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A WSR-88D Radar Observation of Chaff Transport and Diffusion in Clear Sky

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To investigate the distribution of air pollutants dispersion in the horizontal wind fields, a chaff release experiment was carried out by an airplane. The temporal and spatial variations of a chaff plume from an elevated point source using the WSR-88D(NEXRAD) radar. The observed profiles of radar reflectivity were compared with the Gaussian diffusion model at slightly unstable atmospheric condition. The present study shows that the distributions of radar reflectivity from chaffs and their concentration by the model are in general agreement with time variation.

The dispersion coefficients in downwind(σ_x) and crosswind(σ_y) spread data exceeded what has generally been found at Pasquill and Brigg's. The (σ_z) coefficient which describes the vertical spread is less than what is predicted using Pasquill and Brigg's estimates. As a result, it was clearly shown that horizontal and vertical diffusion coefficients are more accurately determined as compared with theoretical coefficients. At longer diffusion distances(than 10km), a radar observation provided the determination of maximum range and diffusion height more qualitatively, too.

Key words : chaff release experiment, airplane, WSR-88D radar, diffusion model, downwind, crosswind, vertical diffusion coefficients

1. Introduction

Most of meteorological radars have been used to measure rainfall intensities or radial velocities from cloud movements. Doppler weather radars are occasionally used to study clear air echo. Sauvageot and Saab[1] and Campistron[2] suggested the possibility of radar observation to investigate the isolated pollution source like a plume. They described that the resonant passive electromagnetic dipoles calls chaff can be used to trace air motions characterizing the environmental mean field or to visualize by radar any air flow particularities. Chaffs experimental techniques have been successfully used in urban PBL studies[3], natural convection observations[4], turbulent diffusion in free atmosphere[5]. Moninger and Kropfli[6] and Martner et al.[7] had remote tracer measurement using chaff and had radar observations of transport and diffusion in clouds and precipitation using TRACIR(tracking air with circular-polarized radar) technique. However, these chaff experiments were examined and detected inside a thunderstorm and analytically determined the chaff concentration required for the detection in clouds with specified background conditions.

Regarding the dispersion of air pollutants, there are not many studies on the relationship between the variation of the air pollutants dispersion pattern and range using the wind fields measured by a Doppler radar. Lee et al.[8] studied an effect of wind field on the atmospheric aerosol concentration using Doppler radar. Their result showed that the variation of horizontal wind fields makes an more important role than the synoptic wind in the fluctuation of concentration of atmospheric aerosol particles. They found that the concentration of atmospheric aerosol particles had a significant variation, depending on the degree of both horizontal and vertical divergence of wind within the boundary layer where the kinematic properties of wind fields were estimated by the VAD method of single Doppler radar. However, actually direct observations for the temporal and spatial concentration distribution of air pollutants have been difficult to obtain, since they are always dispersed by the air movement as well as the limitation of aircraft measurements in clear sky.

Therefore, in this study, to investigate the influence of the horizontal wind fields on the distribution of air pollutants dispersion, a chaff release experiment was carried out by an aircraft. The temporal and spatial variations of a chaff plume from an elevated point source were observed using a Doppler radar(WSR-88D). The observed spatial distribution of the chaffs was compared with the Gaussian dispersion model at slightly unstable atmospheric condition. These results of chaff experiment and simulation will be clearly shown great contribution in the investigation of the diffusion of pollutants under the meso-scale or micro-scale air movement.

2. Experimental Methods

2.1. Chaff release

The chaff experiment was carried out at Grafton (48° 23′ N, 97° 22′ W), North Dakota, U.S.A. as shown in Fig. 1. An airplane of University of North Dakota and a WSR-88D Doppler radar of Mayville, which is located between Grand Forks and Fargo, ND were used at 6 November 1999. On 1333 LST(1933 UTC) chaff of 460g were released at the height of 2286m(7500 ft) where the flight speed of airplane was 100kts. The chaff releaser was a cylindrical hard paper box with diameter 6.5cm and length 76cm. Microwave chaff consists of almost microscopically thin aluminum-coated glass fibers that can be released into the atmosphere in great quantities. In this experiment, the length of chaff was cut to the 5cm and used their fibers number concentration was calculated as follows:

Number of chaff fibers (n) × Mass (m) = Weight(g) ------(1)

