北台灣超大豪雨個案與中尺度天氣現象

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摘要

北台灣在2004年9月10-11日發生超大豪雨事件。由自動雨量站資料顯示，兩個主要大降水區，一個在基隆、大台北地區；另一個在桃園、新竹地區。本研究利用德雷塔資料進行中尺度分析（Mesoscale Analysis），試圖了解超大豪雨中尺度現象與過程。

東觀環境分析結果顯示，該豪雨事件發生在該段時間，以台灣東方和西南方向海面分別存在一個熱帶低壓。西南方向的低壓中心在西南氣流，並和東北方向的低壓之間之東北風，與北台灣地區形成低層風氣旋，並且有明顯風切變。探空資料顯示東向與高度上升為順轉，有明顯的風切變，東觀環境屬於條件性不穩定。

利用民航局桃園國際機場（TIA）雷達的回波與徑向風場資料分析，發現此超大豪雨發生期間的北台灣對流雨帶方向由西北－東南走向，先轉變為東南走向，之後再轉為東北－西南走向，與海面上兩個熱帶低壓的相對位置有關。進一步分析顯示，對流雨帶可以區分為數個準線狀對流系統（Quasi-Linear Convective System；QLCS），其中，QLCS 1發生在台灣西方海面上，持續時間約4小時，並且在系統內部伴隨彎曲回波。QLCS 2發生在桃園國際機場雷達站西北地區，持續時間約4小時，在系統內部伴隨彎曲回波與中尺度迴旋。這些發生在海上的QLCSs，其中隱含著影響飛安的顯著危害天氣。另外，隨著對流雨帶移向北台灣陸地，則是產生了顯著的降水。

關鍵詞：準線狀對流系統、都卜勒雷達、彎曲回波、中尺度迴旋

一、前言

準線狀對流系統（Quasi-linear convective system；QLCS），如雷線（squall line）以及彎曲回波（bow echo）這種型態的組織性對流系統，通常和豪雨、冰雹、地面強風以及龍捲風等劇烈天氣現象的發生有關。最近一些國外的研究指出，許多劇烈天氣事件的產生與QLCS有關，包含了龍捲風和破壞性的直擊風（straight-line winds），這些現象與系統內部的明顯低層meso-γ尺度（2-40公里）迴旋的發展有某種程度的關聯。

北台灣在2004年9月10日至11日產生的超大豪雨個案，發生於夏、秋交替之際。透過雨量累積圖，可以看無降雨主要集中在大台北地區以及基隆、桃園、新竹等地。進一步利用雷達降水回波分析可以發現，在最強降雨產生的前後，有數個meso-γ尺度的彎曲回波以及中尺度迴旋獨立或相併發生，發生的地區在台灣西北方近海以及北台灣陸地。

二、資料來源與分析方法

本研究所使用的資料來源如下：

（1）中央氣象局：板橋及馬公測站每12小時探空資料、地面自動雨量站每小時雨量資料。

（2）民用航空局：桃園國際機場(TIA) 雷達每15分鐘一組降水回波及徑向風場資料。

（3）美國GOES-9衛星每小時紅外線及水氣頻道衛星雲圖。

三、東觀環境與中尺度環境特徵

北台灣在2004年9月10-11日發生劇烈降雨事件。其中，最強降雨發生在9月10日0000 LST(1200UTC)至9月11日0800 LST(0000UTC)。首場，透過雨量資料來說明此個案發生期間，北台灣各雨量站的累積降雨量以及降雨分布情形。圖4為北台灣在2004年9月10日0800 LST至9月11日1200 LST期間的累積降雨圖。由雨量資料顯示，有兩個主要大降水區，一個在基隆、大台北地區；另一個在桃園、新竹地區，這些區域的累積雨量皆達到350毫米以上。藉由雷達回波圖來看對流雨帶在北台灣的發展過程，如圖2所示。在10日0015 UTC，
雷達站西北西方有對流胞產生，到了0555 UTC的時候，可以看到對流系統向東北東方移動，並且有弧狀回波的型態，有逐漸向北的對流胞結合的趨勢，此命名為QLCS1。到了1155 UTC，整個北台灣的對流雨帶呈現東—西走向，可以明顯的看到在雷達站西南西方出現中尺度迴旋以及弧狀回波的型態，在此命名為QLCS2，QLCS1與QLCS2內部的中尺度分析於下一節

