The Interaction of the Upper- and Low-Level Jets in the Development of Mesoscale Convective Systems in a Mei-Yu Front: MM5 Model Simulations

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Abstract

During the period of 21 to 25 June 1991, a Mei-Yu front, observed by the Post-TAMEX Forecast Experiment, produced heavy precipitation along the western side of the Central Mountain Range of Taiwan. According to the analysis done by researchers at National Central University, the occurrence of precipitation systems was highly determined by the development of the southwesterly low-level jet (LLJ) in a region to the south and southwest of Taiwan. This LLJ brought in moisture-laden air from the southwest promoting deep convection. Using the Penn State/NCAR MM5 mesoscale model with grid nesting capability, we found that the development of the LLJ is sensitive to the presence of convective cloud processes. With the activation of cumulus parameterization and cloud microphysics, we found that the model produced a flow structure similar to that reported by Chen et al. (1994). First, there is a northward bound circulation (thermally direct) that developed from the frontal region, which is mainly caused by the thermal wind or the mass-momentum adjustment process when the air mass is entering an upper-level jet streak. We found that convection is triggered by the upper-level flow divergence associated with this circulation. Secondly, there is a 'reversed Hadley' circulation with rising motion in the frontal region and sinking motion equatorward (thermally indirect), which is mainly driven by frontal upright deep convection. The returning flow of this circulation at low levels is further strengthened by the negative pressure perturbation at the cloud base and acts as the cloud inflow. The Coriolis acceleration of this ageostrophic low-level cloud inflow can subsequently lead to the development of the LLJ. Thirdly, there is a circulation that developed from low to mid levels, which has a slantwise structure with rising and sinking motion in the pre- and post- frontal regions respectively. This slantwise circulation is probably maintained by the existence of a conditionally symmetric unstable environment located at low levels ahead of the front. We found that the presence of both the LLJ and the moisture is an essential condition to foster this environment.

1 Introduction

Heavy rainfall with rates of 100 mm day^{-1} to 300 mm day^{-1} occurred over the western plain and mountains of Taiwan on 20-25 June 1991. This weather system was characterized by the passage of a slow moving Mei-Yu front. During this period, a deep midlatitude baroclinic short wave trough developed at upper levels with an orientation from NE to WSW of China. The LLJ extended from Japan to Taiwan and into the South China Sea, and its development was accompanied by the strengthening and the westward movement of the Pacific High. Subsequently, the LLJ, located in the layer between 850 and 700 mb, transported moisture to northern latitudes as evidenced by the migration of high equivalent potential temperature ($\theta_e > 340$ K) shown in the 850 mb analysis. In this system, convection occurred in the region between the upper-level jet and the LLJ.

Statistically, heavy precipitation is closely related to the existence of the LLJ during Mei-Yu season over southeastern China and Taiwan (Chen and Yu 1988). Therefore, the study of the LLJ has been an interesting and important topic in understanding the LLJ intensification mechanism and its relationship with heavy rainfall (Akiyama 1973; Matsumoto 1972; Ninomiya and Akiyama 1974; Tao and Chen 1987). Therefore, this paper is of no exception.

The development of the LLJ has been explored by many investigators. Attempts began with the work of Matsumoto (1973), and Ninomiya and Akiyama (1974). They suggested that the downward mixing of momentum by convection is the cause. This theory can be easily rejected based on the fact that the LLJ does not lie directly underneath the upper-level jet. This simple convective mixing theory cannot account for the strengthening of the LLJ.

The search for the truth continued by hypothesizing that the heating by clouds is responsible for the development of LLJ. Hsu and Sun (1994) suggested that heating by stratiform cloud deepens the low-level pressure trough and thus leads to the development of the LLJ. In contrast, Chou et al. (1990) argued that the convective heating can generate a 'reversed Hadley' circulation with rising motion in the convective region and sinking motion equatorward. The LLJ is produced by the Coriolis acceleration of the return flow in the lower branch of the circulation.

Recently, Chen et al. (1994), and Chen and Chen (1995) found that the intensification of the LLJ is linked to deepening of the the midlatitude cyclone. Their argument is based on the finding that the region having an increase of the LLJ is collocated with that having an increase of isallobaric wind. The Coriolis acceleration of the cross-isobar ageostrophic wind pointing toward the low pressure center results in the development of the LLJ.

