

Characteristics of Land–Sea Breeze Circulation along the West Coast of West Sumatra Using Observations and WRF-ARW Simulations

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Abstract

Land–sea breeze circulation is an important mesoscale atmospheric phenomenon in tropical coastal areas, yet its behavior and interaction with complex topography remain insufficiently understood along the west coast of West Sumatra. This study examined land–sea breeze characteristics and atmospheric dynamics during the 2025 dry season using Automatic Weather Station (AWS) observations and Weather Research and Forecasting (WRF) simulations with the Advanced Research WRF (WRF-ARW) dynamical core. Events were identified using a modified Six Filters method, and three representative cases were selected for numerical simulation and detailed atmospheric analysis. Model performance was evaluated against surface observations, while horizontal, vertical, and time–height analyses examined circulation evolution and structure. A total of 51 events were identified at AWS Digi Minangkabau. Sea-breeze circulation generally developed between 02 and 03 UTC and reached its mature phase between 06 and 09 UTC. WRF-ARW reproduced the observed evolution of near-surface temperature and wind fields and captured the main circulation characteristics. Marine air penetrated inland toward the foothills of the Bukit Barisan, where strong convergence and upward motion occurred. The circulation was mainly confined to the lower troposphere, with a typical depth of 1–2 km and a defined return flow aloft. These findings indicate that land–sea breeze evolution is influenced by differential land–sea heating and topographic modulation by the Bukit Barisan.

Keywords: Atmospheric Dynamics; Coastal Circulation; Land–Sea Breeze; West Sumatra; WRF-ARW.

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Introduction

Land–sea breeze circulation is one of the most important mesoscale atmospheric phenomena in coastal regions and represents a major source of diurnal variability in the lower atmosphere. The circulation plays a critical role in regulating heat and moisture transport, boundary-layer development, convergence, and convective activity, thereby influencing local weather and climate conditions. Beyond the characteristic reversal of coastal winds, land–sea breeze systems contribute to the redistribution of energy and water vapor

between the ocean and adjacent land areas, affecting cloud formation, precipitation development, and air–sea interactions. These processes are particularly important in tropical coastal environments, where strong daytime heating and abundant low-level moisture favor active land–atmosphere coupling and the development of thermally driven circulations (Zhu et al., 2017; Drobinski et al., 2018; Park et al., 2020).

Previous studies have demonstrated that land–sea breeze circulation exhibits substantial variability in timing, duration,

inland penetration, and vertical extent across different coastal environments. Along the west coast of Sumatra, North et al. (2025) showed that sea-breeze circulations occur almost daily and constitute a dominant component of the regional low-level wind system. Similar studies conducted in Seoul, China, and other tropical coastal regions have reported that sea-breeze circulations commonly extend tens of kilometers inland and are typically confined within the lowest 1–2 km of the atmosphere (Park & Chae, 2018; Jia et al., 2022; Muppa et al., 2012). In addition to modifying near-surface winds, these circulations play an important role in transporting moist marine air inland, thereby influencing atmospheric instability and convective development (Davis et al., 2019; Zhu et al., 2017). Collectively, these studies indicate that land–sea breeze circulation is a key mechanism governing coastal atmospheric dynamics, although its characteristics remain strongly dependent on local geographical and meteorological conditions.

Among the factors controlling land–sea breeze evolution, topography is recognized as one of the most important modifiers of circulation structure and intensity. Coastal mountain ranges can alter inland penetration, redistribute convergence zones, modify circulation depth, and enhance vertical motion through interactions between sea-breeze flow and slope circulations (Miao et al., 2003; He et al., 2021). Numerical and observational studies have shown that such interactions may strengthen or weaken sea-breeze development depending on terrain configuration and ambient atmospheric conditions (Allouche et al., 2023). The west coast of West Sumatra provides a particularly interesting environment for investigating these processes because the Bukit Barisan Mountain range lies in close proximity to the Indian Ocean coastline. This geographical setting creates a unique natural laboratory where coastal thermal

forcing and topographic forcing interact over a relatively short spatial scale, potentially exerting a strong influence on the horizontal and vertical evolution of land–sea breeze circulation.

Despite increasing interest in tropical coastal circulations, detailed investigations of land–sea breeze dynamics along the west coast of West Sumatra remain limited. Previous studies in Sumatra have primarily focused on near-surface characteristics of coastal wind reversals and seasonal variability (North et al., 2025), while the coupled horizontal and vertical evolution of the circulation has received comparatively little attention. Furthermore, studies integrating surface observations and numerical simulations remain scarce, particularly in coastal regions characterized by complex terrain. As a result, the role of the Bukit Barisan topography in modulating inland penetration, convergence, circulation depth, and vertical atmospheric structure remain insufficiently understood. A comprehensive description of the atmospheric evolution of land–sea breeze circulation from its onset to mature phase is therefore still lacking for this region.

Accordingly, this study aims to (1) identify the characteristics of land–sea breeze circulation along the west coast of West Sumatra during the 2025 dry season using observations from Automatic Weather Stations (AWS), and (2) evaluate the capability of the Weather Research and Forecasting model with the Advanced Research WRF dynamical core (WRF-ARW) in reproducing the observed circulation and its vertical structure. By integrating surface observations and high-resolution numerical simulations, this study characterizes the horizontal and vertical evolution of land–sea breeze circulation and examines the influence of the Bukit Barisan topography on convergence, moisture transport, and vertical motion. The results contribute to an improved

understanding of coastal atmospheric dynamics in tropical mountainous environments and provide a regional reference for future observational and modeling studies of land–sea breeze systems.

Materials and Methods

Study Area

The study was conducted along the west coast of West Sumatra, Indonesia, a region

directly facing the Indian Ocean and characterized by complex coastal and mountainous terrain (Figure 1). The study area is bounded by a narrow coastal plain and the Bukit Barisan Mountain range, which extends parallel to the western coastline of Sumatra. This geographical setting provides favorable conditions for the development of land–sea breeze circulation and its interaction with topographic forcing (Nayak, 2017).

