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Observation of Aerosols and Clouds Using a Two-Wavelength Polarization Lidar during the Nauru99 Experiment

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Abstract

Lidar observation of aerosols and clouds was conducted from the research vessel "Mirai" in the Nauru99 experiment. The lidar installed on Mirai is a vertically-pointing two-wavelength (532 nm, 1064 nm) Mie scattering lidar with a dual-polarization receiver at 532 nm. During Nauru99 intensive observation period (IOP) phase 2, Mirai stayed at a fixed point approximately 200 km west of the Nauru Island. Analysis was carried out on structure of the atmospheric boundary layer, generation of cumulus clouds, and distribution and optical characteristics of sea-salt aerosols. The upper boundary height of the lowest aerosol layer generally agreed with the atmospheric boundary layer height, and showed a weak diurnal variation having a maximum in the afternoon. Cumulus clouds were often observed at the top of the boundary layer. Backscatter coefficient of aerosols had a large variability, and it had a strong correlation with surface wind speed. Also, the ratio of backscatter coefficients at 1064 nm and 532 nm showed that the particle size was larger when wind speed was high. Furthermore, a layer with a high depolarization was seen above the boundary layer in the windy daytime, that suggests crystallization of sea salt particles. In the phase 1, the effect of the Island on the boundary layer structure was observed.

1. Introduction

Information on vertical distributions of aerosols and clouds over the Pacific Ocean is important in study of radiative processes and interaction between the atmosphere and the ocean. However, data are very little up to now. Although global maps of optical depth of aerosols have been derived from the satellite sensors such as NOAA AVHRR,[1)] data for validating satellite data are not sufficient. Furthermore, there are very limited observations of vertical distributions of aerosols and clouds.

We started observation with a lidar using R/V Mirai operated by Japan Marine Science and Technology Center (JAMSTEC) to observe distributions and optical characteristics of aerosols and clouds over the ocean. The lidar is a two wavelength system using a flashlamp pumped compact Nd:YAG laser. It measures Mie scattering at 1064 nm and 532 nm, and the depolarization ratio at 532 nm. We have carried out observations in five cruises in the western tropical Pacific since February 1999. In this paper, we report the results obtained in the Nauru99 experiment which was conducted by JAMSTEC and Atmospheric Radiation Measurement Program (ARM) of US Department of Energy. Mirai participated in Nauru99 as MR99-K03 cruise.

2. Lidar Observation in Nauru99

2.1 Lidar system

The lidar we developed for Mirai is a two-wavelength Mie scattering lidar having a depolarization measurement capability. A block diagram of the lidar is shown in Fig.1. The lidar employs a Nd:YAG laser as a light source which generates the fundamental output at 1064 nm and the second harmonic at 532 nm. Transmitted laser energy is typically 100 mJ per pulse at 1064 nm and 50 mJ per pulse at 532 nm. The pulse repetition rate is 10 Hz. The receiver telescope has a diameter of 25 cm. The receiver has three detection channels to receive the lidar signals at 1064 nm and parallel and perpendicular polarizations at 532 nm. The received backscattered signals are separated into the two wavelengths with a dichroic mirror, and the two polarization components at 532 nm are separated with a polarizer. An analogue-mode avalanche photo diode (APD) is used as a detector for 1064 nm, and photomultiplier tubes (PMTs) are used for 532 nm. The detected signals are recorded and accumulated with a digital oscilloscope, and the accumulated signals are transferred to the computer and stored on a hard disk. A clinometer is used to record the pitching and rolling angles of the ship at the same time with the lidar data. The angular data is necessary for correcting altitude of the measurement. Also, it can be useful for data analysis of cirrus clouds that sometimes have a strong angular dependence in backscattering. The major specifications of the lidar system are listed in Table 1. The whole system is installed in an air-conditioned shelter with a size of 4 m (L) x 2 m (W) x 2.5 m (H). The container has a glass window on the roof, and the system is operated continuously regardless of weather.

