A Study on the Interaction between Typhoon Prapiroon (2000) and the Mid-latitude Trough

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ABSTRACT

In this paper, hourly black body temperature (TBB) data determined from GMS-5 S-VISSR infrared 1channel, combined with two sets of large-scale analyses data, is used to study the interaction between typhoon Prapiroon (2000) and a mid-latitude trough, and how the interaction modulated the storm's intensity change. The two sets of large-scale analyses data used are six-hourly three-dimensional analyses from the Korean Meteorological Administration and the National Centers for Environmental Prediction of the United States respectively.

Analyses show that the storm's intensity was affected by the trough interaction through different mechanisms in different stages of the interaction. At the beginning, an overlay of upper level southwesterly on the leading side of the trough brought sharp increase of both the vertical wind shear between 850 and 200hPa and the eddy flux convergence of angular momentum (EFC). At the same time, the outflow jet was channeled and strengthened to the northwest of the storm's center. It was suggested that the jet worked as a forcing for vigorous eye-wall convection, while not vice versa, because the enhanced convection was phase-locked to the northwest of the center consecutively for several hours. Otherwise, the convective cells should rotate around the center cyclonically. Negative effect of large vertical wind shear was minor cause the shear was confined only in the upper troposphere above 200hPa. Factors mentioned above contributed together to Prapiroon’s intensification to its lifetime maximum intensity.

Later on, deformation of upper level southwesterly occurred in response to anti-cyclonic outflow of the intensified storm. As a result, both the vertical wind shear and EFC decreased temporarily and the convective cells started to rotate cyclonically around the storm's center. Prapiroon experienced no intensity change during this period, which might be due to the lack of both favorable and unfavorable factors.

The outstanding feature of TBB in the next stage is that the convection in the southwestern half of the storm was suppressed, while that in the northeastern half was enhanced. Accompanied was steady increase of both vertical wind shear and EFC. It was suggested that such an asymmetric distribution of convection was induced by vertical wind shear accompanying with strong winds on the leading side of upper-level trough. However, for this case, the shear was just not strong enough to destroy the eye and there was large eddy import of angular momentum simultaneously. So, the storm's intensity weakened only by about 2m/s in 12 hours after recurving into the mid-latitude, although the convection was extremely asymmetric.

1. Introduction

It has long been noticed that the interaction between a tropical cyclone (TC) and a tropical upper-tropospheric trough (TUTT) or upper level westerly trough can modulate the intensity of TC. However, the precise manner and degree to which upper-level troughs weaken or intensify a TC’s circulation is not yet well understood (Ritchie, 2002). It is still a challenge for forecasters to tell whether an encounter with a mid-latitude trough is ‘good’ or ‘bad’ to a TC’s development.

The upper level trough could be either favorable or unfavorable to a TC. On the favorable side, it was suggested that the asymmetric structures of the outflow layer caused by the upper-level environmental systems could produce large eddy imports of angular momentum. Due to the small inertial stability in the upper troposphere, the response to external forcing can penetrate to the vortex center (Holland and Merill, 1984). Up to now, many composite and case studies (McBride and Zehr, 1981;
Molinari and Vollaro, 1989; DeMaria et al., 1993; Wu et al., 1999; Bosart et al., 2000; Hanley, et al., 2001) have shown that there is a significant relationship between eddy flux convergence of angular momentum (EFC) and TC’s intensity change. The interpretation is that the secondary radial circulation induced by EFC might serve as a catalyst that organize the diabatic sources in such a way as to excite internal instabilities of the system (Molinari and Vollaro, 1990; Challa et al., 1998; Titley and Elsberry, 2000).

An alternative explanation of the favorable side of the trough is that strong upper level divergence, and implied upward motion, in the right entrance of the upper level jet could cause TC to intensify (Chen and Ding, 1979; Hanley, et al., 2001). Numerical studies by Shi et al. (1990, 1997) showed the existence of a circum-jet secondary circulation at the entrance region of the outflow jet, which is thermally direct with the ascending branch located on the anti-cyclonic shear side, and the descending branch located at the cyclonic shear side of the outflow jet. Rodgers et al. (1986; 1991; 1998) suggested that the circum-jet secondary circulation at the entrance region of trough-related outflow jet could modulate TC’s convection and might help to initiate and maintain the eye-wall convective bursts.