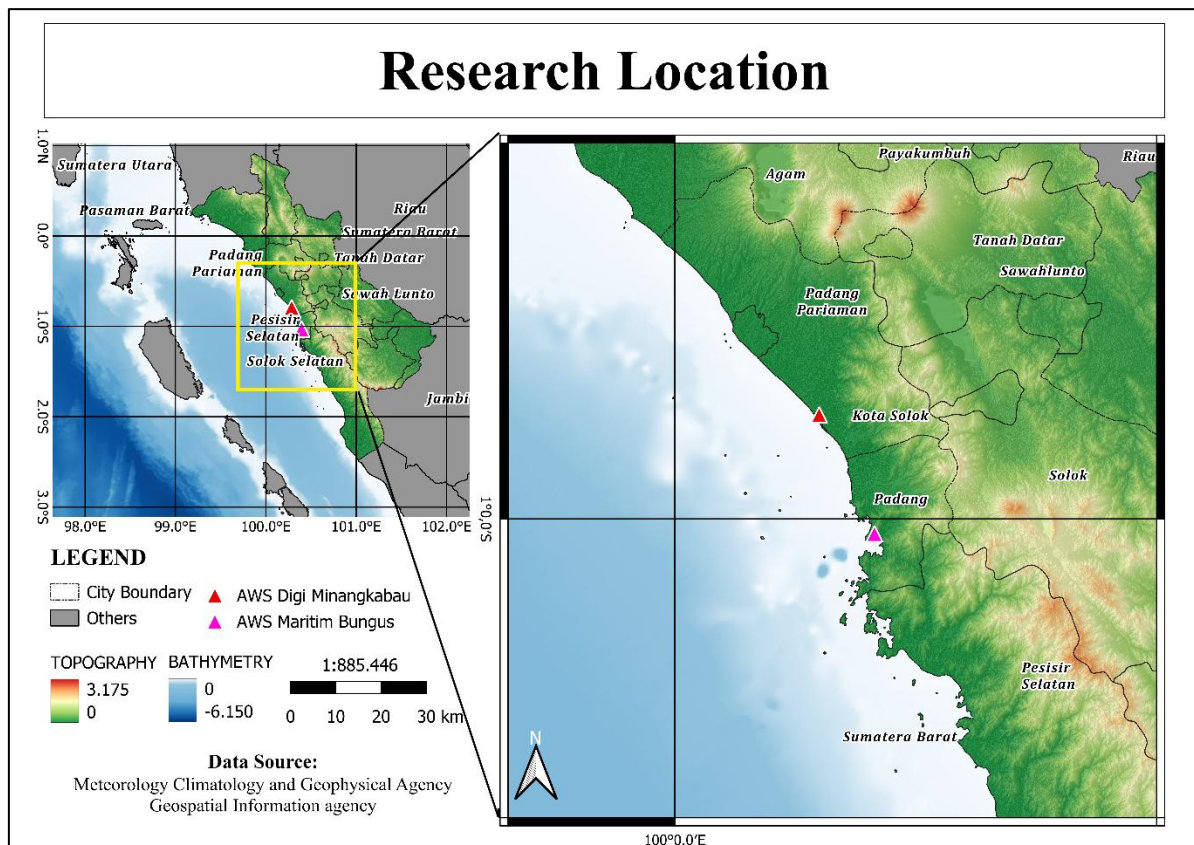


Figure 1. Study area and AWS locations.

Two Automatic Weather Stations (AWS) operated by the Meteorology, Climatology, and Geophysics Agency (BMKG) were used in this study. The first station, AWS Digi Stamet Minangkabau (0.789° S, 100.287° E), is located on the coastal plain and represents inland atmospheric conditions influenced by sea-breeze penetration. The second station, AWS Maritim Bungus (1.030° S, 100.396° E), is situated near the coastline and represents the marine–coastal environment. The combination of these stations enables the

investigation of land–sea breeze evolution from the coastal zone toward inland areas. The analysis focused on the dry-season period from May to September 2025, when land–sea thermal contrasts are typically more pronounced and local mesoscale circulations are less frequently disrupted by widespread rainfall. The proximity of the Bukit Barisan Mountain range to the coastline makes the region particularly suitable for examining the interaction between coastal thermal forcing and topographic influences on land–sea breeze

development (BMKG, 2025; Liang & Wang, 2017).

Observational Data

This study utilized surface meteorological observations from two Automatic Weather Stations (AWS) operated by the

Meteorology, Climatology, and Geophysics Agency (BMKG): AWS Digi Minangkabau and AWS Maritim Bungus (Figure 1). The observation period covered the 2025 dry season from May to September. The characteristics of the observational datasets employed in this study are presented in Table 1.

Table 1. Observational datasets used in this study.

Station	Latitude (°)	Longitude (°)	Temporal Resolution	Variables
AWS Digi Minangkabau	0.789° S	100.287° E	10 min	Wind speed, wind direction, air temperature, relative humidity, pressure, rainfall, solar radiation
AWS Maritim Bungus	1.030° S	100.396° E	1 min*	Wind speed, wind direction, air temperature, relative humidity, pressure, rainfall

*AWS Maritim Bungus observations were aggregated to hourly values for analysis.

Meteorological variables used in this study included wind speed, wind direction, air temperature, relative humidity, atmospheric pressure, rainfall, and solar radiation. These observations were employed for land–sea breeze identification, characterization of circulation properties, and validation of WRF-ARW simulations. Data quality control was conducted prior to analysis to identify missing observations and ensure data reliability. Days with excessive missing data were excluded from subsequent analyses.

The AWS observations were further used to determine the onset time, duration, dominant wind direction, and wind speed associated with land–sea breeze circulation. In addition, observations from AWS Digi Minangkabau were used to evaluate the performance of WRF-ARW simulations through comparisons of near-surface temperature and wind fields.

Identification of Land–Sea Breeze Events

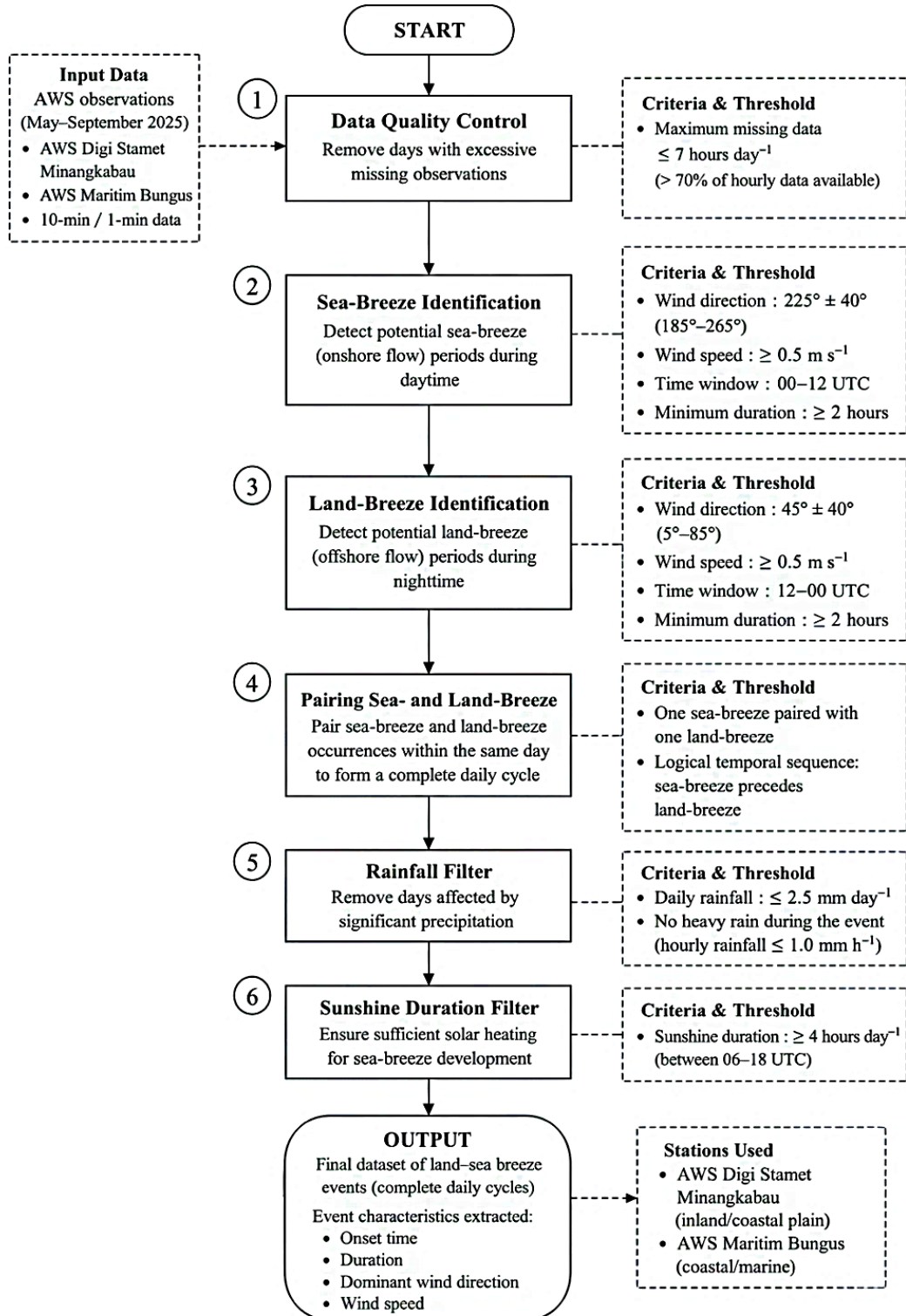
Land–sea breeze events were identified using a six-step filtering framework developed by integrating objective

