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A review of the role of latent heat release in extratropical cyclones within potential vorticity framework

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Abstract

A review of past work in the subject areas of latent heat release in extratropical cyclones, within the concept of the potential vorticity framework or "PV thinking" is presented. It is also aimed to assess to what extent the conventional baroclinic instability theory can be applied to extratropical cyclones involving intense latent heat release. The main results of the previous studies concerning the effect of latent heat release on extratropical cyclones dynamics can be divided into two categories, depending on whether the impact of the diabatically generated PV anomaly on the baroclinic dynamics was very weak or strong. In the weak cases, cyclogenesis is primarily driven by baroclinic dynamics, with latent heat release playing a secondary role. Latent heating influences the baroclinic dynamics as simply by superposing a positive PV anomaly near the cyclone center without significantly altering the PV structure elsewhere. On the other hand, a few studies reveal that latent heat release can enhance largely the cyclone intensity, particularly when the surface thermal gradients are weak and alter significantly the structure of upper-level PV and surface thermal anomalies. The low-level diabatically produced PV anomaly is able to substitute for the absent surface warm anomaly.

Key words: Baroclinic dynamics, extratropical cyclones, latent heat release, potential vorticity

1. Introduction

The extratropical cyclone or low-pressure system is the most common phenomenon on the synoptic scale in mid-latitudes. In some cases, it can have strong winds and precipitation that cause thunderstorms, flooding, structural damage and so on. A great number of theoretical and case studies have investigated the effects of physical processes on baroclinic dynamics and the development of extratropical cyclones. Today it is known that several factors such as latent heat release, surface heat fluxes, and orography may influence the structure and spin up of the cyclone. These studies point out that the release of latent heat is the most important diabatic process among the various physical processes in extratropical cyclones. Also, it is shown that latent heat release may have a complicated interaction with the baroclinic dynamics. Some features of this interaction will be discussed in detail later. Here we will concentrate on the effects of this process in reviewing previous studies.

The use of potential vorticity (PV) framework or "PV thinking" can be the most fundamental approach to study the effect of latent heat release on cyclone development. Since the seminal paper of Hoskins et al. (1985), a large number of studies have used the PV concept to gain a better understanding of extratropical cyclones and processes leading to cyclogenesis. The study of diabatic processes in baroclinic cyclogenesis was less emphasised in Hoskins et al. (1985). They did not go into detail on how latent heat of condensation affects cyclogenesis, except to say that the reduced static stability in saturated air increases the vertical penetration of the induced fields, thus amplifying the feedback. In this paper, we attempt to discuss the effect of latent heat release on extratropical cyclones dynamics within the concept of PV thinking, as found in the previous studies. It is also the purpose of this study to show to what extent the PV conceptual model represented in Hoskins et al. (1985) can be applied to extratropical cyclones involving intense latent heat release throughout the life of cyclones.

After presenting a brief description of the PV concept, diabatically generated PV anomaly and PV conceptual model of baroclinic instability are discussed. Then a review of previous studies concerning the effect of diabatically generated PV anomaly on extratropical cyclones will be presented. It is obvious that this review is not aimed at producing a comprehensive study of all the literature on latent heat release within PV framework (an impossible task). Rather, it concentrates on providing a broadly chronology-cal description of developments in the theory relevant to the study of diabatically generated PV, its influence on mid-latitude cyclones, and the current state of research in this area.

2. Potential vorticity framework

2-1. PV concept and its equation

Potential Vorticity (PV) is a dynamical variable that was formulated independently by Rossby (1940) and Ertel (1942). It is more general than that implied by the Quasi-geostrophic theory and is derived from the non-hydrostatic set of equations with no approximations. The primitive equation model, which describes the dynamics of the atmosphere, consists of:

$$\frac{DV}{Dt}+f\,k\times V+\frac{1}{\rho}\nabla p+gk+F=0 \qquad (1)$$

Thermodynamic equation

$$c_p\frac{DT}{Dt}-\frac{1}{\rho}\frac{Dp}{Dt}=\frac{dQ}{dt}\equiv J \quad \text{or} \quad \frac{D\theta}{Dt}=\frac{J\theta_0}{c_pT} \qquad (2)$$

