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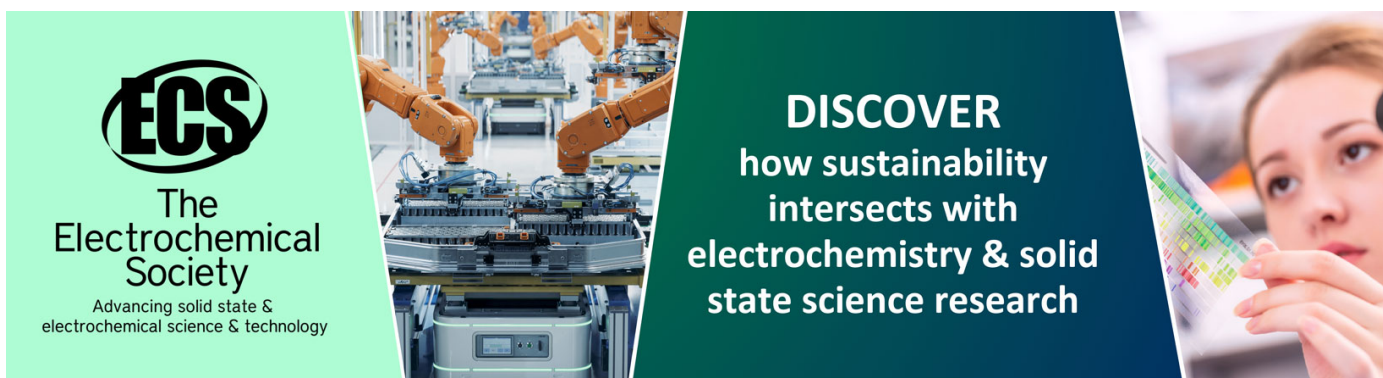
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To cite this article: D M Pera Rosita Dewi *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **303** 012045

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Simulation of Sea Breeze Events in Gulf of Jakarta under Different Synoptic Condition: An Application of WRF Model

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Abstract. The behaviour of the sea breeze developing along the Gulf of Jakarta during days with different synoptic condition is examined using observational data and simulations from the Weather Research and Forecasting (WRF). An objective and systematic selection method is used to detect sea breeze days from observational data. The simulation used three nested grids at 27, 9 and 3 km resolution covering Gulf of Jakarta and its joining region for sea breeze event at November 22th, 2016 which formed under offshore large-scale ambient wind, January 20th, 2017 which formed under westerly large-scale ambient wind, and August 10th, 2017 which formed under easterly large-scale ambient wind. Results show that the development of sea breeze circulation under offshore ambient wind produced lower 10-m wind speed simulation, while sea breeze conditions under westerly large-scale ambient wind are associated with highest surface wind speeds reaching 9.5 ms^{-1} in Gulf of Jakarta. Sea breeze simulation also indicates the formation of calm zone which is 22 - 56 km away from the Jakarta Gulf coastline. Model also shows the formation of thermal internal boundary layer that are about 300-700 m near the coast gradually merged with the mixing layer inland. Performance of WRF on the simulated circulation is studied by conducting value of correlation, RMSE, and MBE. Overall, model simulation agrees fairly well with the observations taken at a near-surface meteorological station.

Keywords : sea breeze, WRF, offshore ambient wind, boundary layer.

1. Introduction

Meteorological conditions in coastal areas are very different from inland areas. The air flow pattern in coastal areas is determined by differences in land-sea temperature, topography, coastline shape, and heterogeneity of land use [1]. Sea breeze is one of the meteorological phenomena caused by land-sea temperature differences. Sea breeze emerges as mesoscale atmospheric circulation which occurs when air masses on land heat up more intensely and faster than air masses in the sea. This thermal contrast will create a pressure gradient force that leads from the sea to the land which causes the onset of air flow to land [2]. Jakarta is a densely populated Metropolitan City located on the north coast of the western part of Java Island, one of the 5 largest islands in Indonesia [3]. Jakarta is located at $6^{\circ} - 7^{\circ} \text{ S}$ and $106^{\circ} - 118^{\circ} \text{ E}$, bordering with Bay of Jakarta in the north, that the sea breeze circulation has the potential to influence the weather system in Jakarta.

Research on sea breeze using balloon pilots has long been carried out in Batavia (now Jakarta) by van Bemmeln in 1912 [3]. However, evidence of the existence of sea breeze circulation that can penetrate on the land had only been reported by Hadi [4] based on observations of L-band radar boundary layer (BLR) in Serpong. Climatological conditions of sea breeze based on BLR observations by Hadi [3] also found that sea breeze fronts could well developed along the northern coastal plains of West Java and spread to the land until a distance of about 60-80 km from the coastline. However, despite the many



studies on sea breeze in Jakarta, there is a lack of attention about the influence of large-scale ambient wind on sea breeze characteristic.

