



Sea breeze simulation over the Malay Peninsula in an intermonsoon period

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[1] This study presents a characteristic intermonsoon weather situation over the Malay Peninsula. The Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) is used to investigate the mesoscale details of the simulated sea breeze circulations over the Malay Peninsula on 23 April 2002. The occurrence of sea breeze collisions occurring in the inland region of the southern Malay Peninsula is noted. On the peninsula-scale, convection was first initiated along the low-level convergence line that became established along the west coastal region of the Malay Peninsula in the early afternoon. Deep clouds that led to thunderstorms developed in the northwestern part of the Malay Peninsula after the sea breeze encountered the mountain wave induced under the ambient easterlies above the mountain ridge line. The convective activity was further enhanced over the central Malay Peninsula because of the interaction between sea breeze front and gap winds from the mountains. This case study suggests that the Malay Peninsula is a potentially fertile ground for many dynamically interesting case studies of land–sea breeze circulations.

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1. Introduction

[2] During the intermonsoon months of April and May, the Inter-Tropical Convergence Zone (ITCZ) is situated over the maritime continent [Chang, 2004]. The converging air masses do not show much contrast in temperature and humidity. Locally driven convective cells dominate and result in high spatial variability of rainfall on scales of 10 km or even less [Nieuwolt, 1968]. Some studies of precipitation over the maritime continent have emphasized the diurnal variability, where convection peaks around mid-afternoon [Oki and Musiaka, 1994; Hirose and Nakamura, 2005]. Diurnal thermally forced local circulations like land–sea breezes and mountain–valley flows [Atkinson, 1981; Blumen, 1990; Abbs and Physick, 1992; Pielke, 2002; Miller *et al.*, 2003] often lead to convective cloud development and afternoon thunderstorms in the intermonsoon periods. However most past studies were dependent on coarse resolution data and their techniques either involved averaging over a large domain or utilizing sparsely distributed station data sets, which may have ignored the local weather features. Less attention was also paid to individual case studies.

[3] The focus of this research is to study the qualitative aspects of sea breezes and their interactions with the terrain

over the Malay Peninsula through a case study using a mesoscale model, Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS[®] [COAMPS[®] is a registered trademark of the Naval Research Laboratory]). From the model simulation results for 23 April 2002, we suggest three mechanisms likely playing important roles in the initiation of afternoon thunderstorms in three locations over the Malay Peninsula associated with local topographic effects. Perhaps more significantly, the mechanisms of this typical episode of intermonsoon thunderstorms provide a clue to explain the three-maxima structure of rainfall distribution along the west coast in the April climatology of the peninsula [Lim and Samah, 2004].

[4] In choosing this particular case, over one decade of Geostationary Meteorological Satellite (GMS) infrared imageries of clouds over the Malay Peninsula in the intermonsoon months were examined and care was taken to avoid cases which stand out from a phenomenological point of view. The initiation and progression of storms in this case is also not unlike many other cases seen in our real-time weather forecast project began since April 2006, where twice daily, we assimilate and forecast up to 48 hours the mesoscale weather in the Malay Peninsula and the wider region of Southeast Asia (related information on the real-time weather forecast project can be found at <http://www1.spms.ntu.edu.sg/~sunshine/WeatherWeb/forecast/Latest/domain1.html>). In fact, the study is part of an on-going programme in Singapore to advance the modeling and understanding of weather in Southeast Asia.

[5] In the literature, the better known studies of real-world sea breezes are found mainly in two places: the Florida Peninsula in North America [Nichols *et al.*, 1991; Rao and

