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Mie Scattering Lidar Observation of Aerosol Vertical Profiles in Jakarta, Indonesia

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Abstract

Vertical profiles of aerosols were observed in Jakarta, Indonesia, with a Mie scattering lidar network system consisting of three lidars located in the coastal, central, and inland areas. The structure of the planetary boundary layer was observed for one week during the September to October 1997 dry season. Radiosonde observation was performed in the same period in Jakarta. The diurnal variation of the boundary layer structure indicating the sea-land breeze circulation was clearly observed in this period. The mixed layer grew in the morning and reached a maximum of approximately 2.5 km in the afternoon. Clean air was brought in at heights up to 1.5 km at around 17:00 by a sea breeze, and a layer of aerosols was formed at the top of the boundary layer by the reverse flow. Aerosol layers were also observed above the boundary layer at altitudes of 2 to 5 km. A trajectory analysis shows a part of the aerosol plume originated from the forest fires in Kalimantan. The boundary layer structure in the wet season was observed in December 1997. The observed aerosol distribution was complicated this season, and it is inferred that the convection in the boundary layer sometimes reached 3 to 4 km in height.

Key Words : lidar (laser radar), aerosol, planetary boundary layer, sea breeze, biomass burning

Running Head : Lidar Observation of Aerosol Profiles in Jakarta

Introduction

Jakarta City faces the Sea of Java in the north and a highland in the south. A typical air pollution phenomenon generated by the photochemical reactions of pollutants and the transportation by sea-land breeze is observed over the City. In fact, a high concentration of ozone is often recorded in inland areas around Jakarta. The wind system over Jakarta combines the seasonal wind and the local wind generated by the sea-land breeze circulation. The seasonal wind is westerly in the wet season and easterly in the dry season. During the transition periods, the seasonal wind is weak, and heavy air pollution is often observed.1)

Lidars are useful tools for measuring distributions of aerosols and pollutants such as ozone, SO_2 and NO_2.2,3) A lidar network system consisting of two Mie-scattering lidars and one differential absorption lidar (DIAL) was constructed in Jakarta in March 1997 through a cooperative research program between Japan and the Republic of Indonesia. To study the planetary boundary layer structure over the City and the transportation of air pollutants by the sea-land breeze, three lidars are installed at three locations in Jakarta along a line perpendicular to the coastline.

In this paper, we report lidar observations of the aerosol profiles during the dry and wet seasons. Vertical profiles of aerosols were observed with the three lidars during one week of the September to October 1997 dry season. A clear diurnal variation of the planetary boundary layer, showing the growth of convection in the morning and the inflow of sea breeze in the afternoon, was observed. Radiosonde observation was carried out in the same period in Jakarta, and the results were used in interpreting the lidar data. Layers of aerosols were also observed above the boundary layer up to an altitude of 5 km. We studied the origin of the aerosol layers by trajectory analysis. The results indicated that some of the aerosol layers originated from the forest fires in Kalimantan where there was heavy forest fire during the dry season in 1997.4) We also studied the boundary layer structure in the wet season of 1997 to 1998.

Lidar System and Observation

The lidar network system consists of two Mie scattering lidars and one differential absorption lidar. The details of the lidar network system were reported in a previous paper.5) The Mie scattering lidars are vertically looking, compact systems for measuring vertical profile of aerosols. The DIAL system was constructed for measuring ozone, SO_2, NO_2, and aerosols, and it has a full scanning capability. In the observations in this paper, the DIAL was pointed vertically and operated as a Mie scattering lidar.

The Mie lidars and the Mie lidar mode of the DIAL employ compact flashlamp pumped Nd:YAG lasers operated at the fundamental wavelength of 1064 nm. Lidar signals are received with 25 cm diameter telescopes and detected with Si avalanche photodiodes (APD). The signals from the APDs are recorded with a two-channel, 12-bit accuracy analog-to-digital converter and transferred to a personal computer. Figure 1 shows a block diagram of the Mie scattering lidar. The major specifications of the Mie scattering lidars are listed in Table 1.