Chaff mass, $m = \rho \times v = \rho \cdot \ell \cdot \pi(\frac{D}{2})^2$------(2),

where the ρ is density and v is volume of chaff, ℓ is the length of each chaff and D is diameter of a chaff. The density of chaff is 0.182g/cm^3, The chaff releaser volume was $76cm \times \pi \times (\frac{6.5cm}{2})^2$. Therefore, chaff mass of a fiber has 0.56×10^{-5} g/fiber($0.182\, g/cm^3 \times 5\, cm \times \pi\, (\frac{0.0028\, cm}{2})^2$) by equation (2). Total number of chaff fibers (n) with 460 g were approximately more than 82,000,000 fibers in a drop.

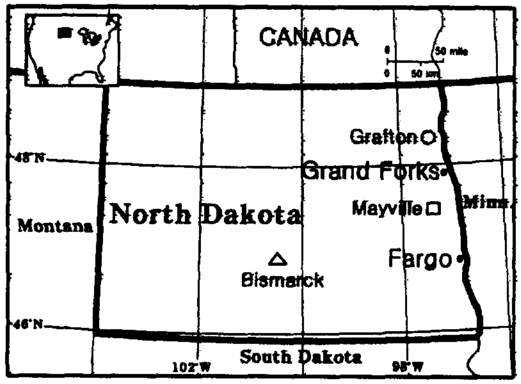

Fig. 1. WSR-88D radar site(□), chaff release point (○), and radiosonde site(△), ND, U.S.A.

2.2. Meteorological condition

The general surface synoptic situation is shown in Fig. 2. It was characterized by a broad, high pressure systems located near the eastern and northern area of North Dakota, where weather was clear. Afternoon surface wind speed in the experimental domain generally weak(2 m/s) near the central U.S. as shown in Fig. 3. At the height of chaff release point, most of wind directions were westerly winds approximately and their speeds (5 m/s) were higher than surface winds. The vertical temperature profile in Fig. 4 shows the conditionally unstable atmospheric condition at 2km height as compared with stable condition near the surface, which has radiation inversion. Convective condensation level was situated over than 600 hPa. There was an elevated inversion layer between 700 and 740 hPa. The dew point decreases with height within the inversion and the humidity at top of the inversion is low.

2.3. Radar observation

The chaff diffusion was observed using the NEXRAD radar, situated 70 km downwind of the an elevated point source. The Next Generation Weather Radar program's network of WSR-88D systems was integrated in advanced Doppler radar capabilities, real-time signal processing techniques, meteorological and hydrological algorithms, and

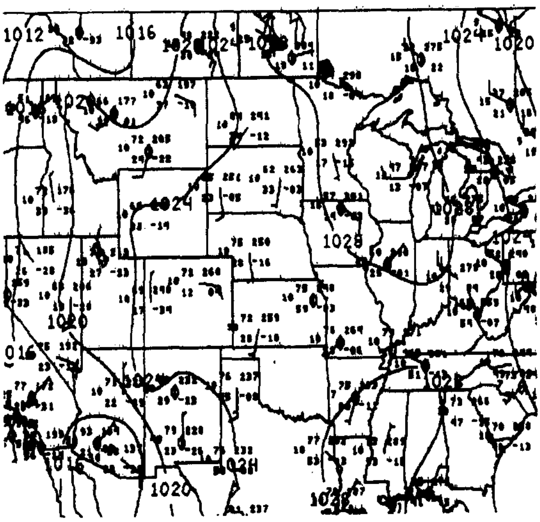

Fig. 2. 2200 UTC(1600 LDT) surface analysis from the U.S. National Meteorological Center for 6 Nov. 1999. Contours represent surfae pressure field using 4-hPa contour interval. Note the eastern and northern area fo North Dakota extended to the center of high pressure system.