說明。另外，對流系統也移入基隆以及大台北地區，且開始有顯著的降雨。在1805 UTC的時候，可以發現對流雨帶轉變為東北—西南走向，強對流雲集中在大台北及新竹地區附近。到了11日0005 UTC的時候，整個對流雨帶在北台灣形成大範圍的降雨，且在稍後逐漸減弱消散。

水氣頻道衛星雲圖如圖3所示，在10日1200 UTC，微弱的鋒面雲系由日本本州南方海面延伸至大陸東南方沿海，其雲系的尾端在台灣北方海面。台灣東北方和西南方海面上分別存在發展中的對流雲系，配合綜觀天氣分析可知為兩個熱帶低壓系統，顯示台灣周圍的環境是相當潮濕的。

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透過綜觀天氣圖來分析超大豪雨發生期間的綜觀環境，繪製為示意圖，如圖4所示。可以看到在台灣東北方和西南方海面上分別存在一個熱帶低壓，受到低壓環境的影響，台灣北部主要盛行東北風，南部盛行西南風。在850hPa與700hPa面上，台灣西北方海面上有風切線，且在850hPa面上台灣附近有低層偏南風存在，而南部有較強的西南風帶來暖溼空氣。另外，溫度露點差小於3度的潮濕區僞見整個台灣地區，顯示當時在低對流層相當潮溼，配合西南風氣流引導大量水氣流入台灣，提供台灣地區降下超大豪雨的水氣來源。

在9月10日0000 UTC的高空探空資料（圖未示）顯示1000mb以下為弱東南風，1000hPa到2000hPa則以西南風為主，風向隨高度順轉，有顯著的暖平流，對流可用位能（Convective Available Potential Energy；CAPE）值為1613.5，0-5公里高度的風切約12，環境的垂直風切為中等偏弱。顯示環境具有中度的風切以及條件性不穩定，整個綜觀環境是有利於對流的發展。

四、準線狀對流系統檔案分析

利用民航局桃園雷達所觀測到的回波瓣和徑向風場來分析QLCS1、QLCS2及其內部所包含的弓狀回波以及中尺度渦旋…等中尺度天氣現象。在弓狀回波凸出前緣的後側通常存在一個孤回波凹陷區，此現象又稱為後側內流凹陷區，其後側通常有強烈後側內流噴流。成因是由于系統後側有明顯的中層下沉之氣流所造成，此後側內流可使得弓狀型態的對流胞在近地面產生下爆氣流（downburst）以及破壞性強風等危害天氣。

首先，發生在台灣西北方海面的QLCS 1，如圖5a所示，內部伴隨之弓狀回波前緣凸出的方向朝東北
方，移動方向為西至東北東方向，其後方有明顯的後側內流凹陷區，整個對流系統的大小在長度約50公里、寬度約40公里的範圍。針對弓狀回波及其後側弱回波區域AB垂直剖面，如圖5b所示，等值線表示回波值（單位：dBZ），陰影區表示風速值（單位：m/s），負（正）值表示吹向（遠離）雷達中心的風，風速單位為裏。最大回波強度在40~45 dBZ之間及所在最大高度為2公里高度，而大於35 dBZ的回波發展高度可達4公里左右。對流系統的發展高度超過8公里以上，QLCS 1的生命週期約4小時。此個案中並無明顯的後側內流噴流，但我們可以發現對流系統在4公里以下為負速度，4公里以上為正速度，顯示此系統在垂直接方向上有明顯的風切甚至是亂流的現象產生。航路上的航空器皆應加以避開通過此區域。

再者，發生於台灣西南海面上的QLCS 2，如圖6a所示，對流系統內伴隨著中尺度渦旋的現象產生，且系統的右方產生一個對流雨帶，在其強回波區具有弓狀回波凸出雨稜的特徵，且有明顯的後側內流凹陷區，其大小約在長60公里、寬40公里的範圍，針對弓狀回波及其後側弱回波區域AB剖面，如圖6b所示，最大回波強度在45~50 dBZ之間及所在最大高度為3公里高度，而大於35 dBZ的回波發展高度可達5公里左右，整個對流系統的發展高度超過8公里以上，QLCS 2的生命週期約4小時。在最大回波區（X=15km）的後側（X=0至15km）有強烈的後側噴射內流，風速值在18至21 m/s（-36至-42 knots）；而系統前方（X=15至30km）有明顯的由前至後的上流，風速值在12至15 m/s (24至30 knots)之間，兩者在最大回波區附近產生顯著的中橢徑向傾斜(midaltitude radial convergence; MARC)現象。QLCS 2在垂直接方向上也有明顯的風切甚至是亂流的現象產生。在強度上更甚於QLCS 1，航路上的航空器皆應避開通過此區域。

