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Roles of Land and Topography on Propagating Convective Systems During the Heavy Rainfall Event of the 2002 Jakarta Flood, Indonesia

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Abstract: The movement direction of propagating convective systems originating from both inland and offshore over the north coast of West Java in Indonesia is determined primarily by the prevailing wind. However, the role of a land-sea contrast and a rugged topography over southern West Java is also expected to affect propagating convective systems by increasing land-sea breezes and enhancing upward motion. These hypotheses are tested using a weather prediction model incorporating convection (up to 3 km height) to simulate the heavy rainfall event during 26–29 January associated with the 2002 Jakarta flood. First, we addressed the influence of land-sea contrast and topography on the local circulation, particularly in the area surrounding Jakarta, by replacing the inland topography over western Indonesia (96°–119°E, 17°S–0°) with a water body with an altitude of 0 m. We then compared the results of model simulations with and without topography. The results show that the main role of the topography here is enhancing the upward motion and generating a deep convective cloud in response to the land-based convective system during 26–27 January 2002, which then continuously and rapidly propagates offshore due to the cold pool mechanism. Furthermore, the land-sea contrast has a significant role in increasing sea breeze under the rapidness of the landward propagation system during 28–29 January 2002, which was strengthened by the gravity waves and resulted in early morning convection over coastal regions.

Keywords: land-sea contrast; topography, propagating convective system, early morning convection, Java

1. Introduction

Heavy rainfall over the north coast of West Java has triggered severe floods in Jakarta, Indonesia [1–5]. These extreme events associated with landward- as well as offshore-propagating convective systems have previously been found to be controlled by prevailing background winds [6–7]. However, the effects of land and topography on this propagating convective system are not fully understood. On a regional scale, a previous study suggested that the sea breeze convergence is strengthened by mountain–valley winds, which enhance precipitation over inland Java [8].

Moreover, the localized spatial asymmetry of the topography over this region produces a heterogeneous rainfall pattern between southern and northern Java, and implies rainfall variability occurs on an interannual timescale. The strengthened sea and valley breeze convergence produces large amounts of precipitation over mountainous regions

[8]. However, no previous studies have investigated the effects of mountainous regions in southern West Java on coastal precipitation associated with extreme flooding events in Jakarta. On the other hand, several previous studies shared a clue about the role of land through Island rainfall enhancement mechanism that mainly creates significant diurnal rainfall [9–12] over the Maritime Continent [8,13–15]. This mechanism shows that a localized buoyancy oscillation modulated by land-sea contrast can produce the mean circulation [12,16–18], thus, may trigger extreme precipitation associated with several floods over the Maritime Continent (i.e., the Greater Jakarta).

In the past four decades, the capital city of Jakarta has experienced floods more frequently during the active period of the Asian monsoon (January–February). However, a severe flood occurred in Jakarta from 29 January to 10 February 2002, reported as the worst flood in the last three decades (1980–2010) in terms of its impact. Given that offshore (26–27 January 2002)- as well as landward (29–30 January 2002)-propagating convective systems may produce extreme precipitation (see: Fig. 1b, d), this event is an ideal case study to investigate the role of land-sea contrast and topography on offshore as well as landward propagating convective systems using a numerical model. In this case, satellite observational data could well-capture the propagation signal; however, it recorded lower precipitation amounts over Jakarta than station observations from 29 to 30 January 2002 (Fig. 1).

Of note, a cyclonic vortex that developed over the Indian Ocean near southwest Java created a predominantly meridional monsoonal flow that produced near-surface flows with a meridional orientation over West Java (Fig. 1). In this case, we hypothesize that the predominant northerly wind may interact with a land by topographically elevated and complex area in southern West Java. To further investigate the role of land and topography in southern West Java on modulating precipitation over its north coast (including Jakarta), we conducted numerical modeling, based on a removing land and flattening topography approach using high-resolution numerical weather predictions from the Weather Research and Forecasting (WRF) model that incorporates convection up to 3 km height. In the following sections, we explain the model set-up and experimental design, and discuss the results of the modeling.

2. Materials and Methods

2.1 Model Set-up

The numerical experiments were simulated using WRF model version 4.1.2 [19] with one-way nested domains, comprising a coarse domain (D01), an inner domain (D02), and an innermost domain (D03), with spatial resolutions of 27, 9, and 3 km, respectively (Fig. 1). The domains have 95 x 70, 109 x 76, and 97 x 91 grid points, respectively. The center of the coarse domain is 8.568°S and 107.038°E. Mercator map projections were used for the model domains. The simulation configuration and physical parameters are summarized in Table 1. The initial and lateral boundary conditions were obtained from the National Center for Environmental Predictions (NCEP) Final Analysis (FNL) Operational Global

Analysis dataset [20] and forecast grids, which have a horizontal resolution of $1.0^\circ \times 1.0^\circ$ at 6 h intervals. The three-day forecasts were evaluated for each Planetary Boundary Layer (PBL) scheme and the model was initialized at 00:00 UTC (07:00 LT), 25 January 2002, with 24 hours is recognized as an appropriate spin-up time for the model.

To further investigate the heavy rainfall event, we validated the simulation results with ground-based observational data from the Agency for Meteorology, Climatology, and Geophysics (BMKG) station [21] and TRMM Multi-Satellite Precipitation Analysis (TMPA) Real Time 3B41RT (TMPA-RT). The TMPA-RT data are calibrated by rainfall gauge data and have been used in several extreme rainfall studies over tropical regions and the Maritime Continent [6, 22–26]. Furthermore, to identify the synoptic conditions related to background winds, we used high-resolution, near-surface ERA5 data from the European Center for Medium-Range Weather Forecasts (ECMWF), with a spatial resolution of $0.25^\circ \times 0.25^\circ$ [27].