Another category of theory invokes the thermal wind adjustment or mass-momentum adjustment mechanism. For a more general interpretation, the mass-momentum adjustment theory proposed by Uccellini and Johnson (1979) can be explained by the thermal adjustment theory. In his theoretical work, Chen (1982) demonstrated that by including the convective heating, the thermal wind adjustment process can generate two circulations with the region of convective heating centered between these two circulations. To the left side of the convective heating region, a thermally direct circulation develops across an upper-level jet which is located at the jet streak entrance region. To the right side, an indirect circulation with sinking motion to the south can lead to the generation of a LLJ by applying the Coriolis acceleration to its low-level return flow. We need to pay special attention to this theory, since the thermal wind adjustment process in response to the convective heating, can provide us with a reasonable explanation for the development of the LLJ. The theory proposed by Chou et al. (1990) can be regarded as a subset of Chen's (1982) theory.

In the past, the role of the LLJ in affecting the heavy rainfall has been focused on its ability to advect warm and moist air into the frontal zone to fuel the convection (Ninomiya, 1984). However, in reality the LLJ does not lie directly underneath the cloud. There is a transverse ageostrophic circulation that develops from the LLJ to the cloud which taps the ample supply of moisture. We feel that the study of this low-level ageostrophic flow is very important. Not only its role as a conveyor belt to transport moisture is important, but also its development can lead to the further intensification of the LLJ.

In brief, in this paper we conducted real-data numerical simulations to examine the role of convection in interacting with both the upper-level jet and the LLJ. We also explored the mechanism that developed ageostrophic circulations and their effects on promoting the development of the LLJ.

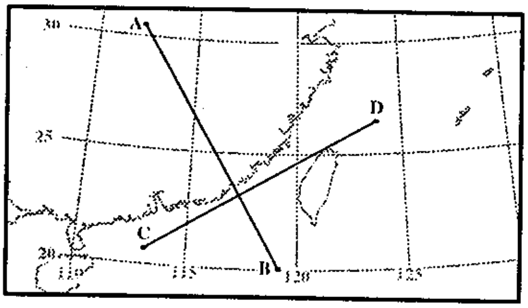

Figure 1: *Schematic diagram showing the simulation domain and lines to represent the orientation of the vertical cross section (x-z).*

2 Model description

We used MM5 version 1 to conduct numerical simulations of the Mei-Yu frontal system. Elements of the Penn State/NCAR MM5 have been described by Dudhia (1993), which should be referred to for details. In brief, MM5 is three-dimensional, nonhydrostatic, and elastic. It uses finite differences and a time-splitting scheme to solve prognostic equations on a type-B staggered grid. Its vertical coordinate, though defined as a function of the reference state pressure, is similar to a terrain-following coordinate. In order to emulate the real-weather, MM5 employs realistic wind, temperature and humidity as the initial and boundary conditions and incorporates topography and sophisticated physical processes to represent the appropriate forcing for the development of weather systems. These processes include clouds, diurnal radiative cycles, surface fluxes of heat, moisture and momentum, as well as other boundary layer processes. Because of the wide variety of physical process schemes that can be used in MM5, we only overview those that are important and are listed as follows:

1. The model in the present study is initialized from National Meteorological Center (NMC) archived global analyses with 2.5° latitude/longitude resolution to the model grid point locations. The first-guess fields are then enhanced by blending in the observational data using an objective analysis technique to introduce mesoscale features. The time-varying lateral boundary condition is provided by repeating the above procedure at 12-h intervals. The time interval that we are interested in is from 0000 UTC 23 June to 0000 UTC 24 June of 1991.

2. Three nested domains were constructed with a grid resolution of 135, 45 and 15 km, and had numbers of grid points in (x,y,σ) of 43 × 28 × 23, 55 × 37 × 23 and 73 × 49 × 23 respectively. The number of σ levels is 24 (1., .99, .98, .96, .93, .89, .85, .8, .75, .7, .65, .6, .55, .5, .45, .4, .35, .3, .25, .2, .15, .1, 0.05, 0.0), which gives 23 layers at which the temperature, moisture and wind variables are defined. A time step of 300 s is used in the coarse grid domain. The schematic representation of the second domain is shown by Fig. 1.

