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IMPACTS OF UPPER-LEVEL COLD VORTEX ON THE RAPID CHANGE OF INTENSITY AND MOTION OF TYPHOON MERANTI (2010)

LI Ying (李　英)[1], GUO Li-xia (郭丽霞)[2], XU Ying-long (许映龙)[3], HU Shu (胡　姝)[4]

(1. State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences, Beijing 100081 China; 2. Tangshan Meteorological Bureau, Tangshan, Hebei 063000 China; 3. National Meteorological Center, Beijing 100081 China; 4. Oceanic Hydrologic Center of Navy, Beijing 100161 China)

Abstract: Typhoon Meranti originated over the western North Pacific off the south tip of the Taiwan Island in 2010. It moved westward entering the South China Sea, then abruptly turned north into the Taiwan Strait, got intensified on its way northward, and eventually made landfall on Fujian province. In its evolution, there was a northwest-moving cold vortex in upper troposphere to the south of the Subtropical High over the western North Pacific (hereafter referred to as the Subtropical High). In this paper, the possible impacts of this cold vortex on Meranti in terms of its track and intensity variation is investigated using typhoon best track data from China Meteorological Administration, analyses data of 0.5×0.5 degree provided by the global forecasting system of National Centers for Environmental Prediction, GMS satellite imagery and Taiwan radar data. Results show as follows: (1) The upper-level cold vortex was revolving around the typhoon anticlockwise from its east to its north. In the early stage, due to the blocking of the cold vortex, the role of the Subtropical High to steer Meranti was weakened, which results in the looping of the west-moving typhoon. However, when Meranti was coupled with the cold vortex in meridional direction, the northerly wind changed to the southerly at the upper level of the typhoon; at the same time the Subtropical High protruded westward and its southbound steering flow gained strength, and eventually created an environment in which the southerly winds in both upper and lower troposphere suddenly steered Meranti to the north; (2) The change of airflow direction above the typhoon led to a weak vertical wind shear, which in return facilitated the development of Meranti. Meanwhile, to the east of typhoon Meranti, the overlapped southwesterly jets in upper and lower atmosphere accelerated its tangential wind and contributed to its cyclonic development; (3) The cold vortex not only supplied positive vorticity to the typhoon, but also transported cold advection to its outer bands. In conjunction with the warm and moist air masses at the lower levels, the cold vortex increased the vertical instability in the atmosphere, which was favorable for convection development within the typhoon circulation, and its warmer center was enhanced through latent heat release; (4) Vertical vorticity budget averaged over the typhoon area further shows that the intensification of a typhoon vorticity column mainly depends on horizontal advection of its high-level vorticity, low-level convergence, uneven wind field distribution and its convective activities.

Key words: upper-level cold vortex; typhoon; intensification; north turning; Taiwan strait

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1 INTRODUCTION

A tropical cyclone (TC) is a strong and massive atmospheric eddy, which generally moves poleward after its genesis over tropical oceans. TCs often have significant impacts on the mid- and higher-latitudes. A TC usually interacts with other weather systems, e.g. westerly trough, jet streams in higher and lower atmosphere, frontal systems, upper-level cold vortex (UCV), among others[1-4]. Unusual changes in TC motions, structures, intensity, wind and rainfall may occur in this stage, and accurate predictions of these unusual changes still remain a challenge. Among them, the impacts of the UCV in the subtropical region (appearing in the upper troposphere at 300 hPa or 200 hPa level, with its downward extension being related to its intensity) on TCs have been addressed since 1970s. Liu[5] pointed out when the distance between a typhoon and a cold vortex was reduced to within about 700 km, and their interactions should be

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Biography: LI Ying, Professor, primarily undertaking research on tropical cyclone.

Corresponding author: LI Ying, e-mail: liying@cams.cma.gov.cn

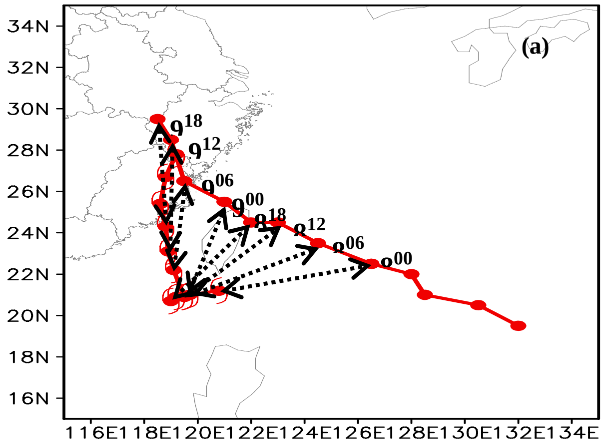
considered. Chen et al.[1] suggested that by changing the ambient circulations around a typhoon center, the UCV could influence it through steering, attraction, changing motion speed and transformation. In their studies, Fei et al.[6] found that when a cold vortex existed above the Subtropical High, the normal temperature, wind, divergence and vorticity fields in the latter would be disrupted, which in return created a favorable environment for the generation of cyclonic vorticity. On one hand, this cyclonic vorticity may weaken the Subtropical High. On the other hand, it may also attract the TC to the north. Ao et al.[7] investigated the typhoons that approached Japan in 1982, out of which 4 cases had interacted with the cold vortex in the upper atmosphere. It was also found that apart from the attraction, a cold vortex may also rotate with a TC interactively. When the cold vortex approached a typhoon within a certain distance, TC transformation may occur. Chen[8] analyzed the north-moving track of typhoon Ofelia (9005) and found that the cold vortex weakened the Subtropical High while steering the typhoon northward through its strong southerly flow. Further studies by Fei et al.[9, 10] showed that both the horizontal and vertical structures of the UCV may also influence the TC motion, mostly by changing the ambient circulation structure around the TC center. Under its influence, a TC may move either to a convergence center near its own center in the upper troposphere or to the nearby divergence center in mid- and lower-atmosphere. Chen[11] investigated the impacts of the UCV in the Subtropical High on the tracks of the typhoon Gladys (9418), and pointed out that when the two systems were about 1000 km apart, the typhoon was most likely steered by the cold vortex and crossed over the Subtropical High.

Tang[12] analyzed the impacts of the UCV in the westerlies on typhoon intensity, and found that when a tropical depression was within 500-1000 km away to the southeast of the cold vortex, the chance for a depression to develop into a typhoon would be higher. However, when the cold vortex was located within 500 km to the west of a typhoon, the latter would be weakened rapidly.

So far, the mechanism for the impacts of the cold vortex in the upper atmosphere on typhoon tracks remains unclear, and there are few findings on TC intensity. Typhoon Meranti in 2010 made a sudden north-turning and reached its strongest intensity just before landfall from China's offshore sea, which was quite unusual in its motion and intensity variation. Nevertheless, during its life cycle, it was accompanied to its north with a cold vortex in the upper atmosphere. Unlike the east-moving cold vortexes in the westerlies that have been extensively addressed in previous studies, the cold vortex was generated over the tropics to the south of the Subtropical High and moved northwestward. However, less attention has been paid to its impacts on typhoon's north-turning track and intensification. This paper tries to address these impacts by using the data from CMA *Typhoon Yearbook*, NCEP GFS 0.5×0.5 grid data, Taiwan radar data and JMA satellite imageries.