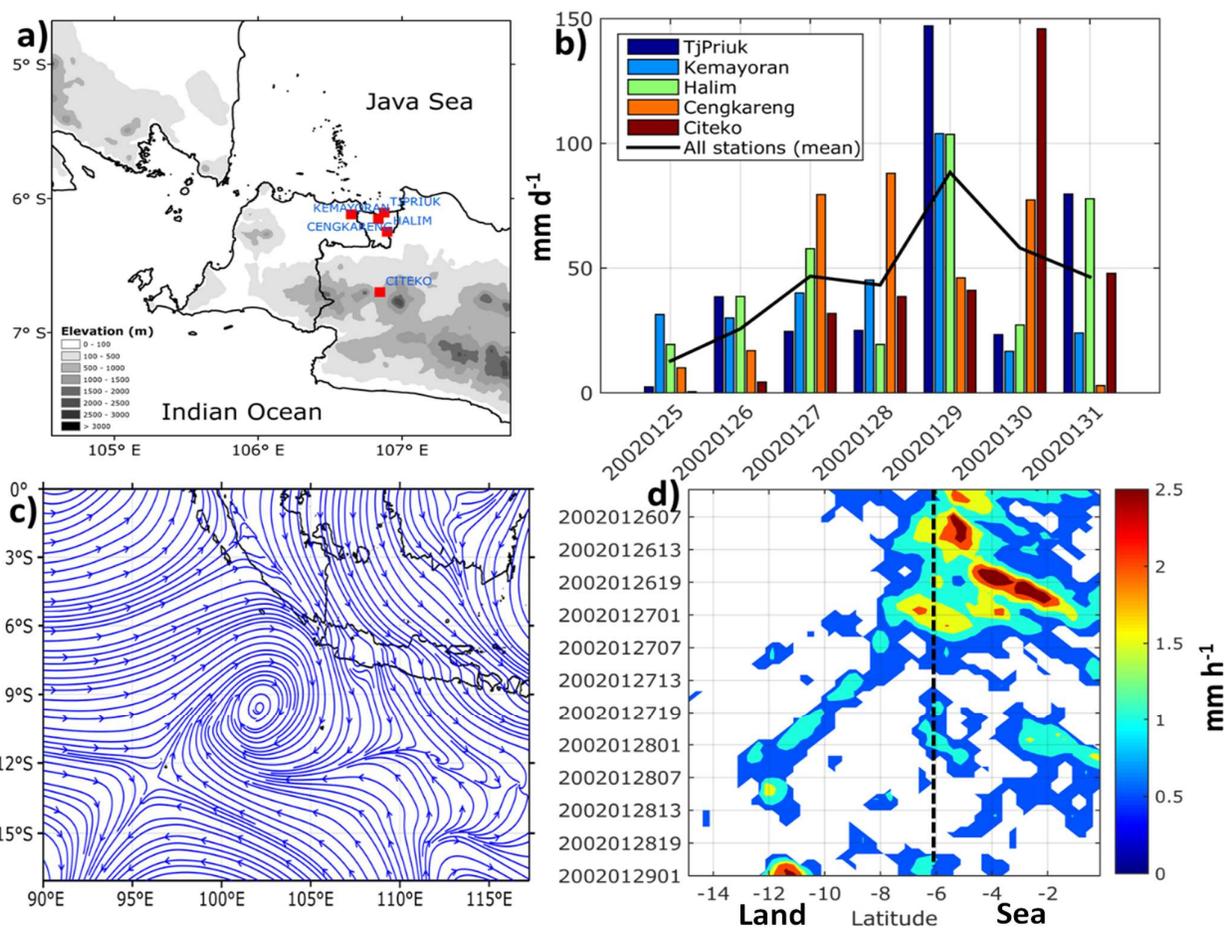


Figure 1. (a) Map of the BMKG station locations. (b) Rainfall amounts recorded by BMKG stations during 25–31 January 2002. (c) Hovmöller diagram showing a time–latitude cross-section along 106.68°E . The black dashed line is the coastline along the north coast of West Java. (d) Composite of the streamlines of near-surface winds (925 hPa) from 25 to 31 January 2002.

2.2 Experimental Design

To investigate the effect of land and topography on a propagating convective system, we used an experimental design (Fig. 2b) involving two scenarios: (1) the actual topographic conditions as the control simulation (CTL); and (2) a modified topography that is flattened (altitude = 0 m) and replaced with the sea (i.e., a water body), which is the scenario simulation (SCE). The CTL and SCE scenario simulations were applied to all domains, focusing on domain 3 (D03). Both experiments include the outermost domain, which captures the effects of regional processes (e.g., wind circulation and sea surface temperature) on the innermost domain circulation. We further analyze the role of land and topography through two selected episodes of propagation: offshore (26–27 January 2002) and landward (28–29 January 2002) propagations of convective systems.

Table 1. Configuration of the Weather and Research Forecasting model for simulating precipitation over the Maritime Continent at horizontal resolutions of 27 km (D01), 9 km (D02), and 3 km (D03).

Configuration	D01	D02	D03
Horizontal grids	95 × 70	175 × 121	199 × 166
Grid spacing (km)	27	9	3
Cumulus scheme	Betts–Miller–Janjic scheme	-	-
Vertical grid	46 layers	46 layers	46 layers
Microphysics	WDM 5-class scheme	WDM 5-class scheme	WDM 5-class scheme
Radiation	RRTMG longwave scheme RRTMG shortwave scheme	RRTMG longwave scheme RRTMG shortwave scheme	RRTMG longwave scheme RRTMG shortwave scheme
Surface layer	Revised MM5 Monin-Obukhov scheme	Revised MM5 Monin-Obukhov scheme	Revised MM5 Monin-Obukhov scheme
Land surface	Unified Noah land-surface model	Unified Noah land-surface model	Unified Noah land-surface model
Planetary boundary layer	YSU scheme	YSU scheme	YSU scheme
Initial boundary condition	FNL 1.0 × 1.0	FNL 1.0 × 1.0	FNL 1.0 × 1.0

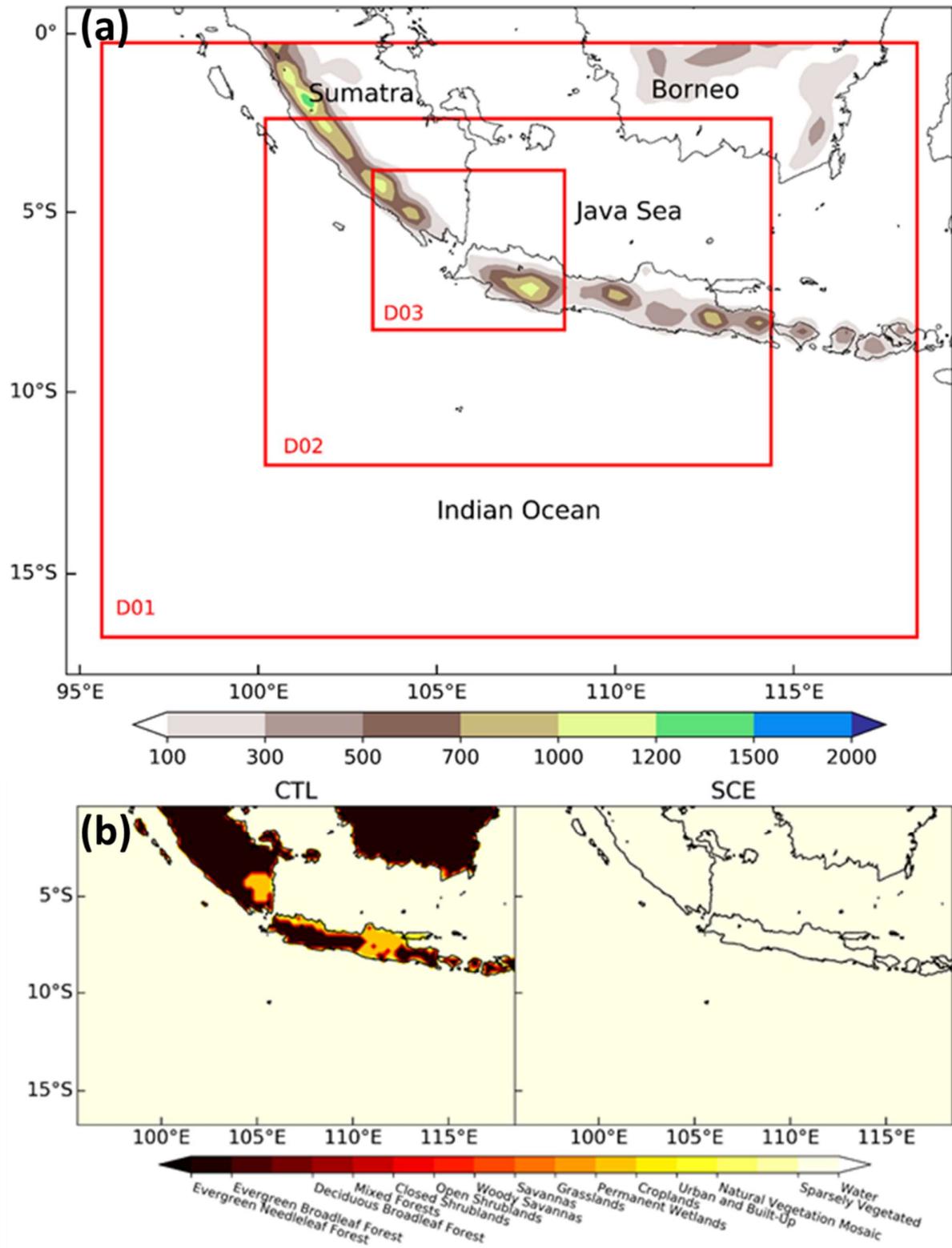


Figure 2. (a) Simulation domains of the WRF model. (b) Land-use scheme used for the control (CTL) and flattened topography (SCE) simulations.