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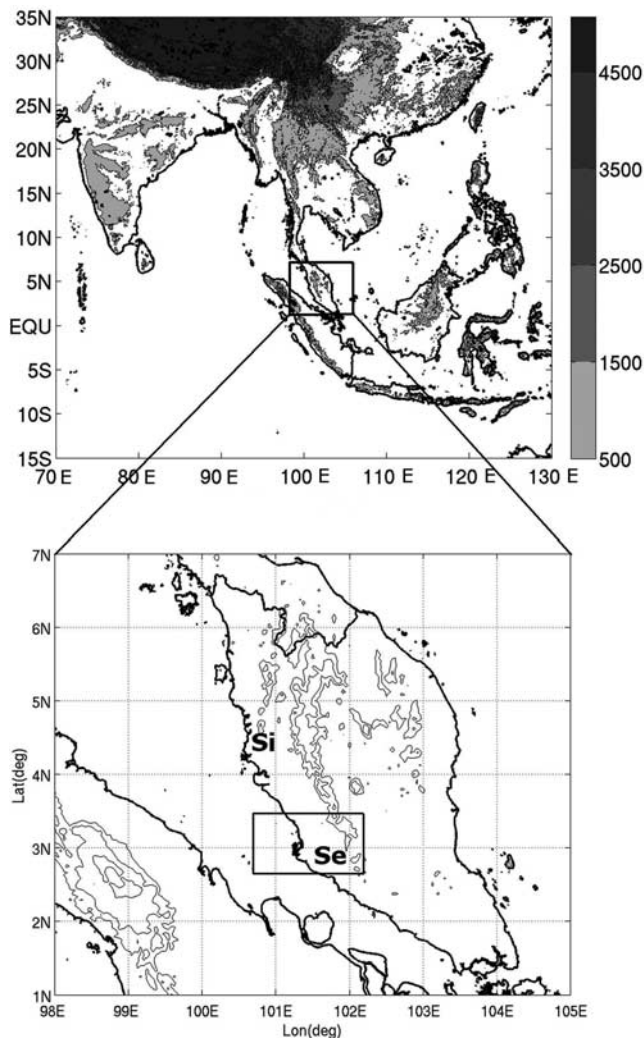


Figure 1. The upper panel shows the location of the Malay Peninsula in tropical Asia. The lower panel shows topography over the Malay Peninsula, in which contour lines are drawn at 500-m intervals. The geographic locations shown are: Sitiawan weather station (Si), Sepang weather station (Se). The small box denotes Kelang Valley region.

Fuelberg, 2000] and Cape York in Australia [*Noonan and Smith*, 1986]. Thus the Malay Peninsula may be compared to these two places. Florida and Cape York have low undulating terrain and so sea breeze collisions are not uncommon. On the other hand, the Malay Peninsula features some of the more complex terrain in the maritime continent, being characterized by mountain ranges (with peaks above 2000 m) separated by narrow valleys. Only the southern part of the peninsula resembles Florida and Cape York in its terrain (refer to Figure 1). Both east and west coast sea breezes encounter high orography over the northern part of the Malay Peninsula so collisions between the two systems are not possible. Instead, daytime sea breeze and upslope flow are likely to combine to enhance the resulting circulation. However, over the southern Malay Peninsula, it is easier for sea breezes from west and east coasts to interact.

[6] Important differences exist in the latitudinal location besides topographic features. Florida and Cape York

are located in the higher tropical latitudes (25–30°N and 11–16°S respectively), while the Malay Peninsula is in the equatorial tropics (1–6°N) where planetary vorticity is much smaller and so large-scale cyclonic organization of weather systems is rare. Sea breezes could penetrate farther inland, with a corresponding increase in depth, at lower latitudes than at higher latitudes [*Abbs and Physick*, 1992]. Thus the Malay Peninsula can be considered as a real-world laboratory uniquely different from Florida and Cape York to study land–sea breezes and the related convective activity.

[7] The Malay Peninsula resembles some mountainous coastal areas in the tropics, where land–sea breeze effects and topographic features coexist, such as the western Ghats of India, islands in the Caribbean (for example, Puerto Rico) and the Indonesian archipelago. In Java and Sumatra weak easterly also prevails during the intermonsoon period, so sea breeze studies in the Malay Peninsula can be relevant to these islands in general. A study by *Hadi et al.* [2002] reported the inland propagation of sea breeze and its interaction with topography over west Java island. As found in *Wu et al.* [2003], through observations in Sumatra island, increased precipitable water during daytime is caused by the transport of water vapor from the ocean by sea breeze. Outside Southeast Asia, *Silva Dias and Machado* [1997] reported afternoon coupling of sea breeze with mountain winds over the Sao Paulo in Brazil. Hence work presented here is likely to be relevant for the regions beyond the Malay Peninsula.

[8] The paper is arranged in the following manner: section 2 gives a brief synoptic overview, section 3 is a description of the model simulations, section 4 presents the results and discussions, and section 5 is the summary of the findings.

2. Synoptic Overview

[9] It is illuminating to first describe the synoptic situation on this day. Over the Malay Peninsula and surrounding regions, this day was characterized by less than average cloudiness in the late morning hours. The clouds mostly began to form at 1400 LT (0700 UTC (All Local Times (LT) quoted in this paper refer to UTC+7h, following the Sun's movement across the sky at 105°E. The standard time adopted by Malaysia and Singapore is actually UTC+8h)) near the Malay Peninsula and Sumatra island. Enhanced cloud activity occurred from around 1632 LT over these regions. A sample IR image taken at 1632 LT (0932 UTC) is shown in Figure 2. The enhanced cloud activity associated with thunderstorms is clearly seen along the west coast of the Malay Peninsula and both coasts of central and south Sumatra. It is unclear whether the enhanced convection on the Malay Peninsula was associated with convergence of a west coast sea breeze with a prevailing easterly wind or with another sea breeze from the east coast.

