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Mesoscale equatorial wind prediction in Southeast Asia during a haze episode of 2005

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Even today fires are still utilized by local farmers in Southeast Asia to clear land. Air pollutants produced from the biomass burning activities from Sumatera, for example, are advected towards the western coast of Peninsular Malaysia during the southwest monsoon and can cause adverse effects on the health of the local population. This study utilized the TAPM (The Air Pollution Model) to predict the low level mesoscale characteristics in an equatorial environment that encompassed the island of Sumatera and Peninsular Malaysia during the burning period in August 2005, when persistent haze was prevalent.

TAPM was able to generate the existence of the daily land and sea breeze conditions near the western coast of the Peninsular Malaysia with relative success with a moderately high Index of Agreement of 0.87 and 0.60 for the zonal and meridional wind components, respectively, even without assimilation of local wind conditions. Strong low level southwesterlies that were generated during the daytime over the Straits of Malacca were associated with sea breeze, while weak southeasterlies simulated from 1900 local time towards midnight were associated with land breeze conditions. The vertical wind profile within the lowest kilometer of the atmosphere showed that the weak southwesterlies were present from mid-morning to sunset, which was interspersed with stronger southwesterlies that generally occurred above the height of 400 m.

The meteorological parameters such as wind speed, temperature, and humidity were successfully simulated by the model with comparatively high correlation coefficients, low RMSEs and high indices of agreement with observed values.

The vertical turbulent kinetic energy profiles showed presence of low level suppression at a height below 600 m during the height of the haze in August 2005, which coincided with the intense burning activities in Sumatera and the elevated levels of pollution in western Peninsular Malaysia. Trajectory analysis showed that aged air particles were advected landwards and seawards throughout the duration of the seven days' simulation from the 7th to the 13th of August 2005. The presence of recirculation features of the land

and sea breeze conditions highlighted the poor transportation capability of low level winds that were unable to cope with the high loadings of aerosols from the biomass burning in Sumatera.

Keywords: equatorial region, meteorological parameters, biomass burning, transportation of haze, Southeast Asia.

1. Introduction

Atmospheric pollution is becoming an increasing problem particularly for developing countries in their strife to achieve enhanced economic status. Not only are the pollutant sources concentrated in the urban and industrialized areas, but transboundary sources can also affect the health of neighbouring population besides its own population. In Southeast Asia, large-scale agricultural activities practiced by farmers and large companies that convert forests into plantations are the root of the air pollution problem mainly because fires are used to clear land during the burning season. These air pollution episodes have been recurring for many years, but received significant attention in the past ten years since the major El Nino event of 1997–1998 when more than 9.5 million hectares were lit which emitted much smoke from the burned areas of Borneo and Sumatera, Indonesia (Qadri, 2001).

Clearly, large-scale uncontrolled burnings can cause environmental disasters by virtue of their transported aerosols that affect neighbouring countries in the region. One such occasion of a major air pollution episode occurred on the 11th of August 2005, where a haze emergency state was declared in the districts of Port Kelang and Kuala Selangor in Selangor, Peninsular Malaysia (New Straits Times, 2005a; 2005b). The Malaysian Air Pollutant Index (MAPI) breached the 300 level, which was considered hazardous to the health of the local community. The haze emergency was lifted on 13th August after the air quality improved and the MAPI levels at an air quality station in Kelang dropped below 150, considered a tolerable level.

The intense phase of burning a few days prior to and during the haze emergency period from the 8th to the 12th August of 2005 is shown in Figure 1. Most of the burning was located in the provinces of northern Riau and southern Sumatera Utara, as shown by the scattered active fire counts. More than 660 hotspots were monitored by the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite for the duration of these five days. Smoke particles from the burning areas in the Riau province in Sumatera were transported to the central western coast of Peninsular Malaysia by the prevailing low level winds of the southwest monsoon. The ensemble backward trajectory analysis that ended in Kelang on the 10th of August showed that sources of pollutants from central Sumatera were advected towards the west coast of Peninsular Malaysia within forty eight hours (Figure 1). The multiple trajectories were calculated by offsetting the meteorological data by a fixed grid factor in the horizontal and a 0.01 sigma unit in the vertical (Draxler et al., 2008). The trajectories were computed by using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Draxler and Rolph, 2003). The 27 possible trajectories showed the probable starting points that originated from Riau, Sumatera.

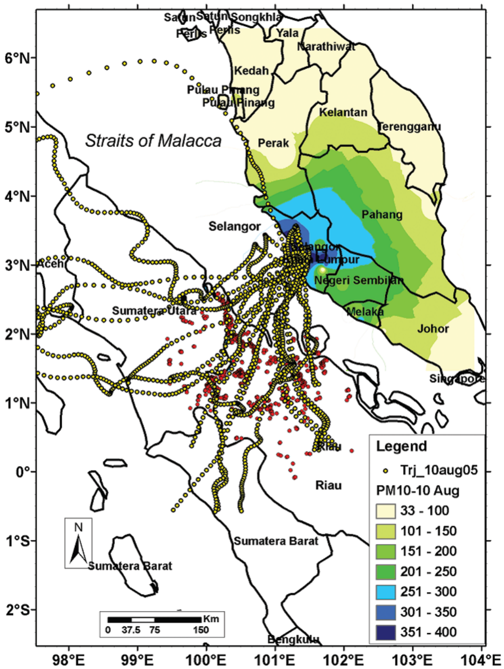

Figure 1. The MODIS active fire counts from 8 to 12 August 2005 (red dots), contours of PM_{10} concentrations ($\mu g\ m^{-3}$) at Peninsular Malaysia, and backward trajectories (yellow) that ended on 10 August 2005 at Kelang are shown on this Figure.

