Study on Formation Mechanisms of Heavy Rainfall Within the Meiyu Along the Mid-Lower Yangtze River and Theories and Methods of Their Detection and Prediction*

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ABSTRACT

As the project of National Key Basic Research Development Program: Research on Formation Mechanisms and Predictive Theories of Major Weather Disasters in China has been fulfilled by 5-yr efforts of Chinese scientists, achieving results of great significance are as follows: 1) development of multi-scale physical models for Meiyu frontal heavy rainfall based on a range of real-time observations; 2) construction of synoptic models for such heavy rainfall; 3) the Meiyu front found to consist of multi-scale systems that represent a subtropical front, which shears structural features of an extratropical front and ITCZ, displaying sometimes a bi-front feature in the mid-lower Yangtze Basin (MLYB). The positive feedback between pre-frontal wet physical processes and over-front strong convective activities as well as interactions among multi-scale systems of the Meiyu front act as the important mechanism for the maintenance and development of the Meiyu front; 4) proposal of theories and methods for quantitative retrieval of multiple mesoscale torrential rains from satellite remote sensings, leading to a line of products; 5) investigation of applicable theories and techniques for retrieving the heavy rainfall system's 3D structure from dual-Doppler synchronous detectings; and 6) development of a system for meso heavy rainfall numerical prediction models with a 3D variational data assimilation scheme included, a tool that played an active role in flood combating and relief activities over the Huaihe River Basin (HRB) in 2003.

Key words: Meiyu front, mechanism, predictive theory

1. Introduction

One of the high-impact meteorological disasters in China is the Yangtze-Huaihe Basin's floods caused by Meiyu frontal heavy rainfall over the mid-lower Yangtze Basin (MLYB) so that the improvement of the ability of their detecting and forecasting is crucial to flooding alleviation and prevention. But the research is confronted with considerable difficulties because of their persistence and abruptness. As a result, the research presents a great challenge for Chinese scientists. The project of Research on Formation Mechanisms and Predictive Theories of Major Weather Disasters in China was established and implemented officially in 1999 specifically for the Meiyu frontal heavy rainfall with their effects on the MLYB floods, a project headed by Chinese Academy of Meteorological Sciences that was responsible for organizing panels of leading experts on heavy rainfall research from the Institute of Atmospheric Physics of Chinese Academy of Sciences, Peking University, Nanjing University and others. Based on data of the 3D structure of the heavy rainfall system through such advanced detectors as weather satellite, Doppler radar, and GPS as well as conventional, intensive observations from the 2001/2002 field experiments, an overall investigation of the genesis mechanisms, detection methods was performed, and predictive theories for the heavy rainfall. After 5-yr efforts, we have now achieved significant advances in the formation mechanisms, detection techniques, and predictive theories, acquiring a wide range of findings that are original and promising, of which some are utilized operationally, producing considerable benefits, and others are most likely to play an active role in the modernization of meteorological undertaking in China by combination with practice

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and further improvement.

2. Multi-scale physical models of Meiyu frontal heavy rainfall over the MLYB

2.1 *Development of such models by use of field experimental data*

The models include those of convective cells ranging from synoptic to meso-γ scale (Zhao et al., 2004), involving a conceptual model at synoptic scale and a model of meso-α weather system, models for convective systems and convective line at meso-β scale, and meso-γ convective cells.

2.1.1 *Conceptual model at synoptic scale*

The synoptic-scale systems related to the Meiyu front are dominantly southwesterly and southeasterly monsoons, Meiyu front itself and shear line in the mid-lower troposphere, West Pacific subtropical highs in the middle troposphere, Meiyu front-associated cyclone or vortex at the mid-lower levels, eastward-traveling trough in the mid troposphere, South Asian high and subtropical westerly and easterly jets at high levels, with their matching and interrelations shown in Figs.1 and 2.

Generally, during the torrential rain, vapor is transported by southeasterly monsoons along the brim of the subtropical high and southwest winds from the Bay of Bengal (BOB) into the MLYB. Analysis indicates that wind pulsation caused by mesoscale jet kernel prior to rainfall is responsible for the increase in precipitable water to occur in hit areas. Activities of a mid-latitude shallow trough at mid-lower levels help to the southward intrusion of weak cold air, which,

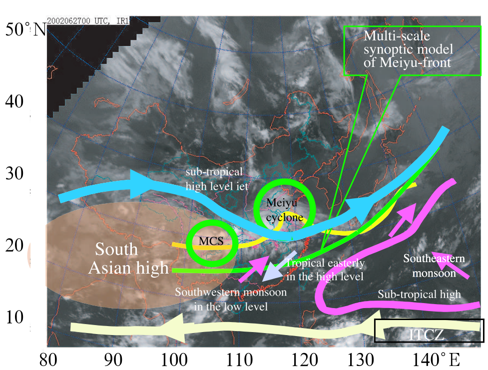


Fig.1. Multi-scale synoptic model of Meiyu-front (Zhao et al., 2004).

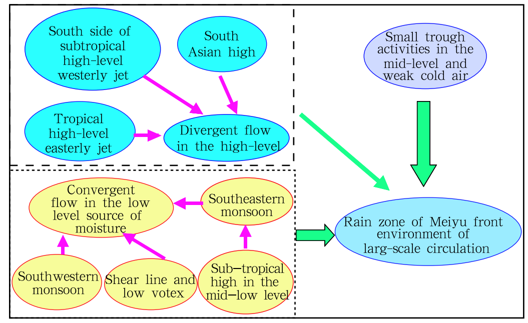


Fig.2. Relationship of all the synoptic systems in the Meiyu front multi-scale synoptic model (Zhao et al., 2004).

when confluent with warm, wet airflows from the southwest, produces a Meiyu front and shear line in the MLYB, which is a condition that contributes to the genesis/development of convective activities. And upper-level divergence happens on the south side of high-level westerly jets (to the north of the South Asian high) in association with easterly jets. These systems at high and lower levels and mid-lower latitudes work in harmony to create synoptic-scale conditions most conducive to the production of Meiyu frontal heavy rainfall.

Mesoscale convective systems (MCSs) for such heavy rainfall normally have its genesis/development ahead of the Meiyu front, and they cover meso-γ to -α scales, either relating to meso-α Meiyu front vortex or cyclone, or to local MCS.

2.1.2 *The model of synoptic systems at meso-α scale*

(1) Two kinds of disturbances for meso-α depressions over the Meiyu front

Two types of meso-low have the genesis/development on the front, one being of meso-low at smaller space/time scales, whose horizontal dimension is on the order of 500-1000 km and lifecycle covers approximately one day, in close relation to the Meiyu frontal heavy rainfall center, and the other type being cyclones. The disturbance manifests itself as a weak form on the front during genesis that grows via intensification into a cyclone under favorable conditions, with its horizontal extent beyond 1000 km and lifespan lasting for a few days, often bringing about torrential rain over a more extensive region. Studies reveal that cold air from the north and weak baroclinicity contribute greatly to the development of such lows. In terms of energy conversion, considerable vortex dynamic energy is produced in the lower troposphere, suggesting that a certain amount of effective potential energy changes to dynamic form to maintain divergent winds.

Different from the traditional model of extratropical cyclone, the Meiyu-front cyclone (low) model is to describe systems having properties of those at low and subtropical latitudes.

(2) Model of meso-α rain mass

Independent of Meiyu frontal cyclone or vortex, meso-α convective systems (MCS-α), generally, experience genesis/development in the Meiyu season, covering 200-500 km. Studies of satellite sensings and radar echoes show that there are convective cells and convective lines at meso-β scale (20-200 km) included the MCS-α. Generally, a MCS-α originates from a few meso-β systems through merging or from a meso-β convective system via development in a suitable environment.

