern coast of Java Island which caused seawater to accumulate in the north of the island of Java. Ekman transport EMT on 23 May 2022 is much larger than the previous days.

Likewise, the EPV on 23 May 2022 had the lowest negative value compared to the previous days. A negative EPV indicates downwelling, and a positive EPV indicates upwelling. The EPV time series every 3 h from 10 May 2022 to 24 May 2022 is shown in Fig. 5.

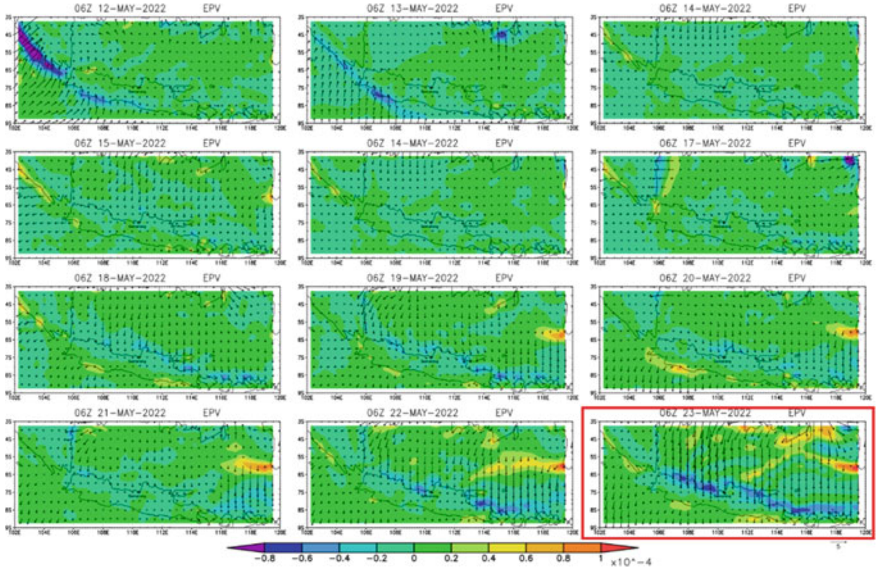

Fig. 4 Evolution of daily EPV (shaded) and EMT (vector) from 12 May 2022 at 06Z to 23 May 2022 at 06Z

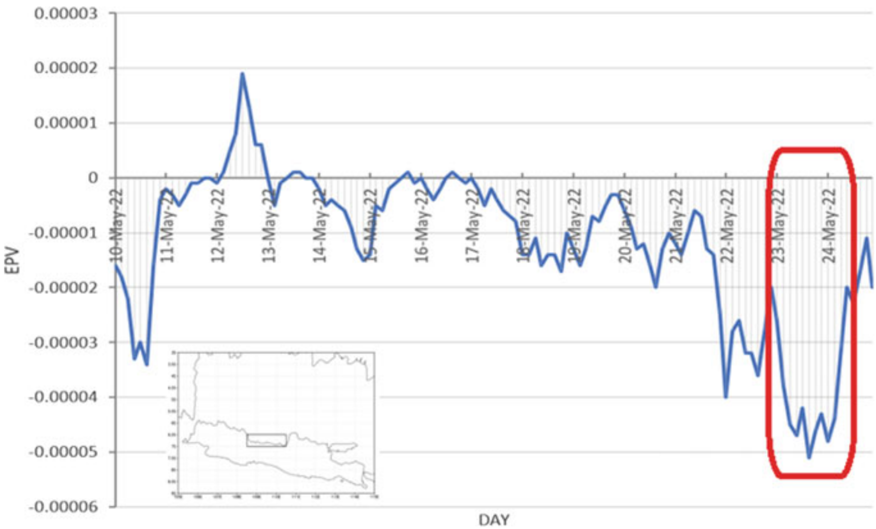

Fig. 5 Time series of EPV from 10 May 2022 to 24 May 2022 for the part of the northern coast area (108.5–110.5 E; 6.5–7 S)

4 Conclusion

Using TBB data from Himawari satellite and ocean surface wind data from ERA5, we have investigated meteorological factors influencing strong wind and increased seawater level over the northern coast of Semarang that caused the coastal flood on 23 May 2022. Our results suggested two potential meteorological factors that play an important role: (1) the formation of MCS over the ocean on the northern coast of Semarang that led to heavy rain over the coast and strong-surface wind speed that potentially enhances tidal waves toward Semarang Island and (2) unusually strong-surface easterly winds leading to increase seawater level through the Ekman pumping mechanism as a result of a balance between Coriolis and turbulent (wind) drag forces. Although our results did not yet quantify how much such factors contributed to the total increase in seawater level as a whole, our results really provided a new perspective on the factors influencing the increased seawater level intruding into Semarang during the coastal flooding on 23 May 2022, in addition to the previously known perspective of astronomical (tidal) forcing.

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Author Contribution All authors are the main contributors, have read the manuscript, and declare no conflict of interest.

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