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The simulation of low-level equatorial local winds in Peninsular Malaysia during the haze episode of 1997 through the LADM

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Abstract

Weak low level winds in the equatorial region pose a problem in the dispersion and diffusion of local pollutants, particularly, when large-scale vegetation burning causes transboundary haze that lasts for few weeks during which the air quality may deteriorate and cause health problems in the neighbouring countries. This paper investigates the patterns of the low level mesoscale wind flow in Kuala Lumpur in which the patterns of the local equatorial low level wind fields were simulated during the height of the major haze episode of Southeast Asia in September 1997. The backward air trajectories from Kuala Lumpur in Peninsular Malaysia that ended on 17 September 1997 showed that nearly all the wind paths originated from Sumatera at the three pressure height levels of 950, 850 and 700 hPa. The mesoscale wind field patterns that influenced the dispersion of smoke from the burning areas that originated from Sumatera, Indonesia were simulated in this study by utilising the Lagrangian Atmospheric Dispersion Model (LADM). Outputs of the low level wind field patterns generated showed the existence of recirculation of air particles from the diurnal regimes such as the land and sea breezes in addition to the weak prevailing winds across the Kuala Lumpur region during the period when pollution levels were high. The patterns revealed that the weak strength of the local winds did not promote effective dispersion of pollutants advected over the area from transboundary sources a few hundreds of kilometres away.

Keywords: equatorial region, haze, low level winds, Malaysia, mesoscale wind forecast, Southeast Asia

Introduction

The haze episode that occurred across the equatorial southern South East Asian region due to burning biomass from the Indonesian forests from September to October 1997 was considered one of the worst air pollution events in the region during the past decade. The health of approximately 300 million people was affected across the region, mainly in Sumatera, Kalimantan and neighbouring countries due to the exposure to the smoke (Mohd. Nasir *et al.*, 1998). The high concentration of particulates released from the biomass burning triggered an increase of as many as 1.8 million cases of respiratory symptoms, respiratory tract diseases and bronchial asthma (Dawud, 1998). A total of 1.5 million cases of asthmatic attacks was reported in four states in Malaysia such as Selangor, Melaka, Sabah and Sarawak at the height of the haze period (Mohd. Nasir *et al.*, 1998). The haze also affected Singapore (Heil & Goldammer, 2001).

It is estimated that the biomass burned in Indonesia alone that coincided with the major El-Nino event in 1997-1998 was comparable to Europe's entire annual carbon emissions from burning fossil fuels (Page *et al.*, 2002). A total of 9.5 million hectares was burnt mainly in Sumatera and Borneo (Rowell & Moore, 2002). The intense, near-continuous and uncontrolled large-scale burning reduced the ability of the atmosphere in dispersing the accumulated smoke particles. The resulting transboundary haze affecting Peninsular Malaysia was reflected by diminished visibility and high PM_{10} concentrations. Kuala Lumpur, the capital city, recorded a value of 525 $\mu g/m^3$ on 15th September 1997 when the daily PM_{10} concentrations exceeded 200 $\mu g/m^3$ from 13th to 16th September. Approximately 222,750 km^2 of land was burned in Sumatera in September as monitored by the National Oceanic Atmospheric Administration (NOAA) satellite, in contrast to an estimated area of only 7000 km^2 in Peninsular Malaysia. This implied that synoptic winds played a major role in the transportation of the transboundary pollutants from Sumatera.

This paper attempts to investigate the patterns of the low level mesoscale wind flow in Kuala Lumpur. The regional wind fields are generated on a short-term time scale of about three days during the high pollution days in September 1997 by utilising a mesoscale model, namely, the Lagrangian Atmospheric Dispersion Model (LADM). A case study modelling approach is adopted to describe in detail the low wind field patterns that contributed to the local dispersion characteristic patterns. The adoption of such an approach is because data from synoptic observations and general circulation models are not quite able to generate mesoscale features important for the study of dispersion of pollutants on a local scale.

In the next section, a brief overview of the local meteorological conditions and the pollution potential of the Kuala Lumpur city is presented. This is followed by the results of the simulation of the mesoscale wind fields. The last section includes a discussion of the dispersion problems in an equatorial environment.