2.1.3 *Meso-β intense convective system*

(1) The 3D structure of the system

As indicated by researchers, the 3D features of a strong meso-β convective system can be summarized as follows: 1) an approximate EW directed Meiyu front or shear line is available at surface; 2) large amounts of warm, wet air in the boundary layer are transferred to an area where a meso-β low is to be formed and a small Richardson number (unsteady zone) is existent; 3) at 700 hPa level, a meso-β low occurs on the east side of the SW vortex, with vigorous SW low-level jets to the southwest and southeast, where the mesoscale low-level jets close to the meso-β low are likely to relate to its formation; 4) a 500 hPa short-wave trough traveling east from the Tibetan Plateau and especially the pre-trough convergent zone aid in the genesis/development of a strong meso-β convective system; and 5) vigorous rising motion happens in the meso-β low, peaking at 400-300 hPa, with updraft beginning to diverge outward above 250 hPa to produce a related mesohigh, divergent air flowing outward mainly in the SE easterly and NE easterly directions. The joint working of high-level intense divergent zones is responsible for steady reinforcement

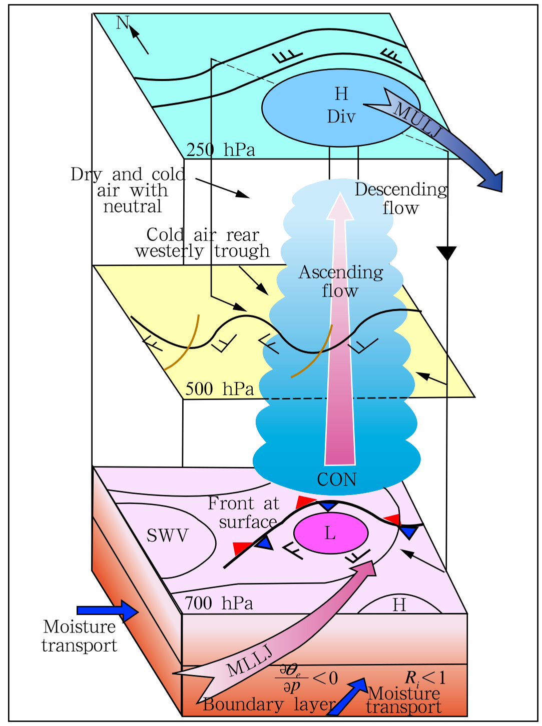


Fig.3. Three dimensional structure of the mesoscale heavy rainfall system (Zhao et al., 2004).

of vertical motion in the troposphere. The close combination of these elements serves as an important cause for exceptionally heavy precipitation from the Meiyu front.

(2) Model of meso-β convective lines

Sometimes a few convective lines may develop in the meso-α convective system and are normally generated from meso-γ convective cells arranged in lines that are typically on the convergence line in the boundary layer.

Figure 4 depicts the production of a new convective line triggered by a boundary-layer convergence line. Initially, meso-γ convective cells develop independently and when a wind convergent line generates at surface, convective cells distributed in a scattered pattern will initially form a convective line along the convergent line. When the first convective line develops strongly enough, outflow in the boundary layer occurs in view of rainfall-caused downdraft. The outflow combined with inflow already inside produces a new convergent line in the boundary layer, leading to

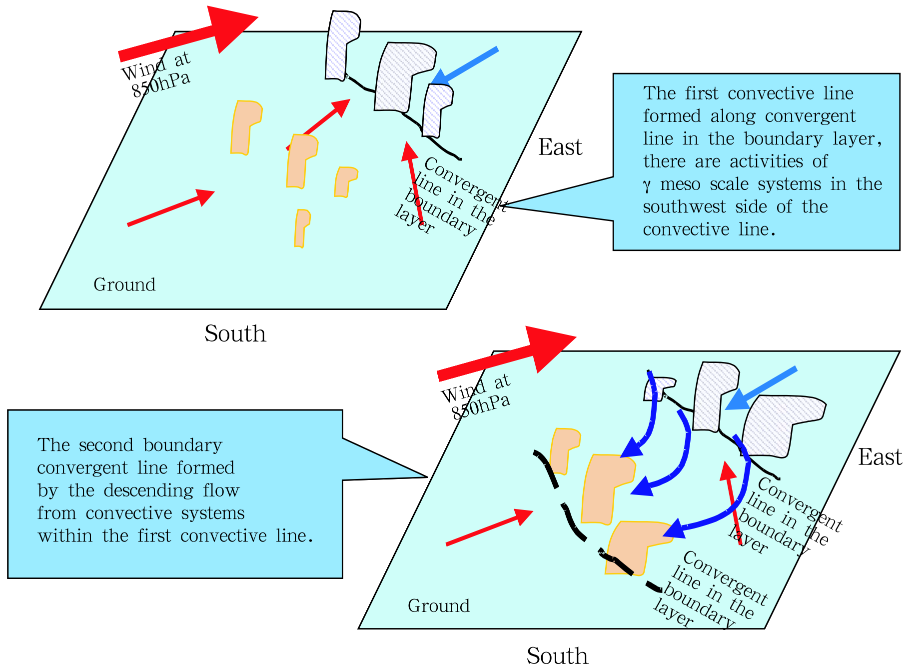


Fig.4. Convective line model with the meso-β scale (Zhao et al., 2004).

another convective line. The shift of the convective line is under the control of prevailing wind direction in the mid-lower troposphere but convective cells on the convective line move along the convergent line.

(3) Development of mesoscale convective system ahead of Meiyu front in relation to high and lower level jets on mesoscale

Through application of a high-resolution (6 km) numerical model to study MCS over the Yangtze-Huaihe Basin and South China Meiyu fronts, it is discovered for the first time that meso low level jets (mLLJ) and meso upper level jets (mULJ) are present in MCS-associated lower level mesolow and high level meso high, respectively, which have been borne from upper-air observations and analysis of vapor and winds in the upper troposphere. The mLLJ is a principal circulation system for mesoscale strong convergence of vapor in addition to vapor transport and the mULJ acts as a mechanism for air flowing out of the MCS. Momentum balance inside the mLLJ and the mULJ and vertically upward transfer of momentum of cumulus convection represent a mechanism for harmonic operation of both of the jets. On the other hand, the release of latent heat intensifies both of the jets. The mechanism producing heavy rainfall is presented in terms of mesoscale systems.

2.1.4 *A model for meso-γ convective cells*

A meso-β convective system or convective line consists of meso-γ convective cells, whose structure is given in Fig.5, and we can see that inflow comes dominantly from southwestern or southeastern warm,

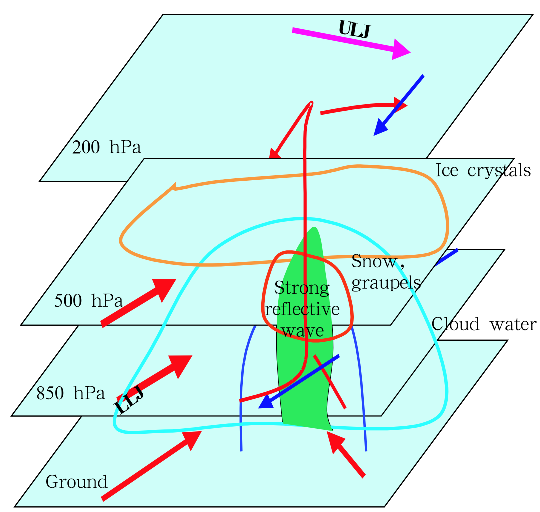


Fig.5. Convective cloud cluster model with the meso-γ scale (Zhao et al., 2004).

humid air and outflow occurs at high levels, with strong echoes coming from the convective cell in the mid-lower troposphere. From the simulation we have the distribution of in-cloud particles as follows: rainwater is largely at mid-lower levels, snow and graupels are in the middle troposphere and ice crystals are mainly in the upper troposphere.

Studies on field experimental data allow us to further improve the models for multi-scale heavy rainfall system, making them re-detailed (Zhao et al., 2004). Nevertheless, a lot remains to be done for the research on heavy rainfall's physical models because the problem is rather complicated in China, especially in the MLYB. New observational and experimental studies should be conducted for in-depth research on dynamic theories and simulations in order to develop more elaborate physical models for heavy rainfall systems so as to provide sound basis for objective and quantitative forecasting of such events in the end.

2.2 *A synoptic model for flood-causing Meiyu frontal heavy rainfall in the Yangtze-Huaihe Basin*

The synoptic model of flood-causing heavy rainfall for the MLYB reveals high impacts of South-China Sea monsoon surge, cold air activities at extratropics, and meso-α disturbances on the east side of the Tibetan Plateau on the MLYB Meiyu frontal rainfall. When the 4 multi-scale systems act in a locked phase intense heavy rainfall along the Meiyu front appears (Tao et al., 2004). In anomalous years (e.g., 1954, 1991, 1996, 1998, and 1999) when severe floods come about, these factors experience singularity. In July of 2003, for example, the HRB was hit by extremely intense flood as that of 1991 caused by 3 strong events happening in succession from the end of June to early July. Figure 6 presents the synoptic model for flood-causing heavy rainfall rainstorms over the HRB in May-August, 2003, during which 3 upper-air troughs move east onto the Meiyu front (Figs.6c and f) to intensify the disturbances resulting in large-scale intense precipitation over the basin on June 29, July 3-5 and 8-10, respectively.

2.3 *Meiyu front structure and its formation and maintenance*

2.3.1 *Structure of Meiyu front*

The Meiyu front active in the MLYB during the flooding season of 1998 serves as a highly typical example of its kind. As indicated by Tao et al. (2004) and Jiang and Ni (2004), the 1998 front has its structural characteristics common to all fronts of its kind during the raining season (e.g., there occurs a $\theta_{\rm se}$ front rather than sharply contrasting temperature feature in the lower troposphere, and the frontal zone consists of a positive vorticity band as well as convergence zones of wind and vapor in the lower troposphere) and displays the typical properties of its own, i.e., the front extends from surface to as high as 600-hPa level (in contrast to the general view holding that it is limited to $<$800 hPa), distributed nearly vertically with its tilt slightly northward; a weak convectively unsteady area is below 900 hPa and air is moistly neutral above the layer to 400 hPa; isopleths of $\theta_{\rm se}$ are distributed almost vertically; frontal baroclinicity is rather weak (see Fig.7).

