Temporal Variation and Vertical Structure of the Marine Atmospheric Mixed Layer over the East China Sea from Mie-Scattering Lidar Data

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Abstract

The marine atmospheric mixed layer (MAML) has an important influence on the diffusion of air pollutants over the East China Sea. We analyzed seasonal and diurnal variations and the vertical structure of the MAML by using continuous Mie-scattering lidar data recorded from March 2008 to February 2010 at Cape Hedo, Okinawa Island, Japan. The height of the MAML showed clear seasonal variation: a summer minimum and a winter maximum, and was significantly correlated with thermal stability (S), which we defined as sea surface temperature minus the temperature at the 850 hPa level. The height of the MAML showed minor diurnal variations in summer: a nighttime minimum and a daytime maximum. We detected the entrainment layer between the MAML and the free atmosphere by analysis of the intensity of fluctuations of aerosol concentrations determined from lidar data. Both the intensity of the fluctuations and the thickness of the entrainment zone increased with increasing S. The altitude of maximum fluctuation was a little above the top of the MAML.

1. Introduction

Atmospheric pollutants originating in East Asia are transported over long distances to Japan. Ohara et al. (2008) used a chemical transport model and light detection and ranging (lidar) observation data to show that air pollutants are transported over the East China Sea in the mixed layer. The structure of the marine atmospheric mixed layer (MAML) over the East China Sea is an important factor in chemical transport models used to predict the behavior of pollutants in East Asia.

Leduc-Leballeur et al. (2011) used radiosonde data to show that the height of the MAML in the Gulf of Guinea increases with increasing sea surface temperature (SST). Sempreviva et al. (2010) used radiosonde and ceilometer data acquired over the Mediterranean to show that the vertical structure of the MAML is dependent on synoptic conditions, such as advection by different air masses.

The Kuroshio Current in the East China Sea flows north-eastward along the eastern edge of the continental shelf. The commencement of cold and dry polar continental air advection over the East China Sea during winter strengthens heat flux at the air–sea interface. Consequently, the upward sensible heat flux in winter is higher than in other seasons (Ishii and Kondo 1993). There have been several intensive observation programs over the East China Sea in winter, for example, the Air Mass Transformation Experiment (Agee and Lomax 1978). Shimoda et al. (2009) used radiosonde data and numerical simulations to show the structure of convective circulation in the MAML in summer. However, the behavior of the MAML over the East China Sea through an entire year has not been revealed.

Routine radiosonde soundings at Minami-daito Island provide useful data for year-round observation of the MAML over the East China Sea. However, data are available only at 0830 and 2030 Japan Standard Time (JST), and the vertical resolution of the radiosonde data is too coarse to resolve the fine details of the MAML structure, such as the entrainment zone at the top of the MAML. On the other hand, lidar data are useful for continuous and detailed measurement of the MAML, including entrainment (e.g., Hageli et al. 2000). Thus, the Mie-scattering lidar equipment at Cape Hedo can provide detailed observations of the temporal variations and vertical structure of the MAML over the East China Sea.

In this study, we estimated the height of the MAML over the East China Sea by using both radiosonde data and lidar data, and statistically compared the results. We then considered the seasonal and diurnal variations of the height of the MAML and their dependency on thermal stability (S) based on the continuous lidar data. We also analyzed the vertical structure of the MAML, especially the entrainment zone at the top of the MAML.

2. Data and methodology

2.1 Radiosonde and lidar data

We used radiosonde data from Minami-daito Island (25.83°N, 131.23°E; 17 m above ground level) and Mie-scattering lidar data from Cape Hedo (26.87°N, 128.26°E; 60 m above ground level) to estimate the height of the MAML for the period from March 2008 to February 2010. Minami-daito Island is about 6 km in diameter and Cape Hedo is at the northern tip of Okinawa Island. The horizontal distance between Minami-daito Island and Cape Hedo is 320 km. Radiosonde observations are recorded by the Japan Meteorological Agency (JMA) twice daily at 0830 and 2030 JST. The radiosonde data contain observed values at various heights including standard isobaric surfaces. It is noteworthy that the vertical resolution of the data is higher around particular points of the temperature and relative humidity profiles, such as at the top of mixed layer. We used potential temperature θ to estimate the height of the MAML.

Lidar observations recorded at Cape Hedo by the National Institute for Environmental Studies of Japan are made at 15-min intervals. Details of the lidar technique were described by Shimizu et al. (2011). In our study, we used the extinction coefficient of a spherical aerosol at 532 nm, α, with vertical resolution of 30 m, to estimate the height of the MAML.