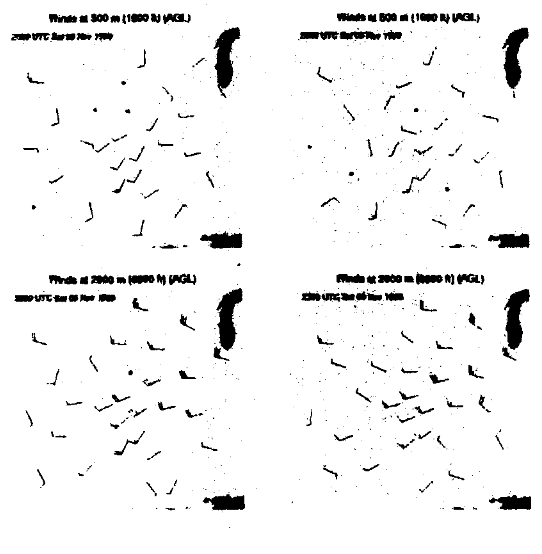

Fig. 3. Surfae wind speed between 500m and 2000m near the central U.S. on 06 Nov. 1999.

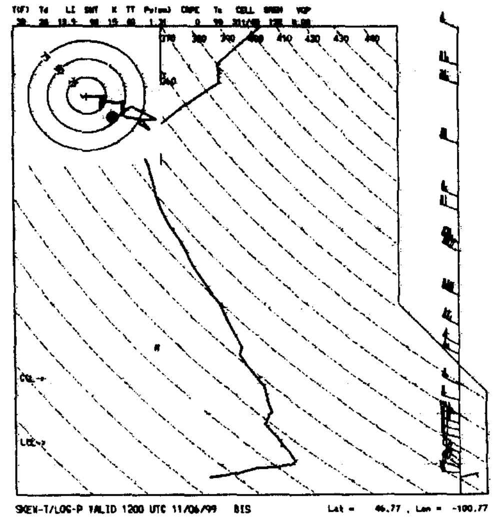

Fig. 4. Vertical temperature profile at Bismarck, North Dakota on 06 Nov. 1999.

automated product processing. Base reflectivity (R) depicted a full 360° azimuthal sweep of echo intensity data and was sampled in a volume scale at every elevation angle. The product was displayed in polar coordinates at 1° × 1-km resolution to a range of 230 km and the data level values ranged from -25 to +65 dBZ in the high sensitivity, clear air scanning strategy. Mean radial velocity (V) depicted a full 360° azimuthal sweep of radial velocity data and was available for every elevation angle sampled. This product was also displayed in polar coordinates as same resolution and range as reflectivity product. In this observation, range folding and incorrect velocity dealiasing were not existed. More detailed characteristics of a radar were explained at Table 1[9].

2.4. Chaff diffusion by Gaussian puff equation

The situation to be modeled here is an instantaneous release of a gaseous or particulate substance to the atmosphere. Most of analytical solutions for this transport mechanism are based on the Pasquill-Gifford Model. The process assumes that the release is either a constant point source that creates a "plume" or it is an instantaneous point source release of a known mass that generates a "puff". For this study, downwind concentrations are estimated based on the following assumptions :

a. The emission is an instantaneous release.
b. The concentrations are distributed as a Gaussian(i.e., Normal Distribution) in the horizontal and vertical directions relative to the wind direction. The atmospheric dispersion coefficients are actually the standard deviations of the distributions in the horizontal(σ_y(m)) and vertical(σ_z(m)) directions.
c. The dispersion along the direction of wind flow is assumed to be equal to the horizontal dispersion. This is not the case in a continuous source emission where a plume is generated because material continues to be released. After a period of time a dynamic steady-state is established, assuming that the release rate and the atmospheric conditions remain constant, where a constant concentration distribution is established.
d. The center of mass of a puff release moves downwind at a constant speed equal to the average wind speed. This is used to determine the maximum concentration at any particular downwind location.
e. Constant wind speed and direction during the entire simulation. For large release events this may not be reasonable. It is however, a reasonable first assumption in most situations that simplifies the calculations.

