Numerical Simulation of the Effects of Moisture on the Reinforcement of a Tropopause Fold

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Abstract: The tropopause fold event that took place on January 1, 1997 over mid-region on the Korean Peninsula is examined by means of a numerical simulation based on a Mesoscale Model (MM5). The purpose of this paper is to investigate the effects of moisture in reinforcing a tropopause fold linked to an explosive cyclone. Two types of simulations were carried out: 1) simulations for moist conditions in which full physical and dynamic processes are considered and 2) simulations for dry conditions in which cumulus parameterization and cloud microphysics process are excluded. The results of the moist condition simulations demonstrate that the intensity of the central pressure of the cyclone was overestimated compared with the observed values and that the location of the center and the pressure deepening rates (~17 hPa/12 hr) complied with the observed values. The potential vorticity (PV) anomaly on the isentropic surface at 305 K continued to move in a southeast direction on January 1, 1997 and thus created a single tube of tropopause fold covering the northern and the middle area of the Korean Peninsula and reaching the ground surface at 0300 UTC and 0600 UTC. The results of the dry condition simulations show that the tropopause descended to 500 and 670 hPa in 0300 and 0600 UTC, respectively at the same location for the moist condition simulation; however, there was no deep tropopause fold observed. A comparison of the simulated data between the moist and the dry conditions suggests that a deep tropopause fold should happen when there is sufficient moist in the atmosphere and significantly large PV in the lower atmosphere pulls down the upper atmosphere rather than when the tropopause descends itself due to dynamic causes. Thus, it is estimated that moisture in the atmosphere should have played a crucial role in a deep tropopause fold process.

Keywords: tropopause fold, MM5 model simulation, isentropic potential vorticity, explosive cyclone

Introduction

There has been a wide range of studies on tropopause fold in the mid-latitudes over the last few decades. They may be classified into three categories: the first one is the studies on the formation and development of a surface cyclone and cutoff cyclone during the development of tropopause fold (e.g., Uccellini et al., 1985; Bell and Bosart, 1993; Lackmann et al., 1997; Browning et al., 2000). The second one covers the material exchanges between the stratosphere and troposphere within tropopause fold. The major concern of these studies is an estimation of the amount of ozone transportation for the period of tropopause fold (e.g., Vaughan et al., 1994; Ravetta et al., 1999; Berthier et al., 2001; Reid and Vaughan, 2004). The third one involves the development and structure of tropopause fold itself through numerical simulations or through observations (e.g., Whiteman et al., 1988; Rotunno et al., 1994; Cox et al., 1995; Bithell et al., 1999; Wandishin et al., 2000).

Most of the early model studies on tropopause fold using a three-dimensional primitive equation model suffered from the small scale of the fold and the coarse resolution of the model (WMO, 1986). However, there have been numerical simulations based on a mesoscale model whose horizontal resolution is 50-150 km (Bush and Peltier, 1994; Lamarque and Hess, 1994). Cox et al. (1995) used an UK Universities' Global Atmospheric Modeling Programme General Circulation Model (UGCM) whose horizontal grid was 1° x 1°. They demonstrated that its resolution is good...
enough to reproduce small scale weather phenomena such as a tropopause fold. Bithell et al. (1999) employed the UK Universities' Global Atmospheric Modeling Programme (UGAMP) model to describe the structure and evolution of tropopause fold in three dimensions. Their examination of tropopause surface shows that during the development of upper-level troughs, vortex roll-up and tropopause folding occur. Ravetta et al. (1999) showed that within the region of tropopause fold, there is a good correspondence between the observation values and MM5 predicted values for such parameters as ozone, temperature, and wind field within tropopause fold. Recently Reid and Vaughan (2004) simulated a tropopause fold with mesoscale model of Cullen (1993) with horizontal resolution of 0.11° and compared the results with observational data. They indicated that the tropopause developed in the rear side of a cold front and that during the fold, atmospheric convective instability was increased by descending dry stratospheric air.

