Potential Vorticity Diagnostics of a Mei-Yu Front Case

GEORGE TAI-JEN CHEN
Department of Atmospheric Sciences, National Taiwan University, Taipei, Taiwan

CHUNG-CHEI WANG
Department of Environmental Management, Jin-Wen Institute of Technology, Taipei, Taiwan

STEFANO CHIH-SHIN LIU
Department of Atmospheric Sciences, National Taiwan University, and Weather Forecast Center, Central Weather Bureau, Taipei, Taiwan

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ABSTRACT

The present study selects the mei-yu frontal case of 12–13 June 1990 over southeastern China, and performs potential vorticity (PV) diagnostic analysis to discuss the mechanism responsible for the intensification and maintenance of frontal vorticity. The mei-yu front had typical characteristics at the western section, and was shallow with weak baroclinity but strong horizontal shear vorticity.

For this particular case, results of piecewise PV inversion indicate that latent heat release associated with both deep convections and stratiform clouds was responsible for the frontal vorticity, and the apparent frontogenesis near 0000 UTC 13 June was driven almost entirely by an outbreak of deep convections along the front, through the conditional instability of the second kind (CISK) mechanism proposed by Cho and Chen. The positive feedback between the mei-yu frontogenesis and cumulus latent heating, in which the front provided low-level convergence and helped organize the convection while latent heating by cumuli generated low-level PV and further enhanced the frontogenetic process, led to rapid growth in shear vorticity along the front. A low-level jet (LLJ) subsequently developed to the immediate south of the front through Coriolis acceleration of isallobaric winds. It is also found that the heating efficiency during this process depended upon the initial low-level PV value when deep convections started, and thus convections south of the front were ineffective in producing a similar response in either PV or wind field. Finally, an upper-level jet streak appeared to provide additional lifting at the outbreak of deep convection in the present case, but its role is secondary compared to the presence of the front itself in providing PV values sufficiently large in the background.

1. Introduction

During the transition period from prevailing winter northeasterlies to summer southwesterlies over east Asia, there often exists a quasi-stationary or slow-moving frontal system called the mei-yu front (or the baiu front by Japanese). The mei-yu front appears on satellite imageries as an elongated cloud band, extending approximately from southern Japan to the interior of southeastern China, and often brings a significant amount of rainfall to the region. Because of its profound impact on weather from late spring to early summer, the mei-yu front has become one of the major topics in research and operational communities.

Regarding the property and structure of mei-yu fronts, some studies suggest that they are similar to midlatitude polar fronts. For instance, Trier et al. (1990) used high-resolution data collected during the Taiwan Area Mesoscale Experiment (TAMEX; Kuo and Chen 1990) and found properties that resemble those of a density current at the leading edge of a mei-yu front. Most other case studies, however, indicate that mei-yu fronts often have horizontal temperature gradients considerably weaker than those found in polar fronts, but can possess strong cyclonic shear (e.g., Akiyama 1973a; Kato 1985). Chen and Chang (1980) pointed out that the eastern and western sections of mei-yu fronts are structurally (and dynamically) different. The eastern section (closer to Japan) is reminiscent of the well-known baroclinic wave, with stronger temperature gradient and tilted vertically toward the upper-level cold center, while the western section (over southern China) is shallow and resembles a tropical disturbance, with a barotropic warm core structure, weak temperature gradient, but strong low-
level horizontal wind shear. Frontal properties similar to those of the latter (western section) were also reported by Trier et al. (1990), when a mei-yu front initially with stronger baroclinicity moved over a warmer surface and the postfrontal air mass was transformed by heat fluxes from the surface.

In different regions, in different cases, and even at different life stages, mei-yu fronts may possess a different magnitude of baroclinicity, and their development is contributed to at a different extent by the baroclinic process. For those frontal systems that lack the configuration for baroclinic development (such as low-level horizontal temperature gradient coupling with an approaching upper-level disturbance), they can at times maintain their cyclonic vorticity and convection for a period, and produce an abundant amount of precipitation without apparent weakening. Past studies have suggested the importance of latent heat release in the maintenance of some mei-yu front cases (e.g., S. Chen et al. 1998), but how exactly the process operate is not well known.

To explain the frontogenesis at the western section, a hypothesis is proposed by Cho and Chen (1995) that the mei-yu front there is maintained through interactions between low-level potential vorticity (PV) anomaly and cumulus convection. In the feedback mechanism similar to the conditional instability of the second kind (CISK), the front helps organize the convection while latent heat release by cumuli enhances low-level PV and the frontogenetic process, leading to rapid growth in shear vorticity along the front. Using a simplified two-dimensional (2D) semigeostrophic model, they also demonstrated the effectiveness of this mechanism, under the idealized conditions that there exists no limit to the latent heat release. Although Cho and Chen (1995) have presented a convincing argument, the existence of the proposed process, and whether it is efficient enough in the real atmosphere, need to be further verified using case studies.

Regarding the low-level jet (LLJ) that often accompanies mei-yu fronts, statistical studies have shown that it is strongly correlated with heavy rainfall (e.g., Akiyama 1973b; Chen and Yu 1988). Many earlier research studies considered LLJs to be the result of downward transport of westerly momentum through vertical mixing induced by cumulus convection (e.g., Matsumoto 1973; Ninomiya and Akiyama 1974). The 2D modeling study by Chou et al. (1990) suggests the importance of cumulus convection and latent heating on LLJ formation. While confirming the vital role of latent heat release on the appearance of both the LLJ and some mei-yu frontal characteristics in a TAMEX case, Hsu and Sun (1994), however, conclude that sufficient heating can be achieved by a large area of stratiform clouds in some cases and that deep convective cumulus clouds are not always necessary. Thus, the roles played by deep convective clouds and stratiform clouds remain to be clarified.

