

Idealized simulation of dual Doppler radar observation using numerically simulated clouds

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Abstract Dual-Doppler radar system is a unique instrument to detect the three-dimensional structure of cloud systems including the rain particle distribution and their movement. In the real observation of cloud systems using dual-Doppler radars, researchers have to choose a variety of options, such as time of collecting three-dimensional volumes or intervals of antenna scans, depend on their altitude, their speed of propagation, and their development activity. All the options are not satisfied, the tradeoff for high spatial resolution is lower time resolutions. Researchers have to determine the options before observation, however, it is difficult to know the effect of the tradeoff for the options they made. To know the better options before the observation, an idealized dual-Doppler observation is made using the numerically simulated cloud systems developed in the same location for observation targets. This documents introduces the process of finding better options on the observation of tropical cloud systems in the western Pacific Ocean.

Keywords: Doppler radar, Dual-Doppler synthesis, Numerical simulation, observation plan, tropical clouds

1. Introduction

Doppler radar is a unique instrument to detect the distribution and movement of rain or ice particles in clouds. It radiates microwave pulses and receives refractions from the mass of rain/ice particles. The received power tells us the density of rain/ice particles along the radar beam, and its phase shift tells us the velocity component of rain/ice particles along the radar beam through the Doppler effect. By its antenna scanning with various azimuth and elevation angles it can detect three-dimensional distribution of rain/ice particles. Usually this kind of radars has the range of tens to hundreds of kilometers, and spatial resolution of several hundred meters, therefore it is useful to observe internal structures of a cumulonimbus cloud to mesoscale convective systems.

Doppler radars have been used on both research and operational purpose for more than twenty years. All the North American, Korean, and some of Japanese operational radars are Doppler radars and they provide precious information for weather forecasting and aviation safety. On the other hand, research Doppler radars are usually used for special phenomena in special locations and are operated for elucidate the unknown structure of severe storms, frontal clouds, typhoons, snowstorms, and also phenomena important for climate.

In some research observation project, Dual-Doppler radar observations were carried out. A single Doppler radar can detect only one component of the speed of rain/ice particles, coming to or away from the radar. On

the other hand, Dual Doppler radar system can detect two component of their speed by observing a spatial volume by two radars simultaneously. Dual Doppler synthesis using those two components of the Doppler velocity, they provide three-dimensional wind field usually about 1-km resolution, which is the main advantage of the Dual Doppler radar observations.

It is known that there are some tradeoffs in the tactics of Dual-Doppler radar observations. For example, high speed antenna scanning keeps steady of target cloud systems within the three-dimensional antenna scans, on the other hand, low antenna scan speed is favorable for getting low noise data and long range data acquisition. In principle, the Dual-Doppler system needs steady state of the target cloud system to make Dual-Doppler synthesis, and also it needs high spatial resolution data. However, it is impossible to satisfy those two aspects. In this study, we investigate the tradeoff between those two aspects by idealized Dual-Doppler observation using numerically simulated cloud systems similar to the observation target location. It is hard to investigate such aspects by using the real cloud systems. However, the numerically simulated cloud systems provide chances to investigate many times with various antenna scans. It is, therefore, useful to find the appropriate observation tactics before observation, which provides good results on Dual-Doppler synthesis. This document introduces how to find the appropriate tactics for Dual-Doppler radar observation in tropical western Pacific. In section 2, the method will be introduced. In section 3,

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the results of Dual-Doppler synthesis with various antenna scan mode on two kinds of targets, and section 4 summarizes the study.

2. Method

2.1 Principle of Dual-Doppler synthesis

As mentioned in last section, Dual-Doppler synthesis is based on the two components of the speed of the mass of rain/ice particles. The theory was introduced by Armijo (1969), and it has been introduced in many good articles, e.g. (Houze 1993). In principle, two components of the movement of rain/ice particles provide horizontal air motion after subtracting fall speed of the particles. The fall speed of the particles can be obtained from radar reflectivity factor (refraction power from the targets) that is related with the density of particles using particle fall speed equation of experience (Joss and Waldvogel 1970, Foote and du Toit 1969). A three-dimensional antenna scan, which is called volume scan, provides the distribution of rain/ice particle densities and Doppler velocities which will be a distribution of three-dimensional horizontal wind field. After that, integration of the anelastic continuity equation (Ogura and Phillips 1962) from top or bottom boundary condition with zero vertical velocities produces three-dimensional wind field. That is called Dual-Doppler synthesis. It is noted that the angle of two radars at the certain observed location is related the accuracy of obtained horizontal air motion, which limits the area of wind field production (Lhermitte and Miller 1970).

