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The Major Research Advances of Mesoscale Weather Dynamics in China Since 2003

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ABSTRACT

This paper reviews the main theoretical progress of mesoscale weather dynamics since 2003, including: (1) The dynamic mechanisms of balanced and unbalanced flow are applied to study the genesis and development problems of mesoscale circulation. The symmetric instability and transverse-wave instability are analyzed in line and vortex atmosphere convection, and further research has been done on nonlinear convective symmetric instability. The interaction between forced convection and unstable convection and the wave characteristics of mesoscale motion are also discussed. (2) Intermediate atmosphere dynamic boundary layer models are developed. The complicated nonlinear interaction is analyzed theoretically between the atmospheric boundary layer and the free atmosphere. The structure of the topography boundary layer, atmospheric frontogenesis, the structure and circulation of the low-level front and other boundary layer dynamic problems are discussed. (3) The formation and development of meso-β-scale rainstorms under the background of the East-Asia atmosphere circulation are diagnosed with the variation of MPV (moist potential vorticity) anomalies. And some physical vectors are modified and applied in the moist atmosphere.

Key words: mesoscale dynamics, mesoscale circulation, mesoscale numerical simulation and diagnoses

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1. Introduction

With Chinese economic boom since 2003, research on mesoscale meteorology have acquired more national funding. Additionally, due to the marked progress of modern atmosphere sounding technology and computer technology, significant advances have been made in the research on mesoscale severe weather. In addition, frequent occurrences of severe storm weather and rainstorm weather in recent years have attracted considerable public attention because of the catastrophic influence to the national economy and people's lives. So the study on the mechanism research and warning technology of mesoscale severe weather are of great concern. With the methods of observation analysis, dynamic diagnoses and numerical forecasting, Chinese meteorologists probe deeply into the organization of mesoscale convective systems (MCSs), in which the dynamic theory of deep and moist convection closely associated with mesoscale severe weather under the condition of the East-Asia atmosphere circulation has made innovative advances.

This paper reviews the progress of research on mesoscale weather dynamics since 2003. In the next section, we summarize achievemnets made in the research on the dynamic mechanism of mesoscale circulation. Section 3 reviews major results on Ekman boundary layer dynamics. Section 4 concludes the main progress in rainstorm and moist atmospheric dynamics. A brief summary is given in the final section.

2. The dynamic mechanism of mesoscale circulation

Observational research shows that mesoscale MCSs are convection storms formed by organic cumulus con-

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vection (Browning et al., 1974; Browning, 1989; Emanual, 1985). Common MCSs in middle latitude regions include: local convective systems (local severe storms etc.), quasi-two-dimensional line convection (squall lines, frontal mesoscale rainbands, etc.), MCCs in round cluster structure atmosphere, and mesoscale convective bands in typhoons with characteristics of vortex circulation (Lu et al., 2001; Gao et al., 2004d; Tang and Tan, 2006; Wu, 2002; Duan et al., 2005). One of their common characteristics is that there is a mesoscale circulation with very strong vertical motion on the quasi-two-dimensional cross-section. Therefore, the organic dynamic mechanism of deep and moist convective is the main scientific problem of mesoscale dynamics (Zhou et al., 2004).

2.1 *Balanced dynamic problems*

Frontogenetical circulation theory under frontal transverse circulation and semi-geostrophic momentum approximation (Sawyer, 1956; Shapiro, 1981; Bennetts et al., 1988), together with the symmetric instability theory (Bennetts and Hoskins, 1979; Emanual, 1982; Emanual, 1983b), put forward the generating mechanism of mesoscale circulation under the condition of basic flow balance (geostrophic balance and thermal wind balance). However, they have clear differences in both mathematical and physical scopes. The former is the secondary circulation induced by the forced term under the condition of ellipse equations, and it is the indispensable circulation to the destroying and recovering of basic flow balance; while the latter is time-varying unstable flow under the condition of the non-ellipse equation. With the theory of balance dynamics, Lu et al. (2004a) applied the concept of "gradient wind momentary approximation" in the vortex atmosphere to discuss the development of mesoscale disturbances in typhoons, which is similar to the geostrophic momentum approximation of Wu (2002). The mesoscale primitive equations in cylindrical coordinates are as follows:

$$v = \tilde{v} + Du = \tilde{v} + D\tilde{u} - D^2(\tilde{v} + D\tilde{u}) + \cdots ,$$
$$u = \tilde{u} - Dv = \tilde{u} - D\tilde{v} - D^2(\tilde{u} - D\tilde{v}) + \cdots ,$$

where, $\tilde{u}$ and $\tilde{v}$ are the reference wind fields,

$$D = \frac{\partial}{\partial t} + u\frac{\partial}{\partial r} + v\frac{\partial}{r\partial \lambda} + w\frac{\partial}{\partial z} .$$