The purpose of the present study, therefore, is to analyze and diagnose a mei-yu front case that is characterized by weak baroclinity but strong horizontal wind shear, and identify the origin of the frontal vorticity. The nonlinear balanced piecewise PV inversion technique (PVIT) developed by Davis and Emanuel (1991) and Davis (1992a,b) has been chosen as our primary tool of diagnosis, mainly because it allows partitioning among different processes, thereby isolation of their individual contributions. The dynamical constraint of “nonlinear balance” during the inversion also has advantages over other relationships such as quasigeostrophy (QG), since it has a higher accuracy (as a closer approximation to the real atmosphere) as well as the fully conserved property of Ertel’s PV (q; Ertel 1942), defined as

$$q = \frac{1}{\rho} \mathbf{\eta} \cdot \nabla \theta,$$

where $\rho$ is air density, $\mathbf{\eta}$ is the three-dimensional absolute vorticity vector, and $\theta$ is potential temperature, compared to the pseudo-PV (PPV) used in QG inversion (Davis 1992a).

Due to the conserved property and invertibility of PV (Hoskins et al. 1985), the PV concept and inversion techniques have been widely applied by researchers in recent years. Examples include studies on extratropical cyclogenesis through upper-level forcing (e.g., Hakim et al. 1996; Thorncroft and Flocas 1997) or vertical coupling of PV anomalies (e.g., Bresky and Colucci 1996), and on the role of latent heat release (e.g., Davis 1992b) or other adiabatic processes and friction (e.g., Stoevinga 1996) in cyclogenesis, as well as diagnoses on other systems such as monsoon disturbance (Chang et al. 1998) and hurricane movement (e.g., Wu and Emanuel 1995; Shapiro 1996). The technique has also been used for numerical model evaluation (Bresky and Colucci 1996), and for improvement of model initial conditions (Huo et al. 1998).

For surface frontogenesis at midlatitudes, Montgomery and Farrell (1990, 1991) examined the process from a PV perspective using a semigeostrophic model, and found that the baroclinic development of the front becomes very complex and sensitive to initial distribution of PV anomalies when moist processes are involved. In a case study, Morgan (1999) also suggests that the contribution from latent heating to frontogenesis was variable, and locations of diabatically generated PV anomalies relative to the front could have a significant impact. Thus, it appears that the presence of strong baroclinicity is helpful in enhancing vertical motion, latent heating, and cyclonic vorticity generation along the front, but the detailed process is not as easily clarified as in the case of cyclogenesis. On the other hand, since our interest here is in mei-yu fronts characterized by weak baroclinicity (and thus lacking significant upper-level PV anomalies), the method of piecewise PVIT should pro-
provide a clearer picture and allow for a more straightforward diagnosis. As will be shown in later sections, through a case study, the role of latent heat release from cumulus convection on mei-yu frontogenesis and LLJ development is examined and discussed from a PV perspective. The case also provides supporting evidence for the CISK mechanism proposed by Cho and Chen (1995) to exist and operate effectively in the real atmosphere.

Section 2 of the paper describes data and the methodology used, including a brief description of the nonlinear balanced piecewise PVIT and the PV prognostic system. Section 3 discusses the case selection, the synoptic condition, the PV partitioning, and the results from piecewise PV diagnostics. Section 4 further examines the CISK mechanism for frontogenesis in our case, the roles played by an upper-level jet streak, as well as the mechanism for the development of an observed LLJ. A further discussion is given in section 5, and major findings are summarized in section 6.

2. Data and methodology

a. Data

In our study, 6-hourly surface and 12-hourly upper-level weather maps from the Central Weather Bureau (CWB) of the Republic of China (ROC) were used to analyze synoptic systems, determine mei-yu frontal positions, and verify objective analyses. Visible (VIS) and infrared (IR) imageries from the Japanese Geostationary Meteorological Satellite (GMS) satellite (every 3 h) were also used to identify and differentiate deep convective cumuli, low clouds, and upper-level cirrus. Six-hourly (at 0000, 0600, 1200, and 1800 UTC) gridded operational analyses from the European Centre for Medium-Range Weather Forecasts [ECMWF; Tropical Ocean Global Atmosphere (TOGA) advanced] were adopted as our primary data source for calculation and diagnosis. The dataset has a horizontal resolution of 1.125° lat x 1.125° lon, and provides geopotential height, temperature, \( u \) and \( v \) components of horizontal wind, relative humidity at eight pressure levels (1000, 850, 700, 500, 400, 300, 200, and 100 hPa).

b. Piecewise PV inversion techniques

The technique of nonlinear balanced PV inversion is described briefly here, following Davis and Emanuel (1991) and Davis (1992a,b). Equation (1), plus the nonlinear balanced equation (Charney 1962), form the basic equation set for PVIT. With the assumption that irrotational winds are much smaller than nondivergent winds, all terms involving the divergent wind and vertical velocity are omitted, and the system can be transformed to spherical coordinates \((\lambda, \phi)\) as

\[
\nabla^2 \Phi = \nabla \cdot f \nabla \Psi + \frac{2}{a^4 \cos^2 \phi} \left[ \frac{\partial^2 \Psi}{\partial \lambda^2} \frac{\partial^2 \Psi}{\partial \phi^2} - \left( \frac{\partial^2 \Psi}{\partial \lambda \partial \phi} \right)^2 \right],
\]

and

\[
q = \frac{g \kappa \pi}{p} \left( f + \nabla^2 \Psi \right) \frac{\partial^2 \Phi}{\partial \pi^2} - \frac{1}{a^4 \cos^2 \phi} \frac{\partial^2 \Psi}{\partial \pi \partial \phi} \frac{\partial^2 \Phi}{\partial \pi \partial \phi} - \frac{1}{a^4 \pi \partial \phi} \frac{\partial^2 \Psi}{\partial \pi \partial \phi},
\]

where \( \Phi, f, \Psi, a, g, \) and \( p \) are, respectively, geopotential, Coriolis parameter, streamfunction for the nondivergent wind, earth’s radius, gravitational acceleration, and pressure; \( \kappa = R/C_p \), and \( \pi = C_p(p/p_0) \) is the Exner function \((p_0 = 10^5 \text{ Pa})\). Given a known distribution of \( q \) and specified boundary conditions (to be described shortly), the two variables \((\Phi \text{ and } \Psi)\) in the system can be solved to give height and wind fields that satisfy the nonlinear balanced relationship.