[10] To clarify the synoptic situation, we make use of weather station data and the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis data over the Malay Peninsula. The Malay Peninsula resides in a data-poor region in the World Meteorological Organization (WMO)

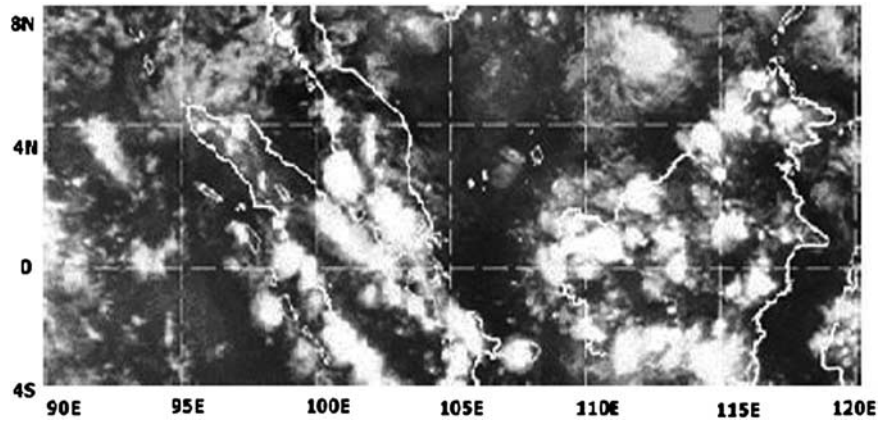


Figure 2. The GMS-5 IR imagery at 1632 LT (0932 UTC) on 23 April 2002 over Southeast Asia.

network of weather observation sites. There are only three radiosonde stations along the west coast of the Malay Peninsula, namely Singapore, Sepang and Penang (see Figure 1 for Sepang’s location). Twice daily soundings from these stations preclude accurate determination of the diurnal cycle. Figure 3 shows the skew-T Log-P and wind profile diagram from the station Sepang (lon/lat: 101.7°E/ 2.71°N) at 0700 LT (0000 UTC) on 23 April 2002. It shows weak easterly wind prevailing in the middle troposphere (above 700 hPa). There appears to be a moist layer in the lower levels (below 850 hPa). The Convective Available Potential Energy (CAPE), 431.2 J kg⁻¹ at this time, indicates moderate conditional instability. These observations are consistent with the enhanced cloudiness as revealed by the GMS IR imagery later that day.

[11] The NCEP-NCAR reanalysis data for 850 hPa, 700 hpa and 500 hpa at time 0700 LT (0000 UTC) on 23 April 2002 were studied to identify synoptic scale features over the Malay Peninsula (not shown). Just as revealed from Sepang station, weak easterly synoptic flow prevailed in the middle troposphere over the entire penin-

sula on this day. Such light wind conditions in the middle troposphere are common during March–April over this region. The weak vertical shear in horizontal wind probably favored the strong convective activity that developed later in the day.

[12] A good perspective at the mesoscales can be obtained from half-hourly radar rain images over the Malay Peninsula. Figures 4a and 4b show the Plan Position Indicator (PPI) maps of radar reflectivity field at 1500 LT (0800 UTC) and 1900 LT (1200 UTC), respectively. We identified four specific rain areas in this period. They are: strong rain activity over the Kelang Valley region as denoted by “A” (Figure 4a); intense rainfall in the northwestern region as denoted by “B” (Figure 4b); intense rain cells localized over the central mountains as denoted by

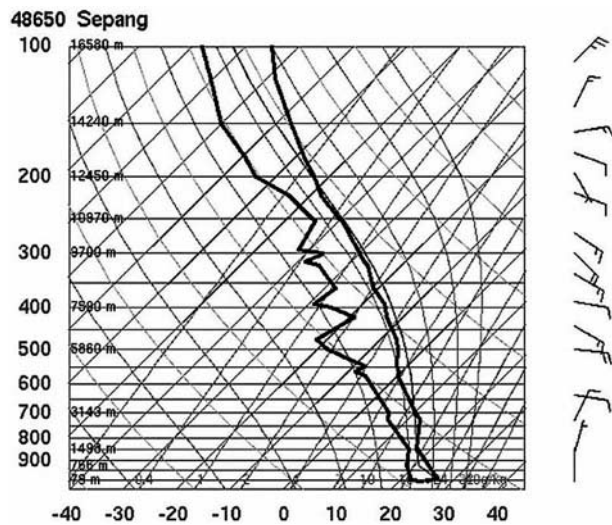


Figure 3. The Skew-T Log-P diagram from the station Sepang at 0700 LT (0000 UTC) on 23 April 2002 (with courtesy from University of Wyoming, <http://weather.uwyo.edu/upperair/>).

