Formation and Characteristics of a Summertime Hailstorm over Northern Taiwan

George Tai-Jen CHEN and Iu-Man TANG

Department of Atmospheric Sciences, National Taiwan University, Taipei, Taiwan

(Manuscript received 26 August 2003, in final form 12 December 2003)

Abstract

Hailstorm is a rather unusual weather phenomenon in Taiwan particularly in the summer season. The hailstorm event occurring over northern Taiwan on 2 July 1998 was investigated using conventional data, Doppler radar observations, and satellite cloud winds. Results showed that an upper-level cold vortex provided favorable conditions for the development and evolution of the storm. The storm appeared to be triggered by the low-level convergence associated with local circulations coupled with the upper-level divergence forced by a jet streak of cold vortex. Backing of winds and vertical shears with height provided by cold vortex appears to be instrumental for the westward propagation and intensification of the convective system. A couplet of mesoscale vortices was observed in the low- and mid-troposphere and was found to be generated by the tilting process on the vertical wind shear through a strong updraft in the convection.

1. Introduction

During the Meiyu season of May and June, the weather over Taiwan area is mainly influenced by the Meiyu front, which causes continuous rains mixed with convective showers, thunderstorms, and heavy rain events. As the season proceeds into summer in July and August, thunderstorms and/or showers associated with the afternoon convection become major weather phenomena if there is no typhoon influence. Over northern Taiwan, the afternoon convection in summer is closely related to the formation and development of local circulations such as sea breezes and upslope winds. Based on the studies of local circulations over northern Taiwan in June–August (e.g., Liu and Su 1997; Chen et al. 2001), sea breezes appeared to converge over northern Taiwan from the coastal areas over the west, the north, and the east. Meanwhile, the upslope winds also developed over both sides of the Snow Mountain Range (Fig. 1).

Although afternoon thunderstorm may cause heavy rain, which often produces flooding locally, it rarely causes severe weather such as hail. Take Taipei City as an example (Central Weather Bureau 1991), there were 225 and 177 thunderstorm days observed in 30 years (1961–1990) in July and August, respectively. In comparison, however, there were only a total of 36 hailstorm events reported officially by the 24 surface stations of the Central Weather Bureau all over the Taiwan island in the last 38 years (1961–1999; 1980 missing) and there were only 6 out of these 36 events occurring in summer. This is perhaps due to the summer environmental condition, which is potentially unstable and only exhibits a relatively weak vertical wind shear unfavorable for severe convective storm to develop. Take the mean July sounding in 1989–1993 as an example, it has a CAPE
value of about 700 m$^2$s$^{-2}$ and a relatively small vertical shear of about $1.0 \times 10^{-3}$ s$^{-1}$ in the middle to upper troposphere between 500 and 300 hPa. The hailstorm occurring over Taipei City and its immediate adjacent areas in the afternoon hour of 1430–1500 LST 2 July 1998 is therefore a rather rare event climatologically. This case was selected in the present study not only because it was a rare event, it also lasted for a long period of time about 20 minutes and produced locally unusual large hailstones with a radius reaching about 2 cm. Therefore, the formation process and characteristics of this hailstorm deserve further investigation.

Chen et al. (1990) studied the severe convective storms developing over Taiwan area in summer and suggested that the westward propagating upper-level cold vortices might have played an important role in changing the environmental conditions and in providing the forcing for triggering convection. They observed that the upper-level cold vortex not only increased the potential instability by lowering upper-level temperature but would also provide lifting for convection initiation by the accompanied upper-level jet streak. Strong convection in all three cases studied occurred over the area where the upper-level divergence would be expected on the left-hand side of exit region of the jet streak in cold vortex. A thermally indirect circulation over the exit region associated with the jet streak in cold vortex was derived by Chen and Chou (1994) indirectly from the thermal structure, the divergence pattern, and the cloud distribution over the vortex region. Ascending motion associated with upper-level divergence on the left-hand side of exit region was suggested to be instrumental for the formation of cloud and convection over the area. These studies all suggested that the westward propagating upper-level cold vortex from the western North Pacific would play an important role in the formation of severe convective storm over northern Taiwan in summer under weak synoptic forcing in the low- and midtroposphere. However, specific processes provided by cold vortex could not be obtained in these studies due to the data sparsity over the oceanic areas. With the help of abundant satellite cloud derived winds particularly in the upper levels, investigation on the specific role of the cold vortex on the formation of strong afternoon convection over northern Taiwan in summer becomes possible for the present hailstorm case.