Local wind conditions

Peninsular Malaysia is influenced by the prevailing southwesterly winds during the southwest monsoon from May to September. The mean monthly surface winds at Subang International Airport, a location approximately 20 km from the Kuala Lumpur city centre, are generally very weak throughout the year, varying from 1 to less than 1.5 m/s. Calm conditions dominate the southwest monsoon for 40% of the time. During the height of the haze period from 12 to 17 September 1997, the daily mean surface winds at the Gombak station in the Kelang valley were generally less than 2 m/s during night-time from 8 pm to 9 am (Figure 1). This indicates the formation of a strong stable layer near the surface of the earth due to the radiative cooling of the ground where turbulence is less diffusive (Moraes *et al.*, 2005). The wind speeds then gradually increased from mid-morning and peaked at approximately 3 pm with an average of 5m/s, and weakened thereafter. The daytime winds were associated with the prevailing southwesterlies and the sea breeze phenomena, while the night-time winds were associated with the land breeze conditions. Kuala Lumpur is situated approximately 45 km from the coast and is influenced both by the land and sea breeze conditions.

Kuala Lumpur city resides in the Kelang valley where its eastern side is bordered by a terrain that peaks over 1,000 m in the Genting Highlands. Its location of approximately 40 km from the Straits of Malacca renders it exposed to the effects of the land-sea breeze and valley winds. As a consequence, ventilation is generally poor. Locally driven land-sea breeze cycles and drainage winds can cause recirculation of pollutants from local and transboundary sources. Therefore, the Kuala Lumpur region is a pollution potential area, where pollutants are likely to be trapped within the valley. The heat island effect in metropolitan Kuala Lumpur is even more pronounced with the continuing expansion of the urban sprawl area (Sani, 1979). Pollution from light to heavy industries and from the emissions of millions of motor vehicles constitutes the predominant source of local urban pollution in the Kelang valley (Ayers *et. al*, 2000). Most metropolitan cities such as Chicago, Houston, Los Angeles and Athens have experienced heavy pollution episodes due to these land-sea recirculations. Heat island effects over major cities may alter the development of local circulations so that air recirculates and draw pollution into the city.

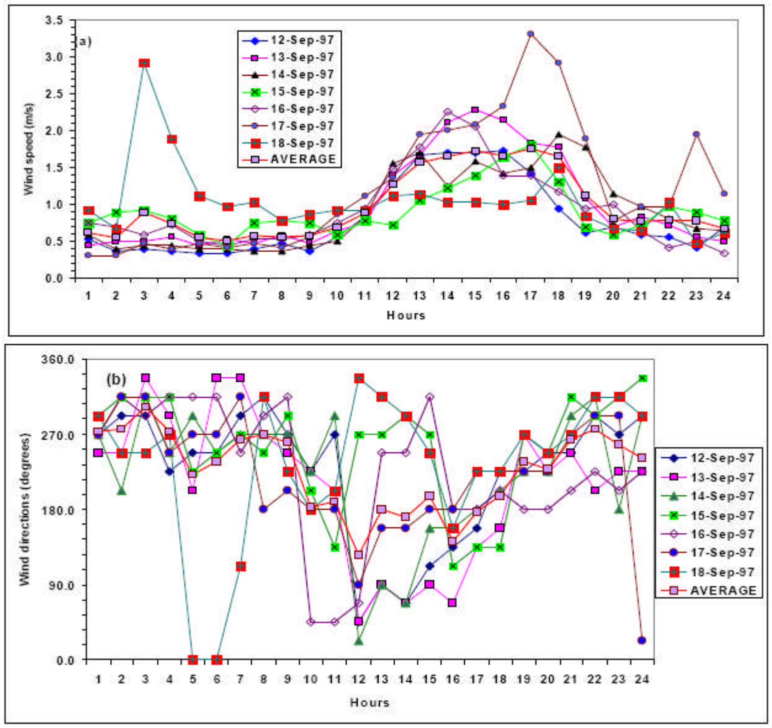


Figure 1. *The (a) hourly wind speeds and (b) wind directions at the Gombak station in the Kelang valley during the height of the haze period from 12 to 17 September 1997*

Light winds and calm conditions in the Kelang Valley that dominate 40% of the year tend to reduce the dispersal capability of local contaminants. Located in an equatorial region, the capital city is affected by stable equatorial atmospheric conditions where the horizontal pressure gradient is weak, particularly during the southwesterly monsoon from May to September, as shown in Figure 2. It illustrates the daily conditional instability of Petaling Jaya in September 1997. Very strong conditional instabilities were found in the planetary boundary layer from the surface to the height of 1 km (12 K/km), which was overlaid by lower instabilities up to the mid-troposphere. However, the low level instabilities were slightly weaker on the 15th and 16th September compared to the previous days, concurrent with the highest PM_{10} concentrations recorded in Gombak. The high conditional instability within the lowest kilometre of the surface indicates strong radiational heating, with a cooler mid-troposphere.