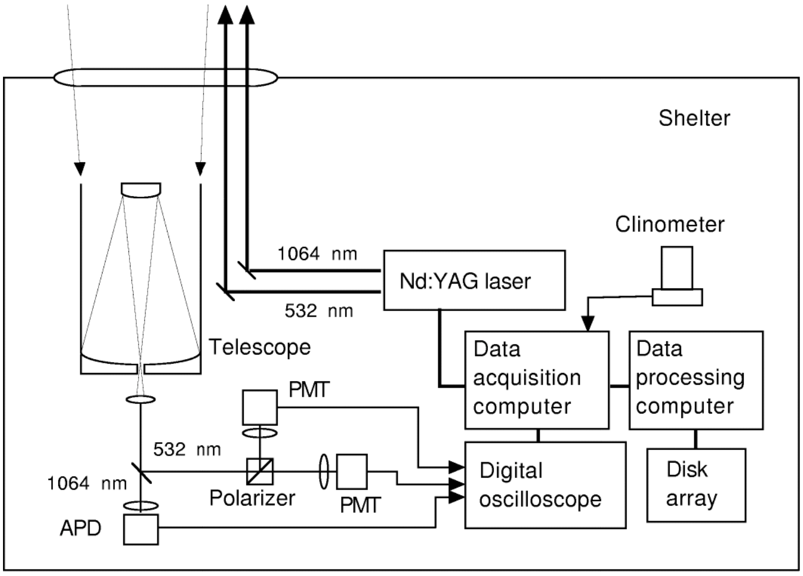

Fig. 1. Block diagram of the lidar system.

Table 1. Specifications of the lidar for R/V Mirai.

Laser		Flashlamp pumped Nd:YAG laser	
	Output power	1064 nm	100 mJ/pulse
		532 nm	50 mJ/pulse
	Repetition rate	10 pps	
Telescope		Schmidt Cassegrain	
	Diameter	25 cm	
	Field of view	1 mrad	
Receiver		3 channels	
		(1064 nm, 532 nm dual polarization)	
Detector		Photomultiplier tubes (532 nm)	
		Avalanche photodiode (1064 nm)	
Data acquisition		A/D converter	

2.2 Observation and Data Analysis Method

The lidar observation was performed during whole MR99-K03 cruise (from 8 June to 18 July of 1999). Lidar signals were accumulated for 20 shots and recorded on a hard disk every 10 seconds. Range resolution was 6 m, and the signals were recorded up to 24 km. From the observed lidar data, we derived cloud distribution (cloud base height and cloud top height), cloud phase, cloud coverage (fraction of detecting clouds in the zenith), planetary boundary layer height (aerosol layer upper boundary height), backscatter coefficient of aerosols, ratio of backscatter coefficient at 1064 nm and 532 nm, and depolarization ratio of aerosols. The ratio of backscatter coefficients at 1064 nm and 532 nm is generally high for larger particle. It can be used for characterizing aerosols[2)] and is also useful to distinguish thin clouds from aerosols. Depolarization ratio of lidar signal is defined as the ratio of the polarization component perpendicular to the transmitted laser polarization to the parallel component. Depolarization ratio reflects nonsphericity of the scatterer. It is close to zero for spherical particles such as water clouds and spherical aerosols, and it is high for ice clouds and dust particles.

Cloud base height was determined from the rising edge in the range-corrected lidar signal at 532 nm averaged for 1 min. Cloud top was detected in the same way from the falling edge. The cloud top determined from lidar is not necessarily the real cloud top but an apparent cloud top because the laser beam does not penetrate optically thick clouds. Cloud phase was determined by averaging depolarization ratio between the detected cloud base and cloud top, and it is defined as crystal when depolarization ratio exceeds 0.1. Cloud coverage was defined for 5-min period as the ratio of the number of data where clouds are detected.

The cloud free lidar data below 7 km were selected for analyzing aerosols in the lower troposphere. Upper boundary height of the aerosol layer, which corresponds to the planetary boundary layer height, was obtained from the gradient of the range-corrected lidar signals at 1064 nm in which the boundary is clearer than in 532 nm signal because of smaller Rayleigh scattering component. Absolute backscatter coefficient was derived using the two-component inversion method known as Fernald method.[3)] Before applying the inversion, the geometrical form factor was corrected. Geometrical form factor, Y(R), describes insufficient overlap between the transmitted beam and the receiver field of view. We estimated Y(R) from the lidar signal in clear conditions where distribution of aerosols in the boundary layer was presumed well mixed. Applying the correction to Y(R) before applying inversion, is important because the underestimation of Rayleigh scattering in the near field lidar signal affects inversion result. In the analysis of the boundary layer, we gave a boundary condition at 5-7 km altitude where the signal was dominated by molecular Rayleigh scattering. We assumed that the lidar ratio (extinction-to-backscatter ratio), S_1, is 24 sr at 532 nm and 40 sr at 1064 nm based on the maritime tropical model of the Optical Properties of Aerosols and Clouds (OPAC).[4)] The obtained backscatter coefficient is not sensitive to the assumption on the S_1. However, the value of S_1 is important when we convert the results to extinction coefficient or optical depth.

