Joint Monitoring and Analysis of Sea Fog Using Dual Visibility Lidar in Ningbo, China

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Abstract. Visibility lidar has obvious monitoring advantages over forward scatter visibility sensors or fog droplet spectrometers; it can measure visibility information over a large area. In 2021, two visibility lidar instruments (1064 or 532 nm wavelengths) were installed in Beilun, Ningbo Zhoushan Port, to monitor sea fog. Comparing their monitoring data to those of forward scatter visibility sensors and a fog droplet spectrometer revealed that the visibility lidar instruments could obtain energy progress information section-by-section in the monitoring path, and could directly reflect sea fog changes. The 1064 nm lidar outperformed the 532 nm lidar regarding sea fog detection. The effective detection range decreased significantly with decreasing visibility; the reliability decreased in low-visibility, uneven atmospheres. In a low-visibility but uniform atmosphere, however, lidar data corresponded well with forward dispersion data. The 532 nm and 1064 nm lidar data sometimes differed at the same monitoring position owing to differing heights and particle reflection angles. During a sea fog event on May 9, 2021, the maximum droplet concentration was 14 cm-3, the maximum liquid water content was 0.21 g·m-3, and the maximum equivalent diameter was 49 μm. The formation of this sea fog was dominated by large particles.

Keywords. Sea fog, visibility lidar, forward scatter visibility sensor, droplet spectrometer.

1. Introduction
It is necessary to improve the comprehensive monitoring strength of marine meteorology and strengthen marine meteorological services to develop a blue economy. To enhance the current understanding of sea fog processes, various fog events that occurred during 2021 over the Ningbo Zhoushan Port area, China, were monitored in a collaborative experiment run by Ningbo Meteorological Bureau and Key Laboratory of Atmosphere Sounding, China Meteorological Administration. The monitoring instruments used in this experiment included two visibility light detection and ranging (lidar) instruments, several forward scatter visibility sensors, and a fog monitor (FM-120) [1]. The horizontal scanning visibility lidar instruments (wavelengths: 532 nm, 1064 nm), which were manufactured by Darsun Laser Technology Co., Ltd. China, can effectively acquire visibility distribution information along a path by detecting backscattering arising from the lasers.
interacting with different atmospheric components[2]. Droplet spectrometers, meanwhile, measure the particle size distributions of cloud and fog using laser forward scattering technology.

Sea fog is the main phenomenon that affects visibility at sea[3]. Within the Ningbo Zhoushan Port area, sea fog mainly appears from March to June; during this period it tends to increase monthly[4]. On May 9, obvious low-visibility sea fog occurred offshore. By monitoring the generation and dissipation processes of sea fog and analyzing the microphysical structural characteristics of the fog during the development stage, the present study aimed to contribute towards improving the operational and shipping meteorological service capabilities of the port area.

2. Materials and Project Site

2.1. Project site
In 2021, sea fog monitoring experiments were conducted by Ningbo Meteorological Bureau and Key Laboratory of Atmosphere Sounding, China Meteorological Administration in the Beilun port area of Zhoushan City, China. Within this area, forward scatter visibility sensors were mounted along the channel and scattered among the islands to monitor local visibility. Furthermore, two visibility lidar instruments were installed on the shore to monitor changes in sea surface visibility within 10 km.

Figure 1. Locations of visibility lidar instruments, and forward scatter visibility sensors. V1, V2, and V3 indicate the locations of visibility sensors; and C and D represent the visibility lidar instruments (C: 8 m altitude, 532 nm wavelength; D: 5 m altitude, 1064 nm wavelength).

Figure 1 shows the locations and monitoring areas associated with the lidar instruments and other sensors used in this study [2]. The monitoring distance of the 1064 nm visibility lidar was >15 km and that of the 532 nm lidar was >10 km. For the purposes of this study, however, the monitoring distances of both lidar instruments were set to 10 km.

2.2. Methods and Data Sources
Fog is characterized by the suspension of very small water droplets and ice crystals in air; it can result in a visibility of <1 km [5-6]. The currently-used fog forecast grading (GB/T 27964-2011) [7] came into inception on March 1, 2012; it defines five types of fog grade based on the extent of visibility, as presented in table 1.
Table 1. Observation levels and fog forecasts.

| Level     | Extent of Visibility (V) |
|-----------|--------------------------|
| Mist      | $1.0 \text{ km} \leq V < 10 \text{ km}$ |
| Heavy     | $0.5 \text{ km} \leq V < 1.0 \text{ km}$ |
| Dense     | $0.2 \text{ km} \leq V < 0.5 \text{ km}$ |
| Strong    | $0.05 \text{ km} \leq V < 0.2 \text{ km}$ |
| Extra Strong | $V < 0.05 \text{ km}$ |

The data used in this study were obtained from the data center of the Ningbo Meteorological Bureau. A fog event occurred locally on May 9, 2021; the relevant analysis data included visibility ($V_i$), FM-120, millimeter wave radar, and lidar data.