Azorin-Molina and Chen stated that large-scale ambient wind is a meteorological factor that mostly influences the characteristic and evolution of sea breeze. Previous research has shown that offshore large-scale ambient wind will strengthen the frontogenesis convergence in core of sea breeze convergence zone, and lead to the reduction in sea breeze intrusion over land [2]. Steele's research found the formation an offshore calm zone when the large-scale ambient wind was offshore [6]. Calm zone is an area with a wind speed of 10 m less than 1 ms^{-1} which formed as the large-scale ambient wind pressure gradient are in equilibrium with the local thermal gradient force between land and ocean [2]. Steele found that when large-scale ambient wind is paralleled the coast with land to the left of the gradient wind (northern hemisphere), sea breeze circulation will induce the formation of coastal jets. Coastal jet is areas that have local maximum wind speeds and are formed about 1 km from the coast. In contrast, the interaction between gradient winds parallel to the coast, where the land is in the right of the gradient wind, sea breeze associated with lower surface wind speeds ranging from $2\text{-}3 \text{ ms}^{-1}$ [6].

Numerical modelling is a method for simulating sea breeze events which is carried out to improve accuracy of the analysis of atmospheric conditions. Weather Research and Forecasting weather modelling (WRF) is the future generation of weather models that can be used to predict medium-scale atmospheres and assimilate these prediction results with local observation data. The influence of large-scale ambient wind is carried out using WRF-ARW to understand sea breeze interactions with synoptic scale flow in Gulf of Jakarta, and its joining area.

2. Data and Methods

2.1 Research area

The research location is Jakarta and Gulf of Jakarta according to Figure 1. Jakarta's topographic conditions are relatively homogeneous and flat. The city of Jakarta is directly adjacent to the Gulf of Jakarta in the north, and the Bogor highlands in the south which is about 50 km from the capital of Jakarta with the highest peak reaching more than 1200 meters. The shape of the Jakarta Gulf coastline is concave. Shoreline orientation of Jakarta Gulf is $270^\circ - 90^\circ$. The axis of the sea breeze center is at 360° and the axis of the land breeze is at 180° . Sea breeze defines as wind direction that deviates $\pm 90^\circ$ from the axis of the sea breeze center [7].

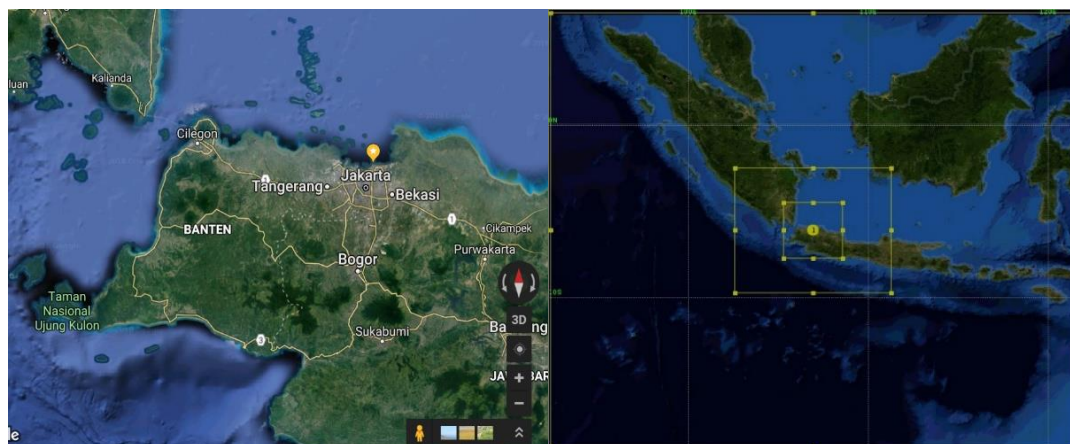


Figure 1. Map showing (a) Jakarta and its joining areas (b) three model domains

2.2 Research data

Data used in this study are described as follows:

1. Meteorological observation data. This study uses the meteorological observation data from August 2016 to July 2017 obtained from the Tanjung Priok Meteorological Station (6.108°S , 106.88°E). These data are used for sea breeze identification and model verification.

2. Zonal and meridional wind component data. The zonal and meridional data at the mid latitude (700 hPa) is obtained from the ECMWF ERA-Interim analysis fields which have $0.125^\circ \times 0.125^\circ$ spatial resolution and 6 hours temporal resolution. These data are accessed from <http://apps.ecmwf.int/datasets/> and used for sea breeze identification.
3. Sea surface temperature data. The sea surface temperature data is obtained from the ECMWF ERA-Interim analysis fields which have $0.125^\circ \times 0.125^\circ$ spatial resolution and 6 hours temporal resolution. Used for sea breeze identification.
4. Sunrise and sunset data. This study uses sunrise and sunset data accessed from <https://www.timeanddate.com>, for which data are used for sea breeze identification.
5. FNL (Final Analysis) data. This study uses the FNL data accessed from <http://rda.ucar.edu> which have $1^\circ \times 1^\circ$ spatial resolution and 6 hours temporal resolution. These data are used for sea breeze simulation.

2.3 Data processing

2.3.1 Sea breeze day identification

Sea breezes identification is carried out by using Borne method. This method identifies sea breeze events when a noticeable wind shift and an immediate period of constant wind-direction occurs during daytime, not due to synoptically forcing, and a threshold sea-land temperature gradient is exceeded [9]. This method is consisted by 6 different filters, to be considered as sea breeze day all requirement must be met.