MM5 model has been widely used to investigate atmospheric phenomena including heavy rainfall, heavy snowfall, and typhoons on the Korean Peninsula and East Asia (Kim and Chun, 2007). Hong and Lee (1987) conducted a simulation for a winter cyclone which accompanied strong winds and produced heavy snowfalls using the Pennsylvania State University/National Center for Atmospheric Research (PSU/NCAR) mesoscale model. Lee et al. (1991) studied the dynamical and thermodynamic characteristics of explosive cyclone on November 29-30, 1982 using MM5 model. Their study showed that first cyclone, upper and lower level jet streak, and secondary circulation in the vicinity of jet streak are well simulated, but that the secondary cyclone overdeveloped. Recently, Lim and Hong (2007) examined the capability of the Weather Reach and Forecasting (WRF) model in simulating heavy snowfall over the Ho-nam province of Korea. They discussed the sensitivity of the results to the vertical resolution and the comparison of results from the MM5 model. This study showed that both models overestimated the intensity of the oceanic low and that the bias was smaller in the case of the MM5 than the WRF run. Many studies of tropopause fold have been performed using model or observational data. However, they scarcely provided no apparent solutions to the fundamental cause of tropopause fold itself and the process that dominates the formation and evolution of the tropopause with a surface cyclone (Wandishin et al., 2000). There is no accurate information about whether the low-level flow acts to bring down the tropopause to facilitate the interaction between the two features or whether the tropopause pulls up the low-level to interact with it (Dixon et al., 2002). However, it is not fully perceived that how the moisture content in the lower troposphere facilitates the development of explosive surface cyclone during the development of tropopause fold.

The present study is to examine the role of moisture in developing the explosive cyclone under the tropopause deformation using a mesoscale model MM5. An explosive cyclone (Lee et al., 2002) is selected for the present study to examine the cyclone developed on January 1, 1997 on the Korean Peninsula. This cyclone event is chosen because winter atmospheric moisture content is normally low. However, the development of the surface cyclone may be possible only by dry atmospheric dynamical processes, without any diabatic heating due to release of latent heat. Concerning this problem, it is not yet easy to describe whether the cyclone can be fully developed into an explosive one without any enhancement of vertical convection associated with the release of latent heat.

Model Descriptions and Experimental Design

Model descriptions

The transportation, and exchange of its momentum between the troposphere and stratosphere happen as mixing by turbulent air within the tropopause fold channel. To describe in detail of a tropopause fold including such small-scale weather conditions, wind profiler and airplane observation data of high
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resolution for time and space are needed. But it was hard to obtain such data for the case in the Korean Peninsula. The NCEP/NCAR reanalysis data were set as the initial values, and a numerical simulation was conducted with PSU/NCAR MM5 mesoscale model. Since there are many previous researches providing detailed explanation of the MM5 model (e.g., Grell et al., 1993; Ravetta et al., 1999; Zhang et al., 2002), this study omitted explanations about the basic equations and dynamic and physical parameters of the model and offered a brief explanation of the model in Table 1. The MM5 employed a terrain following sigma coordinates based on the non-hydrostatic equations.

During model performance, the cumulus parameterization process of Kain-Fritch (Dudhia, 1989) was considered. In the microphysical process, the mixed-phase (Dudhia, 1989) was taken into account. Moreover, for the planetary boundary layer, MRF (Medium Range Forecast) by Hong and Pan (1996) was adopted. For the model, the atmospheric radiation process was comprised of the longwave radiation and shortwave radiation process, which interact with the atmosphere, clouds, rain, and ground (Dudhia, 1989). The 5-layer thermal diffusion was applied to the land surface. The computational domain of the model consists of the 320 (longitude)×320 (latitude) grid points with an 18 km grid spacing. The sigma coordinates had 27 layers vertically. The numerical simulations was initialized over the East Asia region including the Korean Peninsula (100-160°E, 20-65°N) at 1200 UTC December 31, 1996. It was conducted every three hours for 36 hours until 0000 UTC of January 2, 1997.