Following Davis (1992b), to achieve piecewise inversion, a mean PV distribution is first defined (discussed in section 3c) to obtain a balanced mean field using Eqs. (2) and (3). The equations for the perturbation PV \((q')\), obtained by subtracting the mean equations from the total are nonlinear, but can be linearized by introduction of pseudo (tilde) variables for \( q, \Phi, \text{ and } \Psi \) that equal the mean plus half the perturbation, that is, \((\cdot) = (\cdot) + 1/2(\cdot)'\). With all terms retained, the resulting equations [Eqs. (3.3) and (3.4) of Davis (1992b)] are linear and the perturbation PV fields can be divided into any number of parts, and their individual solutions can be added to obtain the total perturbation flow (i.e., \(\Sigma \Phi_n = \Phi', \Sigma \Psi_n = \Psi'\), and \(\Sigma q_n = q'\), where \( n \) denotes the nth part of perturbation). Here, the same boundary conditions as Davis (1992b) are adopted, that is, Dirichlet on lateral boundaries (observed \( \Phi \) and \( \Psi \) for total field, and \( \Phi_n = \Psi_n = 0 \) for perturbations) and Neumann on upper and lower boundaries \((\partial \Phi/\partial n = f_n(\partial \Psi/\partial n) = -\theta \text{ for total, and } \partial \Phi/\partial n = f_n(\partial \Psi/\partial n) = -\theta' \text{ for perturbation fields, respectively})\). Of course, the method described represents just one of the possibilities to achieve piecewise PV inversion. Davis (1992a) compared it with other alternatives, and found that different methods generally do not yield widely different results.

c. Nonlinear balanced prognostic system

The nonlinear balanced prognostic system allows for diagnoses of local tendencies of \( q, \Phi, \text{ and } \Psi \), as well as vertical velocity \((\omega' = d\pi/dt)\) and divergence \((\nabla^2 \chi)\), where \( \chi \) is velocity potential corresponding to a given nonlinear balanced distribution of \( q \). The system consists of five equations, and is described only very briefly here. The first two equations are obtained by taking local time derivatives of Eqs. (2) and (3). The third equation is the Ertel’s PV tendency equation, written as
The mei-yu front appears as a trough running somewhat smoother, another unavoidable outcome of and considered acceptable. The inverted fields are also preserved after PVIT, such differences are both expected due to the imposed nonlinear balanced constraint (Figs. 1a–d). Because only the rotational part of the flow is preserved after PVIT, such differences are both expected and considered acceptable. The inverted fields are also somewhat smoother, another unavoidable outcome of PVIT. The mei-yu front appears as a trough running east–west near 29.5°N in the height field, with corresponding relative vorticity maxima clearly visible. The characteristic feature of strong low-level horizontal wind shear of mei-yu fronts allows them to be identified as zones of maximum cyclonic vorticity (Kuo and Anthes 1982) or maximum PV (Cho and Chen 1995), which by definition is conserved before and after the inversion. On levels other than 850 hPa, the PV-inverted fields also bear close resemblance to ECMWF analyses everywhere (not shown).

Figure 2 presents the vertical velocity on an east–west cross section along 29.25°N (roughly along the mei-yu front) at 0000 UTC 13 June as computed by the balanced PV prognostic system. Upward motion was maximized at two locations along this latitudinal belt, one at about 116°–118°E and the other near 120.5°E, closely matching the positions of deep convective cloud clusters along the front on satellite IR imageries (Fig. 3b). The distribution of 6-h accumulated rainfall of 0000–0600 UTC 13 June also exhibits maximum rainfall along the front, with two distinct centers (both >50 mm) near 29°N, 115°E and 28°N, 119°E, and little rain in other regions (Fig. 4), similarly in good agreement with the clouds and balanced vertical motion, considering the resolution of both synoptic stations and the ECMWF dataset. Accumulated rain during the previous 6 h (from 1800 UTC 12 June to 0000 UTC 13 June) was also maximized along the front, with a smaller peak value at 25 mm near 29°N, 115°E, indicating that the convective rain had started by 0000 UTC 13 June (not shown).

The agreement among Figs. 2 through 4 also suggests that the prognostic system can handle the front at its peak intensity in a satisfactory fashion. Therefore, both theoretical consideration of the value of Ro, and the close resemblance between observations and the nonlinear balanced fields computed, all lead us to conclude that the flow was very close to nonlinear balanced in our mei-yu front case. Hence, the full calculation using nonlinear balanced piecewise PVIT is carried out, and further results are presented in the following sections, including those obtained through the PV prognostic system for the time at 0000 UTC 13 June.

3. Diagnosis of a mei-yu front

a. Case selection and definition of frontogenesis

Since one of our primary objectives is to test the hypothesis offered by Cho and Chen (1995) for mei-yu frontogenesis, in which the baroclinity is not a major factor, it is necessary to select a frontal system with a weak baroclinity. As mentioned in section 1, the complex interactions between baroclinic and moist processes (e.g., Montgomery and Farrell 1991; Morgan 1999), however intriguing in their own right, should be avoided here to keep our analysis and interpretation relatively straightforward. It is hoped that after the role of latent heat release in mei-yu frontogenesis at the western sec-
Fig. 1. The 850-hPa (a) geopotential height (m) and (b) relative vorticity ($10^{-5}$ s$^{-1}$) obtained from the ECMWF analysis for 0000 UTC 13 Jun 1990. (c),(d) As in (a),(b) but are obtained from PV inversion and satisfy the nonlinear balanced assumption. Contour intervals are (a),(c) 6 m and (b),(d) $1 \times 10^{-5}$ s$^{-1}$. Thick dashed line indicates location of 850-hPa mei-yu front from synoptic analysis.