For our analysis of the vertical structure of the MAML from lidar data, we used backscatter intensity data recorded from the end of December 2008 to the beginning of June 2009. One profile of backscatter intensity, comprising 100 shots, is obtained over a period of 10 sec, and 30 sequential profiles are obtained over a period of 5 min. The continuous 5-min observations are repeated with 10-min breaks between observations. Backscatter intensity data are recorded at 6-m intervals from the ground surface to 3000 m above ground level. Because backscatter intensity is approximately proportional to aerosol concentration, we consider that fluctuations of backscatter intensity around the top of the MAML are associated with the turbulence at the entrainment zone (Boers and Eloranta 1986).

2.2 Estimation of height of MAML

To avoid the influence of land, we analyzed only data from more than 300 m above ground level. Furthermore, we used data recorded only when the speed of wind coming from the sea was greater than 1 m s⁻¹ below the 850 hPa level. We defined winds from the sea at Cape Hedo as those approaching the lidar station.
from within the arc from south-southwest clockwise to east-southeast. At Minami-daito Island, we considered that all winds were from the sea. We used JMA mesoscale analysis (MANAL) data, which provides upper wind data at the 1000, 975, 950, 925, 900, and 850 hPa levels every 3 h, to screen out winds approaching Cape Hedo from the land. To negate the influence of cloud, we excluded data when the lidar detected clouds below 3000 m altitude.

We defined the height of the MAML determined from radiosonde data, $H_0$, as the lowest height at which the vertical gradient of potential temperature, $\Delta \theta / \Delta z$, was greater than or equal to 6 K km$^{-1}$ between two observation levels (Sasano et al. 1982), or as the lowest height at which $\Delta \theta / \Delta z$ was greater than or equal to 2 K km$^{-1}$ for four successive observation levels. We defined the height of the MAML determined from lidar data, $H_\alpha$, as the lowest height for which $\alpha$ was greater than $5.0 \times 10^{-3}$ m$^{-1}$ and the vertical gradient, $(\alpha_\alpha - \alpha_{\alpha-})/\alpha_\alpha$, was less than $-0.08$

3. Results

3.1 Height of MAML from lidar and radiosonde data

Table 1 shows our statistical comparison of $H_0$ and $H_\alpha$ at 0830 and 2030 JST. There is a significant correlation between $H_0$ and $H_\alpha$ ($R \geq 0.5$) regardless of time. The means of $H_0$ and $H_\alpha$ at both 0830 and 2030 JST are consistent, as $MB$ ($NMB$) at 0830 JST is $-18$ m ($-2.1$%) and $MB$ ($NMB$) at 2030 JST is $46$ m (5.1%). On the other hand, there are some disagreements between $H_0$ and $H_\alpha$, as both RMSE and NME values are high. We conjecture that the disagreements are caused by one or more of the following: (1) the existence of a floating aerosol layer near the top of MAML over Cape Hedo; (2) the stable layer at the top of the MAML is too small to be detected by radiosonde; (3) the lidar data are provided as 5-min averages, whereas the radiosonde data are instantaneous observations, as discussed by Cooper et al. (1996); and (4) the horizontal distance between Minami-daito Island and Cape Hedo is 320 km, although Stull (1988) mentioned that the height of the MAML varies by only 10% over horizontal distances of 1000 km.

3.2 Temporal variations of height of MAML

a. Seasonal variation

We identified clear seasonal variations of both $H_0$ and $H_\alpha$ (Fig. 1): both are low in summer and high in winter. The height of the MAML is lowest in July ($H_0$, 601 m; $H_\alpha$, 626 m) and highest in December ($H_0$, 1228 m; $H_\alpha$, 1196 m). The seasonal variation of sensible heat flux from the East China Sea to the atmosphere estimated by Ishii and Kondo (1993) also shows a minimum in summer and a maximum in winter. The seasonal variations of the height of the MAML correspond reasonably well to those of sensible heat flux, though there are small differences. For example, the height of the MAML in February is about 300 m lower than that in January, despite the comparable sensible heat flux in January and February. The height of the MAML during the cold season (Nov–Apr) tends to change abruptly (e.g., the difference between November and December in 2009 is 524 m for $H_0$ and 353 m for $H_\alpha$). On the other hand, there is little variation of the height of the MAML during June, July, and August, and the error bars in summer are smaller than in other seasons (Fig. 1). Thus, the height of the MAML in summer is less variable than in other seasons.