3. Results and Discussion

3.1 Heavy Rainfall Observed and Background Conditions

Rainfall recorded by four meteorology stations in Jakarta and surrounding areas revealed a significant increase from 26 to 30 January 2002 (Fig. 1b). Moreover, heavy rainfall (almost 150 mm) on 29 January 2002 occurred over the northern coast of Jakarta (Tanjung Priok Station). The rainfall began on the morning of 26 January 2002 over inland areas and tended to propagate rapidly offshore during the following morning (Fig. 1b). However, landward propagation of the convective system also occurred, with a slower phase of propagation from 26 to 28 January 2002. However, during 26–28 January 2002, moderate intensity precipitation over the coastal region became persistent (Fig. 1b).

Of note, the slower landward propagation was related to the presence of a cyclonic vortex that developed over the Indian Ocean close to the coast of southern West Java on 26–27 January 2002. The cyclonic vortex caused strengthening of a predominant northerly wind with a meridional monsoonal flow over West Java (Fig. 1c). This northerly flow was similar to the cold anomaly that was identified as the main cause of the torrential precipitation during the Jakarta flood from 31 January to 2 February 2007 [1–2]. The heavy rainfall was modulated by the meridional wind [1], temperature, and relative humidity, which were associated with a cold anomaly after the Borneo Vortex had dissipated [2].

One interesting factor is that the offshore propagation of the convective system was in a direction against the prevailing wind. The interaction between the predominant northerly wind and rugged topography of southern West Java might have contributed to the offshore propagation and enhanced convection inland. We further examined this issue with the flattening topography scenario model over domain 3 (Fig. 2a) and compared the rainfall results for this scenario and the CTL simulations for 26–29 January 2002 (Fig. 2b).

3.2 Effect of Land and Topography on Propagating Convective Systems

The effects of land and topography on a propagating convective system are shown in Fig. 3. The presence of a land-based, as well as an oceanic convective system, produced maximum precipitation on 26 January 2002 during the afternoon and at night, respectively (Fig. 3a). In this case, both the land-based convective system and offshore propagation are evident on 26 and 27 January 2002 in the CTL simulation, but are not evident in the SCE simulation.

Interestingly, early morning precipitation over the coastal region also became persistent during 28–30 January 2002 in the CTL simulation, whereas the SCE simulation only captured the landward propagation of the convective system on 27 January (Fig. 3b-c). Consequently, the difference (i.e., by subtracting) between the CTL and SCE simulations reveals large amounts of rainfall over the land and ocean on those days, apart from the afternoon rainfall on 28 January 2002 (Fig. 3d).

This vigorous rainfall depicted in the CTL is related to the general diurnal rainfall pattern over the Maritime Continent under the Island rainfall enhancement hypothesis [8,11,13]. Thus, previous studies also mentioned that removing islands leads to more impact in reducing rainfall than flattening orography over the western Maritime Continent

(Sumatra and Kalimantan Islands) [15]. In this study case, both offshore (26–27 January 2002) as well as landward (29–30 January 2002) propagation of rainfall (Fig. 3b,d) suggested as an implication of removing land and flattening topography treatment in the SCE.

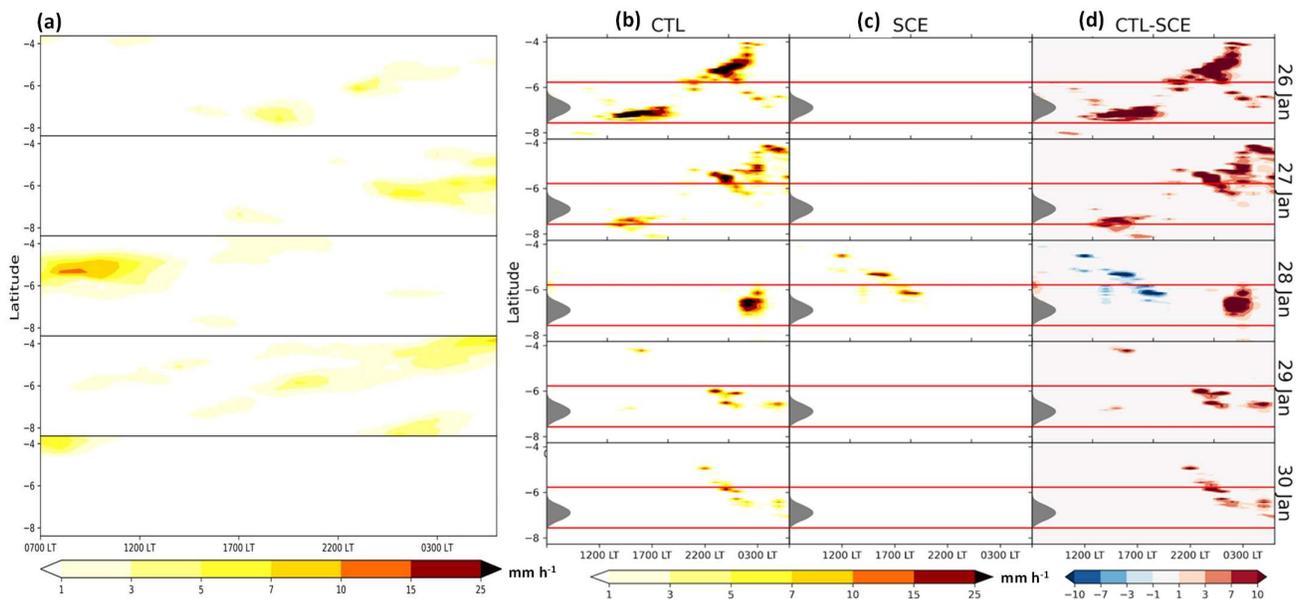


Figure 3. Hovmöller diagram showing a time–latitude cross-section along 106.86°E of daily rainfall from 26 to 30 January 2002 for the (a) TMPA-RT, (b) CTL, (c) SCE, and (d) CTL–SCE simulations.

We now consider the effect of topography on the maximum precipitation obtained from the CTL simulation on 26–28 January, given the qualitative agreement between the model results and observational data, which was also confirmed by the spatial rainfall pattern (Fig. 4a–c). The potential temperatures in the CTL and SCE simulations over West Java are similar (Fig. 4d–f).

However, there are slight differences in humidity between the northern and southern parts of West Java, which indicate the topographic effect of the mountain range might have formed dry (moist) areas in the northern (southern) regions (Fig. 4f). This result is consistent with a previous finding that the topography created upward and downward motions due to the large-scale circulation (i.e., Madden–Julian oscillation), and thus a quasi-stationary convective system near major topographic features over the Maritime Continent [28].