五、結論

本研究利用民航局桃園機場雷達的回波圖和徑向風場的高時、空解析度的資料進行分析發生於2004年9月10日至11日的北台灣超大豪雨事件，且在降水發生前後發現到中尺度渦旋和弓狀回波等中尺度天氣現象。首先，在縱觀環境方面，當時在台灣的東北方以及西南方上空分別存在兩個熱帶低壓，使得台灣北部主要盛行東北風、南部盛行西南風，藉由兩個低壓同時的移動及其相對位置，逐節使台灣地區成為一個大範圍的風切帶，也影響著整個北台灣超大豪雨事件的雨帶走向和內部的中尺度現象之產生。此外，環境探空顯示具有中度的CPAE值以及中度的垂直風切，存在於條件性不穩定環境，中、低對流層層巢，這些都是有利對流發展的環境。

本研究由一個明顯的大範圍組織對流所引發的豪雨事件為起點，進而注意到其中微妙的中尺度天氣現象。透過高時、空解析度的雷達觀測資料，可以清楚的描述到風流對流系統及其內部伴隨的弓狀回波以及中尺度渦旋的組織、發展、合併以及消散等現象。由於海上觀測資料的不足以及海上仍無法對風所產生的災害，所以無從得知是否是破壞性直擊風的現象。透過雷達回波圖和徑向風場資料可以準確發現這些顯著危害天氣，並對航空器提供訊息及警告，進而提升飛航安全。
The Extremely Torrential Rain Case and Its Mesoscale Weather Phenomenon in Northern Taiwan

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Abstract

This study documents the extremely torrential rain case in northern Taiwan on 10-11 September 2004. The automatic rain gauge sites data show there are two major precipitation areas, one is in Keelung and Taipei area; another is in Taoyuan and Hsinchu area. This research utilized the Doppler radar data to precede mesoscale analysis, trying to understand the mesoscale phenomenon and process of the extremely torrential rain case. The result of synoptic environment analysis shows that there are two tropical depressions (TDs) during the occurrence of extremely torrential rain case, one is on northeastern sea level of Taiwan; another is on southwestern sea level of Taiwan. The southwestern TD brings the southwesterly flow and the northeastern TD's northeasterly flow forms a low level convergence flow and there is an obvious wind shear zone in northern Taiwan. The sounding data show the wind veering along with the altitude; the synoptic environment is conditional instability.

By utilizing the reflectivity and radial wind data of Taoyuan International Airport (TIA) radar to analyze the convective rainbands within the heavy rain case in northern Taiwan. It is showed that the convective rainbands transform from northwest - southeast orientation to east - west orientation, and transform into northwester-southeast orientation later, it depends on the relative position of the two TDs. Furthermore, these convective rainbands can divide into several quasi-linear convective systems (QLCSs). Among these QLCSs, QLCS1 occurs on northwestern sea level of Taiwan, its lifetime is about 4 hrs, and there are bow echoes within it. QLCS2 occurs on northwestern sea level of TIA radar site, its lifetime is about 4 hrs, and there are bow
The occurrence of the extremely torrential rain case in northern Taiwan on 10-11 September 2004 is between summer and autumn season. The rain accumulation chart shows the heaviest rainfall occurs from 10 Sept. 2000LST

Keywords: quasi-linear convective systems (QLCSs), Doppler radar, bow echo, mesovortex.

1. Introduction

The Quasi-linear convective systems (QLCSs), such as squall lines and bow echoes, these organized convective systems are often associated with the production of severe weather, such as heavy rainfall, hail, strong surface winds, and tornados. Recently, some foreign researches suggest that many of the severe weather events associated with QLCSs, including both tornados and damaging straigntline winds, are associated with the development of significant low-level meso-γ scale (2-40 km).

Figure 2: The PPI reflectivity of TIA radar site for every 6 hours from 0000 UTC on 10 Sept. to 0000 UTC on 11 Sept. 2004.