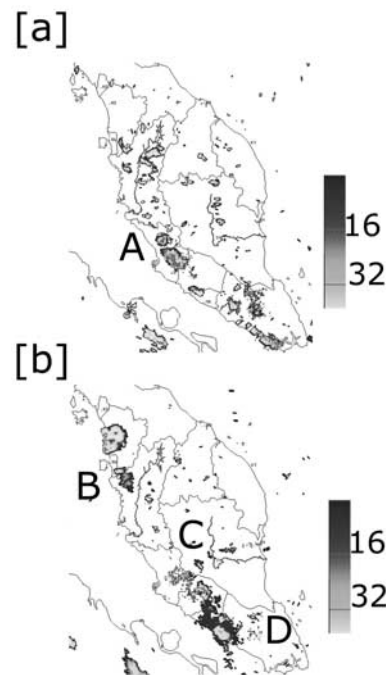


Figure 4. Radar reflectivity (dBZ) images from radar located at the Malay peninsula: (a) at 1500 LT (0800 UTC) and (b) at 1900 LT (1200 UTC).

“C” (Figure 4b); and a large patch of rain echoes over the southern part of the Malay Peninsula as denoted by “D” (Figure 4b). The cloudiness in GMS IR imagery agrees well with these radar observations. From animation of radar rain images, it is revealed that the rain systems moved to the west.

[13] The next section describes the use of a mesoscale model to investigate the role of the sea breeze in the initiation of these mesoscale convective rain systems.

3. Model and Simulation

[14] The model used in this study is the COAMPS developed by the Naval Research Laboratory. The atmospheric model uses nonhydrostatic primitive equations and has state-of-the-art parameterization schemes for multiphase moist physics, radiation, cumulus convection, boundary-layer processes and turbulence [Hodur, 1997]. For the simulations reported here, only the atmospheric analysis and forecast component of COAMPS was integrated, with one-way nesting over multiple domains. The initial and boundary conditions were provided by the Navy Operational Global Atmospheric Prediction System (NOGAPS). Twelve hourly assimilation-forecast cycles were carried out over 7 days to spin up the model.

[15] We performed two realistic and two semi-idealized simulations. The first realistic simulation (referred to as S3) has three nested domains at resolutions of 54 km, 18 km and 6 km, and the second realistic simulation (referred to as S2) has two nested domains of resolutions 6 km and 2 km. S3 uses 75 vertical levels with top 8 levels in the stratosphere acting as sponge layers. S2 has about twice the vertical resolution as S3. S3 and S2 were designed to study synoptic and mesoscale environments, respectively. The realistic simulations were initialized at 1900 LT (1200 UTC) on 22 April 2002. The high resolution in S2 better captures the local circulations like internal gravity waves, sea breezes and mountain-valley winds in the lower troposphere and boundary-layer. Results from the S3 innermost domain were used as a consistency check on the results from the S2 outermost domain.

[16] The single domain semi-idealized simulations have a horizontal resolution of 1 km with 99 vertical levels, with surface terrain covering the Kelang Valley in the central west coast of the Malay Peninsula. The horizontally uniform condition for the idealized simulations was set to be same as the Sepang sounding for temperature and humidity at 0700 LT (0000 UTC) on 23 April 2002 (Figure 3), assuming hydrostatic balance and zero vertical wind. One idealized simulation (referred to as I1) was initialized with zero horizontal wind while the other idealized simulation (referred to as I2) was initialized with the wind profile from the same Sepang sounding. Radiative forcing was switched on for both simulations.

4. Results and Discussion

4.1. Model Validation

[17] The model performance was assessed by comparing S2 simulation outputs with surface observation data, which has a high temporal resolution. Figure 5 shows the diurnal cycle of the simulated and observed meteorological variables on 23 April 2002 for the station Sitiawan (refer to

Figure 1 for Sitiawan’s location). There is reasonably good agreement between the simulated and observed surface wind and relative humidity. The model has a tendency to underestimate the surface temperature during the daytime (0700 LT to 1900 LT). The phases of the simulated and observed diurnal cycles are in agreement with a tolerance of 1h as the peak occurred around 1500 LT. Similar results were obtained from comparisons made at two other inland surface stations. Therefore, the model captures well the daytime atmospheric state conducive for convective activity on 23 April 2002.

