An observational study of fog structure and dynamics with a millimeter-wave scanning Doppler radar

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It is important to obtain mesoscale (~ several kilometers) structure of fog for modeling and forecasting. Recent studies show that fog layer has been observed to have a certain organized structure, such as cellular, roll, or band structure. Other studies show that convective and/or dynamic instabilities, shear instabilities, or gravity waves, have some influences on fog structure and dynamics. Recent advance of remote sensing technology enables us to investigate mesoscale structure and dynamics of fog. Satellites, Lidars, and millimeter-wave radars provide us a fine-scale structure of fog with a resolution of several handled meters or better. Especially, with a millimeter-wave radar, inner structure of fog can be obtained [1]. Kyoto University developed a 35-GHz scanning Doppler radar in collaboration with Mitsubishi Electric Corporation [2]. This radar has 100-kW peak power and 2-m parabolic antenna, hence three-dimensional structure and movement of fogs can be observed. With this radar, observations of sea fog were carried out in Kushiro District, Hokkaido Prefecture in the summer seasons of 1999-2002. Three-dimensional structure of sea fog, vertical and horizontal distributions, and advection were obtained by the radar for the first time.

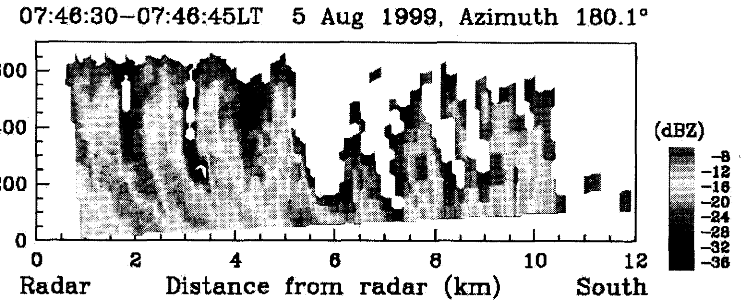

Fig. 1 Vertical cross section of radar reflectivity obtained at 0746 LT on 5 August 1999, shows cellular structure of sea fog.

Fog echo can be classified into the following three typical types: cellular echoes with high radar reflectivity factors (~ −10 dBZ), uniformly distributed echoes with high reflectivities (~ −10 dBZ), and uniformly distributed echoes with low reflectivities (~ −30 dBZ). The two cases of advection fogs with cellular echoes were focused: on 5 August 1999 and 31 July 2000 [3]. Echoes showed structures of cells with a reflectivity of −10 dBZ and with intervals of about 1 km (Fig. 1). This echo pattern moved northward (i.e., from the sea to the land). There was a vertical shear of the horizontal wind at a height around 200 m in both cases, and structures of each cell were upright above the shear line, and leaning below it. The direction and the speed of the echo pattern in both PPI and RHI display agreed well with that of the horizontal wind at heights above the

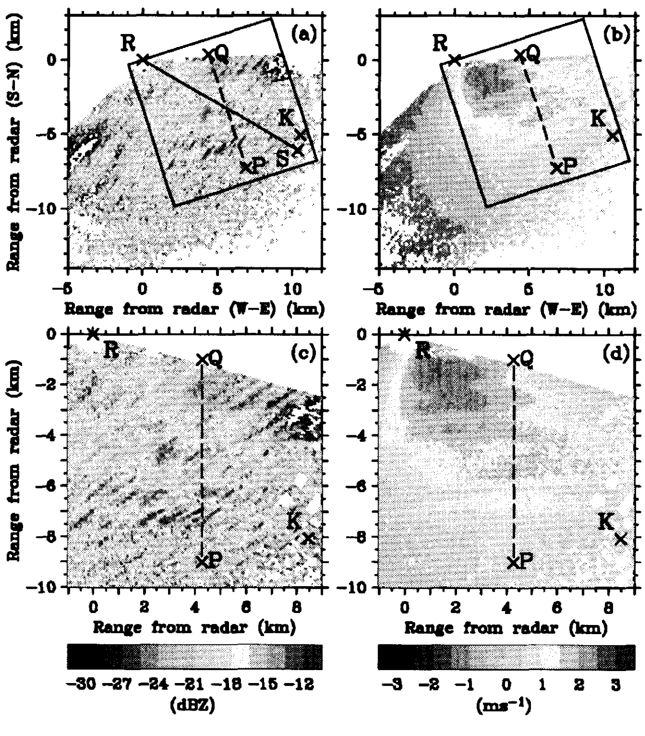

Fig. 2 Horizontal distribution of (a) Radar reflectivity and (b) Doppler velocity obtained at 0129 LT on 1 August 2000. (c) and (d) Extracted data shown in the squares of (a) and (b). This figure shows existence of roll structure (~ 300-400 m scale) in radar reflectivity, and band structure (1.5 km scale) in both radar reflectivity and Doppler velocity.

shear (200 m). These results implies that existence of drizzle drops is implied in the echo cell, and the fog droplets or the drizzle drops with certain falling speeds are being seeded from above.