Taking the first approximation and defining,

$$f_1 = \frac{\tilde{v}}{r} + f ,$$

where f is the Coriolis parameter and r is the radius, we can get,

$$\frac{d\tilde{u}}{dt} = f_1 v', \quad \frac{d\tilde{v}}{dt} = -f_1 u' .$$

Here we call the tangential basic flow $\tilde{v}$ which fulfills gradient wind balance and statistic balance as generalized thermal wind balance:

$$\left(\frac{2\tilde{v}}{r} + f\right)\frac{\partial \tilde{v}}{\partial z} = \frac{g}{\theta_0}\frac{\partial \theta}{\partial r} ,$$

where g is the gravity parameter, θ is potential temperature and θ_0 is the reference potential temperature. In the condition of axisymmetry,

$$\frac{d\tilde{u}}{dt} = 0, \quad \frac{d\tilde{v}}{dt} = -f_1 u' .$$

Set

$$m = r\left(\tilde{v} + \frac{fr}{2}\right) ,$$

then we can get the diagnostic equation of radial secondary circulation:

$$\frac{1}{r}\frac{g}{\theta_0}\frac{\partial \theta}{\partial z}\frac{\partial^2 \psi}{\partial r^2} - \frac{2}{r}\left(\frac{2\tilde{v}}{r} + f\right)\frac{\partial \tilde{v}}{\partial z}\frac{\partial^2 \psi}{\partial r \partial z} +$$
$$\frac{1}{r^2}\left(\frac{2\tilde{v}}{r} + f\right)\frac{\partial m}{\partial r}\frac{\partial^2 \psi}{\partial z^2} - \frac{1}{r^2}\frac{g}{\theta_0}\frac{\partial \theta}{\partial z}\frac{\partial \psi}{\partial r} +$$
$$\frac{4}{r^2}\frac{g}{\theta_0}\frac{\partial \theta}{\partial r}\frac{\partial \psi}{\partial z} = 0$$

where ψ is the streamfunction. Set

$$\frac{g}{\theta_0}\frac{\partial \theta}{\partial r} = S^2 ,$$
$$\frac{g}{\theta_0}\frac{\partial \theta}{\partial z} = N^2 ,$$
$$\left(\frac{2\tilde{v}}{r} + f\right)\frac{1}{r}\frac{\partial m}{\partial r} = F^2 ,$$

the ellipse condition for diagnostic equations is

$$F^2N^2 - S^4 > 0 , \text{ i.e. } \left(\frac{\partial m}{\partial r}\right)_\theta \frac{\partial \theta}{\partial z} > 0 .$$

While the hyperbolic condition for diagnostic equations is

$$F^2N^2 - S^4 < 0 , \text{ i.e., } \left(\frac{\partial m}{\partial r}\right)_\theta \frac{\partial \theta}{\partial z} < 0 .$$

Obviously, the ellipse condition

$$\left(\frac{\partial m}{\partial r}\right)_\theta > 0 \text{ and } \frac{\partial \theta}{\partial z} > 0$$

is just one of the cases, which is the existent condition for radial circulation under the condition of inertia and gravitational stability. As to hyperbolic condition,

$$\left(\frac{\partial m}{\partial r}\right)_\theta < 0 \text{ and } \frac{\partial \theta}{\partial z} > 0 ,$$

it is the inertia instability on isentropic surface under condition of gravitational stability, and it is a kind of symmetric instability. But the balanced model cannot be used to study unstable flow.

2.2 *Unbalanced dynamic problems*

The main theories about convection induced by instability in the atmosphere include conditional symmetric instability (CSI), moist symmetric instability (MSI) and transverse-wave instability (Bennetts and Sharp, 1982; Seltzer et al., 1985; Reuter and Aktary, 1993). It has been proved that symmetric instability with a median size Rossby number is the developing mechanism of quasi-two dimensional meso-β-scale systems (Hoskins, 1974). Linear theories point out that such instability is induced by the thermal wind unbalance of perturbations in the basic flow-satified thermal wind balance. Further research on unbalanced dynamic problems receive more attention. Lu et al. (2004b) discussed unbalance dynamics in vortex atmosphere.

