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DIFFERENCE OF SEA BREEZE IN JAKARTA BETWEEN DRY AND WET SEASONS: IMPLICATION IN NO_2 AND SO_2 DISTRIBUTIONS IN JAKARTA

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Abstract

Characteristics of sea breeze in Jakarta have been investigated in both dry and rainy seasons by numerical simulations with MM5. Field observations of NO_2 and SO_2 concentrations were also performed in August, 2004, the dry season, and March, 2006, the rainy season. Obtained results are as follows: (1) in the dry season sea breeze regularly develops, while in the rainy season it appears only on one-third of the days, (2) convergence of the sea breezes in the dry season and that of the synoptic southwesterly and the sea breeze from Java sea in the rainy season were inferred as important local flow feature on air pollution transport, (3) observed horizontal and vertical distributions of SO_2 and NO_2 indicated strong influence of the flow features in both seasons such as stable stratification formed by the sea breeze in the dry season, and unstable air mass brought in by the synoptic scale southwesterly in the rainy season.

KEYWORDS: *sea breeze, air pollution transport, Jakarta, NO_2, SO_2*

1. Introduction

Jakarta, the capital city of the Republic of Indonesia, has gradually grown into one of the world's most populated cities with nearly 8.34 million people on 661.52 km^2 and an average population density of approximately 13,190 people km^{-2}. Air pollution has been a serious problem in Jakarta due to the high level of fuel consumption by transportation, households and industry.

Jakarta is in the western part of Java Island (see JK in Fig. 2c); Java Island is located at around 6° S in tropical area, and the synoptic scale wind in the area is rather weak. Thus local winds such as land/sea breeze and mountain/valley wind tend to develop, and may affect air pollution in the area. Yet, the local flow system especially sea breeze circulation in this tropical coastal city is not fully understood. Thus, this study clarifies characteristics of sea breeze circulation over western Java in dry and rainy seasons, which determine air-pollution transport over Jakarta.

As a general background for the local flow in the West Java, we will briefly describe climate in the area based on Riehl (1979). Climate in Java Island is classified roughly into two types; the

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"rainy/wet" season from November to March and the "dry" season from May to September, with few weeks in April and October for the transition periods between the dry and wet seasons. There is a clear difference of synoptic scale wind between the rainy and dry seasons; the difference may largely affect nature of the local flow in Jakarta. As shown in Fig. 1a, in rainy season two different synoptic scale winds, that is north westerly blowing from the Pacific Ocean via the equator and southwesterly from the Indian Ocean tend to form convergence zone over Java Island, thereby resulting in occasional heavy rainfall. These synoptic flows seem strongly influenced by the low pressure developed over the northern Australian continent, the low pressure area toward which air mass over Java Island flows as seen in Fig. 1b.

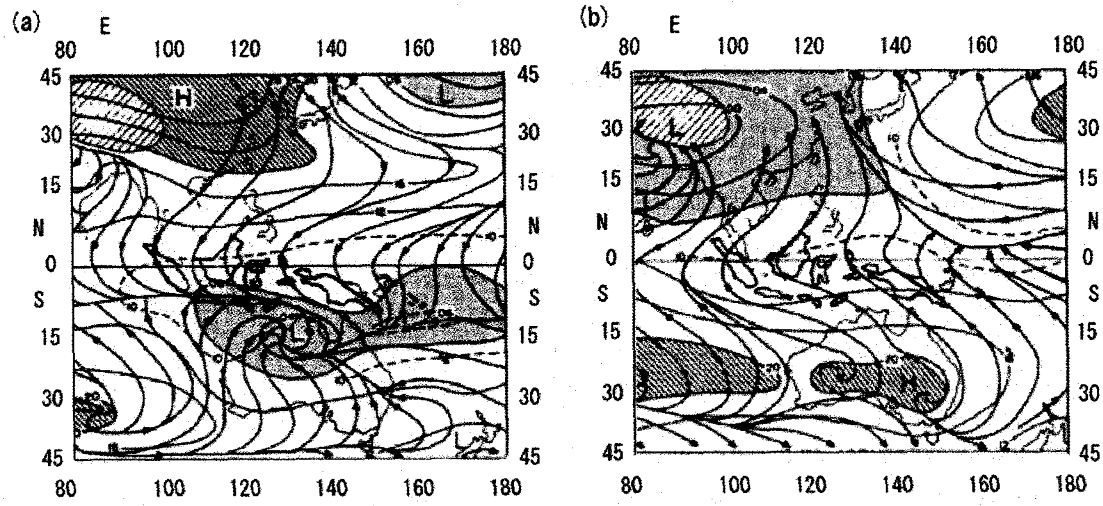

Figure 1. Surface streamlines and sea-level isobars (mb, first two digits omitted): (a) January, and (b) July. Areas with pressure above 1020 mb are shaded; below 1008 mb hatched (adapted from Riehl, 1979).

In the dry season from May to September, southeasterly dominates synoptic scale wind field over Java Island as indicated in Fig. 1b; no large scale convergence is formed, and thus precipitation is scarce. In Jakarta area, it is mostly sunny and regular development of local flows such as sea breeze can be expected.

Sea breeze has been studied mostly in the mid-/high-latitudes and partly in the tropics (see, for example, Atkinson, 1981; Hastenrath, 1991; Simpson, 1994). Though the number of studies in the Jakarta area is limited, Hadi et al. (2000; 2002) discussed sea breeze in the area by using several years' observation with a boundary layer radar (BLR; Tsuda et. al., 1995) situated at Serpong, which is 35 km inland from the coastline, and they found that sea breeze occurs most regularly in the dry season from July to October. They also studied vertical structures of wind, temperature, humidity, and turbulence before and after passage of sea-breeze front, reporting many interesting features such as intensification of sea breeze in the layer between 0.5 and 0.8 km high at Serpong after 1700 – 1800 LST. Their analysis based on data obtained with one BLR placed at 35 km inland, however, seems not to be enough for clarification of dynamical nature of the sea breeze extending from the coastal to inland areas. Thus the detailed numerical simulations of the sea breeze in Jakarta have been made in this study.

2. Methodology and Data

2.1 Calculation domain

To understand the characteristics and the development mechanism of complex local flows, numerical simulation over western Java area was performed using the Fifth-Generation Pennsylvania State University-National Center for Atmospheric Research Mesoscale Model Version 3.6 (hereafter abbreviated as MM5; see Dudhia et al., 2005 for the detail of the software). The simulations were done for 4-9 March 2001 in the rainy season and for 6-19 August 2004 in the dry season. The domain system used in this calculation is a triply nested two-way interacting mesh. The physical processes applied in the simulations are summarized in Table 1. Each domain has 23 vertical grid points for the depth from the earth's surface to 100 hPa. The framework of meteorology in larger scale was provided every 6 hours by the operational archive of ECMWF with a resolution of 0.5° x 0.5°. In each calculation we used a land-use map with 25 categories and 30 second horizontal resolution by United States Geological Survey (USGS); furthermore, we modified the land use map by referring newly urbanized area in Jakarta.

Surface measurement from Geophysics and Meteorology Agency of Jakarta at Sukarno Hatta Airport (SH) was used to compare with the numerical calculation; see Figs. 2b, d for the location.

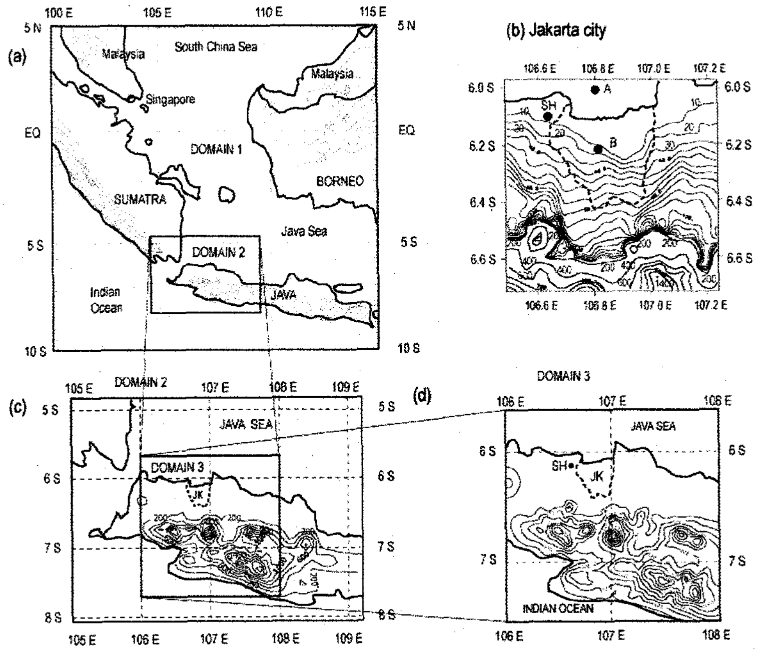

Figure 2. Domain system for MM5 simulation in Western Indonesia area: (a) domain 1, (c) domain 2, and (d) domain 3. Figure 2b shows detailed topography in Jakarta area; SH shows Sukarno Hatta Airport where meteorological data were collected; diurnal variations of temperature at the points A and B will be discussed in Fig. 6. One degree is about 111.19 km for meridional direction, and 110.58 km at 6°S for zonal.

Table 1. Physical processes applied in the simulations#.

Domain	Grid size and number of grids	Subgrid scale cumulous convection	Boundary layer parameterization	Cloud micro-physics	Long wave radiation	Surface
1	27 km (61x61)	Grell	MRF	Mixed-phase (Reisner-1)	RRTM	5-layer
2	9 km (49x58)	None	MRF	Mixed-phase (Reisner-1)	RRTM	5-layer
3	3 km (79x85)	None	MRF	Mixed-phase (Reisner-1)	RRTM	5-layer

See Fig. 2 for the domains, and see Dudhia et al. (2005) for the parameterizations expressed with Grell, MRF, Mixed-phase, RRTM, and 5-Layer. "5-Layer" denotes "Five-Layer Soil Model".