The spatial distribution of the 24-hour average particulate matter concentrations, of size less than 10 microns (PM_{10}) on the 10th of August is also shown in Figure 1. The contours were limited to the area bounded by Peninsular Malaysia as the air quality data was only available from 30 stations in Peninsular Malaysia. Unhealthy levels of more than 300 $\mu g\ m^{-3}$ were found in the state of Selangor, while the other states such as Negeri Sembilan, Melaka, western Pahang and southern Perak were affected by the PM_{10} concentrations that were over the limit of 150 $\mu g\ m^{-3}$ set by the World Health Organization. The time series for mean hourly Malaysian Air Pollutant Index (MAPI) during the entire month of August showed that the 300 mark was breached at the Kelang air quality station on the 10th of August 2005, and peaked to 494 on the 11th of August before dropping below the 300 mark on the 12th of August (Figure 2). The Figure also compared the lower August MAPI values that indicated the good air quality for the preceding years from 2000 to 2004, which highlighted the severity of the haze episode in 2005. Another severe haze episode that occurred during the El Nino event of 1997 also showed that the air quality levels attained a very unhealthy status on the 14th and 15th September.

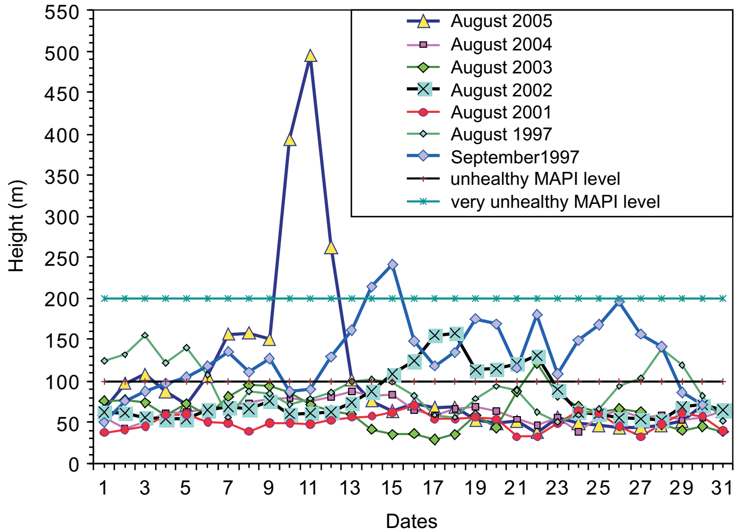

Figure 2. The MAPI readings at Kelang during August from 2001 to 2005, and in September 1997.

Transportation modelling thus far was based on the coarse horizontal scales that highlighted the synoptic-scale conditions of the atmosphere. A study on the haze episode of 1997 in Southeast Asia utilized a 35-km grid horizontal resolution to capture the relatively weak monsoon development of Southeast Asia (Koe et al., 2001; 2003). Another study also simulated the transportation of the anthropogenic sulphate and sulphur dioxide in Southeast Asia by employing the 50 km horizontal grid of the Multiple-scale Atmospheric Transport and CHemical modelling system (MATCH) model (Siniarovinaa and Engardtb, 2005). Mahmud (2008a, 2008b) also utilized the Hysplit model with a coarse resolution of 192 km to investigate the transportation routes of the smoke particles from the active fire counts in Sumatera, Indonesia that advected towards the western coast of Peninsular Malaysia during the haze episode of 2005. Mahmud (2009) also studied the local wind conditions during another haze event in 1997 that coincided with the El Nino episode where easterly winds dominated the east equatorial Indian Ocean (IO) and the maritime continent from July 1997 to May 1998, in contrast to the dominance of westerlies of a neutral El Nino. The surface wind anomalies were mainly easterlies over the equatorial IO which represents the condition of a positive Indian Ocean Dipole that materialized by September 1997(Gadgil et al., 2007).

In this study, a limited area meteorological and air pollution model called The Air Pollution Model (TAPM) is utilized (Hurley, 2005) to investigate the local wind regime of a mesoscale resolution, of scale less than 5 km, to highlight the local features during the haze episode. In this study, an equatorial setting is explored. TAPM was selected for this study as it has simulated meteorological fields for the dispersion prediction of pollutants (Hurley et al., 2005) such as turbulence conditions (Hurley, 1997), the sea-breeze phenomenon (Hurley and Luhar, 2000), air pollution of an industrial area (Hurley et al., 2001), and urban photochemical smog (Hurley et al., 2003).

2. Model configuration

TAPM is a three-dimensional limited area prognostic meteorological and air pollution model. Input parameters to the model include global databases of terrain height, land use, sea-surface temperature, and synoptic meteorological analyses (Hurley et al., 2005). TAPM's default database of global terrain height and land cover characterization at a resolution grid of 1 km is based on data from the US Geological Survey. Further description of the model is given by Hurley et al. (2005). The horizontal wind components are solved from momentum equations, while vertical velocity is solved from the incompressible continuity equation that follows the terrain. Parameters such as potential virtual temperature, specific humidity of water vapour, cloud water and rain water are solved from scalar equations (Luhar et al., 2003).

Pressure is generated by the hydrostatic and non-hydrostatic components. The turbulence closure terms in these mean equations utilize a gradient diffusion approach which consists of a counter-gradient term for the heat flux, with eddy diffusivity determined using prognostic equations for turbulence kinetic energy and eddy dissipation rate (Luhar et al., 2003). The earth's surface is represented by a weighted vegetative canopy, soil and urban land-use scheme which also incorporate radiative fluxes at the surface and upper levels (Hurley et al., 2005).

The Version 3 of TAPM, have included some updated microphysics and prognostic equations for cloud water/ice and rain/snow, as well as the inclusion of several sized partitions of dust particulates, changes to minimum roughness parameters, revision to the turbulence in the top half of the atmosphere and improvement to the minimum level of horizontal turbulence that resulted in a better representation of fumigation break-up (Hurley et al., 2005).