2.2.1 *Symmetric instability and transverse-wave instability in the vortex atmosphere*

Fei and Lu (1996) discussed symmetric unstable flow with the model of symmetric instability increasing mode on the constant gradient flow. The primitive equations in cylindrical coordinates are linearized under the condition of generalized thermal wind balance (Emanual, 1979). Thus the disturbing radial circulation equation is:

$$\frac{\partial^2}{\partial t^2}\left(\frac{1}{r}\frac{\partial^2\psi}{\partial z^2}+\frac{1}{r}\frac{\partial^2\psi}{\partial r^2}-\frac{1}{r^2}\frac{\partial\psi}{\partial r}\right)=$$

$$f_1\frac{\partial}{\partial t}\left(\frac{\partial v'}{\partial z}\right)-\frac{g}{\theta_0}\frac{\partial}{\partial t}\left(\frac{\partial\theta'}{\partial r}\right)$$

Deriving from the above equation, we can get:

$$\frac{\partial^2}{\partial t^2}\left(\frac{1}{r}\frac{\partial^2\psi}{\partial z^2}+\frac{1}{r}\frac{\partial^2\psi}{\partial r^2}-\frac{1}{r^2}\frac{\partial\psi}{\partial r}\right)=$$

$$-F^2\left(\frac{1}{r}\frac{\partial^2\psi}{\partial z^2}\right)+2S^2\left(\frac{1}{r}\frac{\partial^2\psi}{\partial r\partial z}\right)-\frac{S^2}{r^2}\frac{\partial\psi}{\partial z}-$$

$$\frac{N^2}{r}\left(\frac{\partial^2\psi}{\partial r^2}-\frac{1}{r}\frac{\partial\psi}{\partial r}\right)+\frac{1}{r}\frac{\partial\psi}{\partial z}\left(\frac{\partial S^2}{\partial r}-\frac{\partial F^2}{\partial z}\right)-$$

$$\frac{1}{r}\frac{\partial\psi}{\partial r}\left(\frac{\partial N^2}{\partial r}-\frac{\partial S^2}{\partial z}\right)$$

When environmental parameters do not vary with space, we can get the condition for disturbing instability:

$$Ri^*=\frac{F^2N^2}{S^4}<1-\left(\frac{3}{2}+\eta\right)^{-2}$$

where Ri^* is the slantwise convective Richardson number and

$$\eta=-\left[\frac{3}{2}+\frac{c_1}{c_1+c_2}\right]$$

is the eigenvalue of the interflow Kummer hypergeometric equation, c_1, c_2 are eigenvalues of the Hukukara equation. It shows that a kind of disturbance in the vortex atmosphere, propagating along the vertical direction of tangential flow, has the characteristics of inertial gravity waves, and symmetric instability is one of its developing mechanisms.

Supposing environmental parameters vary with space, the developing the equation of symmetric unstable energy induced with the WKBJ (Wentzel, Kramers, Brillouin and Jeffreys) method shows that variations of environment fields (including stratification, temperature gradient, and wind shear) are the reasons for the variation of symmetric unstable energy. But the features of circulation overlapped on the environment field variation cannot be well demonstrated.

In the vortex atmosphere, there is transverse-wave instability propagating along tangential basic flow. With numerical methods, Li et al. (2003) discussed the instability of such disturbances of round vortex systems in baroclinic flow under cylindrical coordinates, which is another kind of instability of the mesoscale inertial gravity wave. They also analyzed the influence of stratification stability parameter N^2, vertical shear of tangential wind $\overline{V}_z$, latent heat of condensation, vortex characteristics and Coriolis parameter f_0 on the growth rate of instability in vortex atmosphere. The results show that in a round vortex there are also Eady mode and mesoscale modality of transverse-wave instability, the disturbing flow of the mesoscale mode appears to be an irregular "cats eye" structure, and slowly propagating disturbances gather on high levels.