identification criteria proposed in previous land–sea breeze studies (Borne et al., 1998; Hwang et al., 2020; Coulibaly et al., 2021; Guo et al., 2023; McCabe & Freedman, 2023). Rather than adopting a single published algorithm, the framework combines complementary criteria describing wind reversal, wind persistence, thermodynamic conditions, precipitation, and solar heating. The resulting procedure was subsequently adapted to the geographical characteristics of the west coast of West Sumatra and the temporal resolution of the AWS observations. The overall workflow used for event identification is illustrated in Figure 2.

The identification process consisted of six sequential steps. First, quality control was applied to remove days with excessive missing observations. Second, potential sea-breeze events were identified based on wind direction, wind speed, and predefined daytime time windows representing onshore flow conditions. Third, potential land-breeze events were detected using corresponding nighttime offshore-flow criteria. Fourth, sea-breeze and land-breeze occurrences were paired to identify complete daily circulation cycles. Fifth,

rainfall-based filtering was applied to exclude days affected by significant precipitation that could disrupt thermally driven circulations. Finally, sunshine-

duration filtering was performed to ensure sufficient daytime solar heating for sea-breeze development.



Note: All thresholds were adjusted based on the characteristics of the west coast of West Sumatra and the temporal resolution of AWS observations.

Figure 2. Workflow of the land–sea breeze identification procedure based exclusively on AWS observations using the modified Six Filters approach.

The modified criteria were adjusted to account for the geographical characteristics of the west coast of West Sumatra and the temporal resolution of the AWS observations. Event characteristics, including onset time, duration, dominant wind direction, and wind speed, were subsequently derived from all identified land–sea breeze events. The resulting event database was then used to characterize circulation properties and to select representative cases for detailed numerical simulation and atmospheric analysis.

Representative Event Selection

Following the identification of land–sea breeze events, all identified cases were

considered as candidate events for numerical simulation. A total of 54 land–sea breeze events were identified during the study period, comprising 51 events at AWS Digi Minangkabau and three events at AWS Maritim Bungus (Table 2).

Candidate events were ranked based on five meteorological characteristics: sea-breeze duration (30%), land-breeze duration (20%), mean sea-breeze wind speed (20%), sunshine duration (20%), and daily rainfall (10%). Each parameter was normalized using min–max normalization before calculating the ranking score. The ten highest-ranked candidate events are presented in Table 3.

Table 2. Identified land–sea breeze events during the May–September 2025 study period

Month	AWS Digi Minangkabau	AWS Maritim Bungus
May	5, 6, 7, 9, 18 , 19, 20, 21, 23, 24, 26, 27 , 28	-
June	2 , 3, 12, 13, 14, 21, 22, 24, 25, 26, 27, 29, 30	-
July	1, 2, 3, 4, 9, 10, 12, 16, 17, 18, 19, 21, 22, 24, 28	-
August	5, 11, 26, 27, 30	13, 15, 26
September	1 , 7, 12, 25, 26	-

*Bold dates indicate representative WRF simulation cases

The representative cases were selected from the ten highest-ranked candidate events to encompass a broader range of land–sea breeze characteristics for model evaluation. Among the highest-ranked candidates, the events on 27 May and 6 May exhibited very similar land–sea breeze characteristics. To avoid selecting two representative cases with nearly identical

atmospheric conditions, the 18 May event was chosen instead because it exhibited stronger sea-breeze intensity and provided a more distinct circulation pattern. This selection was intended to maximize the diversity of the representative validation cases while retaining only high-ranked candidate events.

Table 3. Top ten ranked candidate land–sea breeze events used for representative case selection.

Rank	Date	SB Onset (UTC)	SB Duration (h)	LB Onset (UTC)	LB Duration (h)	Mean SB Speed (m s ⁻¹)	Selected for WRF
1	2025-06-02	02:00	9	13:00	10	4,09	✓
2	2025-05-27	03:00	9	12:00	12	2,78	✓
3	2025-05-06	01:00	10	13:00	11	2,44	
4	2025-06-03	03:00	10	13:00	9	2,77	
5	2025-05-28	02:00	10	12:00	12	1,73	
6	2025-05-18	02:00	7	12:00	12	3,51	✓
7	2025-05-26	02:00	8	12:00	12	2,87	
8	2025-06-27	02:00	10	13:00	10	2,19	
9	2025-07-17	03:00	9	12:00	11	2,36	
10	2025-07-22	02:00	7	12:00	12	3,14	

Accordingly, the three representative events selected for WRF-ARW simulations were 18 May, 27 May, and 2 June 2025.

WRF-ARW Configuration

The simulations were initialized using the Global Data Assimilation System Final Analysis (GDAS-FNL) dataset with a spatial resolution of 0.25° as the initial and lateral boundary conditions, while static geographical fields were generated through the WRF Preprocessing System (WPS). A three-level nested domain configuration with horizontal resolutions of 9 km, 3 km, and 1 km was adopted to represent mesoscale and local-scale atmospheric

processes along the west coast of West Sumatra (Yoon et al., 2021). The model domains and the cross-section transect used for the vertical analyses are shown in Figure 3.

Table 4 summarizes the configuration of the WRF-ARW model (version 4.6.1) used in this study. The selected physical parameterization schemes were adopted based on previous studies demonstrating good performance in simulating sea-breeze circulation and mesoscale atmospheric processes over tropical coastal environments (Yoon et al., 2021; Reddy et al., 2022; McCabe & Freedman, 2025).

