Simulation of land-sea breeze effect on the diurnal cycle of convective activity in the Eastern Coast of North Sumatra using WRF model

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Abstract*— Land-sea breeze can generate the growth of convective clouds and rainfall that cause hydrometeorological disasters. Early identification of the diurnal cycle of convective activities can help in mitigating the impact of disasters. The eastern coast of North Sumatra is directly adjacent to the Malacca Strait that is suitable for the land-sea breeze model simulation. The land-sea breeze circulation affects the atmospheric dynamics. This study aimed to simulate the land-sea breeze circulation using the WRF model and analyzed its effect on the diurnal cycle of convective activity. The convective activity was identified using convective index, moisture transport, and rainfall distribution. ECMWF data from 2016 to 2017 were processed to determine the land-sea breeze rainy days based on Six Filtering Method and heavy rainfall definition. The Himawari-8 satellite data was used to calculate the convective index, and the specific humidity and wind from FNL data was used to calculate the moisture transport. The GSMaP rainfall data was used to depict the diurnal rainfall distribution over Sumatra. The prevailing sea breeze on the eastern coast of North Sumatra was the northeasterly wind. Sea breeze intrusion on the north coast of North Sumatra is characterized by a decrease in temperature, rising humidity, and easterly wind. Spatially, there is a time lag of about 1-2 hours from the peak convection to the formation of rainfall in the eastern coast region of North Sumatra. Peak diurnal rainfall in the eastern coast of North Sumatra generally occurs during midnight.

Keywords*— *land-sea breeze, North Sumatra, WRF, diurnal cycle, rainfall

I. INTRODUCTION

Land-sea breeze is a mesoscale atmospheric circulation caused by a significant difference in temperature gradients between air on the surface of land and oceans [1]. The intensity and formation of land-sea breeze depend on seasonal factors, latitude, and sun during the day [2]. Land-sea breeze circulation is related to weather dynamics in coastal areas, including the convective activity cycle and diurnal rainfall patterns [1, 3]. Weather conditions that occur in coastal areas also differ with those occurring in the oceans and mountains [4]. One indicator of these differences is in the characteristics of diurnal rainfall.

Sea breeze is the flow of wind that moves from the sea towards land and generally occurs during the day, and land breeze is a flow of wind that moves from the land towards the sea that occurs at night [5]. In general, diurnal rainfall in the land area typically occurs in mid- to late afternoon [6], while the characteristics of diurnal rainfall in the ocean region occurred in the late evening to early morning [7].

Various topographic conditions make diurnal variation and local circulation important elements to consider in conducting weather analysis and forecasts in the Indonesian Maritime Continent (IMC) [2]. Previous analysis of the diurnal mechanism of rainfall on the island of Sumatra [8] showed the formation of migration patterns of peak rainfall from the oceans to the mainland and from the land to the oceans associated with land-sea breeze circulation. Therefore, the eastern coast of North Sumatra, which is directly adjacent to the Malacca Strait, is the suitable location to observe the land-sea-atmosphere interaction, particularly the land-sea breeze circulation in Medan City [9].

This study aimed to simulate the land-sea breeze circulation and analyzed its effects on the diurnal convective cycle. The diurnal cycle of convective activity in an area can be identified using several indicators, such as the diurnal cycle of convective activity, moisture transport, and rainfall [10]. The land-sea breeze circulation in the study area that could form on the shoreline has more significant air temperature gradients between land and sea surfaces compared to synoptic pressure gradients [4].

Identification of land-sea breeze circulation can also be done using a model in addition to using observation data [6, 10, 11]. One of the methods that can be used to

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determine rainfall caused by land-sea breeze is the Six Filter Method [12]. The availability of meteorological data, topographic complex, and climate patterns in the study area were also factors that determined the accuracy of identifying land-sea breeze circulation [13].

II. METHODOLOGY

North Sumatra is one of the provinces in the Sumatra Island located at 1° - 4° N latitudes and 98° - 100° E longitudes [14]. This study used data from January 1, 2016 to December 31, 2017. The following were data used in this study: (1) 700-mb wind and moisture from the European Center for Medium-Range Weather Forecasts (ECMWF) re-analysis data with a grid resolution of 0.125° (± 13.875 km); (2) FNL (final) re-analysis data from the NCEP Global Data Assimilation System (GDAS) with a grid resolution of 0.25° (± 27.75 km) and a 6-hour time interval as data input on the Weather Research and Forecasting (WRF) regional model; (3) Himawari-8 satellite data channel IR1 with 10.4 µm wavelength and 2 km spatial resolution to calculate convective index values; (4) GSMaP-Near Real Time (NRT) rainfall estimation data with a grid resolution of 0.1° (± 11.1 km); and (5) the meteorological observation data from meteorological stations in the eastern coast of North Sumatra at Kualanamu (KNO), Belawan (BLW), and Deli Serdang (SPL) (see Table I for details).