Figure 3 indicates the relationship between daily variations of the PM_{10} concentrations and ground wind speed from 1 to 30 September 1997. High PM_{10} concentrations values of more than 200 $\mu g/m^3$ were associated with average wind speeds of less than 1 m/s. The relationship between particulate matter and the prevailing wind speeds can be expressed as an exponential equation (Ramachandran, 2005). In this simple bivariate consideration, the correlation coefficient of -0.62 exists, signifying a moderate inverse relationship between the PM_{10} concentrations and wind speeds.

The wind profile at the Petaling Jaya upper air meteorological station registered on the 16th. September 1997 showed that the low level winds originated from the southeasterly direction, but veered as south westerlies from the height of 1 to 4 km (Figure 4). The winds then backed as southeasterlies and northeasterlies to a height of 7 km. This verified the fact that the low level winds had originated from the burnt areas of Sumatera, whilst above the planetary layer, the wind flow had emanated from the southwest direction, where advection was most likely from the

Borneo region.

A few days prior to and on 15 and 17 September, backward trajectory analysis at low levels of 950 and 850 hPa showed that possible sources of pollutants from central Sumatera were advected towards the west coast of Peninsular Malaysia (Figure 5). These backward trajectories were computed for the selected days by using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Draxler and Hess, 1997). The trajectory was performed to end at Kuala Lumpur (3.15^0N, 101.7^0E) on 15 and 16 September.

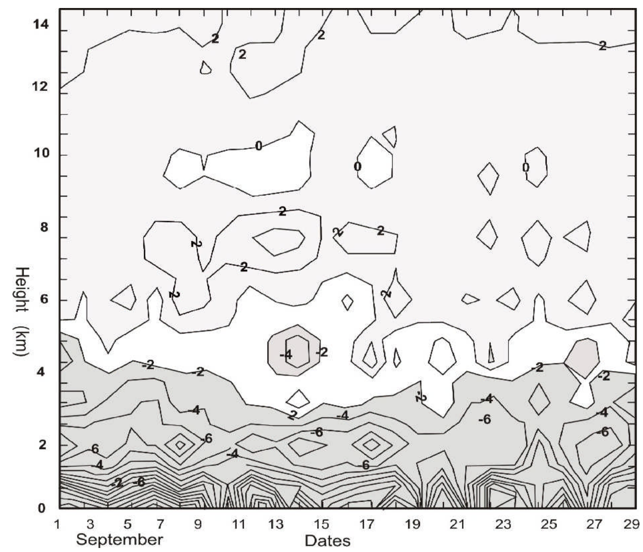


Figure 2. *The vertical distribution of static instability in September 1997 at Petaling Jaya*

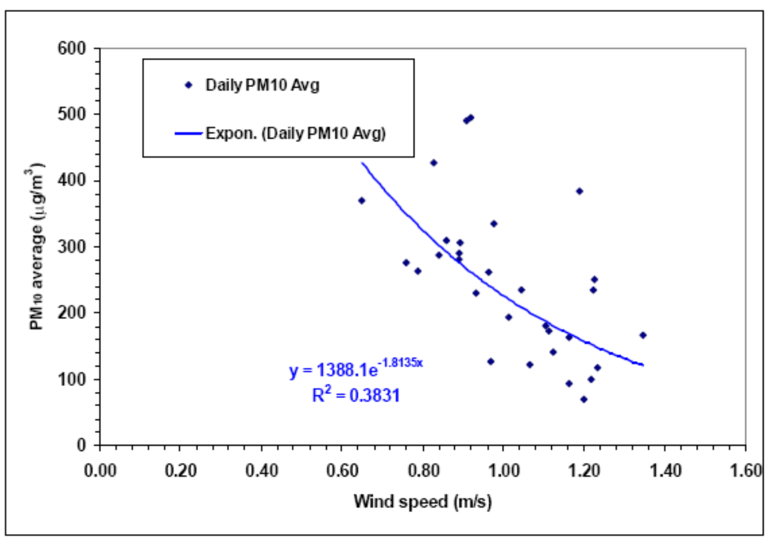


Figure 3. *The relationship between the PM_{10} concentrations and the prevailing wind speeds (m/s) at the Gombak station during September 1997*