Instantaneously released matters at the origin (x=y=z=0) at t=0 can solve for the chaff concentration at any place and time from Eq.(3).

$$\frac{\partial c}{\partial t} = K_x\frac{\partial^2 c}{\partial x^2} + K_y\frac{\partial^2 c}{\partial y^2} + K_z\frac{\partial^2 c}{\partial z^2} \quad \text{----(3)}$$

In this chaff release experiment, two dimensional spreading Eq.(4) was used to the application of Eq.(3), since the vertical reflectivity and radial velocity values of radar were existed at constant height approximately. However actual chaff concentration was calculated at consideration of the vertical diffusion depth d as follows:

$$C(x,y) = \frac{M}{2\pi d\,\sigma_x\,\sigma_y}\exp\left[-\frac{1}{2}\left\{\left(\frac{x}{\sigma_x}\right)^2 + \left(\frac{y}{\sigma_y}\right)^2\right\}\right] \quad \text{----(4)}$$

where

$$M = d\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} C(x,y)\,dxdy =$$

$$dA\int_{-\infty}^{\infty}\exp\left(-\frac{x^2}{2\sigma_x^2}\right)dx \cdot \int_{-\infty}^{\infty}\exp\left(-\frac{y^2}{2\sigma_y^2}\right)dy$$

$$= 2\pi A d\,\sigma_x\,\sigma_y \quad \text{----(5)}$$

$$A = M/2\pi d\,\sigma_x\,\sigma_y$$

By comparing Eqs.(3) and (4), $K_x = \sigma_x^2/2t$ and $K_y = \sigma_y^2/2t$ are obtained. The x represents the downwind or upwind distance from the center of the chaff plume. Here, Eq.(3) shows maximum concentration at chaff release point without considering the viewpoint of a person riding with the flow. Thus, in fixed coordinates, or the Eulerian viewpoint, the x^2/K_x and y^2/K_y term need to be replaced by $(x-ut)^2/K_x$ and $(y-vt)^2/K_y$ term. The dispersion in the cross wind direction may be neglected, since the major transport direction due to the wind is expected to occur along the x-axis. Therefore, the equation describing concentrations in the chaff model at height H given a puff release can be represented by

$$C(x,y,0,t,H) = \left[\frac{Q_T}{(7.875\times\sigma_x\times\sigma_y\times\sigma_z)}\right]\exp\left(-0.5\times\left(\frac{x-ut}{\sigma_x}\right)^2\right)\exp\left(-0.5\times\left(\frac{H}{\sigma_z}\right)^2\right)\exp\left(-0.5\times\left(\frac{y}{\sigma_y}\right)^2\right) \quad \text{----(6)}$$

where Q_T means total mass (g) released. The σ_x, σ_y and σ_z mean longitudinal, lateral and vertical dispersion coefficients (m). The x and y mean the location of the interest point, relative to the source location. H means the effective height(m) from chaff release. The u and t mean average wind speed(m/sec) and time(sec).

The maximum concentration at any downwind distance can be determined as the centerline concentration(y=0). The maximum concentration is reached at time t=x/u. The dispersion coefficients are determined based on the atmospheric stability class and the distance from the source.

3. Results and Discussion

3.1. Horizontal distribution of chaff bundles

The data were range-normalized to yield the log of radar reflectivity. The radar reflectivity, η in m^{-1}, is related to the chaff concentration F in filaments per m^3, by the relation[10)]

$$F=\frac{\eta}{0.18\,\lambda^2}\ , \qquad (7)$$

where λ is the radar wavelength in meters. The concentration of chaff fibers in the air can be computed from the chaff's reflectivity to determine the detectable chaff-concentration thresholds for specified diffusion area. This relationship is based on the assumption that the chaff filaments are randomly oriented and homogeneously distributed in the radar pulse volume. The terminal fall velocity of chaff is smaller than 0.3 m/s and they tend to fall horizontally.

The drift and diffusion of the chaff were monitored by the radar over two hours. Fig. 5(a) shows the perspective view of the chaff release totally at a given hour from 1937 UTC to 2206 UTC, Nov. 6, 1999. Contour surface encloses the region where the average concentration is F>20 filaments per cell. The chaff bundles were widely dispersed and distributed to the northeasterly from released point around 2140 UTC. In Fig. 5(b), chaff bundles were approximately dropped from 2.2 km height to 1.8 km during 5 minutes after they released and they were dispersed to the eastern direction between 1.4 km and 1.8 km height with weak westerly winds. Most of chaffs were well mixed and nearly existed at constant level even though they had some updraft movement with the lapse of time.