2. Data and analyses

Figure 1 presents the topography over northern Taiwan and the geographical locations for the Chiang Kai-Shek (CKS) International Airport, Pan-Chiao rawinsonde station, and other relevant locations discussed in this paper. Taipei City as delineated by solid boundary is located to the north of the Snow Mountain Range. The Sung-Shan Airport is located near the center of the City. Doppler radar is located at the CKS International Airport by “+” sign and rawinsonde station at Pan-Chiao by “■” sign.
volume scan. The CKS Doppler radar is located at 25.08°N, 121.22°E. The Doppler mode scan with a 5-cm wavelength covers the area of 120 km radius with 1-km resolution in both horizontal and vertical spaces. Mesoscale analyses were carried out using surface observations of wind direction, wind speed, and hourly rainfall amount obtained from the Central Weather Bureau (CWB) and other governmental agencies in Taiwan to reveal the local circulations and the distribution of convective rainfall. Rawinsonde data at Pan-Chiao (Taipei) station, which is located at 25.0°N, 121.4°E, were used to analyze the environmental conditions. These data were also used to compute the convective available potential energy (CAPE) and convective Richardson number (Ric) as defined by Weisman and Klemp (1982). The surface and 300 hPa charts analyzed by the CWB were used to illustrate the synoptic situations.

In order to better reveal the detailed environmental conditions, Barnes’ objective analysis scheme (Barnes 1973) was employed to obtain the reanalysis data. Rawinsonde observations and satellite cloud derived winds over East Asia (100°–140°E, 10°–40°N) were used. The latter wind data were provided by University of Wisconsin-Madison Cooperative Institute for Meteorological Satellite Studies (CIMSS) using both infrared and water vapor channels of Japan Geostationary Meteorological Satellite (GMS). According to Velden et al. (1997), these cloud-derived winds are of equivalent quality to the rawinsonde observations and have been widely used in the daily operational forecast models. The abundant cloud derived winds particularly in the upper levels for the present case would greatly enhance the specific details of the cold vortex in the reanalysis data. Gridded operational analyses from the European Centre for Medium Range Weather Forecasts [ECMWF; Tropical Ocean Global Atmosphere (TOGA) advanced; EC/TOGA] with a horizontal resolution of 1.125° long. × 1.125° lat. were taken as first guesses in the objective analysis.

3. Synoptic situations

Surface analysis on the hailstorm day at 0800 LST (0000 UTC) 2 July is presented in Fig. 2a. Note that local time (LST) is UTC plus 8 hours. A frontal system was located over the Japan Sea, the Korea Peninsula, the Yellow Sea, and the Yangtze River Valley. To the south of this system, the Pacific subtropical high pressure center was located near 27°N, 135°E with a ridge extending westward passing through Taiwan into southern China. Weak pressure gradient and weak south-southeasterlies prevailed over Taiwan and its vicinity in ridge area. Synoptically, this is a favorable condition for the local circulations to develop in summer. Figure 2b presents the 300 hPa analysis at the same time. A NE-SW oriented trough was located over northern China to the northwest of the surface frontal system indicating the structure of a typical midlati-
itude baroclinic wave system. A cold vortex was located over the Bashi Channel so that the southeasterlies prevailed over Taiwan and the east adjacent area and the northerlies prevailed to the west of the vortex center over southern China and the northern South China Sea. It originally formed in the western North Pacific near 18°N, 148°E on 26 June as revealed by the cyclonic circulation indicated in GMS-5 water vapor channel cloud images. It moved westward then northwestward along the periphery of the Pacific subtropical high pressure.