3. Grell's cumulus parameterization scheme was used in this study. This scheme is based on the equilibrium assumption. The subgrid scale convection is determined by the destabilization rate of the large scale flow.

4. A three-class cloud microphysics scheme is used to account for the resolvable scale convection. This scheme allows for ice-phase processes in which cloud water is treated as cloud ice and rain water as snow when the temperature is below the freezing point.

5. We used Blackadar's high-resolution PBL scheme to calculate vertical fluxes of heat, moisture and momentum at each vertical layer. The fluxes from the surface are based on similarity theory. In the nocturnal regime, the vertical fluxes are computed from K-theory above the surface layer. In the free-convection regime, these vertical fluxes within the mixed layer are not determined by local gradients, but instead depend on the thermal structure of the whole mixed layer (transilient approach). Above the mixed layer, the calculation of fluxes are again based on K-theory.

6. In order to produce more realistic initial conditions, we employed a four-dimensional data assimilation (FDDA) scheme from 0000 UTC to 1200 UTC of 23 June 1991. During the FDDA period, the model fields are nudged toward analyses of the observed data. Once the assimilation period is complete at 1200 UTC, the model simulation is continued for another 12 h.

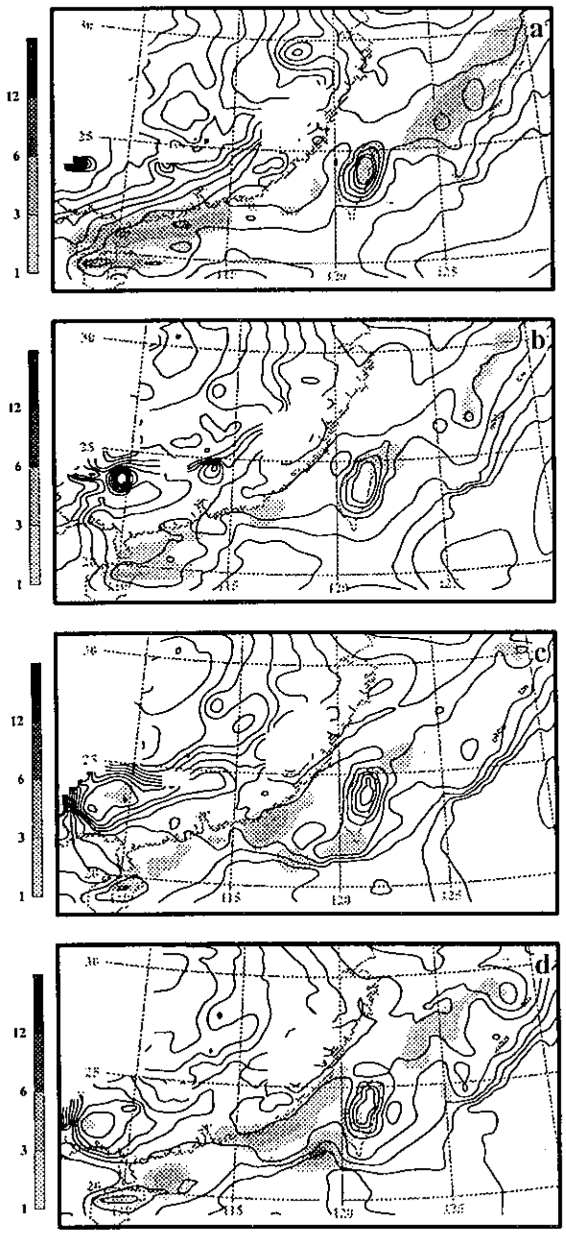

Figure 2: *Horizontal cross sections (x-y) of the accumulated precipitation rate (shaded, interval in mm hr^{-1}) at the surface and the potential temperature θ (solid lines, every 1 K) at a height of 500 m. The time sequence of the plot is for (a) 1200, (b) 1600, (c) 2000 and (d) 2400 UTC of 23 June 1991.*