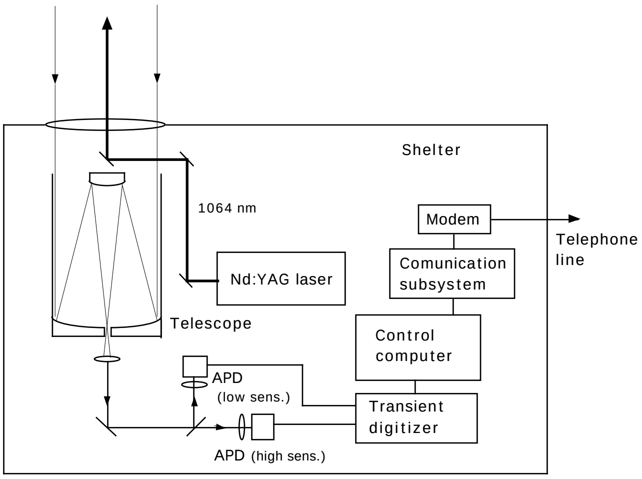

Fig. 1 Block diagram of the Mie scattering lidar.

Table 1 Specifications of the Mie scattering lidar.

Laser	Compact flashlamp-pumped Nd:YAG laser
Wavelength (nm)	1064
Output energy (mJ)	100
Pulse repetition rate (Hz)	10
Receiver telescope diameter (cm)	25
Receiver field of view (mrad)	0.5 - 2
Filter bandwidth (nm)	9
Detector	Avalanche Photo Diode
Analog to digital converter (ADC)	
Sampling rate (Msamples/s)	20
ADC accuracy (bits)	12

The boundary layer was observed by lidar in the dry season from September 25 to 27, 1997 at three locations, Ancol in the coastal area (S 6°7.51′, E 106°50.79′), Gatot Subroto in central Jakarta (S 6°13.76′, E 106°49.05′), and Depok in the inland area (S 6°22.32′, E 106°49.64′). During the observations, lidar signals were accumulated for 100 seconds (1000 shots) on a PC and stored on a hard disk. The measurement is continued intermittently (typically every 10 minutes).

Radiosonde measurements were performed in LAPAN Pekayon (S 6°20.30′, E 106°51.70′) during the same period by the Indonesia Institute of Aeronautics and Space (LAPAN). Figure 2 shows the locations of the three lidars and the sonde observations. Radiosondes (Vaisala RS-95G with GPS receiver) were launched every four hours.

The wet season lidar observation presented in this paper was performed with the lidar in Gatot Subroto from December 31, 1997 to January 5, 1998.

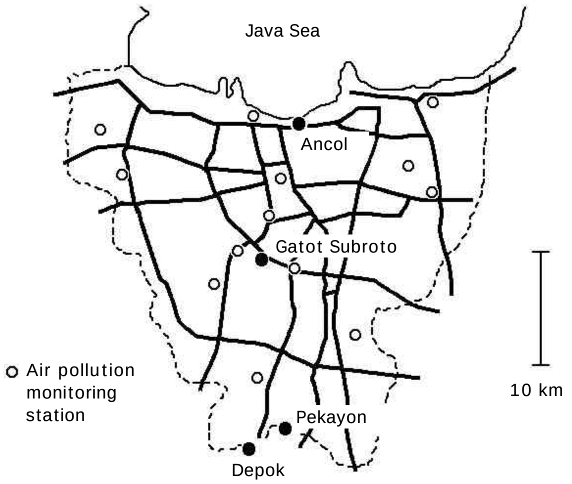

Fig. 2 Locations of the three lidars and the sonde observation in Jakarta.

Results and Discussion

1. Boundary Layer Structure

Figure 3 shows a range-corrected, time-height indication (THI) of the lidar data at the three locations for September 25 to 27. The range-corrected signal, which is approximately proportional to the aerosol backscatter coefficient, is indicated with a color scale. The indicated quantity can be converted to aerosol number density and weight density, if we assume the size distribution and refractive index of aerosols. However, we will first discuss the structure of the planetary boundary layer that can be visualized with the aerosol distribution pattern. We will then discuss the backscatter coefficient, which is an absolute value in an optical sense.