Figure 2 shows the ship track of Mirai during Nauru99 (from June 17 to July 4).

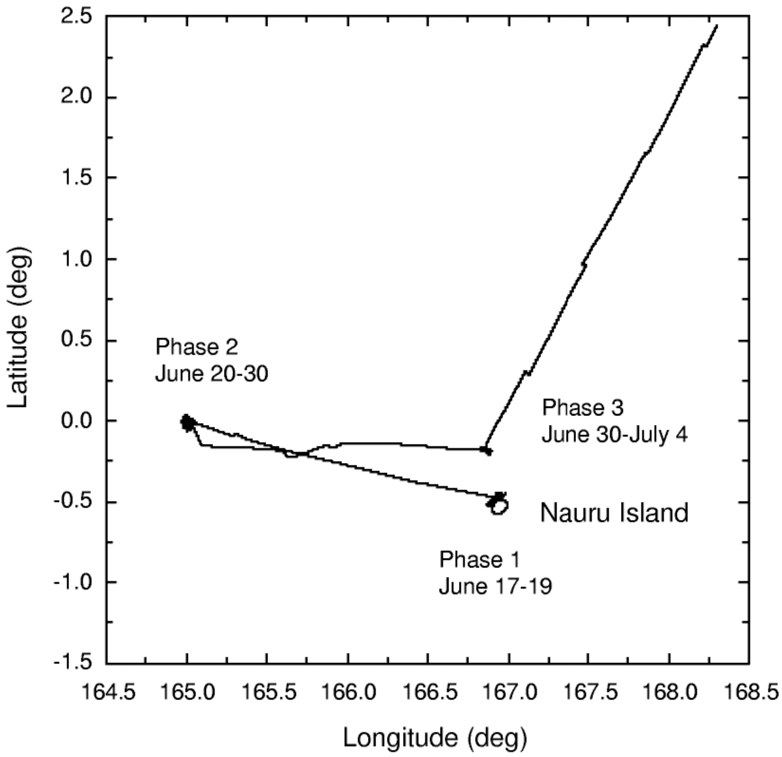

Fig. 2. Ship track of R/V Mirai during Nauru99.

In IOP phase 1, Mirai stayed near the Nauru Island to carry out inter-comparison experiment with the ARM observation site in the Nauru Island. In IOP phase 2, Mirai stayed at a fixed point approximately 200 km west of the Nauru Island for 10 days to perform so-called "large triangle observation" with the ARM site and NOAA's R/V Ron Brown. In IOP phase 3, comparison with Ron Brown was carried out. In the next section, we report the results on the marine atmospheric boundary layer and sea-salt aerosols in IOP phase 2, and on the "island effect" in IOP phase 1.

3. Results of Observation

Figure 3 shows the cloud base height, the cloud top height and the planetary boundary layer height observed with the lidar during the whole Nauru99 IOP. During this period, it was in the convectively suppressed phase. There was only one small precipitation event on June 27. Cirrus clouds were observed in IOP phase 1 and sometimes in IOP phase 2 as seen in Fig. 3. The atmospheric boundary layer height inferred from the aerosol profile was 500-800 m, and cumulus clouds were often observed at the top of the boundary layer.

3.1 Marine Atmospheric Boundary Layer Structure

In IOP phase 2, Mirai stayed at a fixed point (0 N, 165 E) in the middle of the equatorial Pacific. It was a good opportunity for studying marine atmospheric boundary layer structure and distribution of sea-salt aerosols. Figure 4 (a) shows a histogram of cloud base height during IOP phase 2. The most of the clouds were cumulus clouds distributed below approximately 1.2 km. Figure 4 (b) shows a diurnal variation of cloud fraction (hourly average for IOP phase 2) for the clouds below 1.2 km. Local time (LT) is 12 hours ahead of universal time (UTC). Figure 4 (c) shows diurnal variation of histogram of the aerosol layer upper-boundary height during IOP phase 2. The boundary layer height inferred from the aerosol profile showed slight diurnal variation having a peak at around 3:00-6:00 UTC (15:00-18:00 LT). The result is consistent with the radiosonde analysis presented by Takemi.[5)] Figure 4 (d) shows diurnal variation of distribution of clouds. The height ranges where clouds were detected (not only cloud bases) are indicated. It can be seen from Fig. 4 (b) and (d) that cumulus clouds were generated at the top of the boundary layer and the fraction was large at around 4:00-6:00 UTC.