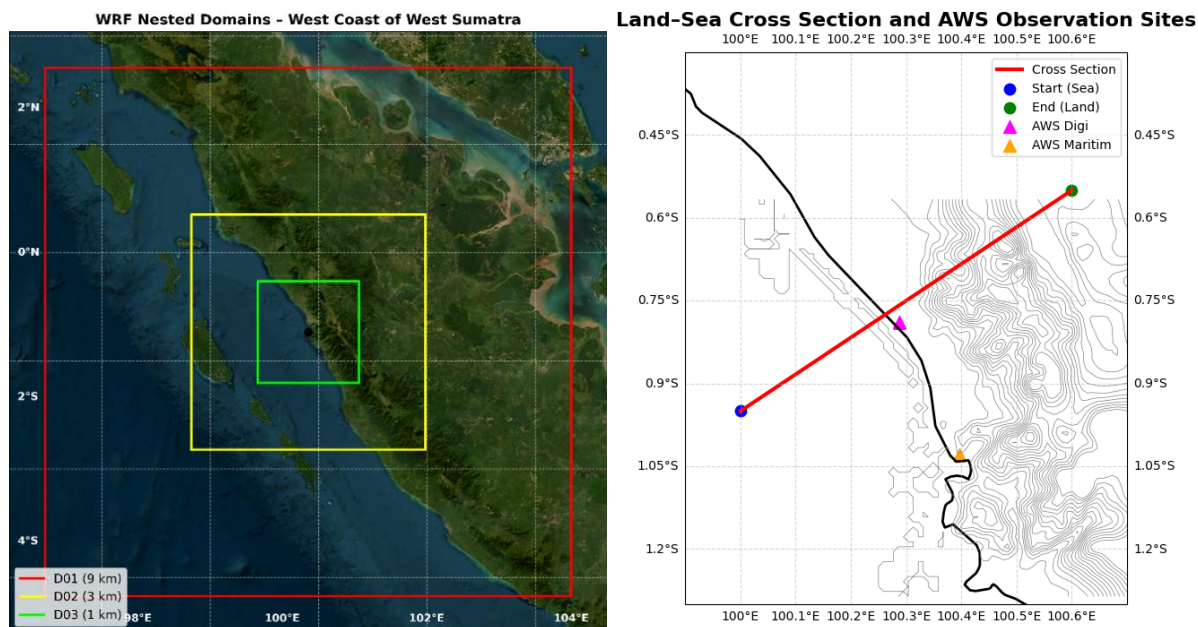


Figure 3. WRF-ARW nested domains and cross-section transect (Sea–Land) used in this study.

In particular, the combination of the MYNN2 planetary boundary layer scheme, Noah-MP land surface model, and RRTMG longwave and shortwave radiation schemes was selected following Yoon et al. (2021), who reported improved numerical prediction of sea-breeze circulation using this configuration. The urban canopy model was disabled following McCabe & Freedman. (2025), who showed that urban parameterizations can overestimate the land–sea thermal contrast in coastal simulations. The Kain–Fritsch cumulus parameterization was applied only in the outermost domain, following the default

configuration adopted by Yoon et al. (2021), while convection was explicitly resolved in the convection-permitting inner domains. Other model settings followed the default Tropical Suite configuration. The complete model configuration is presented in Table 4.

Hourly model outputs included both near-surface meteorological variables and three-dimensional atmospheric fields. The near-surface variables were used for comparison with AWS observations during model validation, whereas the three-dimensional fields were used to investigate the

horizontal circulation, vertical atmospheric structure, and temporal evolution of land–sea breeze events.

Table 4. WRF-ARW model configuration used in this study

Configuration	Domain 1	Domain 2	Domain 3	Reference
Horizontal resolution	9 km	3 km	1 km	Yoon et al., 2021
Grid points (e _{we} × e _{sn})	100 × 100	91 × 91	82 × 82	-
Vertical levels	45	45	45	-
Parent grid ratio	1	3	3	-
Microphysics		WSM6		Tropical Suite
Longwave radiation		RRTMG		Yoon et al., 2021
Shortwave radiation		RRTMG		Yoon et al., 2021
Land surface model		Noah-MP		Reddy et al., 2022
Surface Layer Scheme		MYNN		Yoon et al., 2021
Urban Scheme		OFF		McCabe & Freedman., 2025
PBL scheme		MYNN2		Yoon et al., 2021
Cumulus parameterization	Kain-Fritsch	OFF	OFF	Yoon et al., 2021
Simulation output interval		1 h		-

The AWS observations and WRF-ARW simulations served complementary roles in this study. AWS observations were used to identify land–sea breeze events and to provide reference measurements for model validation, whereas the WRF-ARW simulations were used to reproduce the selected events and examine their spatial evolution and three-dimensional atmospheric structure.

Model Validation

The performance of the WRF-ARW model was evaluated by comparing simulated variables with observations from AWS Digi Minangkabau for the three selected land–sea breeze events. The validation focused on 2-m air temperature (T2), 10-m wind speed (WS), and 10-m wind direction (WD). Statistical metrics were used to quantify the agreement between simulations and observations.

Model performance for temperature and wind speed was evaluated using the Root Mean Square Error (RMSE), Mean Absolute Error (MAE), Mean Bias Error (MBE), and Pearson correlation coefficient (r). These metrics are defined as (Arrillaga et al., 2016; McCabe et al., 2025):

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (S_i - O_i)^2} \quad (1)$$

$$MAE = \frac{1}{n} \sum_{i=1}^n |S_i - O_i| \quad (2)$$

$$MBE = \frac{1}{n} \sum_{i=1}^n (S_i - O_i) \quad (3)$$

$$r = \frac{\sum_{i=1}^n (S_i - \bar{S})(O_i - \bar{O})}{\sqrt{\sum_{i=1}^n (S_i - \bar{S})^2} \sqrt{\sum_{i=1}^n (O_i - \bar{O})^2}} \quad (4)$$

Where S_i and O_i represent simulated and observed values, respectively, $\bar{S}$ and $\bar{O}$ denote their means, and (n) is the number of paired observations.

Because wind direction is a circular variable, its performance was evaluated using Circular Root Mean Square Error (CRMSE) and Normalized Root Mean Square Error (NRMSE). Circular error was calculated by considering the minimum angular difference between simulated and observed wind directions (Arrillaga et al., 2016; McCabe et al., 2025).

$$CRMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (\Delta\theta_i)^2} \quad (5)$$

$$NRMSE = \frac{CRMSE}{180} \times 100 \quad (6)$$

Where $\Delta\theta_i$ is the minimum angular difference between simulated and observed wind directions.

Atmospheric Analysis

Atmospheric dynamics associated with land–sea breeze circulation were investigated using WRF-ARW output from the three selected events. Horizontal analyses were performed using 2-m air temperature (T2), 10-m wind vectors, surface convergence, and Planetary Boundary Layer Height (PBLH) to examine the evolution of thermal gradients, circulation patterns, convergence zones, and boundary-layer development. These analyses were used to identify the initiation, mature phase, and transition stages of the land–sea breeze circulation.

To evaluate the vertical atmospheric structure, cross-sectional analyses were conducted along the A–B transect shown in Figure 3. The analyses included wind fields, virtual potential temperature, mixing ratio, vertical velocity, and U–W circulation. In addition, time–height cross sections were generated at AWS Digi Minangkabau and AWS Maritim Bungus to

examine the temporal evolution of wind structure and vertical motion throughout the circulation cycle. The combination of horizontal, vertical, and time–height analyses was used to characterize the development of land–sea breeze circulation and its interaction with the Bukit Barisan topography.

Results and Discussion

Characteristics of Land-Sea Breeze Events

A total of 51 land–sea breeze events were identified at AWS Digi Minangkabau during the May–September 2025 dry season, whereas only three events satisfied all identification criteria at AWS Maritim Bungus (Table 5). The large difference in the number of detected events indicates that the occurrence of complete land–sea breeze cycles was considerably more consistent at the inland station than at the coastal station. This result suggests that local environmental conditions at Bungus, including complex coastline geometry, surrounding terrain, and the influence of larger-scale atmospheric forcing, may have reduced the frequency of clearly detectable land–sea breeze signatures.