3 Results

Figs 2b, 2c, and 2d show the accumulated rain at the surface for a period of four hours ending at the time specified in the figure, except that shown in Fig. 2a is for twelve hours (0000 UTC - 1200 UTC). The contours of the potential temperature at 500 m at the end of the period are also superimposed on the figures. During the first twelve hours, there is a band of precipitation extending from NE to SW in the simulation domain with the heaviest precipitation at the southern edge of China. However, in the hours that follow, the system over the East China Sea becomes weaker. In contrast, the system over the South China Sea develops strong convection and propagates in a northeast direction from Hainan toward Taiwan. At the end of the simulation (Fig. 2d), the precipitation pattern over a region west of Taiwan resembles to that shown by satellite IR imagery (not shown). Therefore, the model is probably reasonably simulating weather events that occurred in the real atmosphere.

In general, the temperature gradient near the surface for this frontal system is weak at 1200 UTC (Fig. 2a). However, the temperature gradient is strengthened at later times in two regions. The first region is found to extend out from Japan along the Ryukyu Islands. The midlatitude baroclinic frontogenesis process is probably responsible for the tightening of the temperature gradient in this region. The second region is located over the southern edge of the Taiwan Strait. In this region, the increase of temperature gradient seems to be associated with the development of convection.

We use cross section analysis to show the structure of the precipitation system. The location of these cross sections are shown in Fig. 1 by lines AB and CD. These cross sections slice through a developing precipitation system located to the west of Taiwan. The orientation of these cross sections is basically perpendicular and parallel to the frontal direction. For instance, Fig. 3a represents a cross section from NW to SE along line AB at the end of the simulation (2400 UTC), while Fig. 3b represents that from SW to NE along line CD.

When we examine Fig. 3a, we can identify two main features of the cloud system. Namely, this system consists of a deep convective cloud and a relatively shallow cloud slanted from the surface up to a height of 6 km. The temperature gradient at the leading edge of the surface front is weaker than that of the upper levels. Therefore, the atmosphere at low-levels is barotropic in nature, while at upper-levels it is baroclinic. We found that the baroclinic environment at upper-levels plays an important role in organizing the convective activity originating from low-levels. The cross section in the along front direction (Fig. 3b) shows that upper-level stratiform cloud extends over a wide area with one major convective cell imbedded within it. The contours of potential temperature show a gravity wave structure which may be induced by the neighboring convection or the nearby orographic features.

In Fig. 4, we superimposed ageostrophic wind vectors with cloud profiles to show the development of the cloud system viewed in the cross front direction (AB). Before the onset of convection at 1200 UTC (Fig. 4a), the upper-level wind is characterized by a transverse ageostrophic circulation across the upper-level baroclinic zone. The development of this circulation is similar to that discussed by Uccellini and Johnson (1979). The initial development of the convection seems to be related to the upper-level ageostrophic flow divergence. The continuing development of the cloud underneath the southern edge (right side) of this upper-level ageostrophic flow boundary is evidenced by the intensification of the vertical velocity. Meanwhile, a strong inflow at low levels on the right side of the convection develops resulting in moisture transport into the cloud. From low- to mid- levels, some sporadic shallow convection (Fig. 4c) developed in association with this inflow.

Other flow structures are also shown in Fig. 4. A low- to

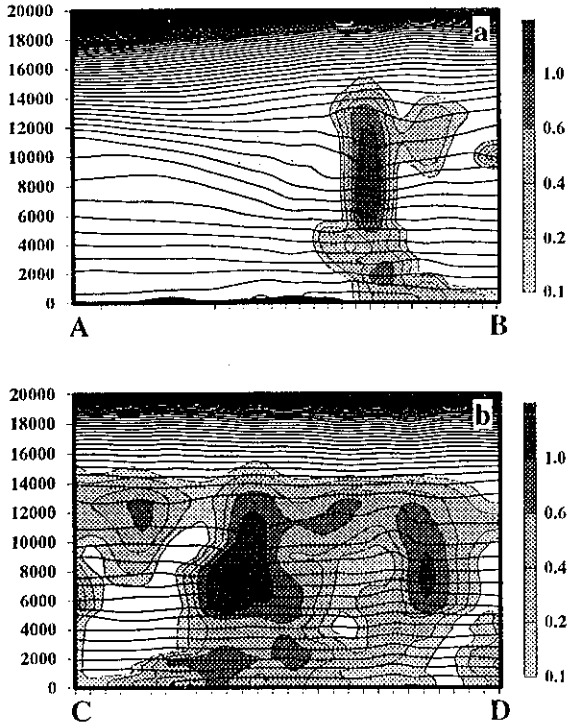

Figure 3: *Vertical cross sections (x-z) of θ (solid lines, every 4 K) and hydrometeor content (shaded, interval in g kg⁻¹) for 2400 UTC 23 June 1991 along the lines (a) AB and (b) CD.*