During the 1998 Meiyu rainfall, a subtropical front corresponding to the Meiyu front on the fringe of the West Pacific subtropical high in the MLYB is characterized by a contrast of humidity with dryness in the south and wetness in the north. The subtropical front represents a transition between zones of moist SW monsoon and downdraft at the brim of the subtropical high, known as a foot-free front. This front and Meiyu front are, respectively, on the south and north side of the large-scale Meiyu rainfall belt, thus constituting a bi-front merging Meiyu front system.

Viewed from its horizontal and vertical structures, the Meiyu front is a system consisting of close-together $\theta_{\rm se}$ isopleths, with a convective cloud belt of deep convective cloud turrets at its leading edge (Fig.8), synoptic scale monsoon surge ahead in the mid-lower troposphere and steady transfer of dry, cold air behind in the mid to higher troposphere (Tao et al., 2001). Besides, after producing strong rainfall, the Meiyu front has transformed its character, suggesting that it become a subtropical front with properties between those of a mid-latitude front and the ITCZ. It is noted

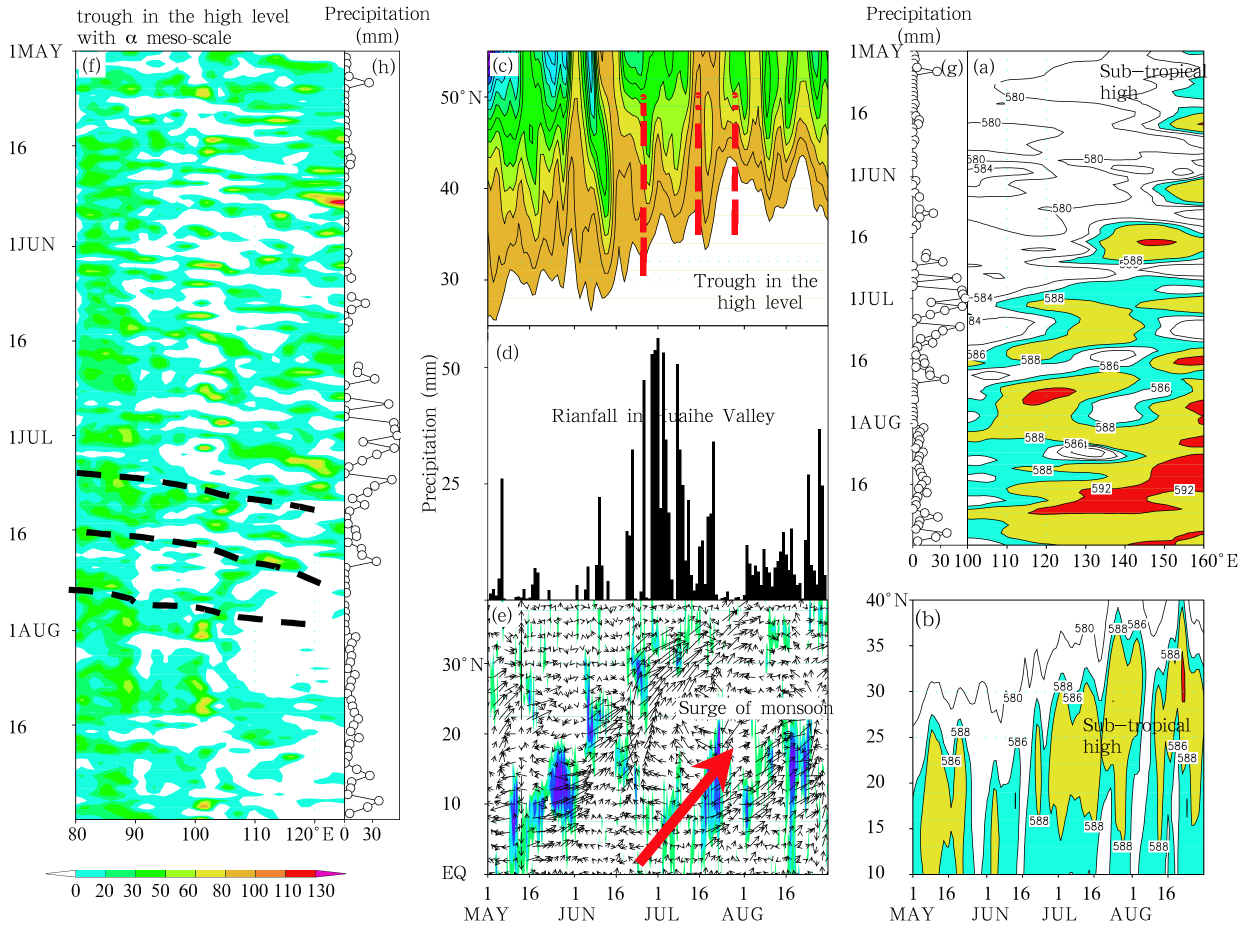


Fig.6. Synoptic model for Huaihe Valley heavy rainfall causing flood in 2003. (a) Longitude-time cross-section of potential hights (unit: dgpm) at 500 hPa along the averaged 27.5°-32.5°N; (b) latitude-time cross-section along the averaged 110°-130°E; (c) averaged potential hights at 500 hPa from 110°E to 120°E. Shaded area represents potential heights ⩽580 dgpm; (d),(g), and (h)daily precipitation in June-Aug. at 17 observation stations in Huaihe Valley (32°-34°N, 115°-120°E). Arrow represents the integrated moisture flux (unit: kg m^{-1} s^{-1}) from ground to 300 hPa, shaded area shows OLR⩽330 W m^{-2}; and (f) longitude-time cross-section of vorticity at 500 hPa (⩾0×$10^{-5}s^{-1}$) (Tao et al., 2004).

that the Meiyu front manifests itself as a bi-front Meiyu rain system in the MLYB (Jiang and Ni, 2004).

2.3.2 *Maintenance of the Meiyu front*

From a case study of the front in the flooding season in 1998 two mechanisms for the front maintenance have been proposed (Jiang and Ni, 2004). The first is the positive feedback between Meiyu frontogenesis occurring in wet physical process and the development of pre-front MCSs, and the second mechanism is the supporting system to the north 1) that acts to supply steadily cold air to the northern side of the front and 2) that is responsible for positive vorticity transport via vorticity advection to the positive vorticity columns at mid-lower levels of the MCSs ahead of the front. It is seen that interactions between MCSs over the Meiyu front as a synoptic-scale vortex are crucial to its development and maintenance. It should be noted that the first mechanism plays a dominant role in the early stage of development and both mechanisms are of equal importance during its mature stage.

2.4 *Mechanism for genesis/development of the mesoscale heavy rainfall system and its dynamic aspects*