2.2.2 *Nonlinear convective symmetric instability*

Xu (1989) proposed a mechanism called "upscale development" for the development of rainbands, where small-scale moist gravitational convection develops first, followed by mesoscale banded organization of clouds due to the release of symmetric instability. But in the actual atmosphere, it is often observed that convective instability and symmetric instability occur at the same time. Emanual (1983a) and Seman (1994) called the mesoscale instability developing in such conditions "nonlinear convective symmetric instability". Kou and Lu (2005) applied the numerical experiment method with the ARPS (Advanced Regional Prediction System) model to analyze the development of nonlinear convective symmetric instability in mesoscale convective systems. The results show that during the development of nonlinear convective symmetric instability, the first is the development of convection, which prepares developing condition for symmetric instability. While the symmetric instability development makes convection organized, strengthens circulation, and prolongs life span, and has a positive feedback on the release of symmetric instability. Accordingly, the model concept of interaction between physical processes is presented.

Then through numerical experiments, Kou et al. (2004a,b) and Lu et al. (2002) discussed the development of mesoscale circulations of symmetric instability under the interaction between wave and flow. The results show that the interaction between disturbances and basic flow includes the following two aspects: (1) the disturbance changes basic flow, then the changed basic flow has feedback on the disturbance; (2) the transportation of mean momentum and heat of the disturbance also changes the structure of the disturbance itself, thus has influence on the development of the disturbance. In the interaction between the disturbance and basic flow, the slantwise circulation of the disturbance, provoked by basic flow, makes the change of basic flow environment unfavorable for the further development of symmetric instability. While the transportation of mean moment and the heat of the disturbance is good for the further development of symmetric instability. The latter's impact is stronger than the former's. So the impact of the transportation of mean moment and the heat of disturbance should be strongly noted.

Additionally, conditional symmetric instability is the intermediate process between thermal instability and conditional instability (Cheng and Lu, 2004, 2006a). The evolution of the atmosphere from instability to stability is achieved through conditional symmetric instability. The formation of convective symmetric instability is related to the allocation of unstable layers. When there is conditional instability at low levels, and deep conditional symmetric instability at upper levels, the circulation characteristics formed by convective symmetric instability are: at the lower levels, vertical upstream appears, while at the upper levels, extensive slantwise upstream appears. The release of symmetric instability energy produces mesoscale cloud bands. When there is conditional instability at low and upper levels, and on the middle level, conditional symmetric instability or weak-stability stratification appear, and the deep vertical upstream will appear from low-level to upper-level. The release of moist gravity instability energy leads to the formation of cloud bands.

2.2.3 *Interaction between forced flow and unstable flow*

To the frontal rainstorm bands, slantwise convective motion can arise due to a secondary circulation, which is forced by the front as well as moist symmetric instability. In the actual atmosphere, it is hard to separate them from each other, because they usually exist simultaneously (David and Philip, 1999). In the deep moist convective motion, which has long life span and larger scale, the convection induced by forcing and instability is more complicated.

Cheng and Lu (2006b) studied the interaction between forcing and instability in the course of breaking and rebuilding of basic flow balance with numerical methods. The results show that unstable flow includes conditional instability and conditional symmetric instability. Unstable flow is ten times stronger than forced flow. Though the magnitude of forced flow is small, it is the trigger mechanism of unstable flow. If there is a deep unstable level in the environment and upward motion with a certain amplitude is forced by the environment, then the upward motion center of unstable flow will be provoked in the upward motion center of forced flow after 0–3 hours, or the already existing upward motion center of unstable flow will be driven to move toward that of forced flow. On the contrary, when the environment forces downward or weak-upward motion, upward motion will be restrained. Then the center of upward motion will vanish. Therefore, the atmospheric environment provides the condition of the release of unstable energy, and forced flow is the release mechanism of unstable convection.

2.3 ***The characteristic wave of mesoscale motion and its structure***

Within the genesis and development process of mesoscale circulation, there also exists the propagation of circulation associated wih the wave characteristic of the mesoscale disturbance. Using Bussinesq equations, Zhang and Shi (2004a) discussed the characteristic wave of mesoscale disturbance with the method of numerical calculation. Zhang and Deng (2005) also studied the instability of the mesoscale disturbance. Those studies show that the wave spectrum characteristics of meso-β-scale waves are related to basic flow. When there is vertical shear in the basic flow, a couple of gravity-inertia waves and a vortex wave all have continuous spectrums. With the increasing of vertical wind shear, continuous spectrum overlapping occurs. In the overlapping regions, the spectrum functions change, that is, the structure of the disturbance changes, which is different from characteristic waves of meso-σ-scale disturbances.