Vertical time cross section of winds and temperature anomalies observed at the Pan-Chiao rawinsonde station in 0800 LST 29 June–0800 LST 7 July is illustrated in Fig. 3. The temperature anomalies were computed using the time mean over the period of 15 June–15 July 1998. The significant veering of the northeast to the southeast winds at 200–300 hPa in 1–2 July reflected the approach of cold vortex into the Bashi Channel to the south of the station. Wind maximum occurred at 250 hPa and gradually increased from 0800 LST 30 June and reached a peak southeast wind of 33 ms\(^{-1}\) at 0800 LST 3 July. The vertical wind shear between 500–300 hPa gradually increased from 3.1 \times 10^{-3} \text{ s}^{-1} (29°) at 0800 LST 1 July to a relatively strong value of 4.3 \times 10^{-3} \text{ s}^{-1} (106°) at 0800 LST 2 July, then reached a peak value of 5.7 \times 10^{-3} \text{ s}^{-1} (153°) at 0800 LST 3 July. These values were much greater than that in the July mean of 1.0 \times 10^{-3} \text{ s}^{-1} as discussed previously. The cold vortex influence was also manifested by the remarkable negative temperature anomalies in the middle to upper troposphere (600–200 hPa) from 2000 LST 1 July. This was also the time when the lower tropospheric winds weakened and backed from the southerlies/southeasterlies under the influence of the Pacific subtropical high pressure ridge. Meanwhile, the wind veering at each level was evident in 600–200 hPa layer, reflecting the circulation influence of cold vortex. The region of cold temperature anomaly coincided with the region of wind veering suggested the vertical extension of cold vortex in this case. The convective instability was enhanced by lowering temperature in the upper troposphere. The effect of cold vortex on the environmental instability is clearly demonstrated in the vertical profiles of mean equivalent potential temperature (\(\theta_e\)) before, during, and after the influence of cold vortex as illustrated in Fig. 4. Convective instability was enhanced during the influence of cold vortex in 2–3 July mainly by the decrease of \(\theta_e\) in the 600–200 hPa level. This is consistent with the vertical extension of upper-level cold vortex as revealed in the vertical distribution of temperature anomaly and wind veering presented in Fig. 3.

Figure 5 presents the sounding at Pan-Chiao station at 0800 LST 2 July. Troposphere was very moist with a nearly saturated condition below 800 hPa. The level of free convection (LFC) at 900 hPa was much lower than the climatological average of 823 hPa, and the unstable layer (i.e., positive area) was so deep with a high CAPE value of 2490 m\(^2\)s\(^{-2}\). This CAPE value was greater than that of the mature squall line environment (1330 m\(^2\)s\(^{-2}\)) observed in Taiwan Area Mesoscale Experiment (TAMEX) in May–June 1987 (Chen and Chou 1993) and was much greater than the climatological mean in July of 700 m\(^2\)s\(^{-2}\) discussed previously. The convective Richardson number (Ric) was large (81.8) due to the moderate vertical shear and the very high CAPE value. It
was much larger than the values ($R_i = 15–35$) favorable for the occurrence of supercell thunderstorm as suggested by Weisman and Klemp (1982). Thus, the environmental conditions for the formation of the hailstorm in the present case were quite different from those for the hailstorm associated with supercell over the Great Plains in the United States (e.g., Bunkers 2002). The $0^\circ C$ level at 4.7 km was close to the climatological average of 4.8 km. This suggested that the bigger hailstone size in the present case was not due to the lowering of freezing level, which is a favorable condition to keep the hailstone from melting. Winds were weak in the lower troposphere under the influence of the Pacific subtropical high pressure and were backing from middle to upper troposphere reflecting the influence of cold vortex.

4. Characteristics of convection

Figure 6 presents the spatial distribution of radar reflectivity of VMI in 1330–1530 LST 2 July at 0.5-h intervals. Convection occurred mainly over northwestern slope area of the SMR with a maximum intensity of 30–40 dBZ at 1330 LST. This was consistent with the surface rainfall observation at 1400 LST as will be discussed in the later section. In the following 0.5 h, convective system A occurred over Kung-Kuan and Yong-Ho areas to the southwest of Sung-Shan Airport (cf., Fig. 1) with a maximum intensity of 40 dBZ.

In 1430–1500 LST, system A slowly moved westward to Yong-Ho/Pan-Chiao area and intensified to a value over 50 dBZ (Figs. 6c, d). During the same period, hail was observed in many locations of Taipei City and Yong-Ho/Pan-Chiao areas where the heavy rainfall was also observed. Meanwhile, a new convective system B with an intensity of 40 dBZ also formed to the east of the system A. System B appeared to be generated over the convergent area within the cyclonic vortex which formed to the east of system A. The eastward propagation of system B was perhaps associated with this vortex as well. The generation of this cyclonic vortex will be discussed in Chapter 5. Based on the locations of surface hail reports, system B did not cause hail in this case. From 1500 to 1530 LST, system A moved westward and weakened, while system B continued to move eastward and intensified to 50 dBZ.