The first filter eliminates the day with a large change in wind direction of the 70 hPa layer. No change in wind direction is greater than 90° , and is calculated as a change between 13:00 local solar time (LST) with LST as UTC + 7, the previous day and the actual day at 13:00 LST. The second filter also relates to the upper layer wind, and eliminates days with gradient wind speed change higher than 6 ms^{-1} for 12 hours (from 1:00 to 13:00 LST) at a layer of 700 hPa. The third filter aims to exclude days with synoptic wind speeds that are too high more than 11 ms^{-1} . These three filters aim to ensure a stable synoptic condition that is favourable for the formation of sea breezes circulation.

The last 3 filters are related to the surface conditions. The fourth filter determinates that minimum temperature difference between the sea and the land needed for developing sea breezes is 3 degrees. The fifth filter shows at a time interval between 1 hour after sunrise and 5 hours before sunset there is a change in surface wind direction $>30^\circ$. Quick changes in surface wind direction are characteristics of sea breezes. The last filter rejects days in which the hourly variation mean of the wind direction during 5 h subsequent to the observed wind shift is not at least 6 times smaller than the shift in question. With this last filter, the wind direction constancy is assured [9].

2.3.2 Running process of the WRF ARW model.

Table 1. WRF-ARW configuration used in the research.

	Domain 1	Domain 2	Domain 3
Resolution	27 km	9 km	3 km
Geographic resolution	5 m	2 m	30 s
Microphysics scheme	WSM-3	WSM-3	WSM-3
Long wave radiation scheme	RRTM	RRTM	RRTM
Short wave radiation scheme	Dudhia	Dudhia	Dudhia
Cumulus scheme	Kain-Fritsch	Kain-Fritsch	Kain-Fritsch
Planetary boundary layer scheme	YSU	YSU	YSU
Surface scheme	NOAH Land Surface	NOAH Land Surface	0

The mesoscale model used in this study is the WRF ARW Version 3.8.1 model. The WRF ARW model was ran by using the Mercator map projection and divided into three domains as shown in Figure 1 b.

The inner domain covers the entire Gulf of Jakarta and Jakarta regions with horizontal grid resolution of 3 km. The remaining 2 domains have horizontal resolution 9 and 27 km. For each simulation the model is run for 30 h, the first 12 h are considered as spin-up time. The simulated time never exceeds 24 h to avoid the possible influence of simulated conditions precedent [6]. The parameterization that used in this simulation is default as shown in Table 1.

The synoptic wind condition is determined using 925 hPa wind speed and direction from the output of WRF simulation. Large-scale ambient flow is divided into three types of flow based on its direction, namely (a) offshore flow is a synoptic scale flow from land to sea and ranges between 112.5° - 247.5°, westerly flow is a synoptic scale flow that blows from west to east and ranges between 247.5° - 292.5°, and easterly flow is a synoptic scale that blows from east to west and ranges from 67.5° - 112.5°.

2.3.3 Verification

The accuracy of the model simulating the observed variables is evaluated using the coefficient correlation (r), the Mean Bias Error (MBE) and the Root Mean Square Error (RMSE). These statistical indexes are computed as follows:

$$\text{Correlation } (r) = \frac{\sum m o - \frac{1}{n} \sum m \sum o}{\left[\sum m^2 - \frac{1}{n} (\sum m)^2 \right] \left[\sum o^2 - \frac{1}{n} (\sum o)^2 \right]} \quad (1)$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^n (M - O)^2}{n}} \quad (2)$$

$$\text{MBE} = \frac{1}{n} \sum_{i=1}^n (M - O) \quad (3)$$

where m and o represent the modelled and observed values of the variables respectively, and n is number of data.

3. Result and Discussion

3.1. Sea breeze under different synoptic condition

After applying the sea breeze selection method to the observational data, 17 sea breeze days are obtained in Tanjung Priok. A summary of selected sea breeze day by each filter is shown in Table 2. The partial acceptance percentage is the ratio of the output days and the input days in each filter, while the absolute acceptance percentage is a ratio of the output days in each filter and the number of days of total input. Filters 1-3 are used to ensure a synoptic stable atmosphere, where in Filter 2 receives all input day. This indicates that throughout the year, the synoptic conditions are favorable for the formation of sea breezes. The Filter 4 is responsible for the most rejection of input days, which rejects 68% of the days that pass through the Filter 4. The high number of rejected days is due to differences in surface temperature of the sea-land that do not meet the requirements for sea breeze formation.