Table 5. Characteristics of Identified Land–Sea Breeze Events over the West Coast of West Sumatra

Parameter	AWS Digi Minangkabau	AWS Maritim Bungus
Number of identified events	51	3
Mean sea-breeze onset (UTC)	02-03	03-04
Sea-breeze onset range (UTC)	01-06	01-07
Mean sea-breeze duration (h)	7.35	6.67
Mean sea-breeze direction (°)	238.13	195.68
Mean sea-breeze speed (m s ⁻¹)	2.62	1.95
Mean land-breeze onset (UTC)	12-13	15-16
Mean land-breeze duration (h)	8.57	3.00
Mean land-breeze direction (°)	55.97	348.96
Mean land-breeze speed (m s ⁻¹)	0.90	0.52

The identified events exhibited relatively consistent onset times throughout the study period. At AWS Digi, sea-breeze onset generally occurred between 02 and 03 UTC, with a wider onset range of 01–06 UTC. A similar pattern was observed at AWS Maritim, where sea-breeze onset

typically occurred between 03 and 04 UTC. The occurrence of sea-breeze onset during the morning hours is consistent with the development of land–sea thermal contrasts following solar heating over land. As the land surface warms more rapidly than the adjacent ocean, a horizontal pressure

gradient is established, initiating the onshore flow characteristic of sea-breeze circulation (Allouche et al., 2025).

The duration of sea-breeze circulation was also relatively stable. Mean sea-breeze duration reached 7.35 h at AWS Digi and 6.67 h at AWS Maritim. These values indicate that once established, the sea-breeze circulation persisted for a substantial portion of the daytime period. The longer duration observed at AWS Digi suggests that inland penetration of marine air remained active even after the initial onset near the coastline. Such behaviour is consistent with the continued maintenance of thermal and pressure gradients between land and ocean during daytime conditions.

Differences between the two stations were more evident in wind direction. The mean sea-breeze direction at AWS Digi was 238.13° , indicating a southwesterly to westerly onshore flow, whereas AWS Maritim recorded a more southerly direction (195.68°). These differences reflect the influence of coastline orientation and the Bukit Barisan topography on the inland penetration of marine air (Miao et al., 2003; He et al., 2021).

Sea-breeze circulation was consistently stronger than land-breeze circulation at both stations. Mean sea-breeze wind speeds reached 2.62 m s^{-1} at AWS Digi and 1.95 m s^{-1} at AWS Maritim, compared with only 0.90 and 0.52 m s^{-1} during the land-breeze phase. This asymmetry indicates stronger daytime thermal forcing than nocturnal cooling during the dry season.

Land-breeze circulation exhibited greater variability than sea-breeze circulation. At AWS Digi, offshore flow generally developed between 12 and 13 UTC and persisted for about 8.6 h, whereas AWS Maritim showed a later onset (15–16 UTC) and a much shorter duration (3 h). This contrast suggests that nocturnal offshore flow was more susceptible to local topographic effects and background

atmospheric conditions. Unlike AWS Digi, AWS Maritim is located within Bungus Bay, where the narrow coastal plain is immediately bounded by the Bukit Barisan Mountains. Such geographical conditions favor interactions between land-breeze circulation, mountain–valley winds, and background synoptic forcing, which can weaken or interrupt nocturnal offshore flow and shorten its persistence (Miao et al., 2015; Allouche et al., 2023). Furthermore, the irregular coastal geometry of Bungus Bay likely modifies local airflow and wind direction, resulting in land-breeze characteristics that reflect the local geographical setting rather than an idealized land–sea-breeze circulation (Lim & Lee, 2021). This interpretation is also supported by the markedly different mean land-breeze direction observed at AWS Maritim (348.96°), indicating a stronger influence of local terrain on the nighttime circulation than at AWS Digi.

Overall, the observational analysis indicates three characteristic features of land–sea breeze circulation along the west coast of West Sumatra: (1) a relatively consistent morning sea-breeze onset with a duration of approximately 6–8 h, (2) stronger and more persistent sea-breeze circulation than land breeze, and (3) clear spatial differences between the inland and coastal stations, highlighting the influence of complex coastal topography and local atmospheric forcing on the development and persistence of land–sea breeze circulation. These observations provide the basis for evaluating the capability of WRF-ARW to reproduce the identified events and their associated atmospheric dynamics.

Performance of WRF-ARW in Simulating Land–Sea Breeze Circulation

The performance of WRF-ARW was evaluated by comparing simulated atmospheric variables with observations from AWS Digi Minangkabau during the three selected land–sea breeze events. Validation was conducted for near-surface

air temperature (T2), wind speed (WS), and wind direction (WD). Statistical metrics were calculated using 24 hourly observation–simulation pairs (00–23 UTC) for each event day, while each WRF

simulation was initialized at 06 UTC on the preceding day to provide an 18-hour spin-up period. The results are summarized in Table 6.

Table 6. Validation Statistics of WRF-ARW Simulations for Selected Land–Sea Breeze Events.

Parameter	Variable	RMSE	MAE	MBE	r	NRMSE (%)
18 May 2025	T2	1.470	1.270	-0.361	0.961	-
	WS	0.519	0.419	0.177	0.929	-
	WD	73.465	-	-	-	40.814
27 May 2025	T2	1.446	1.206	-0.560	0.966	-
	WS	0.504	0.416	0.189	0.903	-
	WD	44.195	-	-	-	24.553
2 June 2025	T2	1.828	1.548	-1.435	0.928	-
	WS	1.473	1.119	-0.018	0.600	-
	WD	69.080	-	-	-	38.378

Overall, the model demonstrated good skill in reproducing the temporal evolution of near-surface temperature throughout the study period. Temperature simulations exhibited high correlation coefficients ranging from 0.928 to 0.966, indicating that WRF-ARW successfully captured the observed diurnal temperature variability associated with the development of land–sea thermal contrasts. RMSE values varied between 1.446 and 1.828 °C, while MAE values ranged from 1.206 to 1.548 °C. In all cases, the model produced negative MBE values, suggesting a systematic tendency to underestimate near-surface air temperature. The strongest temperature performance was obtained during the 27 May 2025 event, which yielded the highest correlation coefficient ($r = 0.966$) and the lowest RMSE (1.446 °C). These results indicate that WRF-ARW was able to reproduce the thermal forcing responsible for the initiation and maintenance of land–sea breeze circulation with a high degree of accuracy.

Wind speed simulations also showed generally satisfactory performance, particularly during the 18 May and 27 May events. Correlation coefficients exceeded 0.90 in both cases, accompanied by relatively low RMSE values of approximately 0.5 ms^{-1} . Positive MBE values indicate a slight tendency for the

model to overestimate wind speed during these events. The ability of WRF-ARW to reproduce the observed wind-speed variability suggests that the model adequately represented the strength of the sea-breeze circulation and its inland penetration during periods characterized by well-defined local forcing.

A notable reduction in model performance was observed during the 2 June 2025 event. Although temperature simulations remained highly correlated with observations ($r = 0.928$), wind-speed performance deteriorated substantially, as indicated by the increased RMSE (1.473 ms^{-1}) and reduced correlation coefficient ($r = 0.600$). This decline suggests that atmospheric conditions during this event were influenced by additional processes that were not represented as effectively by the model. Similar interactions between local sea-breeze circulations and larger-scale atmospheric forcing have been documented in monsoon-affected coastal regions (Jayakrishnan et al., 2021; Allouche et al., 2025). The reduced skill may reflect stronger interactions between local land–sea breeze circulation and larger-scale atmospheric forcing, resulting in a more complex wind field than those observed during the other two cases.