Zhang and Shi (2004b) calculated the structure features of three types of gravity-inertia waves in different basic flow conditions, and three types are symmetric disturbance(propagating along the vertical direction of basic flow), transverse disturbance (along the direction of basic flow) and oblique crossing disturbance (propagating along the direction which has intersection angle with the basic flow). The results show that the structure of meso-β-scale symmetric instability is different from that of meso-σ-scale disturbance. With the decrease of horizontal scale, the vertical wave number of unstable gravity-inertia wave increases. The structure of oblique crossing disturbance is similar to that of transverse disturbance instability. When Ri is small, the vertical structure of streamfunction appears as the "cat eye" flow pattern, which states that in the scope of meso-β-scale, the two instability are from the same root.

Shen et al. (2005a,b, 2006) researched the distributing characteristics of transverse wave disturbances. The results show that in such transverse wave weather systems, the disturbing pressure p' and disturbing vorticity ξ' are in the same or opposite phase in the horizontal direction. The disturbing divergence D' and disturbing vertical velocity ω' also are in the same or opposite phase in the horizontal direction. While ξ differs from D' by $\pi/2$ in phase in the horizontal direction but their distributing structure is in the vertical direction is somewhat different. The total energy for the development of local disturbances mainly comes from available potential energy and basic flow kinetic energy of the mean fields. When studyies about the instability problems of transverse wave disturbance are carried out, they found that when the stratification is relatively stable, and if there is low-level jet or upper-level jet, the transverse wave disturbance will propagate along the direction east of the basic flow. When there is a second shear in the basic flow, the mixed wave instability can be induced. While when there is only the first shear, the transverse wave disturbance is only gravity-inertia wave instability.

2.4 *Gravity wave and E-P flux*

The genesis and development of mesoscale systems have an important relationship with mesoscale circulation in the vertical cross section. So research on gravity wave, which has important influences on vertical motion, is always the problem of concern with mesoscale dynamics. In research about the interaction between gravity waves and basic flow, Ran and Gao (2004) put forward a refined gravity-wave-drag scheme on the basis of McFarlane's parameterization scheme (Gao and Ran, 2003a,b; Ping et al., 2003a,b,c,d) of gravity wave drag. Both the drag effect of momentum flux and the dissipation effect of gravity wave breaking on the mean zonal flow are included in the refined parameterization scheme. Motivated by ageostrophic interactions of waves and basic flow, the generalized relationship between 3-D Eliassen-Plam flux and basic flow are derived, which is suitable to small-amplitude and finite-amplitude disturbances. The expressions of such kinds of 3-D Eliassen-Palm flux and wave activity can be demonstrated in Euler forms and be calculated with observational data or model output data (Ran et al., 2004).

An ageostrophic Generalized E-P flux in a baroclinic stratified atmosphere are developed (Ran et al., 2005a,b,c) aimed at limitation, and the deficiency of the traditional Eliassen-Palm flux associated with wave-mean flow interaction and its subsequent generalization based on the Boussinesq approximation or quasi-geostrophic approximation. This generalized E-P flux can be conveniently used to diagnose and analyze such important phenomena as the upper-level jet acceleration, gravity wave break-up, and stratospheric eruption warming (Gao et al., 2004a).

3. Ekman boundary layer dynamics

There are obvious nonlinear characteristics in the atmospheric boundary layer and its interaction with the free atmosphere, while those characteristics cannot be described by classical Ekman theory. Based on the classical Ekman theory (Tan et al., 2006), a series of Ekman boundary-layer models with medium complication, called the intermediate model for short, which retain the nonlinear advective processes while discarding embellishments, have been developed with the intention to understand the complex nonlinear features of the Ekman boundary layer. Wu (2002) and Tan et al. (2005) and Fang et al. (2005) studied several intermediate boundary layer models, including geostrophic momentum approximation, Ekman momentum approximation, and weak nonlinear boundary layer models. Through analyzing the theoretical framework of the above models, the physical significance is revealed. They also studied the physical meaning and limitation of those theoretical models in describing basic dynamic characteristics of the Ekman boundary layer. And each intermediate model is rather consistent, though the details may be different. So those models can be used in discussing dynamic problems such as the topographic boundary layer, frontogenesis, structures and circulation of the low-level front, the daily variation of boundary-layer, the formation of the low-level jet, and so on. The dynamical characteristics of the Ekman layer and its effect on the low-level motion of free atmosphere are analyzed.