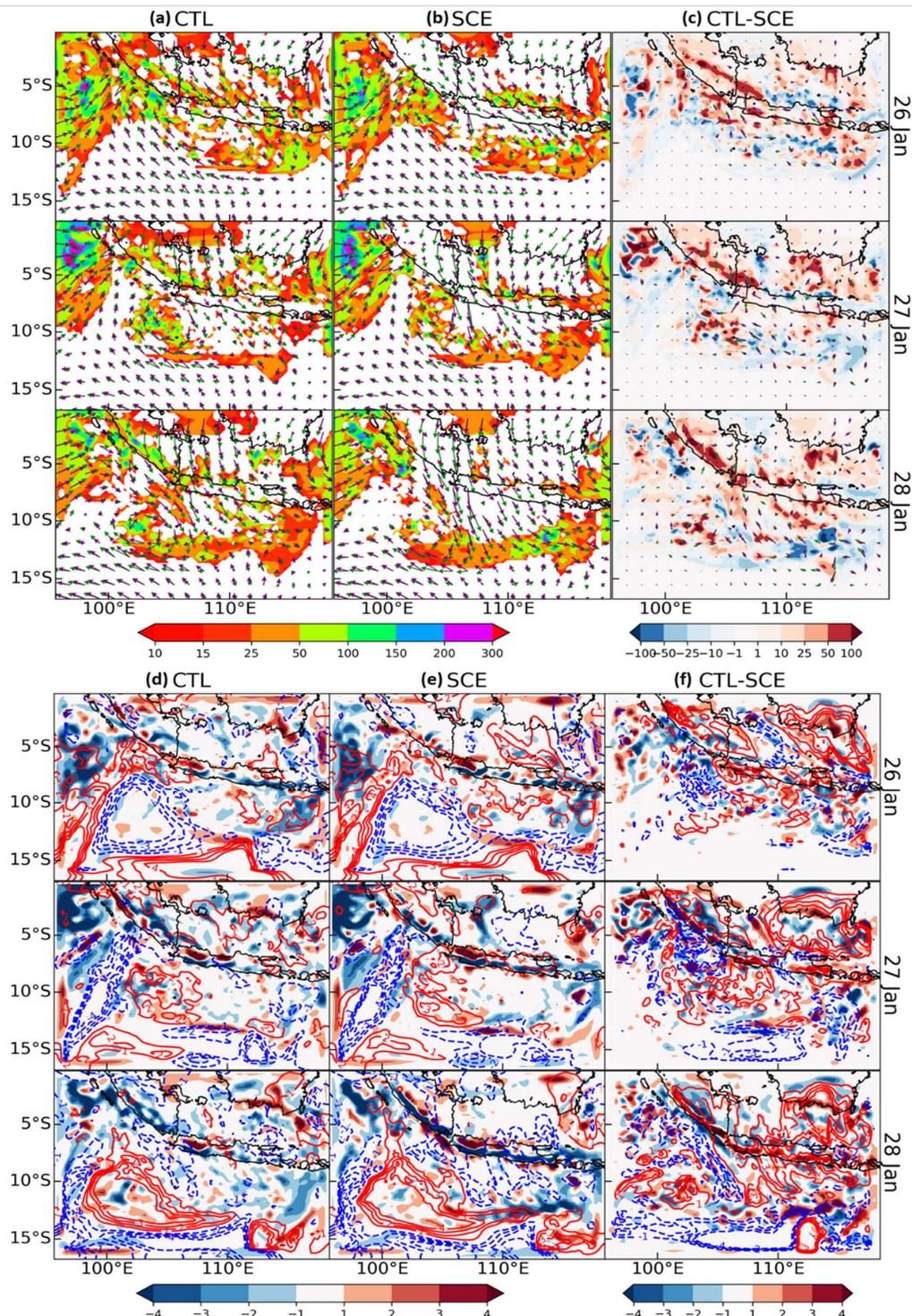


Figure 4. Spatial maps of the CTL, SCE, and CTL-SCE simulation results from 26 to 28 January 2002. (a–c) Daily rainfall (shading) overlain by the near-surface wind average and anomaly at 925 hPa (vectors). (d–f) Daily equivalent potential temperature anomaly with respect to the five-day average (shading and contour lines; blue and red are negative and positive anomalies, respectively).

Moreover, this topography might have triggered the propagating convective system that is evident on 26–27 January 2002 (Fig. 5) as compared with 28–29 January 2002 (Fig. 6). However, Fig. 6 reveals other features regarding the initiation of convection over

coastal regions, which occurred in the morning of 29 January 2002 (01:00–06:00 LT). Therefore, we now discuss the physical and dynamic processes related to the effect of topography on: (1) propagating convective systems; and (2) early morning convection.

Figure 5a and d shows that strong offshore propagation occurred from 13:00 to 00:00 LT, over a distance of >110 km. The offshore propagation did not occur in the SCE simulation (Fig. 5b and e). During 07:00–18:00 LT, the convective system was concentrated over the mountainous region, whereas during 19:00–00:00 SLT the system moved offshore (Fig. 5c and f). This strong offshore propagation is consistent with a previous study that found offshore-propagating convection from inland areas reaches a maximum in daytime [29].