2.4.1 *Front and frontogenesis dynamics*

The geostrophic adjustment frontogenesis theory

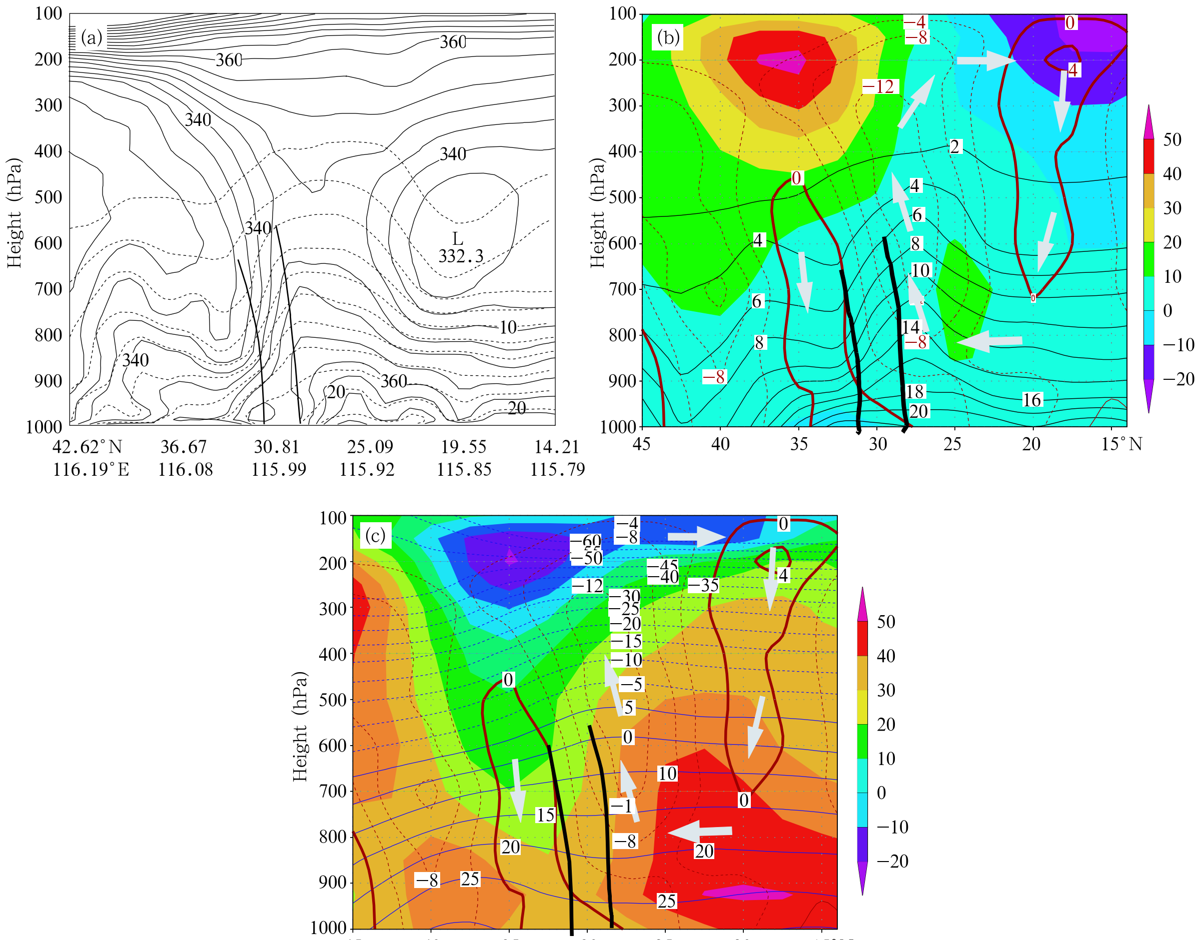


Fig.7. Longitude-vertical cross-section of θ_{se} (solid line, K) and specific humidity (dashed line, g kg^{-1}) along 116°E. (a) The solid line and dash line are upper and lower boundaries between Meiyu frontal region and subtropical frontal region respectively; (b) easterly and westerly (colored area, m s^{-1}), specific humidity (blue line, g kg^{-1}), and vertical motion (red line, 10^{-4} hPa s^{-1}); and (c) southerly and northerly (colored area, m s^{-1}), temperature (blue line, °C), and vertical motion (red line, 10^{-4} hPa s^{-1}). (Solid line is upper and lower boundary of the Meiyu front.)

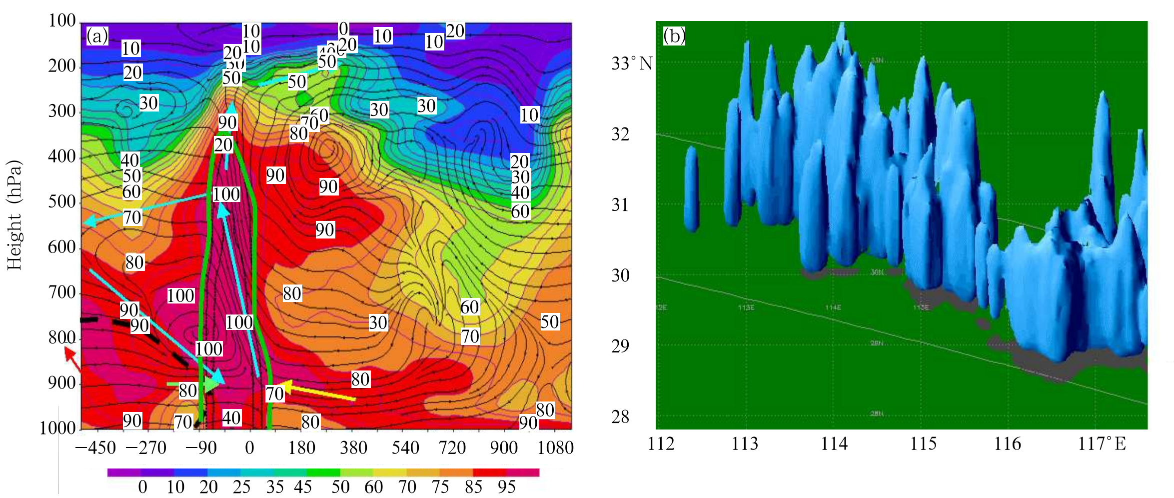


Fig.8. (a) Meiyu front structure analyzed by observational data, and (b) Meiyu front precipitation structure analyzed by TRMM data.

as its improved version (Wu et al., 2004) indicated that in the real atmosphere not all imbalance disturbances reach geostrophic equilibrium via geostrophic adjustment, depending upon the distribution of potential vorticity in initial imbalance flows. For heterogeneous flows with potential vorticity, the imbalance flows are normally unable to reach a complete geostrophic equilibrium. In this case, to address the problem of adjustment frontogenesis, we have to depend on a new equilibrium relation instead of simple thermal wind relation.

Our study shows frontogenesis alternate with frontolysis and apparent oscillations in vertical motion, velocity, and gradients of potential temperature, all of which are associated with oscillations in gravity wave and dispersion during the adjustment and the oscillations bearing some relation to Meiyu front intensity and change in precipitation.

In addition, topographic effects on geostrophic adjustment and frontogenesis are investigated at a theoretical level, indicating that the horizontal distribution features of an initial potential temperature field with its position with respect to a given terrain have significant impacts on geostrophic adjustment and frontogenesis.

Furthermore, we have taken into account the effect of diabatic process on frontogenesis and their interactions as a candidate mechanism for generating a mesoscale bi-rainband in the vicinity of the Meiyu front (Fig.9).

2.4.2 *Study of cloud physics*

Based on a large body of relevant observations, its analysis and mesoscale modelings for the Meiyu rainfall in the MLYB, particularly, cloud physical features and their effect upon intense precipitation are analyzed, indicating that the rainstorm is caused mainly by embedded MCSs with 10 km in horizontal dimensions and 8-10 km in height. Therein cloud physics of the mesoscale heavy rainfall system has its unique characteristics, some of which are highly similar to those of South China rainstorm. The following results are given.

(1) Mixed cold cloud physical processes from three-phase coexistence of vapor, water, and ice particles are the main physical factors for genesis and development of Meiyu rainstorm. Heavier precipitation is produced only when ice particles and cloud water exist on a synchronous basis; a maximum rainfall area moves with the belt of ice-water coexistence and when ice phase weakens or vanishes, and precipitation gets less intense or stops. Numerical simulation also indicates that Meiyu frontal strong rainfall can be generated in warm cloud process, dominated by collision-coalescence of rainwater with cloudwater.

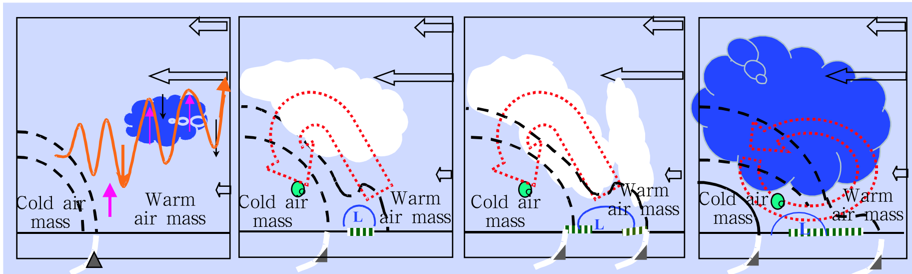
(2) In an intense precipitation system rainwater comes chiefly from melted graupels and snow. Below 0°C layer the collision-coalescence of rainwater with cloudwater, and of melted graupels with cloudwater contributes significantly to rainwater increase.

(3) In-cloud microphysical processes make strong feedback on the dynamic and thermodynamic processes of rainstorm. Condensates, when dropping, produce drag that weakens remarkably rising motion, thereby suppressing the development of microphysical processes inside clouds to diminish rainfall, and, on the other hand, the release of latent heat from phase change in condensates makes mid-level stratification more unstable, leading to increased rainfall.

(4) From the case study of 1998 Wuhan vigorous rainfall from the Meiyu front, we see that during the development of the convectively strong precipitation, rainwater comes largely from self-conversion of cloudwater, augmenting its amount quickly through collision-coalescence with cloudwater, and the ice-phase microphysical process plays a catalysis role in the development/evolution of strong rainfall.

2.4.3 *Theory proposed for instability of a vortex layer on horizontal shear line*

Breaking through the traditional Kelvin-Helmholtz view concerning shear instability, we propose a vortex layer changed from a shear line with strong vorticity shears and in that case the problem of shear line instability changes to that of vortex-layer instability (Wu et al., 2004). Considering vortex-layer produced inducing velocity, we have obtained the criterion theoretically on the necessary condition for vortex-layer instability on the horizontal shear line, i.e., the condition of ($1-R_v+R_{id}>0$) to be met, as



Convective cloud cluster excitated by ascending flow within warm region, which is ahead of Meiyu front.

The local diabatic frontogenesis in the low level is taken place because of the developing of frontal cloud (rain) band, release of latent heat formed cold and the front in low level.

Local diabatic frontogenesis in the low level enhances ascending flow ahead of the front, as a result, the rain band ahead of the front is generated and a meso bi-rainband in the vicinity of the front is formed.