2.2 Field Observation

NO_2 and SO_2 measurements were performed by using passive samplers distributed at 50 locations over the whole Jakarta City in the dry and rainy seasons. Vertical profiles of NO_2 and SO_2 were also obtained at one location with a tall building in the city center. All the measurements were made to get both one-day and one-week averaged concentrations.

3. Results and Discussion

3.1 Characteristic of local flow in the dry and rainy seasons

(1) Evaluation of the accuracy of calculated meteorological variables

Figure 3 compares calculated temperature and wind with observations at Sukarno Hatta (SH) station for 6-11 August 2004 in the dry season and for 5-9 March 2001 in the rainy season; see Figs. 2b,d for the SH location. As illustrated in Figs. 3a, c, in the dry season the calculation relatively well reproduces observed diurnal variation of surface temperature with a little underestimation during the nighttime. In the rainy season the observed temperature shown in the left panel of Fig. 3c depicts rather large variation from day to day probably because of frequent change among cloudy, rainy, and sunny days. The calculated temperature also shows such characteristics, though it sometimes fails to follow the observed diurnal variation; for example, on the cloudy/rainy day the daily maximum temperature is low, while not on the sunny day. Correlation between the calculated and observed temperatures is good in the dry season (the left panel in Fig. 3b) and acceptable in the rainy season (the left panel in Fig. 3d); a significant scatter can be seen in the rainy season (Fig. 3d).

Diurnal variations of observed wind velocity and direction are also simulated acceptably well in the dry season (see the center and right panels in Figs. 3a,b), showing the diurnal alternation of wind characteristic of sea/land breezes; that is, northerly in the daytime and southerly at night. In the rainy season the calculation tends to overestimate wind velocity during 5-6 March 2001 as in the center panel of Fig. 3c. In the rainy season, the range of diurnal variation of the observed wind direction at SH is rather small. However, the wind direction still shows a diurnal change such as NW in the

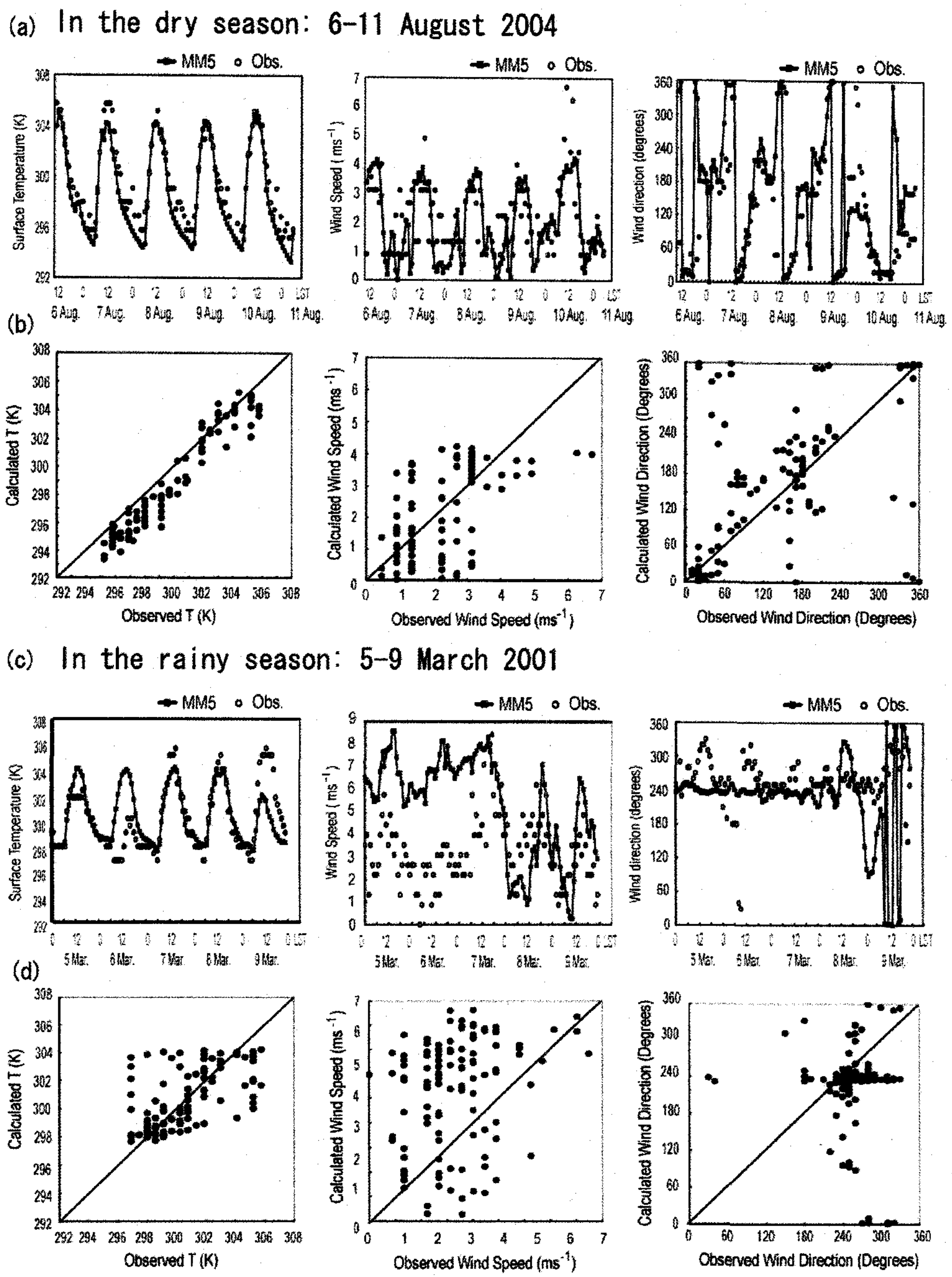

Figure 3. Comparison of calculated and observed meteorological variables of temperature and wind at Sukarno Hatta Airport (SH in Figs. 2b,d): (a) and (b) for the dry season (6-11 Aug. 2004), and (c) and (d) for the wet season (5-9 Mar. 2001). Temperature, wind speed, and wind direction are shown in the panels from left to right in Figs. 3a and c, respectively. Figs. 3b and d are the scatter plots for these observed and calculated variables. In Figs. 3a, c, the calculation results are denoted by solid line and the observations are with circles (o).

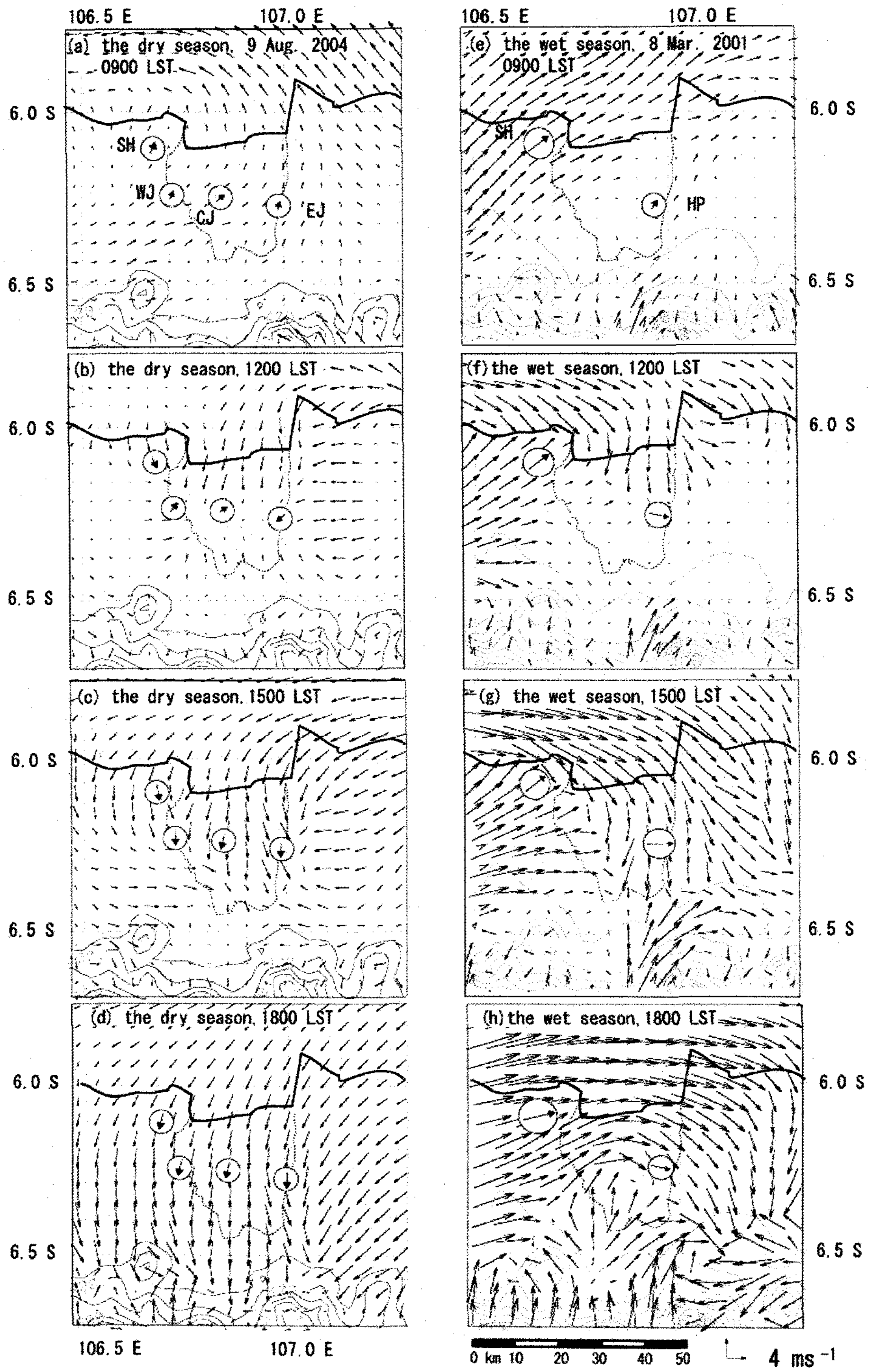

Figure 4. Comparison between calculated and observed winds: (a)-(d) on 9 Aug 2004, and (e)-(h) on 8 Mar 2001. The weather stations are: SH (Sukarno Hatta), WJ (West Jakarta), CJ (Central Jakarta), EJ (East Jakarta), and HP (Halim P). The arrows encircled show the observed winds, and the others are the calculated.

daytime (wind from Java Sea; semi sea-breeze mode) and SW at night (wind from inland area). The calculated wind direction largely fluctuates only on 9 March when the calculated wind speed is weak (see the center and right panels in Figs. 3c,d); thus we judged the correlation between the calculated and the observed wind is acceptable in terms of both velocity and direction on 8 March 2001.