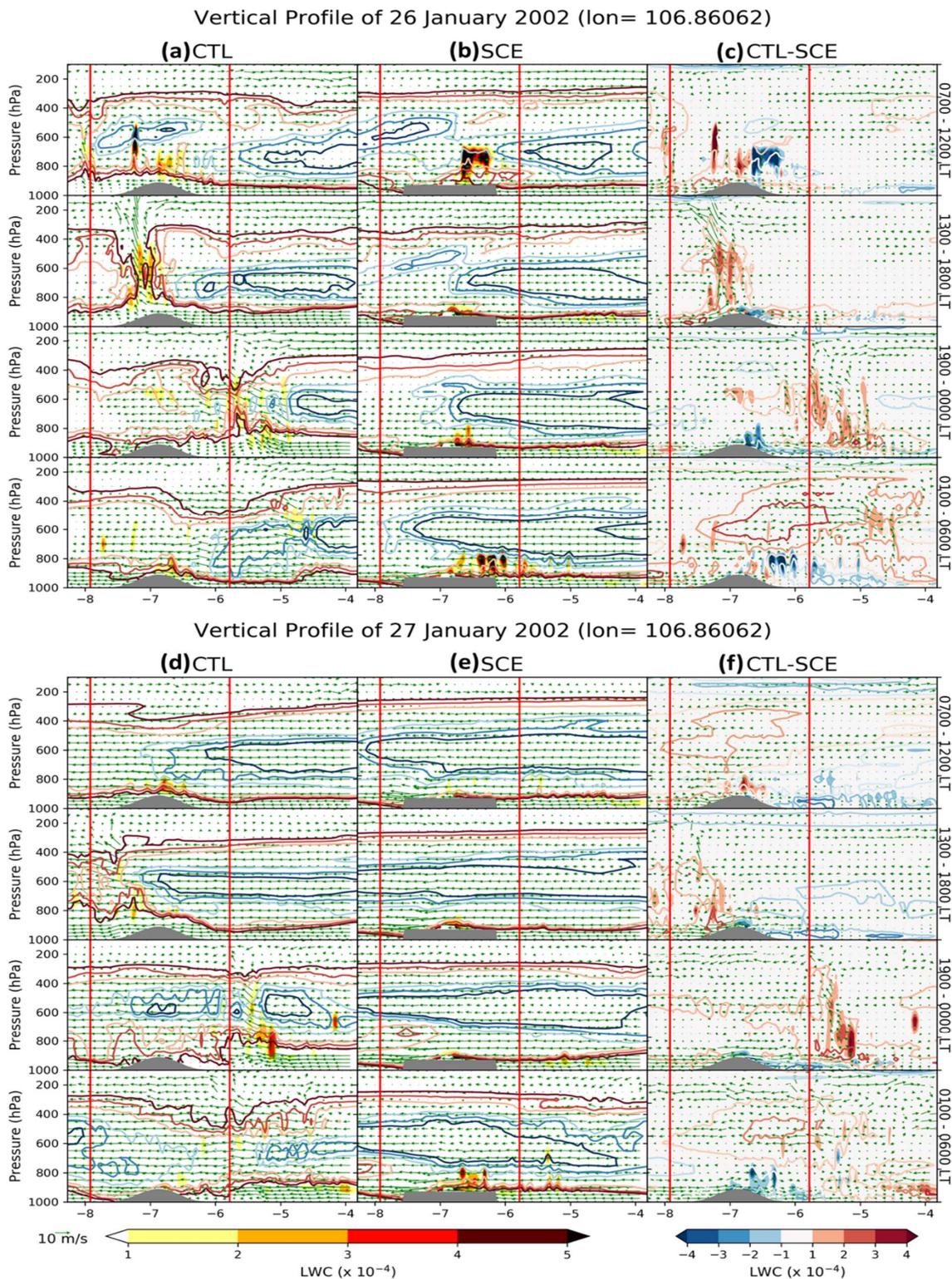


Figure 5. Temporal evolution of the wind (vectors; vertical component multiplied by a factor of 40), cloud mixing ratio (shading), and equivalent potential temperature anomaly (contours) along 106.68°E, which are shown as vertical–latitude cross-sections. For simplicity, 343 K was subtracted from the equivalent potential temperature, and blue (red) lines indicate negative (positive) values. The contour intervals are 1.5 K and contours start from -0.5 K (0.5 K). (a–c) CTL, SCE, and CTL–SCE simulated six-hourly results from 07:00–12:00 LT to 01:00–06:06 LT on 26 January 2002. (d–f) Same as (a–c), but for 27 January 2002.

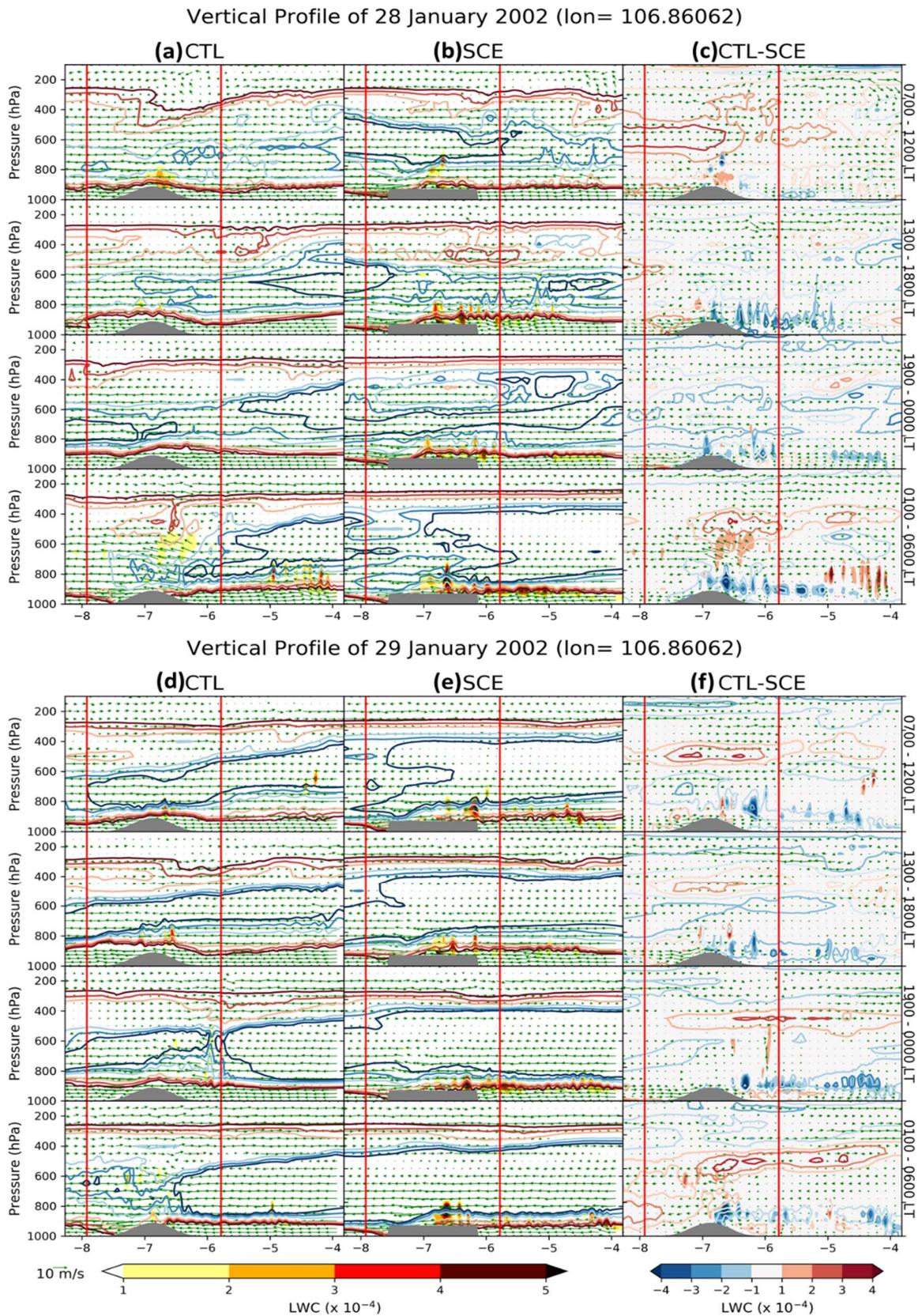


Figure 6. Same as Fig. 5, but for (a-c) 28 January 2002 and (d-f) 29 January 2002.

To further understand the physical processes that caused the offshore propagation during 26–27 January 2002, we analyzed the hourly evolution of cloud water vapor, equivalent potential temperature, and meridional vertical wind vector. On 26 January, the land-based convective system formed from 13:00 LT over the southern part of the mountainous area and propagated northward to the coastal area (18:00 LT) (Fig. 7).

Notably, the cold pool created by the decaying convective cloud over the mountainous region travelled downward and triggered the formation of new convective cloud over the coastal region. In this case, the presence of the cold pool is evident from the lower equivalent potential temperature over the near-surface (<1 km) (Fig. 7c). This is consistent with a previous study that showed offshore-propagating systems are driven by a surface cold pool [7,29] and the squall line mechanism over the eastern Maritime Continent [30].

At the same time, a new oceanic convective cell developed adjacent to the coastal region. The two convective cells grew rapidly next to the cold pool over the coastal area on 20:00 LT on 26 January 2002 (Fig. 7a and c). This thunderstorm system then merged into a single cell and propagated offshore until 23:00 LT. At 00:00 LT, the cold pool formed a new convective cloud system from the decaying cloud and propagated landward as the prevailing northerly wind strengthened over the mountainous region until 06:00 LT (Fig. 7d and f). For the SCE simulation, the initial convection developed inland in the afternoon and propagated offshore due to the slow development of several small convective cells located a line extending from land to ocean (Fig. 7b and e). Another type of thunderstorm occurred over the mountainous area due to a squall line mechanism [30].