2 ACTIVITIES OF TYPHOON MERANTI AND UPPER-LEVEL COLD VORTEX

Figure 1a shows the tracks of typhoon Meranti (TC symbol line) and the UCV (dotted line) in 6-h intervals, and Figure 1b presents the minimum sea level pressure variations in the vicinity of the typhoon center. Meranti originated at about 2100 UTC on 7 September 2010 over the Pacific off the south tip of the Taiwan Island, then it began to move west without any significant change in intensity. After 0400 UTC on 8 September, it entered the northeastern South China Sea. At around 1200 UTC on the same day, it apparently slowed down in motion, and looped around in about same the location from midnight, seemingly moving nowhere. From the morning of 9 September, Meranti started to move north, entering the Taiwan Strait and getting intensified all its way north. At 0600 UTC, it became a severe tropical storm and developed into a typhoon close to Jinjiang, Fujian province at 1800 UTC, then made landfall on the coast of Shishi at 1900-2000 UTC on the same day, with the maximum wind speed reaching force 12 on the Beaufort scale (35 m/s) and the minimum central pressure down to 975 hPa. Meranti continued to move north with a weakening intensity after its landfall. After entering the Zhejiang province at 1100 UTC on 10 September, it became a tropical depression, and finally its locating was stopped at 1800 UTC.



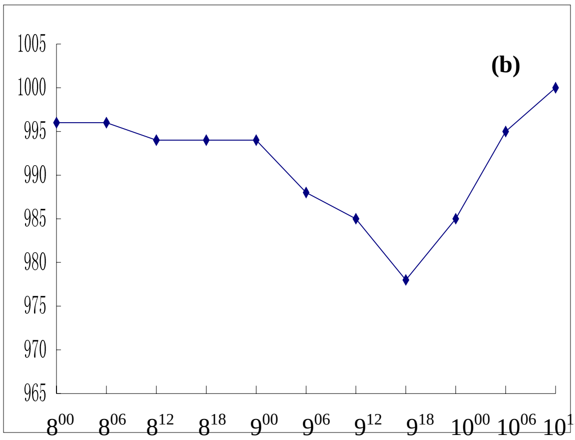
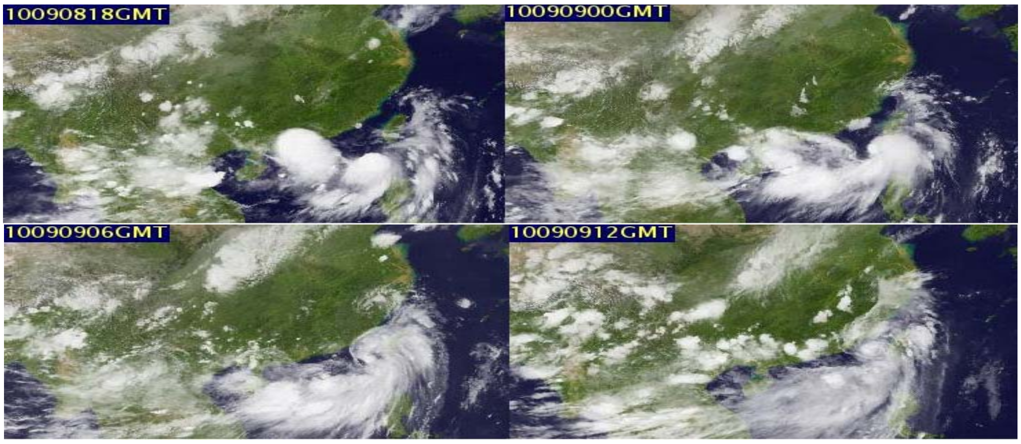


Figure 1. (a): 6-hourly tracks of typhoon Meranti (line with TC symbol) and the UCV (dotted line); (b): temporal evolution of minimum sea level pressure (hPa) near the typhoon center. (Data in Figure 1a and in *x*-coordinates in Figure 1b refer to the dates and subscripts show the hours in UTC).

Before the genesis of Meranti, there were upper-level eddy activities over the western North Pacific to the south of the Subtropical High, associated with some cold centers. In Figure 1a, the dotted line shows its track based on cold vortex center at 200 hPa. On 7 September, the UCV was mainly active over the tropical ocean to the east of 128°E and to the south of 20°N. At 0000 UTC the next day, the cold vortex was located to the northeast of newly-generated typhoon center, and then moved to the northwest. At 1800 UTC on 8 September, it made its first landfall in northern Taiwan. At 0000 UTC on 9 September, it entered the Taiwan Strait with weakening intensity, while Meranti slowly moved west and stagnated. At 0600 UTC on the same day, UCV vortex made the second landfall over the junction of Fujian and Zhejiang provinces, roughly located to the due north of the typhoon center. And suddenly Meranti turned right north instead of spinning around at 0300 UTC, 9 September, and it was almost along the same meridian line as the cold vortex. Since then, both moved north. At 1800 UTC on that day, the cold vortex merged into a mid-latitude westerly trough and disappeared. Throughout the process, the two centers were approximately 6 latitude meshes apart.

GMS infrared satellite image shows the Meranti's entry in the Taiwan Strait (Figure 2). At 1800 UTC on 8 September before turning north (Figure 2a), Meranti was a 'comma' cloud system, and a cloud band was rolling in from southwest. At the same time, a larger cloud cluster was located along the South China coast to the northwest of the cyclone. At 0000 UTC the following day, this cloud cluster was merging with the Meranti cloud band from northwest to south (Figure 2b), showing a large typhoon tail that covered the entire South China Sea (Figures 2c and 2d). About the time of landing (Figure 2e), the tail of Meranti was disappearing, its cloud system gradually became stand-alone, with its structure becoming symmetric on a very small scale. The zonal coverage of the cloud system was about 300 km, roughly equivalent to the width of the Taiwan Strait. The typhoon eye was only about 40 km, but clearly visible. Compared to the 500-km average radius of a usual TC, it was just a 'midget' typhoon. After landing (Figure 2f), the typhoon eye disappeared and Meranti remained as a comma cloud, gradually out of sight. Some cloud systems also developed near the center of the upper-level cold vortex, but they were relatively thin and loose, appearing like upper air cirrus.



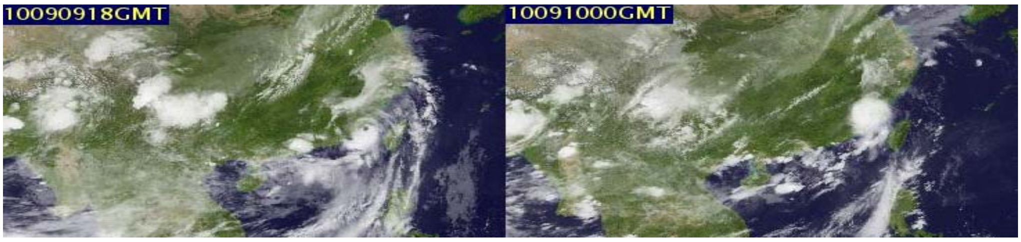


Figure 2. A GMS infrared cloud image from Japan.

From above, in the northwest motion of the UCV across the northern Taiwan, Meranti first slowly moved west and looped around the same location, and then it moved right north and entered the Taiwan Strait, with intensity being significantly increased. In this process, the cold vortex was about 6 latitude meshes apart from the typhoon center, and its impact on the typhoon activity could not be simply ignored.