Strong vertical wind shear is the main adverse side of an upper-level trough. The interaction between the shear associated with the upper-level trough and TC causes ‘ventilation’ of the warm core of TC or an asymmetry in the cloud/precipitation distribution that is less favorable for intensification than is a symmetric cloud/precipitation distribution (Ritchie, 2002).

Although former studies have provided insights into the mechanisms of TC-trough interaction, it has proved particularly difficult to apply these insights to individual cases. Quite different conclusions could be made based on different data and different analysis techniques (Ritchie, 2002). For example, there have been several studies about the role of the upper-level trough in the intensification of Hurricane Opal (1995) (Rodgers et al., 1998; Bosart et al., 2000; Persing et al., 2001; Shapiro et al., 2002). Bosart et al. (2000) calculated the symmetric balanced vortex outflow using analyses from European Center for Medium-Range Weather Forecasts (ECMWF) and their results implied a large contribution from environmental forcing, while Persing et al. (2001) concluded that the hurricane intensification was not due to a trough interaction based on the calculation of eddy vorticity flux using the output from Geophysical Fluid Dynamics Laboratory (GFDL) hurricane forecast model.

The remote sensing data have been proved to be helpful with this challenge (Rodgers et al., 1998; Bosart et al., 2000; Hanley, 2002). Rodgers et al. (1998) used the observation from SSM/I to study the latent heat release cycle in the eyewall region of hurricane Opal (1995). They speculated that the gradient wind adjustment processes associated with Opal’s outflow channel (initiated by a diffluent trough) might have helped to initiate and maintain the eyewall convective bursts. Hanley (2002) illustrated the evolution of the TC-trough interaction as seen in water vapor imagery and proposed that some types of trough interactions might be identifiable from satellite imagery.

In this paper, black body temperature (TBB) data determined from GMS-5 S-VISSR infrared 1channel, combined with large-scale analyses data, will be used to study the interaction between typhoon Prapiroon (2000) and a mid-latitude trough. Typhoon Prapiroon (2000) recurved near East-China coast at 30°N due to the existence of a mid-latitude trough. The storm kept on intensifying before arriving at the turning point and weakened quite slowly after crossing it until it made landfall in Korean Peninsula. Heavy rainfall and strong wind were brought by it to East-China and Korean Peninsula. The purpose of this study is to understand the role of TC-trough interaction in the intensity change of Prapiroon. The following questions are to be answered: What’s the relationship between EFC/vertical wind shear and Prapiroon’s intensity change? How did the storm’s convection evolve as Prapiroon interacted with the trough and how did it relate to the intensity change? Through which mechanism could the trough modulate Prapiroon’s intensity change?

Followed in section 2, the data used will be introduced. A general description on Prapiroon’s track and intensity, the basic features of large-scale circulation and the underlying surface will be given in section 3. Diagnosing results of vertical wind shear and EFC based on two sets of large-scale analyses data will be given in section 4. In section 5, the evolution of Prapiroon’s convection in different stages of TC-trough interaction and its relationship with the storm’s intensity change will be studied using TBB data. Conclusions and discussion will be made in section 6.
2. Data description

Six-hourly best track data from China Meteorological Administration (CMA) will be used to describe the intensity change of Prapiroon. It's noticed that there are always some differences in the best-track intensity from different sources. Due to the lack of air-flight reconnaissance, it is quite hard to tell which one is better. So, the best-track intensity from CMA will be compared with those from two other sources, Regional Specialized Meteorological Center (RSMC) Tokyo and Joint Typhoon Warning Center (JTWC). It'll be shown in the next section that the general trend of intensity change revealed by CMA best track is credible.

The hourly TBB data with 1/20 degree resolution are determined from GMS-5 S-VISSR infrared 1 channel. All the data were downloaded from the website: http://weather.is.kochi-u.ac.jp/sat/GAME/.

Six-hourly three dimensional analyses from the Korean Meteorological Administration (KMA) were obtained on a 1.875° latitude-longitude grid at 12 standard pressure levels: 1000, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, and 50 hPa. The analyses are constructed using a Global Data Assimilation and Prediction System (GDAPS).