As the mechanism for frontogenesis was almost unrelated to baroclinity in our mei-yu front case, traditional definitions of front and frontogenesis in terms of horizontal temperature gradient become inappropriate. Likewise, the surface low-pressure trough associated with mei-yu fronts is usually much weaker than that observed in polar fronts, and cannot serve as a good indicator for frontal intensity (cf. Figs. 1a and 1c). Kuo and Anthes (1982) have suggested using relative vorticity maxima at low levels because the cyclonic shear is closely related to cloud band and precipitation, while Cho and Chen (1995) also suggest that a mature mei-yu front can be identified at low levels by a zone of maximum positive PV anomaly. In the present study, we adopt the view of Kuo and Anthes (1982) and define
frontogenesis as an increase in relative vorticity at 850 hPa, such that topographic influence and effects of surface friction can be kept at a minimum level.

b. Synoptic description

The 850-hPa east Asian synoptic weather map indicates that over southern China there existed an east-west-oriented wind shift line near 29°N at 1200 UTC 12 June 1990, with southwest winds to the south and mostly southeast winds to the north (Fig. 5a). This wind shift line possessed cyclonic vorticity and marked the position of the mei-yu front at its western section. Immediately to its north, temperatures (thin dashed lines) were generally lower, but the contrast with higher temperatures to the south was small, as expected (since we deliberately chose such a case). Note also that farther north and northwest of the wind shift line, temperature rose again and little cold air existed to give indication of baroclinic development. Likewise, the postfrontal height gradient (solid lines) at 850 hPa and surface pressure gradient (not shown) were weak. Twelve hours later at 0000 UTC 13 June (Fig. 5b), the wind shift line remained at nearly the same position, but the cyclonic vorticity increased significantly with the appearance of a clear west-southwesterly LLJ (at 12–15 m s⁻¹) to its immediate south. Since the height gradients over the region were nearly unchanged during the 12-h period (cf., Fig. 1a), the presence of the LLJ and the subsequent enhancement of cyclonic vorticity along the mei-yu front were obviously not related to a synoptic development, but rather, to a local one (Figs. 5a,b). It is interesting to note that the diurnal temperature variation was particularly large well behind the front near 34°N,
109\degree E, likely caused by elevated terrain in the region under clear sky conditions overnight (0000 UTC corresponds to 0800 LST; cf. Fig. 3). The wind shift line at 700 hPa from 110\degree to 120\degree E was also running east-west along 29\degree N (not shown), at the same position as 850 hPa, indicating that the front was nearly vertical in the lower troposphere.

The weather map at 500 hPa indicates that the flow was generally zonal over southern China at 1200 UTC 12 June and remained so at 0000 UTC 13 June (Figs. 5c,d). This suggests a limited role played by the baroclinic process in maintaining the mei-yu front. At this time, another synoptic-scale trough was located at northern China, too far north to affect the mei-yu front. At 300 hPa the flow was also mostly zonal (Figs. 5e,f). It is interesting to note that at 0000 UTC 13 June an upper-level jet (ULJ) streak was located near 30\degree N, 118.5\degree E, to the immediate north of the mei-yu front, such that the region of deep convection was located at its rear-right quadrant (Fig. 5f). How much the upper-level di-

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**Fig. 5.** Synoptic weather maps at 850 hPa for (a) 1200 UTC 12 Jun and (b) 0000 UTC 13 Jun 1990. Solid and dashed lines are height contours (m) and isotherms (\textdegree C) analyzed at intervals of 10 m and 1\degree C, respectively. Thick dashed lines are isotachs analyzed at 5-kt (or 2.5 m s\(^{-1}\)) intervals and starting from 20 kt (or 10 m s\(^{-1}\)). Both mei-yu frontal position and jet axis are indicated. (c),(d) and (e),(f) As in (a),(b) but at 500 and 300 hPa, respectively. (c),(d), (e),(f) Intervals of height contours are 60 m, while those of isotherms are (c),(d) 3\degree and (e),(f) 5\degree C. (c),(f) Isotachs in are analyzed at 10-kt (or 5 m s\(^{-1}\)) intervals, starting from 60 kt (or 30 m s\(^{-1}\)).
convergence and rising motion induced by the transverse circulation associated with the jet streak contributed to the enhancement of convection along the mei-yu front at this time is a question that needs to be addressed in our study. We will do that in section 4b.

c. Mean field and PV partitioning

When using the piecewise PV inversion as a diagnostic tool, researchers often choose the life span average of a case as the mean field, especially those who study extratropical cyclogenesis (e.g., Davis and Emanuel 1991; Davis 1992a; Bresky and Colucci 1996). However, unlike migratory cyclones, our mei-yu front case was quasi-stationary, and most of the PV anomaly associated with the front itself would become the mean instead of perturbations had the life span average been used. This would cause difficulties in result interpretation. It appears that a mean for a period substantially longer than the case’s life span would be a better choice in our case. Chen (1994) used averages of successive 15-day periods to reveal transition of large-scale circulations through the mei-yu season. Thus, we adopted the average of 1–15 June 1990 as the mean field, for the length being both long enough to avoid the problem described earlier, and at the same time short enough to only include large-scale features during the season of the case. This mean field corresponded to a smoothed distribution of PV over southern China (not shown), and therefore reduced the possibility that ambiguities in interpretation might be introduced by artificial enhancement or weakening of PV perturbations simply because they appeared at different locations.