4.2. Paradigms of Sea Breeze Interactions

[18] Next, the sea breeze activity leading to thunderstorm development on 23 April 2002 will be described. A useful concept while discussing the structure of idealized sea-breezes is an analogy to density currents studied extensively in the laboratory [Simpson, 1994]. Other excellent reviews of sea-breeze systems may be found in Atkinson [1981], Abbs and Physick [1992], and Miller et al. [2003]. In the simplest scenario, cold denser (sea) air is flowing toward the sea-breeze front at low levels, and is swept up and backward at the leading edge of the current. A compensating subsidence over the sea completes the sea-breeze circulation cell. The sea breeze circulation system is affected by synoptic scale winds, boundary layer convective cells, land-use types and sea surface temperature variability.

4.2.1. Interaction Between Sea Breeze and Lee Waves

[19] Here we discuss the interaction between the west coast sea breeze and lee waves over the northwestern Malay Peninsula. The sea breeze from the west coast developed at 1600 LT in the afternoon. The sea breeze front advanced inland and the terrain shape modified its structure. This is a general tendency for sea breezes upon meeting complex terrain, e.g., Hadi et al. [2002] also reported the deformation of the sea breeze front because of the complex terrain over west Java. In our simulation, there was also lee wave formation over the mountain ridge [cf. Durran, 1990] under the influence of the low-level easterly wind. Figures 6a and 6b show the advancing west coast sea breeze front meeting the lee waves. The sea breeze front is denoted by northeast pointing arrow and lee wave by west pointing arrow. This is evidenced by cloud isosurface denoted by “B” in Figure 6b, the location of which agrees with the feature “B” in Figure 4b. The cloud formation in the lee waves as noted in the present simulation is a general mechanism for convective cloud initiation.

[20] A clearer view of the interaction between the sea breeze and lee wave can be seen from Figure 7. It shows a longitude-height section of the w-field taken along the line xx' as shown in Figure 6a. There are two vertical wave-trains in the interaction zone: the western wave-train is the internal gravity wave associated with the advancing sea breeze and the eastern wave-train is lee wave above the northwestern mountain ridge. In the model simulation, deep cloud development ensued after the advancing sea breeze wave interacted with the quasi-stationary mountain lee wave. The cloud top can be seen just behind the vertical section.

[21] The convective feature “C” in Figure 6b is a local feature forced separately by inland topography and concurs