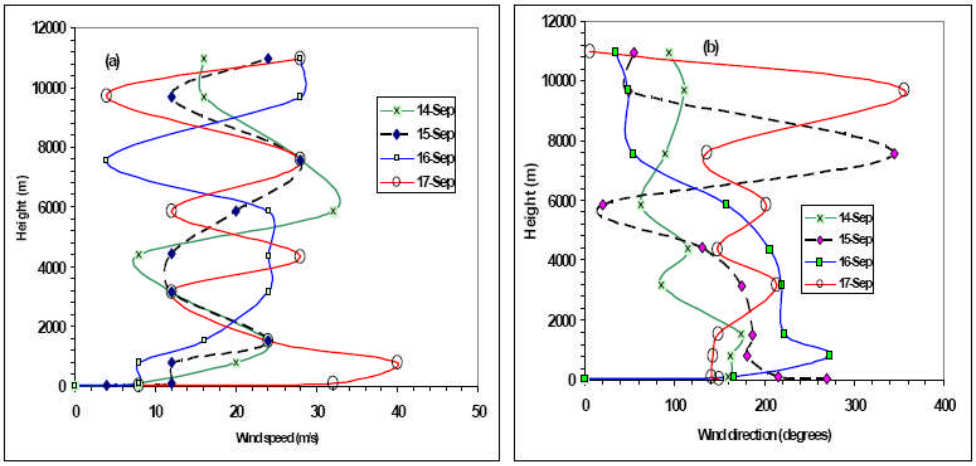


Figure 4. *The vertical profiles of the (a) wind speeds and (b) wind directions from the Petaling Jaya upper air station from 14 to 17 September 1997*

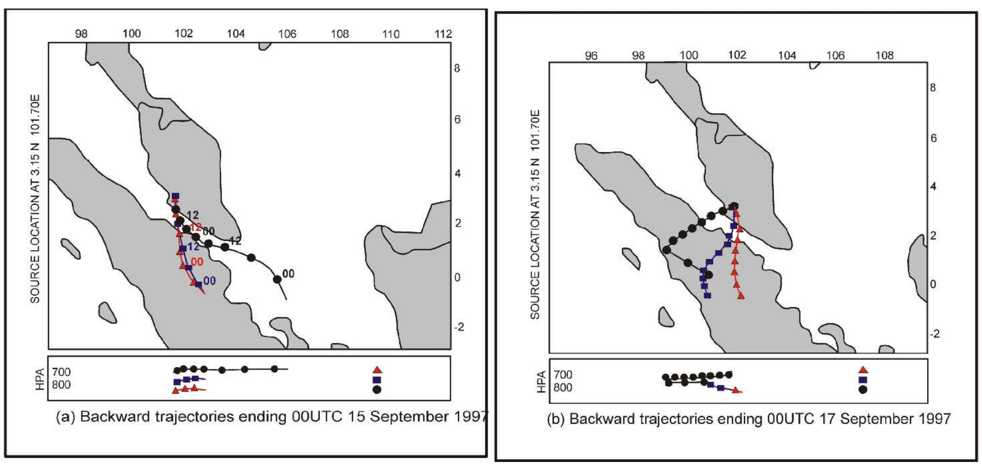


Figure 5. *(a) The backward trajectories ending on 15 September 1997 showed that pollutants from the Sumatera region were advected towards Peninsular Malaysia. (b) The backward air trajectory from Kuala Lumpur ending on 17 September 1997 showed nearly all the paths originated from Sumatera at the three height levels of 950, 850 and 700 hPa*

The synoptic scale meteorological conditions over the southern Southeast Asian region were investigated by studying the National Centre for Environmental Prediction (NCEP) general circulation output. The low level synoptic-scale streamlines a few days prior to 16th September 1997 showed the presence of prevailing south west monsoon regime in the northern hemisphere. In the southern hemisphere, the prevailing south easterlies were dominant across Indonesia (not shown). September is considered a transition period between the waning south westerlies and the onset of the northeasterly monsoon. The presence of an anticyclone at 700 hPa over southern South China Sea on 16th September acted as a lid that capped further vertical mixing of aerosols to higher heights. As a consequence, continual emission of pollutants - from the transported haze consisting mainly of smoke particulates - into the stable, equatorial air resulted in further accumulation of pollutants.