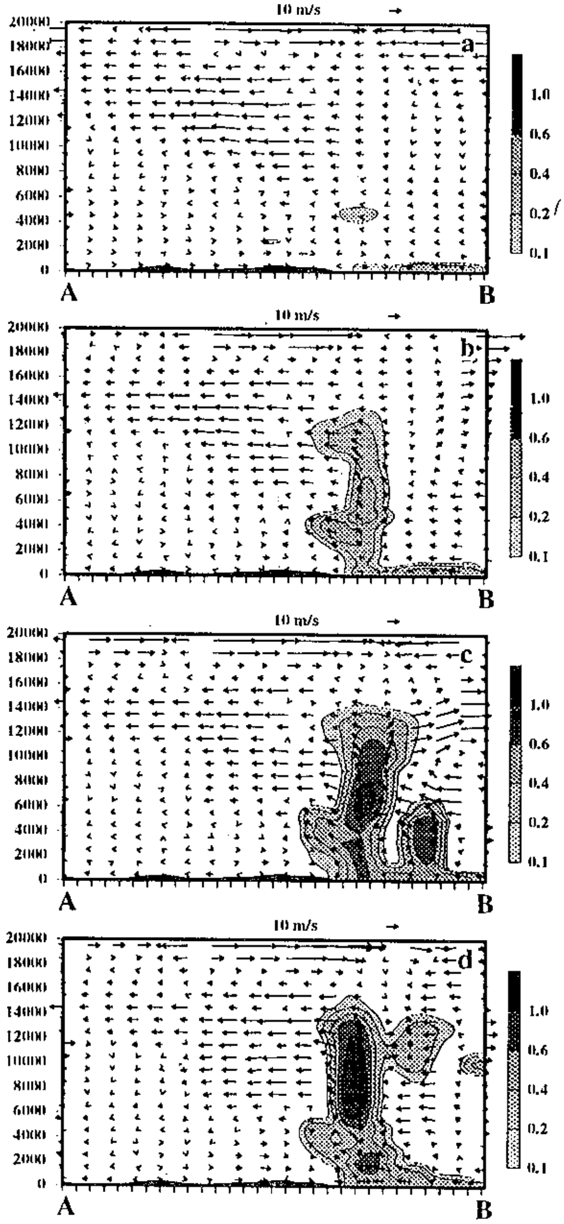

Figure 4: *Vertical cross sections (x-z) of ageostrophic wind vectors and hydrometeor content (shaded, interval in g kg^{-1}) along the line AB for (a) 1200, (b) 1600, (c) 2000 and (d) 2400 UTC of 23 June 1991.*

mid-level flow with a slanted structure developed to the left of the convection. This flow induced a weak circulation with returning branches coming from northern latitudes to provide convergence at the base of the convection. There is also a circulation that developed to the right side of the convection with rising motion in the frontal zone and sinking motion equatorward. Chou et al. (1990) called this circulation the 'reversed Hadley' circulation. They found that this circulation is driven thermally by convection.

In order to show the mechanism generating the transverse circulation associated with the upper-level baroclinicity, in Fig. 5, we superimposed the normal wind V with the ageostrophic wind vector to examine the relationship between the upper-level jet and the ageostrophic circulation. We found that the strongest ageostrophic flow is located at the core of the jet. Therefore, the upper-level jet dynamics may play an important role in driving this transverse circulation. In fact, in this study, we found the confluence flow associated with the upper-level jet streak to be the main reason for the development of such a circulation across the core of the upper-level jet.