Tang and Tan (2006) analyzed the structure of a land-falling tropical cyclone, using a slab boundary layer model with a constant depth. Asymmetry is found in both the tangential and radial components of the horizontal wind in the tropical cyclone boundary layer at landfall. For a steady tropical cyclone on a straight coastline at landfall, the magnitude of the radial component is greater in the offshore-flow side and the tangential component is greater over the whole sea, while smaller in the offshore-flow side. So the total wind speed on the sea surface is larger on the offshore-flow side. Therefore, larger rubbing effects on land surface will lead to larger radial inflow, and nonlinear advection results in the downstream radial inflow reaching its maximum. But the rubbing effect on the sea surface makes the action of tangential flow smaller than that on land.

Yuan and Tan (2004) used a two-dimensional nonlinear baroclinic Eady wave model to study the dynamic mechanisms for the rapid growth of initial balanced perturbations in the baroclinic system. The advection effect of baroclinic shear flow on perturbation vorticity leads to the "potential vorticity unshielding" of initial perturbation potential vorticity (PV), which includes the rapid growth of initial perturbations in the linear system. Due to dissipating the local perturbation PV, friction modifies the structures, especially the horizontal distribution, of PV anomalies, and accordingly weakens PV unshielding of the initial perturbation PV so as to restrain the transient growth of initial perturbation kinetic energy. The nonlinear effect induces the rich vertical structures of perturbation PV anomalies, which weakens PV unshielding of the initial perturbation PV, consequently restraining the rapid growth of initial perturbations with large amplitude.

Zhang and Tan (2002) studied the dynamic characteristics of daily wind variation in the planetary boundary layer (PBL), with a time-dependent semi-geostrophic Ekman boundary layer model (SG), including the slowly varying turbulence viscosity with height and advection acceleration effect. An approximate analytical solution of this model is derived by using the WKB method. The features of the daily wind variation in the PBL mainly depend on three factors: the latitude, horizontal momentum advection, and eddy viscosity. Results show that the vertical variable turbulence viscosity has little influence on daily wind variation in the PBL at low latitudes; however its effect may be exacerbated in middle and high latitudes. In comparing with the constant turbulence viscosity case, the decreasing (increasing) with height turbulence viscosity produces a large (small) maximum wind speed (MWS) in the PBL; however, the turbulence viscosity has a mid-layer peak in the vertical gives rise to a higher height of occurrence of MWS.

Zhang and Tan (2006) used a 3-D nonhydrostatic mesoscale numerical model (MM5) to simulate the formation and evolution processes of mid-latitude classic baroclinic waves as well as the frontal systems with and without surface drag in the dry and moist atmosphere, with special emphases on the low-level frontal structure and frontogenesis The results show that in the dry case, surface drag force has two-way effects on surface frontogenesis. On the one hand, the surface drag weakens the low-level frontogenesis and it is less inclined to develop the baroclinic wave due to the dissipation. On the other hand, the surface drag induces a strong ageostrophic flow, which prolongs low-level frontogenesis and finally leads to the enhancement of the cold front. Compared with the no surface drag case, the surface drag increases the frontal slope, especially in the boundary layer where the front is almost vertical to the surface, and then enhances the prefrontal vertical motion. All these conclusions expanded the analytical theory of Tan and Tan and Wu (1990). In the moist atmosphere, the influence of surface drag on frontal rainbands is also obvious. The surface drag weakens the convection, and reduces the energy dissipation near the surface when the initial relative humidity is relatively weak. At this time, the confluence-induced post-frontal updrafts move across the cold front and reinforce the prefrontal convection, which is beneficial to the maintenance of the rainbands in the cold sector. Given the enhancement of relative humidity, the moist convection dominates the low-level frontogenesis while the retardation of surface drag on energy dissipation is not obvious, therefore the effects of surface drag on low-level frontogenesis and precipitation are reduced.