2.2 Tactics on antenna scan mode

The selection of antenna volume scan mode controls the accuracy of Dual-Doppler synthesis, however, it is not easy to determine the antenna scan mode because contradicting aspects are required. In the principle of Dual-Doppler synthesis, target cloud system is assumed to be steady state during the volume scan. Since Doppler radars make volume scan with number of conical antenna scans which takes several minutes, two radars with different location detect a certain resolution volume in different moment except near the surface. Within the duration of a volume scan the target cloud system could be developed, which produces inconsistency of two component of Doppler velocity by two radars. To reduce the inconsistency, smaller number of antenna scans in one volume scan is preferable. On the other hand, to obtain high spatial resolution wind field larger number of antenna scans is needed for one volume scan. Moreover, to derive accurate vertical velocity, horizontal divergence in high spatial resolution is needed. This study mainly discusses this tradeoff.

It should be noted that the antenna rotating speed couldn't be very fast, because Doppler radar signal processor needs to average a number of microwave pulses (usually 32 to 128 pulses) to derive significant Doppler velocity distribution with less noise. The pulse repetition frequency (PRF) of microwave pulses is fixed in each radar (usually at most 1000 to 2000 pulses per second). As a result, antenna rotation speed is limited usually at around 3 round per minute. Therefore, antenna rotation speed cannot solve the tradeoff above.

The selection of antenna volume scan mode mainly depends on the scientific strategy for the target cloud systems. Key elements are, height, moving speed, and developing speed or vertical velocity of the target. Tropical tall cloud system with strong vertical air motions is quite hard to determine appropriate antenna scan mode, because it needs larger number of scans to cover up to high altitude and also to keep the assumption of steady state. One solution to solve the tradeoff is variable interval of antenna elevation angle. That is, small interval of elevation angles when the antenna pointing lower altitude, and larger interval of elevation angles when the antenna pointing higher altitude. This method reduces the number of antenna scans in a volume scan by reducing vertical resolution somewhat at higher altitude. It is physically reasonable to reduce the vertical resolution at higher altitude where air pressure is low, for which contribution to the continuity equation in Dual-Doppler synthesis is proportional to its density.

However, it is still uncertain to choose how many antenna scans with which elevation angles with how many minutes for one volume scan? In this study to determine appropriate antenna scan mode, idealized Dual-Doppler observation is made using numerically simulated cloud systems. The numerical simulations are made using a non-hydrostatic cloud-resolving model, Advanced Regional Prediction System (ARPS) (Xue et al. 2000). In this case study our target is tropical cloud system developed over the ocean in western tropical Pacific. The numerical simulations are initiated by radiosonde data observed by R/V Mirai in this area (MR00-K04 cruise). The numerical model predicts three components of air motion, three kinds of hydrometers and two kinds of cloud particles including ice phase, ocean surface heat and momentum fluxes, radiative heating, and turbulent kinetic energy. The horizontal grid interval is 1 km and stretched vertical grid interval from 30 meters near the ground level to 1000 m at tropopause. The calculated cloud system is a squall line including active convective area and wide spreading stratiform area.