Mesoscale modelling

Meteorological modelling was performed by utilising the Lagrangian Atmospheric Dispersion Model

(LADM) to investigate the local wind field conditions in Kuala Lumpur during the haze episode. LADM is a mesoscale weather forecasting model which exploits the Lagrangian upward differencing scheme to predict the wind field and turbulence of the atmosphere. This differs from downscaling techniques such as those employed by limited area models which offer better information on smaller scales than an output from a general circulation model in terms of finer resolutions that can capture finer synoptic-scale features (Arritt & Goering, 1999). Thus, they can highlight the local circulation effects as a result of topography or water bodies more effectively. However, despite reducing the number of grid points, increasing spatial resolution and thus reducing computational cost, they have the dual disadvantage of generating lateral boundary errors from the imperfect global circulation model output, as well as limiting the time range of the model forecast (Pan *et al.*, 2000).

In contrast, the LADM is able to predict the three-dimensions of local winds, temperature, mixing heights and turbulence in a gridded complex terrain. It is a hydrostatic, scaled pressure coordinate system with a height represented from 1 to 10 km by 24 sigma levels. This hydrostatic model is able to forecast weather on a short time scale of less than 4 days (Physick *et al.*, 1994).

The LADM wind field model is represented by equations of fluid dynamics in the sigma coordinate system (Physick *et. al,* 1994). Modelling of the inter-regional transportation and smog dispersion requires detailed upper air data that include the turbulent mixing height. The turbulence components solved for the finite difference integration includes the vertical and horizontal diffusion terms. Parameterisation of the surface boundary layer is represented by the relationship of momentum, heat and evaporation fluxes that are integrated into the bulk Richardson number for proficient iteration of the surface heat equations (Louis, 1979). Convective boundary layer height is also represented (Deardoff, 1974). An internal boundary layer is also incorporated within the land-sea interface to account for the sea breeze phenomena (Physick *et al.*, 1989).

Long-wave radiative cooling and short wave radiative heating of the atmosphere are represented by a scheme that includes water vapour and carbon dioxide emissivities during an iteration that lasts for three days (Atwater & Brown, 1974; Mahrer & Pielke, 1977). Boundary conditions are represented for the surface, upper level and lateral conditions. Wind speed is considered zero at the ground surface. Fluxes such as sensible heat, evaporation, soil and radiation are represented at the surface. Reflection of the upward propagating waves from the top of the model is avoided with increased horizontal diffusion from a height of 8.5 km (Physick *et al.,* 1994).

Lateral boundary conditions incorporated in the model include a buffer zone between the inner domain and the boundary of the limited area model to prevent noise affecting the inner domain (Physick *et al.*, 1994). The vegetation canopy scheme in the lower boundary is also included (Kowalczyk *et al.,* 1991).

During initialisation, surface pressure, winds and temperature are adjusted for topography. Initialisation in late evening is performed to allow for radiational cooling that produces a nocturnal boundary layer over land. This also allows the winds to adjust to the terrain environment before radiational heating develops at sunrise (Physick *et al.*, 1994). The second 24 hours data contain mesoscale perturbations from diurnal heating and orographic influences. The model does not run for more than 3 days as noise from the boundaries of the outermost grids would affect the inner region. One of the limitations of the model is that it does not simulate moist processes, clouds or rain but does represent the effect of cloud cover estimates at low, middle and high levels. In other words, the LADM predicts mesoscale changes to a background synoptic flow that assumes slow changes in the wind field (Physick *et al.,* 1994).