TABLE I. The coordinates of the meteorological stations used in this study [15]

StationName	*WMO ID number*	*Lon*	*Lat*	*Elevation*
SPL	96031	3.621630°	98.714938°	25 masl
BLW	96033	3.788168°	98.714808°	3 masl
KNO	96035	3.6403°	98.8786°	23 masl

In this study, rainy days caused by land-sea breeze was identified using Six Filter Method from a previous study of Borne et al. [3] with input data of 700-mb wind. After filtering the rain events, a case study was conducted by choosing a day of land-sea breeze incident in North Sumatra and created a simulation using the WRF model with input of FNL data downscaled to 9 km, 3 km, and 1 km spatial resolution at one-hour intervals.

Land-sea breeze circulation was analyzed by studying moisture transport distribution as was done in the study by Xiaoxia et al. [16]. The results of a previous study [17] showed that moisture transport plays an important role in convective cloud formation, also known as convective activity in the area. The onset of sea-breeze is characterized by temperature drops and rising surface air humidity [5]. Analysis of the cloud peak temperature value (TB) from the Himawari-8 satellite was used to calculate the convective index value (CI). The cloud peak temperature limit value of 230 K was used for the convective index calculation [18].

III. RESULT AND DISCUSSION

Land-sea breeze-caused rainy days was identified by applying the Six Filter Method to data from 2016 to 2017. The first 3 filters obtained 59% of the total filtered days. The next filter was done by considering incidents of heavy rain (more than 50 mm/day) and appeared with 7% of the total filtered days. From the 7 % filtered results, the model was simulated for the case of October 1, 2017 in this study. A previous study indicated that the simulation model of atmospheric condition in North Sumatra showed good results [19].

A. Global-scale weather analysis

On October 1, 2017, MJO was in phase six and inactive over Sumatra Island (Figure 1a). The condition of the inactive MJO did not affect increasing rainfall in the Sumatra region. IOD values in October 2017 were about ±0.05 (Figure 1b), which means IOD was neutral. The SOI index value in October 2017 was +5 (Figure 1c) which meant the condition was a weak-La Niña.

(a)

(b)

(c)

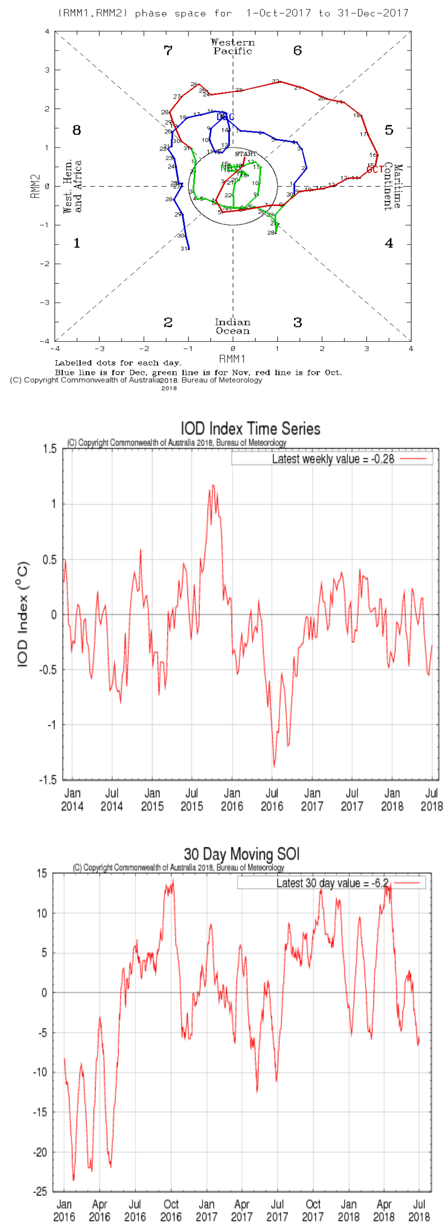

Fig. 1. (a) Diagram MJO phase period 1st October – 31st December 2017; (b) Graph of IOD value for the period January 2014 - July 2018; (c) Graph of SOI value for the period January 2014 - July 2018 [20].