Another important feature shown by Fig. 5 is the development of the LLJ located at the bottom-right corner of the cross section. It appears that the development of the LLJ is closely related with the development of the low-level cloud inflow. The generation of this cloud inflow may be due to the down pressure gradient acceleration associated with the negative pressure perturbation usually found at the base of a cloud.

The flow structure that we have described in Figs. 4 and 5 is in an excellent agreement with that shown in the schematic diagram (Fig. 6) summarized by Chen et al. (1994) based on their diagnostic analysis of a Mei-Yu frontal system during TAMEX IOP5 from 31 May to 2 June 1987. Like our case, their system is also characterized by a deep upper-level trough which is induced by the interaction of the midlatitude short wave trough with the Tibetan Plateau. However, unlike our case, their system develops a strong midlatitude cyclone at low-levels. Consequently, they attribute the development of the LLJ to the intensification of the cyclone. Despite the difference in the low-level cyclone intensity, our flow structure across the front is still amazingly similar to theirs. Therefore, the intensification of the midlatitude cyclone should not become the only condition for the development of the LLJ. In this study, we demonstrate that some other means may be possible.

4 Summary

We used the Penn State/NCAR MM5 mesoscale model to conduct numerical simulations to explore the development of the LLJ in a Mei-Yu front which was associated with heavy precipitation systems that occurred in the region to the south and southwest of Taiwan during the period 23-24 June 1991. This weather system was characterized as having a deepening midlatitude short wave trough with an orientation from NE to SSW of China. The initial development of the LLJ along the western Pacific rim from Japan to Taiwan and into the South China Sea is attributed to the intensification and westward migration of the Pacific High.

Our numerical experiments showed that the development of the LLJ is sensitive to convective processes. Once the cloud got started, the intensity of the LLJ got stronger. This allowed more moisture-laden air to be advected in to fuel the convection. This shows a positive feedback between the LLJ and the convection.

In spite of the fact that the LLJ is important to the development of cloud, deep convection did not occur atop the LLJ. Instead, convection usually occurred in the region SE of the upper-level jet and NW of the LLJ, i.e., in an area between the upper- and low-level jets. The link between the LLJ and the convection depends on the development of ageostrophic wind which acts as the cloud inflow across the LLJ to the convection. This low-level ageostrophic inflow is generated by the negative pressure perturbation induced by convective activity and further enhanced by conditional symmetric instability. Ironically, the LLJ played a very important role in fostering the creation of this conditionally symmetric unstable environment by flattening the absolute momentum (M) surface and by advecting moisture into the vicinity of the frontal zone. Therefore, air can move freely along the constant M surface in a region between the LLJ and the cloud and becomes unstable due to the fact that $\partial\theta_e/\partial z < 0$. Thus, the development of this ageostrophic inflow can lead to the intensification of the LLJ. Obviously, the LLJ and heavy precipitation cycle can continue as long as the processes maintaining the LLJ or the convection are not interrupted by other means.

The dynamics of the upper-level jet were also found to be important in our case. At the jet confluent entrance region, the development of an ageostrophic flow, moving across from the warm side to the cold side of the jet, can be explained by the thermal wind adjustment process. The divergence of this ageostrophic flow on the warm side can provide a triggering mechanism for the onset of the underlying convection. Once the cloud developed, this northward bound ageostrophic flow is further enhanced by the release of latent heat and the additional divergence associated with the cloud top outflow.

Like its counter part to the north, a southward bound ageostrophic flow is also generated in response to the same forcing introduced by the cloud processes. The generation of the 'reversed Hadley' circulation (Chou et al. 1990) is closely related to the development of this southward bound ageostrophic flow. The Coriolis acceleration of the returning flow in the lower branch of the circulation can also induce the LLJ. However, we feel that the contribution by the 'reversed Hadley' circulation to the development of the LLJ is limited, since the intensity of the corresponding easterlies at the upper branch of the circulation are always weaker than that of the LLJ westerlies.