3. Observations and Results
A typical low-visibility event occurred from 19:30 on May 9 to 00:30 on May 10, 2021, as shown in figure 2 (a, b). At 18:30, the visibility range was ~20 km (Figure 2 (a, b)); this then decreased to <1 km (954 m) at approximately 19:35 at station V1 during the onset of the sea fog. The visibility range at V1 remained below 1000 m, before increasing to 1013 m after 23:20, owing to dissipation of the sea fog. During this period, the visibility range at V2 was approximately 1000 m; it only fell below 1000 m for 1 h (between 23:36 and 00:36 on the next day). Meanwhile, at V3 the visibility was <1000 m from 19:55 to 01:31 on the next day. Thus, the low visibility range of V3 (located on the island) was longer than those of V1 and V2, which were located on the mainland. From 20:05 on May 9 to 00:05 on May 10, the visibility range at V3 decreased from ~500 m to 300 m (average visibility = 380 m). The sea fog then gradually dispersed and the visibility began to rise slowly. This indicates that the fog lasted longer and was thicker on the sea surface than along the coast, as shown in figure 2 (a, b).
Figure 2. Visibility comparisons between (a) lidar C (150 m from V2 at 110°) and forward scatter sensor V2, (b) lidar D (150 m from V1 at 100°) and forward scatter sensor V1, (c) 5 km intersection of lidar C at 110° and lidar D at 90°, and (d) 10 km intersection of lidar C at 122° and lidar D at 100°. All data shown for the period from May 9, 15:00 to May 10, 00:30, 2021.

Low visibility events clearly occurred during the period from May 9, 19:20 to 23:45, 2021, as displayed in Figure 3; they were detected in dual visibility lidar scan images. Initially, visibility started to decline to <1.0 km at approximately 19:20 on May 9 (the heavy fog stage), as displayed in Figure 3 (a). Visibility then varied, but remained <1 km, before 23:45 on May 9, as displayed in figure 3 (b-f). Dense or strong fog occurred between 19:50 and 23:30.

Figure 3. Scan images from visibility lidar instruments at different times (UTC+8) during May 9–10, 2021.

Figure 4 shows spectra of the fog droplet size distributions during the low-visibility fog. The max spectrum was normally distributed, while being skewed towards larger droplet sizes. The peak
occurred at a diameter of 28-34 μm. Clarifying the distribution characteristics and microphysical parameter changes at various stages of the fog life cycle can help to improve forecasts of dense fog and strong dense fog [8-9]. During the onset of the May 9 sea fog event, namely the formation stage, the liquid water content (LWC) was low (<0.01 g·m⁻³). During the maturation stage, the LWC increased to ~0.15 g·m⁻³; the maximum was 0.21 g·m⁻³. Furthermore, the number of fog droplets exceeded 40, with a maximum of 48.

![Figure 4](image.png)

**Figure 4.** Fog droplet size distribution characteristics of fog process; D = diameter.

### 4. Discussion

As can be seen from figure 2, the lidar instruments' retrieved visibility at 150 m from each installation point showed the same trends as nearby forward scatter visibility sensors. The data were very consistent during low visibility, heavy, or dense fog periods. During high visibility conditions, however, as the forward scatter visibility sensors V1 and V2 were located on the coastline, 150 m from the first monitoring values of the lidar instruments, the data were different. During sea fog, the decreasing trends in visibility were very consistent between the two types of instrument. The inversion visibilities of lidar instruments C and D at the 5 and 10 km intersections showed the same downward trend and the low visibility values obtained almost coincided. During the period of high visibility, the height difference at 5 km was 24 m, whereas at 10 km it was 51 m, so the data were different. For lidar C, Vi at 2 km was close to the forward dispersion of forward scatter visibility sensor V3. Compared with V3, the inversion visibility and the average visibility showed the same trend across several different angles; there was little difference under low visibility.

At 16:42 and 18:48 in the direction of 122°, lidar C recorded an uneven atmosphere within 10 km during the onset of the sea fog; the visibility fluctuated greatly during this time (figure 5 (a, b); blue and yellow curves). The laser beam scans at 0.8° elevation and 2° resolution delivered a height of 140 m at 10 km, so the visibility was quite different from that obtained by the forward scatter visibility sensor. At 20:53, during the sea fog maturity stage, the atmosphere was uniform within 10 km in this direction, with an average visibility of ~250 m (figure 5 (c); green curve). At 00:38 on May 10, during the sea fog dissipation stage, the visibility changed greatly within 3 km of the sensor, but the atmosphere was uniform at 3-10 km; the average visibility was ~4700 m (figure 5 (d); red curve). This result matched that obtained from the forward scatter visibility sensor, owing to the sea fog height exceeding 140 m during the mature stage.
5. Conclusions
Dual visibility lidar instruments showed obvious advantages regarding the monitoring of sea fog in the channel of the studied port area, and of fog in the nearby sea area. Furthermore, they could monitor a larger sea area than front scatter visibility sensor or fog droplet spectrometers. By analyzing a low-visibility sea fog process in the offshore channel of Beilun port on May 9, 2021, the following conclusions can be drawn.

The characteristics of the sea fog area in the offshore channel were very obvious, the boundary was relatively clear, the land visibility was high, and the visibility within the offshore channel was relatively low. The spectrum was normally distributed (inclined towards larger droplets), the spectral width of the dense fog was ~36 μm, and the peak occurred at a diameter of 28-34 μm. The maximum droplet number concentration was 14 cm⁻³, the maximum liquid water content was 0.21 g·m⁻³, and the maximum equivalent diameter was 49 μm.

The effective detection range of the lidar instruments decreased significantly with decreasing visibility. The reliability of remote monitoring data decreased under low visibility and in an uneven atmosphere. Under a low-visibility but uniform atmosphere, the remote monitoring data corresponded well with those of forward scatter visibility sensors. The altitudes of the installation positions of the visibility lidar instruments, the elevation during scanning, and the wavelength of the laser for each lidar instrument all influenced the detection data. Lidar instruments with wavelengths of 532 nm and 1064 exhibited great differences at the same monitoring position but could monitor visibility at different heights. To improve real-world applicability, it would be better to use lidar instruments with a wavelength of 1064 nm when establishing a monitoring network. Future research should investigate the influence of adjusting the radar scanning strategy, with the aims of more accurately reflecting changes in visibility and achieving data fusion between multiple radars.

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