Experiment designs

In an attempt to simulate a tropopause fold and investigate the roles of moisture in the atmosphere during the case event, two experiments were conducted for the case cyclone. First, for the “moist” simulation, we used full-model physical parameterization to understand an atmospheric condition of synoptic scale during the fold event and where, when, and how deep tropopause fold event would happen under the most similar conditions to the actual atmospheric conditions. Secondly, a dry simulation was conducted with the cumulus parameterization process and microphysical process removed from the moist one. The “dry” experiments were performed on the assumption that there was no moist feedback in the atmosphere. By comparing the dry simulation results with the moist ones, the roles of moist in the atmosphere were examined during the fold.

Moist simulation

Isobaric analysis

The synoptic isobaric surface analysis of this cyclone was made using the observation data, NCEP/NCAR reanalysis data, and GMS water vapor images. In this section, in order to check how well the MM5 simulated the dynamic and thermodynamic process of the atmosphere associated with tropopause fold, the model and observation results at surface and 500 hPa were compared for 0000 UTC and 1200 UTC January 1, 1997. In addition, it is examined how valid it was to investigate the roles of moist during the fold using a mesoscale model.

Figure 1 shows the observed distributions of surface pressure (Fig. 1a, b) at 0000 UTC and 1200 UTC January 1, 1997. Figs. 1c, and 1d are the distributions of sea level pressure (0000 UTC) and accumulated precipitation (1200 UTC) by numerical simulations of MM5. From the pressure distribution observed on the
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surface, it is evident that a cyclone of central pressure 1008 hPa was developing in the northern region of Korean Peninsula (127°E, 39°N) at 0000 UTC January 1, 1997. It moved northeast to enter East Sea for the next 12 hours until 1200 UTC, making an explosive development to −16 hPa/12 hr and locating the center around 132°E, 42°N. For the same period, the model produced the following results; a cyclone of central pressure 993 hPa was developing in the northern region of Korean Peninsula (127°E, 39°N) at 0000 UTC January 1, 1997. Korea has a weak rainfall zone of 4-7 mm in the north-south direction along a cold frontal zone centered near the West Coast. The precipitation in the figure was accumulated results every three hours during the simulation period.

The numerical simulation results show that the rainfall zone continued to move eastward, while the cyclone deepened the central pressure to 976 hPa at 1200 UTC around the northern East Sea (132°E, 42°N). It gained speed quickly and developed fast to −17 hPa/12 hr moving northeast between 0000-1200 UTC January 1. The comparison between the model results and the surface weather chart suggests the centers of the two cyclones were located in the almost same position but their sizes were different much. The previous studies (e.g., Hong and Lee, 1987) on numerical simulation of an explosively developing cyclone pointed out the same problem. However, as for the pressure deepening rates for the 12 hours, there was no great difference between the −16 hPa/12 hr.

Fig. 1. Distributions of pressure and rainfall amounts. The sea surface charts for (a) 0000 UTC and (b) 1200 UTC January 1, 1997 are obtained by observations. The distributions of sea level pressure and rainfall amount for (c) 0000 UTC and (d) 1200 UTC January 1, 1997 are obtained by MM5 simulation.
12 hr of the observation and the −17 hPa/12 hr of the model. Accordingly, MM5 relatively well simulates the observed rate of pressure deepening.

Figure 2 shows the observed geopotential and temperature and the model-simulated geopotential, temperature, and PV (potential vorticity) for the 500 hPa pressure level. For observed chart, there was a significant elliptic trough developed in the middle of China (120°E, 38°N) at 0000 UTC January 1, 1997. A thermal trough developed across the trough and thus reinforced the barodinicity of the atmosphere (Fig. 2a). At 1200 UTC January 1, 1997 12 hours later, the cyclonic circulation became even stronger around the trough and moved eastward, forming a cutoff cyclone on the 500 hPa surface in the northern Korean Peninsula (127°E, 40°N) (Fig. 2b). Although the thermal trough kept its existence, the barodinicity of the atmosphere did not increase any more. The mesoscale model simulated the 500 hPa pressure level for the same period. The analysis results show that there was pressure, temperature troughs apparently developed in the middle of China (120°E, 38°N) at 0000 UTC January 1, 1997, and that there was located cyclonic PV of 1.6 PVU or more at the bottom of and around the upper of the trough axis (Fig. 2c).