The partitioning of PV perturbations into those from different physical processes in the present study largely followed that of Davis and Emanuel (1991) and Davis (1992b), but was modified slightly to fit the profile of our case, as shown schematically in Fig. 6. The potential temperature perturbation ($\theta'$) at 925 hPa (interpolated from values at 1000 and 850 hPa) was defined as the component at the lower boundary (denoted by $lb$). The upper-level ($ul$) component included PV perturbations ($q'$) and $\theta'$ from 400 to 150 hPa. In the lower to middle troposphere between 850 and 500 hPa, $q'$ was further partitioned into perturbations related to latent heat release (saturated; denoted by $ms$) and those not related (unsaturated, $mu$). Through sensitivity tests, past modeling studies have suggested the vital role played by...
latent heating in maintaining cyclonic vorticity along the mei-yu front (e.g., Kuo and Anthes 1982; C. Chen et al. 1998; S. Chen et al. 1998). Here, we have assumed that latent heating was the only primary source for midlevel positive PV perturbations. This should be a reasonable assumption, at least in a qualitative sense, since the possibility for baroclinic frontogenesis has been ruled out and no other mechanism for frontal vorticity growth (such as large-scale convergence) was present in our case. In addition, precipitation occurred at nearly every surface station where midlevel $q'$ was positive. Nonetheless, a threshold that the relative humidity must be at least 70% was enforced (in addition to $q' > 0$) for the perturbation at a grid point to be considered as latent heating–related. The 70% threshold, also chosen by David (1992b), was low enough to include PV that might be advected out from precipitation area but high enough to exclude PV of upper-level origin, and in our case had reasonably good correspondence with the frontal zone and cloudy areas (not shown). All midlevel grid points that did not satisfy these two criteria simultaneously were placed in the mu group. We also further partitioned the ms perturbations into two parts, one from deep convections (denoted as msd) and the other from shallower stratiform clouds (mss). This procedure was subjectively done based on cloud signatures at each grid point, through the combined use of VIS and IR imageries. Only cloud areas that are bright on both channels were classified as deep convections, including, for example, in Fig. 3b (0000 UTC 13 June), the five bright regions inside $15^\circ$–$30^\circ$N, $110^\circ$–$121^\circ$E, as well as the one centered near $26.5^\circ$N, $108^\circ$E. The remaining part of the ms that is not classified as msd is automatically grouped into mss.

The total PV at 850 hPa from 1200 UTC 12 June to 0000 UTC 13 June 1990 is presented in Fig. 7 (1 PVU $= 10^{-6}$ K m$^2$ kg$^{-1}$ s$^{-1}$). The mei-yu front was accompanied by a clear PV maximum as suggested by Cho and Chen (1995), and remained stationary near $29.5^\circ$N to the west of about $117^\circ$E. Figure 8 presents the entire domain for performing the piecewise PV inversion, which consisted of $31 \times 26 = 806$ grid points ($99^\circ$–
132.75°E, 15.75°N–43.875°N). The smaller domain covering southeastern China depicts the display area used in Figs. 1 and 7. Finally, the narrow region from 109.125° to 117°E, 29.25° to 30.375°N (8 × 2 = 16 grid points) was considered the frontal position, and the mean relative vorticity within this region was used to define the intensity of the mei-yu front as described previously in section 3a. Both the display area and the region used to compute frontal intensity were at least several grid points away from lateral boundaries, and therefore the calculation should be free from the influence of boundaries.

d. Piecewise PV diagnostics

Through piecewise PV inversion, total winds satisfying nonlinear balanced relationship were partitioned into portions induced by individual PV (or θ) perturbations (Fig. 6). The contribution of each process toward the mean 850-hPa relative vorticity along the mei-yu front (narrow region in Fig. 8) can then be compared and discussed. Before we start this discussion, a comparison between the inverted mean frontal relative vorticity and that computed from ECMWF winds (before inversion) at 850 hPa seems appropriate and perhaps necessary (Fig. 9a). The two time series are quite close during the course of our case. Both curves show significant intensification of the front at 0000 UTC 13 June and the inverted ζ value exceeded 5 × 10⁻⁵ s⁻¹ shortly after deep convections broke out near 29°N (Figs. 3 and 9a). As indicated by satellite imageries, strong convections at 1800 UTC 12 June were still located south of the front (south of 27.5°N, not shown). Partitioning results among individual processes (Fig. 9b) indicate that the contribution from PV perturbations related to midlevel latent heat release (ms) was nearly identical to the total contribution. Therefore, latent heating was the major contributing process and explained almost all the frontal intensity in our case, while the remaining processes had a combined contribution of nearly zero. Over the 18-h period, both upper-level (ul) and lower boundary (lb) perturbations had weak negative contribution toward frontal vorticity, and their effects were roughly cancelled by the positive contribution from midlevel perturbations not related to latent heating (mu).

Further examination revealed that the positive contribution of mu came from the basic configuration of PV near the frontal zone, that is, maximum along the front with lower values farther away at both sides. This pattern corresponds to lower pressure (trough) along the front and higher pressure at both sides, and hence contributes to cyclonic vorticity and frontal intensity. In other words, positive mu contribution arose from the presence of the mei-yu front itself. Not surprisingly, mu had effects secondary to ms most of the time, and had nearly no contribution to the apparent frontogenesis at 0000 UTC 13 June (Fig. 9b). As pointed out by Bretherton (1966), a positive θ anomaly at the lower boundary
has effects equivalent to a positive PV anomaly and vice versa. The temperature pattern at 850 hPa, with colder air near the front and warmer air both to the south and north (Figs. 5a,b), corresponded to a negative PV anomaly, causing negative contribution from lb (Fig. 9b). It is worth mentioning that such a temperature distribution (colder air along the front), through hydrostatic balance, would reflect at layers just above the lower boundary as a trough, thereby offsetting the effect of $\theta'$. As this reflection (above 925 hPa) has been partitioned into mu by us, in Fig. 9b the two curves of lb and mu do appear to be out of phase and tend to cancel one another. As discussed by Holopainen and Kaurola (1991) and Davis (1992a), the cancellation between $\theta'$ on the lower boundary and $q'$ above is almost exact within a thin layer, and in some situations can lead to ambiguities in interpretation when the two components are treated separately. Since both mu and lb were of minor importance compared to ms in our case, further elaborate treatment of this problem, using methods discussed by Davis (1992a), did not seem necessary here.