Inspection of the GDAPS analyses showed that two fundamental requirements (Molinari and Vollaro, 1990) were met for most of the time (figures not shown): (i) the location of the storm on the 1.875 latitude-longitude grid, as defined by maximum midtropospheric relative vorticity, was at the grid point nearest to its true location in nature; and (ii) the maximum vorticity occurred at the same point throughout the lower and middle troposphere, as it must in the mature stage of a TC.

Six-hourly analyses data from the National Centers for Environmental Prediction (NCEP) of the United States are also used for comparison in this paper when diagnosing the vertical wind shear and EFC. The horizontal resolution is 2.5 degree latitude/longitude and there are 12 levels vertically (1000, 925, 850, 700, 600, 500, 400, 300, 250, 200, 150, 100hPa).

3. A General Description of the Storm

According to the best track from CMA, Prapiroon formed at 19°N, 132°E on August 26, 2000 (fig.1a). It moved northward at the beginning and then turned toward northwest a few hours later. The track showed a trend turning to the southwest on the 28°, but soon turned back to northwestward 12hours later. After a period of slow moving, Prapiroon speeded up toward northwest and turned to northeastward near the coast of eastern China around 30°N. The real line in fig.1a denotes the period when Prapiroon had the intensity of a typhoon (The maximum wind speed is greater than 32.6m/s). It could be seen that Prapiroon upgraded to a typhoon after it speeded up northwestward before recurvature and didn't degrade until it made landfall in Korean Peninsula after recurvature. Synoptic analyses (fig.2) show that, Prapiroon's recurvature was due to the existence of a mid-latitude trough. In accordance with the purpose of this study, we'll focus on the storm's intensity change from 12UTC 29 to 12UTC 31, which is approximately the time period when Prapiroon interacted with the trough before its landfall.

The intensity of Prapiroon from CMA, RSMC Tokyo and JTWC best-track datasets is all shown in fig.1b. The discrepancy among the three datasets is relatively large when the cyclone is weak. The largest difference reaches about 10m/s. As Prapiroon intensifies, the discrepancy becomes smaller. It could be seen that, after 12UTC 29 Aug., the largest difference is only about 5m/s. A noteworthy feature is that there is no difference between CMA and JTWC datasets in the time when the cyclone upgraded to a typhoon (18UTC 29). The same also happens for the time when the cyclone degraded from a typhoon (12UTC 31). However, the upgrading time shown by the data from RSMC Tokyo is 12 hours later (06UTC 30) and the degrading time 6 hours earlier (06UTC 31). The lifetime maximum intensities from the three datasets are 35m/s (CMA), 36m/s (RSMC Tokyo) and 38.6m/s (JTWC) respectively. Both CMA and RSMC Tokyo datasets show that the storm reached the lifetime maximum intensity at 12UTC 30, when it arrived at the turning point (fig.1a), while the time in JTWC dataset is 6 hours earlier (6UTC 30). It could be concluded that the general trend of intensity change revealed by CMA best track is credible after 12UTC 29 August.
Calculations of the intensity change in 6 hours (fig.3) show that the intensity change from CMA is exactly the same or at least has the same sign as that from either RSMC Tokyo or JTWC for most of the time (6 in 9 time levels). The same also happens for the intensity changes in 12 and 24 hours. To avoid confusion and for simplicity, the dataset from CMA will be used without doubt at those time levels. However, at the rest time levels (such as 18UTC 29, 00UTC 30 and 06UTC 31 in fig.3), the intensity change from CMA is different from both RSMC Tokyo and JTWC. Analyses concerning those time levels will take the discrepancy into consideration and any conclusions will be drawn prudently.

It’s quite common that a TC weakens quickly after it moves into the mid-latitude or recurves to the east of a trough, due to the low sea surface temperature (SST) or large vertical wind shear. However, that’s not the case for Prapiroon, which intensified to its lifetime maximum intensity at the turning point (around 30°N) and weakened quite slowly after crossing the turning point until it made landfall (fig.1 and fig.2). The decrease of maximum wind velocity in the 24 hours from 12UTC 30 to 12UTC 31 is only 2m/s (CMA) or 5m/s (RSMC Tokyo and JTWC).