The cyclonic vortex became stronger until 1200 UTC January 1, while the maximum PV kept moving eastward and to the bottom of the trough, gradually heading for the lower trough and expanding. The Korean Peninsula was located under the trough axis in...
the downstream of cyclone vorticity, when a cyclonic circulation was cutoff in the 500 hPa pressure level (Fig. 2d). The maximum PV of 1.6 PVU or more surrounded the trough bottom and rotated, being positioned at the bottom of the trough almost the same as the center of the cutoff cyclone. There was an air of strong vorticity of stratospheric origin in the upper level atmosphere of the Korean Peninsula.

The comparison of observation and model numerical experiments suggested that there were some connections between the development, subsequent evolution and reinforcement of a cutoff cyclone in the 500 hPa pressure level and the cyclonic vorticity within the trough axis. The analysis results are consistent with those of the diagnostic study on the cutoff cyclone formation in the upper atmosphere by Bell and Bosart (1993). According to their trajectory analysis results, the air mass of northwest moves from the cyclonic shear of a jet streak to the trough axis and is caught up by the cutoff cyclonic circulation. Then as it escapes from the trough axis the rates slow, it regains momentum towards the upper northwest direction and forms a closed trajectory, thus accumulating high vorticity around the trough axis.

Evolution of moist PV

Figure 3 presents the positions of PV anomaly on the 305 K isentropic surface every three hour from 0000-0900 UTC January 1, 1997 with MM5. Fig. 3a shows the PV anomaly on the 305 K isentropic surface at 0000 UTC, Fig. 3b shows the PV anomaly at 0300 UTC, Fig. 3c shows the PV anomaly at 0600 UTC, and Fig. 3d shows the PV anomaly at 0900 UTC January 1, 1997.

**Fig. 3.** PV anomaly on the isentropic surface of 305 K by MM5 simulation: (a) 0000 UTC, (b) 0300 UTC, (c) 0600 UTC, and (d) 0900 UTC January 1, 1997.
surface at 0000 UTC January 1, 1997. The air of stratospheric origin with 1.6 PVU or more was penetrated into the area of the middle of China (120°E, 37°N). At this moment, Korea had negative PV anomaly along the East coast. As time progressed, the upper level positive PV anomaly got stronger in vorticity, moved southeast to the Korean Peninsula, and started to penetrate the negative PV anomaly over the Yellow Sea at 0600 UTC. At 0900 UTC three hours later, the upper level positive PV anomaly increased its vorticity counterclockwise and explosively developed enclosing the Korean Peninsula. This results were well consistent with the analysis results of the water vapor images of GMS (Fig. 4a-4d) and the distributions of PV anomaly in Fig. 5b-5c.

The water vapor images on January 1, 1997, are given in Fig. 4, where dark regions represent very dry air. The image at 0000 UTC January 1 in Fig. 4a
reveals a conspicuous dark region, labeled D, near the east coast of China (120°E, 35°N). It is easily recognized that the region match very well with the upper-level PV trough given in Fig. 5b. The cloud head developed near Baekdu Mountain of the northeast of this dry air, which corresponds with the center of surface cyclone in Fig. 1a. At 1200 UTC January 1, the upper-level very dry air marked with D in Fig. 4 continued propagating southeastward and rapidly developed into an intense cyclone located at the north side of East Sea, enclosing Korean Peninsula. The surface low was located about east of the center of the cloud head and cloud shield are distributed along the cold frontal zone expanding from the cloud head. The analysis of water vapor images indicates that very dry air was located over and to the northwest of the center of rapidly developing cyclone at 0000 UTC and 1200 UTC 1 January.