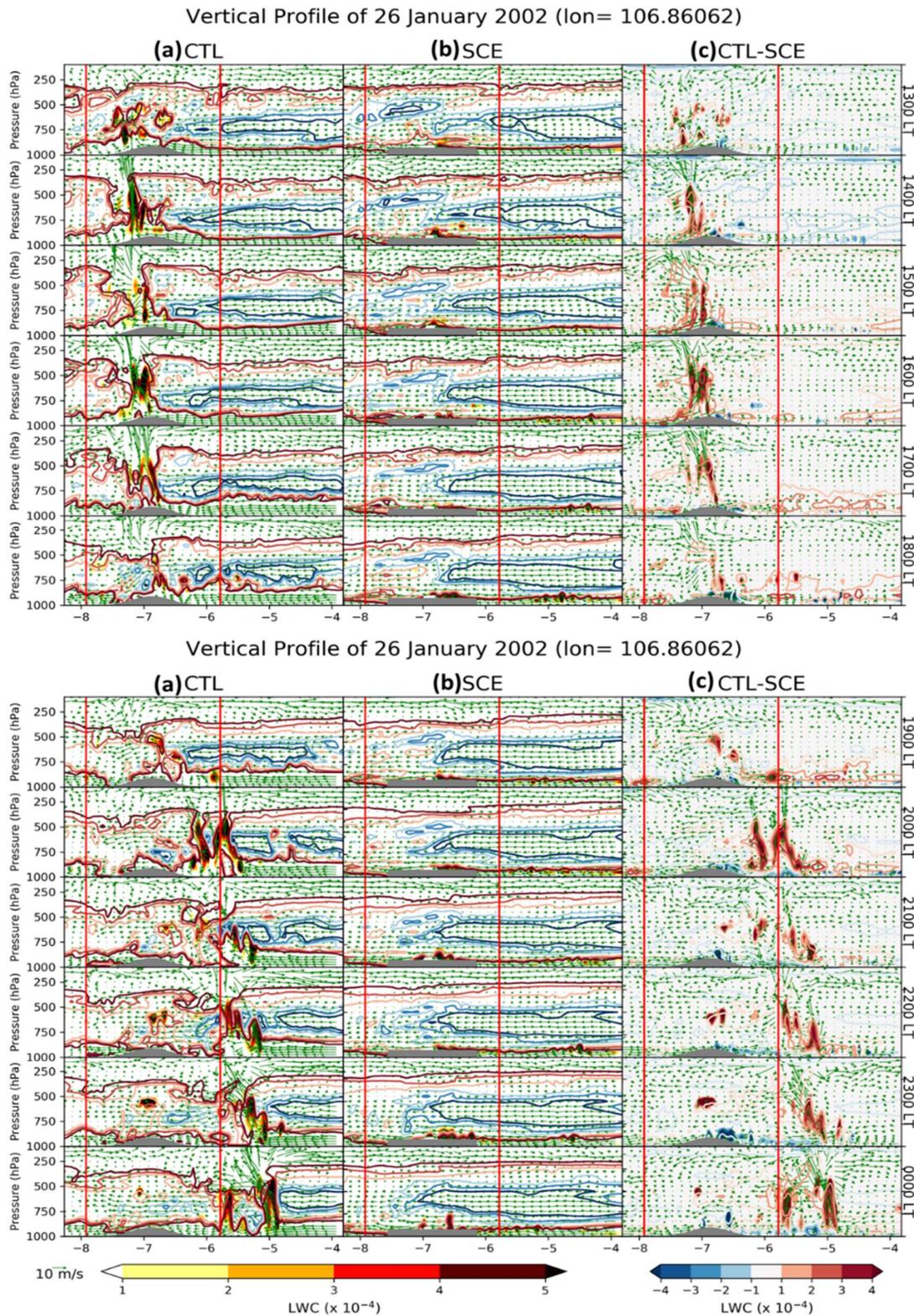


Figure 7. Same as Fig. 5, but for the hourly evolution from 13:00–00:00 LT on 26 January 2002. The blue contour line over the near-surface (<1 km) is the cold pool.

The development of this thunderstorm system associated with the leading edge of a propagating surface cold pool is consistent with the results of the present study. This distinctive offshore propagation also occurred on the following day on 27 January 2002 (Fig. 8). A land-based convective system developed over the mountainous area from 13:00 LT and strengthened until 18:00 LT (Fig. 8a).

However, the cold pool that formed from the decay of the convective cloud system appeared at 16:00 LT over the southern mountainous region. The cold pool created a new convective cloud system over the southern mountainous region and forced the existing convective cloud system to move northward. Interestingly, several convective cells connected the mountain and sea regions at 19:00 LT, and then the convective system over the mountainous region diminished at 20:00–00:00 LT (Fig. 8a).

A cold pool that developed from the decaying cloud over the coastal region created a new convective cell over the ocean at 22:00 LT, which propagated landward due to the strong northerly background winds (Fig. 8a and c). In this case, we conclude that the interaction between the predominant prevailing wind and topography, in association with the cold pool mechanism, controlled the propagation direction of the convective system. However, this was not the case for the SCE simulation (Fig. 8b).