Three sets of volume scans are applied on the simu-

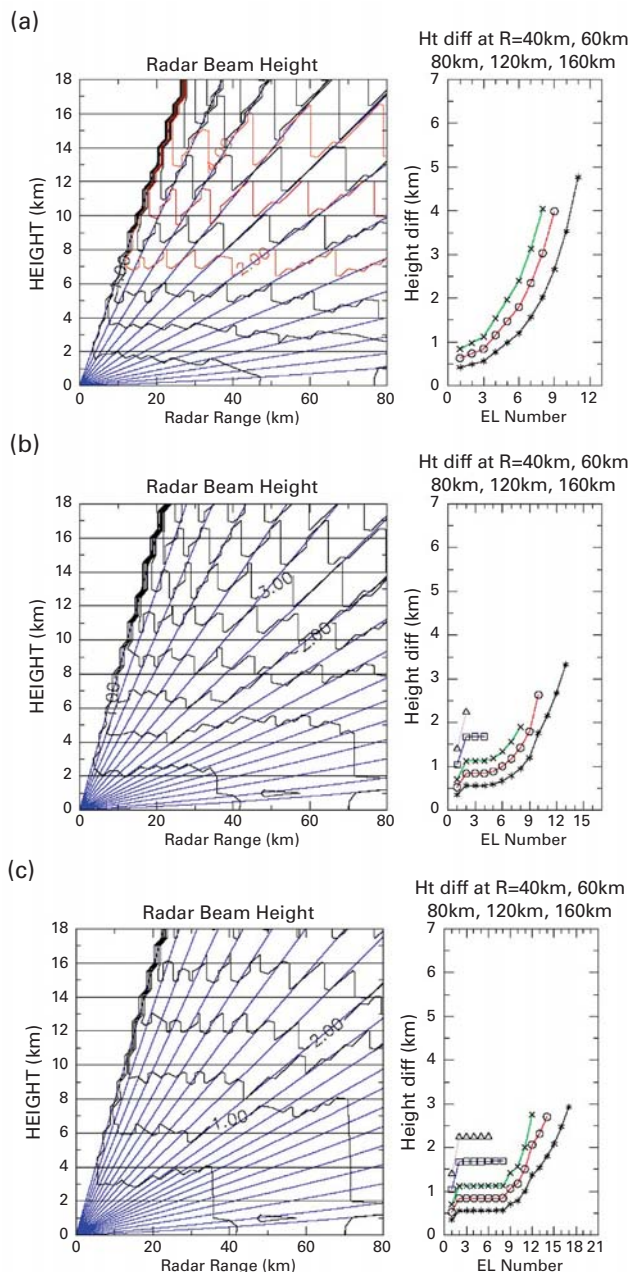


Figure 1: Vertical distribution of radar beams (curves) with vertical intervals of radar beam centers (contours with 0.5 km intervals) for three volume scan modes, (a): 13 angles with 6 minutes mode, (b): 17 angles with 7.5 minutes mode, and (c): 21 angles with 10 minutes mode. Right panels indicate vertical interval of scans at various ranges (distance from the radar), with asterisks at 40 km, open circles at 60 km, and X at 80 km, square at 120 km, and triangles at 160 km range.

lated squall line with elevation angles from 0.5 to 40 degree. The numbers of elevation angles are, 13, 17, and 21, and the data acquisition times are, 6, 7.5, and 10 minutes. As mentioned above the elevation angles are defined with small interval in low elevation angle. The vertical distributions of radar beams are illustrated in

Figure 1. All the modes take antenna scans less than 1 km vertical intervals below 3 km height. On the other hand in the upper troposphere at 14 km, the vertical intervals of radar beams vary from about 2.5 to 4 km. The coarser vertical resolution will destroy the retrieved distribution of wind field in next section.

It is assumed that a single scan takes 20 seconds (3 round per minutes antenna rotation speed is assumed). The numerical model outputs 20 seconds interval data of simulated squall line to take the effect of duration for each volume scan into account (the time to take on elevating antenna is ignored). Each single scan of volume scans is taken from the simulated squall line of 20 seconds intervals. After that wind fields are synthesized in the manner of Dual-Doppler synthesis as in section 2.1.

3. Results

This section illustrates results of wind field synthesized from three volume scan modes listed in last section. The Dual-Doppler syntheses are calculated for two areas inside of squall line, convective area and stratiform area.

Figure 2 describes horizontal distribution of radar reflectivity and horizontal wind field. Radar reflectivity indicates the density of rain/ice particles. The squall line propagates north-westward at speed of about 15m/s. Figure 2(a) shows this squall line has a range of about 150 km, and active convective area ahead with strong radar reflectivity. In the comparison of Figure 2(b) and 2(c), from numerical simulation and Dual-Doppler synthesis, radar reflectivity and horizontal wind field show pretty good consistency with some magnitude difference. Between -5 to 5 of vertical axis in Figure 2(c) no wind field are calculated, because the angle of two radars from the points are nearly 180 degree and the accuracy of winds are quite low since the radars are located at coordinate (0,0) and $(-60, 0)$.