Figure 2 shows the relationship of daily mean $H_0$ to daily mean thermal stability, $S_T$ (we defined as $SST$ minus temperature at 850 hPa altitude), for each season from March 2008 to February 2010. To calculate $S_T$, we used the SST determined daily by the JMA at about 1100 JST near Cape Hedo on the basis of satellite data calibrated with buoy and ship observations (Guan and Kawamura 2004). We neglected the diurnal variation of SST, because, unless surface wind speed is less than 2 m s$^{-1}$, the diurnal range of SST is less than 1.5 K (Webster et al. 1996). For the temperature at the 850 hPa level over Cape Hedo, we used data recorded in MANAL every 3 h. Thus, we used up to eight $S_T$ values when calculating the daily mean.

![Fig. 1. Seasonal variations of monthly mean height of the MAML estimated by radiosonde ($H_0$) and by lidar ($H_\alpha$) from March 2008 to February 2010.](image)

![Fig. 2. Scatter plot of daily mean thermal stability ($S_T$) versus daily mean height of the MAML estimated by lidar ($H_\alpha$) from March 2008 to February 2010. Data points are color-coded by season. The line used to calculate the daily mean.](image)
There is a significant correlation ($R = 0.81, N = 445$) between daily mean $H_s$ and daily mean $S$. The height of the MAML is associated with $S$. The slope of the regression line indicates that $H_s$ increases approximately 75 m for each 1 K increment of $S$. The correlation coefficients for $H_s$ and $S$ are 0.75, 0.27, 0.77, and 0.83 for spring (Mar–May), summer (Jun–Aug), autumn (Sep–Nov), and winter (Dec–Feb), respectively. We suppose that the low correlation coefficient in summer is caused by the relatively constant diurnal cycle of the height of the mixed layer, especially in summer: a nighttime minimum and a daytime maximum. Johnson et al. (2001) showed similar diurnal variations and explained that the diurnal cycle of the height of the mixed layer is consistent throughout the year, but it is absent more often in spring and winter than in autumn and winter.

b. Diurnal variation

There have been a few previous studies of diurnal variation of the height of the MAML. For example, Betts et al. (1995) reported a predawn maximum in the North Atlantic (28°N, 24°W) on the basis of 3-hourly sondes, whereas Johnson et al. (2001) reported an afternoon maximum in the tropical zone of the western Pacific from 6-hourly sondes. We analyzed the diurnal cycle of the MAML throughout the year by using lidar measurements over the East China Sea (Fig. 3). The difference of the maximum and minimum values of $H_s$ was 28% of daily mean $H_s$ in summer, whereas it was 17–19% in other seasons. Thus, there is a small (about 150 m) diurnal variation of the height of the MAML, especially in summer: a nighttime minimum and a daytime maximum. Johnson et al. (2001) showed similar diurnal variations and explained that the diurnal cycle of the height of the mixed layer was caused by the relatively large (up to 2–3 K) diurnal cycle of SST.

Fig. 3 also shows that the diurnal variation in winter is comparable in amplitude to the variation in summer, while the diurnal cycle in winter is reversal to the cycle in summer: a daytime minimum and a nighttime maximum. However, the implication is not clear and needs further consideration.

3.3 Fine vertical structure of the MAML from lidar data

For our analysis of vertical structure of the MAML, we defined $H_s$ as the mean and $\sigma$ as the standard deviation of backscatter intensity over 5-min periods (30 data points) for each height (e.g., Supplement 1). The values of $\mu$ and $\sigma$ are approximately proportional to the mean and standard deviation of aerosol concentration, respectively. We analyzed the profiles of $\mu$ and $\sigma/\mu$ from December 2008 to June 2009.

To clarify the relationship between the vertical structure of the MAML and $S$, we examined $\mu$ and $\sigma/\mu$ profiles for three ranges of $S$: 3–12 K, 12–15 K, and 15–24 K. The individual $S$ ranges were selected to provide an approximately even distribution of samples across the entire range. To eliminate the effect of differences of the height of the MAML, we normalized the heights of the $\mu$ and $\sigma/\mu$ profiles by dividing them by $H_s$, thus producing dimensionless profiles (Figs. 4a and 4b). We then calculated the average value of $\mu$ (Fig. 4a) and the median value of $\sigma/\mu$ (Fig. 4b) for each dimensionless height for each $S$ range. The profiles of averaged $\mu$ in Fig. 4a were normalized by the value at the top of the MAML (dimensionless height = 1).