The distribution of PV at 305 K with 12-hour interval is given in Fig. 5, where the wind vectors are superimposed on the distribution. The outer contour of PV represents 1.6 PVU in the figure. Therefore, the region of PV greater than 1.6 PVU is considered to be composed of stratospheric air, based on the WMO definition of dynamical tropopause (WMO, 1986). A trough involving a PV vortex in Fig. 5a is located at the northern region of China (110°E, 42°N), to northwest from the Korean Peninsula. This corresponds the situation prior to the development of the cyclonic storm over the Korean Peninsula, compared to Fig. 1a.
As for the horizontal circulation, the winds around the trough in Fig. 5a are almost parallel to the PV contours, making cyclonic flow. Twelve hours later, the PV trough in Fig. 5b is elongated almost in meridian, moving to southeast direction, and is located at the central region of China (120°E, 39°N), strengthening the PV vortex.

There is also intensification in both the northwesterly at the western flank of the trough and the southwesterly at its eastern side, respectively. At 1200 UTC January 1, the intensified PV vortex is found at the northern region of Korean Peninsula in Fig. 5c. At 0000 UTC January 2, as shown in Fig. 5d, the PV trough displaced to the East Sea between Korea and Japan, without its further extension in the southward. The severe storm is now in weakening stage in Korean Peninsula.

**Tropopause fold process**

A vertical cross section of PV was analyzed to examine the dynamic and thermodynamic relationships between the upper and lower atmosphere with a dynamic tropopause of 1.6 PVU during the cyclone development and see if MM5 model simulated a tropopause fold event well. The vertical cross section was chosen in the south-north, east-west, and northwest-southeast direction with time as shown in Fig. 7. The south-north cross section was selected in the northern Korea (around 126°E) 0000-0900 UTC January 1, 1997 where the descending of a dynamic tropopause of 1.6 PVU was the most significant. The results are shown in Fig. 7. The bold solid line represents the dynamic tropopause (1.6 PVU), while the thin solid line does the vertical distribution of potential temperature.

Figure 7a shows the south-north cross section at 0000 UTC January 1, 1997. There was a small amount of positive PV around 1,000-1,500 km (northern Korea), and the upper tropopause remained around 300-350 hPa without revealing any particular characteristics. However, there was a strong growth of the lower level positive PV in the neutral atmosphere where the potential temperature (PT) was distributed vertically and the upper level dynamic tropopause descended rapidly around 1,500 km at 0300 UTC, connecting the upper and lower atmosphere with a post-like tube whose horizontal width was about 150-200 km (Fig. 7b). Such a structure happened as the effects of diabatic heating due to latent heat release while the moist air was forced to rise along the mountain, increased the lower-level instability and thus positive PV developed in lower atmosphere. The high positive PV in the lower level interacted with that of the upper level. They also exchanged rapid feedback actions, developing a strong surface cyclone in the northern Korea.

At 0600 UTC January 1, 1997, the high positive PV in the lower atmosphere was located near 550 hPa around 900-1,300 km. But the high PV value of more than 1.6 PVU in the upper level was disconnected from the lower flow and broke into several pieces, getting weaker and slowly moving southward (Fig. 7c). Fig. 7d is the vertical cross section at 0900 UTC January 1, 1997. A great deal of positive PV in the lower level became stronger a little bit near 500 hPa around 900-1,200 km. The isopleths of 1.6 PVU in the upper level made a rapid descent to near 690 hPa around 1,500 km but didn't connect the upper level 1.6 PVU and the lower level with a tube like at 0300 UTC. It is interpreted that the isopleths of upper level...
1.6 PVU moved faster than the lower one and thus the positive PV of the former moved southward fast while that of the latter did slowly.