Figure 3 describes development of convective tower ahead of the squall line from the numerical simulation. The top of the strong convective tower (horizontal coordinate of 105 in left panel) has developed about 2 km in the 7 minutes and 40 seconds, which could produce the inconsistency of data detections by two radars during a volume scan.

Figure 4 illustrates the vertical distributions of synthesized wind fields at the same cross section of Figure 3. Figure 4(a) shows that the volume scan with 13 elevation angles could not fill all the grids of high spatial resolution, even each grid data is constructed by collecting data inside a radius of 1 km. In Figure 4(b), the mode (b) of 17 elevation angles still shows some lack of data, it describes good retrieval of the updraft core tilt-

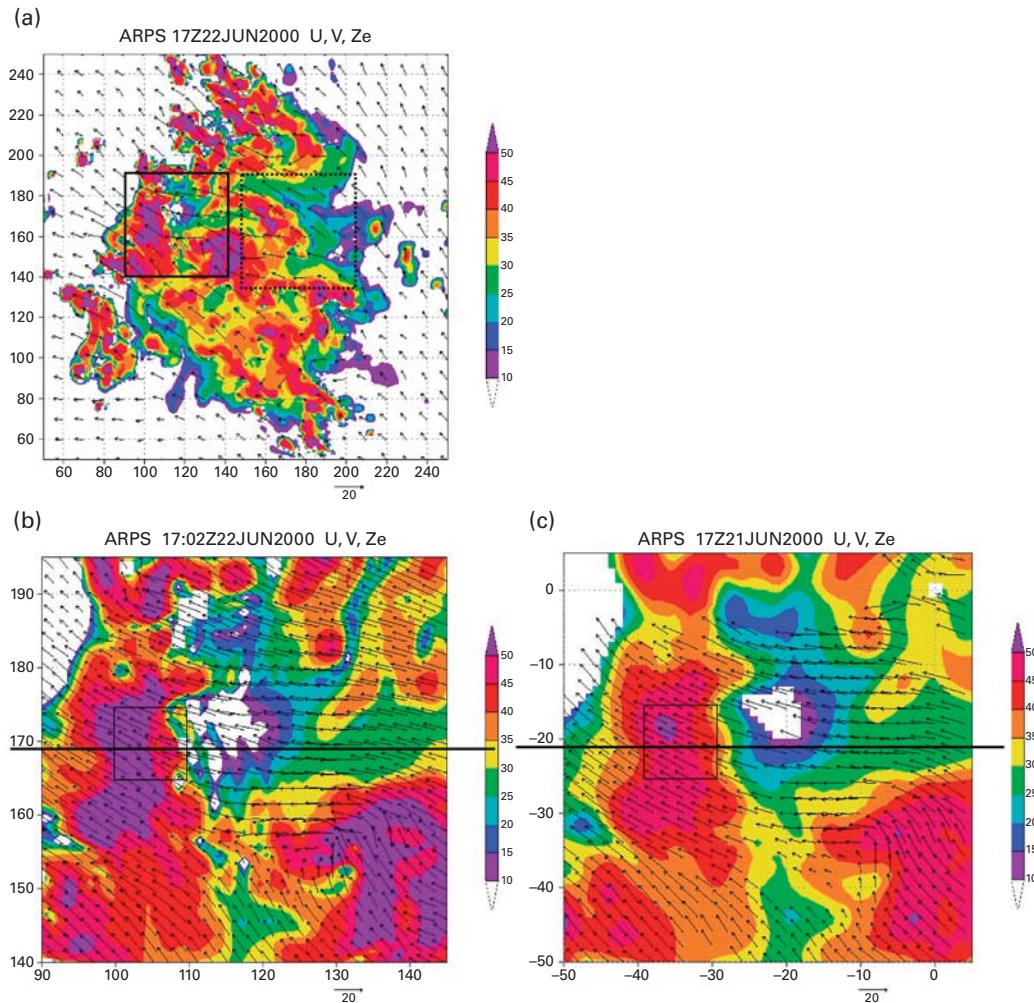


Figure 2: Horizontal distribution at 500 m level of simulated squall line of its whole view (a) and expanded view of simulation (b) and Dual-Doppler synthesis by volume scan mode b (c). Color shading shows radar reflectivity (dBZ) and vectors show horizontal wind field. A small square in (b) and (c) are updraft core area, which will be discussed later. The horizontal lines in (b) and (c) are the position of vertical cross section discussed later. A small square with solid line in panel (a) indicates the area of (b) and (c). Another small square with broken line is the calculating area for stratiform area.