3 BACKGROUND OF MERANTI AND UPPER-LEVEL COLD VORTEX AND THEIR EVOLUTIONS

3.1 *Circulation background*

From large-scale circulation patterns, in the early stage when Meranti was formed (figure omitted), the Subtropical High center at 500 hPa was over the ocean to the southeast of the Japan, showing a zonal band linking with the Continental High to the south of 30°N over the mainland China. At the same time, there was a stronger depression near Mongolia (102°E, 42°N). At 0000 UTC on 9 September, the depression moved east to 110°E, and the Continental High was weakened and moved south. Consequently, the Subtropical High retreated east as a fragment and progressed south, but there was stronger southerly flow between it and the typhoon in the southwest. The upper-air circulation pattern at 200 hPa was similar to that at 500 hPa, but the cyclonic circulation to the southwest of the Subtropical High was the UCV, which was extending about 10 degrees in latitude or longitude and covering the top of the typhoon center. The southerly flow between the eastern boundary of the cold vortex and the Subtropical High was also clearly visible. Because the UCV moved north ahead of Meranti, it contained the activity of the Subtropical High together with the westerly trough. During the period when the UCV made landfall over the Fujian province and moved north to a high-latitude baroclinic zone, the Subtropical High still maintained to the east of the cold vortex, allowing the southerly flows between the two systems to dominate the Taiwan Island and Taiwan Strait, and enhancing the traction that drove the typhoon north from the southern Taiwan Strait.

Figures 3c and 3d show water vapor flux and wind vector fields at 850 hPa. Before Meranti moved north, its vortex circulation dominated the region from the northern Philippines to the Taiwan Island including its surrounding waters, together with the water vapor jet from the South China Sea. A low-level water vapor jet around the typhoon broke into two branches from the north and south sides of the Taiwan Island respectively (Figure 3c, shaded). When it entered the Taiwan Strait, the low-level jet around the typhoon was enhanced (Figure 3d), providing abundant moisture and heat for its development. The water vapor from the north side of Taiwan Island was transported to the bottom of the upper-level cold vortex and then entered the baroclinic zone.

From the analysis above, it is evident that the existence of the UCV could contain the activity of the Subtropical High and change the steering flow for the typhoon. At the same time, through its meridional coupling with typhoon circulation, the overlapped circulations may affect the structure and intensity of the typhoon. In addition, the long connection of Meranti with the low-level water vapor jet is another favorable factor for TC development.

3.2 *Interactive evolution of upper-level cold vortex and Meranti*

Figures 4a, 4b and 4c present the vertical vorticity (shaded) starting from the typhoon center (point A) to the cold vortex center (point B) and the vertical profile of horizontal wind vectors. As shown in the figure, when Meranti was just formed (0000 UTC, 8 September), a positive vortex column extended vertically from the lower level up to about 500 hPa only, and its horizontal range spanned approximately 5 latitude meshes, with its maximum value reaching about $24\times10^{-5}\,s^{-1}$. To the east of the typhoon, however, the upper-level cold vortex was significantly larger and stronger. The horizontal range of its positive vorticity covered 10 latitude meshes, vertically extending from 400 hPa up to 100 hPa, with its maximum value ($30\times10^{-5}\,s^{-1}$) being found at about 200 hPa. From the perspective of wind vector distribution at this time, the upper level beyond 400 hPa above the typhoon was dominated by a strong northerly flow to the west of the cold vortex. As the upper-level cold vortex moved northwest, the upper northerly flow over the typhoon was weakened, and the airflow between the typhoon and the cold vortex changed to a southerly flow at 0000 UTC on 9 September (Figure 4b). Since then, the upper atmosphere above the typhoon was characterized by a southerly flow from the east of the cold vortex (Figure 4c), and northerly wind component was decreasing. In this process, the positive vorticity of the cold vortex was weakened, while the positive vorticity of the typhoon was enhanced, especially the o between 300 hPa and 400 hPa was increased significantly. It was also noted that, at 0000 UTC on 9 September, positive vorticity in the lower troposphere below the cold vortex was developing, and a negative vorticity zone appeared between it and the positive vorticity of the typhoon, which may be related to the low-level jets from both north and south sides of Taiwan Island, i.e. the positive (negative) vorticity was generated at the south (north) side of the low-level jet (figure omitted). At 1800 UTC on 9 September, Meranti became full-fledged, and its positive vortex column was strengthened and extended upward, with its horizontal range, its vortex column height and intensity being stronger than those of the cold vortex. On the other hand, the cold vortex was weakened, and its cyclonic circulation was visible only at 200 hPa level (figure omitted). Later on, it merged into the westerly trough and disappeared.

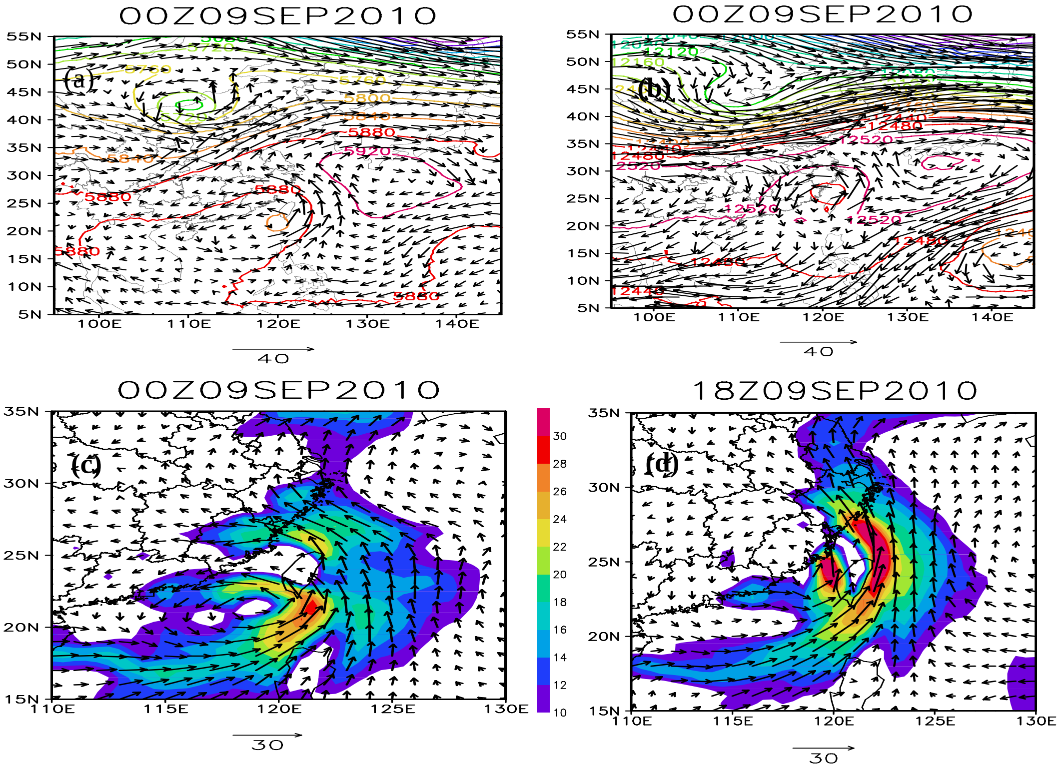


Figure 3. Geopotential height field and horizontal wind vector field at 0000 UTC on 9 September 2010 at 500 hPa (a) and 200 hPa (b); horizontal water vapor flux at 850 hPa at 000 UTC (c) and 1800 UTC (d) on 9 September (shaded sections show only the regions that are no less than 10 g s^{-1} hPa^{-1} cm^{-1}).

From above, it was quite clear that the vorticity column gained strength in the process of typhoon development. From the prospect of corresponding changes in horizontal wind vectors and vertical vorticity at 300 hPa (Figures 4d, 4e and 4f), the positive vorticity center was located near the cold vortex center, and the typhoon was below the cyclonic circulation of the cold vortex. At 0000 UTC on 8 September, the northeasterly flow of the cold vortex provided positive vorticity to the upper atmosphere over the typhoon. As the cold vortex moved to the north of the typhoon, the positive vorticity advection was weakened at about 0000 UTC on 9 September. However, because the typhoon was in the vicinity of the shear line created between the northerly and westerly flows of the cold vortex, stronger vorticity still remained in the upper level of the typhoon. At 1800 UTC on the same day, the Subtropical High extended west to reach within about 10 latitude meshes from the Continental High. The cold vortex was located between the strong negative vorticity zones of these two Highs. It presented a stronger north-south positive vorticity zone that stretched to deformation. As Meranti was located to the south of the vorticity zone, it could get additional positive vorticity on its way north. In this sense, enhanced positive vorticity over the typhoon was related to the advection supply from the cold vortex.