Continuity equation

$$\frac{D\rho}{Dt}+\rho\nabla\cdot V=0 \qquad (3)$$

where V is the velocity vector, f is the Coriolis parameter, k is the unit vertical vector, ρ is the density, p is the pressure, g is the gravitational force, $\boldsymbol{F}$ is the frictional force vector, c_p is the specific heat at constant pressure, T is the temperature, J is the rate of heating per unit mass, and θ is the potential temperature.

By manipulating the foregoing equations a relationship for the material derivative of potential vorticity can be obtained (Ertel 1942)

$$\frac{D}{Dt}PV=\frac{1}{\rho}(\zeta_a\cdot\nabla\dot{\theta}+\nabla\times F\cdot\nabla\theta) \qquad (4)$$

$$PV\equiv\frac{1}{\rho}\zeta_a\cdot\nabla\theta \qquad (5)$$

where PV is the potential vorticity and ζ_a is the three dimensional absolute vorticity vector. PV is a dynamical tracer of air parcel that is conserved in the absence of diabatic heating and friction. The quantity PV is now commonly known as the Rossby-Ertel potential vorticity. Using the hydrostatic approximation, PV will be

$$PV=-\zeta_{a\theta}\frac{\partial\theta}{\partial p}=-(\zeta_\theta+f)\frac{\partial\theta}{\partial p} \qquad (6)$$

where $\zeta_{a\theta}$ is the vertical absolute vorticity and ζ_θ is the vertical relative vorticity both in isentropic coordinates. To get a picture of what this equation means we can imagine a vortex tube bounded by the two isentropic surfaces. If the θ surfaces move further apart the tube is stretched and thinned and thus the magnitude of the vorticity is increased to conserve the potential vorticity, or vice versa. As an application, the conservation of PV states that as stratospheric air descends into the troposphere, the air mass is stretched and the static stability ($-\partial\theta/\partial p$) decreases significantly. Consequently, the absolute vorticity ($\zeta_\theta+f$) increases with respect to parcel trajectories as long as the stratospheric PV values are preserved.

Kleinschmidt (1950) applied the PV concept to the upper troposphere to explain observed cyclogenesis events. He was apparently the first to relate the advection of a stratospheric reservoir of high PV associated with a low tropopause to cyclogenesis, going so far as to state that the stratospheric reservoir "is essentially the producing mass of the cyclones".

2.2 Diabatically generated PV anomaly

As seen in equation (4), in the presence of diabatic heating and friction PV is no longer conserved. The right hand side (rhs) of (4) states that positive PV is generated either by a gradient of diabatic heating in the direction of the absolute vorticity or by frictional generation of vorticity in the direction of the θ gradient. Therefore, PV disturbances can be created by various forms of friction and diabatic heating in addition to PV advection by invisid flow. The main sources of diabatic heating could be due to: (1) latent heat release as a result of condensation or sublimation, (2) surface heat fluxes, (3) radiative processes, and (4) turbulent mixing. We will concentrate primarily on the effect of latent heat release in clouds.

Equation (4) can be approximated as

$$\frac{D}{Dt}PV\cong\frac{1}{\rho}(f+\zeta)\frac{\partial}{\partial z}\left(\frac{D\theta}{Dt}\right) \qquad (7)$$

Using equivalent potential temperature as $\theta_e=\theta+(L/c_p)q$, where L is the latent heat of condensation and q is the specific humidity, and assuming that air parcel ascends along a constant θ_e line, we find

$$\frac{D\theta_e}{Dt}=\frac{D\theta}{Dt}+\frac{L}{c_p}\frac{Dq}{Dt}=0 \qquad (8)$$

or for saturated air

$$\frac{D\theta}{Dt}=-\frac{L}{c_p}\frac{Dq}{Dt}\cong-w\frac{L}{c_p}\frac{\partial q}{\partial z} \qquad (9)$$