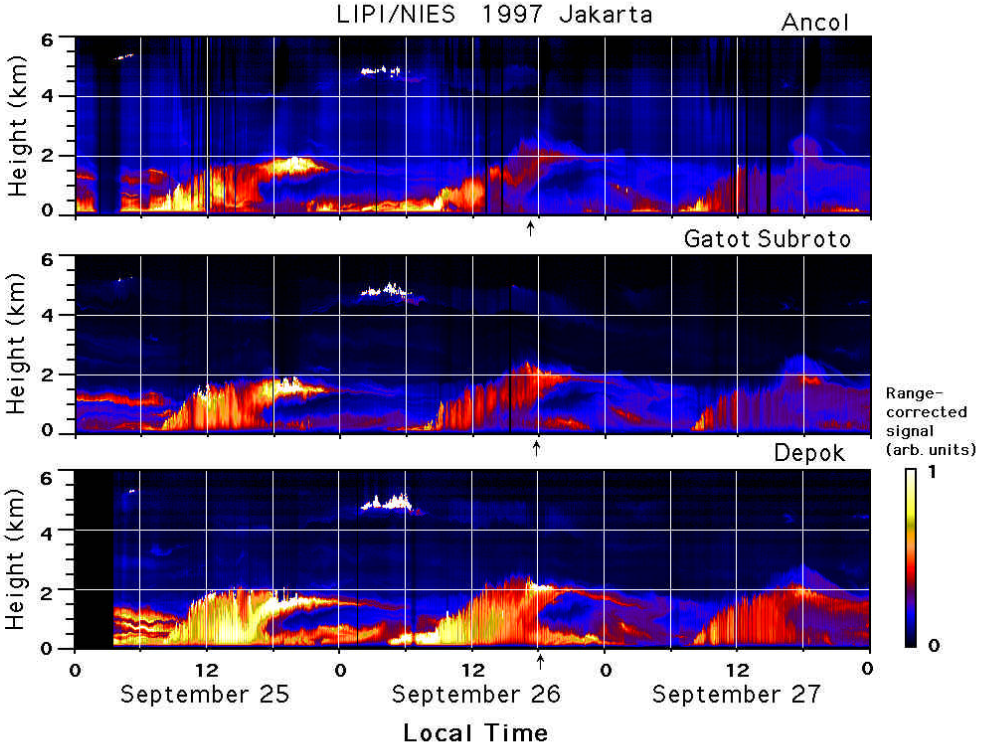

Fig. 3 Temporal variation of the vertical profile of aerosols from September 25 to 27, 1997. The range-corrected, time-height indication (THI) is shown with a color scale.

Figure 3 clearly shows the diurnal variation of the planetary boundary layer structure. The mixed layer started to grow in the morning and reached a maximum height of approximately 2.5 km in the afternoon. The growth of the mixed layer is similar to that observed in Japan in the summer except that the maximum boundary layer height in Japan is 1 to 1.5 km.6) Short-term variations (approximately 1 hour) in the boundary layer height that reflect convective cell activity7) were also observed in Jakarta, for example from 9:00 to 15:00 on September 26 at Gatot Subroto.

At around 17:00, air masses with low aerosol concentration entered at a height of approximately 1 km. It is presumed that these air masses were transported by a sea breeze. By comparing the time at which the front of the air mass passed over the three locations, we can see that there was a time lag and the air mass was transported from the sea. An arrow at the bottom of each panel of Fig. 3 indicates the front of the clear air mass on September 26. The time lag was approximately 65 min between Ancol and Depok (distance about 20 km), corresponding to a velocity of 5 m/s. The structure of the sea breeze was previously observed with a scanning lidar in Tsukuba, Japan.8) Though the movement of sea breeze is similar, the aerosol concentration was higher in the sea breeze area observed in Tsukuba. To discuss the absolute concentration of aerosols, we derived the scattering ratio (the ratio of the total backscattering to Rayleigh scattering) by solving the lidar equation using Fernald's method9) assuming the extinction-to-backscatter ratio or the lidar ratio for aerosols, which is known as the S_1 parameter. We assumed S_1 = 50 sr, considering the continental polluted aerosol in the Optical Properties of Aerosols and Clouds (OPAC) model10). Figures 4 (a) through (c) show the results. The baseline for each plot is shifted by 3 from the previous one. The scattering ratio obtained is not sensitive to S_1 in this case because the aerosol layer was not optically dense.