4. Rainstorm and moist atmosphere dynamics

4.1 *Mei-yu front rainstorm*

The mei-yu frontal system is one of the most important systems which generate summer precipitation in China (Dong and Zhao, 2004). The past dynamic and thermodynamic studies on the mei-yu front rainstorm provided much improvement. In recent years, studies emphasize the occurrence and development of mesoscale convective systems in the east Asia atmosphere circulation.

Liao and Tan (2005) analyzed a mei-yu front rainstorm and found that weather systems with different scales have significant influence on the rainstorm. The stable, deep northeast-southwest oriented short-wave trough to the north of the mei-yu front, coupled with the low vortex systems moving from the southwest, was favorable to the genesis and development of the anti-cyclonic disturbance located northward to the mei-yu front. And the subsequent formation and enhancement of a lower anti-cyclonic vortex was expected to be crucial for the initiation and maintenance of the low-level shear line and the low-level vortex along the mei-yu front. The latent heating from the MCSs along the mei-yu front resulted in the formation of the mesoscale convective vortex (MCV), and meanwhile the MCV enhanced the low-level convergence near the low-level shear line and thus led to the initiation of the low-level vortex embedded in the low-level shear line. There were four different vertical circulations within the mei-yu front, which were important for the interactions among the different scales weather systems in both the upper- and lower-levels. These vertical circulations possessed the different structures and dynamic roles at different rainfall stages. The development of a convective disturbance within the mei-yu frontal system and the initiation of subsequent heavy rainfall were associated with the vertical circulation across the front and upper level ageostrophic vertical circulation, while the development of the convection would modify the vertical circulation structure. At last, when the heavy rainfall weakened, the vertical circulation was restored again.

Regional differences of the mei-yu front rainstorm are very obvious. Li et al. (2005) and Jing et al. (2004) analyzed the characteristics of three species of rainstorms on the mei-yu front, and revealed the main differences in structure and forming mechanisms of those three species of rainstorms, including: (1) Heavy rainstorm system in the initial developing cyclone is the meso-σ-scale cyclone forming and developing in the east of the mei-yu front. When the system is strong, the vertical motion's stretching height is not high, and the positive vorticity column, the convergence column, together with the maximum heating and humidity, exist in the lower troposphere. (2) When the meso-β-scale rainstorms occur, the temperature difference from north to south in the mei-yu front is small. The strengthening of convergence in the deformation field in the lower troposphere triggers the release and development of a meso-β-scale deep convective system (MCS). When it matures, the positive vorticity column exists in the whole troposphere. The deep convergence can reach the middle troposphere, and the maximum ascending velocity and the maximum heating occur in the middle higher troposphere. (3) The heavy rainstorms developing in the upper reaches of the Yangtze River often occur in the synoptic situation where there exists a deep trough in the middle troposphere in the north and a southwest vortex (SW vortex) in the lower troposphere in the south. When the cold-dry air invades from the middle troposphere, the SW vortex develops strongly upward because of the strengthening of the convergence in the lower troposphere and the release of strong potential instability. When it grows mature, the positive vorticity column exists in the whole troposphere and deep convergence can reach the middle lower troposphere. The maximum scending velocity with the maximum heating occurs in the middle troposphere.

Hu (2005) and Wu et al. (2004) studied the development and propagation mechanism of a mesoscale convective system on the mei-yu front. Using a linear model which includes simple cumulus convective parameterization, the study discussed the occurrence, propagation and dispersion properties of deep inertia gravity waves which occur throughout the whole troposphere over the Yangtze River valley with equivalent barotropic properties. The results show that low-level humidity and its horizontally non-homogeneous characteristicds directly related to the cumulus heating field have an important influence on the wave speed and stability of the disturbances. The areas where the unstable evolution occurs most notably are around the south border of the "low-level moisture frontal zone". This leads to that the MCSs are most likely active in this area.

4.2 *Moist weather dynamics*

A moist atmosphere is closely related to the formation and development of cumulus convection in mesoscale atmosphere motion. So it is very important to consider the degree of moisture in atmosphere. Liu and Gao (2003) considered that condensed liquid water would partially drop out of the air parcel after an infinitesimal perturbation, so a new form of Brunt-Vaisala frequency N_m^2 with the mixing ratio of saturated vapor θ_{se} is derived and discussed. So is a refined equivalent potential temperature.