One of the disadvantages of TAPM is the limitation of maximum horizontal domain extent that cannot exceed 1500 km × 1500 km. This is due the model equations that neglect the curvature of earth and assume a uniform distance grid spacing across the domain (Hurley, 2005). Therefore, areas larger than this size cannot be included in the analysis of prognostic meteorological or pollutant modeling.

The synoptic model output from LAPS (Limited Area Prediction) or GASP (Global Analysis and Prediction) provided for by the Bureau of Meteorology, Australia (Luhar et al., 2005) provides the input to the meteorological component of TAPM. Boundary conditions for the outer grid of the model are obtained from GASP at a horizontal resolution of 100 km at 6 hourly intervals.

Statistical analysis was performed by means of the root mean square error (RMSE), which evaluates the variation between model and observed values and is a measure of the size of the error produced by the model. Low RMSEs indicate that the errors generated by the model are small and close to observed values. An ideal simulation is achieved when the RMSE is zero. Other statistial parameters utilized in this study are the systematic RMSE ($RMSE_S = \sqrt{\sum_{i=1}^{N} (\hat{P}_i - O_i)^2 / N}$), and the unsystematic (random) ($RMSE_U = \sqrt{\sum_{i=1}^{N} (\hat{P}_i - P_i)^2 / N}$), where $\hat{P}$ is the regressed predicted value, O_i and P_i are the observed and predicted parameters. $RMSE_S$ evaluates variation of the fitted linear regression between predicted and observed values, while the $RMSE_U$ calculates the difference between fitted linear regression and the predicted values. Ideally, the RMSEs and $RMSE_U$ should be as small as possible. The RMSEs assesses the model errors that are predictable, while the $RMSE_U$ assesses the errors not simulated mathematically (Luhar et al., 2004).

Other standard parameters computed in this study include the correlation coefficient, which measures the degree of conformity between the modeled and observed values, and the index of agreement ($IOA = 1 - \left[\sum_{i=1}^{N} (P_i - O_i)^2 / \sum_{i=1}^{N} (|P_i - O_{mean}| + |O_i - O_{mean}|)^2 \right]$). The IOA is a sensitive indicator, where a value of 1 signifies a perfect conformity between model and observed values, while a value of 0 signifies total disagreement (Luhar et al., 2004). Several other skill indicators were also evaluated. $Skill_V$ is the skill score that compares standard deviation of the model to the observed. A value of 1 indicates a perfect skill in predicting the parameter concerned. $Skill_R$ is ratio between the RMSE and the standard deviation, where a value less than 1 indicates a high skill. $Skill_E$ is the ratio between the $RMSE_U$ and the std deviation of the observed values.

3. Results and discussion

The hourly observed meteorological data at the Kelang station in the state of Selangor, which recorded high values of MAPI, was utilized in this study. Kelang is a small semi-urban area with relatively flat local terrain located about 10 km from the western coast of Peninsular Malaysia, which is adjacent to the Straits of Malacca. Approximately sixty kilometers to its east is the Main Range highlands that peak to heights at 1 km.

TAPM was run for a period of seven days from the 7th to the 13th of August 2005 in order to assimilate the wind field conditions a few days prior to the peak air pollution episode of 11th August. Three nested domains of 50×50 horizontal grid points at 30, 10, and 3 km spacings were chosen for this study (Figure 3). These domains were centered at the Kelang station at 3°6'N and 101°24'E. The lowest five of the 25 vertical levels were selected at 10, 25, 50, 100 and 150 m.

The low level wind regime at the height of 10 m within the inner-most grid of 3 km illustrates the existence of land and sea breeze circulations in addition to the prevailing southwesterly monsoon between the land area in the western coast of Peninsular Malaysia in Selangor, and part of the Straits of Malacca for

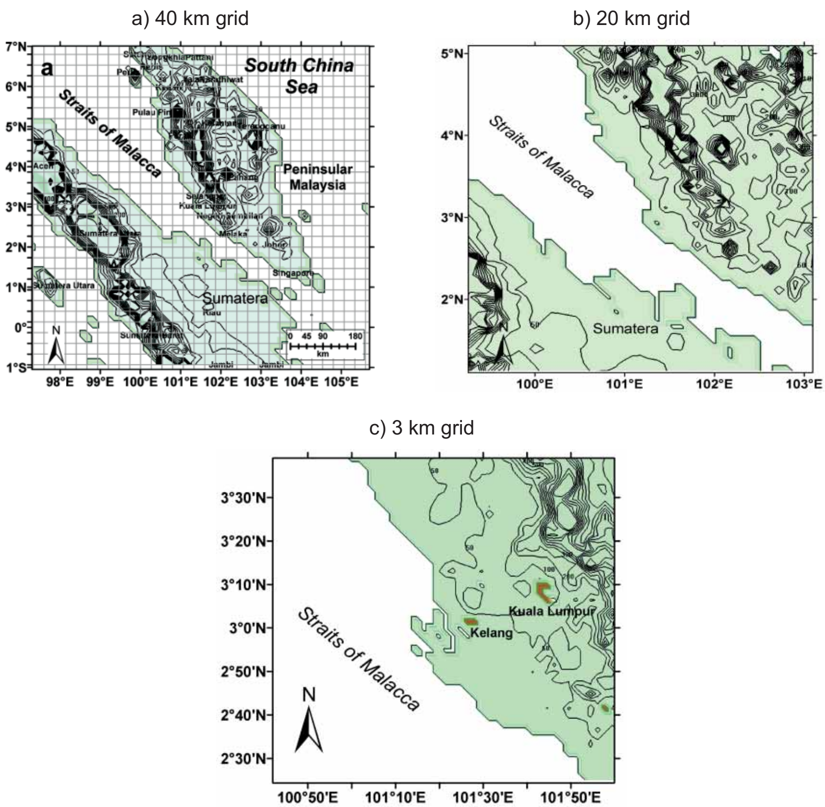

Figure 3. The three nested domains of the model runs at (a) 30 km, (b) 10 km, and (c) 3 km grid spacings.