As shown in the 850 hPa chart (Figures 4c, 4f, and 4i), the maximum vorticity occurred near the typhoon circulation center and to the north of the Taiwan Island. In the early stage of Meranti, no low-level southwesterly jet stream was directly connected with it as the Subtropical High was to the east of the typhoon (0000 UTC, 8 September). As the UCV was moving northwest and the Subtropical High was extending west, a southwesterly low-level jet was gradually built up in the eastern part of the typhoon, which then broke into two branches at both south and north of the Taiwan Island under its topographic effect (0000 UTC, 9 September). At the same time, strong positive vorticity existed close to the low-level jets, while a zone of low wind speed appeared between the low-level jets, making the Taiwan Strait located in a negative vorticity domain. When the southerly flow from the upper-level cold vortex overlapped with the typhoon, the southwesterly low-level jets in the east of Meranti was strengthened (1800 UTC, 9 September), which in return enhanced both positive and negative vorticity nearby, eventually forming a strong dipole of vorticity and facilitating convective development.

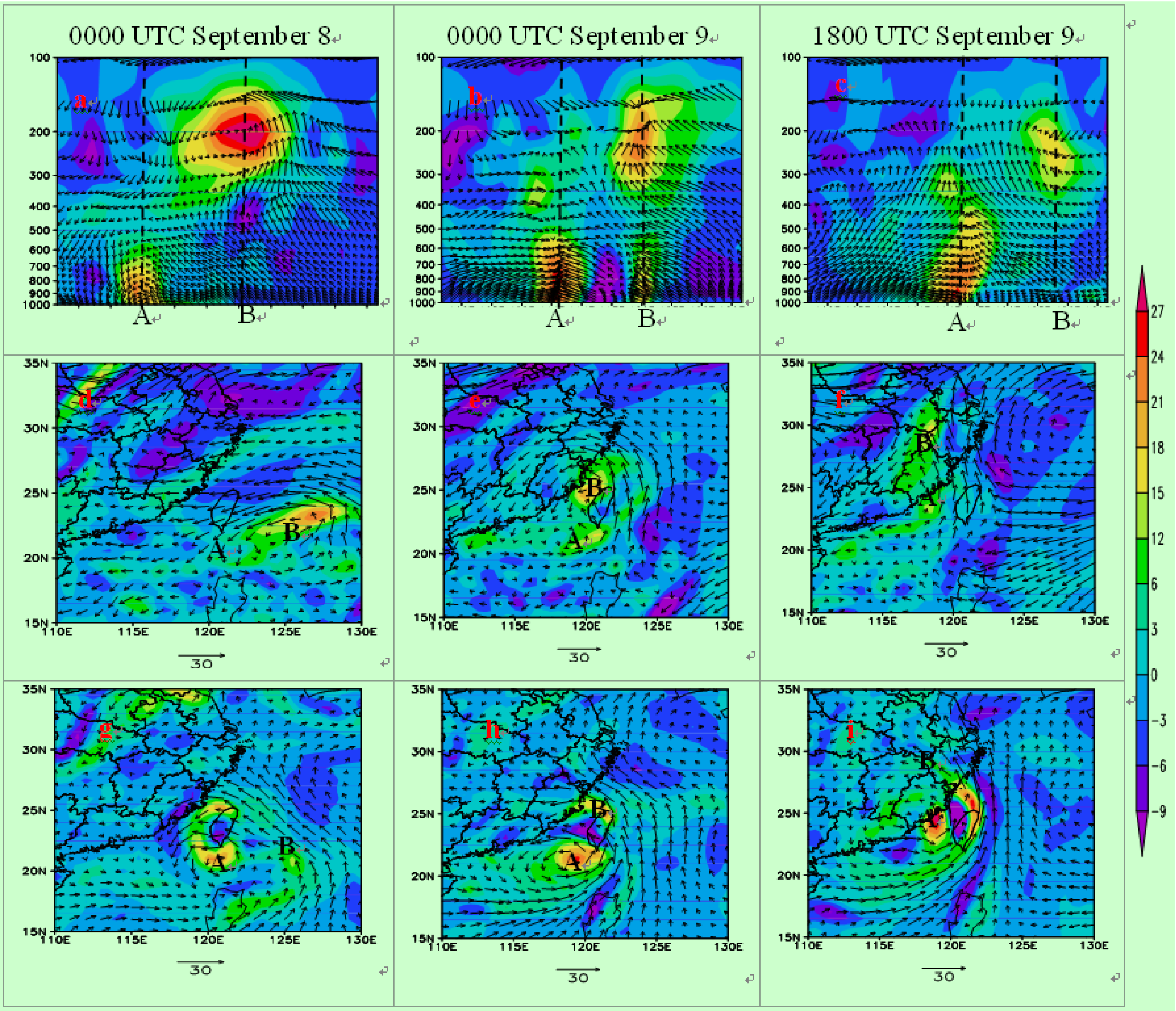


Figure 4. Vertical vorticity (shaded, 10^{-5} s^{-1}) and horizontal wind vectors (a, b, c) along a line connecting the typhoon center (A) and the upper-level cold vortex center (B), and horizontal wind vectors and vertical vorticity at 300 hPa (d, e, f) and 850 hPa (g, h, i). a, d, g: 0000 UTC, 8 September; b, e, h: 0000 UTC, 9 September; c, f, i: 1800 UTC, 9 September.

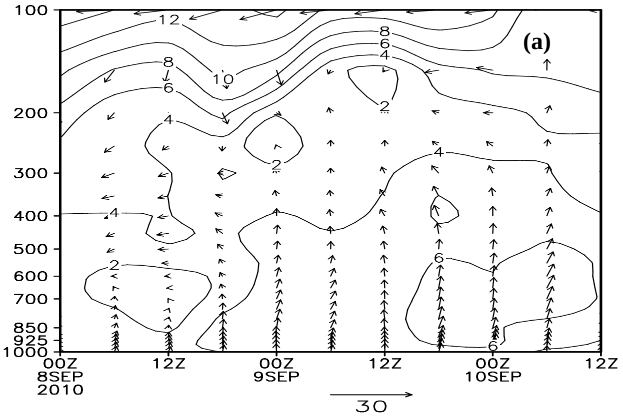
The above analysis shows that an upper-level cold vortex horizontally provides positive vorticity to Meranti, and the overlap of its southerly wind on top of Meranti tends to strengthen the southwesterly low-level jet related to Meranti, which is conductive to vorticity development.

4 IMPACTS OF THE UPPER-LEVEL COLD VORTEX ON TYPHOON MERANTI

4.1 *North-turning track*

After genesis over the western North Pacific, a typhoon generally moves west under the steering easterly flow of the Subtropical High in the south. When Meranti was formed, due to some activities of the upper-level cold vortex to its east, the steering role of the Subtropical High was weakened, with its westbound motion slowing down and looping around almost in the same location. When the cold vortex moved northwest till to the north of the typhoon, the upper-level northerly flow over the typhoon changed to a southerly flow, while the Subtropical High was protruding west and the southerly flow to its west seemingly enhanced the steering role on Meranti.