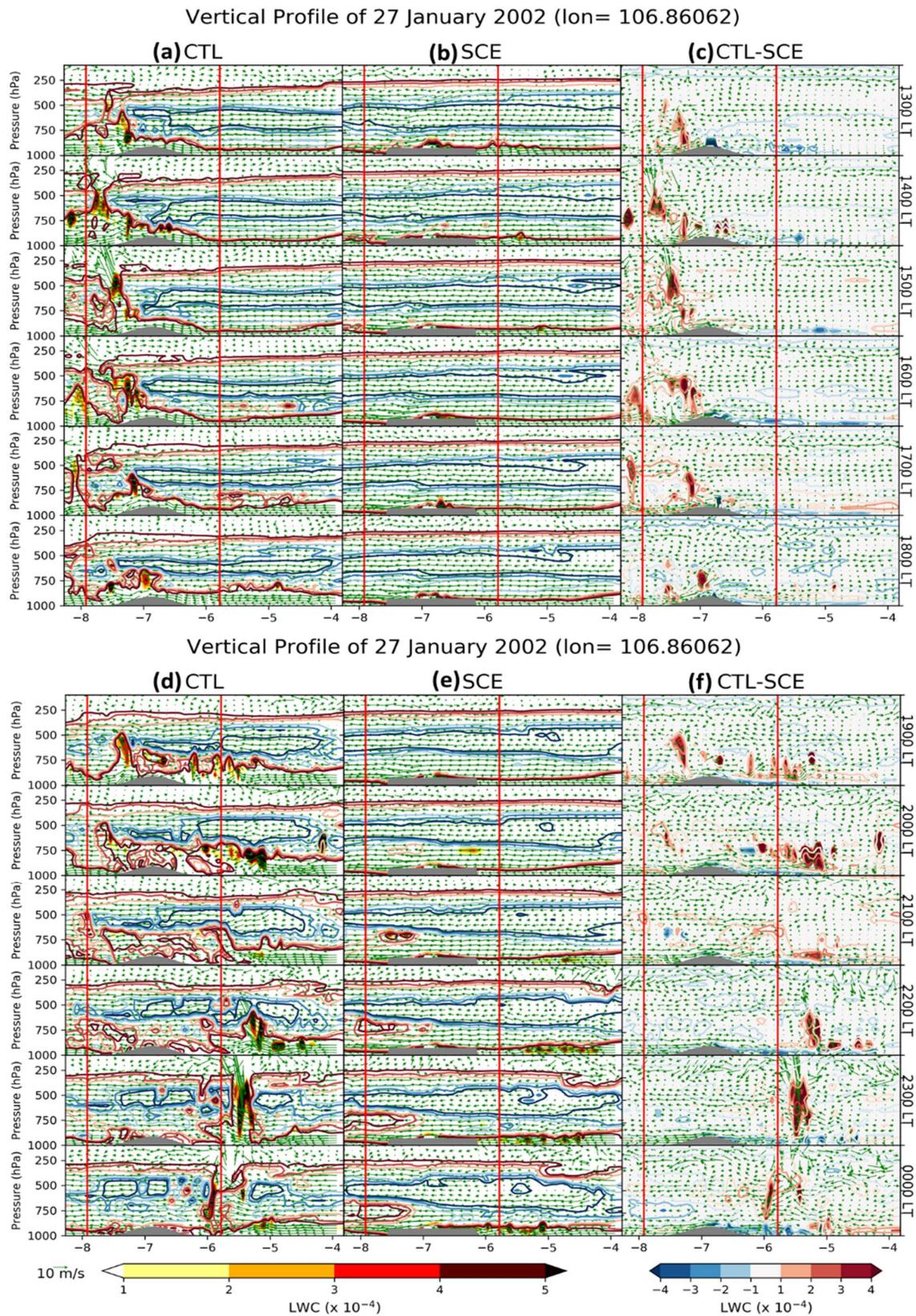


Figure 8. Same as Fig. 7, but for 27 January 2002.

This rapid landward propagation of the oceanic convective system triggered a deep convective system over the mountainous region during the early morning on the following day (Fig. 9a). For the SCE simulation, early morning convection also occurred and appears to be strongly connected to the convective system over the ocean (Fig. 9b). In such a case, the early morning convection may also be affected by a gravity wave, which was further examined for the following day (Fig. 9).

The SCE simulation results (Figs 7–9) suggest that the flattened topography does not significantly enhance northerly winds over the ocean or produce enhanced precipitation. This result is consistent with a previous study that reported greater surface roughness on a flat island has an influence on a high-wind regime [31]. Thus, forcing caused by the thermal contrast between the land and sea is the main factor [31] controlling the diurnal cycle of precipitation over the Maritime Continent [32].

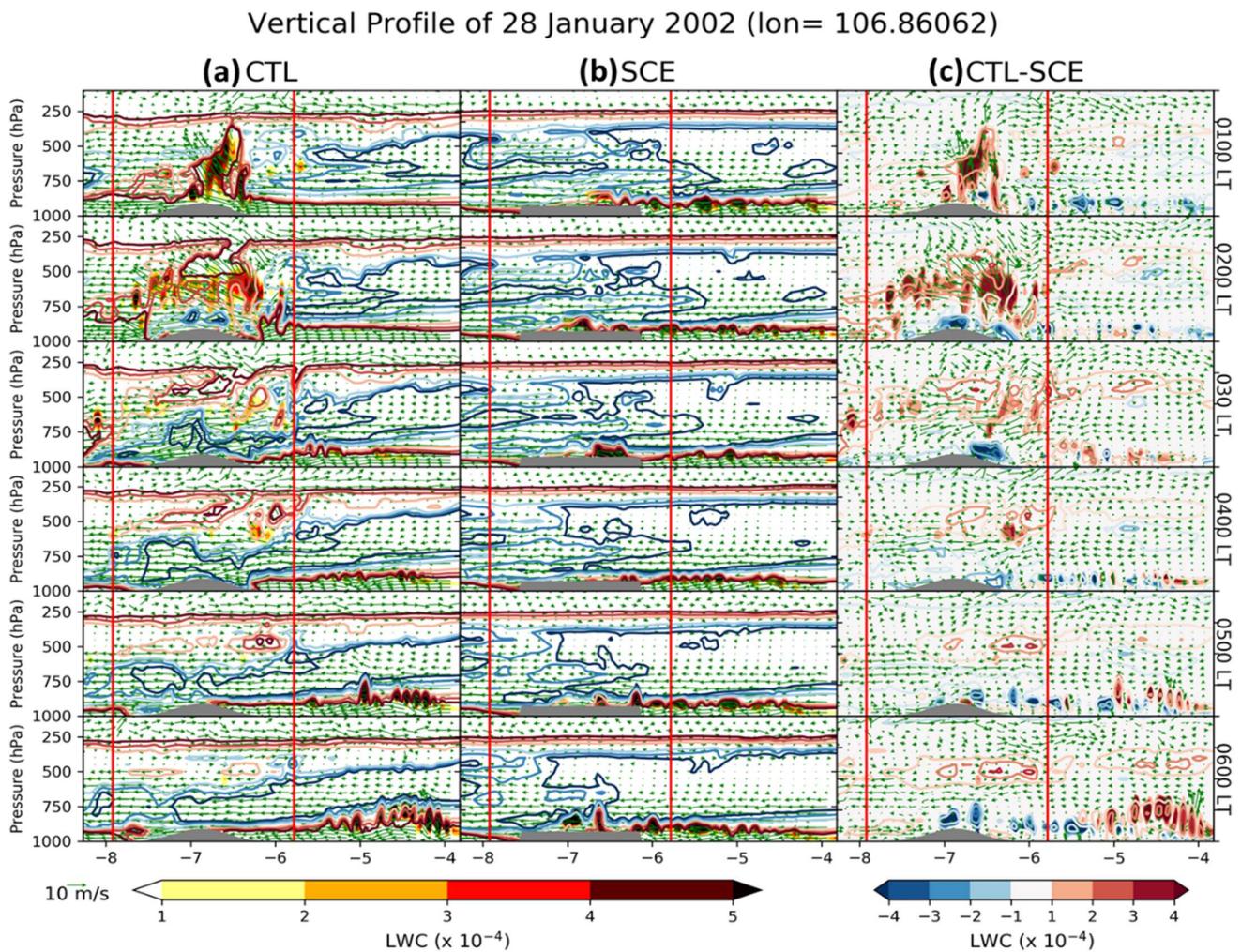


Figure 9. Same as Fig. 8, but for 01:00–06:00 LT on 28 January 2002.

3.2 Effect of Gravity Wave on Early Morning Precipitation

Another interesting feature that can be explained by the simulation results is the early morning precipitation over the coastal region on 28–30 January 2002 (see Fig. 6). A previous study noted that the early morning precipitation peak over the north coast of West Java is strongly related to extreme precipitation [6]. We found that the early morning precipitation peak is clearly evident on 28–29 January 2002 (Figs 9–10). In the case of 29 January 2002, initial convection over the coastal region occurred suddenly at night (22:00 LT) and rapidly propagated landward (02:00 LT).

The initiation of this convection over the coastal region is difficult to explain solely in terms of the prevailing northerly wind. We found a wave-like structure expressed as a negative equivalent potential temperature anomaly at ~500–700 hPa which correspond to recently study [29]. The layered structure of the anomaly was disrupted when initial convection developed at 22:00 LT. This is consistent with a study [30] that suggested the strong prevailing wind could create strong asymmetry between the windward and leeward areas, thus generating gravity waves via a thermal contrast, as well as an upward deviation of the horizontal flow in response to the enhanced diurnal heating mechanism.