Results

The modelling approach attempts to simulate in detail the local scale wind field patterns over the Kelang valley. The initial outermost domain included the southern Southeast Asia region of Peninsular Malaysia and Sumatera which together encompassed an area of 1600 km^2 with horizontal dimension grid point spacing of 20 km. Subsequent integration through a one way nesting mechanism was performed for the inner domain grid intervals of 20 km, 10 km and 5 km. The vertical profiles of temperature, specific humidity and local wind condition were initialised at several specified heights on the 14th September 1997 from the upper air station at Petaling Jaya which lies approximately 20 km from Kuala Lumpur.

Results were studied on the second day of simulation to allow for sufficient spin up time for the dynamical equilibrium between the internal physics and information from the boundaries. Simulation was initiated at 0300 hr for the first day and runs for a temporal period of 48 hours until 0000 hr on the third day. The simulation produced moderate to weak south westerlies which developed from Day 1 across the Kuala Lumpur valley.

The time series distribution of the simulated wind field vectors for Kuala Lumpur across the 5 km grids on the 15th September 1997, twenty-four hours after initialization is shown in Figure 6. The local wind field conditions simulated at 7 am exhibited the presence of a slight land breeze to the south of Kuala Lumpur (Figure 6a). The wind field near the terrain to the north of Kuala Lumpur was generally very weak and flowing generally in a northerly direction. Leeward winds of the main Range to the east of Kuala Lumpur were flowing in the northeast direction.

The onshore flowing south westerlies and the effect of the local area sea breeze circulation from the Straits of Malacca that were flowing inland towards Kuala Lumpur was evident at 10 am, although the strength of the onshore and offshore winds were weak and less than 5 m/s (Figure 6b). Figures 6c and 6d show the wind field on Day 2 at 2 pm and 5 pm, respectively, where the channelling of the prevailing south westerlies in the Straits of Malacca and the inflow of sea breeze towards the foothills in the northwestern region of Kuala Lumpur were evident. The wind field pattern just after sunset at 7 pm, showed that the sea breeze in the Straits of Malacca had weakened, but the wind field over land was still evident although the strength of the winds had weakened slightly compared to that at 5 pm (Figure 6e). By 9 pm, the wind field had weakened considerably, particularly, the calm conditions over the Straits of Malacca and the weakened onshore winds to the east of the Main Range mountains (Figure 6f).