Figure 3: The water vapor satellite chart at 1200 UTC on 10 Sept 2004.
The extremely torrential rain case and its mesoscale weather phenomenon in northern Taiwan.

The extremely torrential rain case in northern Taiwan occurred on 10-11 September 2004. First, the rainfall accumulation and distribution chart (Figure 1) shows the rainfall occurs from 10 Sep. 0800LST to 11 Sep. 1200LST and the major rainfall areas are concentrated in Taipei, Keelung, Taoyuan and Hsinchu area. By utilizing the radar reflectivity data, we can find there are several bow echoes and mesovortices of mesoscale formed isolated or accompanied before and after the occurrence of the heaviest rainfall on the northwestern coastal and land in northern Taiwan.

2. Data source and analysis approach

The data source of this research are used as follows:

(1) Center Weather Bureau (CWB): Panchao and Makung sounding data for every 12 hour; the hourly rainfall data of automatic rainfall station at surface.

(2) Civil Aeronautical Administration (CAA): The reflectivity and radial wind data of TIA radar data for every 15 min.

(3) GOES-9 satellite chart for hourly IR and Water Vapor channel imagery.

3. Synoptic and mesoscale environment characteristics

The extremely torrential rain case in northern Taiwan occurred on 10-11 September 2004. First, the rainfall accumulation and distribution chart (Figure 1) shows the rainfall occurs from 10 Sep. 0800LST to 11 Sep. 1200LST and the major rainfall areas are concentrated in Taipei, Keelung, Taoyuan and Hsinchu area. The rainfall accumulation exceeds 350 mm in these areas.

Figure 2 shows the developing process of the convective rainbands in northern Taiwan via radar reflectivity charts. At 0015 UTC on 10 Sept., the convective cells occur in the west-northwest sea level of radar site. At 0555 UTC, the convective system moves toward east-northeast and there is bow-shaped echo within it, combining with the north convective cell gradually, it is named QLCS1 here. At 1155 UTC, the convective rainband transform into east-west orientation in northern Taiwan, it is obvious that there are mesovortex and bow-shaped echo occurring in the west-southwest sea level of radar site, it is named QLCS2 here. The mesoscale analysis within the convective system of QLCS1 and QLCS2 will describe in next section. In addition, the convective system begins moving into the northern Taiwan land and occurs significant precipitation. At 1805 UTC, the convective rainband transform into northeast-southwest orientation, and the strong convection areas
are concentrated in Taipei and Hsinchu area. At 0005 UTC on 11 Sept., the convective rainband forms an extended precipitation in northern Taiwan and it begins weakening and dissipating later.

The satellite imagery of water vapor channel shows as in Figure 3. At 1200 UTC on 10 Sept., it reveals the light frontal cloud extended from southern sea level of Kyushu to southeastern coast of China. The tail of the frontal cloud is on the northern sea level of Taiwan. There are two developing convective cloud on the northeastern and southwestern sea level respectively. Accompanying with the analysis of synoptic weather chart, we know that are two tropical depressions (TDs); and the environment is quietly moist around Taiwan.

We summarize the synoptic environment of the extremely torrential rain case by Figure 4. There are two TDs on the northeastern and the southwestern sea level of Taiwan respectively. Owing to the circulation of the two TDs, it prevail northeasterly wind on northern Taiwan, and southwesterly wind on southern Taiwan. We can see the shear line in northwestern Taiwan on 850mb and 700mb. There are low level jets near Taiwan on 850mb. In addition, the wet area (T-Td<3°C) covered overall Taiwan area, it reveal that is quite moisture at lower troposphere. Accompanying with the great deal of water vapor by the southwesterly flow, it support the source to cause the extremely torrential rain for Taiwan area.

The 0000UTC sounding data of MaKung site (not shown) reveals there has light southeasterly wind below 1000mb, and it prevailed the southwesterly wind from 1000mb to 200mb. It also indicated that low-level winds veered with height, meant to be obvious warm advection. The CAPE (Convective Available Potential Energy) value is 1613.5m^2 s^{-2} The environmental vertical shear is from moderate to light, and the value is about 12 ms^{-1} 0-5 km AGL. It indicated that the environment possesses the moderate vertical shear and conditional instability; the synoptic environment is favored to the development of convection.