Radar reflectivity of CAPPI at 3 km and radial winds at 0.5 and 2 km at 1430 LST 2 July prior to the occurrence of hail and rainfall are presented in Fig. 7. Convective system A devel-
Fig. 6. Radar reflectivity (dBZ) of vertical maximum indicator (VMI) observed at the CKS International Airport (‘+’ sign) at (a) 1330, (b) 1400, (c) 1430, (d) 1500, and (e) 1530 LST 2 July 1998. Sung-Shan Airport is indicated by ‘⊙’ sign. The radius is 25, 75, and 120 km for inner, middle, and outer circle, respectively.
opened to an intensity of 50 dBZ over the area where strong horizontal convergence would be expected by the large gradient of reversed radial winds at 0.5-km level. A signature of anticyclonic vortex was suggested by radial winds at 2-km level to the immediate southwest of system A. Figure 8 presents the similar analyses at 1445 LST when rainfall and hail started to occur. System A moved westward and intensified in the last 15 minutes over the low-level convergent area with a maximum intensity of 58 dBZ. An echo-free area appeared to extend in an NW-SE direction to the southeast side of system A. It was collocated with the strong northwestward inflows into the convective system at 0.5 km height. In other words, the NW-SE oriented echo-free area coincided with the area of strong northwestward inflows into the convective system (Fig. 8b). This suggested that the strong convective updraft occurring over the area of large reflectivity gradient located over the northwestern boundary of strong inflows as indicted by a star sign in the figure. No hook echo in the vicinity of strong updraft core was observed in this case. This is similar to the hailstorm case studied by Nelson (1987) and is different from a classical supercell thunderstorm case studied by Browning (1965). Existence of a couplet of vortices in the immediate vicinity of strong updraft core was suggested by the radial wind pattern. An anticyclonic vortex to the immediate southwest of the strong updraft core was indicated not only at 2 km level as at the previous time but also at 5-km level at this time. A weak cyclonic vortex was also discernible to the northeast of strong updraft core at both 2-km and 5-km levels. Fig-

Fig. 7. Radar reflectivity (dBZ) of constant altitude plan position indicator (CAPPI) at 3 km (a), and radial wind (ms\(^{-1}\)) at 0.5 km (b) and 2 km (c) at 1430 LST 2 July 1998. Radial winds analyzed at 2 ms\(^{-1}\) intervals with negative values (dashed) towards radar and positive values (solid) away from radar. X (EW) and Y (NS) axes are in km. The CKS International Airport Doppler radar is located at (0, 0) with a “+” sign and the “@” sign 40 km to the east is Sung-Shan Airport.
Figure 9 presents the similar analyses at 1500 LST. Slightly weakening of system A was indicated in CAPPI reflectivity at 3 km (Fig. 9a) and also in the vertical extension of high reflectivity in the range height indicator (RHI, not shown). The anticyclonic vortex intensified at 2-km and 5-km levels and extended downward to 0.5-km level. As illustrated in the figure, the radial wind pattern in the immediate vicinity of strong updraft region appeared to shift northeastward with height. This suggested that the vortex center, which was located at the central position between the areas of maximum reversed radial winds, tended to tilt slightly towards northeast with height as well. To the northeast of strong updraft core

---

Fig. 8. Radar reflectivity (dBZ) of CAPPI at 3 km (a) and radial wind (ms$^{-1}$) at 0.5 km (b), 2 km (c), and 5 km (d) at 1445 LST 2 July 1998. Strong northwestward inflow is indicated by an arrow in (b) and strong updraft region is indicated by a star sign ($\ast$) in (c) and (d).
the weak cyclonic vortex again was discernible at 5 km.

A theoretical study by Klemp (1987) suggested that a cyclonic-anticyclonic couplet can be generated by tilting process on the vertical wind shear with a cyclonic vortex on the right-hand side and an anticyclonic vortex on the left-hand side of the vertical shear vector. It was also found in that study that the perturbation pressure is related to the vertical shear with the high pressure on the upstream and low pressure on the downstream of the vertical shear vector. Based on Klemp's theoretical study, the relationship among vortices, perturbation pressure, and vertical shear vectors in this case as would be expected from the morning sounding at Pan-Chiao rawinsonde station is presented in Fig. 10. The anticyclonic (cyclonic) vortex formed to the southwest (northeast) of strong updraft and was located on the left (right) hand side of the vertical shear vector (facing towards the shear direction) in the layer 850–600 hPa and 600–400 hPa. To reveal the formation process of mesovortices, the tilting