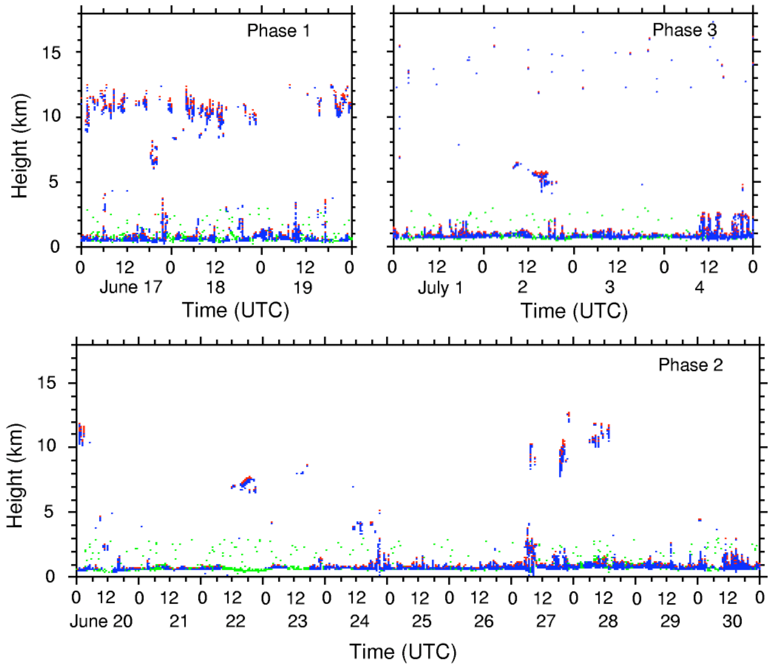

Fig. 3. Cloud base height (blue), cloud top height (red) and planetary boundary layer height (green) observed with the lidar during Nauru99.

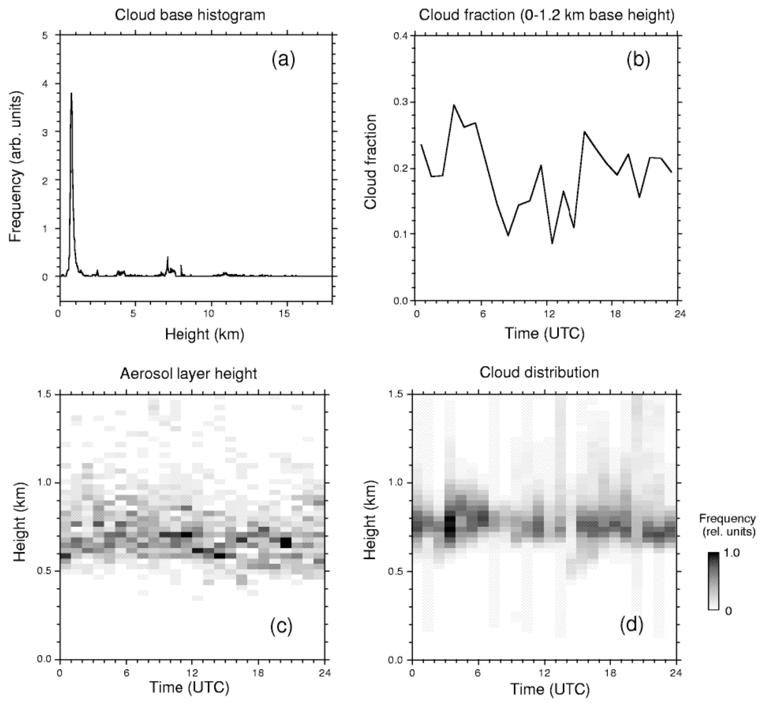

Fig. 4. Histogram of cloud base height in IOP Phase 2, diurnal variation of cloud fraction, diurnal variation of histogram of the aerosol layer upper-boundary height, and diurnal variation of distribution of clouds. The gray scale for (c) and (d) indicates frequency in relative units.