4. The analysis of QLCS cases

We use the reflectivity and radial wind data observed by TIA radar to analyze the QLCS1 - QLCS2 and the embedded mesoscale weather phenomenon within it, such as bow-shaped

Figure 5 (a) The 2 km CAPP radar reflectivity at 0555 UTC on 10 Sept. 2004.
(b) The AB vertical cross-section of Figure 5a, the contour indicates the reflectivity(unit:dBZ). The shaded indicates the wind velocity, negative (positive) colors indicate velocities toward (away) from radar center.
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First, the QLCS1 occurs on the northwestern sea level of Taiwan. As shown in Figure 5a, there is a bow-shaped echo within it, the apex is northeastward and moves from west to east-northeast, there is an obvious rear inflow notch within the system, and the size of this convective system is about the length of 50 km and the width of 40 km. Figure 5b is the AB vertical cross-section of the bowshaped echo and its rear-inflow notch shown in Figure 5a. The contour indicates the reflectivity (unit : dBZ); the shaded indicates the wind velocity, negative (positive) colors indicate velocities toward (away) from radar center. The radar site is on the right side. The maximum intensity of reflectivity is about 40~45 dBZ with 2 km height, and the development height of the reflectivity larger than 35 dBZ is about 4 km height. The development of the convective system is top above 8 km height; its lifetime is about 4 hours. There is strong rear inflow jet from X=0 km to X=15 km behind the maximum reflectivity region (X=15 km). The wind velocity

Second, as shown in figure 6a, the QLCS2 occurs on the northwestern sea level of Taiwan. This convective system accompanies with mesovortex and occurs a convective rainband at the right side. It possesses the bow-shaped characteristic and significant rear inflow notch, the size is about the length of 60 km and the width of 40 km. Figure 6b is the AB vertical cross-section of the bow-shaped echo and its rear-inflow notch shown in Figure 6a. The maximum intensity of reflectivity is about 45~50 dBZ with 3 km height, and the development height of the reflectivity larger than 35 dBZ is about 5 km height. The development of the convective system is top above 8 km height; its lifetime is about 4 hours. There is strong rear inflow jet from X=0 km to X=15 km behind the maximum reflectivity region (X=15 km). The wind velocity

Figure 6  (a) The 2 km CAPPI radar reflectivity at 1135 UTC on 10 Sept. 2004. (b) The AB vertical cross-section of Figure 5a, the contour indicates the reflectivity(unit:dBZ). The shaded indicates the wind velocity, negative (positive) colors indicate velocities toward (away) from radar center.
is from -18 to -21 m/s (-36 to -42 knots); there is an evident front-to-rear ascending updraft current prior to the strong convective region (from X=15km to 30km), the wind velocity is from 12 to 15 m/s (24 to 30 knots). It occurs the obvious midaltitude radial convergence (MARC) near the maximum reflectivity region (X=15km). QLCS2 also has the wind shear even turbulence, but the intensity is stronger than QLCS1. Thus, the aircrafts should keep away this area.

5. Conclusion

This research uses the high time-space resolution reflectivity and radial wind data of the TIA radar to analyze the extremely torrential rain case in northern Taiwan on 10-11 September 2004. It also finds some mesoscale weather phenomenon, such as bow echoes and mesovortices before and after this case. First, the synoptic environment showed that there are two TDs on the northeastern and southwestern sea level of Taiwan respectively. So, it prevailed northeasterly wind in northern Taiwan and southwesterly wind in southern Taiwan, it makes Taiwan area form an extensive shear zone by the relative motion and its position of two TDs. It also affects the orientation of rainband and the production of mesoscale phenomenon within the convective system. In addition, according to the sounding data, it indicates that the environment possesses moderate CAPE and vertical shear; it's under the conditional instability environment and moisture at the lower troposphere, these are beneficial for the development of convection.

This research begins from the extremely torrential rain case caused by the extensive well-organized convection system, and notices the subtle mesoscale weather phenomenon. We depict the organization, development, merging and dissipation of the bow echoes and mesovortices within QLCSs clearly by the high resolution time-space radar data. We can't find the damaging straight-line winds in this research because of the lack of observing data on the sea level and there is no disaster caused by strong winds. The reflectivity and radial wind data of the TIA radar shows us the significant weather timely. Therefore, we can not only provide the information and warnings to aircrafts but enhancing the aviation security in advance.