Cui et al. (2003a,b,c) derived the moist potential vorticity (MPV) equation from complete atmospheric equations including the effect of mass forcing, with which the theory of Up-sliding Slantwise Vorticity Development (USVD) is proposed based on the theory of Slantwise Vorticity Development (SVD). Several numerical simulations, such as a torrential rain event along the Yangtze River-Huaihe River mei-yu front and a frontal cyclogenesis over the Western Atlantic Ocean, are performed and they all show the applicability and importance of the USVD in the development and movement of these synoptic systems.

Gao et al. (2004b) investigated the impacts of cloud-induced mass forcing on the development of the moist potential vorticity (MPV) anomaly associated with torrential rains. And the mass forcing shows a positive tendency for the MPV anomaly. It may be used to track the propagation of rain systems for operational applications.

The condensation probability function is originally introduced into the thermodynamic framework with $(q/q_s)^k$. The generalized moist potential vorticity (GMPV) is thus defined by Gao et al. (2004c) and its tendency equation is derived. A series of the dynamic properties of GMPV are applied to operational nowcasting. For example, using the sensitiveness of GMPV to the temperature and humidity, the summer hot and humid weather in Beijing can be forecasted (Gao et al., 2005a,b).

Due to the important role that vectors play instead of scalars in the dynamic analysis of synthetic systems, new vectors have been proposed for analyzing mesoscale systems. Gao et al. (2005c) focuses on several of them- convective vorticity vector (CVV), moist vorticity vectors (MVV) and dynamic vorticity vectors (DVV).

There is evidence of limitations of the PV when applied to deep convective systems where the vertical vorticity is still important, but the orientation of gradient of the potential temperature is almost horizontal so that the $\omega_a \cdot \nabla\theta \to 0$. In this case, PV is surely not a good dynamic tracer. What's more, compared with some variables such as momentum and absolute vorticity, PV as a scalar loses much more information. Gao et al. (2004d) introduced a new convective vorticity vector [CVV, defined as $(1/\rho)(\omega_a \times \nabla\theta)$] in a two-dimensional framework. Through the analysis of the different terms in the CVV equation, it is found that the correlation coefficient between the vertical component of the CVV and the sum of the cloud hydrometeor mixing ratio is 0.81. Therefore the vertical component of the CVV is a cloud-linked parameter and can be used to study tropical convections. Further analysis reveals that the tendency of the vertical component of the CVV is primarily determined by the interaction between the vorticity and the zonal gradient of cloud heating. In other words, the vertical component of CVV has a close relationship with the development of deep tropical convection, and it is a very good dynamic tracer for the development of deep convection.

Recently, Gao et al. (2006a,b) studied the three-dimensional convective vorticity vector and its association with a heavy rainfall event in China. It is found that the convective vorticity vector can serve as an important physical parameter in the analysis of both 2D and 3D convective development. The tendency equation of the vertical component of the convective vorticity vector is also derived and calculated to examine the primary physical process that is responsible for this tendency. The covariance between vorticity and diabatic heating is found to be primarily responsibility.

5. Summary

This paper summarizes the important progress of Chinese mesoscale weather dynamics in the past several years. The dynamic mechanism of balanced and unbalanced flow is applied to the study of the genesis and development of mesoscale circulation. The results point out that balanced flow under ellipse conditions produces a secondary circulation, while flow under non-ellipse conditions produce unstable flow. Both of the above are important reasons for the formation and development of mesoscale circulation. The former is forced circulation and the latter is the circulation caused by the released unstable energy under forcing action. There is gravity-inertia instability in the vortex atmosphere, including transverse-wave instability and symmetric instability. The structure and propagation of a characteristic wave in mesoscale motion is also studied. The refined drag parameterization scheme of gravity-inertia wave is used to discuss the interaction between gravity waves and basic flow. An intermediate dynamic model of the atmospheric boundary is developed. And the nonlinear characteristics of dynamic processes of the atmospheric boundary are understood theoretically. The interaction among mei-yu front rainstorm courses with different scales, the propagation of the gravity-inertia wave induced by moist fronts and the modification effect of adding the water vapor factor to meteorological parameters in moist processes are also reviewed in this paper.

However, much research has been not been described due to length limitations of this paper. Readers can peruse the listed references at the end of this paper. We believe that with further understanding and the deepening of observational research, the study of mesoscale weather dynamics will progress more quickly.

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