Table 2. Summary of the selected sea breeze days by each filter of the selection method for Tanjung Priok

Filter	Input days	Output days	Partial acceptance percentage (%)	Absolute acceptance percentage (%)
1	365.0	312.0	85.5	85.5
2	312.0	312.0	100.0	85.5
3	312.0	284.0	91.0	77.8
4	284.0	91.0	32.0	24.9
5	91.0	45.0	49.5	12.3
6	45.0	17.0	37.8	4.7

In order to analyze an appropriate sea breeze condition during different synoptic condition, 3 days of the selected sea breeze days have been chosen: November 22th, 2016 which formed under light offshore large-scale ambient wind ranged 1-2 m s⁻¹, January 20th, 2017 which formed under strong westerly large-scale ambient wind ranged 7 – 9 m s⁻¹, and August 10th, 2016 which formed under moderate easterly large-scale ambient wind ranged 5-7 m s⁻¹.

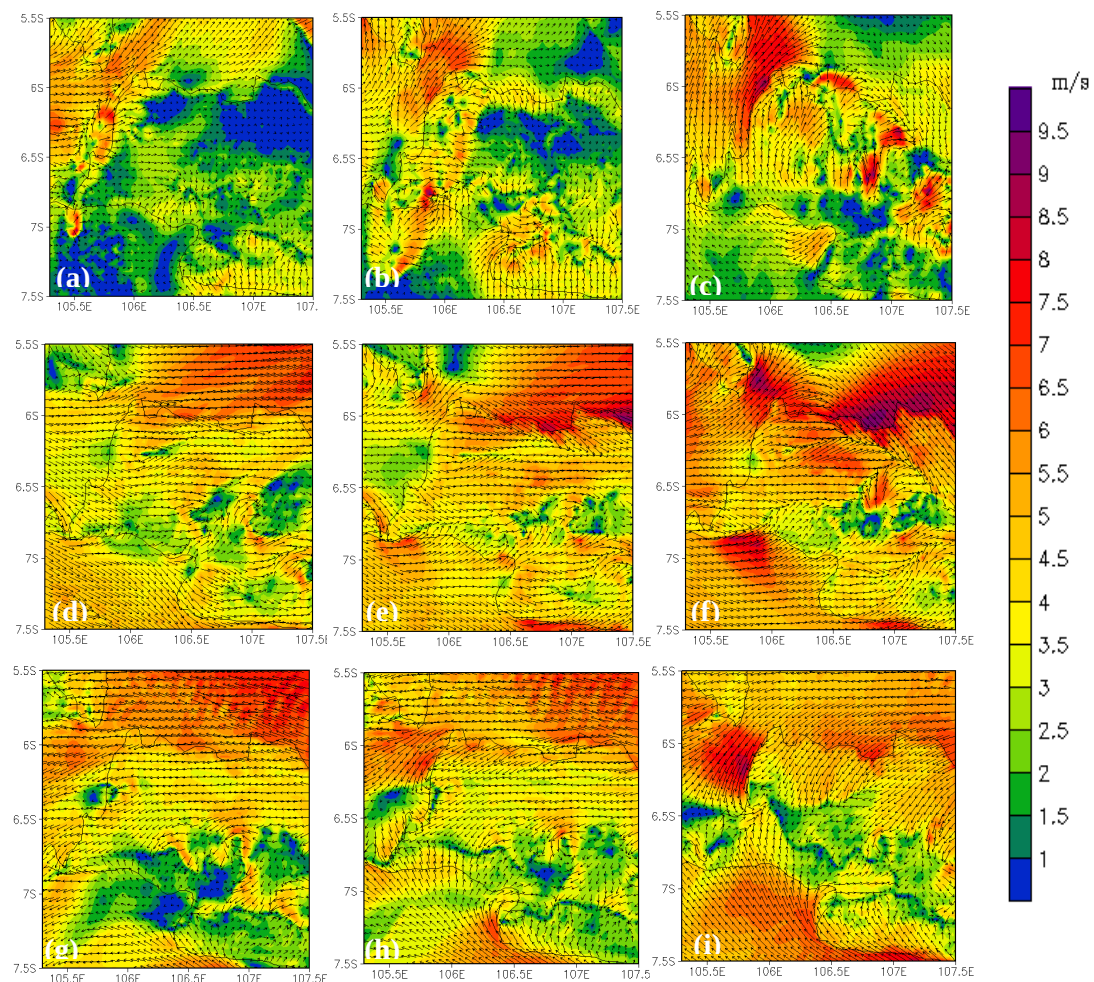


Figure 2. Plot of 10m wind speed (shading, ms⁻¹), and direction (arrows) of sea breeze events identified in Jakarta by the filter method at 10:00 UTC, 12:00 UTC, and 16:00UTC respectively for 22 November 2016 (a-c), 20 January 2017 (d-f), and 10 August 2016 (g-i)

From the Figure 2 a,d,g, it is shown that sea breeze onsets occurred between 1000-1100 LST, which these results are consistent with Hadi who found that sea breeze onsets in the Jakarta area generally occurs between 11:00 - 14:00 LST [3]. Sea breeze condition under large-scale offshore ambient wind indicates the formation of regions with minimum wind speed or calm zone which is about 22-56 km offshore from the Gulf of Jakarta as shown on Figure 2 a-c. In the literature, the calm zone phrase in the context of sea breeze is the minimum wind speed caused by the orientation of the pressure gradient ambient wind which is opposite to the orientation of the land-ocean thermal pressure gradient. According to Arritt, the existence of the calm zone shows the limit of sea breeze circulation offshore. This is shown by the pattern of surface wind divergence in the calm zone region. The thermal pressure gradient of land-sea causes the wind to blow from the sea to the land, in the opposite direction to the

offshore gradient wind that leads from the land to the sea (south to north). The calm zone first appears near the coastline and moves towards the sea as shown on Figure 2 a-c, indicating that as the heating in the mainland reaches its maximum, the sea breeze circulation on offshore region or the water body area affected by the sea breeze is increasing. Sea breezes under the large-scale offshore ambient wind are associated with lower surface wind speeds than the other ambient wind patterns. This is due to the gradient wind being in the opposite direction to the sea breeze that the resultant sea wind speed is low.