The three profiles of average $\mu$ within the MAML are similarly uniform (Fig. 4a) and decrease above $H_s$, indicating that aerosols are well mixed below $H_s$, owing to convection, regardless of $S$. In general, the aerosol concentrations are high in the mixed layer and low in the free atmosphere, and there is a transition zone around the top of the mixed layer in which the aerosol concentrations decrease gradually. The median of $\sigma/\mu$ reaches a maximum around $H_s$ (Fig. 4b), reflecting entrainment at the transition zone. Furthermore, if the normalized entrainment thickness is defined as the range over which the median of $\sigma/\mu$ is greater than 0.05, the dimensionless thicknesses of the entrainment layers are 0.25 for $S$ of 3–12 K, 0.26 for $S$ of 12–15 K, and 0.29 for $S$ of 15–24 K. Thus, we consider that the entrainment thickness amounts to about 25–30% of the height of the MAML. Stull (1988) summarized that the average of entrainment thickness is about 40% of the height of the mixed layer based on some researches by lidar measurements and laboratory experiments. Hence the entrainment thickness over East China Sea estimated by this study tends to be thinner than the previous results. However, it is not evident whether the difference is significant because the entrainment thickness depends on the
estimated methods and the definitions.

Figure 4c demonstrates the dependency of the median of $\sigma/\mu$ profiles on $S$, around the entrainment zone. To eliminate noise in the lidar data, we calculated the median of $\sigma/\mu$ for each height (6-m intervals) for each $S$, range, and subtracted the value of $\sigma/\mu$ at $H_0 + 200$ m from the value at each data point. Noise influences the value of $\sigma$ for higher altitudes of the MAML, because the noise level is proportional to the square of elevation above the lidar equipment (see Supplement 1). We set the reference level at $H_0 + 200$ m because the vertical profile of the median of $\sigma/\mu$ at $H_0 + 200$ m is nearly constant for each range of $S$. The height of the $\sigma/\mu$ peak is $12-36$ m higher than $H_0$, for every $S$, range. This result is similar to that of Lammert and Bosenberg (2006), who showed that the height of the mixed layer determined on the basis of aerosol variance is a little higher than that determined on the basis of aerosol gradient. Further, we suggest that the higher the $S$, range, the greater the maximum of the median of $\sigma/\mu$ (Fig. 4c), which indicates that entrainment intensity is dependent on $S$. If we define the thickness of the entrainment zone as the range of heights over which the median of $\sigma/\mu$ is greater than zero in Fig. 4c, the thicknesses are $336$ m for $S$, of $3-12$ K, $366$ m for $S$, of $12-15$ K, and $378$ m for $S$, of $15-24$ K. Therefore, we also suggest that the higher the $S$, range, the greater the thickness of the entrainment zone.

4. Conclusions

The 30-m resolution lidar from Cape Hedo provides useful data for analysis of seasonal and diurnal variations and of the vertical structure of the MAML over the East China Sea. We estimated the height of the MAML from the gradient of the extinction coefficient of a spherical aerosol measured for 5 min by a 532 nm laser every 15 min from March 2008 to February 2010. We also investigated the vertical structure of the MAML and the thickness of the entrainment zone by using high-resolution lidar backscatter intensity data, for which vertical resolution was 6 m and time resolution was 10 sec, from the end of December 2008 to the beginning of June 2009.

The existence of the MAML over the East China Sea was relatively consistent throughout the year. The correlation coefficients between the heights of the MAML determined from lidar data and from radiosonde data were greater than 0.5 at both 0830 and 2030 JST, and the monthly means and seasonal variations determined by both methods were consistent. We found that the height of the MAML had a clear seasonal variation (low in summer and high in winter), which reflects the seasonal variation of $S$. Our analysis showed that the height of the MAML increased by about 75 m for each 1 K increase of $S$. The height of the MAML had a small (about 150 m) diurnal variation in summer: a nighttime minimum and a daytime maximum. The difference of the maximum and minimum of $H_1$ was 28% of daily mean $H_1$, in summer.

The vertical structure of the MAML over the East China Sea is similar to the vertical structure of the mixed layer observed in other studies over land. We found that the vertical profile of aerosol concentrations within the MAML is nearly uniform and independent of $S$. We found that the entrainment zone determined from lidar data amounted to 25–30% of the height of the MAML. The height of the maximum fluctuation of aerosol concentrations was $12-36$ m higher than the top of the MAML for the full range of $S$, we considered. We suggest that both the intensity of these fluctuations and the thickness of the entrainment zone increase with increasing $S$.

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Supplement

An example of our analysis of the vertical structure of the MAML from backscatter intensity data is shown in Supplement 1.

References


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