Combination of the bi-rainband and the main cold front is gradually decayed.

Fig.9. Feedback conceptual model of moist physical process and diabatic frontal genesis.

well as $U(y,t) > U[A(t)]$ is to be present, which suggests that the matching of the environmental fields suppress the development of disturbances on the shear line so that the mesoscale development interacts with the environmental fields.

2.4.4 *Wet potential vorticity anomaly and impermeability theory with its applications*

An equation of wet potential vorticity is derived on a dynamic basis under the forcing of heat and mass, and the impermeability of substances of wet potential vorticity was proved (Wu et al., 2004). It is clarified that anomaly of wet potential vorticity under the heat/mass forcing is caused by intense precipitation in a rainstorm system. Analysis shows that the level for wet potential vorticity abnormality is mainly between 700 and 500 hPa, with the central maximum exceeding 1.4 PVU.

2.4.5 *Theoretical research of nonlinear sub-critical symmetric instability*

Sub-critical symmetric instability may occur when the criteria of linear and nonlinear symmetric instability are satisfied synchronously (Wu et al., 2004) and the criterion of sub-critical instability constrains the initial disturbance's amplitude, which in fact shows the key role of the nonlinear term(s) in the Boussinesq equation. When initial disturbance amplitude exceeds a given critical value, nonlinear sub-critical symmetric instability is likely to occur.

3. Significant advances in theories and methods for quantitatively retrieving mesoscale heavy rainfall from remote sensings

3.1 *Research of theories and techniques for quantitatively retrieving mesoscale heavy rainfall from satellite images*

The theories and methods for quantitatively reducing mesoscale features using satellite sensings have been receiving more and more worldwide attention, which represents an unnegligible research direction for atmospheric sounding. In Chinese Project 973, it is attempted to explore theories and techniques for retrieving mesoscale rainstorm by means of cloud-derived winds, mesoscale multi-level dynamic and thermodynamic fields, cloud classification, distribution of intracloud various-phase particles, precipitation parameters, and properties of the underlying surface as satellite sensings (Zhang et al., 2004), and we have worked out a range of satellite sensing products ranging from large- to cloud-scale, whereupon a system of such products for mesoscale heavy rainfall research is established, showing its great prospect.

3.1.1 *Research of satellite sensing retrieval of parameters indicative of atmospheric and surface features related to mesoscale heavy rainfall within Meiyu front.*

(1) A simple traced-cloud tracking scheme is

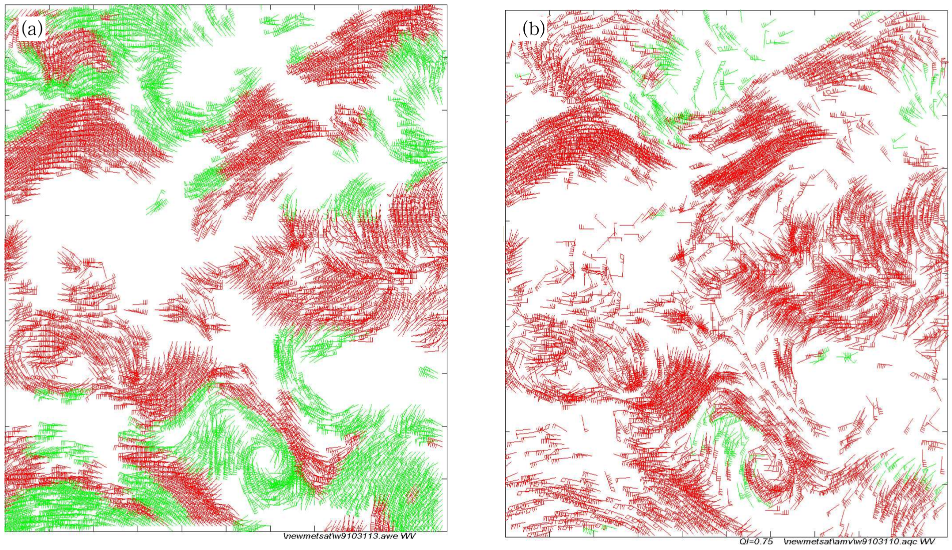


Fig.10. Comparison of moisture wind from China (a) and European Meteorological Satellite Organization (b).

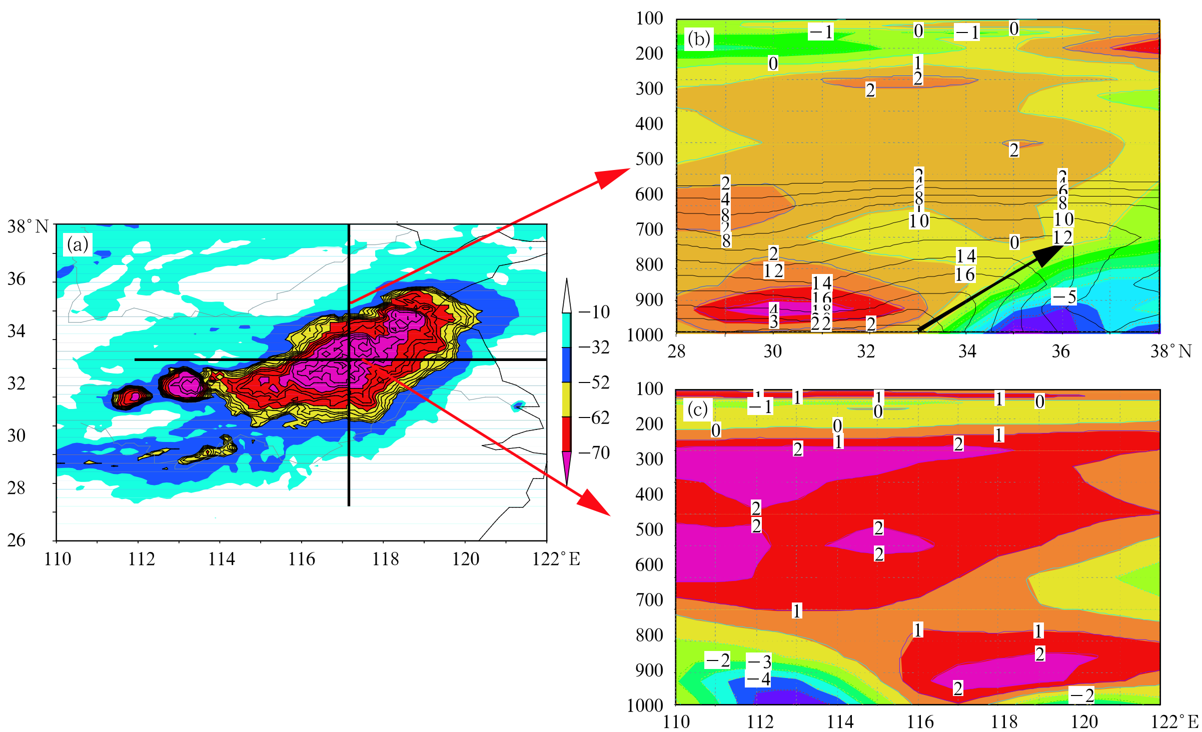


Fig.11. Three dimensional structure of temperature and moisture of cloud cluster with mesoscale retrieved by ATOVS data. (a) June 22, 2002 from TBB data; (b) cross-setion of T and q with heights along 117°E; and (c) as in Fig.11b, but for along 32°N.

developed for reducing environmental wind parameters of mesoscale heavy rainfall by means of satellite sensings, thus improving the algorithm of specified height of cloud-trail winds, imposing the control on the quality of such winds derived for rainstorm development and proposing the applications of these products in weather analysis and forecasting (Fig.10), of which the first three items have been highly assessed by experts on cloud-derived winds research in the world (Xu et al., 2002).

(2) Satellite images are utilized to quantitatively retrieve environmental temperature/humidity fields of the mesoscale heavy rainfall system. A retrieval model is established for reducing atmospheric temperature/humidity profiles within mesoscale heavy rainfall system−a nonlinear physical retrieval model, whose products are well indicative of mesoscale features to a certain degree (Fig.11), and a related system is constructed for soundness validation and error analysis for ATOVS retrievals, resulting in error of -2 K (20%) for RMS for the temperature (humidity) profiles, thereby overcoming the hitherto unsolved problem of no access to the 3D structures of atmospheric temperature/humidity under cloudy sky. And now we have means to treat all-weather satellite sensing of the atmosphere at an initial stage, allowing us to acquire mesoscale physical fields during satellite passage.

(3) Retrieval of cloud-top microphysical structure parameters permits to qualitatively differentiate cloud types and cloud phase features.

In the context of China-run satellite FY-1C/D data, the identification of cloud phase features is applied to the analysis of strong rainstorm cloud features. And on this basis investigation is made of cloud vertical structure, leading to the recognition of multi-level clouds with thin cirrus at high level and water cloud at lower levels.

Based on the analyzed microphysical properties of cloud-top particles, it is attempted to quantitatively reduce cloud optic thickness and the effective radius of these particles by use of multi-channel sensings.