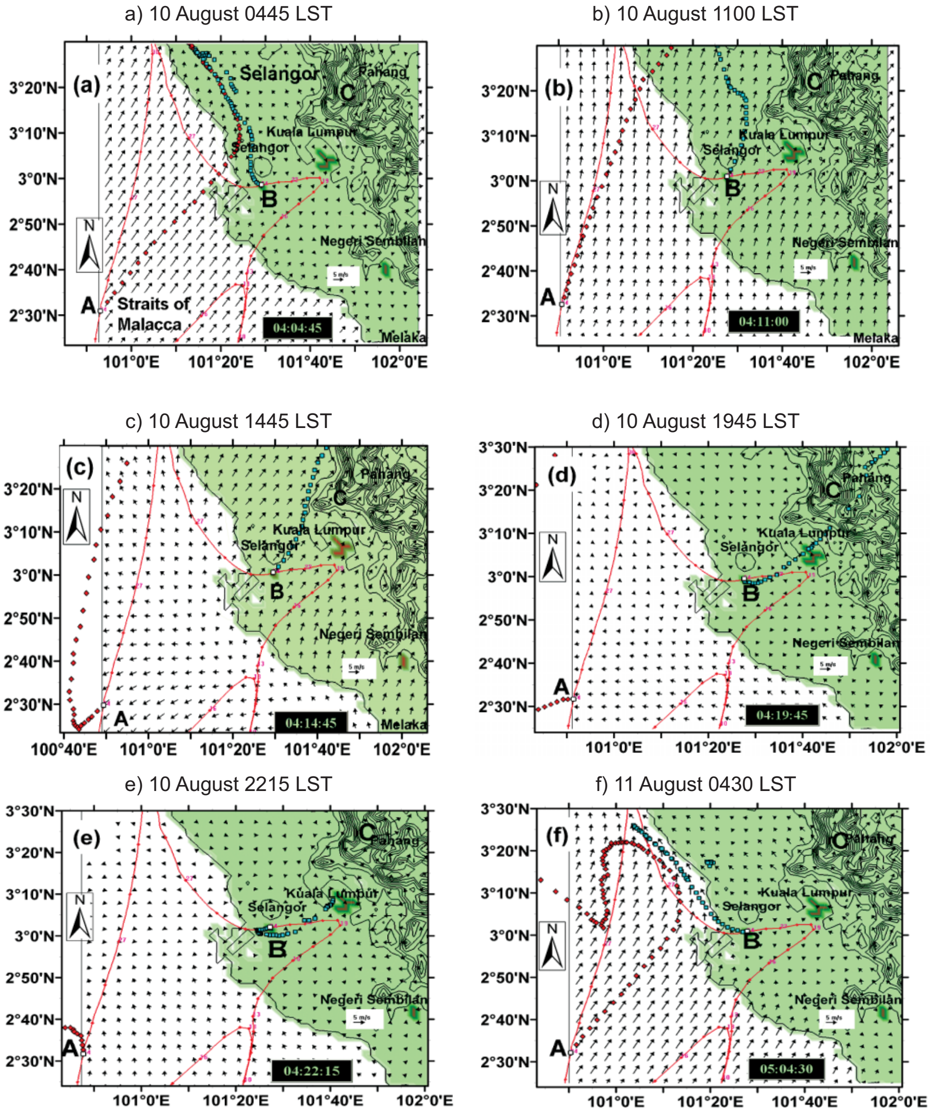

Figure 4. The selected hourly simulated wind regime on 10 and 11 August, within the Straits of Malacca and part of Selangor. The centre of the map is at Kelang, noted by B. The notation of 04:04:45 refers to the simulation time on Day 4 at 0445 LST.

the entire duration of simulation. Strong southwesterly winds were found in the Straits of Malacca at 0445 local standard time (LST) on Day 4 (corresponding to the 10th of August), whilst in Selangor, onshore sea breeze regime was evident (Figure 4a).

The moderate southwesterlies (more than 5 ms^{-1}), generated over the Straits of Malacca implied the dominance of the prevailing southwest monsoon. However, overland, the wind speeds were weaker with magnitudes of less than 1 ms^{-1} associated with the land breeze phenomenon (Figure 4a). By 1100 LST, the wind over the Straits of Malacca changed from the southwesterly direction to a more southerly direction. However, prevailing southwesterlies were still prevalent over land (Figure 4b).

The wind regime over the Straits of Malacca on the 10th of August weakened further at 1445 LST due to the presence of the diverging wind vectors that were located parallel to the coast in the Straits of Malacca (Figure 4c). Southwesterlies, associated with the divergence were evident over the land area on the western coast of Peninsular Malaysia. On the same day at 1945 LST the winds over land and sea weakened further and were of varying directions (Figure 4d). Similar wind conditions as those found three hours previously were evident at 2215 LST (Figure 4e). However, six hours later at 0430 LST on the 11th of August, the winds changed direction, and followed the wind patterns 24 hours previously as shown in Figure 4a. Stronger winds prevailed from the southwest direction over the Straits of Malacca although the strength of the wind speeds was weak over land, associated with the land breeze (Figure 4f). This sequence of simulation showed that the wind regime on the 10th of August was weak due to the divergence of winds over the Straits of Malacca that coincided with the intense burning activities in the province of Riau, Sumatera.