By selecting a square of 10° lat./long. around the typhoon center as the averaged zone (applicable hereinafter), the average horizontal wind vectors and speeds at the 1000-100 hPa level (Figure 5a) plus the mean *u* and *v* wind speeds for 1000-200 hPa (Figure 5b) are calculated. As shown in the figure, before 1200 UTC on 8 September, a strong northeasterly flow prevailed over the typhoon at the 300-100 hPa level, from which down to 500 hPa an easterly flow dominated. Below 500 hPa, a weak southerly flow was detected, and the typhoon was then just moving west. From 1200 UTC, 8 September to 0000 UTC, 9 September, the cold vortex gradually moved to the northeast of the typhoon, the Subtropical High was protruding west, and the low-level southerly flow of the typhoon was strengthened. However, the upper-air northerly was also gaining strength significantly, with both mean zonal and meridional winds in the whole level almost becoming zero. The typhoon steering flow was found so weak that Meranti went nowhere but simply looped around, instead, where it had been. After 0000 UTC, 9 September, the cold vortex moved roughly to the north of the typhoon, and the typhoon upper-level was under the southerly flow from the east of the cold vortex. The mean southerly flow was rapidly intensifying, while the zonal wind remained weak, and the typhoon immediately turned north from stagnation. After 18 September, the upper-level cold vortex moved north into the westerly trough. Being governed by the southwesterly flow in front of the trough, Meranti moved further north, while the zonal wind speed increased. All this shows that an upper-level cold vortex may play an essential role to steer a typhoon north, entering the Taiwan Strait soon.



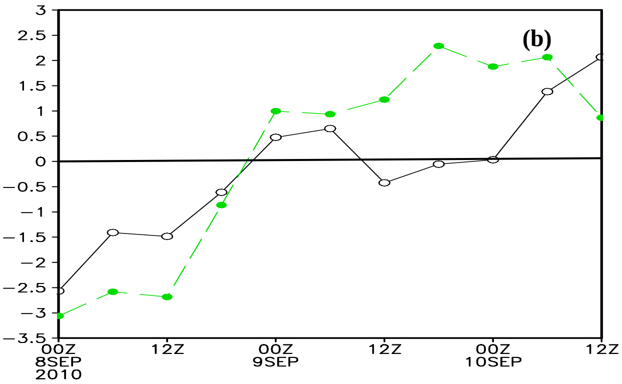


Figure 5. (a) Vertical distribution of the mean horizontal wind vectors and speeds in the typhoon zone from 0000 UTC 8 September to 1200 UTC 10 September 2010 and (b) temporal evolution of the mean level-wise horizontal wind components (m/s, *u*, solid line; *v*, dotted line) in a 1000-200 hPa typhoon zone.

Moreover, the cold vortex moved north earlier than Meranti so that a depression passage was formed between the Subtropical High and the Continental High, which was "attracting" the typhoon to move north. Chen et al.[1] studied the typhoon attraction by a depression circulation system, and suggested that when two systems were close enough to each other (generally < 5 latitude meshes), at the side of a typhoon which was close to the depression, the pressure gradient force tended to decrease rapidly, and at farthest side of a typhoon, the gradient force remained unchanged, such pressure difference would push the typhoon toward the depression system. Figure 6(a) shows distributions of the mean wind vector fields and meridional gradient force ($-g\frac{\partial h}{\partial y}$) at the 1000-100 hPa level, before the typhoon changed its direction. As shown in the figure, the typhoon and the upper-level cold vortex circulation coexisted in a large cyclonic circulation, to the east of which there was a strong southerly flow. Generally, the pressure gradient force to the south of a depression circulation is positive (pointing to north), and that to its north is negative (pointing to south). As also shown in the figure, at 0000 UTC, 9 September, just before Meranti was about to change direction, the central intensities of both positive and negative gradient forces to the south and north sides of the typhoon were more or less equivalent, but its north side was near the cold vortex, to the south of which lied a positive gradient force zone with 4 latitude meshes apart from the typhoon center. So the southbound gradient force in the north of a TC tends to be weaker, and the massive northbound gradient force remains in its south. This north-south pressure difference may enhance the TC north-moving tendency. Figure 6b shows the distribution of the gradient force vectors, with the northbound gradient force in the south of Meranti obviously advantageous over the southbound force in its north. At the same time, as a strong pressure gradient existing between the eastern side of the typhoon and the Subtropical High, the westbound pressure gradient force in the east of the typhoon was more prominent than the eastbound force in its west. However, the typhoon mainly moved north with a tiny westbound component only, explaining that the ambient northbound steering flow prevailed while the geostrophic force may also push the typhoon north. After changing its direction, Meranti still maintained the same north-south phases with the UCV. A similar difference was still found in the pressure gradient forces on both sides of the typhoon (figure omitted), implying that the typhoon was attracted by the cold vortex to some extent.

Therefore, TC track changes are closely related to an upper-level cold vortex. Most importantly, the steering flow from the cold vortex changes from northerly to southerly, enhancing its role to steer a typhoon north. On the other hand, the pressure reduced by the UCV also adds a minor attraction to the typhoon.

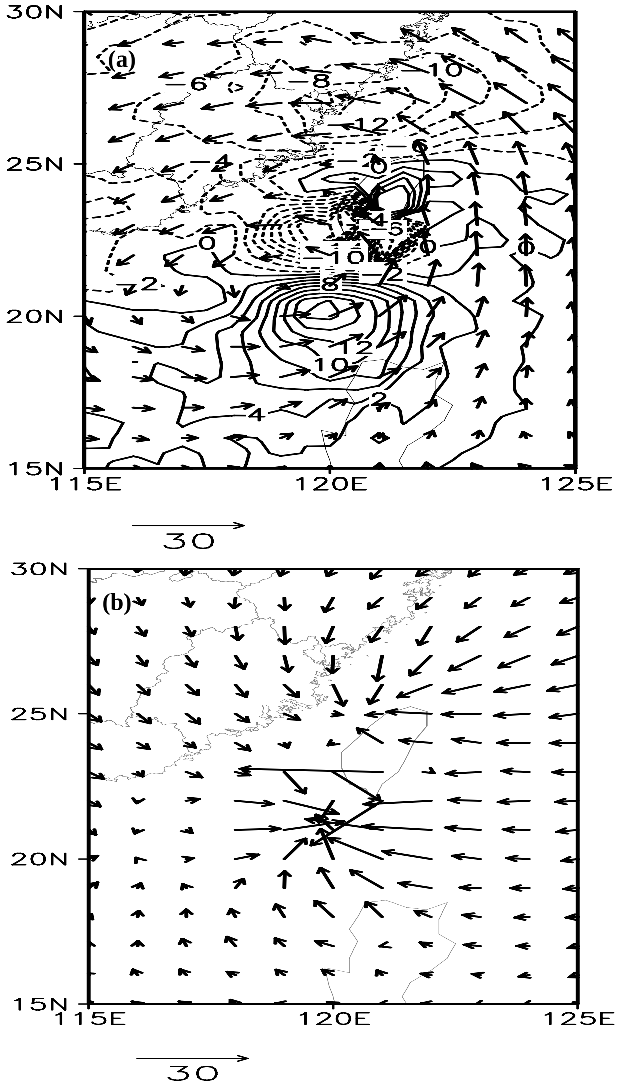


Figure 6. (a) The mean wind vectors and meridional pressure gradient force (10^{-4} m s^{-2}), and (b) the vectors of pressure gradient force across 1000-100 hPa at 0000 UTC, 9 September.