To further examine accuracy of the MM5 output winds, available observed winds were plotted on the map of the calculated wind field in Fig. 4. Figures 4a-d are for 9 August 2004 (the dry season), and Figs. 4e-h for 8 March 2001 (the rainy season). Figure 4 suggests the simulation for 9 August 2004 shows very good performance, while that for 8 March 2001 in the rainy season is not so good in the western part of Jakarta at 1200 and 1500 LST. One possible explanation for this worse performance in the rainy season may be the cloud microphysical processes are not yet well modeled, though we applied almost the most advanced module available (see Table 1).

(2) Synoptic scale wind modified by topography in the lower layer over Java Island

In the previous chapter, we summarized general characteristics of the climate in Java Island based on the literature (Riehl, 1979). Here we briefly look at the synoptic scale winds on the specific days of 9 August 2004 in the dry season and 8 March 2001 in the rainy season on which days we will analyze diurnal variation of the winds later in 3.1 (5).

Figure 5a shows the synoptic scale wind at 3 km AGL, at 1500LST on 9 Aug 2004 (the dry season), was easterly and is consistent with that in Fig. 1b, while the same synoptic scale wind but on 8 March 2001 (the rainy season) in Fig. 5b indicates SSW was dominant. This SSW in Fig. 5b is also consistent with the wind in Fig. 1a; that is, the convergence line, which was formed by the synoptic scale SSW and over Java Island found in Fig. 1a has already moved northward, the SSW wind, which generated the convergence line together with NW, covers the entire island in Fig. 5b.

Wind in the lower atmosphere, for example, below 3 km AGL (above ground level) over the island (Figs. 5c, d) is modified thermally and mechanically by the local topography such as shape of coast line and location of mountains. In the dry season, the synoptic scale southeasterly is blocked below the height of the mountains extending along the south coast of the western Java Island; altitude of the highest mountain is 3019 m and the average height of the mountains is about 1500 m. Thus the plain area on the north of the mountains has no prevailing synoptic wind, and local flows generated by the local topography tend to develop there later as shown in Fig. 7. During the daytime with strong horizontal differential heating northerly has developed in the northern part of Java Island (at 1500 LST in Fig. 5c) and the synoptic southeasterly is separated around the mountains, and channeling of the flow through canyons and valleys can be found in the southern part of the western Java Island (Fig. 5c).

At 1500 LST on 8 March 2001 (Fig. 5d), in the lower atmosphere the synoptic scale southwesterly is blocked by the mountains along the south coast of Java Island but the wind partly flows around the west end of the mountains and intrudes into the northern part of the Western Java Island. Fig. 5d also shows the northwesterly and northerly develop; these winds can be regarded as sea breezes because of the nature of their directions' diurnal changes.

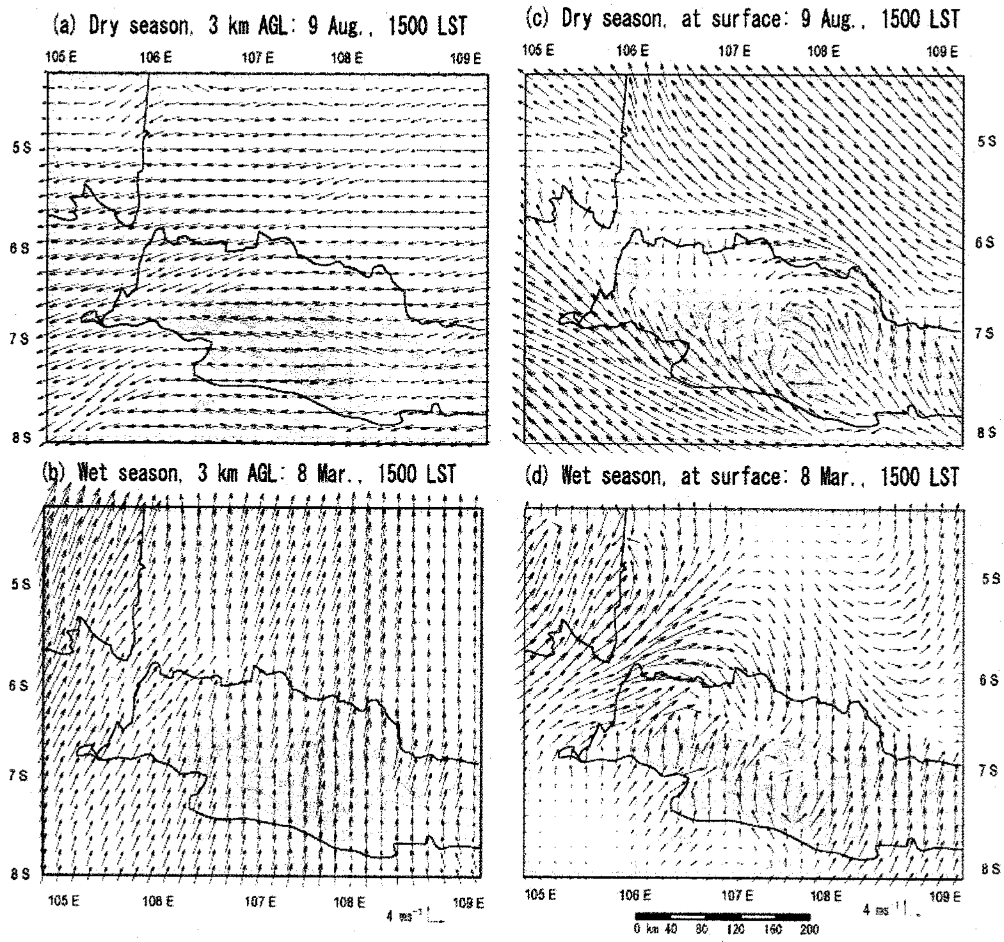

Figure 5. Calculated wind fields over the Western Java at 1500 LST in both the dry season (9 Aug. 2004), (a) and (c), and the rainy/wet season (8 Mar. 2001), (b) and (d): (a) and (b) at 3 km AGL, and (c) and (d) at the earth's surface level.

(3) Diurnal variations of temperatures over both land- and sea-surfaces

Figure 6 shows diurnal variations of calculated temperatures near the surfaces at 12 km off the coast and 12 km inland (see point A and C in Fig. 2b for the locations). In the dry season (Fig. 6a) the maximum difference of the daytime surface temperature between land and sea varied from 4.4° C to 5.5° C during 7 to 10 August. As in Fig. 6a, the diurnal variation of the temperature in the dry season is stable and does not change largely from day to day. Hence periodic development of sea breeze is inferred.

In contrast, in Fig. 6b (the rainy season) the diurnal pattern of temperature over the land surface varies daily because of occasional cloudiness and precipitation. For example, on sunny day, 5 March, the difference of the daily maximum temperature between the land and sea surfaces is about 5.5 °C, while it is about only 2.5°C on cloudy day of 6 March, thus indicating that sea breeze can occasionally develop in this season.

(4) Diurnal variation of horizontal flow field

In this subsection we will discuss characteristics of the sea breezes in the dry and rainy seasons.

The sea breeze occurrence in Jakarta shows clear difference in its frequency between the dry and rainy seasons. For example, in March 2001 in the rainy season, the sea breeze was found to appear on about 11 days of 31 days based on the wind observations at SH and HP (see Fig. 2e for SH and HP). This corresponds to two days' sea breeze formations in the 6-day simulation, 4-9 March 2001. Thus we estimated the sea breeze occurrence for about one-third of the days in March 2001 in the rainy season. The "sea breeze" was judged by characteristic temporal variation of the winds in the coastal area of Jakarta. Similar analysis also showed that the sea breeze developed everyday in August 2004.