Sea breeze conditions under westerly large-scale ambient wind are associated with highest surface wind speeds than the other sea breeze events reaching 9.5 ms^{-1} in Gulf of Jakarta, and lower wind speed in land as shown by Figure 2 d - f. Sea breeze direction blows from northwest due the influence of westerly large-scale ambient wind. When the ambient wind is parallel to the coastline, the thermal pressure gradient and the synoptic scale flow pressure gradient are not completely opposite on the same dimension, so the thermal pressure gradient does not have to overcome the synoptic scale flow pressure gradients for the sea breeze to enter the land, this causes the calm zone does not form when the sea breeze blows under the westerly or easterly large-scale ambient wind. Sea breeze conditions under easterly large-scale ambient wind are associated with higher surface wind speeds than sea breezes under offshore flows, but are relatively lower with sea breeze under westerly flow as shown by Figure 2 g - i. It is caused by the wind speed of easterly large-scale ambient wind which is lower than westerly large-scale ambient wind, therefore the resultant sea breeze under easterly flow is lower than westerly flow. Due of the influence of easterly large-scale ambient wind, sea breeze also blows from northeast.

Horizontal intrusion of sea breeze can be seen from how far the sea breeze convergence zone (SBCZ) entered the land. SBCZ is defined as an area where two or more thermally induced air masses from the Java Sea, Sunda Strait, Indian Ocean south of Java Island, and Gulf of Jakarta combined to form areas with low horizontal speeds and relatively high vertical wind speeds.

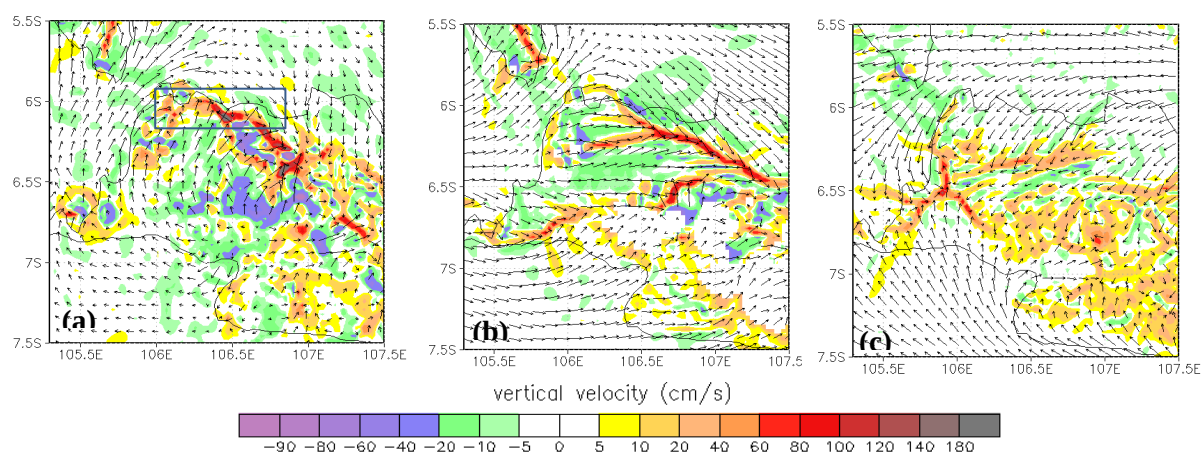


Figure 3. Plot of simulated vertical velocity (shaded, cm s^{-1}), and simulated surface wind direction (arrows) at 15:00 UTC for sea breeze events at (a) 22 November 2016, (b) 20 January 2017 (d), and (c) 10 August 2016.

The SBCZ conditions under offshore large-scale ambient wind indicates the presence of sea breeze that is held near the northern coastline of Java island as shown on Figure 3 a. This is due to the offshore ambient wind, that makes sea breezes originating from the southern side of the island of Java can intrude further on land, and obstruct sea breeze intrusion from the north side of the island of Java. This is in accordance with the findings of Miller explaining that offshore ambient winds can reduce the maximum intrusion of sea breeze on land [2]. In contrast, the SBCZ conditions under westerly large-scale ambient wind show that strong westerly ambient wind pushes the SBCZ towards the other direction and reduces the intrusion of SBCZ as shown on Figure 3 b. And during the easterly large-scale ambient wind, due to the orientation of the easterly ambient wind which has the opposite direction to the sea breeze which originates from the west side of Java Island, it causes sea breeze originating from the Sunda Strait,

unable to intrusion further on land, and stuck near the coastline as shown on Figure 3 c. These all implies, the sea breeze from Gulf of Jakarta can intrude further inland during easterly large-scale ambient wind, and its position is pushed to southwest.