4.2 *Intensification before landfall*

4.2.1 VERTICAL WIND SHEAR

It is generally assumed that an ambient vertical wind shear (VWS) affects the “ventilation” of a typhoon. A stronger VWS inhibits TC intensity, while a weaker VWS favors a TC warm-core structure, thus contributing to TC maintenance and development. Study results show that the VWS has larger impacts on a TC core structure[13-15]. Recently, in their statistical studies on the correlation of North Atlantic TC intensities with VWS, Zeng et al.[16] found that both the vertical shear and translational speed have negative effects on TC intensity. TCs featuring stronger intensity, slow motion and lower-latitude location were substantively subject to high-level VWS. In contrast, weaker, faster-moving TCs in higher latitudes were largely subject to a mid- and low-level VWS.

The differences of the mean vector winds between 200–850 hPa, 200–500 hPa, and 500–850 hPa levels of the typhoon have been calculated to represent the vertical shear in the whole, middle and lower troposphere respectively. Figure 7 shows the temporal evolution of Meranti’s vertical wind shears, from which it can be noted that the low-level vertical shear (dotted line) was relatively weak in the typhoon process and maintained a speed of about 1 m/s. The vertical shear at the whole level and the one at the upper level showed similar tendencies. From its genesis at 0000 UTC on 8 September to 0000 UTC the next day, Meranti changed little in intensity. The VWS was virtually above 5 m/s, with a maximum of 11 m/s. After 0000 UTC on 9 September, VWS speed was reduced to about 3 m/s with Meranti being enhanced. At 1800 UTC on the same day, VWS began to increase when Meranti developed into a typhoon. As shown in Figure 5a, before 0000 UTC on 9 September, under the influence of the cold vortex, the typhoon upper-level was dominated by a strong northerly flow, which was just in an opposite wind direction at its low-level. The large difference in wind speeds led to a strong vertical shear. Later on, the northerly wind changed to a southerly wind at the 200 hPa level, keeping the same direction as the low-level wind, and weakening the vertical shear. Therefore, when the upper-level cold vortex was located to the north of the typhoon, the change of its upper-level flow direction weakened the ambient vertical wind shear, it facilitated Meranti’s development.

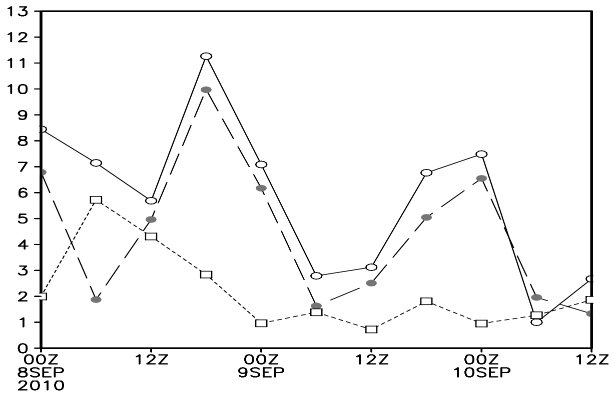


Figure 7. Temporal evolution of the VWS speed (m/s) at the whole level (solid line), upper level (dash line) and low level (dotted line) in the typhoon zone.

4.2.2 ACCELERATION OF THE SOUTHERLY WIND

The above analysis shows that when the typhoon and the UCV are in the same phase, the stronger southerly flow from the east part of the cold vortex will be overlapped with the southerly flow from the east part of the typhoon, which is eventually thickened and enhanced. Figures 8a and 8b give the profile of meridional wind speed and divergence crossing the Taiwan Island along 121°E, showing the wind direction change about 200 km away from the east of the typhoon center. At 0000 UTC on 9 September, before turning north, at the typhoon upper-level the northerly flow of the cold vortex was changed into a southerly flow, and there were two high wind centers associated with the upper-level cold vortex and the typhoon zone, together with strong divergence and convergence centers. The stronger southerly wind prevailed to the east of Meranti below 200 hPa. At 0600 UTC on 9 September, both of the centers of Meranti and the UCV were in a same south-north phase, and both high- and low-level southerly flows were overlapped. The upper-level strong southerly was extending in the meridional direction, which was accelerating upper and lower winds via air stress, and consequently the whole layer of southerly flows to the east of the typhoon center was thickened. Meanwhile, the strong southerly center in the east part of the cold vertex was located further north relative to the typhoon, forming a massive but thick divergence zone above the typhoon and enhancing low-level convergence as well. As a result of blocking by Taiwan's topography, a weaker southerly was found to the north of Meranti’s strong southerly center, and it also contributed to the convergence and updraft of the southerly flows. Then Meranti entered the Taiwan Strait, along with well-developed southerly flows to the east of the typhoon. Figures 8c and 8d show the enhanced southerly to the east of Meranti, for which the high-level cold vortex plays a major role. The strong high-level southerly and divergence to the east of the typhoon pumped the cyclone north, providing a tangential acceleration for its fast development.

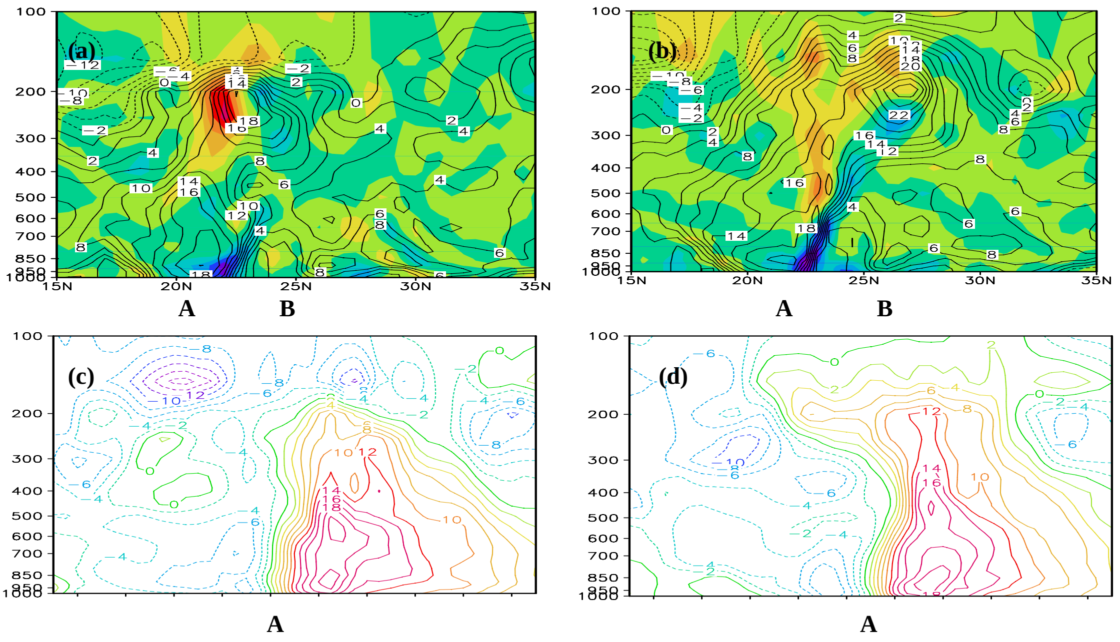


Figure 8. Vertical profiles of meridional wind speed (m/s) and divergence (a, b) crossing the Taiwan Island along 121°E, and the zonal vertical profiles of meridional wind crossing the typhoon center (c, d) at 0000 UTC, 9 September (a, c) and 0600 UTC, 9 September (b, d) respectively.