3.2 Distribution and Optical Characteristics of Sea-Salt Aerosols

Aerosol backscatter coefficient at 532 nm, ratio of backscatter coefficients at 1064 nm and 532 nm, and depolarization ratio at 532 nm are shown in Fig. 5 for June 26-29 in IOP phase 2. Although geometrical form factor of the lidar system is corrected, the data below 200 m may not be reliable. In aerosol data analysis, data including clouds below 7 km were rejected. Distribution of the detected clouds is also shown in the top of Fig. 5. Backscatter coefficient showed large variability. The value in the boundary layer (at a height of 480 m) ranged from 3×10^{-7} to 4×10^{-6} m^{-1} sr^{-1} . The ratio of backscatter coefficients at the two wavelengths also showed variability and changed from 0.4 to 1. This suggests there was variability in particle size or in aerosol type. Depolarization ratio shown in the bottom of Fig. 5 exhibits an interesting feature. Slightly higher depolarization ratios were observed above the boundary layer in the daytime of June 28 and 29 (June 27, 22:00-June 28, 7:00 and June 28, 18:00-June 29, 3:00 in UTC).

We studied time variation of backscatter coefficient of aerosols, the ratio of the two wavelengths, and surface wind speed during the whole period of Nauru99 IOP Phase 2. Figure 6 shows the time variations of these parameters. We also plot integrated backscatter coefficient (IBC) at 532 nm, which we discuss later. We can see there is a correlation between backscatter coefficient and surface wind speed. The ratio of backscatter coefficients at 1064 nm and 532 nm also has a correlation with wind speed. Other meteorological parameters (not shown here) do not show significant features during the period except for the precipitation event on June 27. We can conclude from the results that aerosols observed are sea-salt particles generated by the wind. The results indicate sea-salt aerosol concentration is high and the particle size is large when wind speed is high. Also, the high depolarization layer observed above boundary layer (Fig. 5) in the daytime of the windy days is probably due to the crystallization of sea-salt particles.[6)]

IBC is a parameter accurately obtained from lidar data. IBC is useful because it can be converted to optical depth by multiplying lidar ratio. In Fig. 6 (c), IBC for height ranges of 0-1 km and 0-4.5 km are indicated. The difference is not large, and we can see that most of aerosols are distributed in the boundary layer. If we use S1 =25 sr, optical depth is approximately 0.075, at the maximum in IOP Phase 2.

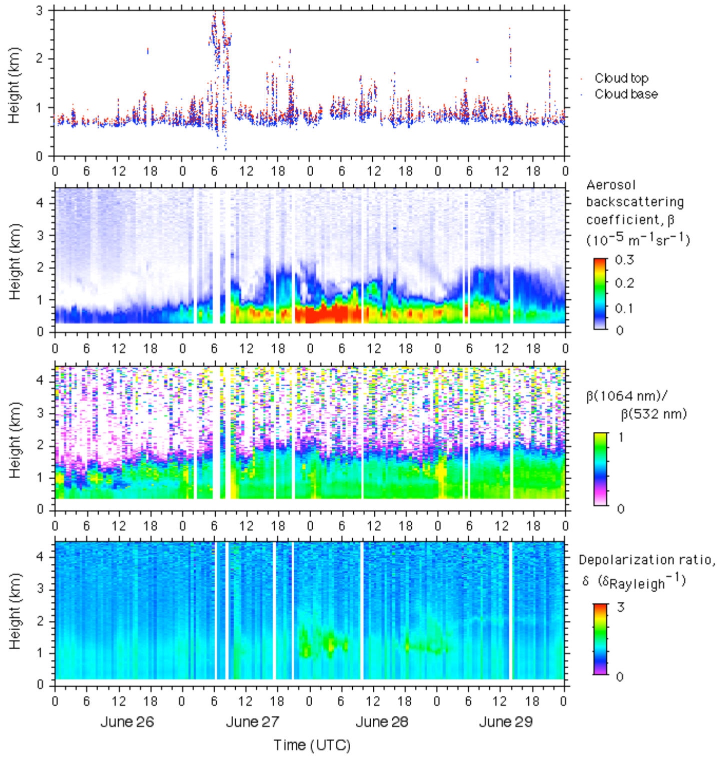

Fig. 5. Cloud distribution, aerosol backscatter coefficient at 532 nm, ratio of aerosol backscatter coefficients at 1064 nm and 532 nm, and depolarization ratio at 532 nm observed in IOP Phase 2.

