NOTES AND CORRESPONDENCE

**Structure of a Sea-breeze Front Revealed
by Scanning Lidar Observation****By Hideaki Nakane and Yasuhiro Sasano***Atmospheric Environment Division, the National Institute for Environmental Studies,
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Vertical structure and air motion around a sea-breeze front have large effects on transport of air pollutants. Field observations (e.g., Simpson *et al.*, 1977; Keen and Lyons, 1978; Ogawa *et al.*, 1986), laboratory experiments using water tanks (Simpson and Britter, 1980; Mitsumoto *et al.*, 1983) and numerical simulations (e.g., Estoque, 1961; Pearson, 1973; Kondo and Gambo, 1979) have given information on the general characteristics of sea-breeze or lake-breeze fronts. Simpson *et al.* (1977), Simpson and Britter (1980) and Mitsumoto *et al.* (1983) also pointed out that a sea breeze often forms a gravity current with a head that is an isolated vortex with strong swirls.

In order to observe the detailed structure of the sea-breeze front which has complex structure and rapid motion, measurement methods with high temporal and spatial resolution are indispensable. Lidar is one of the instruments which have potential for such measurements.

We successfully observed the vertical structure of a sea-breeze front with high spatial resolution in short measurement time by a lidar using aerosols as tracers; this observation gives the shape and turbulence structure of the sea-breeze front.

2. Inland penetration of the sea-breeze front

Lidar observation of the sea-breeze front was carried out over the region in the Kanto plain

about 60 km north-east of Tokyo, Japan on Feb. 15, 1984 using the ground-based large lidar of the National Institute for Environmental Studies (NIES) (Shimizu *et al.*, 1985). The observed region was the 10 km $\times$ 10 km area indicated by the square in Fig. 1. The distance from the center of this region to the east coast facing the Pacific Ocean is about 35 km. Within the region between the lidar site and the coast, there are two lakes surrounded by a flat terrain with a height of 20–30 m above sea level (a.s.l.).

The surface weather map at 9:00 JST on that day shows that an anticyclone was over the East China Sea and a cyclone was located over the Pacific Ocean 1000 km east of the Kanto district. Since the large-scale pressure gradient over the Kanto district was 0.006 mb/km at 9:00 JST and it decreased till the evening, the wind was weak during the daytime although the wind system was complex.

Though some scattered clouds were seen, the intensity of solar radiation integrated over the daytime was 298.8 cal cm⁻² (Yamaguchi and Fujinuma, 1985), which was about 2/3 of that during the summer time. The temperature of the ground surface reached its maximum of 16.2°C at 11:00 JST at NIES, and the sea surface temperature was 7°C 30 km off the east coast (estimated from the data offered by Ibaraki Prefectural Fisheries Experimental Station). Before 11:00, the atmospheric pressure

Fig. 1 Inland penetration of the sea breeze. Hatched areas are sea or lakes. Measurement sites A-K supplied continuous chart records of wind directions and wind velocities. Dash-dotted lines are the positions of the sea-breeze front at 14:00, 15:00, 16:00, 17:00 and 18:00 JST estimated from the wind data. Arrows are wind vectors at 17:00 JST. Lidar measurements were carried out over the region bounded by the broken line.

at Aerological Observatory near the point J indicated in Fig. 1 was higher than that at the coastal measurement site (Choshi Local Meteorological Observatory) which is 25 km south-east from the point C. During the period from 11:00 to 17:00, the pressure at the inland measurement site was lower than that at the coastal site and after 17:00 the inland pressure became higher again. The diurnal variation of the pressure difference between the coastal and inland sites as stated above was favorable for inland penetration of a sea breeze.

The time when the wind direction changed from offshore to onshore is shown at each point (A-K) in Fig. 1. This shows that the change in wind direction occurred sequentially from the coastal region to the inland region.

Figure 2 depicts the temporal changes in relative humidity, temperature, wind direction and wind velocity at the point G in Fig. 1. A little after 17:00 JST, the wind direction changed from WNW to ENE, the wind speed increased from 1.5 m/s to 2.7 m/s, the temperature decreased from 4.5°C to 3.0°C and the relative humidity increased from 25% to 48%. Similar changes in the meteorological elements were

observed at all points (A-K) where these meteorological elements were observed, though the points B, D, F, H and K measured only wind direction and wind velocity. Changes in wind direction shown in Fig. 1 except for the data at the point I and J were obtained from such record charts as those in Fig. 2 offered by Ibaraki Prefecture Government. The point I is Environmental Research Center of the University of Tsukuba and the point J is the meteorological tower of Meteorological Research Institute.

The facts stated above indicate that a cool and humid air mass from the coast penetrated inland against the offshore wind; this means that a gravity current with a distinctive front structure advanced inland that day. The diurnal variation of the pressure difference between the inland and coastal measurement sites suggests that this gravity current was a sea breeze. The positions of the sea-breeze front at 14:00, 15:00, 16:00, 17:00 and 18:00 JST were interpolated from the frontal passage times and are indicated in Fig. 1 by dash-dotted lines.

Fig. 2 The temporal changes in relative humidity, temperature, wind direction and wind velocity at the point G in Fig. 1.

3. Lidar observation and data processing

The lidar observation started at 17:05 JST. First, a PPI (Plan Position Indicator) measurement for 2 minutes was carried out, followed by an RHI (Range Height Indicator) measurement for 2.2 minutes from 17:08 JST. The PPI measurement gives an aerosol distribution in a horizontal plane while the RHI measurement gives that in a vertical plane. The height of the plane scanned by the lidar in the PPI mode with the elevation angle of 0.2° was 74 m (106 m) a.s.l. at the near (far) edge of the observed region. The range resolution along the laser beam was 30 m. The angular resolutions in PPI and RHI measurements were 0.27° and 0.1° , respectively. These angular resolutions correspond to the approximate range resolution of 47 m and the height resolution of 17 m at the center of the observation area.