It is well known that SST plays a crucial role in affecting the intensity change of TCs. Fig.1a shows the weekly mean SST field centered on 30 Aug. 2000. The data used are Reynolds SST data provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA, from their Web site at http://www.cdc.noaa.gov/. It could be seen that, the storm was over a warming ring over 28.5°C from 00UTC 29 to 00UTC 30. Although SST under the storm’s center decreased gradually as the cyclone moved northward after that, it was not less than 26.5°C until 06UTC 31, which was suggested to be a critical temperature for TC’s development (Chen and Ding, 1979). The storm reached its lifetime maximum intensity over the sea surface warmer than 27°C, in accordance with the results of Baik et al. (1998). They found that 87% of the observed storms in Northwestern Pacific have their maximum lifetime intensities over 27-29°C sea surface. Although the critical temperatures mentioned above might be different in different studies, it could be concluded that SST provides a favorable background for Prapiroon’s intensification to its lifetime maximum intensity at the turning point and its maintenance after that. However, SST is only one of the factors that could modulate the TC’s intensity change. How strong the storm’s maximum potential intensity (MPI) is and to what extent the storm could be close to its MPI also depend on the atmospheric environment. So, it’s important to understand the role of the interaction between Prapiroon and the trough, even if the basic requirement of SST for development or maintenance seems to be met.

4. Diagnosing of Vertical Wind Shear and EFC

4.1 Vertical wind shear

The vertical wind shear is calculated according to the wind averaged in a circle of 5° latitude / longitude radius around TC center. Fig.4 shows the evolution of vertical wind shear between 850hPa and 200hPa calculated using GDAPS and NCEP data respectively. Generally speaking, vertical wind shear calculated using GDAPS data is larger than that using NCEP data, which might be due to the higher horizontal resolution of GDAPS data. The discrepancy between the two sets of data implies that quantitative relationship between vertical wind shear and TC’s intensity change is difficult to be achieved because the calculation strongly relies on the data used.

Anyway, the trends shown by the two sets of data are quite consistent with each other after 18UTC 29, when the storm reached the intensity of typhoon. From then on, the vertical wind shear decreased a little by about 2m/s in 6 hours, and increased sharply to over 10m/s at 06UTC 30. But that was a temporary phenomenon. Six hours later, the shear decreased again to about 5m/s and then started to increase gradually in the following 18 hours to the second maximum of about 15m/s. Later on, the shear began to decrease once again and the decreasing trend continued after the storm’s landfall to less than 10m/s at 18UTC 31 (not shown in the figure).

Also shown in the figure is the storm’s intensity change in 6 hours at according time levels. The records, which are different from both RSMC Tokyo and JTWC, are labeled by question marks. It’s notable that the storm kept on intensifying and reached its lifetime maximum intensity later on (fig.1a) when the vertical wind shear increased suddenly by approximately 10m/s at 06UTC 30. In order to figure out why there was such a sharp increase of wind shear and how the storm could continue intensifying in
such a high shear environment, the vertical distribution of horizontal wind and vertical wind shear is analyzed (fig.5). It could be seen that the sudden increase of vertical wind shear at 06UTC 30 was due to the onset of strong southwesterly over the storm in the upper troposphere. The stream field on 200hPa (fig.6) manifests clearly a change of the flow pattern over the storm. At 00UTC 30 (fig.6a), the circulation over the storm’s center was anti-cyclonic. While to 06UTC (fig.6b), the anti-cyclonic flow was substituted by the uniform southwesterly in the front of an upper-level trough, which brought about the sharp increase of vertical wind shear between 200 and 850hPa. However, the large shear was confined narrowly in the upper troposphere (fig.5). That might be the reason why such a large shear could not make the storm weakening. As several studies (Elsberry and Jeffries, 1996; Yu et al., 2002) have pointed out that the change of wind with height is not linear in troposphere, it may not be comprehensive to represent tropospheric shear with the shear between only two layers.