(4) Research of retrieving rainfall parameters via microwave and optical sensings.

The combination of the operational-level rainfall estimation system with the system of retrieving rainfall using microwave data fills the gap in operational precipitation estimation via satellite images in China, and its algorithm is accepted by the International Precipitation Working Group (IPWG) and published on Internet <www.isac.cnr.it/-ipwg>.

(5) Research fruits of retrieving surface parameters from satellite sensings are utilized to detect surface moisture and floods on a trial basis.

Extraction of surface parameters is made from remote sensings and the time-dependent variations in regional sensible/latent heat are obtained via retrieval. Classified detection and analysis are conducted of the severe flood in Jiang-Huai Basin in 1998 and the HRB flooded area in 2003 by means of TMI low-frequency microwave sensings and AMSU images, indicating that the retrieval from the former is superior to that from the latter.

(6) A synoptic-scale conceptual model is constructed for genesis/development of Meiyu frontal MCC from the analysis of satellite images.

The conceptual model was developed from the study on satellite-sensed cloud mass on June 20-23, 2002 (Fig.12), where in the mid-higher troposphere monsoon vapor plume extends from the BOB to the MLYB; Jiang-Huai shear-line nephsystem, upper-air shortwave trough nephsystem and monsoon cloud surge interact with each other, a favorable situation of combined cloud types for genesis/development of rainstorm cloud masses.

Also, it is discovered that MCC develops in large-scale water clouds, consisting of multi-layer clouds (compact ice cloud and cirrus available), with maximum rainfall areas on the side of the ice cloud where compact ice cloud is changing to water cloud and also on the windward side of convective cloud masses at

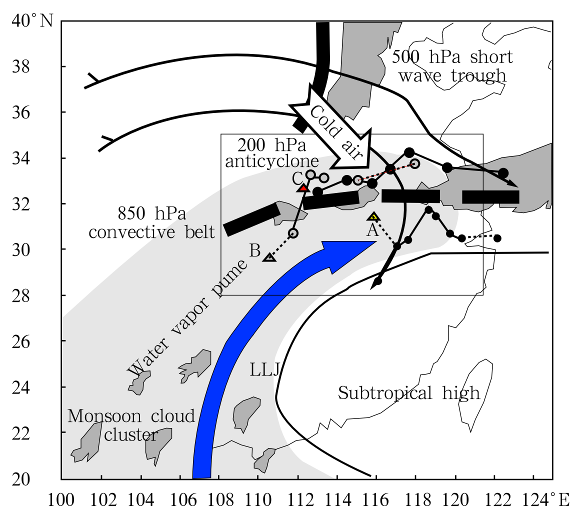


Fig.12. Conceptual model of heavy rainfall cloud cluster within Meiyu front on June 20-23, 2002 analyzed by satellite data.

upper-air levels, where located are areas of the maximum gradient of cloud-top brightness temperature.

Inside precipitable ice clouds the extents of ice water are much greater in the horizontal and vertical compared with those of rainwater. To total precipitation of MCC ice water makes its greatest contribution. Cloud water is dominantly below 10 km and cloud ice is between 8 and 18 km above surface. Areas with brightness temperature lower than -52°C are zones with extremely abundant rainwater, ice, cloud water, and cloud ice, where the total amount of precipitable ice and cloud ice is much greater than that of rainwater and cloud water.

3.2 *Research of theories and methods for retrieval of mesoscale heavy rainfall system from Doppler radar soundings*

As an important means, Doppler radar is responsible for heavy rainfall detection, warning, and especially nowcasting. With efforts we have developed techniques for Doppler-radar data preprocessing, quality control, single- and dual-Doppler radar windfield retrieval (Cheng et al., 2004), which are likely to be utilized in 126 sets of new-generation weather radar worked out in China Meteorological Administration so as to further improve the ability to detect and nowcast rainstorm.

The following highlights are given.

(1) A new approach is proposed to the quality control and analysis of radar soundings, making the control reach a new level.

An effective method is proposed for removing radar velocity uncertainty by which two sets of radar echo images close temporally are treated for pinpointing the movement of each rainfall-hit area, with which to check the possibility of uncertainty of a velocity field, if available, is removed. Also, a fast median filter is developed suitably for treating Doppler radar signals, thereby not only improving computational efficiency but keeping the signals undamaged and filtering out stochastic pulse noise effectively as well.

(2) A scheme is proposed for estimating rainfall by using TRMM data and three elements of areal mean precipitation intensity. For heterogeneous distribution of TRMM/PR measured rainfall we produced a scheme for the correction based on obtained result that the Meiyu frontal rainfall intensity distribution follows a logarithmic normal distribution as well as a scheme of utilizing a threshold method for estimating areal mean rainfall intensity by three elements (the magnitude of the threshold, precipitation category, and data resolution).

(3) We succeeded in retrieval of 3D windfields using dual-Doppler soundings, obtaining for the first time 3D real-time data of meso-α rainstorms in the 2002 field experiments (Fig.13). Besides, the approach to retrieval using single-Doppler data has been attempted.

(4) A technique is developed for analyzing 3D wind structure using wind profiler data during heavy rainfall. From the radar meteorological equation we are allowed to get the vertical structure of rainfall echo intensity in sounding space on a cross section, the content of in-cloud water and the mean Doppler velocity of raindrop descent above the radar station, with which to correct the vertical soundings from the wind profiler. As a result, we get the height-dependent variations of the 3D wind distribution inside the precipitating cloud body.

(5) We have acquired the characteristics of mesoscale Meiyu torrential rain structure on a case-study basis. Analysis was made of rainstorms at meso-α, -β, and -γ scales for their features by means of satellite sensings, Doppler radar network, dual-Doppler wind retrieval, and echo treatment in combination. From case studies we propose the mechanisms of rainstorm as follows. Lower-level wind shear serves as the principal cause of the event, and the merging of echo cells acts as an indispensable mechanics for rainstorm and is produced under the effect of a convergence line or shear line at lower levels, with the merging starting from lower to high levels.

(6) Preliminary attempt is made by use of GPS-IPW data in the detection of mesoscale torrential rainfall.

Compared with radar-received echo intensities, GPS-IPW data are able to indicate an intense rainstorm process much more ahead of time. Variations

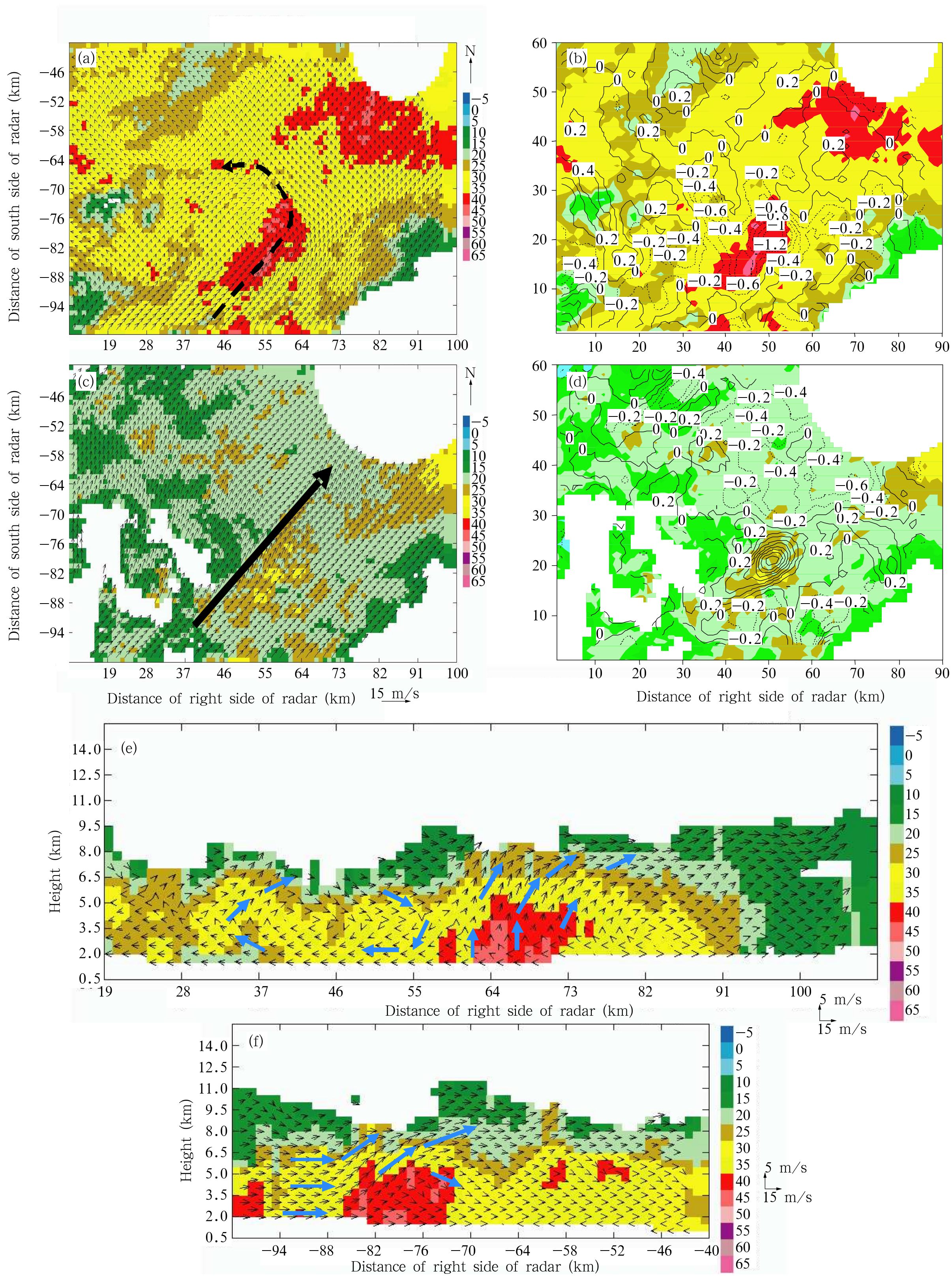


Fig.13. Three dimensional wind fields retrieved by radar data (a, b, c, and d) horizontal wind and divergence field at 4 and 7-km levels, respectively, (e, f) vertical cross-section of wind from west to east and from south to north, respectively.