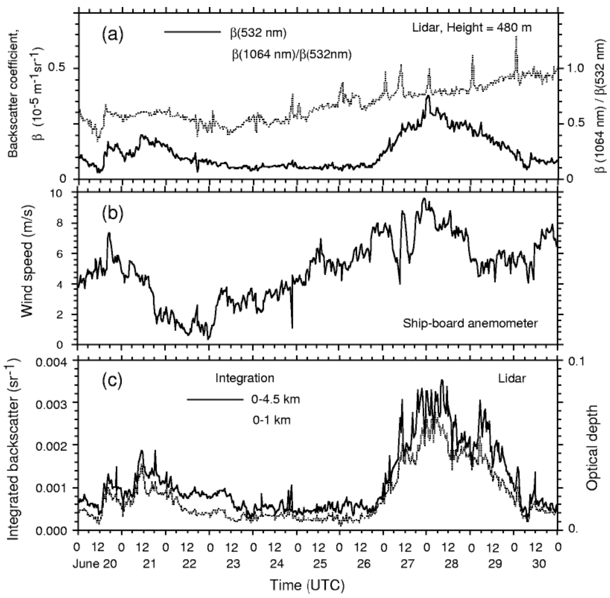

Fig. 6. Temporal variation of aerosol backscatter coefficient at 532 nm and ratio of aerosol backscatter coefficients at 1064 nm and 532 nm, surface wind speed, and integrated backscatter coefficient at 532 nm.

Figure 7 shows backscatter coefficient at a height of 480 m as a function of surface wind speed. The result scatters, but it can be fitted by an exponential function presented by Hoppel et al.[7] and O'Dowd and Smith[8] which describes the relationship between density of sea-salt aerosols and surface wind speed. The present lidar observation also showed a dependence of particle size (the ratio of backscatter coefficients at 1064 nm and 532 nm) on wind speed. This result is consistent with the in-situ measurements of size distribution and scattering coefficients by Hoppel et al.[7] Dependence of IBC and optical depth on wind speed is similar to that of backscatter coefficient because IBC is almost proportional to backscatter coefficient in Fig. 6.

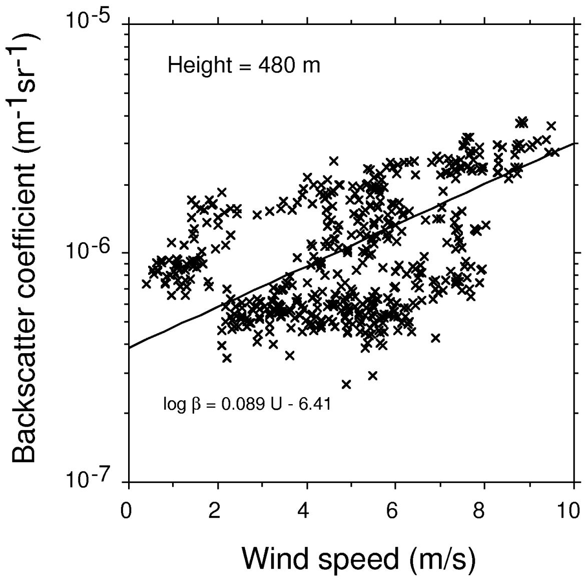

Fig. 7. Dependence of aerosol backscatter coefficient at 532 nm on surface wind speed.

3.3 Island Effect

In IOP phase 1, Mirai moved periodically in and out the lee side of the Nauru Island. Figure 8 shows temporal variation of boundary layer height, cloud base height, and cloud top height. Location of Mirai is shown in the bottom. Mirai was in the lee side of the Island when the latitude of the ship was low. We can see correlation between the ship location and the height of boundary layer and cloud height, for example from 21:00 of June 18 to 6:00 of June 19 UTC. The height was higher in the lee side of the island. The difference was clear in the daytime. It has been observed with ground based lidars that boundary layer height above land has a strong diurnal variation.[9] It is much higher than that above the ocean in the daytime. The present result is consistent with these observations.