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B. Regional-scale weather analysis

Gradient wind analysis on October 1, 2017 showed a dominant pattern of wind movement from the southern hemisphere towards northern hemisphere (Figure 2). Gradient wind patterns in the north-eastern coast of North Sumatra region at 07.00 LT and 19:00 LT were dominantly moving from the west-southwest direction. There was an Eddy Circulation disturbance in the Indian Ocean at the western part of Sumatra.

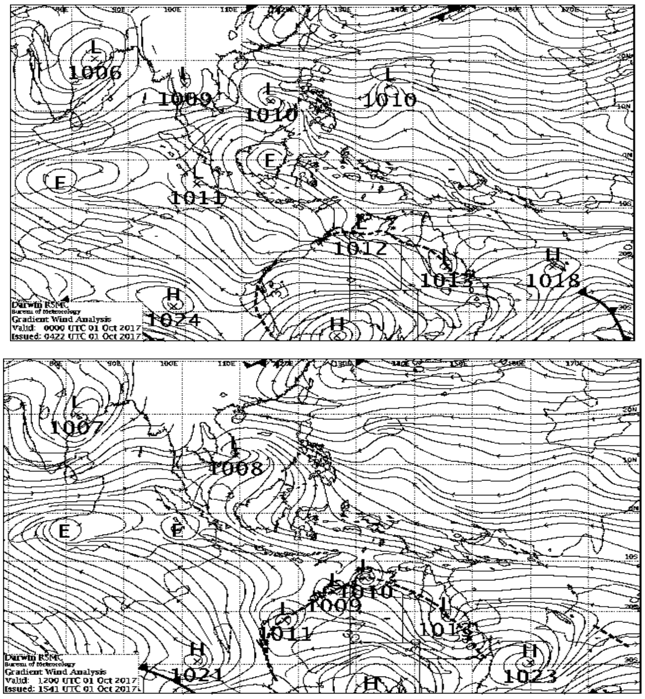

Fig. 2. Gradient wind analysis on 1st October 2017; (top) 07.00 LT and (bottom) 19.00 LT [20].

C. Surface air temperature and humidity analysis

Analysis of the decreasing temperature and increasing humidity based on observational data (Figure 3) showed that the onset of sea-breeze incident on the eastern coast of North Sumatra on October 1, 2017 was more varied, occurring in the range between 11.00-17.00 LT.

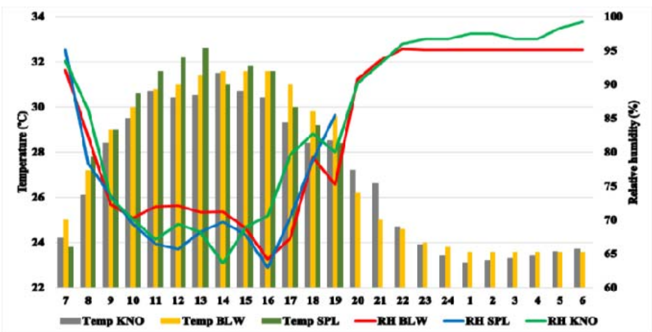

Fig. 3. Surface air temperature and humidity on October 1, 2017 observed in meteorological stations (Local Time).

In Kualanamu (KNO), the onset of sea-breeze incident occurred at 11.00 - 12.00 LT when air temperature decreased by 0.3°C and air humidity increased by 2.3%. In Deli Serdang (SPL), the onset started at 13.00 – 14.00 LT with temperature decrease by 1.6°C and humidity increase by 1.5%. By comparing the changes in temperature and humidity of the surface air, the onset of sea-breeze intrusion on October 1, 2017 was more clearly seen in Deli Serdang, although it first occurred in Kualanamu. Meanwhile, at Belawan station (BLW), the sea breeze intrusion started at 16.00 – 17.00 LT with temperature decrease by 0.5°C and humidity increase by ~2%.

D. Surface wind analysis

Based on the WRF model simulation, surface wind analysis showed a clear difference between the period of the sea- and land-breeze incidents on the eastern coast of North Sumatra on October 1, 2017 (Figure 4). At 10.00 LT, the sea breeze intruded the southern coast of the eastern coast of North Sumatra from the southwest direction at a speed of 5-8 kt. At 14.00 LT, the sea-breeze intrusion was obvious into the coastline. At 18.00 LT, the land-breeze started to move from the southwest direction with a speed of 6-17 kt on the northern coast of North Sumatra. In the next hour, the land-breeze speed had increased but did not last long.