Fig. 6 shows the radar reflectivities of chaff diffusion at 30 minutes interval from their release time approximately. At 1937(after 4 min. from chaff release) UTC Nov.6, 1999 chaff was dispersed to the northeastern direction with a subsiding motion, since a large bundle of chaff was dropped in a moment when they were released at a height of 2.2 km. At 2007 UTC, radar echo was flowed under the 1.6 km height and the strongest value to the 39.6 dBZ in the center of chaffs distribution. Generally reflectivity values of chaff diffusion after 2036 UTC were weaker than 35 dBZ and had wider ranges. After 2106 UTC, chaff bundles were dispersed to the eastern direction with reflectivities less than 22 dBZ and disappeared at 2206 UTC(for two hours after chaff release, approximately).

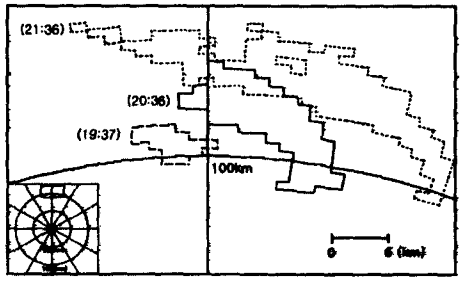

Fig. 5(a). The perspective view of the chaff release at a given hour from 1937 UTC, 2036 UTC, and 2136 UTC, 06 Nov. 1999.

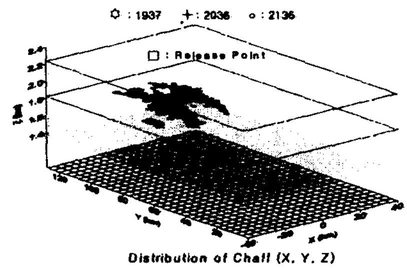

Fig. 5(b). The total chaff release from 1937 UTC to 2206 UTC, 06 Nov. 1999.

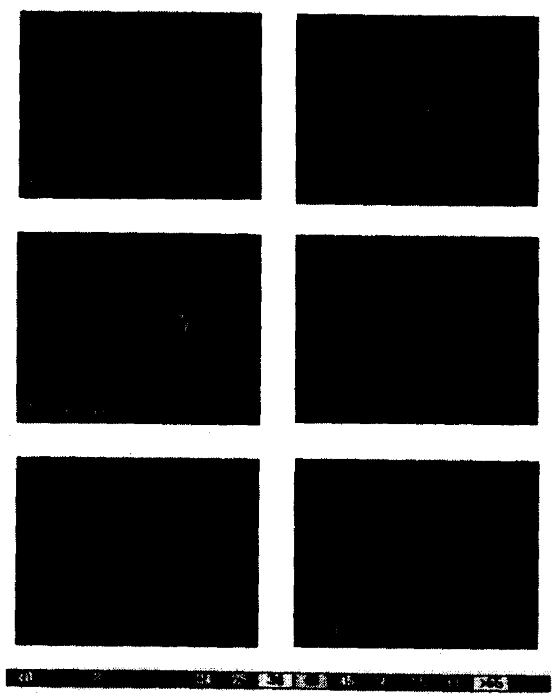

Fig. 6. The radar reflectivities of chaff diffusion at 30 minutes interval from chaff release time approximately.

The wind data were derived from the radar's Doppler velocity measurements using velocity-azimuth display(VAD) analysis. At Fig. 7, westerly winds were prevailed at the release height of chaff bundles. And at lower elevations than 2 or 2.2 km heights, there was slightly westerly winds or southerly winds. Most of winds were not strong at chaff dispersion layers. They had less than 7.7~10.3 m/s approximately and weaker and weaker near the surface layer from 2000 UTC. The horizontal distribution of radial velocities were shown in Fig. 8. At the beginning time(1937 and 2007 UTC) of chaff release, the Doppler velocities were prevailed to the northern and northeastern direction. It means chaffs were moved away from a radar site. At 2036 UTC, speed of targets increased from the eastern or southeastern and produced an increasing Doppler frequency shift even though it was westerly winds under 2 km height. This convergence phenomenon had occurred at chaff dispersion area and might be given an effect of strong dispersion to the north-eastern at 2106 UTC. Most of chaff were dispersed slightly to the north and moved away the radar site with the passage of time after 2136 UTC.