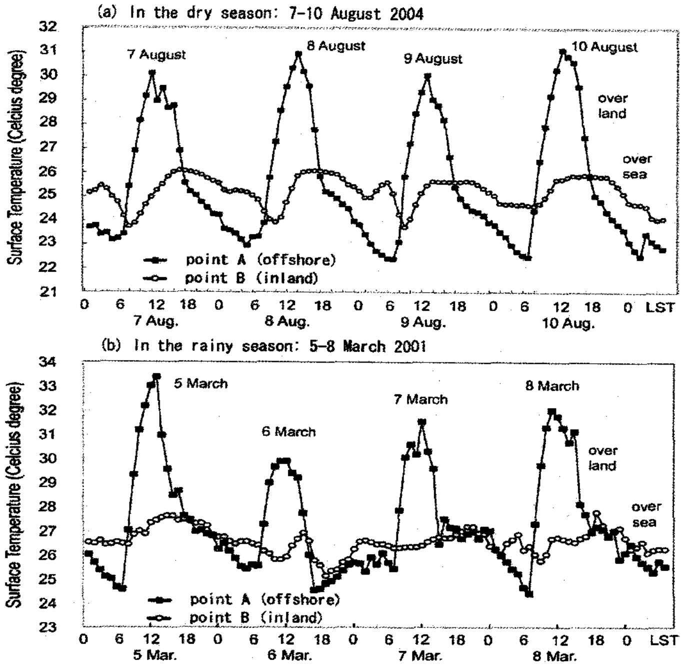

Figure 6. Diurnal variations of calculated temperature at land and sea surfaces: (a) the dry season (7-10 Aug. 2004) and (b) the wet season (5-8 Mar. 2001). The solid circles are for land surface (at point B in Fig. 2b) and the open circles are for sea surface (at point A in Fig. 2b).

As described in 3.1(2), in the dry season the synoptic southeasterly is blocked in the lower atmosphere by the mountains running from west to east along the southern coast line, and Jakarta area has very week synoptic wind. Hence sea breeze tends to develop as shown in Fig. 5c.

On the other hand, in the rainy season the synoptic scale weather is generally unstable because of the large scale convergence line formed by southwesterly and northwesterly (see an averaged January situation in Fig. 1a), which situation often causes cloudy or rainy day in Jakarta. In March 2001, this synoptic scale convergence line already moved northward and thus the Java Island was covered by the synoptic scale southwesterly. In this stage, the synoptic southwesterly intrudes into the northern plain in West Java through the mountains gap as seen in Fig. 5d, and when this intruding wind is strong, the sea breeze in Jakarta is totally suppressed. It may be, however, noted that sea breeze develops more frequently in the northern plain of the central Java where the synoptic scale southwesterly and southerly are largely interrupted by the high mountains (see Fig. 5d).

Based on the analysis above, we can roughly conclude sea breeze in Jakarta area develops on

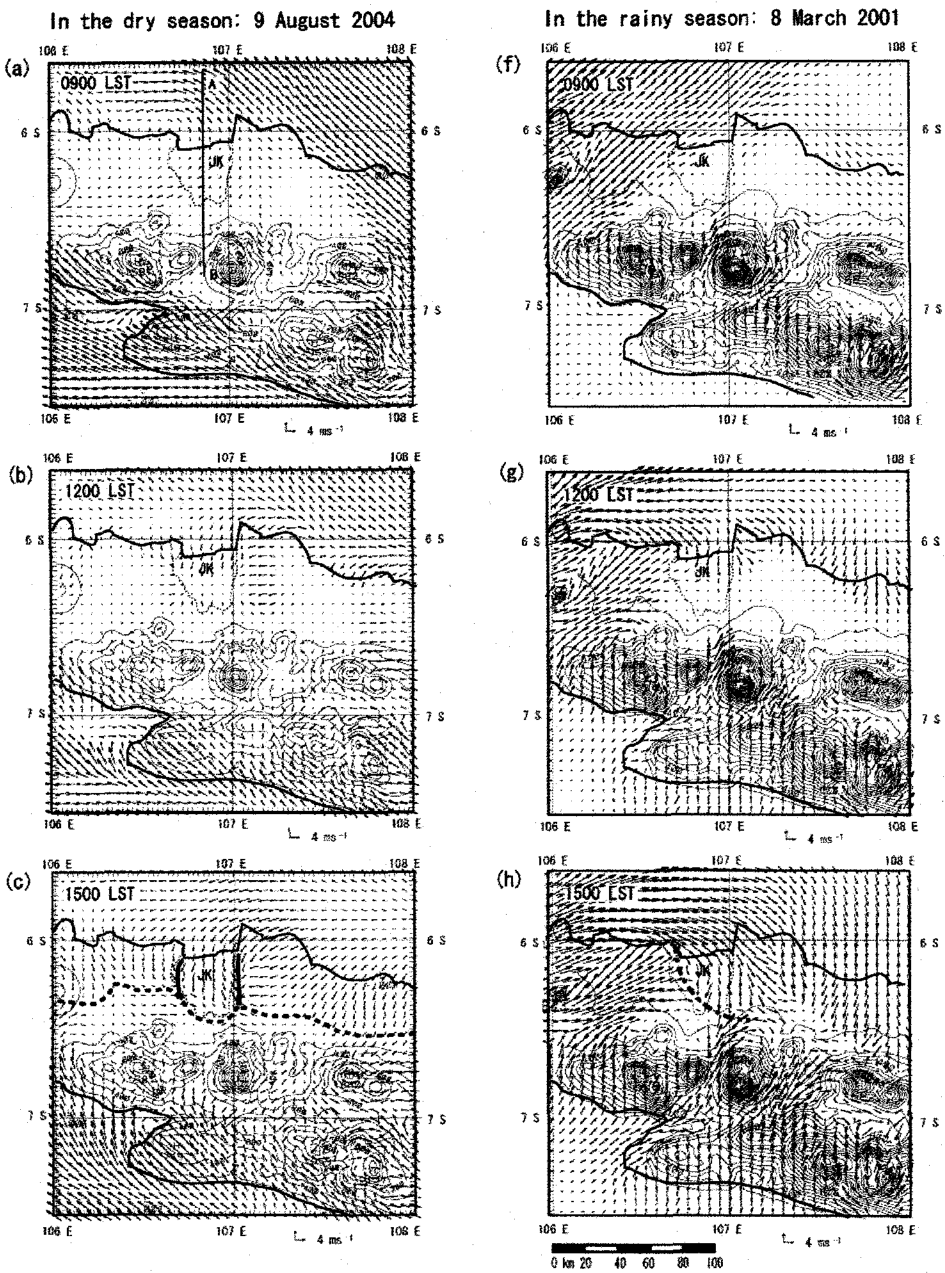

Figure 7. Temporal change of calculated surface winds on sea breeze days: (a)-(f) on 9Aug 2004 (the dry season) and (g)-(i) on 8 March 2001 (the rainy season); winds are plotted every 3 hours from 0900 to 2100 LST. The dashed line in Fig. 7c shows the sea breeze front and the solid lines as parts of the dashed line denote the convergence of the sea breezes from different coasts near Jakarta (JK). The dash-dotted line in Fig. 7i shows the convergence of the synoptic southwesterly and the sea breeze. Vertical cross sections of temperature and wind along the line AB in Fig. 7a are discussed in Fig. 8.

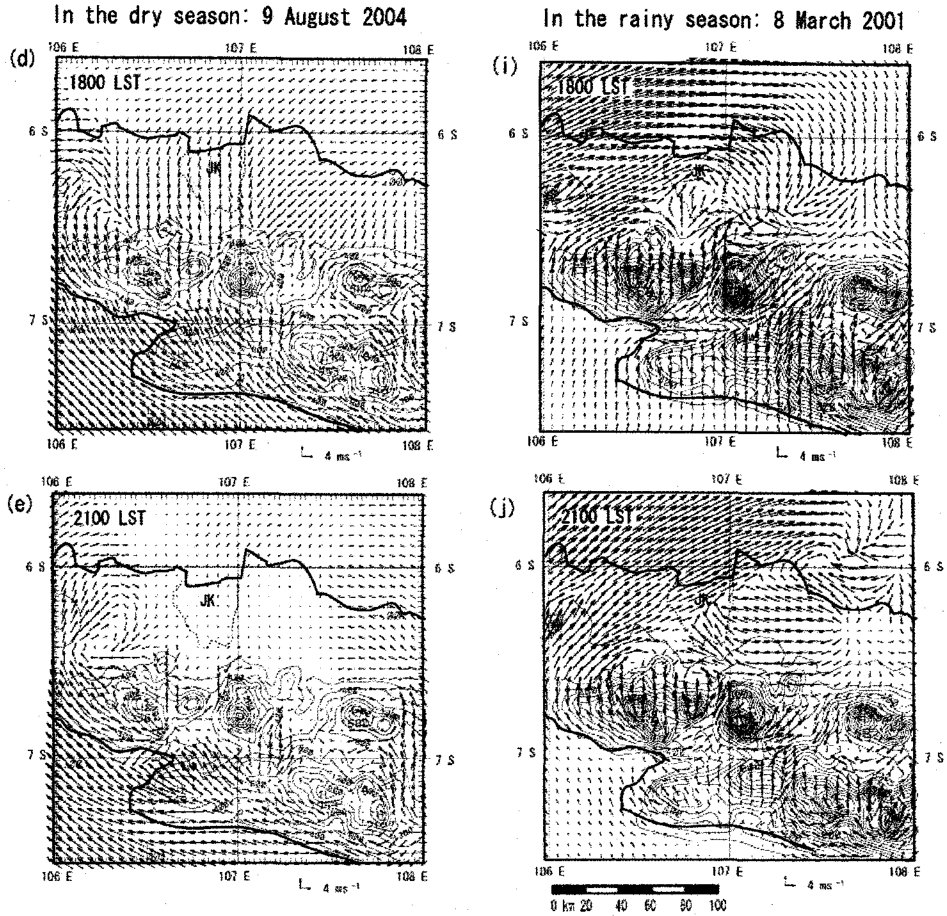

Figure 7. Continued.

almost all days in the dry season and about one-third of the days in March in the rainy season. Thus we chose one day each from the dry and rainy seasons to examine diurnal variation of flow field on typical sea breeze day. Temporal development of surface wind on these days is plotted in Figs. 7a-f for 9 August 2004 and Figs. 7g-l for 8 March 2001.