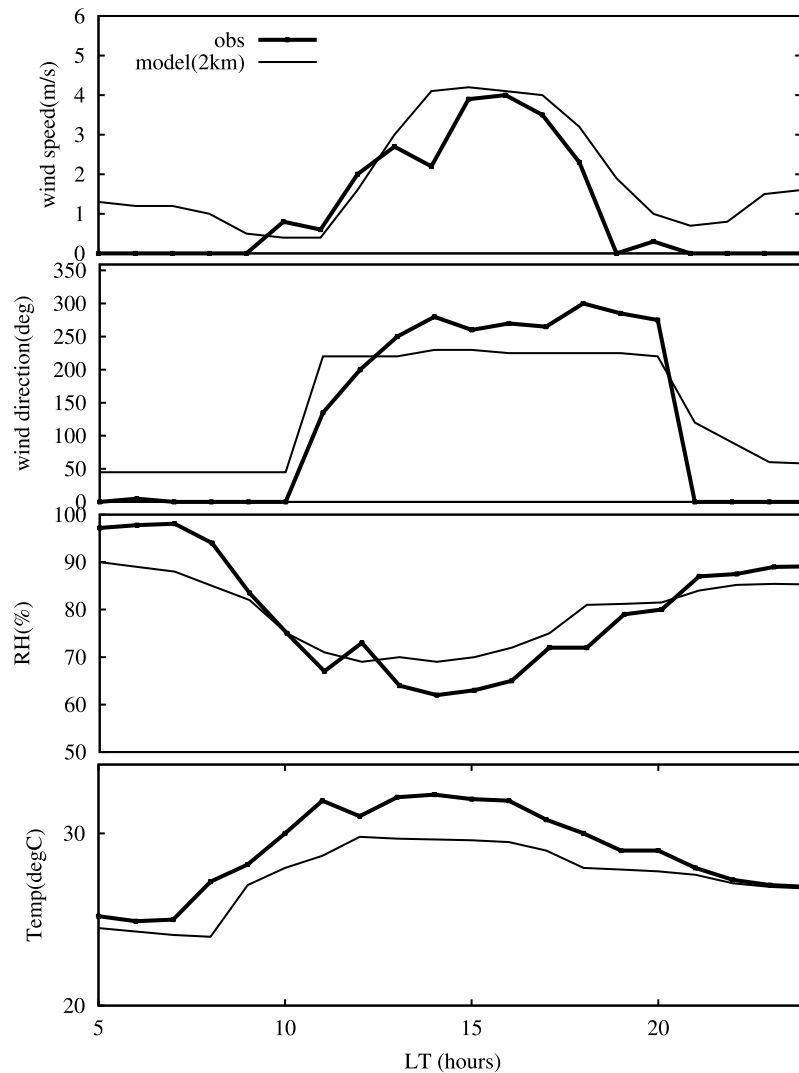


Figure 5. A comparison between model simulated (thin lines) and observed (thick lines) parameters at the surface station Sitiawan on 23 April 2002.

with the rainfall feature “C” in Figure 4b. It is also visible in Figure 7.

4.2.2. Sea Breeze Collisions

[22] We investigated the possibility of sea breeze collisions over the southern Malay Peninsula as mentioned earlier. Horizontal sections of u -field (zonal wind) showed the frontal nature of the west coast sea breeze (not shown). The sea breeze in the east coast was weaker than in the west coast as assessed by low-level zonal wind strength. Horizontal sections of w -field (vertical velocity) on the $z = 600$ m vertical level are shown in Figures 6a, 6b, and 6c for 1600 LT, 1900 LT and 2000 LT, respectively. The sea breeze fronts first aligned along the coastline (red arrows in Figure 6a). By 1900 LT, the fronts have advanced significantly inland, while remaining nearly parallel to the north–south axis of the peninsula (Figure 6b). There can be seen nearing east and west coast sea breeze fronts as denoted by red arrows. The east and west coast sea breeze collided at 2000 LT (Figure 6c) in the southern Malay Peninsula initiating convective activity. Animations of the sequence of images made the collisions of west and east coast sea breezes even more apparent. Observations show

that the rain in the southern Malay Peninsula is most intense earlier at 1900 LT (label “D” in Figure 4b). Thus the model’s sea breeze collisions may be lagged by one hour and other convective rain features in the southern Malay Peninsula are not captured.

4.2.3. Interaction Between Sea Breeze and Gap Winds

[23] The S2 simulations captured well the sea breeze system but do not resolve gap flows from the narrow valleys in the mountains. So, 1 km resolution (higher resolution) simulations over the Kelang Valley in the central Malay Peninsula were carried out to highlight the effect of gap flows and their interaction with the west coast sea breeze front. These are the semi-idealized simulations: without a background flow (I1) and with a uniform easterly flow of 5 m sec^{-1} (I2).

[24] Figure 8 shows the results from the I1 and I2 simulations. The I1 simulation shows mostly southwesterly winds hence a sea breeze system moving inland. The sea breeze advanced moist air onshore but convergence is not so strong. Shaded area is the convergence in unit of s^{-1} . On the other hand, the I2 simulation shows the interaction between the sea breeze front and gap flows. The texts “Bentung”