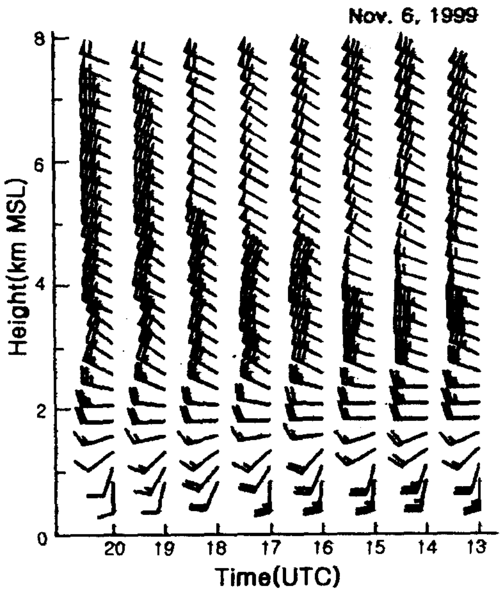

Fig. 7. WSR-88D velocity azimuth display(VAD) wind profile product on 06 Nov. 1999.

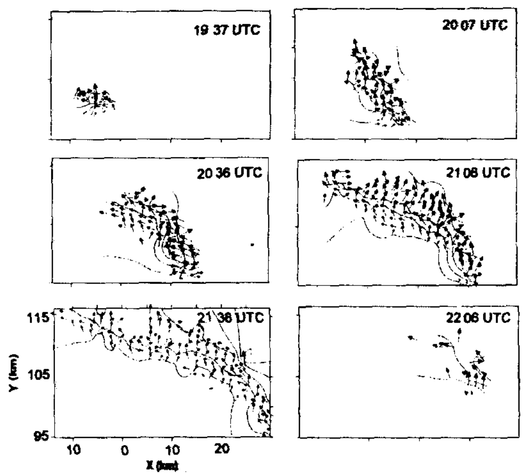

Fig. 8. The horizontal distribution of radial velocities from 1937 UTC to 2206 UTC on 06 Nov. 1999.

3.2. Comparision of radar data and dispersion model

3.2.1. Determination of dispersion coefficients

To compare the diffusion patterns between actual radar observation data and model calculation, the x, y coordinate conversion was complished from polar coordinate and interpolated to the cartesian grids the radar reflectivity data which were obtained from each volume scan. Each grid was made the sizes of 5 km to the x direction and 2 km to the y direction. The downwind and crosswind diffusion standard deviations(σ_x, σ_y) of each chaff plume were calculated for each value of y and z(Eq. 8) , x and z (Eq. 9) by using

$$\sigma_x(y,z) = \left[\frac{\int x^2\, \overline{F}(x,y,z)\, dx}{\int \overline{F}(x,y,z)\, dx} - \overline{x}(y,z)^2 \right]^{1/2} \qquad \text{------(8)}$$

$$\sigma_y(x,z) = \left[\frac{\int y^2\, \overline{F}(x,y,z)\, dy}{\int \overline{F}(x,y,z)\, dy} - \overline{y}(x,z)^2 \right]^{1/2} \qquad \text{------(9)}$$

$$\sigma_z^2(x,y) = \frac{\sum_{i=1}^{n} \left\{ z_i(x,y) - \overline{z}(x,y) \right\}^2}{n-1} \qquad \text{------(10)}$$

, where $\overline{F}$ is the temporal average concentration.

These were determined at each grid point by averaging the volume scans that had a measurable number of filaments at that grid point. Grid points near the center of the plume may have had data from all 13 volume scans which would have contributed to the average. In Figure 9, the plots show the width of the plume at the height of their maximum concentration at each value of the downwind distance x or y. The σ_x and σ_y variated to the larger values as time goes by and slope of line distribution of σ_x had more than σ_y, relatively. This means diffusion of east-west has wider than north-south direction. The σ_z values (Eq. 10) which are indicated to the vertical diffusion coefficient with time had not so larger difference as compared with σ_x and σ_y. They had shown near constant values (below 100 m or 80 m +/- 20) with the lapse of time at all the regions. This means vertical diffusion of chaff bundles was little and dispersed at constant level heights. In actual, reflectivity values of WSR-88D Doppler radar were not observed at other elevation angles and the maximum concentration was observed near the original chaff release height at 0.5° elevation. After 2147 UTC, radar reflectivities were weak and chaffs were disappeared to the wide ranges.