The accuracy of simulated wind direction was assessed using normalized circular root mean square error (NRMSE) to account for the circular nature of directional data. Among the three events, the 27 May case produced the lowest directional error, with an NRMSE of 24.55%, indicating the best agreement between simulated and observed wind directions. The 18 May and 2 June events exhibited higher NRMSE values of 40.81% and 38.38%, respectively, suggesting greater directional variability and larger discrepancies between model output and observations. Nevertheless, the model successfully reproduced the primary transition from offshore to onshore flow and the subsequent reversal associated with the land–sea breeze cycle.

Taken together, the validation results demonstrate that WRF-ARW was capable of reproducing the principal characteristics of land–sea breeze circulation along the west coast of West Sumatra. The model consistently captured the evolution of near-surface temperature and wind fields, particularly during the 18 May and 27 May events, which exhibited the strongest agreement with observations. Although model performance declined during the 2 June event, the overall results provide sufficient confidence to use the simulations for investigating the horizontal and vertical atmospheric dynamics associated with the selected land–sea breeze cases, as discussed in the following section.

Atmospheric Dynamics of Representative Land–Sea Breeze Events

1. Atmospheric Evolution during the 18 May 2025 Event

The 18 May 2025 event represents a typical land–sea breeze circulation case over the west coast of West Sumatra. The circulation developed following daytime heating over land, which generated a land–sea thermal contrast and induced onshore flow from the Indian Ocean. Similar thermally driven mechanisms have been widely recognized as the primary driver of sea-breeze formation in tropical coastal regions (Allouche et al., 2025).

Although Figure 5 presents the representative horizontal evolution of the circulation for 27 May 2025, a comparable development was also observed on 18 May. Marine air penetrated inland toward the foothills of the Bukit Barisan, where convergence became increasingly organized. The displacement of convergence away from the coastline suggests a strong interaction between the sea breeze and local topography. Similar topographically induced convergence has been reported in coastal mountainous environments where sea-breeze flow interacts with terrain barriers and slope circulations (Miao et al., 2003; He et al., 2021).

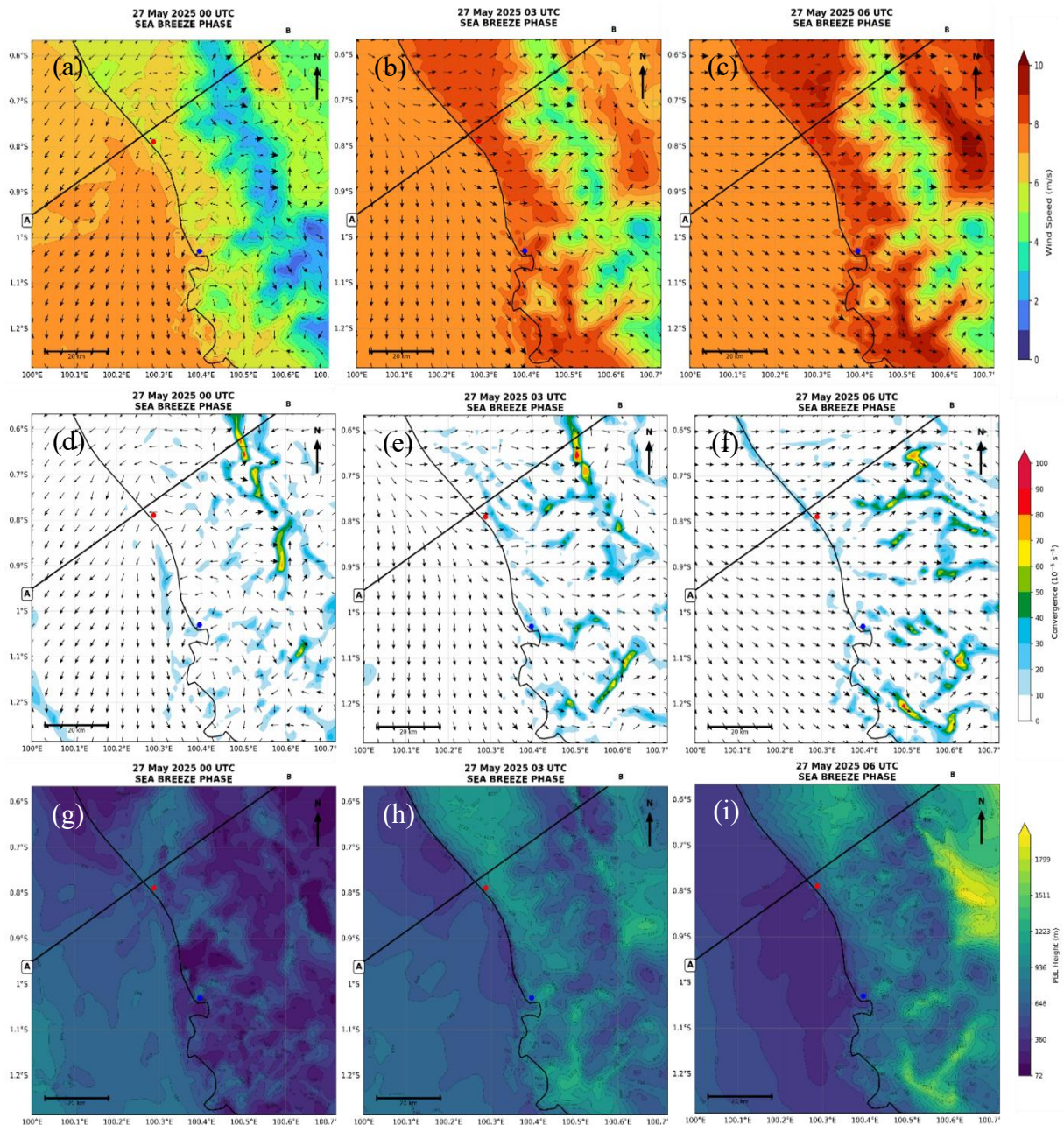


Figure 5. Horizontal evolution of land-sea breeze circulation on 27 May 2025: (a–c) Near-surface air temperature (T_2 ; shaded) and 10-m wind vectors at 03, 06, and 09 UTC, respectively; (d–f) Surface convergence (shaded) at 03, 06, and 09 UTC, respectively; (g–i) Planetary Boundary Layer Height (PBLH; shaded) at 03, 06, and 09 UTC, respectively.

The vertical structure of the circulation was characterized by low-level onshore flow, moisture transport toward inland regions, and enhanced upward motion over the foothills. As illustrated by the representative vertical structure in Figure 6, the circulation extended through approximately 1–2 km of the lower troposphere. Comparable circulation depths have been reported in several coastal regions, indicating that sea-breeze

circulations are generally confined to the lower atmosphere (Park & Chae, 2018; Jia et al., 2022). Overall, the 18 May event demonstrates a well-organized land-sea breeze circulation strongly influenced by both thermal forcing and topographic modulation.

2. Atmospheric Evolution during the 27 May 2025 Event

The 27 May 2025 event exhibited the most persistent land–sea breeze circulation among the three selected cases and corresponded to the best overall model performance. The horizontal evolution of the circulation is shown in Figure 5. A pronounced thermal gradient between land and ocean promoted the rapid development of onshore flow, followed by inland penetration of marine air toward the foothills of the Bukit Barisan.