The vertical velocity analysis of SBCZ for the 3 sea breeze events show that under offshore ambient wind, the vertical velocity value at the core of SBCZ reaches more than 1.8 m s^{-1} , relatively higher than the vertical velocity value under westerly/easterly ambient wind. This indicates that sea breezes under offshore ambient wind conditions experience a strengthening of convergence in the SBCZ region or a strengthening of the frontogenesis convergence. This finding is in accordance with Arritt's research which states that the interaction of weak-medium offshore ambient wind with sea breeze results in a reinforcement of frontogenesis convergence [10]. Behind SBCZ, an area of updraft with a lower positive vertical velocity value is formed. Secondary updraft behind this SBCZ can be formed due to low level convergence, friction with the surface, thermal instability that causes the rising of air masses [2]. Around the SBCZ, a downdraft area with a negative vertical velocity value is also seen. This downdraft area is part of the repeated updraft and downdraft pattern associated with convective activities on land [11].

To study the vertical extent of the sea breeze circulation, the north-south vertical cross section of meridional wind component, and water vapor mixing ratio is examined. The Figure 4 and 5 show the vertical circulation at 1500 UTC, which is representative of the hour in which sea breeze reached its maximum development on surface. From Figure 4, the vertical extent of sea breeze under offshore ambient wind reaches 820 hPa, relatively higher than westerly ambient wind which reaches 910 hPa and easterly ambient wind which reaches 870 hPa. The vertical intrusion of sea breeze is found at the very front of the sea breeze, and can be identified as a sea breeze head (SBH). Figure 5 shows that behind the SBH, the air mass with a high-water vapor mixing ratio value flowing on land, following the spread of SBF on land and is indicated as sea breeze gravity wave (SBG). SBG is a spreading of moist, and cold air masses carried by the sea breeze. At the top of the sea breeze circulation, a return flow that blows from the south towards the north is detected on the 3 sea breeze events, this indicates that the sea breezes are able to maintain their closed circulations.

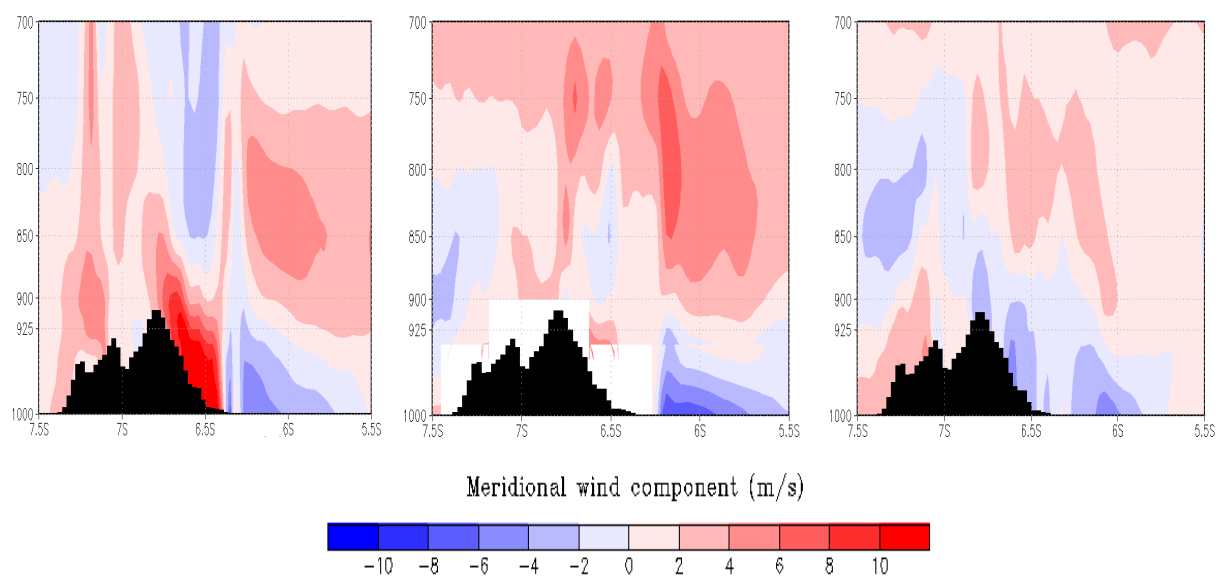


Figure 4. Cross section N-S of simulated Meridional wind component at 15:00 UTC for sea breeze events at (a) 22 November 2016, (b) 20 January 2017 (d), and (c) 10 August 2016.