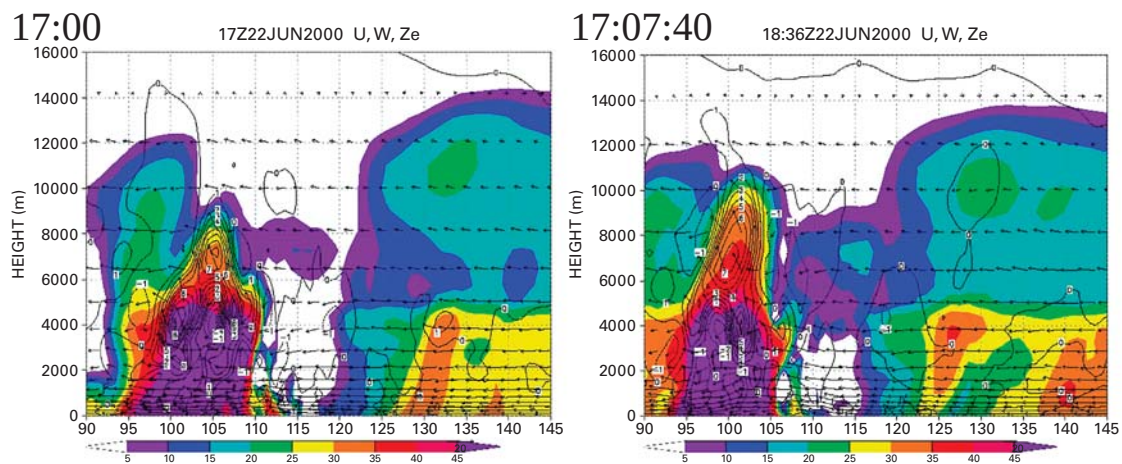


Figure 3: Vertical cross section of simulated squall line in convective area along the horizontal line in Figure 2(b). Color shade indicates radar reflectivity, contour indicates vertical air motion, and vectors indicates wind field along this cross section. Right panel shows a distribution 7 minutes and 40 seconds later than left panel.