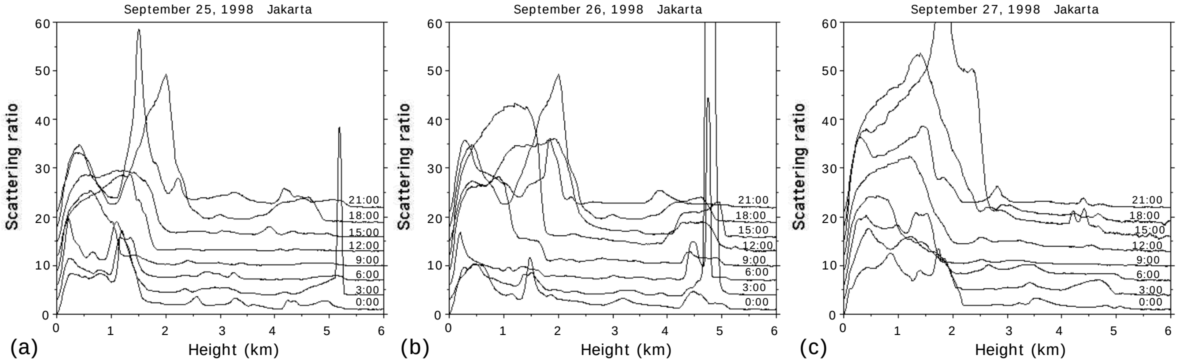

Fig. 4 Scattering ratio (the ratio of the total backscattering to Rayleigh scattering) derived from the lidar data.

The results show that the scattering ratio at 1064 nm was 14 to 17 in the planetary boundary layer before penetration of the clean air mass from the sea, and approximately 5 in the sea breeze region. In contrast, the scattering ratio at 532 nm observed in Tsukuba was 1.5 in the boundary layer and 1.9 in the sea breeze front. If we convert the values to those at 1064 nm using the λ^{-4} dependence of Rayleigh scattering and $\lambda^{-1.5}$ dependence of Mie scattering, they become 3.6 and 6.1, respectively. The concentration of aerosols in the sea breeze was higher than that in the land area in the event observed in Tsukuba. The scattering ratio of aerosols in the sea breeze in Tsukuba was comparable to that in Jakarta, but the scattering ratio in the land area was much lower in Tsukuba. This caused the difference in the observed aerosol structures. Furthermore, the sea breeze front moved 1.5 times faster in Jakarta than in Tsukuba.

The results of the radiosonde observations are shown in Figs. 5 (a) through 5 (d). Figure 5 (a) shows meridional wind velocity indicated with a color scale. Negative velocity indicates the wind from the sea, and positive velocity indicates the wind from the land. Figures 5 (b), (c), and (d) indicate potential temperature, potential temperature gradient, and relative humidity, respectively. Figure 5 (c) shows that there was a temperature inversion with a gradient larger than 0.6 (deg/100m) at a height of approximately 2 km, which corresponds to the height of the planetary boundary layer observed with the lidars. It is also seen that there was another strong inversion, as large as 4 deg/100m, at an approximate height of 5 km. In Fig. 5 (a), a sea breeze was seen in the afternoon at heights up to 1.5 km; the sea breeze was especially strong on September 26. Reverse flows are seen above sea breeze at a height of approximately 2 km. The relative humidity was high (60 to 70%) in the planetary boundary layer, and the structure is similar to that of the aerosol distribution measured with the lidars. Figure 5 (d) shows that the air masses transported from the sea had a low relative humidity (about 50%).

The sea breeze velocity of 5 m/s obtained from the lidar data on September 26 agreed qualitatively with the wind speed measured with sonde, but there is not sufficient wind data for quantitative comparison. Northerly wind was observed at 15:00 in Pekayon near Depok, however, the clean and dry air mass from the sea was actually observed at 18:00 with the lidar in Depok. This suggests that aerosols were distributed above the sea near the coast, and it took time to transport the clean air mass located offshore. The wind structure and the aerosol distribution observed by the lidar suggest that the layered structure observed at the top of the boundary layer in the nighttime was formed by the reverse flow of the sea breeze.