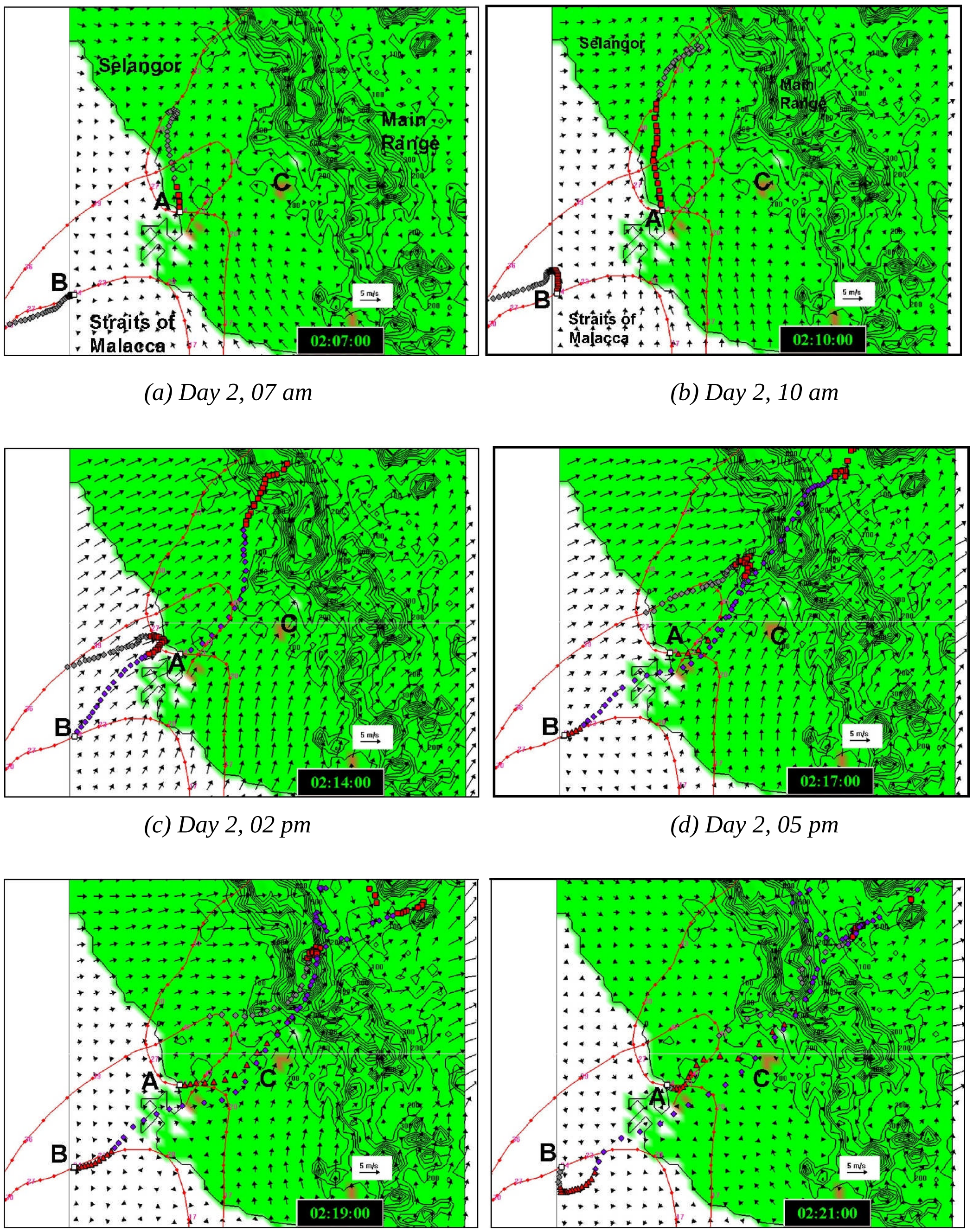
The simulation of the low level wind field to some extent verifies the low level wind data recorded at the Gombak station where the wind speeds associated with the land breeze effects were weaker during night-time from 8 pm to 9 am (Figure 1). The stronger wind speeds during the daytime were influenced by the sea breeze, with a peak that generally occurred at approximately 3 pm.

Spatial characteristics of the trajectory were examined with the objective of obtaining information on the 'smoke transport'. The simulation illustrated the upwind association of the smoke with the PM_{10} concentrations at the air quality monitoring station in Gombak site in Peninsular Malaysia, by tracking the space-time characteristic of trajectories within the investigated domain.

In this investigation, air particles were traced forward for a period of 2 days, and an air particle was released every 15 minutes. Two air particle source points were selected, one at the Kelang station on the coast of Peninsular Malaysia, located at $3^0$0.62'N, 101^0 24.484'E (represented as point A), and the other, at a point located at 2^0 43'N, 100^0 42'E in the Straits of Malacca (represented as point B), that epitomized a foreign source. A tracer that began at 1 am on Day 2 showed that the air particle at B had advected southwest by 7 am in the direction towards Sumatera (Figure 6a). At the Kelang station, the air particle was directed mainly northwards on the land area throughout the duration of the 6 hours. In the next three hours, the air particle from B had moved in a north-eastward direction, advected by the weak winds over the Straits of Malacca (Figure 6b). The air particle from A was still advected in a northerly direction.

By 2 pm, the sea breeze over the Straits of Malacca had strengthened considerably in the northeasterly direction. The aged air particles from location B were transported in a northeasterly direction towards Peninsular Malaysia. Particles released 8 hours prior to 2 pm had reached the western coast of the peninsula near location A. But the air particle that was released from the Kelang station was still directed landwards, towards the north of the Kelang Valley (Figure 6c).

Although the wind field pattern was similar to 2 hours previously, the situation at 7 pm showed that the strength of the winds across the land area had weakened slightly to less than 3 m/s (Figure 6e). The onshore and offshore winds continued to weaken considerably by 9 pm (Figure 6f). The air particle from B was still near-stagnant in the Straits of Malacca, which implies slow advection. The situation was similar for the air particle that originated from A, in Kelang, which moved slowly in a northeastward direction.