in GPS-IPW data are well indicative of rainstorm to happen, via their slow increase 1-2 days before and sharp increase 4 hr just prior to rainfall. During precipitation IPW shows its higher correlation to rain intensity. Moreover, GPS-IPW data make response to rainfall a few hours ahead of radar echoes. Such data act as a good assistant for radar observations in the warning of meso-to-small-scale strongly convective weather.

4. Development of a mesoscale heavy rainfall prediction model system with a 3D variational assimilation scheme included and its successful applications to flood fighting and relief activities over the HRB in 2003

In the context of the national project we formulated a 3D variational data assimilation system that is combined with the AREM mesoscale heavy rainfall rainstorm numerical model to form a new system of models for the purposes (Yu et al., 2004; Ni et al., 2004; see Fig.14). The system has its unique features: 1) a suitable framework for rainstorm dynamics, E mesh for high-precision calculation of vorticity and divergence, and a conformal positive definite vapor advection difference scheme; 2) selection of the η-coordinate in which reasonable treatment is made of model calculations so as to get better forecasts of geopotential height and temperature in the lower troposphere; and 3) useful dynamic framework, much less artificial dissipation and smoothing for better forecasting local mesoscale systems. This model system experienced test run on an operational basis in flood prediction in 2002 and 2003 by weathermen with Hubei Anhui and Shanghai, Meteorological Bureaus and introduced to more than 10 provinces of China. The test run shows the system to have higher ability to forecast the devel opment of heavy to extremely strong rainfall systems, with prediction of hit areas and beginning time improved remarkably.

Overall assessment of the system after test run in Hubei and Anhui Meteorological Bureau is as follows: 1) It is discovered that the system is a better guide to forecast the position of a dominant rainbelt in the flooding season; 2) it has higher accuracy, persistence, and stability of the rainbelt shift meridionally; and 3) it can give indication to the hit area and time of the dominant rain band and aid in forecasting precipitation amount (mm), except for the central intensity underestimated.

Based on the numerical rainfall system, more precise forecasts were made including the start of the Meiyu season on June 22-24, 2003, sudden northward shift of the subtropical high on June 30 that led to the rainbelt moving into the Jiang-Huai Basin for

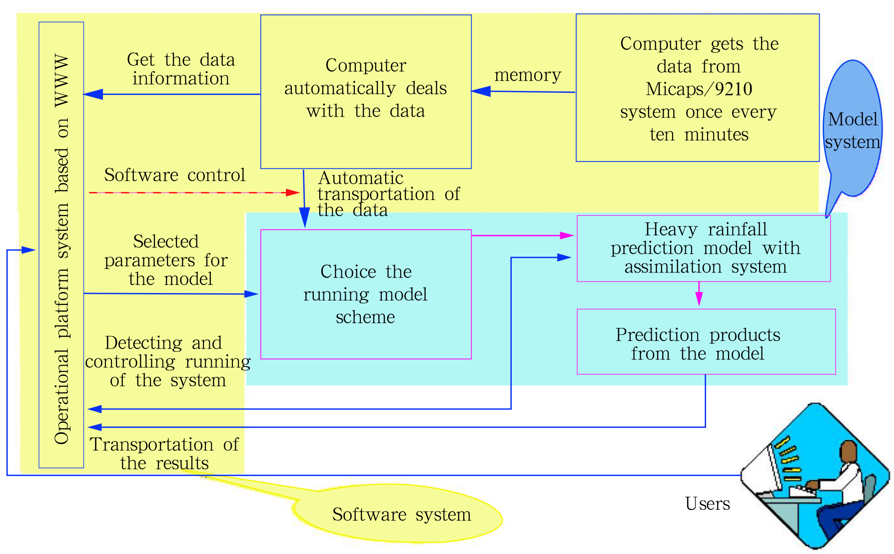


Fig.14. Operational flow chart of heavy rainfall prediction system.

precipitation there.

In particular, during 29 June to 3 July (Figs.15-17) the HRB experienced the third process of rainfall persistent for some days in 2003 after the flooding season began. The successive 5-day widespread strong precipitation made Wangjiaba water-control station discharge water for the first time as from 1991. The rainstorm-related genesis, development, position, time

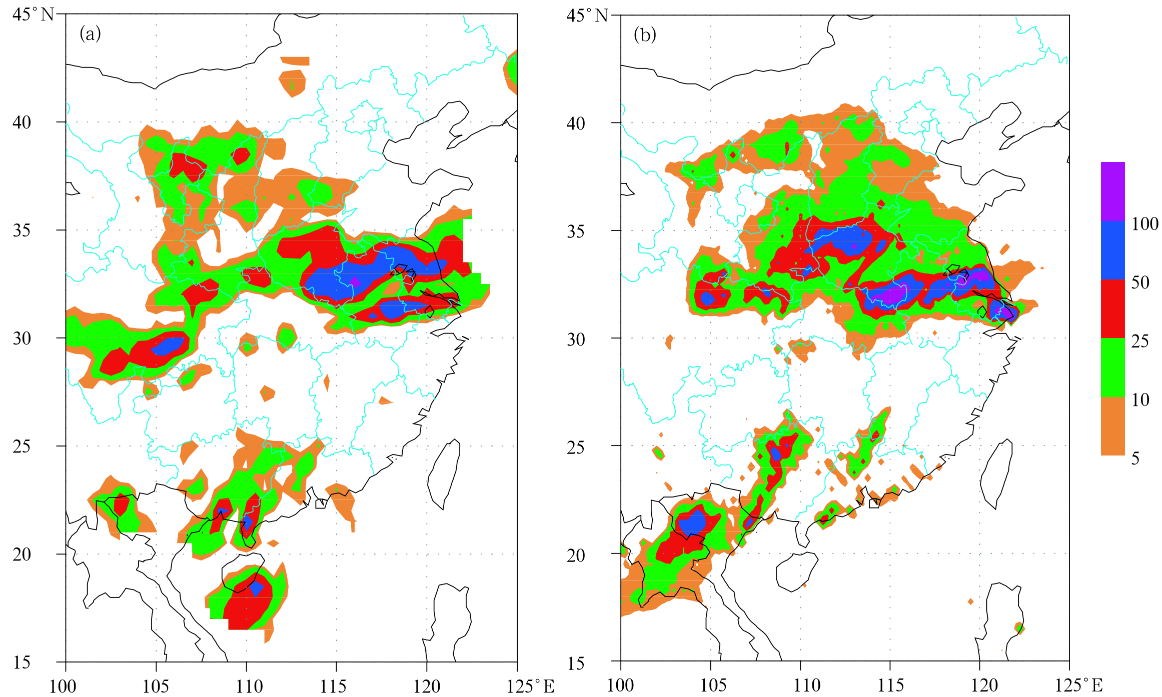


Fig.15. Precipitation distribution from 08Z 29 to 08Z 30 June 2003. (a) observed and (b) predicted.