The major contributor to 850-hPa frontal vorticity, ms, was further partitioned into perturbations associated with deep convections (msd) and those associated with shallower stratiform clouds (ms, Fig. 9c). During the 18-h period analyzed, these two types of PV perturbations appeared to have their own contribution. Latent heat release from stratiform clouds contributed about $2 \times 10^{-5} \text{s}^{-1}$ toward the total frontal vorticity steadily, and therefore helped maintain the front. In this particular case, however, the significant intensification of the mei-yu front at 0000 UTC 13 June (to almost $5 \times 10^{-5} \text{s}^{-1}$ in $\zeta$) was mainly attributed to the heating associated with deep convections (Figs. 3b and 9c).

4. Mechanism of mei-yu frontogenesis

a. Mei-yu frontogenesis by CISK

In the previous section, it was shown that the mei-yu front intensification coincided with the outbreak of deep convections along the front, and the PV perturbation induced by the associated latent heat release at midlevels (i.e., msd) almost fully explained the frontal development at 0000 UTC 13 June in our case. In this section, we further examine whether this frontogenetic process was a result of the CISK mechanism proposed by Cho and Chen (1995) using the PV prognostic system. The argument can be explained in terms of Eq. (4), whose four terms on the right-hand side represent, respectively, the horizontal and vertical advection of $q$, the effect of diabatic heating/cooling, and friction. If we consider only the effect of condensational heating based on a standard profile for cumuli (maximum heating at midlevels), it can be seen from Eq. (4) that PV would be generated below the level of maximum heating and destroyed above it. In addition, the rate of PV growth (or decay) is directly proportional to both the vertical gradient of heating/cooling rate and the absolute vorticity. As discussed by Cho and Chen (1995), the western section of mei-yu fronts is usually shallow and exhibits an equivalent barotropic structure, which implies that pressure and isentropic surfaces are nearly parallel and hence the vertical component of $\eta$ is rather close to PV, the isentropic absolute vorticity. Thus, the rate of PV generation is proportional to the magnitude of PV itself (in a barotropic atmosphere), and its initial value determines the subsequent effect caused by the same cumulus convection. Owing to this highly nonlinear feedback mechanism, a frontal discontinuity was reached within a finite time in the 2D semigeostrophic model of Cho and Chen (1995), under the ideal condition that there was no limit to the latent heat release from the cumulus convection.

At 1800 UTC 12 June, the region near 29.25°N, 117°E was covered mostly by lower clouds with scattered convection (not shown), but within the next 6 h deep convections broke out and developed into large clusters (Fig. 3b). Coincident with this outbreak of deep convections, the mei-yu front at 850 hPa intensified rapidly, with an increase in $\zeta$ from $4.9 \times 10^{-5} \text{s}^{-1}$ at 1800 UTC 12 June to $8.0 \times 10^{-5} \text{s}^{-1}$ at 0000 UTC 13 June and a simultaneous increase in maximum PV from 0.53 to 0.86 PVU (Fig. 7b). The cross section of vertical velocity computed by the PV prognostic system (Fig. 2) illustrates that at 0000 UTC 13 June the location of strongest upward motion (near 117°E) matched well with deep cloud clusters (Fig. 3b). In addition, the ascent was evident even in the lower troposphere where moisture was abundant, so latent heat release at middle levels must have been strong. From cross sections of instantaneous PV and height tendencies computed by the PV prognostic system (Fig. 10), one can see that PV was being generated at lower levels and destroyed at upper levels over the region of deep convection, and this was accompanied by a height fall at lower levels and a height rise aloft. As discussed by Hoskins et al. (1985), the growth in PV values implies local height fall and increase in cyclonic vorticity at lower levels. In the current case, it is demonstrated that active cumulus convection can drastically enhance the low-level positive PV anomaly, and leads to formation of a pressure trough and strong horizontal wind shear, both of which are common characteristics of mei-yu fronts. The case also provides supporting evidence that the CISK mechanism proposed by Cho and Chen (1995) does occur in the real atmosphere and can be responsible for mei-yu frontogenesis, especially at the western section. In Fig. 10, PV is being destroyed above the level of maximum heating (located near 550 hPa), which partially explains the lack of a strong PV anomaly aloft and the shallowness of the frontal structure. From thermal wind relationship, Chen and Chang (1980) have also pointed out that latent heating at midlevels in this type of mei-yu frontogenesis would cause the pressure trough to diminish with height.

To investigate the effect of initial PV value to front-
ogenesis, we reduced the perturbations relevant to mid-
level latent heating (ms in Fig. 6) by half, and performed
the piecewise inversion and computed the balanced flow
field again. By doing this, the low-level absolute vor-
ticity was considerably reduced because the 850-hPa PV
as well as the downward penetration of PV-induced cir-
culation from levels above 850 hPa were both decreased.
The results are presented in Fig. 11. The distribution of
balanced vertical velocity on the cross section along
29.25°N (Fig. 11a) is very similar to that obtained with
midlevel perturbations fully retained (cf. Fig. 2), so the
heating rate from condensation should be almost iden-
tical. The efficiency of this heating in PV generation at
low levels near 116.5°E, however, is now significantly
reduced, while the rate of PV destruction aloft is also
lowered (Fig. 11b). Indeed, the efficiency of low-level
PV generation by the same heating does depend upon
the initial value of absolute vorticity, consistent with
what would be expected from the CISK argument as
proposed by Cho and Chen (1995). A similar depen-
dency between cyclone growth and absolute vorticity is
also observed near the center of rapid-deepening extra-
tropical cyclones (e.g., Gyakum et al. 1992).