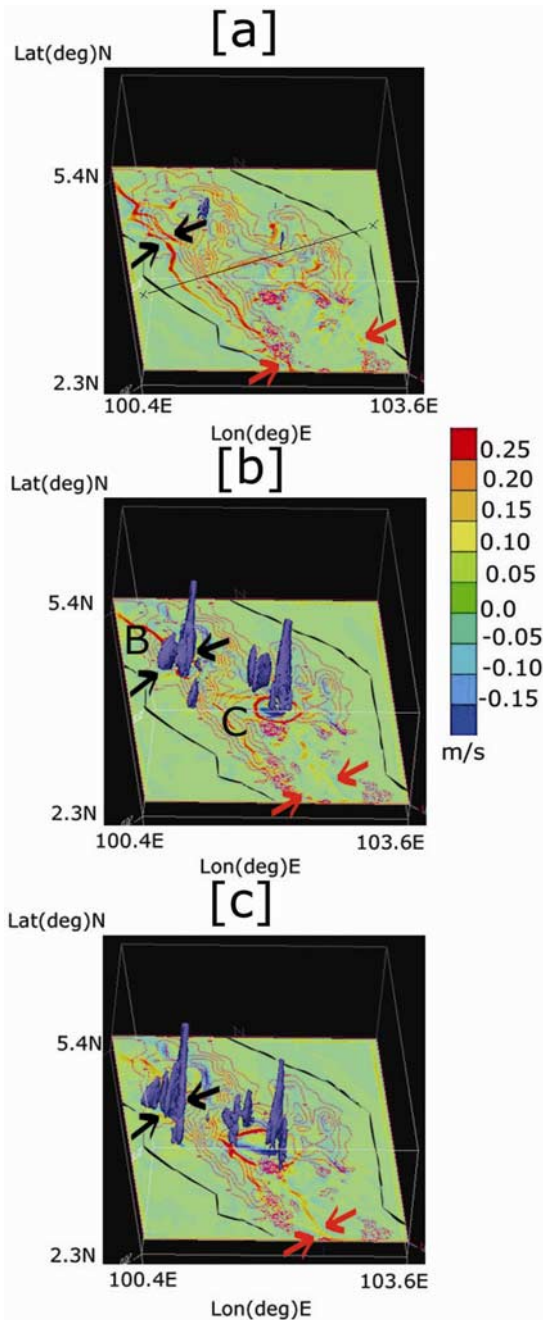


Figure 6. The horizontal sections of w -field on the $z = 600$ m vertical level at: (a) 1600 LT (0900 UTC), (b) 1900 LT (1200 UTC), and (c) 2000 LT (1300 UTC) on 23 April 2002. Isosurface of cloud water mixing ratio is shown at 0.1 g/kg. The contours represent terrain height with an interval of 200 m and magenta color contours show 200 -m terrain height.

and “Jelebu” in Figure 8 mark the Bentung mountain gap and Jelebu mountain gap, with northeasterly gap winds. The gap flow from these mountain gaps collided with the sea breeze and enhanced the convergence downstream (refer features “X” and “Y” in Figure 8) triggering convective development. Although a detailed comparison between radar observations and the semi-idealized simulation (I2) is not entirely justified, the occurrence of intense rain cells

identified as “A” in Figure 4a is consistent with the simulated sea breeze-gap wind interaction over the Kelang Valley region.

5. Summary

[25] The main features of sea breeze interactions over the Malay Peninsula during a typical intermonsoon situation on 23 April 2002 were simulated using the COAMPS model. The 2 km resolution simulation (S2) showed that the vertical velocity field was organized in the form of internal gravity waves both at the mountain ridge and at the advancing west coast sea breeze front. In southern Malay Peninsula, clouds were initiated because of the collision of sea breezes from both the east and west leading to convective initiation in the late afternoon. This inference for convective initiation is consistent with the work of *Rao and Fuelberg* [2000] on Florida Peninsula. There was interaction between quasi-stationary lee waves and the west coast sea breeze front over northwestern Malay Peninsula. The lee waves were formed under the influence of a synoptic easterly wind in the lower troposphere. Convective cloud development could be initiated by the lee waves alone, but deep clouds only develop after the superposition of the internal gravity waves ahead of the sea breeze front and the lee waves. In central Malay Peninsula, convective activity was enhanced by the collision between the sea breeze and gap winds from the mountains. This is plausibly important for intermonsoon thunderstorm initiation and development in the Kelang Valley region.

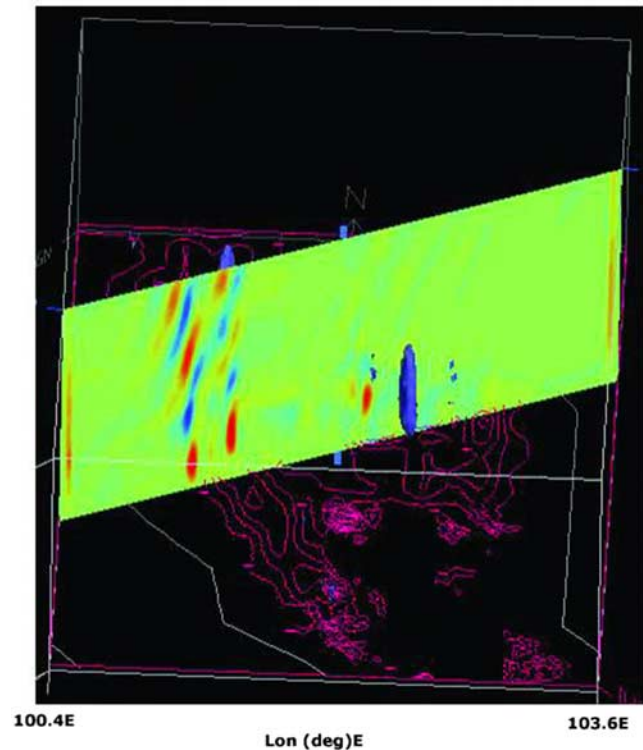


Figure 7. A longitude-height section of vertical velocity, with vertical axis up to 4 km height, across the Malay Peninsula at 1800 LT (1100 UTC) on 23 April 2002. Isosurface of cloud water mixing ratio is shown at 0.1 g/kg. The color bar is same as in Figure 6.