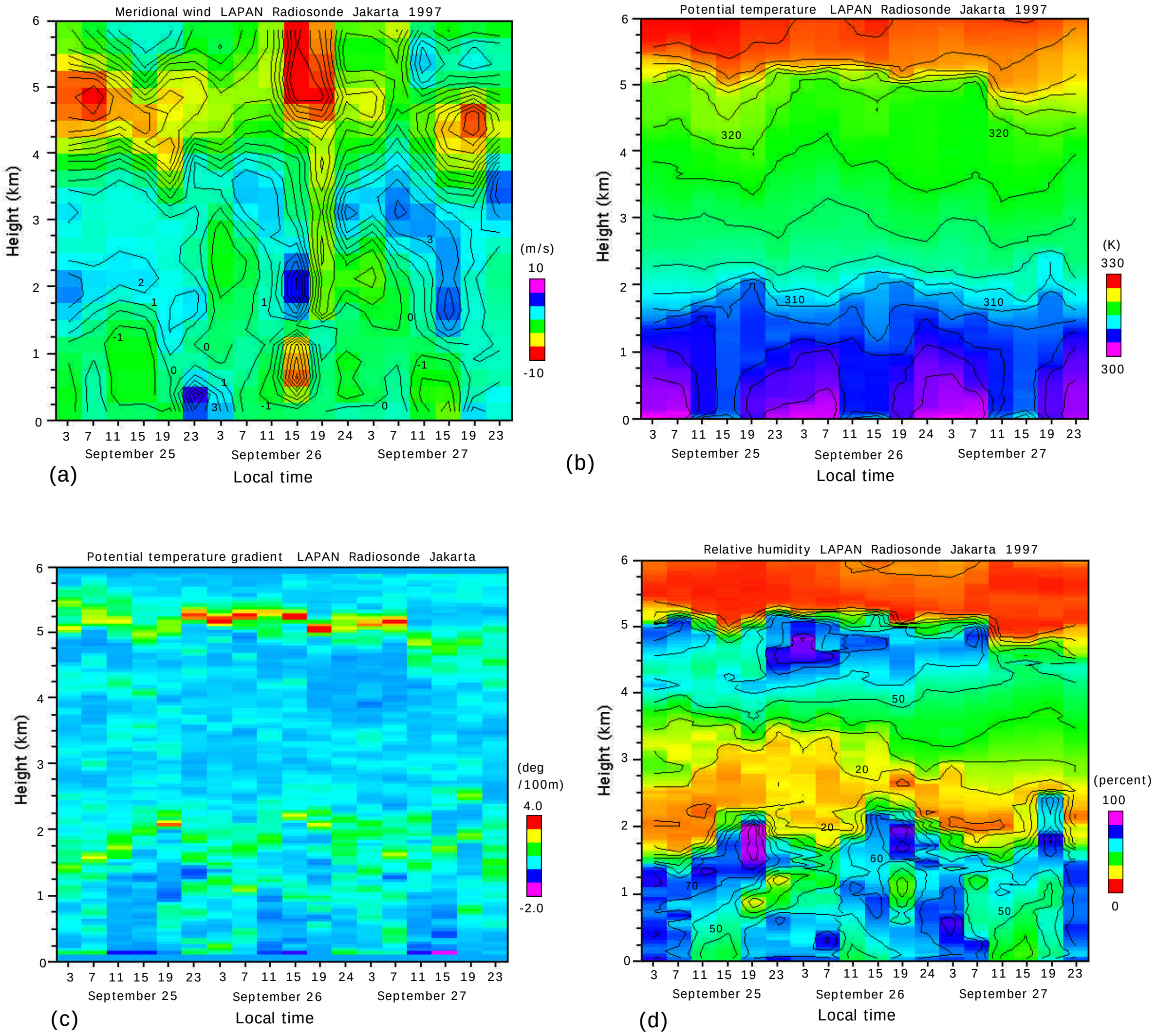

Fig. 5 Results of the radiosonde observation. (a) Meridional wind velocity, (b) Potential temperature, (c) Potential temperature gradient, and (d) Relative humidity. Radiosondes were launched every four hours.

The spatial structure of the aerosol distribution extracted from the lidar profiles is indicated in Fig. 6. Because there are only three locations to indicate spatial structure, we simplify the aerosol vertical profiles and connected the characteristic layered structure by eye. The gray scale in the figure indicates the qualitative aerosol concentration. Figure 6 indicates that the maximum mixed layer height in the afternoon was higher in the inland location. For example, it was 2.4 km at Depok and 1.8 km at Ancol at 15:00 on September 26. In the nighttime, the height of the structure at the top of the boundary layer was slightly lower in the inland location. For example, it was 1.75 km at Depok and 1.9 km at Ancol at 3:00 on September 26, 1997. The structure of the aerosol distribution near the surface was complicated.