4.2.3 THERMAL ADVECTION

The analyses of circulation of the UCV at the 400, 350, 300, 250, 200 and 150 hPa levels showed that (figure omitted), in life cycle of the cold vortex, all layers had a cold core structure, with the only exception at the 150 hPa level. Figure 9 presents temperature fields (*K*) at 150 hPa and 300 hPa and horizontal wind vector fields at 0000 and 1800 UTC on 9 September As it was noted, at about 0000 UTC, 9 September, a nearby warm core was associated with the cold vortex center, supplying warm advective flows to Meranti under cyclonic circulation at 150 hPa (Figure 9a). At about 1800 UTC, the warm core in the cold vortex zone weakened (Figure 9c), but there was still weak warm advective flows to the typhoon zone, which was favorable for maintaining the typhoon's warm core. Both Meranti's warm core and cold core structures of the vortex were visible at 300 hPa (Figure 9b, d), and they exchanged warm (cold) advective flows each other. Due to asymmetry of cyclonic circulation, the cold advection from the cold vortex to typhoon was weaker than the warm advection from typhoon to the cold vortex. Later, the typhoon's warm core and southerly flow were enhanced, and the warm advection to the cold vortex became even more evident. This was a factor for weakening of the cold vortex, while cold advection from the vortex to the upper level of the typhoon became weaker. Meanwhile, a northeasterly cold advection from the west boundary of the cold vortex mainly arrived at the northwest of the typhoon's outer band, having little effect on the typhoon's warm core, but affecting the stability of atmospheric stratification ($\frac{\partial\theta_e}{\partial p}$) to the north of the typhoon instead. The vertical distribution of $\frac{\partial\theta_e}{\partial p}$ crossing the typhoon center, in which at about 0000 UTC on 9 September, a cold center was detected within 400-500 hPa just near the cold vertex center, while its overlapping with the low-level warm air parcel created a strong instable convective zone (figure omitted). Afterwards, the cold vortex moved north, releasing the energy from the convective instability below it. The warm core above the typhoon was expanding and the downward heat transfer became more evident, which was favorable for maintaining the typhoon's warm core.

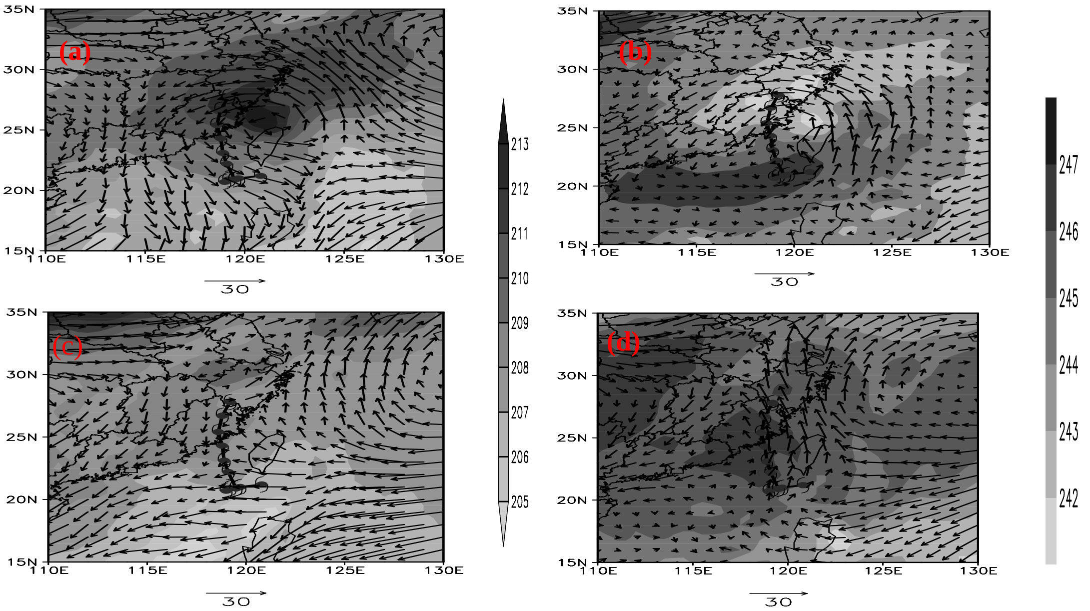


Figure 9. Temperature fields (shaded, *K*) and horizontal wind vector fields at 150 hPa (a, c) and 300 hPa level (b, d) at 0000 UTC, 9 September (a, c) and 1800 UTC, 9 September (b, d) respectively.

4.3 *Vertical vorticity budget*

Our analysis shows that in Meranti's development process, its vertical vorticity is increased and vertically stretched. To analyze the factor that contains Meranti's vorticity variation, the following vorticity equation is used to calculate the vorticity budget averaged in the typhoon zone.

$$\frac{\partial\zeta}{\partial t}=-(u\frac{\partial\zeta}{\partial x}+v(\beta+\frac{\partial\zeta}{\partial y}))-\omega\frac{\partial\zeta}{\partial p}-(f+\zeta)\nabla\cdot V-(\frac{\partial\omega}{\partial x}\frac{\partial v}{\partial p}-\frac{\partial\omega}{\partial y}\frac{\partial u}{\partial p})+R$$

in which the left side is the local vorticity variation item; the first term on the right is the advection of absolute vorticity, the second item represents vorticity vertical transport, the third item gives horizontal divergence, the fourth item is for the twisting, and *R* stands for the residual term. It is generally assumed that *R* is the combined result of friction and cumulus effects on vorticity vertical transport, which cannot be expressed in a vorticity equation. Here it is calculated as a residual term in the equation. The typhoon north-moving speed is deducted in the operation.

Figure 10 shows the time-height profiles of the terms of vorticity equation averaged on a typhoon area. From the perspective of the local vorticity variations (Figure 10a), at 0000 UTC on 9 September when Meranti changed its direction, it got its vorticity from lower to upper levels; till 1800 UTC, 9 September, the vorticity at all levels increased except slight decrease at the mid-level at 0600 UTC. The increase was most significant near 300 hPa and 850 hPa, corresponding to the rapid development of Meranti. Later on, the vorticity decreased at all levels.

In terms of the contribution of the equation terms to the vorticity increase, in the process of Meranti's evolution, the advection term mainly contributes to positive vorticity transport at levels above 400 hPa in the early stage. The low-level positive vorticity input was available mainly from 1200 UTC, 9 September to 0000 UTC, 10 September (Figure 10b). The upper positive vorticity input was mostly related to the advection transport from the UCV, but at a late stage, it was mainly the advection transport from the low-level jet zone in the typhoon periphery. The vertical transport term is related to vertical motion, allowing Meranti to gain positive vorticity at the upper level, and lose it at low levels (Figure 10c). The horizontal divergence term provides enhanced vorticity at mid- and low-levels due to convergence, and decreased vorticity at upper levels as a result of strong divergence (Figure 10d). Its contribution to the typhoon vorticity is just contrary to the vertical transport term, with a similar value. All this suggest that the vorticity gains and losses generated from typhoon convergence/divergence are roughly balanced through vorticity allocations by the vertical motion of the typhoon. The twisting term (Figure 10d) mainly allows a typhoon to gain vorticity at mid- and low-levels (below 500 hPa) and lose it at upper levels. It is due to a stronger vertical shear in the upper-level ambient winds that contains the growth of vertical vorticity. However, vertical shear is weaker at low levels (see Figure 7), but its vertical motion is quite uneven (as a strong vorticity dipole), to enable a typhoon to gain vorticity. The input from the advection term alone is not enough to offset the upper-level vorticity depletion, but the residual term makes a greater positive contribution to the vorticity at upper levels (Figure 10e), showing that such sub-grid systems as cumulus convection play a positive role in increasing the upper-level vorticity, the friction of underlying surface plays a role in vorticity depletion at lower layers (below 850 hPa). But it can be compensated by the positive contribution from the divergence and twisting terms.