The local flow over Jakarta in the morning of both the dry and rainy seasons is characterized by weak surface wind, as shown in Figs. 7a, g. In the analyzed days of the dry season, the sea breeze usually started between 1000 and 1100 LST in the coastal region of Jakarta. At the same time flow heading from rural area to the Jakarta city center was generated because of heated urbanized surface in Jakarta (see Fig. 7b). Thus a convergence zone was formed over Jakarta, and it is found in satellite images that convective clouds frequently appear.

On the other hand, in March 2001 in the rainy season, sea breeze develops (see Fig. 7h) only when the synoptic scale southwesterly is weak and does not directly dominate the flow field in Jakarta. On the days for the sea breeze found, it started about 1200 LST.

Distance of sea breeze penetration from Java Sea showed large difference between the dry and rainy seasons. In the dry season, the sea breeze over Jakarta became strong throughout the afternoon. At 1500 LST in Fig. 7c, the sea breezes developed over the entire northern coastline in West Java and their fronts reached at about 30 km from the coastline as shown in Fig. 7c. Figure 7c also shows that in Jakarta, three kinds of sea breezes were generated, i.e. one from the gulf of Jakarta and the others from two broad peninsulas located at the east and west of the gulf, and they form two convergence lines illustrated with thick solid lines in Fig. 7c. As will be discussed later, these convergence lines largely regulate air pollutant's distribution in Jakarta. By 1800 LST (Fig. 7d), the sea breeze front arrived at the foot of the southern mountains and the sea breezes entirely covered the northern plain. By 1900 LST (not shown) the sea-breeze circulations gradually started to decay and ceased around 2000 LST. At 2100 LST (Fig. 7e) almost no wind was found in Jakarta.

In contrast, in the analyzed days of March 2001 in the rainy season the sea breeze in Jakarta stopped before 1800 LST as illustrated in Fig. 7i. Synoptic WSW wind, the southerly and southwesterly did not allow sea breeze's penetration (Figs. 7h, i). Though the sea breeze covers the eastern Jakarta at 1500 LST (Fig. 7h), it could not further penetrate inland because the synoptic scale southwesterly, which blew through the gaps in the southern mountains, suppressed the sea breeze (Fig. 7h). A convergence line between the synoptic scale wind and the sea breeze was formed (see the dash-dotted line in Fig. 7h), and it divided Jakarta into two parts; the western part was affected rather by marine air from Indian Ocean, which was brought in by synoptic south-westerly, while the eastern part was covered by the air from the Java Sea.

(5) Diurnal variation of the vertical structure of the sea breeze

Vertical structures of wind and potential temperature in sea breeze situation were examined. Figure 8 illustrates vertical cross sections of wind and potential temperature along line A-B in Fig. 7a from 1300 to 1800 LST on 9 August 2004 in the dry season and on 8 March 2001 in the rainy season.

Figure 8a shows an early stage of the sea breeze development at 1300 LST on 9 Aug 2004; the sea breeze covered only half of the Jakarta city, with its front being located at 15 km from the coast. In Fig. 8a the upward flow at the sea breeze front is indicated as largely enhanced by the "urban" wind blowing from rural area toward the city center, hence resulting in the height of the front with more than 2 km. In Fig. 8a, the other local flows such as up-slope and valley winds are also found at 60 km inland. Between the areas of the "urban" wind and the up-slope wind a mixed layer with weak wind is found to develop.

By 1500 LST (Fig. 8b) the "urban" wind was overcome and absorbed by the sea breeze. Then the sea-breeze front further advanced inland, and the whole Jakarta city was covered by marine air after 1600 LST (not shown). During these hours the convective mixed layer with weak wind existed between the sea breeze and up-slope wind areas.

In the dry season the sea breeze started to merge with the up-slope wind at 1700 LST (not shown). Finally the marine air reached at the hill of about 60 km from the coast at 1800 LST (Fig. 8c). Then, the sea breeze gradually reduced its wind speed. By 2100 LST (not shown) the sea breeze stopped. By 2400 LST (not shown) land breeze started and continued until 0700 LST.

Intrusion of the sea breeze into Jakarta area was suggested to generate complex vertical structures of wind and temperature such as sea breeze front, thermal internal boundary layer (TIBL), return flow,

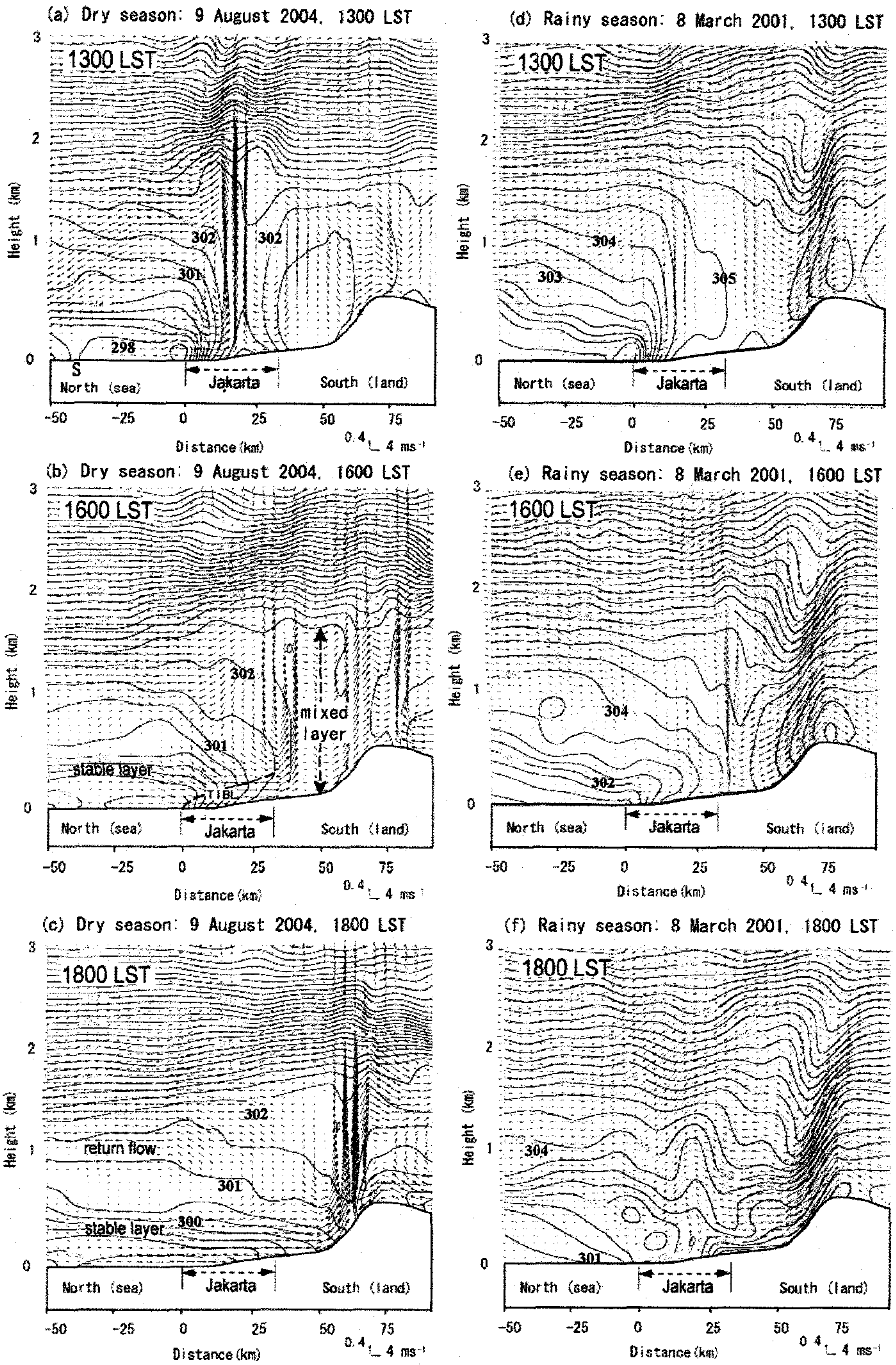

Figure 8. Vertical cross sections of potential temperature (K) and wind vectors along line A-B (see Fig. 7a) at 1300, 1600, and 1800 LST on 9 August 2004 (Figs. 8a-c) and 8 March 2001 (Figs. 8d-f). Contour interval is 0.5 K.

and stable layer at the top of sea breeze layer. As illustrated in Figs. 8b, c, in the coastal Jakarta the upper part of the sea breeze layer was stably stratified with its depth of about 200 m extending from 200 m to 400 m high, while the depth of the sea breeze layer itself was about 400 m. This stable layer was formed as: an original stable stratification of the marine air was enhanced by the subsidence associated with sea breeze circulation behind the sea breeze front. Figures 8b,c also suggest that behind but close to the sea breeze front, the depth of sea breeze layer can be increased up to 0.8 to 1 km AGL in appearance because of the entrainment of upper air associated with strong upward flow at the front; this vertical profile of the north-south wind component is qualitatively supported by an observational study made at about 35 km south of the Jakarta coast on 11 October 1993 (Hadi, et al., 2000).

The thermal internal boundary layer (TIBL) was also formed in the lower part of sea breeze layer as shown in Fig. 8b, as an example; this is also qualitatively supported by Hadi et al. (2000) which showed an unstable layer in the lower part of the sea breeze layer, that is, the layer with negative value of Brunt Väisälä frequency squared, N^2.

As described above, in March 2001 in the rainy season the sea breeze was estimated to develop only on one-third of all the days since the synoptic scale southwesterly suppresses development of the sea breeze. This southwesterly may modify the sea breeze in Jakarta and form the convergence line with the sea breeze as shown by the dash-dotted line in Fig. 7h; the convergence further suggests to result in upward flow and thus lead to the vertical structures of potential temperature and wind at 30 km from the coast line at 1600 LST (Fig. 8e).