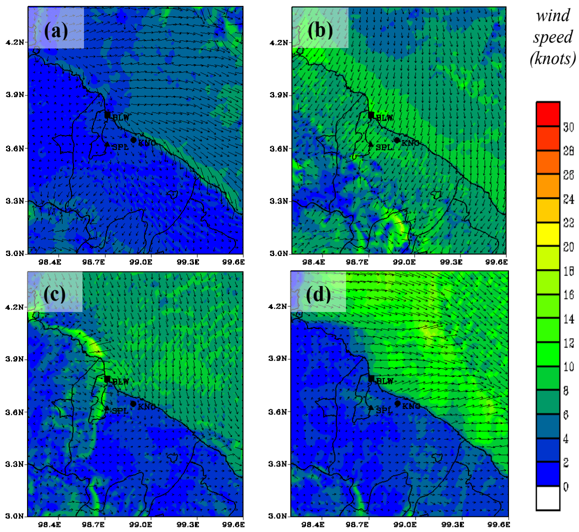

Fig. 4. Surface wind on 1st October 2017; (a) 10.00 LT, (b) 14.00 LT, (c) 18.00 LT, and (d) 22.00 LT.

E. Moisture transport analysis

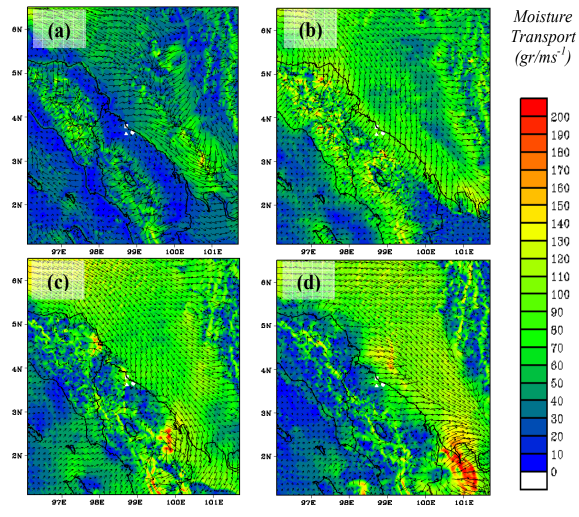

Fig. 5. Moisture transport on 1st October 2017; (a) 10.00 LT, (b) 14.00 LT, (c) 18.00 LT, and (d) 22.00 LT.

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The Analysis of moisture transport on October 1, 2017 showed the change of water vapor concentration in the Malacca Strait and Sumatra Island (Figure 5). The moisture transport started at 10.00 LT. At 12.00 LT, the water vapor entered the coastline of Sumatra Island from the east and west. At 14.00 LT, there was an increase in the concentration of water vapor around the Bukit Barisan Mountains. At 18.00 LT, the water vapor concentrated around the Bukit Barisan Mountains and began to decrease and shift toward the North Sumatra coast. The synoptic wind movement from the southwest direction influenced this movement of water vapor. At 22.00 LT, the moisture was moving from the southern part of the eastern coast of North Sumatra toward offshore. In the following hours, the moisture was moving toward the north-east sea and intruding into the Malaysia Peninsula.

F. Convective analysis

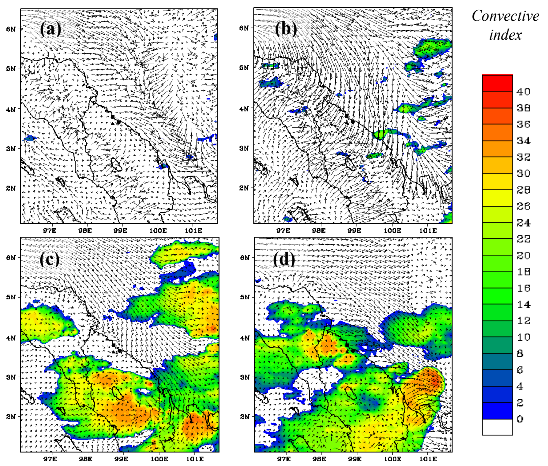

Fig. 6. Convective index on 1st October 2017; (a) 10.00 LT, (b) 14.00 LT, (c) 18.00 LT, and (d) 22.00 LT.

Figure 6 shows the horizontal distribution of convective index on October 1, 2017 in the study location. It shows that convection intensity at night was stronger than in the early morning. The convection area around Bukit Barisan Mountains began to form at 14.00 LT. At 18.00 LT, the convective activity intensively increased in Sumatra Island. At 22.00 LT, the convection area moved closer to the three observation stations and reached the maximum convective index at 01.00 LT. This convection area apparently moved towards the Malaysia Peninsula.