The effect of the presence of the front on deep con-
vections was also examined by removing all positive
PV perturbations at midlevels (including ms and the
portion of mu where \( q > 0 \)). This removed primarily
the front itself and perturbations associated with the
clouds, including both cumulus and stratiform type.
Once the frontal system itself is removed, the balanced
vertical velocity is very weak everywhere (Fig. 12).
Similar to results of C. Chen et al. (1998) and S. Chen
et al. (1998), this suggests a close, interdependent rela-
tionship between cumulus convections and the mei-
yu front, in which the front provides low-level conver-
gence and helps organize the convections, while cu-
Cumulus convections give rise to frontogenesis and maintain the front through the CISK-like mechanism. Here, the quasi-stationary mei-yu front does not provide much additional lifting because of its weak cross-frontal temperature gradient, rather, it provides a higher PV background value that makes cumulus heating more efficient.

Because of the strong feedback between CISK and frontal PV anomaly, under the ideal condition (that latent heating could be infinitely supplied by cumulus convection) used by Cho and Chen (1995), a reduction in initial low-level PV can only delay the development of the frontal discontinuity in their simulation. In the real atmosphere, however, the length of effective heating of a cumulus is limited by its own life cycle, and therefore the initial value of $\eta$ along the front when the convection starts does play a crucial role in determining the subsequent maximum intensity of the front, as illustrated in Fig. 11.

b. Role of upper-level jet streak

Although total contribution of the upper-level PV perturbation toward the 850-hPa frontal $\zeta$ was slightly negative (Fig. 9b), it is worthwhile and perhaps necessary to examine the role played by the upper-level jet streak observed in Figs. 5e,f. Here, although a baroclinic development with coupled upper- and lower-level PV anomalies is not expected, as discussed previously, the favorable position of the jet streak could still provide additional uplift and enhance the convection. In fact, even at 1800 UTC 12 June when deep convections were mostly to the south of the mei-yu front, they were also under the right entrance quadrant of the upper-level jet streak at 200 and 300 hPa (not shown). The distribution of $q'$ at 300 hPa at 0000 UTC 13 June showed positive perturbation centered at 37.5°N, 116°E with negative values south of 30°N (Fig. 13), consistent with the strong wind shear associated with an upper-level jet streak (whose core was near 30°N, 118.5°E; cf. Fig. 5f). Similarly, $q'$ at 200 hPa also showed characteristics largely caused by the presence of the jet streak (not shown). Thus, we removed all PV perturbations at 200 and 300 hPa (portions of ul) at 0000 UTC 13 June within the rectangular area of 27°–32.625°N, 112.5°–123.75°E, and recalculated the corresponding, nonlinear balanced, fields through PV inversion. Here, by replacing the total $q$ inside the specified domain (i.e., at regions with greater magnitude of $q'$) by the mean $q$, no significant discontinuities are introduced along domain boundaries, and therefore no special treatment is needed. The resulting vertical velocity (Fig. 14a) was significantly weaker once the upper-level $q'$ related to the jet streak was removed, and the strongest upward motion at 600 hPa near 117°E was only about 62% of its counterpart with all $q'$ retained (cf. Fig. 2). The weaker latent heat release also significantly reduced the efficiency of the PV generation at lower levels, and to a somewhat lesser degree the PV destruction aloft as well (Fig. 14b). Therefore, the upper-level jet streak appeared to provide an additional lifting mechanism and enhanced the upward motion, thereby leading to more active cumulus convections. However, from the previous section one can see that had the frontal system not existed in the first place, no deep convections would develop even with the presence of the jet (Fig. 12). Thus, the upper-level jet streak played an additional but secondary role in enhancing the cumulus convection, which led to rapid mei-yu frontogenesis in our case.
c. Mechanism for the development of LLJ

At 0000 UTC 13 June as the mei-yu front intensified due to the outbreak of deep convection, a clear west-southwesterly LLJ, reaching about 12–15 m s\(^{-1}\), also appeared to the south of the front near 27.5\(^\circ\)N (Fig. 5b). The 850-hPa nonlinearly balanced flow induced by midlevel PV perturbations related to latent heating (ms in Fig. 6) is shown in Fig. 15. Due to cumulus heating, the low-level PV generated (Fig. 10a) was associated with strong low-level cyclonic shear across the front, with easterly wind components to the north and westerly components to the south (Fig. 15). The westerlies' branch was slightly stronger than the easterly one, and reached almost 10 m s\(^{-1}\) near 27\(^\circ\)N, 116\(^\circ\)E. This location agreed well with the LLJ that appeared at 0000 UTC 13 June and the intensity could account for most of the observed increase in wind speed near the LLJ (cf. Fig. 5b). Similar evolution and response in the flow field at 1500 m to the effect of latent heating was also obtained in the model sensitivity tests conducted by Hsu and Sun (1994). Thus, the intense midlevel diabatic heating lowered the pressure along the front near the surface, and led to isallobaric winds into the front from both sides. Through Coriolis acceleration, the westerly flow was enhanced to the south of the front, and appeared as a jet when superimposed on the background southwesterlies. From a slightly different perspective, the horizontal convergence and cross-frontal scale contraction could be viewed as results of Ekman layer pumping induced by cumulus convection. It is worthwhile to note that despite the large ms-induced easterly winds north of 30\(^\circ\)N in Fig. 15, the observed winds north of the front changed very little from Fig. 5a to Fig. 5b. As seen in Figs. 5c and 5d, the 500-hPa westerlies over the region strengthened considerably by 0000 UTC 13 June, and close examination also revealed that 850-hPa westerlies also increased during the 6-h period before 0000 UTC 13 June due to mu-related \(q'\) at midlevels, thereby offsetting the effect from ms-related \(q'\). Since the region north of the front was under the left entrance quadrant of the ULJ with clear overnight conditions (cf. Figs. 3b and 5f), it is speculated that the increase in 850-hPa winds was related to downward transfer of westerly momentum by the sinking branch of the transverse circulation associated with the ULJ at its entrance region.