At 1800 LST in the late afternoon (Fig. 8f), the sea breeze in Jakarta is indicated to totally disappear. Though figure is not shown, during the nighttime strong down-slope winds enhanced by the synoptic southwesterly and southerly covered the Jakarta area in the rainy season; the situation was very different from the dry season in which weak mountain wind and land breeze were formed.

3.2 Effect of Local Flow on Air Pollution Transport in Jakarta

(1) Field observation and estimation of emission source distribution for SO_2 and NO_2

To see effect of the flow system in Jakarta, including sea breeze, on air pollution transport, we conducted field observations for NO_2 and SO_2 over the Jakarta city using passive samplers both in August 2004 in the dry season and in March 2006 in the rainy season.

In the observation of August 2004, both one day (9 August; a weekday) and one week (10-17 August) average concentrations of NO_2 and SO_2 were measured with passive samplers distributed at 50 locations over Jakarta; the same samplers by Green Blue Co. were used in the previous study (see Kitada and Regmi, 2003, and Regmi et al., 2003 for detail).

Similarly, in the March 2006 observation, we measured NO_2 and SO_2 also as both one day (6 March; a weekday) and one week (8-15 March) average concentrations; the passive samplers were distributed at the same locations as the August 2004 observation.

To understand relation between the observed concentrations and their emission sources, source-distributions of NOx and SOx in Jakarta were investigated. The obtained emission source distributions in 2004 are plotted in Figs. 9a, b for NOx and SOx, respectively; the unit is in ton (as

SO_2 or NO_2) km^{-2} $year^{-1}$. The distributions in Fig. 9 were estimated by using the emission sources in 1995 by JICA and Bapedal (1997) and GDP growth factor of Jakarta from 1995 to 2004; energy consumption in the sectors of transportation, industry, household and office was considered for the estimation.

In SO_2 emissions in Fig. 9b, power plants and other industries are dominant sources, which are situated in the west and the east of Jakarta as well as in the coastal area. The largest source strength is about 500 ton SO_2 $km^{-2}year^{-1}$. In the city center of Jakarta, car emission is an important source with no significant industrial emissions (see Table 2).

The highest NOx flux of 1000 ton-NO_2 km^{-2} $year^{-1}$ is found in northern coastal Jakarta where power plants and industries located. The largest contribution to the NOx emission, however, comes from road traffic with its highest rate at about 600 ton-NO_2 km^{-2} $year^{-1}$. Total emission in Jakarta city is summarized in Table 2.

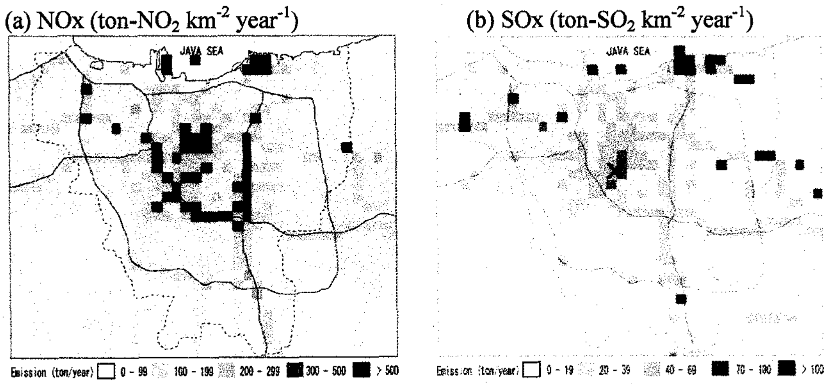

Figure 9. Estimated emissions of (a) NOx and (b) SOx in Jakarta in 2004. The symbol "X" in Fig. 9b shows an office building where the vertical observations were conducted.

Table 2. Estimated emissions of air pollutants*: (a) the city of Jakarta and (b) the Greater Jakarta# in 2004 (ton $year^{-1}$).

	NOx (as NO_2)	SOx (as SO_2)	HC
(a) Jakarta City			
Transportation	99,181 (77.7%)	8,815 (24.4%)	95,522
Factories	25,799 (20.2%)	25,050 (69.3%)	no data
Household/office	2,676 (2.1%)	2,276 (6.3%)	no data
Total	127,656 (100%)	36,141 (100%)	95,522
(b) Great Jakarta Area			
Transportation	142,414 (74.0%)	12,657 (18.4%)	137,159
Factories	44,198 (23.0%)	51,236 (74.3%)	no data
Household/office	5,954 (3.0%)	5,064 (7.3%)	no data
Total	192,566 (100%)	68,958 (100%)	137,159

*See text for the method of estimation; # The Greater Jakarta includes the city of Jakarta and the surrounding municipalities of Bogor, Depok, Tangerang, and Bekasi.

(2) Characteristic flow system and its possible effects on air pollution transport

As we discussed earlier, there is large difference of wind system in Jakarta between the dry and rainy seasons. In the dry season, synoptic scale wind is the southeasterly, which is blocked by the high mountains, and thus the lower atmosphere over Jakarta, located to the north of the mountains, is not largely affected by the synoptic scale wind. Thus the local flow, i.e. sea breeze, regularly develops in Jakarta.

On the other hand, in the rainy season the synoptic scale southwesterly and southerly frequently intrude into the Jakarta area through mountains gaps. Hence the sea breeze in the area appears only on one-third of all the days, and its development is rather limited within the northeastern part of Jakarta because of the strong influence of the synoptic southwesterly.

With these differences in mind, we will first discuss possible effect of the sea breeze in the dry season on air pollution transport. Sea-breeze is widely known to play an important role in the transport of air pollutants by forming characteristic meteorological situation such as sea-breeze front, a large circulation consisting of sea breeze at lower layer and its return flow at upper layer, and the thermal internal boundary layer over land surface near coast (e.g., Kitada, 1987; Kitada and Kitagawa, 1990). Thus, it can be expected in the dry season that the pollutants from Jakarta will be released into fully-developed sea-breeze layer and move with sea breeze front. On the other hand, the flow field influenced by the synoptic scale wind, i.e., the southwesterly, may be important in the air pollution transport.

(3) Observed- and calculated-fields of NO_2 and SO_2: horizontal distributions

Observed spatial distributions of NO_2 and SO_2 at the ground level are plotted in Figs. 10a-d for the dry season and Figs. 10e-h for the rainy season.

One-day observed NO_2 in Fig. 10a (the dry season) shows clear effect of sea breezes on the day, indicating the sea breezes from several directions merge in the southern part of Jakarta and thus the pollutant tends to gather in central Jakarta. On the other hand, in the wet/rainy season, the sea breeze develops only in the northeastern part of Jakarta (see Figs. 7h, i) since the southwesterly limits the development, and thus one day averaged winds are very weak for almost whole Jakarta area (see Fig. 10e). Hence the concentration fields of NO_2 (Fig. 10e) and SO_2 (Fig. 10f) more correlate with the corresponding emission source distributions. It may be noted that the winds plotted on Figs. 10e-g are from 4-9 March 2001 and not from 6-15 March 2006. Thus these winds may be regarded as examples of a "sea breeze" day in March.

One week averaged wind field is very different between the dry and rainy seasons. In the dry season, since almost same diurnal variation of wind field is repeated everyday, the one-week-averaged wind field in Figs. 10c, d is very similar to the one-day-averaged shown in Figs. 10a, b. On the other hand, in the rainy season, the synoptic scale southwesterly, which conceals weak sea breezes developed in two days among one week, dominates one-week-averaged flow field as shown in Figs. 10g, h.