Results of lidar observation in the wet season are shown in Fig. 7. The observation was carried out from December 31, 1997 to January 5, 1998 at Gatot Subroto. Unfortunately, sonde observation was not performed in this period. Although it was the wet season, there was little rain during this period. There were cirrus clouds on December 31 and occasionally on the other days at altitudes of 11 to 14 km. There were almost no clouds at altitudes of 5 to 10 km. The aerosol distribution observed in this period was much more complicated than that observed in the dry season. The diurnal variation showing the growth of the mixed layer was not clear in this season, and clouds were often observed around the top of the planetary boundary layer. It is inferred from the distribution of aerosols and clouds that the convection sometimes reaches 3 to 4 km in altitude, for example on January 3, 1998. It is not clear from the observed data, however, whether the apparently larger convection in the wet season is due to the activity of clouds, i.e. the activity driven by the energy released by condensation of water vapor. This is a subject for future study. Also, because of the El Nino in 1997, the results presented in this paper may not reflect typical seasonal variations of the region. Further lidar and radiosonde observations are required for climatological analysis.

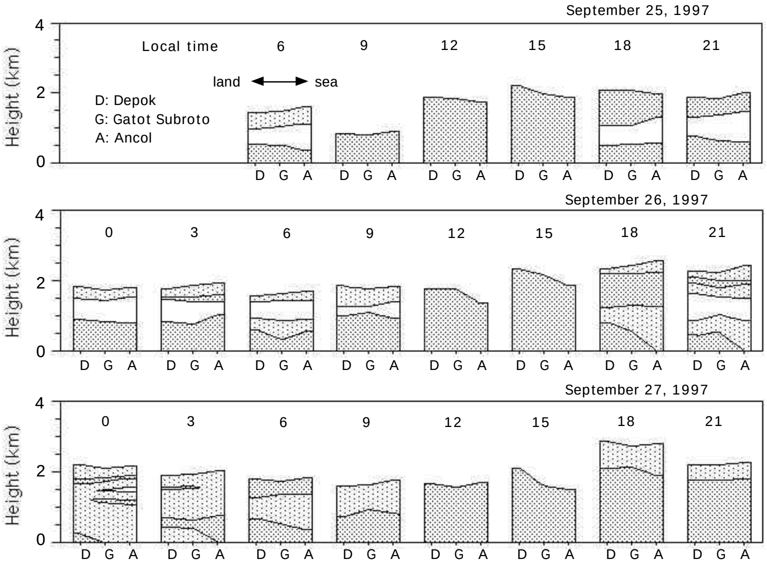

Fig. 6 Simplified spatial structure of aerosol distribution extracted from the lidar profiles at the three locations. Gray scale indicates aerosol concentration qualitatively.

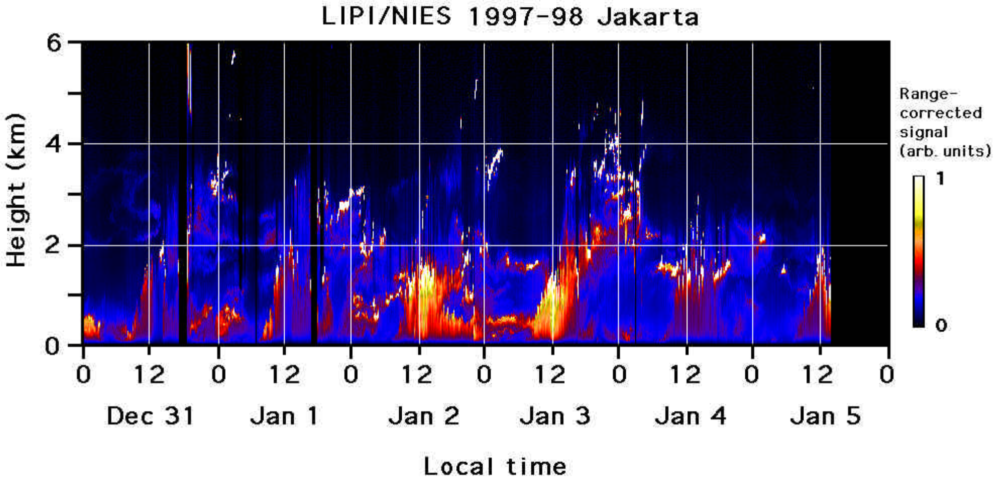

Fig. 7 Temporal variation of the vertical profile of aerosols (range-corrected THI) from December 31, 1997, to January 5, 1998.