Trajectory analysis was performed from a source located at 2°43'N 100°40'E in the Straits of Malacca to represent a polluted air particle that originated from Sumatera, represented by A in Figure 4, and another source at the Kelang station (B), which represents the air particles from Peninsular Malaysia. The air particles were released at midnight on Day 2 (the 8th August of 2005), after a spin-up time of 24 hours, and their trajectories were traced. Figure 4a shows the paths travelled by the air particles from point A on Day 4, which still resided over the Straits of Malacca 52 hours after the first air particle was released, indicating the slow advection of air. The time interval between the air particles is 15 minutes. The aged air particles that originated from the coastal station at point B remained over land along the coast for the entire 72 hours, but were not transported further inland. Only seven hours later were the air particles directed further inland in the state of Selangor, advected by the southwesterlies (Figure 4b). Newer air particles released from point A were directed further westwards three hours later, due to the divergence of winds over the Straits of Malacca (Figure 4c). The aged air particles from point B continued to travel further landwards in Peninsular Malaysia (Figure 4c).

More recent air particles released from point A were directed further westward towards Sumatera by 1945 LST in the opposite direction to the newer air particles released from point B, which were directed inland towards the Main Range in Peninsular Malaysia (Figure 4d). This was due to the divergence of air in the Straits of Malacca, parallel to the coast of Peninsular Malaysia. The air particles from point A continued their westward advection towards Sumatera at 2215 LST on the 10th of August, while the air particles from point B were directed eastwards. Due to the weak wind conditions over the Straits of Malacca and the land breeze over Selangor, the divergent flow over the Straits of Malacca directed the air particles westwards towards Sumatera and any particles over Selangor eastwards. By 0430 LST on 11th August, the air particles from point A were flowing in a northeastward direction over the Straits of Malacca, following the prevailing southwesterly winds, as the divergent feature had dissipated (Figure 4f). The strength of winds over the Straits of Malacca had increased by this time due to the disappearance of the divergent feature. Meanwhile, the air particles from point B over Selangor were directed seawards, due to the land breeze circulation (Figure 4f). This situation was similar to those observed 24 hours earlier (Figure 4a).

The time series between simulated parameters and observed variables at the height of 10 m showed some similarity, where the diurnal patterns were well simulated (Figure 5). The mean observed wind speed at the Kelang station was relatively low at 1.3 ms^{-1}, with a standard deviation of 0.53 (Table 1). In contrast, the predicted wind speed was generally higher in magnitude than the observed wind speed. Maximum daytime predicted wind was observed by midday to early afternoon at a speed of more than 4 ms^{-1}, except on the 11th August 2005. The mean predicted windspeed of 2.64 ms^{-1} was relatively higher than the

Table 1. The statistical evaluation of four meteorological parameters.

Statistical parameters	Wind speed (ms^{-1})	Zonal winds (ms^{-1})	Meridional winds (ms^{-1})	Temperature (°C)	Humidity (%)
Observed mean	1.30	–0.24	0.80	29.18	72.67
Predicted mean	2.64	–0.36	1.22	28.12	67.16
Standard deviation of prediction	1.10	1.86	1.78	3.34	15.34
Standard deviation of observed	0.53	0.79	0.81	3.34	11.19
Correlation coefficient	0.62	0.62	0.54	0.90	0.80
Index of agreement (IOA)	0.53	0.86	0.60	0.92	0.83
RMSE	1.69	1.50	1.55	1.85	10.79
Bias-Systematic RMSE	1.15	0.36	0.65	–1.06	–5.51
Systematic RMSE	1.36	1.96	–.45	1.12	5.59
Unsystematic RMSE	0.87	2.13	1.49	1.47	9.19
$Skill_V$ (1 skill)	2.07	2.35	2.21	0.999	1.37
$Skill_R$ (<1 skill)	3.02	1.90	1.93	0.552	0.964
$Skill_E$ (<1 skill)	1.63	2.69	1.85	0.44	0.82

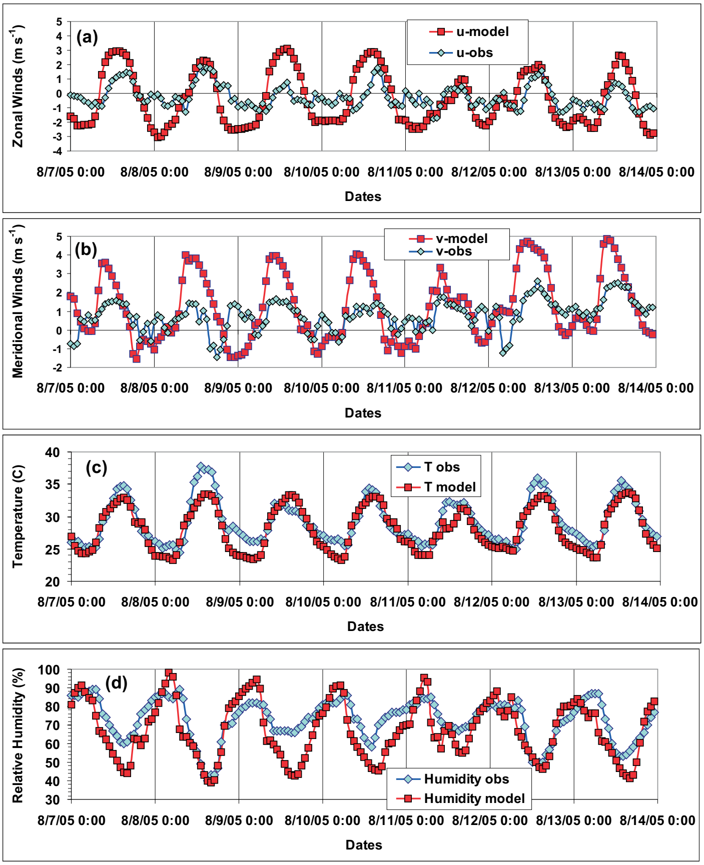

Figure 5. The time series of the simulated and observed meteorological parameters for (a) zonal and (b) meridional wind components, (c) temperature, and (d) humidity at the Kelang station from 7 to 13 August 2005.

observed wind speed. A t-test showed that the means from the two distributions were significantly different. However, the correlation coefficient was moderate at 0.62, with an IOA of 0.53. The TAPM model was moderately skillful in predicting the wind speed from the values of the $Skill_V$, $Skill_R$ and $Skill_E$.