As the circulation intensified, convergence became concentrated over inland regions, while planetary boundary layer development remained active throughout much of the daytime period. The sustained transport of marine moisture inland indicates favourable conditions for maintaining the circulation after its initial formation. Similar relationships between boundary-layer growth, moisture transport, and sea-breeze persistence have been documented in tropical coastal environments (Jia et al., 2022; Yoo et al., 2025).

The mature circulation structure is illustrated in Figure 6. A well-defined onshore flow occupied the lower troposphere, while compensating return flow developed aloft, forming a classical sea-breeze circulation cell. Strong upward motion over the foothill region coincided with maximum convergence, indicating efficient coupling between coastal thermal forcing and topographic effects. Similar topographically induced convergence has been reported in coastal mountainous environments (Miao et al., 2003; He et al., 2021). These characteristics suggest that the interaction between land–sea thermal gradients and the Bukit Barisan topography was particularly effective during this event, resulting in the most persistent circulation observed in this study.

3. Atmospheric Evolution during the 2 June 2025 Event

The 2 June 2025 event displayed a more complex circulation structure than the previous cases. Although a clear land–sea breeze cycle was identified, the horizontal and vertical organization of the circulation was comparatively weaker. The event also corresponded to reduced model performance for wind-related variables, suggesting the influence of additional atmospheric processes.

Despite these differences, marine air still penetrated inland and generated convergence over both coastal and inland regions. Such dual convergence patterns have been reported in other coastal environments where sea-breeze circulations interact with local terrain and evolving background flows (He et al., 2021; Zhu et al., 2017). Compared with the representative circulation shown in Figures 5 and 6, the 2 June event exhibited a less coherent distribution of convergence, vertical motion, and moisture transport.

Nevertheless, the fundamental characteristics of land–sea breeze circulation remained evident. Onshore flow dominated the lower atmosphere during the daytime period, while upward motion developed over inland regions and foothills. The circulation depth remained within approximately 1–2 km of the lower troposphere, although the cell was less symmetrical and less persistent than in previous events. This depth aligns with observations from Seoul and other coastal regions, where sea-breeze circulation is largely confined to the lower troposphere (Park & Chae, 2018; Jia et al., 2022). These findings suggest that local thermal forcing remained important, but its influence was partly modulated by larger-scale atmospheric conditions—a behavior also documented in monsoon-influenced coastal environments (Jayakrishnan et al., 2021; Allouche et al., 2025).

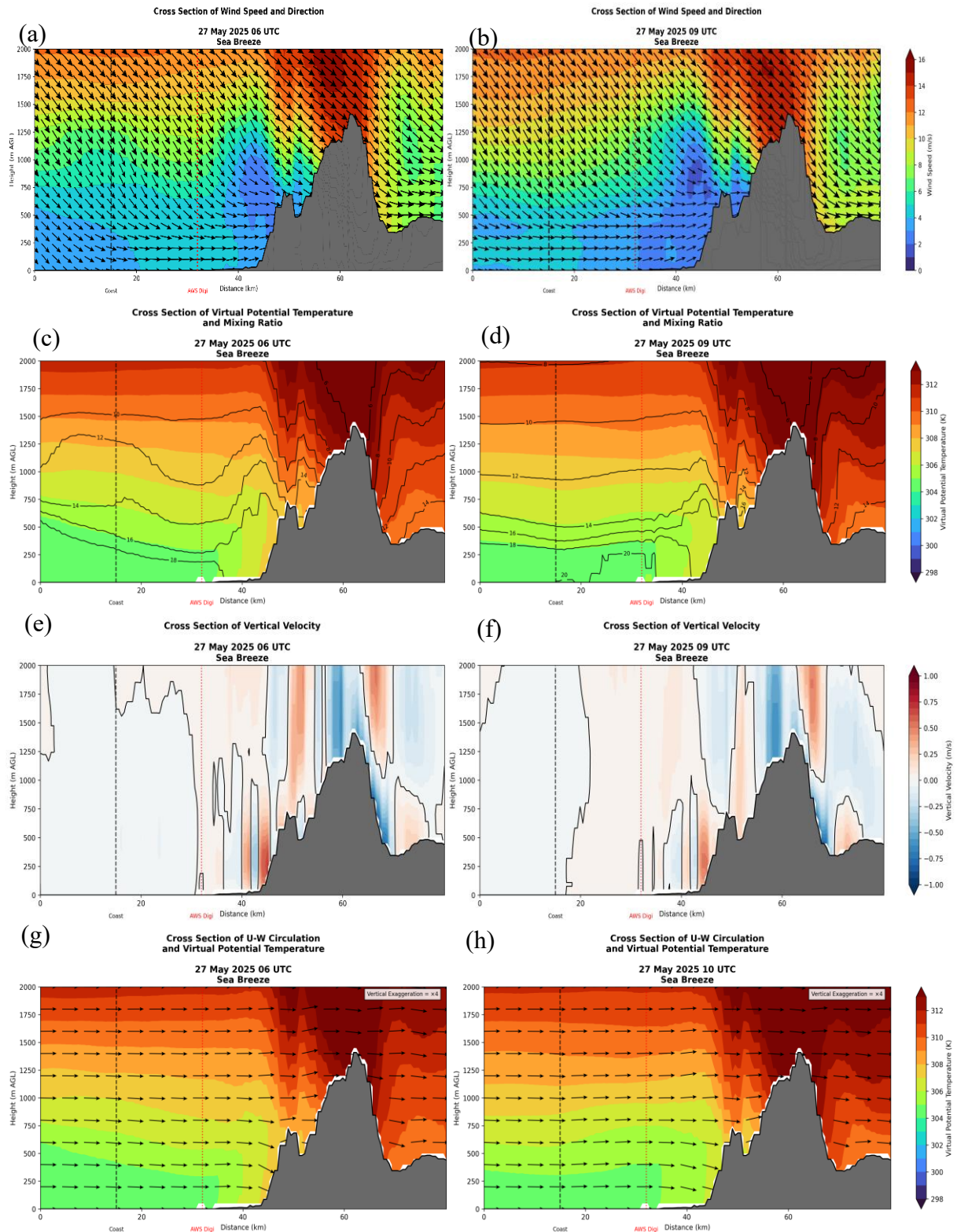


Figure 6. Vertical structure of land–sea breeze circulation during the mature phase of the 27 May 2025 event: (a–b) Cross-sections of wind speed and wind vectors at 06 and 09 UTC, respectively; (c–d) Cross-sections of virtual potential temperature (θ_v ; shaded) and mixing ratio (contours) at 06 and 09 UTC, respectively; (e–f) Cross-sections of vertical velocity at 06 and 09 UTC, respectively; (g–h) U–W circulation cross-sections at 06 and 10 UTC, respectively.

Comparative Characteristics of the Three Events

Although all three events exhibited the fundamental characteristics of thermally

driven land–sea breeze circulation, substantial differences were observed in their spatial organization, persistence, and vertical structure (Table 7). The similarities among the events include a relatively consistent sea-breeze onset between 02 and 03 UTC and a mature phase occurring

between 06 and 09 UTC. This consistency suggests that the initiation and development of land–sea breeze circulation along the west coast of West Sumatra are strongly controlled by the diurnal cycle of surface heating, which establishes a recurring land–sea thermal contrast during the dry season.