Equation (9) can be related to the effective static stability using the split of θ into a reference and deviation parts, $\theta=\theta_{ref}(z)+\theta'$, as

$$\frac{D\theta'}{Dt}+\left(\frac{d\theta_{ref}}{dz}+\frac{L}{c_p}\frac{\partial q}{\partial z}\right)w=0 \qquad (10)$$

Multiplying equation (10) by g/θ_{ref} and using static stability definition $N^2=(g/\theta_{ref})\,d\theta_{ref}/dz$ gives:

$$\frac{Db'}{Dt}+N^2_{eff}\,w=0 \qquad (11)$$

$$\frac{Db'}{Dt}+(N^2+\frac{gL}{c_p\theta_{ref}}\frac{\partial q}{\partial z})w=0 \qquad (12)$$

Since $\partial q/\partial z<0$, equation (12) indicates that diabatic heating acts to decrease the static stability and thus to enhance the vertical motion in the region of heating. One approach, which has been used in some extratropical cyclogenesis studies, to parameterize the effect of latent heat release is to model the reduced stability to moist ascent.

Using equations (8) and (9), equation (7) can also be shown as

$$\frac{D}{Dt}PV\cong\frac{1}{\rho}(f+\zeta)\frac{\partial}{\partial z}(-w\frac{L}{c_p}\frac{\partial q}{\partial z}) \qquad (13)$$

Equations (7) and (13) state that the rate of change of PV is a function of the vertical gradient of the rate of change of potential temperature or specific humidity, respectively.

Kleinschmidt (1950) studied the possibility of the creation and destruction of PV by diabatic processes mainly through the latent heat release in frontal clouds. He pointed out that the frontal zone exhibits a PV generation-depletion dipole oriented along streamlines, which is shown schematically in Figure 1. The implication is that air parcels that ascend through the frontal zone initially experience a positive gradient of heating and therefore a region of PV production, achieving a maximum value of PV at the level of maximum heating (ascent). After air parcels have passed through the level of maximum heating the gradient changes its sign, and parcels experience PV destruction.

As shown by Haynes and McIntyre (1987, 1990), using equation (4), the volume integral of anomalous PV is given by

$$\frac{D}{Dt}\int_V \rho PV dV=\oint_S(\dot{\theta}\zeta_a+\theta\nabla\times F).\eta d\sigma \qquad (14)$$

where S is the surface enclosing volume V, $d\sigma$ is the differential element of area on S, and η is the unit vector normal to the surface and pointing outwards. This implies that the mass-weighted PV in a material region cannot be changed by diabatic heating or friction which are purely internal to the region (Haynes and McIntyre 1987, 1990). Diabatic heating in a region leads to material sources and sinks of PV that must be exactly in balance so that no ρPV is created or destroyed (Figure 2a). This guarantees the existence of negative PV anomaly by diabatic heating.

Kleinschmidt's viewpoint about a PV dipole due to diabatic heating was challenged later by the examination of air parcel motion through the warm front by Persson (1995), Stoelinga (1996), and Wernli and Davies (1997).