The zonal (east-west, u) and meridional (north-south, v) winds are investigated instead of the wind directions as direction is a circular function (Figures 5a and 5b). Meridional wind components of 2 ms^{-1} that alternated between southerlies and northerlies were attained during the first five days of the simulation (Figure 5b). Weak northerlies were usually dominant during night-time, in contrast to the strong southerlies of more than 3 ms^{-1} that were attained during midday. The mean observed and predicted meridional winds were weak southerlies at 0.8 ms^{-1} and 1.2 ms^{-1}, respectively (Table 1). The correlation coefficient between the predicted and observed parameters is moderate, at 0.54, with an IOA of 0.6, indicating a moderate prediction.

The zonal winds were mostly from the east, with the predicted winds generally stronger than the observed winds at 0.36 ms^{-1} and 0.24 ms^{-1}, respectively (Table 1). The IOA was relatively higher at 0.86 for the zonal than the meridional wind components. The skill indicators of $Skill_V$, $Skill_R$ and $Skill_E$ were slightly higher for the zonal than the meridional wind components, which implied that for this period of study, fewer errors were generated by the zonal winds than the meridional wind components.

According to the National Oceanic Atmospheric Administration (NOAA) Climate Prediction Centre report, a weak El Nino event occurred from late 2004 to early 2005, and was followed by neutral conditions throughout the remainder of the year 2005. During this weak El Nino, significant westerly wind anomalies, increased sea surface temperatures and anomalous convection were confined near the western dateline. Therefore, the period of this study coincided with neutral (or normal) conditions in the equatorial Pacific Ocean. This is in contrast to an earlier study by Mahmud (2009) who investigated the low level wind conditions during the 1997 major El Nino event over the same area of interest. This study showed that the IOAs for the meridional and zonal winds were higher by 17 % and 68 %, respectively during the neutral conditions of 2005 in contrast to the lower IOAs during the major El Nino event of 1997 (Mahmud, 2009). The anomalous weak mean zonal westerlies recorded at the Peninsular Malaysia stations during the strongest El Nino of the century was linked to the equatorial Indian Ocean Oscillation (EQUINOO), the atmospheric part of the Indian Ocean Dipole (Gadgil et al., 2007), which plays an important part in the monsoon activity (Mahmud, 2009).

Good IOAs were displayed by the humidity and temperature parameters with values of more than 0.8, compared to the moderate agreement displayed by either the wind speed or wind components. The IOA was generally of the same magnitude as the correlation coefficients, although the values were generally higher compared to the correlation coefficients.

The RMSEs of all the meteorological parameters were generally higher than the predicted standard deviations, except for temperature. Ideally, the RMSE values that are smaller than the standard deviations are considered a skillful model. The $RMSE_S$ was also relatively smaller than the RMSE, whereas the $RMSE_U$ was generally smaller than either the $RMSE_S$ or RMSE. Although the requirement for a good and skillful model is that the $RMSE_U$ should be larger than the systematic RMSE, the results showed otherwise. The magnitudes of the RMSE from this study were comparatively larger than the RMSEs obtained in the state of Selangor for the 1997 haze episode during the major El Nino event (Mahmud, 2009).

In this study, bias for parameters such as wind components, wind speed, temperature and humidity all indicated overforecast of the predicted values compared to the observed. Only a slight negative bias was found for temperature compared to a higher degree of underforecast displayed by humidity. The correlation coefficients were variable for the various parameters investigated. High correlations of more than 0.8 were obtained for temperature and relative humidity, but the correlations for wind speed, zonal and meridional wind components were moderate at 0.62, 0.62, and 0.54, respectively. These correlation coefficients were higher in contrast to the lower correlations obtained during the 1997 El Nino event (Mahmud, 2009).

The TAPM model was very skillful in predicting temperature but less for the other parameters (Table 1). The $Skill_R$ showed values of less than 1, indicating skillfulness in predicting parameters such as temperature and relative humidity, while $Skill_E$ showed that the model was skillful in generating the wind speed, temperature and relative humidity.

Vertical wind profiles were also investigated in this study. Light easterlies were interspersed with westerlies throughout the depth of the lowest kilometer from sunset to 0900 LST, and from 0900 LST to sunset, respectively, throughout the simulation (Figure 6a). The easterlies were only confined to the lower half of the kilometer, while westerlies were generally more dominant above the height of one kilometer throughout the day. The zonal westerlies were stronger from the 9th of August to the 10th of August (corresponding to hours 72 to 96). The winds were generally weak westerlies throughout the day, except for a few days during the evening time, in contrast to the strong westerlies, particularly above 600 hPa from the 12th to the 13th of August (corresponding to hours 122 to 155).

The high burning activity in Sumatra caused an increase in the PM_{10} concentrations in Kelang when the strength of the westerlies within the depth of 400 m to 1200 m was weak. During the height of the haze episode, the PM_{10} concentrations were higher when the weak westerlies were present during the daytime, corresponding to the sea breeze, peaking from 1200 LST to 1800 LST. Likewise, strong westerlies of more than 6 ms^{-1} were dominant throughout the lowest part of the planetary boundary layer from hours 122 to 155, corresponding to the 12th to 13th of August, in conjunction to the reduced burning activities in Sumatera and thus lower PM_{10} concentrations.