Table 7. Comparative characteristics of three selected land–sea breeze events.

Characteristic	18 May 2025	27 May 2025	2 June 2025
Sea-breeze onset (UTC)	02	03	02
Sea-breeze duration (h)	7	9	9
Mature phase (UTC)	06–09	06–09	06–09
Surface convergence	Strong and organized	Widespread and fragmented	Strong and relatively organized
PBL development	Rapid and intensive	More persistent	Extensive and organized
Moisture transport	Intensive	Continuous	Intensive and continuous
Upward motion	Concentrated over mountain slopes	Widespread and persistent	Strong and sustained until transition phase
U–W circulation structure	Well-defined	Relatively weak but persistent	Most complete
Dominant characteristic	Strong circulation organization	High circulation persistence	Most complete land–sea breeze cycle

The 18 May 2025 event was characterized by the strongest circulation organization. Surface convergence developed as a coherent zone extending from the coastal plain toward the foothills of the Bukit Barisan, while ascending motion remained concentrated over the eastern portion of the study area. The U–W circulation pattern was clearly identifiable, indicating efficient coupling between low-level onshore flow and compensating return flow aloft. These characteristics suggest that the interaction between thermal forcing and topographic effects produced a highly organized mesoscale circulation structure.

In contrast, the 27 May 2025 event exhibited the greatest circulation persistence. Although the convergence pattern appeared more spatially fragmented than in the 18 May case, moisture transport from the ocean remained active for a longer period and the sea-breeze circulation persisted throughout much of the daytime cycle. The prolonged development of the planetary boundary layer and the sustained presence of upward motion indicate that the thermally driven circulation remained active for an extended duration. This

behavior suggests that atmospheric conditions on 27 May were particularly favorable for maintaining the sea-breeze system after its initial formation.

The 2 June 2025 event displayed the most complete land–sea breeze cycle among the three cases. Strong and relatively organized convergence was observed during the mature stage of the circulation, while upward motion remained active until the transition toward the evening land-breeze phase. Unlike the previous events, the circulation evolution captured both the mature sea-breeze stage and the subsequent transition toward offshore flow. The resulting U–W circulation structure was the most complete among the selected cases, indicating a well-developed coupling between daytime onshore flow and nighttime offshore circulation.

The time–height analysis further reveals several common characteristics shared by all events. The sea-breeze circulation was generally confined to the lower troposphere and rarely extended above approximately 1–2 km altitude. The strongest onshore flow was consistently observed below 1

km, while ascending motion developed above regions affected by convergence and topographic lifting. These recurring features indicate that the land–sea breeze circulation along the west coast of West Sumatra is primarily a shallow mesoscale phenomenon whose vertical extent is strongly influenced by both coastal thermal gradients and the nearby Bukit Barisan topography.

Overall, the comparison demonstrates that differences among the three events are primarily associated with the degree of circulation organization, persistence, and completeness rather than with the fundamental mechanisms governing their development. Despite variations in intensity and structure, all events consistently show the combined influence of differential land–sea heating and topographic forcing, confirming that these two processes constitute the primary controls on land–sea breeze evolution in the study region.

General Characteristics of Land–Sea Breeze Circulation along the West Coast of West Sumatra

The observational and numerical analyses indicate that land–sea breeze circulation is a recurrent mesoscale phenomenon along the west coast of West Sumatra during the dry season. Despite variations among the selected events, the circulation exhibited relatively consistent onset times between 02 and 03 UTC and generally reached its mature phase between 06 and 09 UTC. Similar diurnal behavior has been reported along the west coast of Sumatra and other tropical coastal regions, where the evolution of sea-breeze circulation is primarily controlled by differential heating between land and ocean surfaces (North et al., 2025; Allouche et al., 2025).

A key characteristic identified in this study is the strong influence of topography on circulation development. Rather than remaining confined to the coastline, marine

air consistently penetrated inland toward the foothills of the Bukit Barisan Mountain range. The strongest convergence and upward motion were frequently observed over inland and foothill regions, indicating that the interaction between coastal thermal gradients and mountainous terrain plays a major role in regulating circulation evolution. Similar topographic modulation of sea-breeze circulation has been documented in coastal mountainous environments, where terrain influences convergence patterns, penetration distance, and circulation intensity (Miao et al., 2003; He et al., 2021).

The vertical structure of the circulation was characterized by low-level onshore flow, compensating return flow aloft, and a circulation depth of approximately 1–2 km. Time–height and cross-sectional analyses revealed that the strongest sea-breeze influence remained confined to the lower troposphere, consistent with observations reported in other coastal regions (Park & Chae, 2018; Jia et al., 2022). These results indicate that land–sea breeze circulation along the west coast of West Sumatra develops as a shallow but well-organized mesoscale system.

The WRF-ARW simulations successfully reproduced the principal characteristics of the observed circulation, including the timing of sea-breeze development, inland penetration of marine air, convergence patterns, and vertical circulation structure. Collectively, the results demonstrate that the evolution of land–sea breeze circulation in the study region is governed by the combined effects of differential land–sea heating and topographic modulation by the Bukit Barisan Mountain range. This interaction represents the dominant mechanism controlling coastal atmospheric dynamics along the west coast of West Sumatra.

Conclusion

This study characterized land–sea breeze circulation along the west coast of West Sumatra during the 2025 dry season using AWS observations and WRF-ARW simulations. A total of 54 land–sea breeze events were identified during the study period, comprising 51 events from AWS Digi Minangkabau and three events from AWS Maritim Bungus. The results indicate that sea-breeze circulation generally developed between 02 and 03 UTC, reached its mature phase between 06 and 09 UTC, and typically persisted for 7–9 h. Horizontal, vertical, and time–height analyses consistently showed that marine air penetrated inland toward the foothills of the Bukit Barisan, where enhanced surface convergence, planetary boundary-layer development, and upward motion led to the development of a well-organized circulation cell extending to approximately 1–2 km above ground level. These findings indicate that the evolution of land–sea breeze circulation in the study area is jointly controlled by differential land–sea heating and topographic modulation associated with the Bukit Barisan Mountain range.

Model validation demonstrated that WRF-ARW reproduced the observed land–sea breeze characteristics with consistently good performance for near-surface temperature (correlation coefficients of 0.93–0.97 and MAE of 1.21–1.55 °C), although wind-speed performance exhibited greater variability among events (correlation coefficients of 0.60–0.93). The model also successfully captured the timing of sea-breeze development, inland penetration of marine air, the evolution of convergence and boundary-layer growth, and the vertical circulation structure. Overall, the findings demonstrate that WRF-ARW provides a reliable framework for investigating mesoscale coastal circulations over complex tropical terrain while providing new insight into the interaction between coastal thermal forcing and the Bukit Barisan topography along the west coast of West Sumatra.

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Author Contribution

Reinal Taruna Wahyu Halawa: Conceptualization, data curation, formal analysis, investigation, methodology, software, visualization, writing—original draft, and correspondence. Latifah Nurul Qomariyatuzzamzami: Conceptualization, supervision, validation, methodology, writing—review and editing. Yosafat Donni Haryanto: Validation, supervision, and writing—review and editing. Avrionesti: Validation, supervision, and writing—review and editing.

Conflict of Interest

The authors declare no conflict of interest.

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