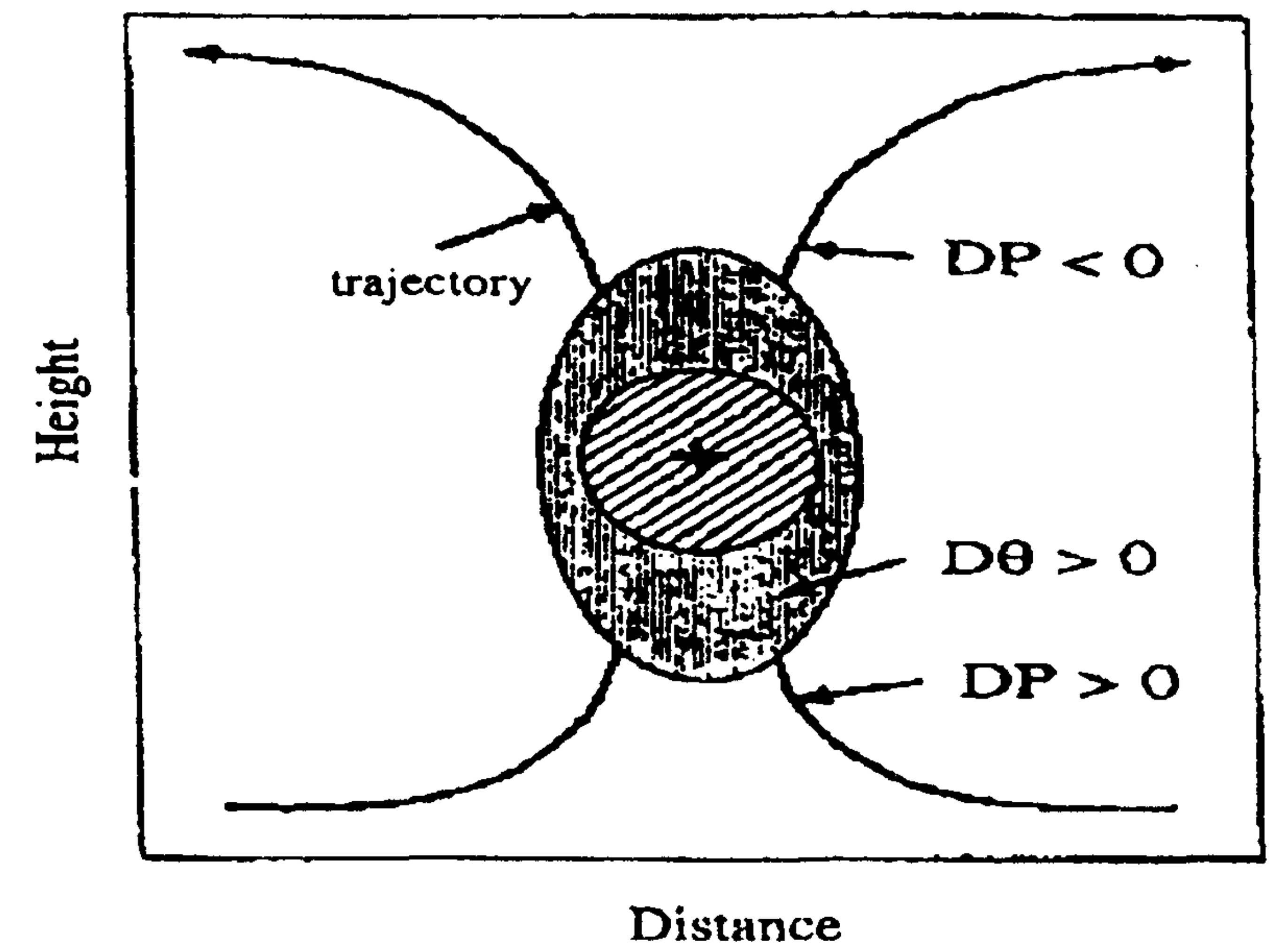


Figure 1. A schematic of diabatically generated PV anomaly for an idealized case of condensation in a frontal zone. Air-parcel trajectories are shown by the bold lines with arrows. Dθ and DP indicate material tendencies of potential temperature and potential vorticity, respectively (Wernli and Davies 1997).