The meridional winds were generally southerlies (less than 4 ms^{-1}) within the lowest 400 m, and superseded by relatively stronger southerlies, of up to 10 ms^{-1}, above 400 m throughout the entire simulation (Figure 6b). High PM_{10} concentrations were present when low southerlies were dominant throughout the planetary boundary layer from the beginning of the simulation until the 11th of August. Stronger southerlies were present from the hours of 122 to 155, corresponding to the 12th and 13th August. It can be summarized that the PM_{10} concentrations were high during the daytime (from midday to sunset) were weak southwesterlies, generally less than 2 ms^{-1}, within the lowest half of the kilometer corresponding to the sea breeze.

The hourly turbulent kinetic energy (TKE) profiles on individual days from the 9th to the 11th of August 2005 are shown in Figures 7a to 7c. The

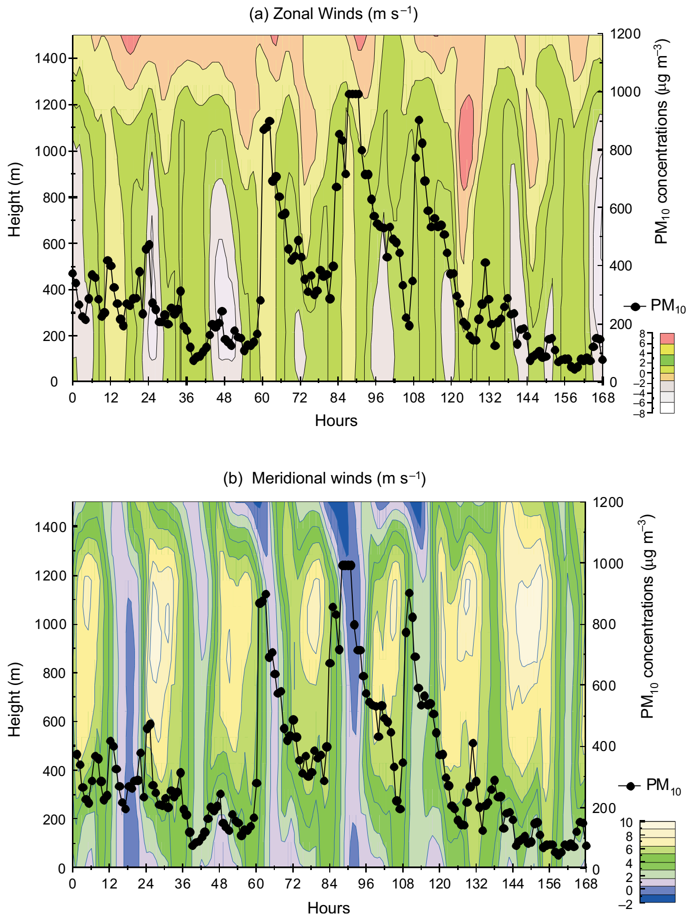

Figure 6. The vertical profiles of the (a) zonal and (b) meridional wind components, and the hourly PM_{10} concentrations.

TKE profile on the 9th of August was the most suppressed profile which showed that the turbulence was capped below 600 m, compared to a slightly higher height of 800 m on the next day. Turbulence was less suppressed on the 11th of August compared to the two previous days, where the maximum TKE of 1.58 m^2s^{-2} was attained at 1000 LST at a height of 200 m. Figure 7d shows the different average daily TKE vertical profiles. The lowest magnitude was found on the 9th of August, and the highest magnitude was presented by the profile on the 12th of August. This Figure also shows that the lowest profile of TKE coincided with the day when pollution levels in Kelang were high (the 10th of August). Turbulence increased on the 12th of August, which coincided with the slight decrease in pollution levels recorded at Kelang.

4. Conclusion

The statistical evaluation from this study had shown that the TAPM model was moderately skillful in predicting the meteorological parameters, with relatively high correlations between the predicted meteorological parameters such as temperature and humidity compared to the observed values. The presence of land and sea breeze circulations and the divergent feature of winds over the Straits of Malacca limited the efficient dispersion of pollutants from Sumatera. Trajectory analysis showed that the aged polluted air particles from the Straits of Malacca were advected landwards and seawards on a daily basis, in addition to the divergence feature that recirculated the air particles back towards Sumatera and towards Peninsular Malaysia. Further eastward movement of air particles towards the east of Peninsular Malaysia were blocked to a certain extent by the Main Range mountains. Weak TKE within the lowest ki-

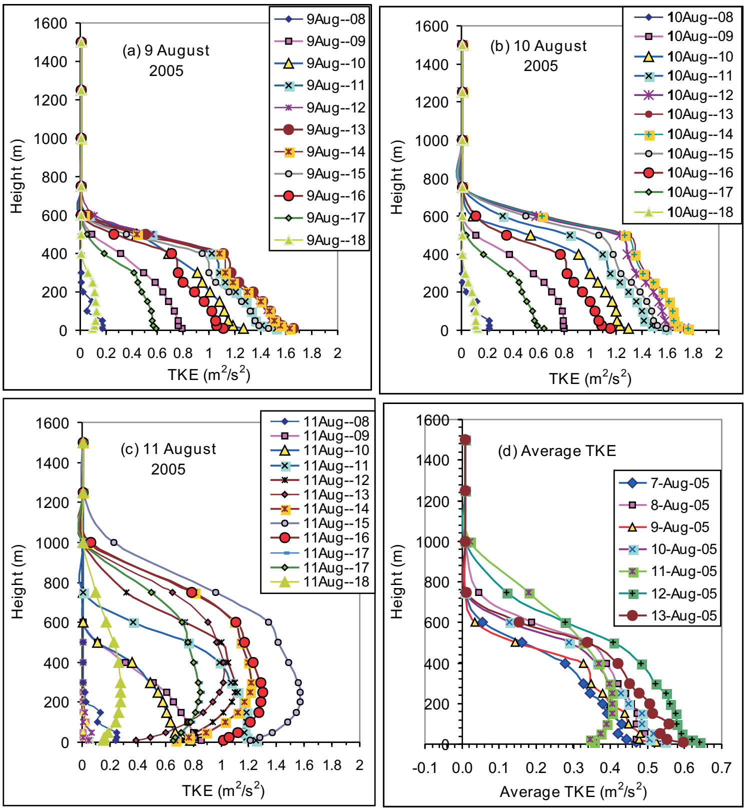

Figure 7. The TKE profiles on (a) 9 August, (b) 10 August, and (c) 11 August 2005. The average daily TKE is shown in (d).