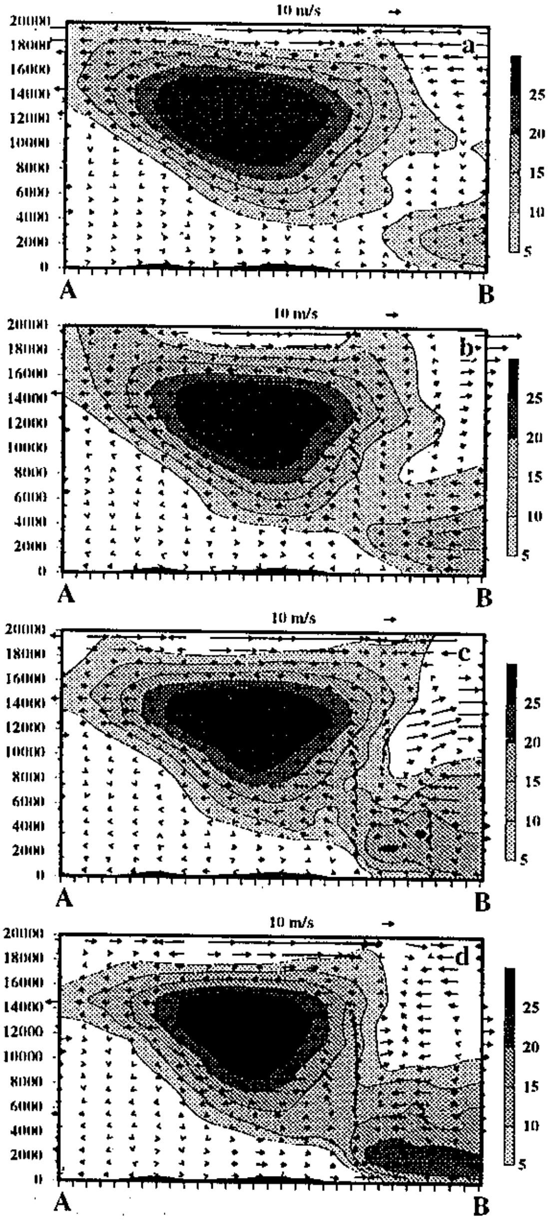

Figure 5: *Vertical cross sections (x-z) of ageostrophic wind vectors and normal wind speed (shaded, interval in ms^{-1}) along the line AB for (a) 1200, (b) 1600, (c) 2000 and (d) 2400 UTC of 23 June 1991.*

Despite assertions made by Chen et al. (1994), our results indicate that the intensification of the midlatitude cyclone does not become a necessary condition for the development of the LLJ, since the midlatitude cyclone in our case is neither strong nor becoming strong. However, in our systems we have mesoscale cyclones being generated toward the later stages, of which the generation is closely related to the development of mesoscale convective systems.

In summary, our case is characterized by the fact that the developing LLJ is located to the southeast of the entrance region beneath the upper-level jet, and the deep convection occurs in the region between these two jets. The ageostrophic wind divergence associated with upper-level jet appears to be an important trigger for the onset of deep convection. According to our results, the intensification of the LLJ is partially caused by the Coriolis acceleration of the flow associated with the 'reversed Hadley' circulation. The generation of the strong cloud base inflow is found to be another important factor that determines the development of the LLJ. A more thorough and comprehensive description regarding the development of the LLJ and the role of the conditional symmetric instability that occurred at low levels will be presented at the Workshop.

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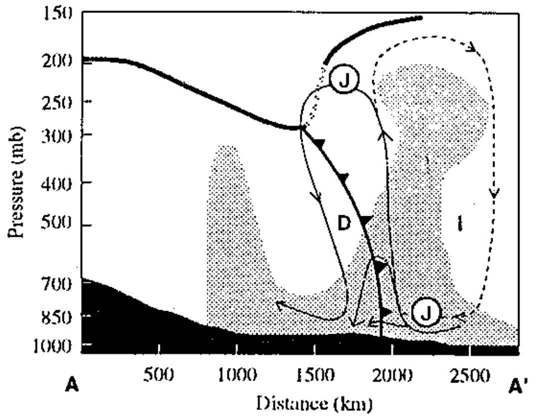

Figure 6: *Schematic diagram showing the flow structure of an observed Mei-Yu front (after Chen et al. 1994). The thin solid line depicts the direct (D) circulation while the thin dashed line depicts the indirect (I) circulation. The heavy solid line shows the frontal position. The character 'J' denotes the jet positions. The thick heavy line represents the tropopause boundary. Regions with relative humidity greater than 70% are shaded.*

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