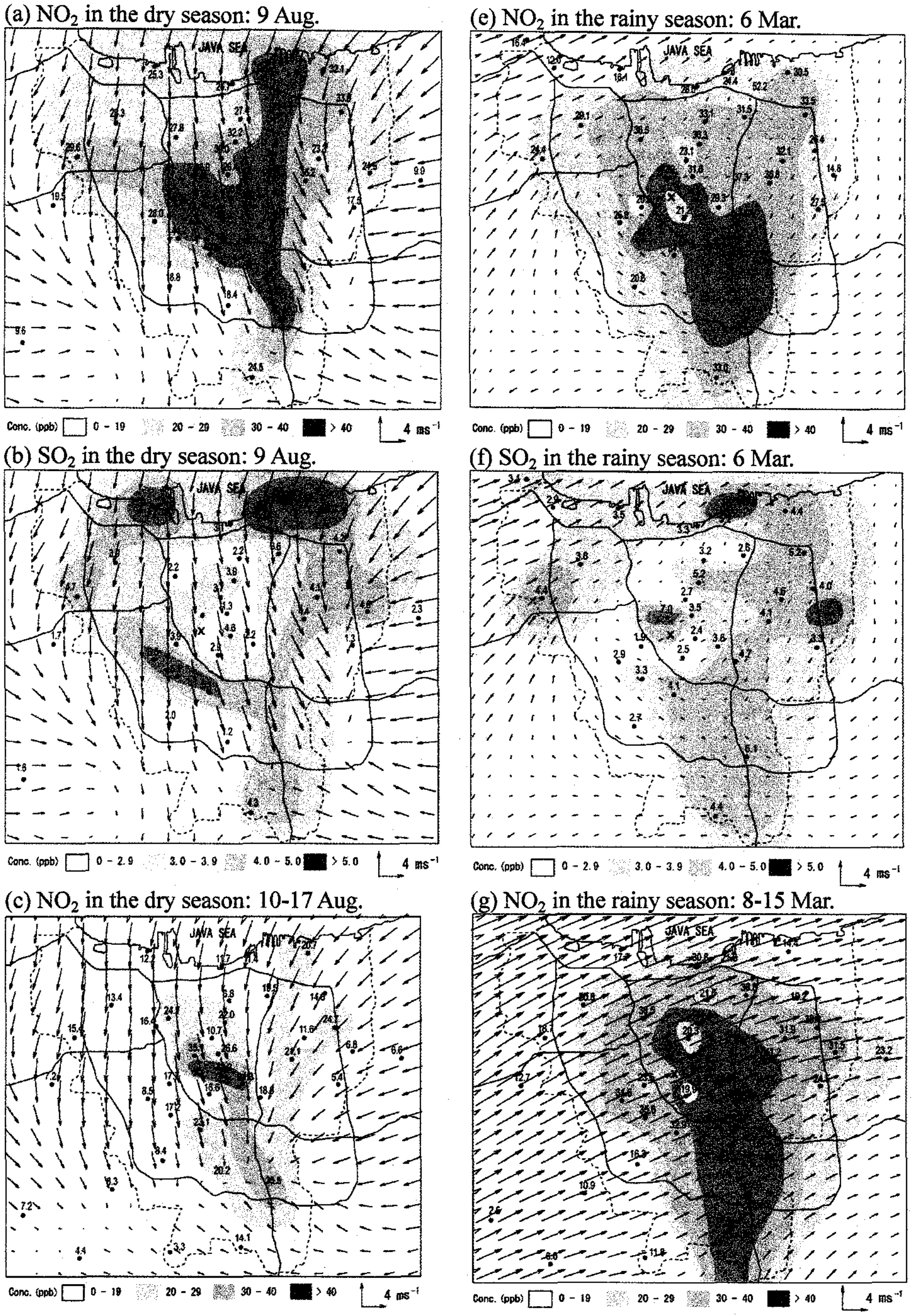

Figure 10. Observed NO_2 and SO_2 in ppb over Jakarta area: Figs. 10a,b and Figs. 10c,d are for 1 day (9 Aug. 2004) and 1 week (10-17 Aug. 2004) observations in the dry season, respectively; similarly, Figs. 10e, f and Figs. 10g, h are for 1 day (6 Mar. 2006) and 1 week (8-15 Mar. 2006) in the wet season. Winds are either one day or one week averaged; however, note that those in Fig. 10e,f and in Fig. 10g,h are from 8 March 2001 and from 4-9 March 2001, respectively.

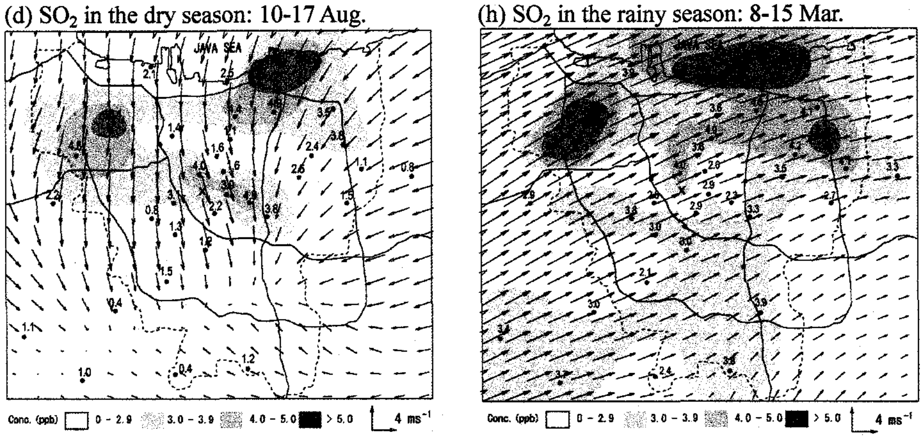

Figure 10. (continued.)

In Figs. 10c,d,g,h, it is notable that one-week-averaged NO_2 and SO_2 concentrations are higher in March (the rainy season). One of the possible reasons for this is reduction of solar radiation in the rainy season; meanwhile, it is known that there are no significant differences in fuel consumption in Jakarta between the dry and rainy seasons (BPS, 2004). The reduced solar radiation may decrease chemical oxidation rates of $NO_2 \rightarrow HNO_3$ and $SO_2 \rightarrow SO_4^{=}$, hence possibly resulting in higher NO_2 and SO_2 concentrations. Figure 11 shows that the results of the preliminary chemical calculations in which solar conditions in March and August in Jakarta are modified by changing cloud cover percentage from 0 to 80% and sensitivities of NO_2 and SO_2 concentrations to the cloud cover are examined; the chemistry model used in the simulations is sub-module of a chemical transport model (Kitada et al, 2000; Kitada and Regmi, 2003). The results in Fig. 11 suggests that the 80% cloud cover in March can lead to by 40% larger concentration for NO_2 but only by 1.2% larger value for SO_2 than the no-cloud cover in August does. The assumption of the reduced solar radiation is rationalized because the weather in March in the "rainy" season is mostly cloudy and the precipitation amount is rather small about 4-5 mm day^{-1}, most of which occurs during the nighttime.

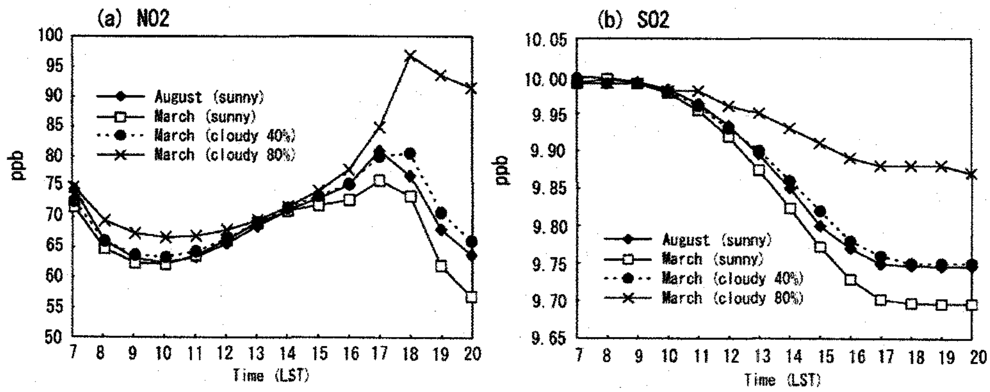

Figure 11. Effect of cloud cover on the chemical consumption (oxidation) of NO_2 and SO_2, a model calculation (see text for the detail); the calculation adopted solar condition in March and August in Jakarta, and made sensitivity test of (a) NO_2 and (b) SO_2 to the cloud cover percentage varied from 0 to 80%.

One week averaged SO_2 in Fig. 10d suggests that its high concentration zone is rather confined in the coastal area; that is different from the one-day averaged in Fig. 10b. The SO_2 emission sources are concentrated in the coastal industrial area (Fig. 9b) and discharge SO_2 at heights of 50-100 m above ground as point sources. Thus the SO_2 is likely injected into stable marine air near the coast, and move inland with sea breeze. If sea breeze is weak, then TIBL (thermal internal boundary layer) starts to develop close to the coast and thus the pollutant (SO_2) disperses rapidly into TIBL and do not reach inland with high concentration. In this sense, the day of 9 Aug. for the one-day observation can be regarded as rather strong sea-breeze day, and the depth of TIBL near the coast was shallower, hence resulting in higher concentration in Jakarta. On the other hand, during the one week from 10-17 August, strength of the sea breeze varied from day to day, and thus the one week averaged SO_2 in Fig. 10d shows rather lower concentration in inland area than Fig. 10b; the one week averaged- (Fig. 10d) and one day averaged- (Fig. 10b) SO_2 concentrations were 3.0 and 4.5 ppb, respectively.

(4) Observed vertical distributions of NO_2 and SO_2

Vertical profiles of SO_2 and NO_2 were also measured by using passive samplers placed on the balconies and roof of a 100m tall office building located at the city center of Jakarta and about 10 km from the coastline (see "X" in Fig. 9b). Thus the following things can be expected in the dry season: (1) the sea-breeze front may arrive at the place around noon (see Fig. 7b); (2) then the depth of TIBL (thermal internal boundary layer) will be at most 200 m (see Fig. 8b) before 1600 LST, and (3) after 1800 LST the city is covered by a stable layer (see Fig. 8c). In contrast, in the rainy season the sea breeze is weak, and the lower atmosphere is rather well mixed vertically.

The obtained profiles in Fig. 12 show an interesting feature; in the dry season (see the solid lines in Fig. 12b), SO_2 concentration at 110 m high is larger than that at 10 m in both one-day and one-week observations while the SO_2 profiles in the rainy season (the dashed lines in Fig. 12b) do not show such features. Main reason for this difference can be attributed to the difference of sea breeze between the dry and rainy seasons. As described above (Fig. 9b and Table 2), main contributor to the SO_2 emission is elevated point sources (power plants etc.) located along the coast. Thus, in strong sea breeze situation in the dry season, SO_2 discharged from the stacks may migrate in stable marine air toward the city center with relatively high concentration, hence resulting in the higher SO_2 at 110 m high in the profiles for the dry season (the solid lines in Fig. 12b). On the other hand, in the rainy season the SO_2 concentration at 110 m high is nearly equal to that in the lower layer (the dashed line in Fig. 12b); the reason may be that the sea breeze situation similar to it in the dry season seldom occurs because the sea breeze from the Java sea is largely suppressed by the synoptic scale southwesterly as discussed in 3.1; furthermore, since the southwesterly blows over the land in the Western Java before reaching Jakarta, the air may be rather vertically well mixed over Jakarta, thus leading to uniform profiles shown in the dashed lines in Fig. 12b.

The NO_2 profiles in Fig. 12a show the same features as SO_2 such as nearly uniform vertical profiles in March (the dashed lines) and those with relatively large gradient in August (the solid lines), indicating again that the developed sea breeze forms a stable layer over the Jakarta city in the dry season (August) and thus leads to the higher NO_2 concentration near the surface because of strong

NOx emission by car, while in the rainy season (March) the weak sea breeze and the influential synoptic scale wind of the southwesterly blowing over the West Java may result in well mixed NO_2 vertical profiles.