lometer of the planetary boundary layer associated with low turbulence and suppressed convection increased the levels of pollutants during the height of the pollution period. During nighttime, the low hourly TKE profiles were associated with the weak wind speeds of land breeze circulation. The simulation of low level wind condition is a problem that has yet to be resolved by TAPM, where the low heat flux under stable nighttime conditions produces large errors in the wind predictions (Luhar et al., 2007), and as shown by the results of this study where the low level wind speeds were overpredicted.

This study did not investigate the dispersion characteristics of the model due to area of investigation that was bounded by the 3 km grid, and the emission sources did not fall within the grid area, which limits the inclusion of all transboundary sources of emission. Further studies will include use of a larger domain area to include the sources of pollutants from Sumatera and tuning of several model parameters for equatorial applications.

The weak strength of the low level winds in the equatorial region is not conducive in transporting the smoke and pollutants from the burning areas. The dominance of the recirculation features of the land and sea breezes within the lowest kilometer of the boundary layer, in addition to the topography of Peninsular Malaysia hindered further eastward transportation of any polluted air. Based on the mesoscale meteorological modeling performed in this study and by Mahmud (2009), it can be suggested that there are some local low level weather patterns such as the stagnant wind conditions, anomalous zonal winds during a major El Nino event or the presence of the wind divergence that are not favourable for biomass burning. The different national Meteorological Departments in the neighbouring countries could assist the policy makers in providing advice against open burning when the unfavourable low level mesoscale meteorological conditions exist or are predicted.

Clearly another way to mitigate the transboundary haze conditions is to ban or reduce the numbers of widespread and intense open burning. The activities of the farmers who engage in biomass burning should be monitored by the local authorities so that widespread burning would not occur at the same time. Prescribed burning in a controlled manner where the individual farmers or plantation estate managers engage in a programme conducted by the local authorities is perhaps a way forward. The cooperation between the local authorities and farmers should be fostered where burning could be performed in a timely manner and in small amounts, if indeed open burning is allowed. The best practice that benefits the neighbouring countries are through zero burning which is successfully applied in Malaysia.

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SAŽETAK

Prognoza mezoskalnog ekvatorijalnog vjetra u jugoistočnoj Aziji tijekom episode suhe mutnoće 2005. godine

Mahmud Mastura

Još i danas u jugoistočnoj Aziji poljoprivrednici spaljuju zapuštene i obrasle dijelove tla. Prilikom izgaranja biomase stvaraju se onečišćujuće tvari koje se na primjer advektiraju od Sumatre prema zapadnoj obali Poluotočne Malezije (tzv. Malaja) tijekom jugozapadnog monsuna što može uzrokovati nepovoljne učinke na zdravlje tamošnje populacije. U ovoj studiji se koristi TAPM (model onečišćujućih tvari) za prognoziranje mezoskalnih karakteristika u graničnom sloju u ekvatorijalnom okruženju koji okružuje otok Sumatru i Poluotočnu Maleziju tijekom razdoblja izgaranja u kolovozu 2005. kada je prevladavala postojana suha mutnoća.

TAPM je uglavnom uspio generirati uspostavu uvjeta za obalnu cirkulaciju blizu zapadne obale Poluotočne Malezije s umjereno visokim indeksom slaganja od 0.87 i 0.60 za zonalnu i meridionalnu komponentu vjetra, čak i bez asimilacije lokalnog vjetra. Jaki jugozapadni pasati koji se javljaju tijekom dana nad Malajskim prolazom su povezani sa smorcem dok su slabi jugoistočni pasati simulirani od 19:00 h po lokalnom vremenu do ponoći, povezani s kopnenjakom. Vertikalni profil vjetra unutar najnižeg kilometra atmosfere je pokazao da slabi jugozapadni pasati pušu od jutarnjih sati do zalaza sunca, a jači jugozapadni pasati se javljaju iznad 400 m visine.

Meteorološki parametri kao što su brzina vjetra, temperatura i vlaga su uspješno simulirani modelom s usporedivo visokim koeficijentima korelacije, niskim korijenom srednje kvadratne pogreške (RMSE) i visokim indeksima slaganja s opaženim vrijednostima.

Vertikalni profili turbulentne kinetičke energije su pokazali njeno smanjenje ispod prvih 600 m tijekom suhe mutnoće u kolovozu 2005., što se podudara s intenzivnim spaljivanjem biomase u Sumatri i povišenim nivoima onečišćenja u zapadnoj Poluotočnoj Maleziji. Analiza trajektorija je pokazala da je starost čestica onečišćenja koje su advektirane i prema kopnu i prema moru bila i do 7 dana tijekom simulacije od 7. do 13. kolovoza 2005. Postojanje recirkulacije unutar obalne cirkulacije ukazalo je na slabu sposobnost premještanja površinskog vjetra koji nije uspijevao značajnije transportirati visoke koncentracije onečišćenja nastalih uslijed izgaranja biomase na Sumatri.

Ključne riječi: ekvatorijalno područje, meteorološki parametri, izgaranje biomase, prijenos suhe mutnoće, Jugoistočna Azija.

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