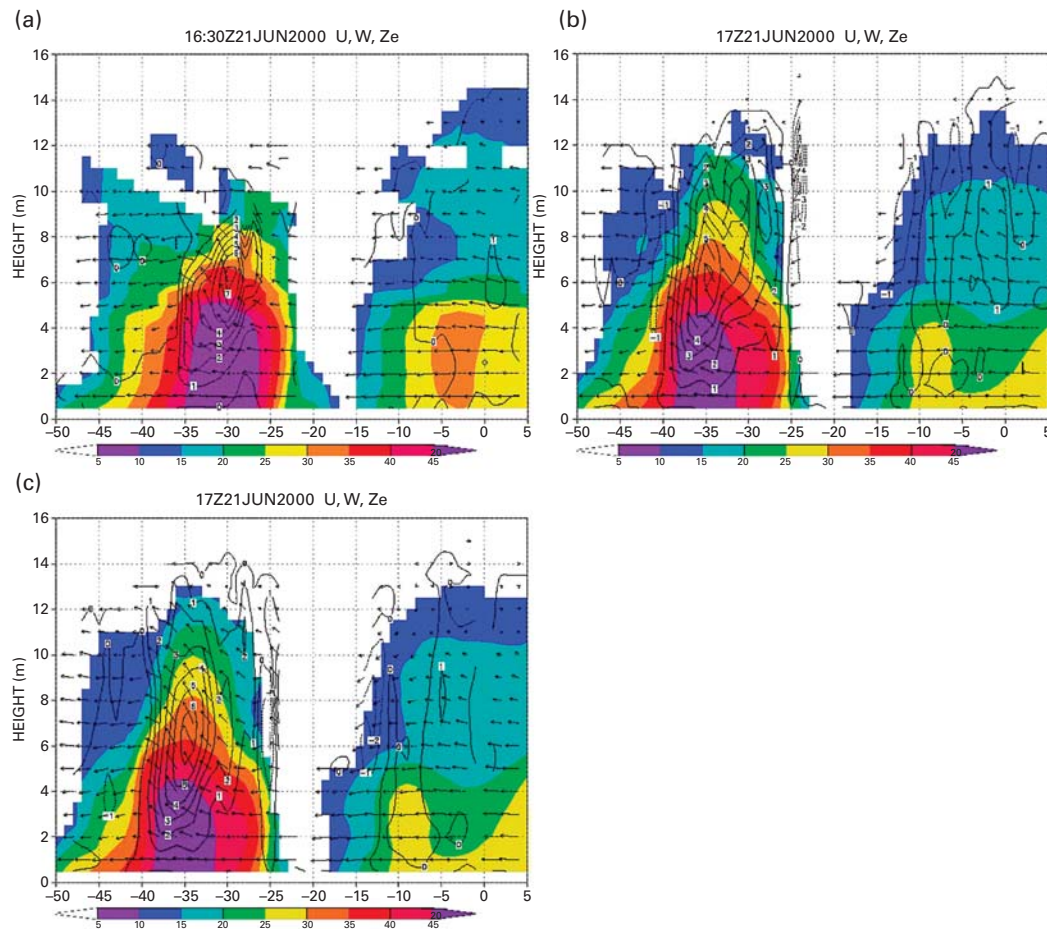


Figure 4: Vertical cross sections of wind field and radar reflectivity synthesized by Dual-Doppler radars for volume scan mode a (a), for mode b (b), and scan mode c (c). Shade, contour, vectors are same as in Figure 3.

ing rightward as simulation is Figure 3. The result of mode (c) in Figure 4(c) on 21 elevation angles shows much smoother distribution, however, the updraft core is rather elected than the simulated updraft core.

Figure 5 illustrates the averaged vertical air motion inside the updraft core indicated in Figure 2(b), (c). The simulated vertical air motions in Figure 5(a) show elevated maximum level and weakening with time. The synthesized vertical air motions in Figure 5(b) show that the maximum level of the curve of mode (b) coincides with earlier maximum of simulation than that of mode (c). It is considered that time to take those volume scans results in the difference of synthesized updraft curve. The synthesized updraft speeds are about 30 percent less than simulated speeds. It may come from the difference of acquired resolution of divergence field.

The comparison of synthesized wind field from three volume scan modes describes interesting aspects. The mode (b) shows better retrieval of vertical wind field distribution more consistent with simulated (real) distribution. On the other hand, the mode (c) shows smoother and high resolution distribution, however, it could

include more deformation at the rapidly developing updraft core due to long duration taking larger number of scans. This result suggests that the volume scan mode (b) with 17 elevation angles is better than any other modes for this tropical squall line case.

On the stratiform area, the figures of horizontal and vertical distribution is omitted, because they don't have significant difference between mode (b) and (c). Figure 6 illustrates the averaged vertical wind speed on the stratiform area, which is referred to a small broken line square in Figure 2(a). The upward wind at upper troposphere is weakening with time, but rather steady for downward wind in lower troposphere. The synthesized winds in Figure 6(b) show the similar vertical wind especially for mode (b). The vertical distribution of mode (c) shows inconsistency of the magnitudes and maximum level of wind speed. It seems that longer duration to take a volume scan may affect away from steady state assumption. It is clear that the volume scan mode (b) is the better than any other modes also for the stratiform area of the squall line.