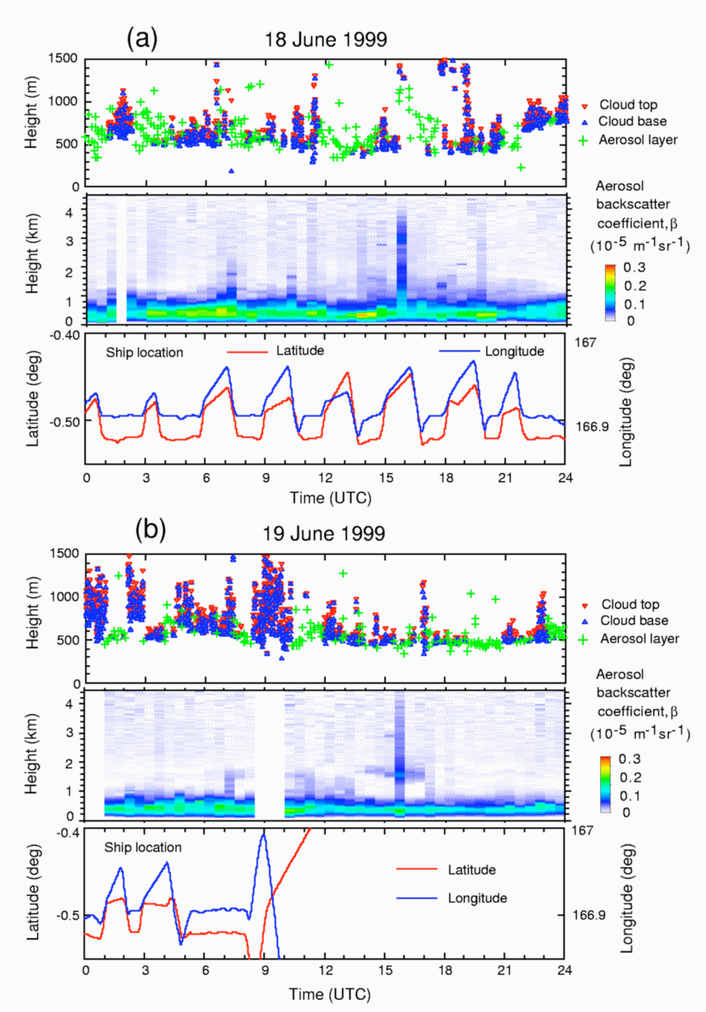

Fig. 8. Temporal variation of boundary layer height, cloud base height and cloud top height, backscatter coefficient at 532 nm, and location of R/V Mirai.

4. Conclusion

We conducted observation of aerosols and clouds with a two-wavelength lidar from R/V Mirai. We obtained cloud structure, vertical profile of aerosol backscatter coefficient, ratio of backscatter coefficient at the two wavelengths, and depolarization ratio. We also obtained integrated backscatter coefficient that can be converted to optical depth.

We observed a correlation between backscatter coefficient of sea-salt aerosols and surface wind speed. The ratio of backscatter coefficients at 1064 nm and 532 nm also showed strong correlation with wind speed, indicating particle size was large when wind speed is high. Furthermore, high depolarization layer observed above the boundary layer in the windy daytime showed the crystallization of sea salt. We also obtained some examples on the effect of island on boundary layer height.

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2 波長偏光ライダーによるNAURU99 におけるエアロゾルと雲の観測

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要旨

NAURU99 において、２ 波長(532nm, 1064nm)偏光(532nm)ライダーを用いたエアロゾルと雲の観測を海洋地球研究船「みらい」で行った。NAURU99 のphase ２ の集中観測ではみらいはナウル島から約200km 離れた赤道太平洋上で１０日間の定点観測を行った。ライダーデータより大気境界層の構造、積雲の生成、海塩エアロゾルの濃度分布と光学的性質の観測を行った。ライダーで得られたエアロゾル層の高度はラジオゾンデの大気境界層高度と対応し、午後にわずかに高くなる日変化がみられた。境界層の上端付近に積雲の生成がしばしば見られた。海塩エアロゾルの後方散乱係数は海上風速と強い相関を持ち、２ 波長のライダーデータから粒径も風速の強い場合に大きいと推定されることが示された。さらに風速の強い日の昼間、大気境界層の上層に偏光解消度の高い層、すなわち非球形粒子を含む層がみられた。これは、海塩粒子の結晶化によるものと推定される。集中観測のphase1 では、大気境界層の構造の島の効果による違いが、昼間に明瞭にみられた。