In order to obtain the concentration profiles of aerosols as a function of range, it is necessary to solve the lidar equation. The Fernald's solu-

tion (Fernald, 1984; Sasano and Nakane, 1984) was applied to obtain the concentration profiles of aerosols in terms of the volume extinction coefficient.

In the Fernald's solution, the aerosol extinction to backscatter ratio, S_1 , must be assigned. We assumed the value of 50 for S_1 (Nakane *et al.*, 1985). We also analyzed the same data by assuming the values of 20 and 80 for S_1 , and examined the sensitivity of the solution to S_1 . We found that S_1 affects the magnitude of the volume extinction coefficient of aerosols, but that it has little influence on the general features in the pattern of aerosol distributions. This assures us of getting the structure of sea-breeze fronts irrespective of the assumed parameter S_1 .

4. Results and Discussion

Figure 3 indicates the horizontal concentration distribution of aerosols obtained by the PPI measurement. A distinct boundary which divides the region into two parts runs from north to south. This boundary coincides with the location of the sea-breeze front, judging from the analysis in section 2. Plume-like structures can be seen in the region west of the boundary. However, aerosol distribution seems rather homogeneous with high concentration in the eastern region. This difference suggests that the meteorological condition and the properties of the air mass in each side were substantially different. Although we have no information on the properties of aerosols in the eastern region, it is possible that the high humidity and sea-salt particles increased the concentration of aerosols in this region.

We conclude from these facts that the boundary corresponds to the sea-breeze front.

Figure 4 represents the vertical cross-section of the concentration distribution of aerosols, which was obtained by the RHI measurement over the dash-dotted line in Fig. 3. In the figure, we can find a boundary where the concentration of aerosols has a steep gradient. The location of the boundary on the ground level is 7.5 km away from the lidar site and coincides with that of the sea-breeze front at the moment when the lidar observation was carried out. Therefore, the region having high concentration of aerosols

Fig. 3 The vertical cross-section of the concentration distribution of aerosols obtained by the urement. The aerosol concentration in terms of the volume extinction coefficient, α_1 , is displayed by ten color slice levels. (The volume extinction coefficient due to air molecules, α_2 , is as large as $1.33 \times 10^{-5} \text{ m}^{-1}$ at $T=15^\circ\text{C}$, $P=1 \text{ atm}$).

Fig. 4 The vertical cross-section of the concentration distribution of aerosols obtained by the RHI measurement over the dash-dotted line in Fig. 3.

can be regarded as the head of the sea breeze as shown by Simpson *et al.* (1977).

In the head of the sea breeze, the aerosols with high concentration occupy the bottom layer and the region just behind the frontal surface of the sea breeze. This aerosol concentration distribution pattern with the meteorological data shown in Fig. 2 suggests that the cool and humid air from the sea is considered to have flowed from the right to the left in the bottom

layer and then to have risen behind the frontal surface. This air must have returned to the right through the upper part of the head. Such a flow pattern was observed by Ogawa *et al.* (1986) in their field observations. Thus, the flow can be classified into three regimes, *i.e.* the in-flowing sea breeze (I), the returning flow (II) and the ambient wind (III).

There can be seen some billows in the upper part of the head; this suggests the existence of

turbulence. These billows are similar to those in gravity current heads observed in a laboratory water tank and explained as the result of the Kelvin-Helmholtz instability and/or the gravitational instability (Britter and Simpson, 1978; Simpson and Britter, 1979; Simpson and Britter, 1980).

The upper part of the head has warmer and clearer air than the bottom layer because of entrainment of the warm and clear air out of the head due to the instabilities stated above (Simpson and Britter, 1979). Therefore, it is anticipated that there are temperature inversions between the bottom layer of the head (I), the upper part of the head (II) and the region of ambient air (III). Since a steep gradient in the concentration of aerosols is expected in each inversion layer, an edge enhancement technique (Sasano *et al.*, 1982) is useful to get the interior structure of the frontal head.

By taking a finite two-dimensional differentiation to enhance the aerosol distribution structure (Fig. 4), we can easily recognize the boundaries dividing the atmosphere into the three regions, I, II and III as shown in Fig. 5.

Parameters characterizing the structure of the sea-breeze front obtained from Fig. 4 and Fig. 5 are summarized as follows:

- 1) the thickness of the bottom layer (I) is about 300 m,
- 2) the head of the sea-breeze front reached

higher than 1300 m,

- 3) the frontal surface formed an angle of 45° with the ground surface below 500 m, 14° below 1000 m and 6° above 1000 m, and
- 4) the wavelength of the billows in the upper layer was about 2 km.

The meteorological data also give the characteristics of the sea-breeze front as follows:

- 5) the advance rate of the sea-breeze front was 3.3 m/s,
- 6) the direction and velocity of the sea-breeze and the ambient wind were ENE, 8 m/s and WNW, 5 m/s, respectively, and
- 7) the relative difference in the air density between in and out of the sea-breeze head was 0.58%.

The data related to 6) and 7) were measured by the instruments installed at the height of 200 m of the meteorological tower of Meteorological Research Institute which is located at the point J in Fig. 1.

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Fig. 5 The two-dimensional differentiation of Fig. 4 for enhancement of the aerosol distribution structure. The two-dimensional gradient of the volume extinction coefficient for each pixel is displayed by ten gray slice levels.

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掃引型ライダー観測によってとらえた海風前線の構造

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