Figure 8a presents a cross section across the Korean Peninsula in northwest-southeast direction (see Fig. 6) at 0300 UTC January 1, 1997. The upper and lower atmospheres were connected with a single tube whose widths were about 200 km around 1,000 km away from north by 1.6 PVU just like in Fig. 8b. Figure 8b presents a cross section of the central Korea in the east-west direction (see Fig. 6) at 0600 UTC January 1, 1997. The 1.6 PVU of the upper atmosphere was descending to about 950 hPa around 1,100 km in the figure.

Based on the analysis results of Figs. 7 and 8, the tropopause was connected to the lower atmosphere in the west coast of northern Korea, and the upper level 1.6 PVU (dynamic tropopause) descended as time progressed. There occurred a tropopause fold event twice with three hours intervals. In such a condition, the upper air of strong vorticity made a sudden movement down along the tropopause fold surface over the unstable lower atmosphere that existed earlier and exchanged the momentum with the lower atmosphere, reinforcing the cyclonic circulation of the lower air. Thus, it contributed to the explosive development of the cyclone while it is moving to East Sea.
Dry Simulation

Evolution of dry PV

The roles of moist in intensifying tropopause fold were investigated with MM5 by giving the moist effects to the microphysical process considering the general atmospheric conditions (Figs. 3, 7, and 8) and giving no moist effects to the process under the dry atmospheric condition with no moist and cloud. Figure 9 shows the results of dry simulation of PV at 305 K isentropic surface at intervals of three hours. The positive PV anomaly of 1.6 PVU or more was located at 120°E, 35°N at 0000 UTC January 1, 1997. At 0300 UTC January 1, the upper level positive PV
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Anomaly migrated eastward and descended to the central region of Korean Peninsula with a little bit increased vorticity by 0600 UTC. At that moment, the upper level positive PV anomaly centered at 120°E, 33°N. By 0900 UTC, the upper positive PV anomaly continued to move eastward with little changes to the strength and descended down to the southern region of Korean Peninsula.

Comparison of Fig. 9 with Fig. 3 shows maximum southward latitude and center of 1.6 PVU isopleths in the moist simulation nearly corresponded with that of dry simulation. It turned out that the vorticity developed stronger when the moist effects were considered than when they were not. It has concluded that absolute vorticity had bigger impacts on the PV than stability in the upper level, in addition, and that presence of moist in the low level influenced PV development.

Figure 10 shows the results of the PV in the 305 K isentropic surface considering the moist effects (moist PV) being subtracted by those of the same surface considering no moist effects (dry PV). Of course, it is difficult to argue that the difference definitely represent the moist effects.

However, on the assumption that the difference included the effects of absolute vorticity by the moist (i.e., PV is the multiplication of absolute vorticity and stability); the evolution of the upper level vorticity by the moist process was examined with the difference. Fig. 10a shows the results at 0000 UTC January 1, 1997. There is no significant characteristic of PV development on the 305 K surface. However, there

![Diagram of PV development](image)
was weak positive PV anomaly developed in the northern Yellow Sea and weak negative PV anomaly the northern Korea at 0300 UTC (Fig. 10b). However, at 0600 UTC, the positive PV anomaly grew stronger. As time progressed, the values of positive and negative PV anomaly moved eastward to the Korean Peninsula as a pair. By 0900 UTC the positive and negative PV anomalies were located over the northern Korean Peninsula and the northern East Sea respectively (Fig. 10d). There was positive PV anomaly penetrating into the negative PV anomaly and developing itself by the moist effects even though they were week. The results were almost corresponded with the difference between moist and dry PV.

Thus, assuming that the upper atmosphere is usually drier than the lower atmosphere, it is suggested that moist plays a role in the formation of the upper vorticity even though the effects are hard to measure in quantity due to the resolution the model and the research goals.