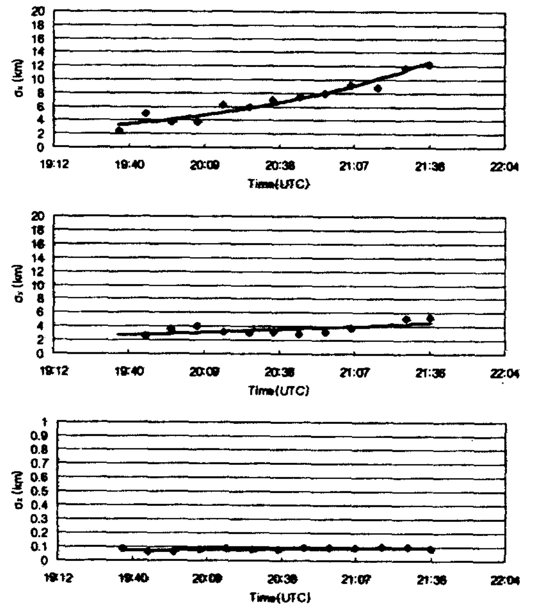

Fig. 9. The width of the plume at the height of chaff maximum concentration at each downwind distance.

Figure 10 shows the variation of Z height as a function of downwind x or y distance. Near the radar(at $x, y < 6, 95$ km), it has approximately 1.3~1.8km height. Further downwind the plume spreads slowly in Z until, for $x, y > 20, 100$ km, $Z \approx 1.4 \sim 1.7$ km height, or the boundary layer height. This is reasonable value, indicating that the chaff is spread rather uniformly throughout the boundary layer. It means that the changing depth of the boundary layer in this experiment was not occurred and the distribution of chaff in the vertical suggests that the turbulence in the boundary layer was sufficient to make the effects of chaff fall speed negligible.

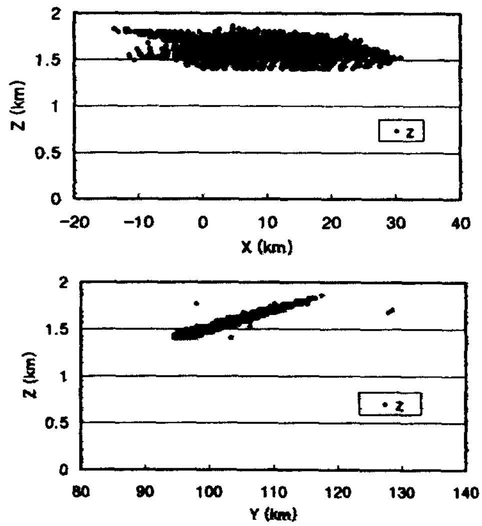

Fig. 10. The variation of z height as a function of downwind x or y distance.

3.2.2. Comparison of the concentration by radar and dispersion model

Figure 11 shows the horizontal chaff spreads versus downwind distance(km) as compared with theoretical distribution values. The σ_x and σ_y values obtained by radar observation are higher than what is predicted by the Pasquill[11] and Brigg's[12], and the difference of their gradients along downward direction and distance were considerably higher than others. In addition, each power regression equation of σ_x and σ_y values was obtained from this experiment with the Brigg's and Pasquill's dispersion coefficients for open country at slightly unstable atmospheric condition.

They showed larger values than theoretical ones. And their diffusion speed was not high as shown at duplicated marks, however they were widely well dispersed to the downwind distance as compared with theoretical ones in the figure. The horizontal chaff spreads variances were little rapidly changed at the 10 km distance from radar site. This may be explained that theoretical diffusion coefficients had different values than experimental one above 10 km at least. The σ_z value was obtained at Eq. (10) and its average value(79.6 m) was used to the equation of Gaussian dispersion model, since the vertical distribution of material in the chaff bundles were changed to the maximum at 1.86 km height from minimum value at 1.4 km height.