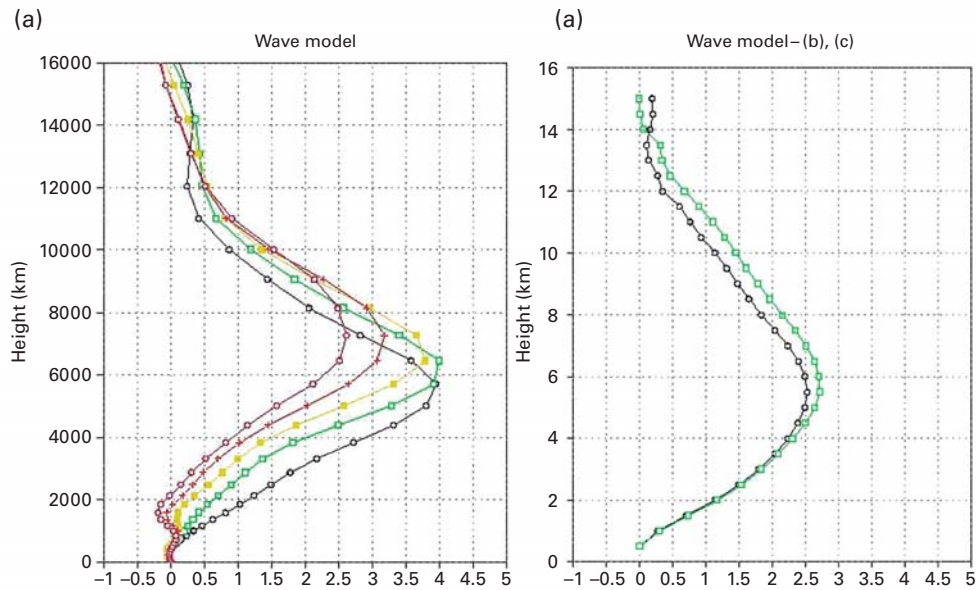


Figure 5: Vertical distribution of horizontally averaged updrafts inside the updraft core. (a) simulated vertical winds with 2 minutes interval on the order of black, green, yellow, red and purple, (b) synthesized vertical winds of mode-b in black line and mode-c in green line.

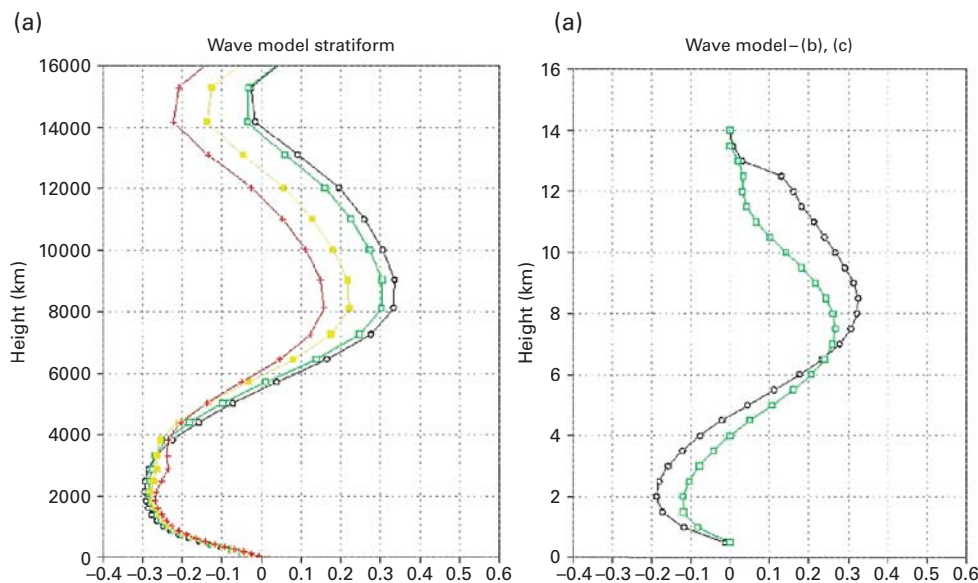


Figure 6: Same as Figure 5 except for stratiform area.

4. Concluding Remarks

In this study, an appropriate volume scan mode on Dual-Doppler radar observation for specific target is derived. Utilizing a numerically simulated cloud system, idealized observation using Dual-Doppler radar system is made, and the comparison of synthesized wind field between several volume scan modes results in an appropriate mode. This study shows that the volume scan mode of 17 elevation angles taking 7.5 minutes produces good wind field for tropical area observation over

the warm ocean. It is shown that inappropriate volume scan mode may produce data with more error on wind distribution. Therefore, it is useful to investigate appropriate volume scan mode before observation. A numerically simulated cloud system is vital to investigate the volume scan mode for specific target of cloud systems. Although it is useful and effective for planning Dual-Doppler observation, it is rare to be published. The idea could be a consensus for the researchers using Dual-Doppler radar observations.

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