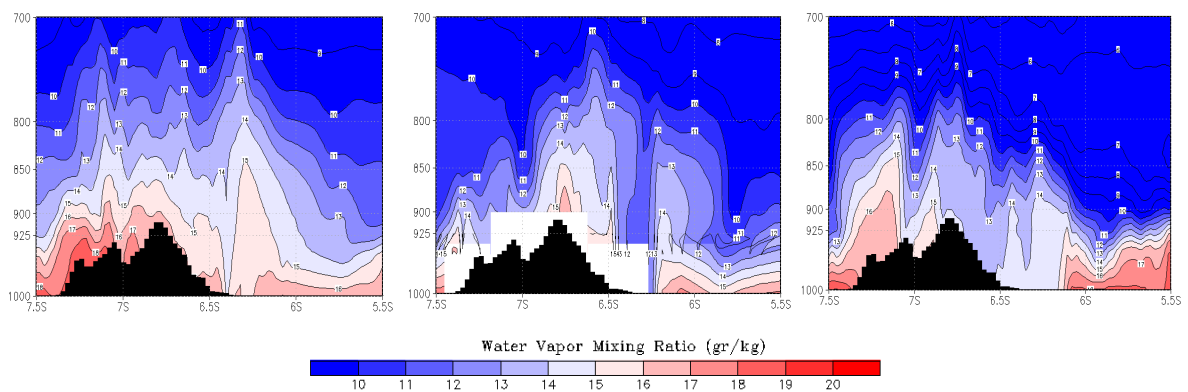


Figure 5. Cross section N-S of simulated water vapor mixing ratio at 15:00 UTC for sea breeze events at (a) 22 November 2016, (b) 20 January 2017 (d), and (c) 10 August 2016

Planetary boundary layer height (PBLH) is an important parameter as it represents limiting of the boundary layer heating, convection, pollutant mixing, and low-level circulating, in which PBLH is influenced by sea breeze advection leading the formation of thermal internal boundary layer (TBL) [12]. Figure 6 shows deep boundary layer over land reaches more than 1600 meters, while on ocean and coastal areas, a shallower boundary layer is seen. The region of shallower boundary layer on coastal areas can be identified as TBL, and the value ranges between 300-700 meters. From Figure 6, we can see the difference in characteristic between TBL under westerly ambient wind, and easterly ambient wind. Under westerly ambient wind, the formation of TBL over land leads to the southeast, following the direction of the sea breeze that blows from northwest (Fig. 6b) to the southeast. In contrast, under easterly ambient wind, the formation of TBL over land leads to the southwest following the direction of the sea breeze (Fig. 6c). Here also can be seen that TBL gets merged with the generic inland PBL much away from in land.

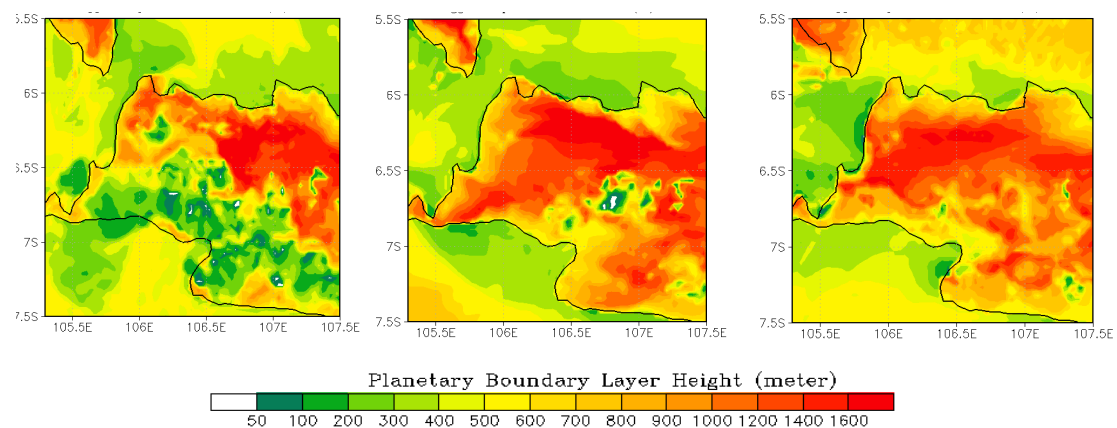


Figure 6. Simulated boundary layer height at 15:00 UTC for sea breeze events at (a) 22 November 2016, (b) 20 January 2017 (d), and (c) 10 August 2016

3.2 Model Evaluation

Evaluation of the WRF model is done by comparing the simulation values with the observational values from the Tanjung Priok Meteorological Station. Wind direction and wind speed are chosen as the main meteorological variables to compare, because they are used to study wind fields which are the main objectives of this study. Surface temperature (T) and relative humidity (RH) were also compared as well because they can be used to study the main features of sea breezes such as: daily evolution, sea wind front (SBF), and land sea wind intrusion.

Table 3. Statistical skill scores for different parameters from sea breeze simulation

Simulation Time	Parameter	R	RMSE	MBE
22 November 2016	T	0.82	1.93	1.04
	RH	0.80	10.91	-7.93
20 January 2017	T	0.75	1.42	-0.31
	RH	0.15	11.46	2.63
10 Augustus 2016	T	0.88	1.82	-1.40
	RH	0.88	7.67	3.29

In general, the verification results indicate that the WRF model is able to simulate the daily pattern and observed trend of surface temperature in Tanjung Priok. This is shown through the high positive correlation coefficient, and low RMSE. The verification results of relative humidity also indicate that the WRF model is able to simulate the daily pattern and observed trend of relative humidity in Tanjung Priok, except for January 20th 2017 where the correlation value is relatively low.