Fig. 9. Same as in Fig. 8, except for 1500 LST 2 July 1998.
term in the vorticity equation was estimated by using the environmental vertical wind shear and Doppler radial winds. The vertical wind shear at Pan-Chiao rawinsonde station in 600–400 hPa was $2.27 \times 10^{-3}$ s$^{-1}$. The convergence over the echo-free area was estimated to be $1.2 \times 10^{-3}$ s$^{-1}$ at 0.5 km and $1 \times 10^{-3}$ s$^{-1}$ at 5 km at 1445 LST. As the strong convection indicated by the strong radar reflectivity extended up to 10 km height, the strong updraft of 10 ms$^{-1}$ would be expected by continuity equation. Therefore, the vorticity generation in the vorticity equation through tilting process was estimated to be $9.1 \times 10^{-6}$ s$^{-2}$ in this case. Thus, it only needed 2–3 minutes to generate a mid-level cyclonic vortex of $1.25 \times 10^{-3}$ s$^{-1}$ as observed in Fig. 8d. The vortices in this case were different from those vortices frequently observed in mesoscale convective systems at the horizontal scale of 100–200 km, which can be explained by balanced dynamics (Davis and Weisman 1994). The westward propagation and intensification of convection system A were also supported by the upward perturbation pressure gradient over the area of downshear side of the updraft region in the middle and upper troposphere. On the other hand, the convection system B on the upshear side of the updraft region would be suppressed by the downward perturbation pressure gradient. Therefore, the backing of the winds and vertical shears under the influence of an upper-level cold vortex appears to be instrumental for the westward propagation and intensification of the convective system A in this case.

5. Surface mesoanalyses

Surface streamline and rainfall analyses are presented in Fig. 11 for the period of 0800–1600 LST 2 July. Offshore flows associated with land breezes and/or downslope winds were observed along the northern and northwestern coastal areas at 0800 LST. This indicated that local circulations had developed well under the weak synoptic forcing with weak pressure gradient in the subtropical Pacific high pressure ridge (cf., Fig. 2a). Sea breezes and upslope winds developed in the following hours. By 1400 LST, sea breezes prevailed over northern Taiwan and tended to converge in the Taipei Basin and its immediate vicinities from the northeast, the northwest, and the southwest. Meanwhile, convective activities as revealed by radar reflectivity (cf., Figs. 6a, b) started to occur over the Taipei Basin and the sloping areas of the Snow Mountain Range (SMR). Apparently, these convective activities were triggered by the convergent flows of sea breezes and the upslope flows over the mountain slope. Convective rainfall occurring over the southern portion of the SMR was not related to the hailstorm and thus was not discussed in this paper.

Over the convergent area to the southwest of the Taipei Basin, convective rainfall occurred at 1500 LST with a maximum value of 20 mm h$^{-1}$ as observed at Kung-Kuan station. Outflows from the convective downdrafts prevailed
Fig. 11. Surface streamline analyses at (a) 0800, (b) 1400, (c) 1500, and (d) 1600 LST 2 July. A full barb indicates 1 ms$^{-1}$, half wind barb 0.5 ms$^{-1}$ and pennant 5 ms$^{-1}$. Dashed lines are isohyets in mm h$^{-1}$ analyzed for 1, 5, 10 mm h$^{-1}$. Hourly rainfall (mm h$^{-1}$) is plotted at each station.
over the area to the east of the convective rainfall center. This mesoscale feature was indicated by the wind shift from the previous northwesterly winds to the westerly winds. Meanwhile, a cyclonic vortex formed to the east of the convective rainfall center. It appears to be generated by the downdraft outflows from the west and the sea breezes from northern coastal area. Convective system B as shown in Fig. 6d formed over the convergent area of this cyclonic vortex. The eastward propagation of system B appeared to be associated with this vortex. At 1600 LST, sea breezes weakened and the outflows prevailed to the west and northwest of the convective rainfall area. As a result, onshore flows over northwestern coastal areas at earlier time periods changed to offshore flows. Two rainfall centers were analyzed with the primary one of 18 mm h\(^{-1}\) occurring at Shin-Zhuang and secondary one to the east of Kung-Kuan. They were consistent with the convective systems A and B discussed in the previous section.

6. Upper-level cold vortex

Figure 12 presents the reanalysis wind fields of 250 hPa at 0800 and 1400 LST 2 July using Barnes’ scheme as discussed in Chapter 2. The reanalysis data are in a better agreement with the observations as compared to the EC/TOGA gridded data. For example, 22.5 ms\(^{-1}\) wind was reanalyzed at the grid over northern Taiwan (24.75°N, 121.50°E) at 1400 LST. It is closer to 25 ms\(^{-1}\) as reported at the nearby Pan-Chiao station (25.0°N, 121.4°E) as compared to 15 ms\(^{-1}\) of EC/TOGA gridded wind. At 0800 LST, a NNW-SSE oriented jet streak over the northeastern quadrant of cold vortex was located to the east of Taiwan. Northern Taiwan was located on the cyclonic side of the exit region where horizontal divergence prevailed. As the cold vortex moved northwestward in the following 6 h, the accompanying jet streak also moved towards northern Taiwan. Meanwhile, divergence intensified on the cyclonic side of jet streak over exit region with the maximum divergence center located over northern Taiwan.