5. Discussion

The present case study provides evidence that in shallow mei-yu frontal systems with weak baroclinity but
rather strong low-level horizontal wind shear, the CISK mechanism proposed by Cho and Chen (1995) can be responsible for their frontogenetic process. It is demonstrated that through active cumulus convection, the low-level positive PV anomaly associated with the front can be enhanced rapidly, leading to further development of a pressure trough and horizontal wind shear. Such a process is in contrast to the well-known baroclinic instability, and represents a possible mechanism for the formation and maintenance of a class of shallow fronts with barotropic characteristics. As discussed in section 4a, the efficiency of cumulus heating and thus the effectiveness of this CISK mechanism depend upon the initial PV at low levels. It follows that only when deep convections coincide with the mei-yu front (where $\eta$ was maximized) would the heating produce its largest impact possible. In the present case, deep convections also occurred continuously south of the mei-yu front at 1200 and 1800 UTC 12 June (Fig. 3a). Although they were quite active for a lengthy period, the cumulus heating was relatively inefficient because the PV values over the region of convection were low and thus the Rossby radius of deformation $L_R = (gh)^{1/2}/\eta$, where $h$ is the depth) was too large (cf. Fig. 7a). As a result, there was no apparent growth in PV south of the front at these times, and neither was a LLJ led to develop (Fig. 5). It is common for these deep convective clusters to form ahead (south) of the mei-yu front (e.g., C. Chen et al. 1998; S. Chen et al. 1998), and it remains to be seen whether in some rather extreme instances these deep convections could affect the dynamics and/or movement of the mei-yu front. In our case, these prefrontal convections appeared to have very little effects on the front, and the frontal intensity was mostly maintained through heating associated with local stratiform clouds before the outbreak of deep convections along the front near 0000 UTC of 13 June (Fig. 9c; cf. Fig. 3).

It should be noted that in the present study we deliberately chose a frontal case primarily driven by cumulus convection and latent heat release. There are nevertheless also mei-yu fronts with strong horizontal temperature gradient and developed through baroclinic instability, such as the one studied by Trier et al. (1990). Since during the mei-yu season the atmospheric environment is often warm and moist at low levels and convectively unstable over southeastern China, we believe that the CISK mechanism is likely to play some role of varying degree in many frontal systems, especially those with active frontal convection. The interaction between baroclinic processes and the CISK mechanism is intriguing and could be very complex, and deserves further research.

Regarding the mechanism for LLJ development, Chen et al. (1994) studied a case in TAMEX and concluded that the southwesterly flow was enhanced when a synoptic-scale cyclone developed to its northwest. In their study, the cyclone deepened through baroclinic instability, and accompanying the development both the upper-level jet and LLJ (of synoptic scale) intensified. In the present study, in contrast, the mei-yu front was shallow and equivalent barotropic, and the mesoscale LLJ was a by-product of the frontogenetic process through the CISK mechanism, which was enhanced due to the presence of the upper-level jet streak. In theory, if the heating is efficient enough, the upper-level divergence induced by continuous convection could also affect the local structure of the jet aloft by enhancing the westerlies north of the convection and reducing them to the south (e.g., Chen et al. 2003). This aspect is interesting, but remains untouched in our present study.

6. Summary

The present study employs the nonlinearly balanced piecewise PV inversion techniques developed by Davis and Emanuel (1991) and Davis (1992a,b), and performs diagnostic analysis on the 12–13 June 1990 mei-yu frontal case over southeastern China from a PV perspective. The front possessed weak cross-frontal temperature gradient but strong horizontal wind shear at low levels, and it was shallow with little vertical tilt. These properties are in contrast to those of midlatitude polar fronts, but are commonly found in the western section of mei-yu fronts (Chen and Chang 1980). Mechanisms for the maintenance of these frontal characteristics, as well as the roles played by an upper-level jet streak and a LLJ are examined and discussed. Major findings can be summarized as the following:

1) Through piecewise inversion, it is found that PV perturbations related to midlevel latent heat release were largely responsible for the maintenance and intensification of frontal cyclonic vorticity in the present case. Contributions from shallower stratiform clouds were steady and mostly maintained the front, while the rapid increase in frontal vorticity (at 0000 UTC 13 June) was coincident with, and almost entirely attributed to, the outbreak of deep convective cloud clusters along the front.

2) Further diagnosis suggests that the CISK mechanism proposed by Cho and Chen (1995) was responsible for the mei-yu frontogenesis near 0000 UTC 13 June in the present case, and provided evidence for its effectiveness in the real atmosphere. The positive feedback between cumulus-scale CISK and the low-level PV anomaly associated with the front led to rapid growth in low-level frontal vorticity. In this process, the front provides low-level convergence and helps organize the convection, while latent heating by cumulus convection generates low-level PV and further enhances the front.

3) In the CISK mechanism for mei-yu frontogenesis, the efficiency of the condensational heating from cumulus convection and the subsequent production rate of low-level PV depend on the initial PV value itself. As a result, convections developing to the south of
the front at regions with smaller initial PV values did not cause a similar vorticity growth.

4) In association with the frontal intensification, the growth in low-level horizontal wind shear also led to the appearance of a well-structured LLJ immediately south of the mei-yu front. In this case, the mesoscale LLJ formed when the cyclonic circulation induced by a low-level PV anomaly superimposed on the background southwesterlies, and was a local by-product of the frontogenetic process.

5) An upper-level jet streak moved to a favorable position relative to the low-level mei-yu front at 0000 UTC 13 June. The rising branch of its transverse circulation at the rear-right quadrant appeared to provide additional lifting and enhanced the cumulus convection.

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