(a) Day 2, 07 am *(b) Day 2, 10 am*

(c) Day 2, 02 pm *(d) Day 2, 05 pm*

(e) Day 2, 07 pm *(f) Day 2, 09pm*

Figure 6. *Wind fields at the height of 10 m across the inner domain of Kuala Lumpur at (a) Day 2, 07 am, (b) Day 2, 10 am, (c) Day 2, 02 pm, (d) Day 2, 5 pm, (e) Day 2, 7 pm, (f) Day 2, 9 pm. The letter A represents the Kelang station, B is a location in the Straits of Malacca, and C represents Kuala Lumpur*

The smoke particulates produced from the intense daily burning in Sumatera during the weak to calm low level equatorial winds in that September were not effectively dispersed, as was shown by the trajectory analysis. This was one of the reasons why the low level air quality in Kuala Lumpur deteriorated. Air pollutants over the land area on the western coast of Peninsular Malaysia were directed landwards throughout the duration of the simulation, while the polluted air from the Straits of Malacca exhibited the recirculation characteristics. Polluted air from the Straits of Malacca was directed seaward towards Sumatra during the nighttime, while during the daytime, the aged air particle was flowing inland towards Kuala Lumpur on the western coast of Peninsular Malaysia following the sea breeze which was embedded within the weak prevailing southwesterlies.

The additional accumulation of the particulates from the uncontrolled biomass burning as well as the aged particulates suspended in the air from the previous days' burning aggravated the haze situation. During night-time, the stable layer above the surface of the earth formed by radiative cooling rendered turbulence less diffusive. During daytime, the convective layers were higher than the stable layer, and dispersive eddies dominated in concert with the higher wind speeds. The role played by sea and land breezes in the recirculation of the pollutants also favoured the low level mixing, thus ensuring that pollutants were not dispersed efficiently. Turbulence statistics were not performed in this study, as they are beyond the scope of this investigation.

Discussion and conclusion

This paper does not attempt to emulate the dispersion characteristics of the haze since the limited area model could not include the source of pollutants released from Indonesia. This is because most of the particulates have diffused during their transportation from southern Sumatera or from northwest Kalimantan. However, investigation was focused on the generation of the local wind field conditions in the Kelang valley that can influence the movement of transboundary pollutants following the local wind trajectories across the south western coast of Peninsular Malaysia.

The sequence of wind field pattern at one hour intervals showed that the weaker wind speeds during night-time were associated with the land breeze, while the slightly stronger winds during the daytime were related to the sea breeze regime embedded in the weak prevailing south westerlies. In all, the output from the model does provide for the development of the diurnal pattern of the low level wind field as observed information is not always available in sufficient detail.

At the height of the haze period, the wind speeds were generally lower than the few days earlier or a few days later. The sea breeze and land breeze phenomena were apparent from the trajectory of air particles selected and the 10 metre wind vectors shown during the 48-hour duration of the simulation.

It must be noted that dispersion modelling in low wind conditions is important for in such conditions pollutants are not able to travel far and thus affect the areas near the source that may retain high concentrations. Methods have been developed to account for modelling under weak conditions including streamwise diffusion and variable eddy diffusivities (Sharan *et al.*, 1996). However, there still exist limitations from homogeneous wind fields and restrictions concerning the shape of the source (Moreira *et al.,* 2005).

Similarly, detailed measurements of the sea breeze phenomenon have been difficult to implement due to complicating factors such as effects of inland topography that interact with the sea breeze (Darby *et al.,* 2002). Doppler lidar measurements found two scales of flow of the sea breeze that consist of a shallower but stronger breeze, and a deeper but weaker sea breeze that occurred later in the day (Banta *et al.*, 1993). Land and water contrast was responsible for the shallow sea breeze, and the sudden onset of deeper but weaker sea breeze is associated with coastal mountains (Darby *et al.*, 2002). Coastal topography also plays a role in the sea breeze development. However, more complex features, such as the variability of the flow near the coastal terrain, the absence of the Coriolis effect on the sea breeze winds, and the absence of the compensatory return flow, are not investigated as they are beyond the scope of this paper. Urban boundary layers may exhibit wind-temperature wind field structures that are different from rural areas due to the underlying urban environment surface complexities such as industrial, residential or vegetated areas (Tong *et al.*, 2005). As recirculation is a major pollution problem with coastal areas, the preliminary study on low level wind field patterns of Kuala Lumpur deserves further investigation.

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