Cross-contour ageostrophic winds computed together with areas of divergence at 0800 and 1400 LST 2 July are presented in Fig. 13. At 0800 LST, cross-contour ageostrophic flows prevailed over the exit region of jet streak from cyclonic to anticyclonic side. Divergence was observed on the cyclonic side of the exit region. Thus, it is clear that the jet streak was accompanied by a rather strong thermally indirect secondary circulation over the exit region with a forced upward motion of cold air. As the jet streak moved northwestward in the following
6 h, the area of divergence and accompanied upward motion also moved over northern Taiwan. During this period convection developed over the Taipei Basin and its vicinity as revealed by radar reflectivity (Figs. 6a, b). Divergence over northern Taiwan reached a maximum at 1400 LST, and this was the time prior to the occurrence of convective rainfall and hail over the Taipei Basin and its vicinity. The existence of jet streak and the accompanied secondary circulation in the cold vortex was suggested to be important for cloud formation by Chen and Chou (1994).

To further reveal the influence of jet streak on the occurrence of hailstorm over northern Taiwan, vertical P-velocity at the grid over northern Taiwan (24.75°N, 121.5°E) was computed kinematically using O’Brien’s adjustment scheme (O’Brien 1970). Figure 14 illustrates the vertical profiles of divergence and vertical velocity at 1400 LST July 2. Divergence prevailed in the upper troposphere with a maximum value of about $2.8 \times 10^{-5}$ s$^{-1}$ at 250 hPa, while convergence prevailed in the middle- and lower-troposphere with a relatively small value as compared to the large divergence in the upper troposphere. Although upward motion existed throughout the whole troposphere, it was much stronger in the upper troposphere and reached a maximum value of about $-12 \mu$b s$^{-1}$ at 300 hPa. Apparently, the strong horizontal divergence as well as the strong accompanying upward motion in the upper troposphere was associated with the secondary circulation of the jet streak over exit region. It is important to note that the development of local circulations produced large con-
vergence value near the surface. The relatively weak upward motion together with the decrease of convergence with height in the lower troposphere was consistent with the surface mesoanalyses (cf., Fig. 11b), which illustrated the sea breeze convergence over northern Taiwan under the weak synoptic forcing of the subtropical Pacific high pressure ridge. Therefore, the convective storm in this case appeared to be triggered by the low-level convergence associated with sea breeze circulations coupled with the upper-level divergence forced by a jet streak of cold vortex.

7. Summary

A rare weather event of summertime hailstorm occurring over northern Taiwan on 2 July 1998 was investigated using conventional observations, EC/TOGA gridded data, GMS cloud derived winds, and Doppler radar observations. Environmental conditions and local circulations were analyzed to reveal the role of upper-level cold vortex and the sea breezes in the development of the storm. Doppler radar observations at the CKS International Airport were used to reveal the structure and evolution of the convective system. Results can be summarized as follows.

1) The approach of an upper-level cold vortex increased vertical shear and enhanced convective instability favorable for developing a severe convective storm which produced hail over northern Taiwan.

2) The convective storm appeared to be triggered by the low-level convergence forced by local circulations coupled with the upper-level divergence forced by a jet streak of the cold vortex.

3) Backing of the winds and the vertical wind shears provided by the cold vortex appeared to be instrumental for the westward propagation and intensification of the convective storm.

4) A mesoscale vortex couplet formed in the mid-level with the anticyclonic vortex to the southwest and the cyclonic vortex to the northeast of the strong updraft core. This couplet of vortices was generated efficiently by tilting process through strong updraft over the moderate vertical shear environment provided by a cold vortex.

Acknowledgments

Thanks are to Dr. C.T. Terng of the CWB for providing satellite cloud derived winds, to Mr. H.C. Chou of the CAA for providing Doppler radar data, and to Mr. A.S. Wang and Mr. C.S. Chang for preparing the manuscript. This work was supported by the National Science Council under the Grant NSC 92-2111-M-002-006.

References