Roles of moist in tropopause fold

Figure 11 shows the PT and north-south vertical cross section of dry simulated PV along the West Coast from 0000 to 0900 UTC on January 1, 1997 (see Fig. 6). The thick and thin solid lines represent the 1.6 PVU and PT, respectively. Fig. 11a is a vertical cross section of PT and PV at 0000 UTC January 1, 1997. The isopleths of upper level 1.6 PVU stayed around 350-300 hPa over the entire region, and there was weak lower level positive PV around 1,000 km (northern Korea). At 0300 UTC,
three hours later, the high values of lower level positive PV underwent no large change compared to before, the dynamic tropopause of 1.6 PVU descended slopingly to 500 hPa along the dense PT surface (Fig. 11b). The dynamic tropopause slowly descended to 670 hPa by 0600 UTC and then rose again to 580 hPa by 0900 UTC (Figs. 11c, d). During the tropopause fold moving up and down, the lower level positive PV did not develop much and they were not connected together with a single tube.

Figures 8 and 11 are compared to examine the role of atmospheric moisture in the development of tropopause. The companion indicates that the tropopause fold in the dry simulation is not as deep as in the moist simulation. Another aspect is that PV of 1.6 PVU was formed strong in the lower troposphere in the moist simulation but very weak in the dry simulation. In details, moist simulation showed that the isopleths of 1.6 PVU of upper and lower level were connected with a post-like tube around 1,500 km (northern Korea) at 0300 UTC January 1, 1997. This feature was shown through the north-south cross section covering the West Coast. However, in case of dry simulation, the tropopause descended to 500 hPa around 1700 km only with a slope. At 0600 UTC January 1, 1997, the moist simulation showed that the isopleths of upper 1.6 PVU descended to near 550 hPa around 400 km and almost reached the ground descending to near 960 hPa around 1,100 km (central Korea). The cross section selected with east-west direction through the central Korea. However, in case of dry simulation, it descended to near 600 hPa around...
400 km and did to 600 hPa around 1,900 km (not shown in the figure) with a slope. Those results can be explained by arguing that there is weak PV formed in the lower atmosphere when there is no enough moisture, that weak PV cannot pull down the tropopause, and that the tropopause cannot descend any more accordingly.

It is interpreted that a deep tropopause fold takes place when the tropopause descends a little bit and the lower atmosphere pulls down the tropopause strongly rather than when the tropopause itself descends to the ground or the lower troposphere. Hoskins et al. (1985) argued that there should be a certain degree of instability in the lower atmosphere when the upper atmosphere induces the circulation of the lower atmosphere in applying the isentropic PV theory. The results are in the same line with his proposal. During deep tropopause fold, the moist in the atmosphere induces instability in the lower and pulls down descending tropopause. This feature was similar to a structure of summer typhoon that upper level forms a huge vortex tube connected to the lower level.

**Summary and Conclusions**

Comparison observation and model simulation shows that the MM5 model has a tendency to simulate the central pressure value of a cyclone stronger than the observed value, but well simulate the central location and the pressure deepening rates of cyclone, which represented the strength of cyclone development for 12 hours. In case of 500 hPa, it found that the model well simulated the formation of a cutoff cyclone and development of thermal trough in consistent with observed results. They were explained that the formation, subsequent evolution and reinforcement of a cutoff cyclone were related with the cyclonic vorticity accumulated within a pressure trough.

The moist simulation showed that the analysis result of a positive PV anomaly of 1.6 PVU or more well consisted with that of the GMS satellite images (Fig. 4) and the distributions of the PV anomaly (Fig. 5). As for the tropopause fold of the moist simulation, the dynamic tropopause made a sudden descent and formed 1.6 PVU tube whose horizontal width was about 150-200 km at 0300 UTC. In addition, the tropopause descended to penetrate deep into the lower tropopause to 960 hPa at 0600 UTC January 1, 1997.

Dry simulation shows the maximum descending height and location of 1.6 PVU were almost the same as that of moist simulation, but the vorticity was low, compared to that of the moist simulation. Thus, the present study suggests that moisture in the atmosphere turned out to play a crucial role in reinforcing a deep tropopause fold. However, more studies are required to characterize definitively the effect of atmospheric moisture on reinforce of tropopause fold.

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