At 12UTC 30, the upper-level southwesterly was deformed (fig.6c), which should be a result of the response to the anti-cyclonic outflow of the intensified storm. So, the upper level average wind and the vertical wind shear decreased correspondingly. After that, the southwesterly became dominant once again (fig.6d-h) and the shear increased gradually to about 15m/s as the storm moved northward. Fig.5 shows the upper-level southwesterly penetrated downward gradually to 700hPa simultaneously. From 12UTC 30 to 00UTC 31, the storm’s intensity change in 6 hours was either equal to 0m/s or a minor -2m/s, corresponding to low or moderate shear. Discrepancy among different best track datasets exists at 06UTC 31, when CMA showed no intensity change in 6 hours, while RSMC Tokyo showed -5m/s decrease and JTWC -3m/s decrease. Taken the larger shear and lower SST into consideration, it is speculated that a decrease of the maximum wind velocity is more reasonable.

The shear showed a trend to decrease after 06UTC 31 and was lower than 10m/s at 18UTC 31 (not shown in the figure) when the storm was over land. It could be deduced that the main cause of Papiroon’s quick degrading after landfall was the land while not vertical wind shear.

4.2 EFC

EFC is calculated following Molinaro and Vollaro (1990), which has been widely used in the studies on TC-trough interaction (Hanley et al., 2001; Bosart et al., 2000; and so on). Fig.7 shows the evolution of EFC at 200hPa within 300-600km radial band. It could be seen that, similar to the result of vertical wind shear, the calculation of EFC also strongly relies on the data used. The largest difference reaches over 10m/s/day. However, general trends of the two datasets are quite consistent with each other.

It could be seen that EFC became larger and larger as the storm moved gradually closer to the mid-latitude trough and was over 10m/s/day for the first time at 06UTC 30. That maximum is corresponding to the overlay of upper-level trough, which also brought about a sudden increase of vertical wind shear between 200 and 850hPa. Due to the confinement of large shear in upper troposphere, the increase of EFC might have contributed to the storm’s intensification to its lifetime maximum intensity.

At the next time level (12UTC 30), EFC decreased back to below 10m/s/day and then continued to increase again. In accordance with the decrease of vertical wind shear, the temporary decrease of EFC should also be caused by the deformation of upper level trough in response to the anti-cyclonic outflow of the intensified storm. After 18UTC 30, EFC kept on being larger than 10m/s/day for a consecutive 24 hours and met the definition of trough interaction proposed by Hanley et al. (2001). Such an increase of eddy import of angular momentum might have provided favorable conditions for the storm’s maintenance in an environment with increasing vertical wind shear.

Fig.8 shows us the inward shift of large EFC on 200hPa. The first approach of large EFC to the storm’s inner circulation occurred at 06UTC 30 with the maximum EFC over 25m/s/day. Six hours later, that EFC center disappeared due to the deformation of the upper level trough. However, the existence of the mid-latitude trough is still manifested by the large EFC values around 900km away from the storm’s center. After that, the persistent TC-trough interaction began which was manifested by the inward shift of large EFC area since 18UTC 30 on, accompanied by the increase of both the value and the area extent of positive EFC.
5. **TBB features**

As what we care is the interaction between Prapiroon and the mid-latitude trough, we study only the TBB features from 00UTC 30 on, when the storm was going to interact directly with the trough 6 hours later. It should be noted that all the figures of TBB in this section are about half an hour later than the time labeled. Analyses show that the evolution of Prapiroon’s TBB could be approximately divided into four stages.

The first stage is from 00UTC to 05UTC 30, when there was anti-cyclonic circulation on 200hPa over the storm. During that period, the convective cells in eye-wall region rotated around the storm’s center (fig.9a-d) cyclonically. At the same time, the low TBB region (colder than –70°C) became smaller in area but more organized around the eye. According to the best track from CMA, Prapiroon’s intensity kept unchanged during this period, while both RSMC Tokyo and JTWC show a steady intensification (about 3m/s in 6 hours).