2. Aerosol Layer above the Planetary Boundary Layer

Layers of aerosols were also observed above the planetary boundary layer in the dry season. Figure 8 shows a range-corrected, time-height indication of the lidar data measured at Gatot Subroto with an enhanced color scale. The top of the aerosol layer at approximately 5 km in altitude corresponds to the temperature inversion observed in the radiosonde data shown in Fig. 5 (c). It is seen in Fig. 5 (d) that relative humidity was also high (60 to 80%) below the temperature inversion. From Fig. 4, the scattering ratio in the plume layer at altitudes of 2 to 5 km is 1 to 5. Occasionally, strong scattering is seen from clouds formed in the plume layer. The aerosol distribution at altitudes of 2 to 5 km was inhomogeneous, and the distribution does not reflect the structure of potential temperature. Instead, it can be seen that the aerosol distribution is affected by the change of wind velocity. It is presumed that the aerosol layers were transported by the wind.

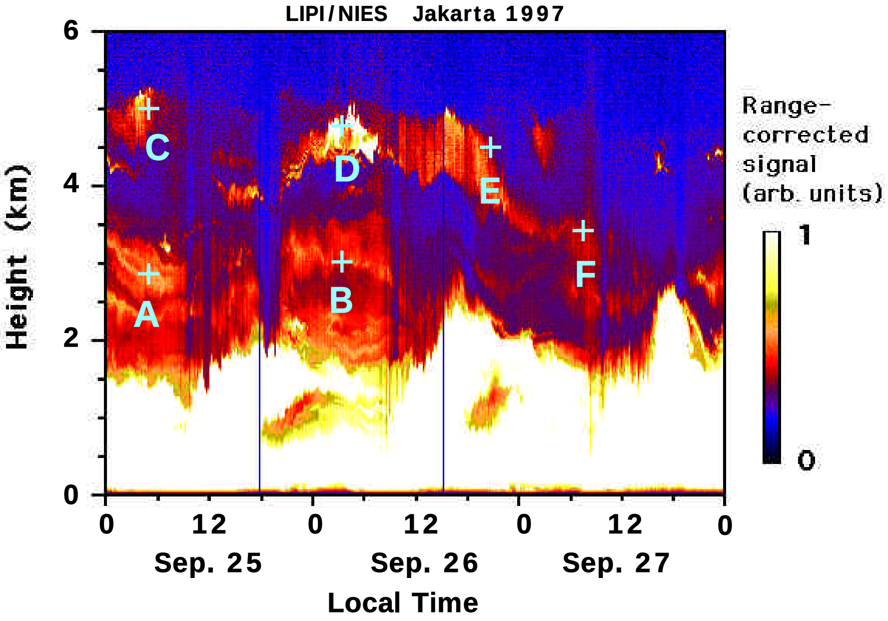

Fig. 8 Range-corrected, time-height indication of the lidar data from September 25 to 27, 1997 indicated with an enhanced color scale.

We performed a back trajectory analysis using the reanalysis data of the European Centre for Medium Range Weather Forecasts (ECMWF). Three-day back trajectories are shown in Fig. 9 for the altitudes and times indicated in Fig. 8 with markers A to F. The CGER-GMET system at the Center for Global Environmental Research of the National Institute for Environmental Studies was used. The fourth order Runge-Kutta method was applied to interpolate the data. The results indicate that the aerosol layer at an altitude of approximately 3 km on September 25 and 26 (A and B in Fig. 8) came from Kalimantan where a large forest fire burned during the period.4) The forest fire of 1997 did not significantly affect Jakarta. The main part of the forest fire plume was transported to the west by the easterly seasonal wind at lower altitudes. In fact, the ozone column contents measured with the Earth Probe TOMS were high above and west of Kalimantan during the lidar observation in September 1997, but not very high over Jakarta. They were only slightly higher than the climatological value (TOMS Home Page, http://jwocky.gsfc.nasa.gov/). However, at an upper altitude of 3 to 5 km, the northerly wind component was large. Aerosols rising to that high altitude were transported to the south. Though the total ozone was not high above Jakarta, we can observe a correlation between ozone and aerosols in the forest fire plumes if we observed vertical profiles of ozone with our DIAL system. The plume at higher altitudes (C, D, and E in Fig. 8) came from further east as seen in Fig. 9. There was also a large forest fire in Irian Jaya during the period, and it is a possible source of the plume.4)