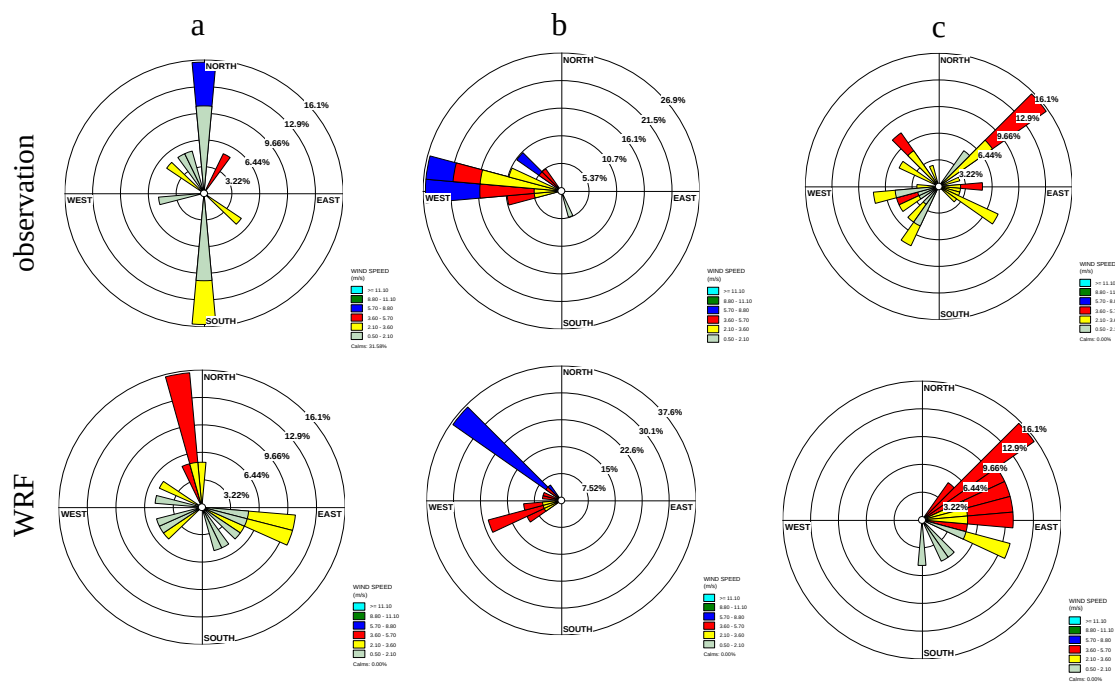


Figure 7. Wind speed and direction comparison of observed and simulated sea breeze days in Tanjung Priok on (a) 22 November 2016, (b) 20 January 2017, and (c) 10 Augustus 2016

Figure 7 shows wind speed and direction comparisons of WRF model simulations and observations in Tanjung Priok. Overall, it can be seen that the WRF model is able to simulate the wind direction of sea breeze, although there are differences in simulating the direction of the land breeze. Under offshore large-scale ambient wind, sea breeze direction is from north as shown by Figure 7 a, indicating sea breeze is able to penetrate inland. Sea breeze blows from west-northwest during westerly large-scale ambient wind and from northeast during easterly large-scale ambient wind, as shown by Figure 7 a and Figure 7 b respectively. This indicates the direction of sea breeze is highly influenced by direction of large-scale ambient wind. The wind speed and direction comparison of observed and simulated also show that the sea breeze intensity of the WRF model is overestimate to the observed sea breeze intensity.

4. Conclusion

The aim of this study was to investigate the influence of synoptic condition to sea breeze characteristic by applying WRF model to Jakarta and Gulf of Jakarta. An objective and systematic selection method was used to detect sea breeze days from observational data. The model simulations refer to the 22 November 2016, 20 January 2016, and 10 August 2016 which was chosen to analyse an appropriate sea breeze condition during different synoptic condition, therefore the drawn conclusions could be generalised: The development of sea breeze circulation under offshore ambient wind produced lower 10-m wind speed simulation, while sea breeze conditions under westerly large-scale ambient wind are associated with highest surface wind speeds reaching 9.5 ms^{-1} in Gulf of Jakarta. Sea breeze simulation indicates the calm zone formation which is 22 - 56 km away from the Jakarta Bay coastline. SBCZ intrusion under offshore ambient wind showed a reduction on its spatial intrusion over land, while SBCZ under westerly/easterly ambient wind showed that SBCZ position pushed towards the other direction. Model also shows the formation of thermal internal boundary layer that are about 300-700 m near the coast gradually merged with the mixing layer inland. Performance of WRF on the simulated circulation is studied by conducting value of correlation, RMSE, and MBE. Overall, model simulation agrees fairly well with the observations taken at a near-surface meteorological station.

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