Three-dimensional roll structure of fog induced by Kelvin-Helmholtz instability (KHI) was presented for the first time [4]. The case of fog with a roll structure observed on 1 August 2000 was analyzed with a millimeter-wave scanning Doppler radar and a rawinsonde data. Roll structure in a fog layer with a horizontal scale of ~ 300-400 m was observed (Fig. 2 (a) and (c)). When the roll structure was observed, extremely large vertical shear (exceeding 50 m s^{-1} km^{-1}) existed below 120 m altitude. The direction of the shear was perpendicular to the roll direction. The Richardson number was less than 0.25 at the shear altitude. This indicates that the fog roll structure was induced by KHI.

Band structure of fog associated with gravity waves was shown for the first time [5]. Band structure in fog having radar reflectivity > −21 dBZ and a scale of ~ 1.5 km was observed (Fig. 2 (a) and (c)). The band structure was also observed in Doppler velocity (Fig. 2(b) and (d)). The band structure in both radar reflectivity and Doppler velocity propagated northwestward with a speed of 4.17 m s^{-1} (Fig. 3). From linear gravity-wave theory it is estimated that the observed gravity waves had a horizontal wavelength of 1.5 km and period of 6 min.

Within the band structure induced by the gravity waves (horizontal scale ~ 1.5 km), roll structure with a smaller horizontal scale (~ 300-400 m) was also observed in radar reflectivity. A previous study has shown that this smaller-scale roll structure is caused by shear-induced KHI. For the first time this study shows that two factors, gravity waves and KHI, can cause multi-scale structure in fog.

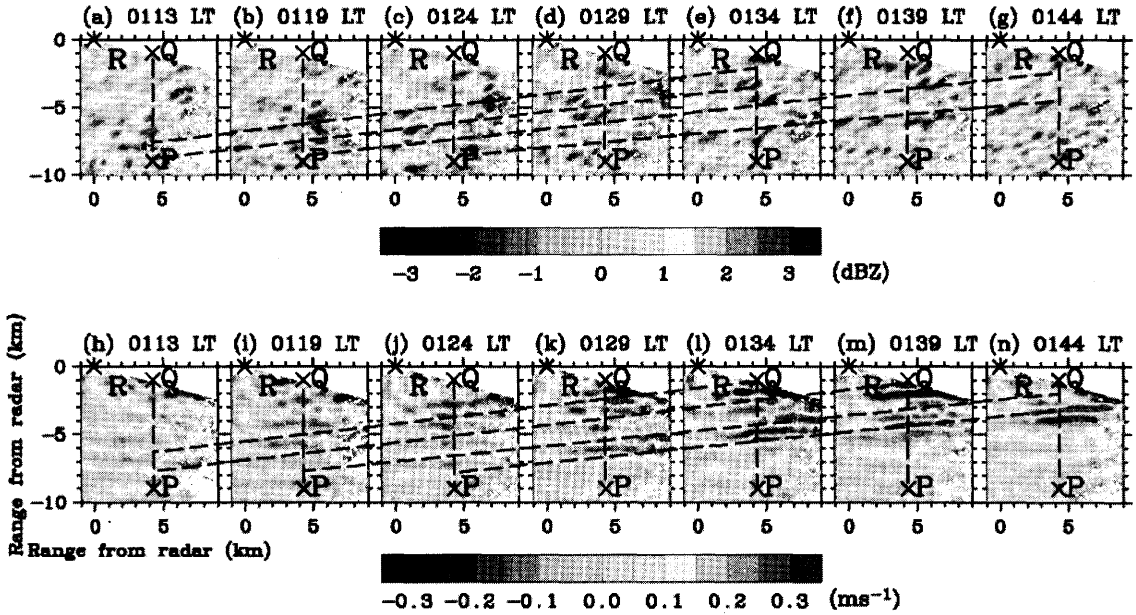

Fig. 3 (a)-(g) Radar reflectivity and (h)-(n) Doppler velocity fluctuations obtained at every 5 minutes at 0113-0144 LT on 1 August 2000, shows structure and propagation of band structure (1.5 km scale).

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