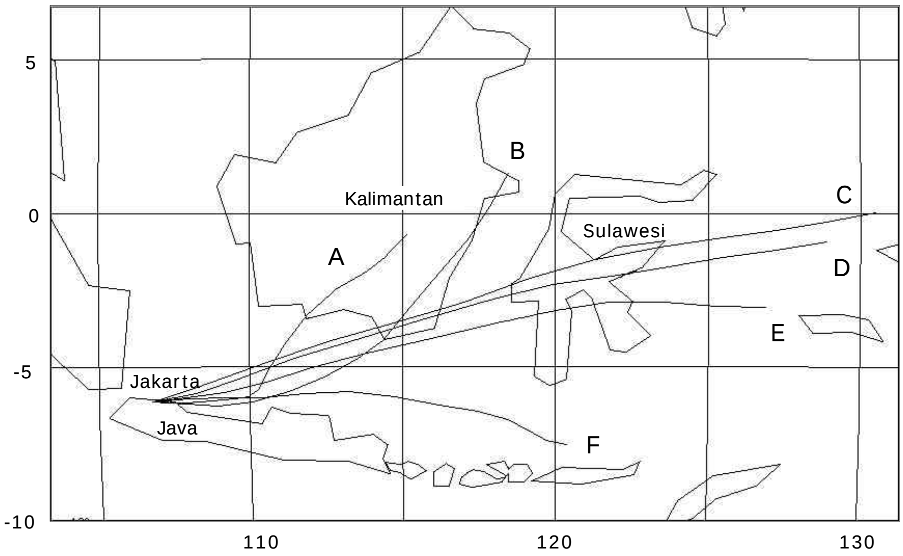

Fig. 9 Three-day back trajectory for the altitudes and time indicated in Fig.8 with the markers A to F.

Conclusions

The structures of the planetary boundary layer and aerosol plumes in the free troposphere over Jakarta were observed with a network consisting of three Mie scattering lidars. A diurnal variation of the boundary layer structure with sea-land breeze circulation was observed in the dry season. The top of the aerosol layer corresponded to the height where a temperature inversion was observed with the radiosondes. The maximum boundary layer height was approximately 2.5 km. At around 17:00, clean air masses transported by sea breeze were observed. The scattering ratio observed with the lidar was 14 to 17 in the planetary boundary layer and approximately 5 in the air masses brought in by the sea breeze. The air masses moved at 5 m/s. A dense aerosol layer was also found to form at the top of the boundary layer due to the reverse flow above the sea breeze.

The structure of the boundary layer in the wet season was much more complicated. The diurnal variation of the aerosol distribution was not as clear as in the dry season, and clouds were often observed around the top of the boundary layer. The apparent convection seen from lidar data sometimes reached 3 to 4 km in altitude.

Aerosol layers presumed to be generated by forest fires were observed above the planetary boundary layer at altitudes up to 5 km in the dry season. A trajectory analysis revealed that the aerosol plume at 3 km altitude came from the direction of Kalimantan, where heavy forest fires occurred during the observation.

The result of the lidar observation shows that network observations with lidars are useful for observing the structure of the planetary boundary layer that is closely related to air pollution phenomena. We plan to further study the air pollution of Jakarta during the observation period in September 1997 reported in this paper using data from air pollution monitoring stations in Jakarta City.

The DIAL system in the lidar network was operated as a Mie lidar in the present work. It can, however, be operated in its normal configuration to measure tropospheric ozone. The simultaneous observation of ozone and aerosols is a future subject for study to investigate the correlation between distributions of ozone and aerosols in forest fire plumes. We also plan to continue the observation with one of the Mie lidars to obtain vertical profiles of aerosols and clouds for climatological studies.

Acknowledgements

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