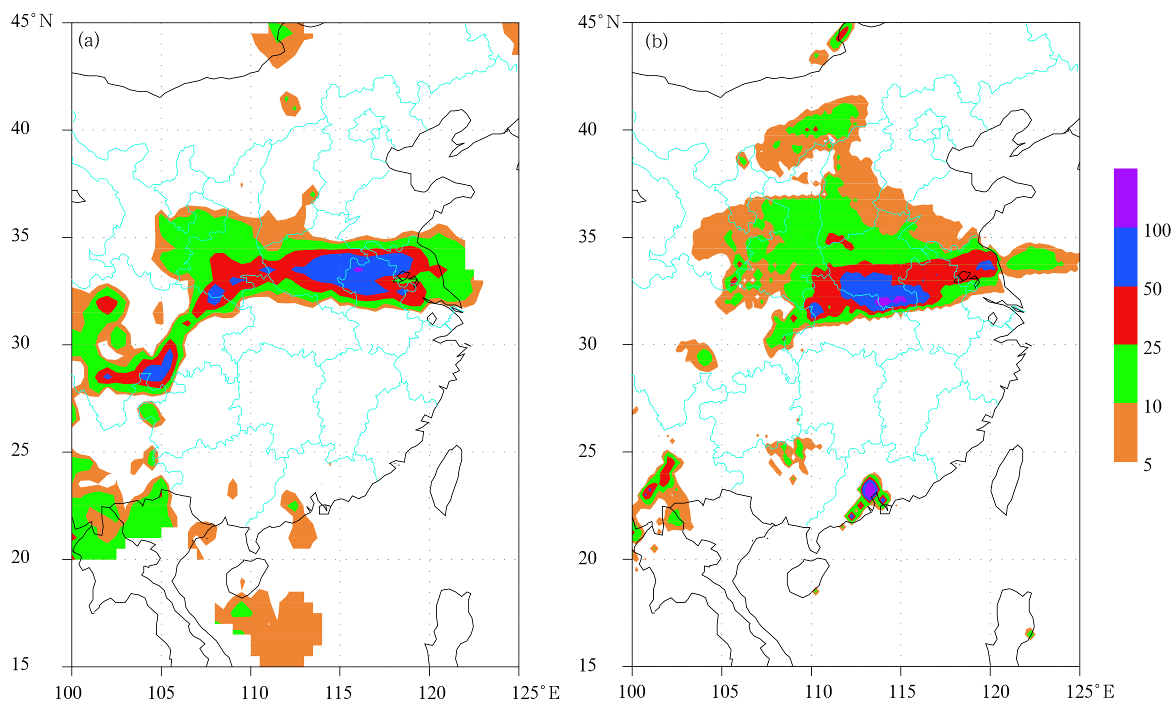


Fig.16. Precipitation distribution from 08Z 1 July to 08Z 2 July 2003. (a) Observed and (b) predicted.

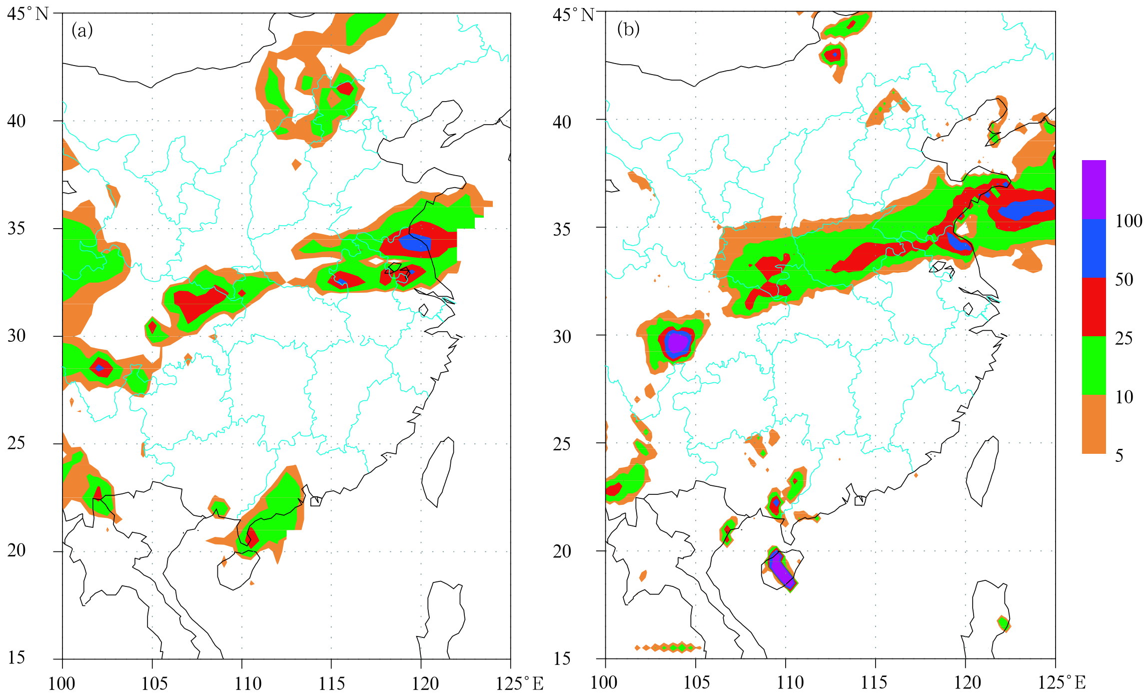


Fig.17. Precipitation distribution from 08Z 2 to 08Z 3 July 2003. (a) Observed and (b) predicted.

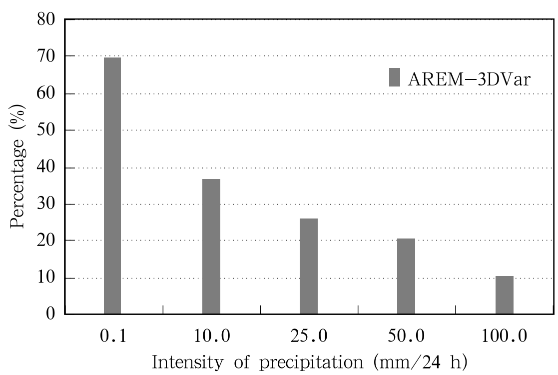


Fig.18. Monthly averaged TS score for precipitation prediction in the mid-lower Yangtze River in summer of 2003.

interval and intensity field were better predicted, offering useful forecasts to the flood fighting at a crucial time (Fig.18).

5. Conclusions and discussions

As one project of state key basic research development program, the Research of Formation Mechanisms and Predictive Theories of Major Weather Disasters in China has been carried out for 5 years, leading to encouraging progress in the research of structure, mechanisms, predictive theories, and detecting methods of heavy rainfall within Meiyu front, thus laying a sound foundation of further study of the heavy rainfall within Meiyu front as well as its detection, prediction and warning. Part of the main findings, original in character and promising application, as concerns the above three aspects is briefly introduced as follows.

(1) On the basis of analysis of multiple kinds of real-time observations from 2001/2002 field experiments, a model is proposed for multi-scale physical processes of heavy rainfall within Meiyu front, consisting of the structures of meso-α, -β and -γ intensely convective systems with their development mechanisms.

(2) A synoptic model is developed for flood-causing heavy rainfall, including in itself South China Sea monsoon surge, West Pacific subtropical high, cold air activities at extratropics, and the eastward-moving disturbance at meso-α scale from the east of the Tibetan Plateau. When they act jointly, rainstorm results in the MLYB.

(3) It is established that the frontal zone consists of coherent θ_{se} contours, a band of convective clouds composed of deeply convective turrets at its leading edge, synoptical-scale monsoon surge ahead and cold,

dry air transport at the rear of the front-all constitute the system of Meiyu front, with its structure between extratropical front and ITCZ, thus falling into a type of subtropical front system. The Meiyu front system may manifest itself as a bi-front form. The maintenance mechanism lies in the positive feedback between frontogenesis from pre-front wet physical process and intense convection development on the Meiyu front. Additionally, interactions between MCSs over the Meiyu front as a high-level vortex at the rear of the front play a crucial role in its development and maintenance.

(4) Satellite sensings are used to formulate the theories and methods for the retrieval of cloud-derived winds and multi-level mesoscale dynamic and thermal fields, cloud kinds, water phases distributed inside cloud, precipitation parameters and surface properties, achieving a wide variety of products ranging from large- to cloud-scales, thereby laying a sound foundation for further progress in theories and techniques for quantitatively estimating mesoscale rainstorm from satellite images and operational applications.

(5) A range of theories and methods are proposed for retrieving mesoscale heavy rainfall structure using Doppler radar soundings, especially dual-Doppler data in reducing the 3D wind field. The real-time data of the meso-β rainstorm 's 3D wind field were acquired for the first time in the 2002 field experiment.

(6) The mesoscale heavy rainfall prediction mode system is self-developed with a 3D variational data assimilation scheme included and it is shown that the system has higher ability of rainfall forecasting, as demonstrated in the 2003 field experiment, and made contribution to the flood combating and disaster relief over the HRB in 2003.

In spite of the progress in mesoscale rainstorm research in China with the joint efforts of Chinese scientists, because the rainstorm system is rather complicated in structure, with its occurrence in group, abrupt and explosive, our achievements cannot meet the needs of in-time detection and effective prediction of such weather disasters as expected by governments and there is a bigger gap compared with international level. For Chinese meteorologists it is a formidable task in a long time to make in-depth study on mesoscale rainstorm in China in order to improve the detection level and quantitative prediction. We believe that we can achieve the aim of in-time detection and correctly forecasting the genesis/development in 10-20 yr under the support of our government so as to make our contribution to preventing and alleviating weather calamities as well as strengthening total capability of sustainable development of society and economy.

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