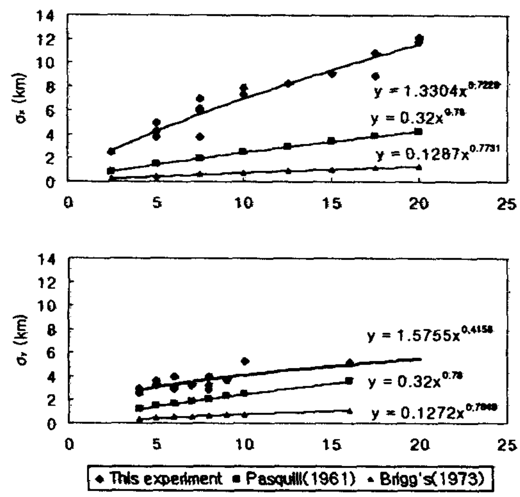

Fig. 11. The horizontal chaff spreads versus downwind distance(km) as compared with theoretical distribution values.

In Figure 12(a) and 12(b), the radar reflectivities and chaff dispersion concentration by experimental σ_x, σ_y and σ_z values were shown. In the Gaussian dispersion model, H(the effective height of plume rise) value used 400 m value which had the difference between chaff release height(2.2 km) and their fallen height(1.8 km) by the bundles weight within 5 minutes. This figure well shows and explains that theoretical σ_x and σ_y values of Pasquill and Brigg's may be greatly underestimated than radar observation values at upper boundary layer, since the distribution of chaff reflectivities and their concentration by model are in general agreement with time variation. The maximum concentration values occurred as moving to the slightly eastern side from center of the chaff release point. After 2136 UTC, they were horizontally spreaded over the 40km range which had more than 5 dBZ. This chaff diffusion was continued over 2 hours as compared with most diffusion experiments were taken over periods of a few minutes to an hour. It means the atmospheric thermodynamic state was not unstable and wind was not so strong(5 m/s) at around 1.5～2 km height. In addition, the radar had not too much attenuation from atmospheric clouds, precipitation droplets and aerosols etc., since it was very clear weather situation.

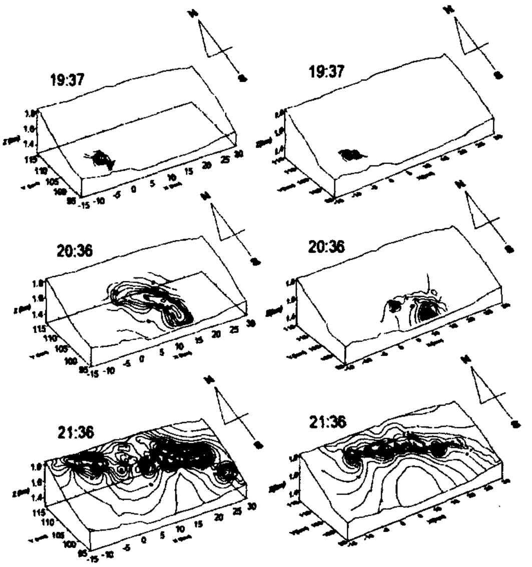

Fig. 12. The radar reflectivities(a) and chaff dispersion concentration by experimental σ_x, σ_y and σ_z values.

4. Conclusions

This study shows that Doppler radar can be an useful tool in studying transport and diffusion of air pollutants. In this experiment using an airplane and a WSR-88D radar, detailed data of chaff bundles diffusion was able to produce during more than 2 hours at slightly instable atmospheric condition. After 3 or 5 minutes released by an airplane, fall speed of chaff and their vertical diffusion heights were not dominant factors in the transportation of chaffs. They were horizontally spread over 40km by the wind and thermodynamic situation. The concentration of chaff bundles diffusion agree well with this model equation involving σ_x, σ_y and σ_z obtained by radar reflectivities. Downwind(σ_x) and crosswind(σ_y) spread data exceeded what has generally been found at Pasquill and Brigg's, probably because the wind direction during this experiment was not steady. And vertical spread data(σ_z) is less than what is predicted using Pasquill and Brigg's estimates, because of the finite boundary layer depth in this case. It was observed that the height of maximum concentration did not increase with increasing distance from the chaff release point. This differs from the results of Willis and Deardorff[13](1976).

The radar observation using chaff in clear sky is rather easy and correct to perform on standard deviation for application of diffusion equation. This may be solve the problem had a smaller scale dispersion model would limit the capability of the model to forcast beyond available data. Therefore, an experiment such as this may be recommended that radar can provide more qualitative data for concentration measurements at longer distances (than 10 km). These results of chaff experiment and simulation should be clearly shown great contribution in the investigation of the diffusion of pollutants under the meso-scale or micro-scale air movement.

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