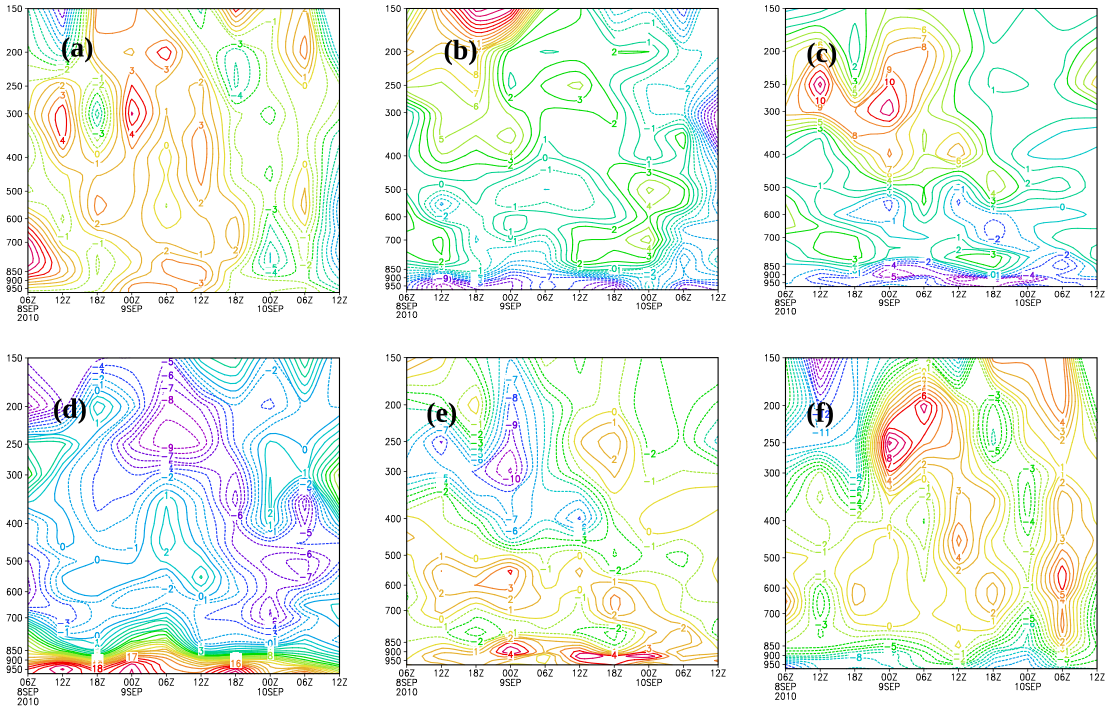


Figure 10. Height-time evolution of mean vorticity budget in the typhoon zone. a: local vorticity variation; b: advection term; c: vertical transport term; d: horizontal divergence term; e: twisting term; f: residual term.

Comparing various term values, the magnitudes of Meranti's vorticity budget terms were equivalent. In the north-moving process of Meranti, at the lower level, vorticity advection and residual terms (friction effect) and the vertical transport term decrease the typhoon vorticity, but the strong convergence effect was sufficient to fill in the gap, and the twisting term also provides positive vorticity. At the upper level, the effect of upper-level divergence and twisting term tend to reduce the vorticity, while the vertical transport term, vorticity advection and residual terms (cumulus transport effect) may increase it. Among all, the contributions of the vertical ascending motion and cumulus convection to the upper level vorticity are apparently greater than the advection term. Overall, during Meranti's intensification stage, the positive vorticity at all levels was partially supplemented by convergence and inhomogeneous wind distribution at mid- and low-levels, upward vertical transport, horizontal advection terms and activities of the sub-grid system at the upper levels. In summary, the evolution of Meranti was closely related to convergence/divergence motions, vertical motion, vorticity gradient, and activities of sub-grid systems.

Based on the similar vorticity budget diagnosis on composite data of several typhoons that sustained for long time even after their landfall[17], it was found that all vorticity terms had similar contributions but with different values. Out of them, the values of the vertical transport and twisting terms were lower by an order of magnitude than that of other terms. But in the case of Meranti, they were in the same magnitude, suggesting from another aspect the importance of vertical transport and twisting terms for a rapidly developing typhoon. The advection term is also a positive contributor at the upper levels by providing typhoon with positive vorticity advection from the upper-level westerly as in the previous case. In this case, it was the cold vortex to the south of Subtropical High that supplied it to Meranti, and both underlined the effects of vorticity advection on a typhoon.

5 CONCLUSIONS AND DISCUSSIONS

In 2010, typhoon Meranti abruptly turned north into the Taiwan Strait, soon reached the typhoon intensity and landed on the Fujian province. During the process, to the south of the Subtropical High over the western North Pacific, an upper-level cold vortex moved northwest counterclockwise towards the north boundary of Meranti. The maximum horizontal range of the UCV spanned up to 10° lat./long., with its vertical range extending from 400 hPa to 100 hPa. Its center was located at the 200 hPa level, which was about 6 latitude meshes apart from the typhoon center, and the two cyclonic circulations were overlapped and mutually interactive. The analysis showed the important influence of the cold vortex on Meranti's sudden north-turning and its rapid development.

As for its impacts on the typhoon track, the cold vortex contained the typhoon-steering role of the Subtropical High in the early stage, and Meranti moved slowly westward with a looping track. However, when it coupled with the upper-level cold vortex from the north, the Subtropical High protruded westward, and the steering flow from the cold vortex changed from northerly to stronger southerly flow, which overlapped with the southerly flow in the east part of the typhoon at a lower level, enhancing the role to steer the typhoon northward, and the reduced pressure caused by the cold vortex also played a role in attracting the typhoon north.

Dynamically, its impacts on typhoon intensity mainly include: 1) wind direction change of the upper-level cold vortex over the typhoon, which weakened the vertical shear of typhoon's ambient winds; 2) horizontal transport of positive vorticity advection; 3) overlapping of the southwesterly jet stream from the east boundary of the cold vortex with the low-level southwesterly jet from the east boundary of the typhoon, which may thicken and enhance the southerly flow, increasing typhoon's tangential wind speed on the one hand, and enhancing its low-level jet on the other, so that a strong vorticity dipole is formed due to Taiwan's topographic effects, which was favorable for intensive convective motion and typhoon development.

Thermodynamically, the upper-level cold vortex provided weak and cold advection to the outer band of the typhoon, which favored moisture condensation and created strong unstable convective stratification. The latent heat released by unstable energy was also favorable for enhancing the warm core of the typhoon.

A diagnosis of the Meranti vorticity budget further suggested that as Meranti entered the Taiwan Strait, its vertical motion, strong low-level vorticity dipole, together with positive vorticity advection of the cold vortex, played an essential role in vorticity column extension and rapid development of typhoon cyclonic circulations.

This paper focuses on some important impacts of the upper-level cold vortex that are located to the south of the Subtropical High on Meranti's north-turning and intensification, but the cold vortex is not the sole key factor. Eastward motion of the westerly trough and eastward retreat of the Subtropical High are among other factors for enhancing the southerly steering flow at mid- and lower-levels of the typhoon. Meanwhile, abundant moisture transported by low-level jets and the topographic forcing also have important impacts on the development of the typhoon. It should be noted that it is quite common for typhoons to bring in moisture from low-level jet streams and move into the Taiwan Strait before landfall, but they are usually weakened soon. To better understand and forecast the mechanism of the abrupt changes of typhoons like Meranti before landfall, more attention should be given to the possible impacts of some systems that are often neglected, e.g. the upper-level cold vortex to the south of the Subtropical High. Last but not least, the impacts of the Taiwan Strait on both scale and intensity of Meranti also deserve further investigation.

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