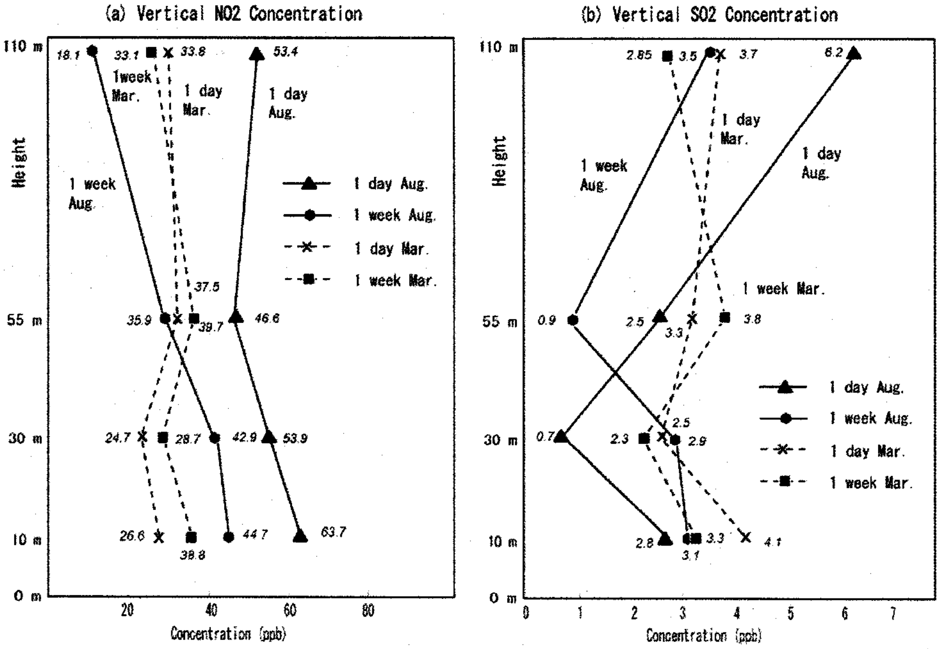

Figure 12. Vertical profiles of observed (a) NO_2 and (b) SO_2 in the dry (solid line) and rainy seasons (dashed line).

4. Summary and Conclusions

Characteristics of sea breeze over Jakarta and its relation to air pollution were investigated by numerical simulation of meso-scale flow and field measurements of NO_2 and SO_2 both in the dry and rainy seasons. PSU-NCAR MM5 for meso-scale meteorological simulation and passive samplers for NO_2 and SO_2 measurements were used. To our knowledge, this is the first detailed numerical simulation of meso-scale flow in Jakarta. Obtained results are as follows:

1. Simulations of the "twelve-day" in the dry season and "five-day" in the rainy season reproduced meteorological observations at Sukarno Hatta in Jakarta (Fig. 3) and flow fields in the western Java (Fig. 4) well in August 2004 (the dry season) and acceptably well in March 2001 (the rainy season).
2. In the dry season (August 2004), Java Island was always under the influence of synoptic scale southeasterly and easterly. However by the high mountains running from west to east along the southern coast of Java island, the synoptic scale wind is blocked below about 3 km high above the mean sea level, and thus Jakarta in the leeward plain on the north of the mountains was

generally under weak wind in the boundary layer when local wind did not exist.

3. On the other hand, in March nearly at the end of the rainy season, the synoptic scale southwesterly dominated the northern part of Java Island in upper layer; in the lower layer near surface, the southwesterly partly intruded into the northern plain through the mountain-gaps and largely flowed around the west end of the mountains to reach Jakarta area.
4. Based on the calculated wind field together with wind observations in Jakarta, we can roughly conclude sea breeze in Jakarta develops on almost all days in the dry season and about one-third of the days in the rainy season. The following characteristics of the sea breeze in Jakarta were made clear: in the dry season the sea breeze usually starts around 1100 LST, and by about 1600 LST its front reaches the south end of Jakarta, at about 30 km from the coastline, i.e., the whole Jakarta is covered by marine air around 1600 LST. Then the sea breeze front further advances inland to the foot of the mountains located at about 60 km from the coastline by 1800 LST. By 1900 LST the sea-breeze circulation gradually decay and ceases around 2000 - 2100 LST.
5. On the other hand, in the rainy season the sea breeze in Jakarta stops before 1800 LST. Though the sea breeze from Java Sea covers eastern Jakarta at 1500 LST, it can not further advance inland because the synoptic scale southwesterly which blows through the gaps in the southern mountains, suppresses the sea breeze.
6. Convergence lines are formed in Jakarta on the sea breeze day in both the dry and rainy seasons. In the dry season, sea breezes from three different directions produce convergence in Jakarta area, i.e. one from the gulf of Jakarta (northerly) and the others of northwesterly and northeasterly from two broad peninsulas located at the east and west of the gulf, while in the rainy season the synoptic scale southwesterly and the sea breeze from Java sea form a convergence line, and it divides Jakarta into two regions: the western part is affected rather by the air originated from Indian Ocean, while the eastern part is covered by the air from Java Sea.
7. In the dry season the sea breeze layer is 400 – 500 m in depth, and the thermal internal boundary layer (TIBL) develops in the lower part of sea breeze layer. Upper part of the sea-breeze layer is stably stratified with its depth of about 200 m extending from 200 m to 400 m high. In contrast to the dry season, in the rainy season the atmosphere over Jakarta is rather well mixed because the air mass, which is brought in the area by the southwesterly, travels long over the up-and-down land area.
8. The observed spatial distributions of NO_2 and SO_2 both in the dry and rainy seasons strongly reflect their characteristic emission source distributions. However, they showed also clear influence of the sea-breeze features of the area in the dry season such that the sea breezes from several directions merge in the southern part of Jakarta, and thus the pollutants of the whole Jakarta tend to gather into this area. On the other hand, in the rainy season the pollutants distributions were rather affected by the synoptic scale southwesterly. It should also be noted that reduced solar radiation in the rainy season resulted in higher one-week-averaged NO_2 and SO_2 concentration compared with the dry season.
9. Vertical profiles of observed SO_2 and NO_2 in the city center showed strong influence of the stable layer formed by the sea breeze from the Java Sea in the dry season, and showed rather uniform vertical profiles affected by unstable stratification associated with the southwesterly from the Indian Ocean in the rainy season.

Acknowledgements

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References

Atkinson, B.W. (1981): *Meso-scale Atmospheric Circulations*, Academic Press, 495 pp.

BPS (2004): *Jakarta in Figures 2004*, BPS-Statistics of DKI Jakarta Province, 524 pp.

Dudhia, J. and Gill, D. (2005): *PSU/NCAR Mesoscale Modeling System Tutorial Class Notes and User's Guide: MM5 Modeling System Version 3,* Mesoscale and Microscale Meteorology Division, National Center for Atmospheric Research.

Hadi, T.W., Horinouchi, T., Tsuda, T., Hashiguchi, H. and Fukao, S. (2002): Sea Breeze Circulation over Jakarta, Indonesia: A Climatology Based on Boundary Layer Radar Observations, *Monthly Weather Review,* **130**, 2153-2166.

Hadi, T.W., Tsuda, T., Hashiguchi, H. and Fukao, S. (2000): Tropical sea-breeze circulation and related atmospheric phenomena observed with L-band boundary layer radar in Indonesia, *Journal of the Meteorological Society of Japan,* **78**, 123-140.

Hastenrath, S. (1991): *Climate Dynamics of the Tropics*, Kluwer Academic Publishers, 488pp.

JICA and Bapedal (1997): *The study on the integrated air quality management for Jakarta metropolitan area: Final Report,* Volume I, Main Report, 10 Chapters.

Kitada T. (1987): Turbulence structure of sea-breeze front and its implication in air pollution transport – application of turbulence model - , *Boundary Layer Meteorology*, **41**, 217-239.

Kitada, T. and Kitagawa, E. (1990): Numerical analysis of the role of sea-breeze fronts on air quality in coastal and inland polluted areas, *Atmospheric Environment*, **24A**, 1545-1559.

Kitada, T., Okamura, K., Nakanishi, H., and Mori, H. (2000): Production and Transport of Ozone in Local Flows over Central Japan – Comparison of Numerical Calculation with Airborne Observation – , *Air Pollution Modeling and Its Application XIII*, Kluwer Academic/Plenum Publishers, 95-106.

Kitada, T. and Regmi, R. P. (2003): Dynamics of air pollution transport in late wintertime over Kathmandu Valley, Nepal: As revealed with numerical simulation, *J. Applied Meteor.,* **42**, 1770-1798.

Regmi, R.P., Kitada, T. and Kurata, G. (2003): Numerical Simulation of Late Wintertime Local Flows in Kathmandu Valley, Nepal: Implication for Air Pollution Transport, *J. Applied Meteor.,* **42**, 389-402.

Riehl, H. (1979): *Climate and Weather in the Tropics*, Academic Press, 611 pp.

Simpson, J. E. (1994): *Sea-breeze and Local Wind*, Cambridge University Press, 234 pp.

Tsuda, T., Fukao, S., Yamamoto, M., Nakamura, T., Yamanaka, M.D., Adachi, T., Hashiguchi, H., Fujioka, N., Tsutsumi, M., Kato, S., Harijono, S.W.B., Sribimawati, T., Sitorus, B.P., Yahya, R.B., Karmini, M., Renggono, F., Parapat, B.L., Djojonegoro, W., Mardio, P., Adikusumah, N., Endi, H.T. and Wiryosumarto, H. (1995): A preliminary report on observations of equatorial atmosphere dynamics in Indonesia with radars and radiosondes. *J. Meteor. Soc. Japan,* **73**, 393-406.