The second stage started at 06UTC 30 when the overlay of upper level southwesterly happened (fig.9e and fig.10b). Such a change in synoptic pattern was accompanied by the joining between the cloud system of Prapiroon and that of the mid-latitude trough (fig.10a-b). At that moment, the eye-wall convection to the northwest of the center burst out vigorously. Several former studies (Shi et al., 1997; Rodgers et al., 1998; Hanley, et al. 2001; and so on) have pointed out that such an outbreak of intense convection could be related to the channeling and strengthening of outflow jet by upper-tropospheric trough. The convection could be enhanced in response to either the outflow jet-induced import of eddy relative angular momentum or ascending motion associated with the circum-jet secondary circulation. From fig.6a-b, it could be seen that the westerly jet displaced southward from 00UTC to 06UTC 30. At the same time, the maximum wind velocity of the jet increased by approximately 10m/s. There was a jut over 20m/s to the west and northwest of the storm’s center, which implies channeling and strengthening of the outflow jet. Fig.12 shows us the corresponding increase of upper level divergence over the west half of the storm. At 00UTC (fig.12a), there was a large convergence area to the west of the center with minimum value lower than –2x10^{-5}s^{-1}. To 06UTC (fig.12b), that convergence region disappeared and was substituted by divergence. As a result, the upper level circulation became a uniform divergent pattern.

From 06UTC on, vigorous convection was phase-locked to the northwest or west of the center for a consecutive 6 hours (fig.9e-j). The cyclonic rotation of convective cells around the storm’s center stopped. The implication of this fact is that the jet worked as a forcing for vigorous eye-wall convection here, while not vice versa. It’s speculated that this mechanism help Prapiroon intensifying to its lifetime maximum intensity. Cause it’s difficult to tell the exact position of deep convection according to IR information due to the contamination of cirrus, a SSM/I 85 GHz image is referred to for confidence (Fig.11). It could be seen that heavy rain indeed occurred in the northwestern part of Prapiroon’s eye-wall region at 09UTC 30, in accordance with that shown by IR image (fig.9h).

Next stage of TBB evolution started around 12UTC 30 (fig.10c), when the eye-wall convective cells started to rotate around the storm’s center again. As mentioned above, the uniform southwesterly was deformed by the storm’s upper level circulation at that time. Accompanied was the retrieval of strong wind region northward (fig.6b-c) and the wind speed was lower than 10m/s (fig.6c) in the southwest half of the storm. Accordingly, convergence appeared once again to the west of the center (fig.12c). As the convective cells rotated around the storm’s center in following hours till 18UTC 30 (hourly figures not shown), the eye became clearer and larger little by little, while no intensity change was reported during this stage.

The outstanding feature of the forth stage (from 18UTC 30 on) is that the convection in the southwestern half of the storm was suppressed, while that in the northeastern half was enhanced (fig.10d-f). Similar asymmetric distribution of convection has long been noticed in both observational and modeling studies (Ritchie, 2002). It was suggested that the asymmetry was induced by strong vertical wind shear accompanying with strong winds on the leading side of upper-level trough. As pointed out by Ritchie and Elsberry (2001), the favored ascent region is to the down-shear left quadrant of the TC. Clearing of the deep convection and formation of a dry slot can occur on the up-shear side in response to forced subsidence.
It’s speculated that the same mechanism work for this case. The reasons are as following. From fig.4, we could see the increase of vertical wind shear from 18UTC 30 to 06UTC 31, which was induced by strong winds on the leading side of the mid-latitude trough. Manifested by fig.6d-f was an intensifying westerly jet in both the strength and area extent to the north of Prapiroon. Such a development of upper level jet brought about not only the rise of wind speed but also the increase of divergence (fig.12d-f), which should have worked to boost the convection to the north of the storm’s center. However, the deflection of divergence center to the down-shear left quadrant is marked only at 06UTC 31 (fig.12f). This phenomenon is due to the existence of different synoptic systems over the storm while not only the approaching trough uniquely. That is the anti-cyclone to the southeast of the storm, which also brought about upper level divergence. To the southwest of the center, upper level convergence was persistent and became stronger in both the center value and area extent during this period (fig.12d-f). Thus the convection was suppressed in according region. The dry slot to the southwest of the eye manifests the break of eye-wall.

However, the asymmetry in convection mentioned above didn’t make the storm filling quickly. It could be seen from fig.10d-f that the storm’s eye remained clear and complete although the eye-wall was broken partly by the mid-latitude trough. That’s speculated to be caused by a not strong enough vertical wind shear and an increasing eddy import of angular momentum. Correspondingly, a minor decrease of about 2m/s in maximum wind velocity was reported during this period.

6. Conclusion and discussion

A major conclusion of this study is that Prapiroon’s intensity was affected by the trough interaction through different mechanisms in different stages of the interaction.