G. Rainfall analysis

The horizontal distribution of heavy rainfall (rainfall ≥ 10 mm / hour) on October 1, 2017 in the study location was shown in Figure 7. Rainfall distribution on October 1, 2017 showed that dominant rainfall occurred at midnight. Rainy areas over Sumatra began to form at 19.00 LT which was about 1-2 hours after the peak convection occurred (Figure 9). At 21.00 LT, rainfall occurred near the three observation stations until 01.00 LT. Observation data showed that maximum rainfall occurred in Kualanamu at 22.00 LT - 01.00 LT (Table 2). Diurnal rainfall cycle also showed that the total rainfall in midnight was greater than in early morning. This showed that local factors were important in the formation of diurnal rainfall on October 1, 2017.

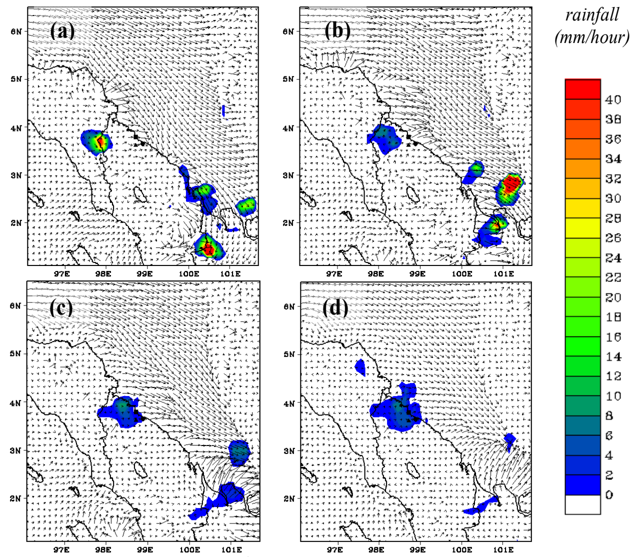

Fig. 7. Rainfall distribution on October 1, 2017; (a) 19.00 LT, (b) 21.00 LT, (c) 23.00 LT, and (d) 01.00 LT.

Figure 4 shows the onset of sea-breeze that started at 10.00 pm in the coastal area, which was consistent with the observation in Belawan Meteorological Station (see Figure 3). In the afternoon, the wind direction changed toward the sea until morning (onset of land-breeze). The onset of land-sea breeze can also be observed by the movement of water vapor (moisture) (Figure 5). During the onset of sea-breeze, water vapors were forced inland and rose up due to Bukit Barisan Mountains, and became convective and orographic clouds (Figure 6). Consequently, the rain was first observed in the mountain area. Afterward, rainfall moved toward the sea by the land-breeze during evening (Figure 7). This model simulation was confirmed by the observation in KNO and BLW (Table II).

TABLE II. Time series of rainfall on October 1, 2017 based on observation in KNO, BLW, dan SPL. Incomplete data in SPL was due to limited observation period (only 12 hours).

Observation time (LT)	Rainfall (mm/3-hours)		
	KNO	BLW	SPL
07.00 – 10.00	0	0	0
10.00 – 13.00	0	0	0
13.00 – 16.00	0	0	0
16.00 – 19.00	0	0	0
19.00 – 22.00	31.5	9.5	-
22.00 – 01.00	66.1	40.5	-
01.00 – 04.00	5.2	9.0	-
04.00 – 07.00	5.2	1.0	-
Accumulated	**108.0**	**60.0**	-

IV. CONCLUSION

In general, the onset of sea-breeze on the eastern coast of North Sumatra occurred at 10.00 - 12.00 LT and would last until 18.00 – 20.00 LT. The prevailing sea-breeze on

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the eastern coast of North Sumatra was the northeasterly wind. Sea-breeze intrusion on the north coast of North Sumatra was characterized by a decrease in temperature, rising humidity, and easterly wind. Maximum diurnal rainfall in the eastern coast of North Sumatra generally occurred during midnight. The intrusion of the sea-breeze from the Malacca Strait and from the Indian Ocean in the western part of Sumatra transported moistures into Bukit Barisan Mountains. The strong land-breeze could carry concentrated water vapor in Bukit Barisan Mountains toward the coastal and offshore areas. Spatially, there was a time lag of about 1-2 hours from the peak convection to the formation of rainfall in the eastern coast region of North Sumatra.

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