Our proposed mechanism for early morning convection and precipitation over the north coast of West Java involving meridionally propagating gravity waves is consistent with recent studies [29], and is also supported by previous studies of offshore propagation of convective systems due to gravity waves [30–35]. Topographically induced gravity waves have a larger amplitude in the windward direction and descend on leeward slopes [31]. The topography produces low-level circulation that is strengthened by the height of the topography. This possible mechanism occurred persistently during the three days of heavy rainfall over the coastal region during the severe 2002 Jakarta flood.

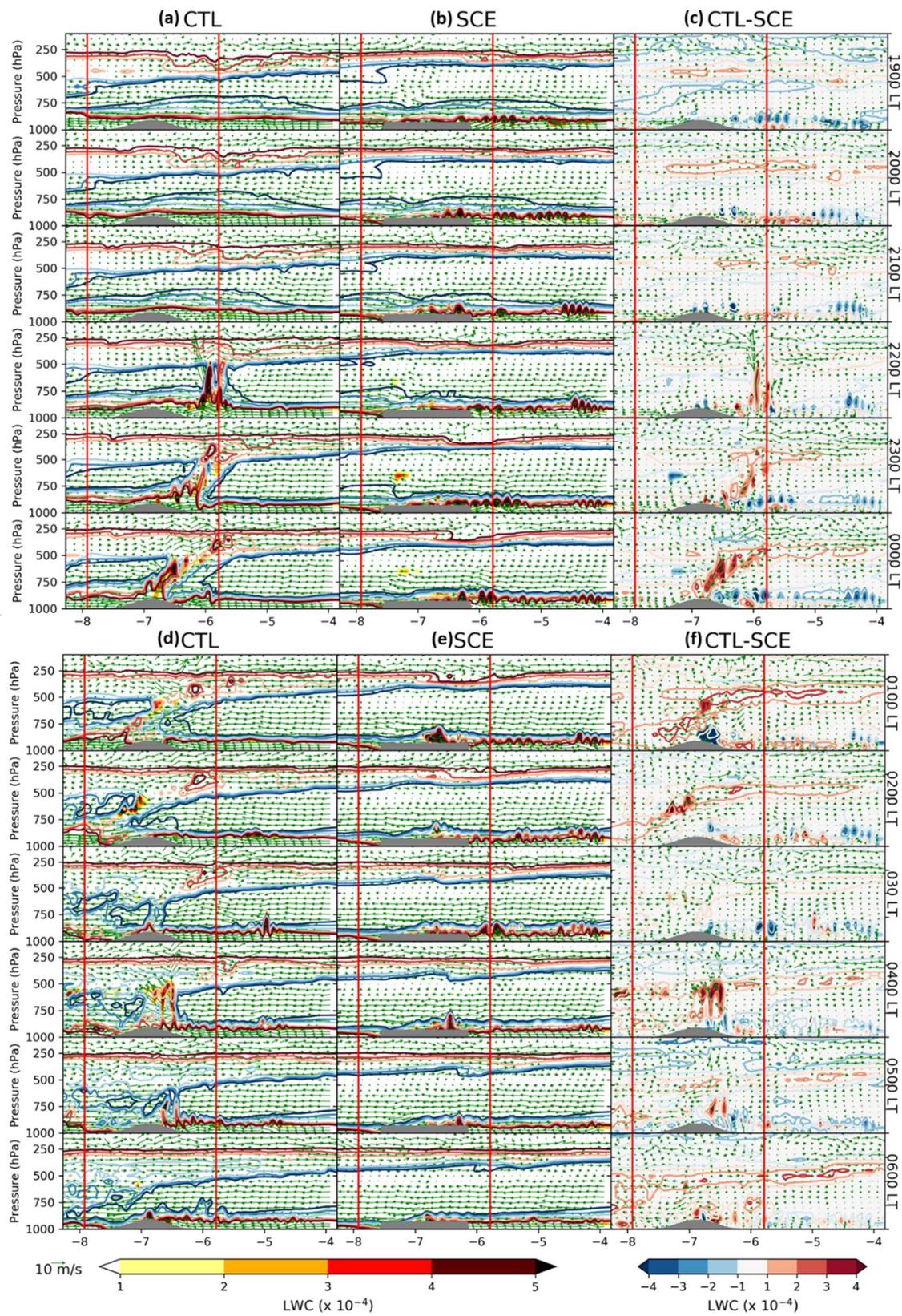


Figure 10. Same as Fig. 7, but for 19:00–06:00 on 28–29 January 2002.

5. Conclusions

We investigated the role of land and topography on propagating convective systems, based on a case study of the heavy rainfall event during 26–29 January 2002 that produced a severe flood in Jakarta, using high-resolution (3 km), numerical weather predictions from the WRF model. To investigate the land and topography, we selected episodes which were divided by two types of propagation systems: (1) 26–27 January 2002 during an offshore propagation episode which assumed the leading role of topographic effect on the propagation of convective system, (2) 28–29 January 2002 serve as a landward propagation which represented land-sea contrast on the propagation of convective system. This numerical experiment shows that the simulated rainfall is qualitatively consistent with satellite and station data. In this case, synoptic weather conditions were influenced by a cyclonic vortex off the south coast of West Java, which enhanced the near-surface prevailing northerly wind.

We found that during 26–27 January 2002, the rugged topography over southern West Java significantly enhances upward convective motion over the mountainous region. Hence, the dominant role of the topography over western Java is producing offshore propagation. These results are consistent with a previous study [24] that showed diurnal and topographic forcing led to ~20% rainfall enhancement, as reflected by offshore-propagating modes of convection. The topography of southern West Java drives offshore propagation due to the cold pool mechanism, which is in a direction opposite to the prevailing northerly wind. The cold pool also triggers thunderstorms and allows convective cells to coalesce and separate into new cells. With the prevailing northerly winds strengthening, the new convective cells tend to propagate landward, leading to maximum precipitation over the coastal and mountainous regions. This cold pool has previously been identified from night-time land surface cooling and a low-level flow anomaly near the leading edge of the cold anomaly [25].

We also found that the land-sea contrast may have a role in a strong landward propagation during 28–29 January 2002, which is strengthened by wave-like activity associated with a meridionally propagating gravity wave. This study agrees with a previous study [26] that showed near-surface cooling induced by enhanced rainfall generated gravity waves, which then caused an offshore-propagating diurnal cycle of precipitation. Furthermore, our results demonstrate that disruption of the gravity wave coincides with initial convection over the coastal region in the early morning, which is consistent with the previous study [7, 21]. This result also corresponds to the early morning precipitation peak related to extreme precipitation and strong landward and offshore propagation of a convective system. In addition, the landward propagation is consistent with a previous study that suggested this results in the timing of peak precipitation being more random [6, 25].

However, the early morning precipitation peak identified in the present case study was also a feature of the 2007 Jakarta flood, which had a semi-diurnal pattern superimposed on the diurnal cycle, with the largest precipitation peak during the early morning

[2]. Thus, our study indicates a slight chance that the same process will occur again in the future despite the interaction between the topography and the northern coastal area of Java needs to be associated with a similar combination of synoptic and mesoscale dynamics.

Supplementary Materials: Not applicable.

Author Contributions: E.Y. is the main contributor. Conceptualization, E.Y.; methodology, D.E.N.; validation, T. and R.M.; formal analysis, E.Y.; writing—original draft preparation, E.Y.; writing—review and editing, E.Y. and D.E.N; visualization, D.E.N, T., R.M; funding acquisition, E.Y. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflicts of interest.

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