At the beginning, an overlay of upper level southwesterly on the leading side of the trough brought sharp increase of both the vertical wind shear between 850 and 200hPa and EFC. At the same time, the outflow jet was channeled and strengthened to the northwest of the storm’s center. Disagreements exist concerning the cause-result relationship between outflow jet and enhanced convection (Hanley et al. 2001). For this case, vigorous convection was phase-locked to the northwest of the storm’s center after the channeling and strengthening of outflow jet by mid-latitude trough occurred. Former tendency of rotating around the storm’s center cyclonically stopped. This fact implies that the jet worked as a forcing for vigorous eye-wall convection here, while not vice versa.

Negative effect of large vertical wind shear during this period was minor cause the shear was confined only in the upper troposphere above 200hPa. As several studies (Elsberry and Jeffries, 1996; Yu et al., 2002) have pointed out that the change of wind with height is not linear in troposphere, it may not be comprehensive to represent tropospheric shear with the shear between only two layers. So, analyses on the vertical distribution of shear might be helpful in forecasting or understanding TC’s intensity change.

The enhanced eye-wall convection caused by the jet, confinement of large vertical wind shear in upper troposphere, and large EFC contributed together to Prapiroon’s intensification to its lifetime maximum intensity during this period.

Later on, deformation of upper level southwesterly occurred in response to anti-cyclonic outflow of the intensified storm. Such a deformation of trough has been mentioned by several other studies (Molinari et al., 1995; Kimball and Evans, 2002), which is inevitable as both the trough and the storm act to change the other. Different from the studies mentioned above, no split of the low occurred for this case. Anyway, corresponding drop of shear occurred, accompanied by a simultaneous decrease of EFC and the weakening of out-flow jet. Due to the minishing of asymmetric environmental forcing, the convective cells started to rotate cyclonically around the storm’s center once again. Prapiroon experienced no intensity change during this period, which might be due to the lack of both favorable and unfavorable factors.

The outstanding feature of TBB in the next stage is that the convection in the southwestern half of the storm was suppressed, while that in the northeastern half was enhanced. Accompanied was steady increase of both vertical wind shear and EFC. It was suggested that such an asymmetric distribution of convection was induced by vertical wind shear accompanying with strong winds on the leading side of
upper-level trough. Different from former simulation studies (Ritchie and Elsberry, 2001) is that the deflection of the favored ascent region to the down-shear left quadrant is not marked at all time levels. This phenomenon is due to the existence of different synoptic systems over the storm while not only the approaching trough uniquely. For this case, the shear was just not strong enough to destroy the eye. So, the storm’s intensity weakened only by about 2m/s in 12 hours after recurving into the mid-latitude, although the convection was extremely asymmetric.

Although general trends shown by different analyses dataset are consistent with each other for the calculation of both vertical wind shear and EFC, there is always discrepancy between them quantitatively. So, it’s difficult to get any quantitative relationship between vertical wind shear or EFC and TC’s intensity change.

It’s notable that the change of vertical wind shear and EFC is almost in phase as shown by fig.4 and fig.7. The implication is that the mid-latitude trough brought not only favorable inward eddy transport of angular momentum but also the unfavorable vertical wind shear simultaneously, which is in accordance with former studies. This fact makes it quite difficult to forecast the TC’s intensity change when the trough interaction occurs. Satellite data with high time and space resolution provide a helpful tool in tackling the difficulties mentioned above and other difficulties such as the cause-result relationship between enhanced convection and the jet.

Mechanisms mentioned in this paper are mainly dynamic. The mid-latitude trough always brings cold and dry air. It has long been noticed (Chen et al., 2002) that an intrusion of strong cold air could disrupt the warm core structure of TC and cause it filling or extra-tropical transition, while a proper weak cold air might contribute to TC’s intensification, sometimes even rapid intensification, which is almost impossible to forecast nowadays. The thermal-dynamic processes related to these phenomena are interesting topics for future study concerning the effect of trough interaction on TC’s intensity change.

The TCs’ intensity change relies on the balance between favorable and unfavorable forces. It’s always difficult to get any definite relationship between any one factor (EFC, vertical wind shear, SST, and so on) and the intensity change. One way to solve this problem is to analyze all the factors synthetically with the help of numerical models.

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