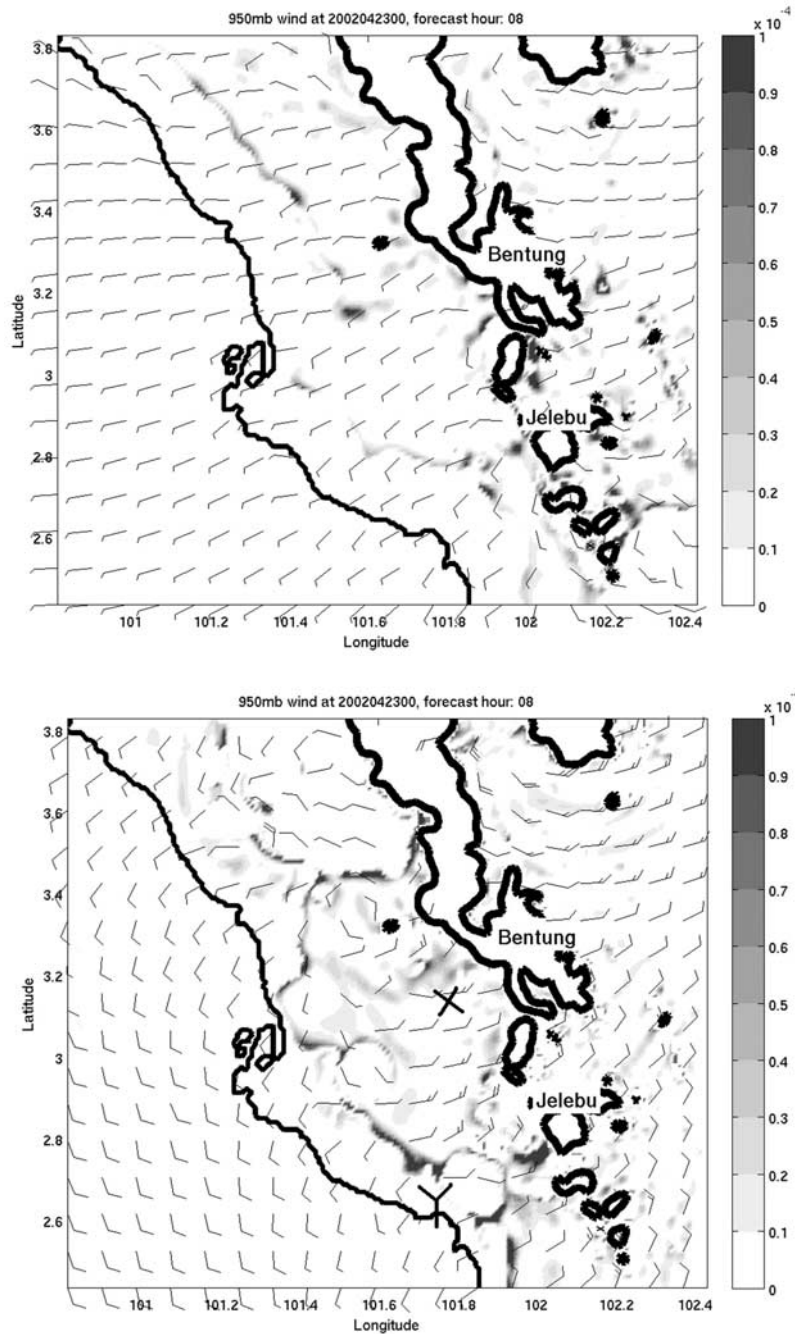


Figure 8. The horizontal distributions of 950-mb wind field at 1500 LT (0800 UTC) on 23 April 2002. Upper and lower panels represent simulation without a background flow and with a uniform easterly flow, respectively. The thick contour depicts terrain higher than 500 m. The wind barbs are plotted at every six grids.

[26] There are probably multiple mechanisms associated with thunderstorm development over the Malay Peninsula in an intermonsoon period. This paper introduced a few paradigms for sea breeze interactions leading to convective activity in the Malay Peninsula. Analytical studies by Rotunno [1983] revealed that wave structure of sea-breeze is not unexpected within the tropics. However we are not aware of modeling studies that show sea breeze collisions or sea breeze interaction with lee waves and gap winds over the

Malay Peninsula as found in the present simulations. Future observational and modeling studies would be useful in confirming the dynamical and thermodynamical details of convective initiation associated with sea breeze activity in the Malay Peninsula.

[27] **Acknowledgments.** The authors would like to thank Meteorological Services Division, National Environment Agency, Singapore and Malaysian Meteorological Department for providing the surface observation data.

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