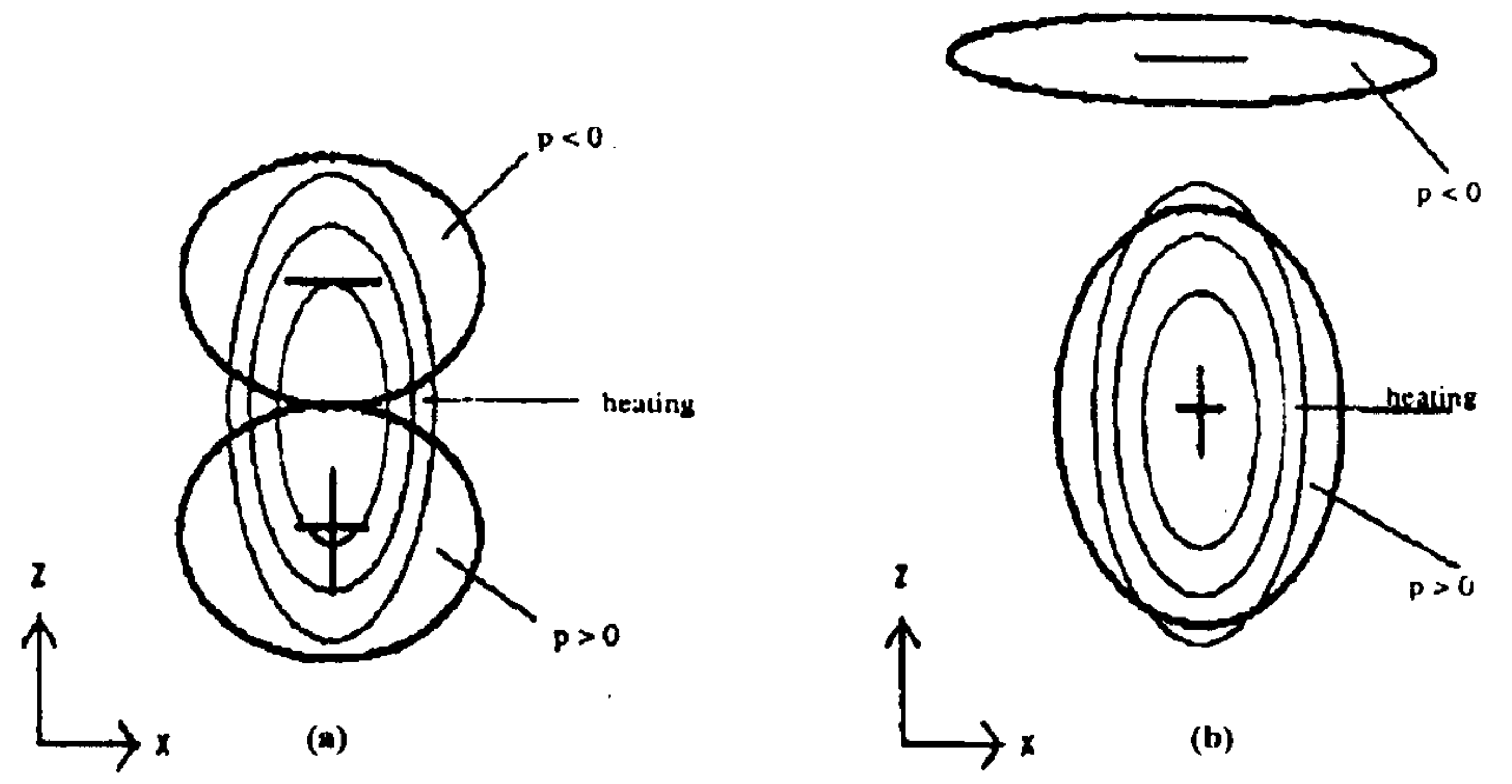


Figure 2. A schematic of diabatically generated PV anomalies for (a) impulsive heating source and (b) steady state heating source (Birkett 1998).

It is suggested that if the heating occurs as an impulse (Figure 2a) tis will produce a positive anomaly below the maximum heating, and a negative anomaly above the maximum heating. If the heating occurs over much longer time scales, so that it is near steady state, a different PV structure will emerge. A positive PV anomaly will reside coincident with the heating maximum, and a negative PV anomaly will be distinct from the heating region and possibly by dispersed away (Figure 2b).

2.3 PV conceptual model of baroclinic instability

Hoskins et al. (1985) have produced an exhaustive review of the use of potential vorticity in meteorology. Of particular relevance to rapid cyclogenesis they propose a mechanism for the development of a dry

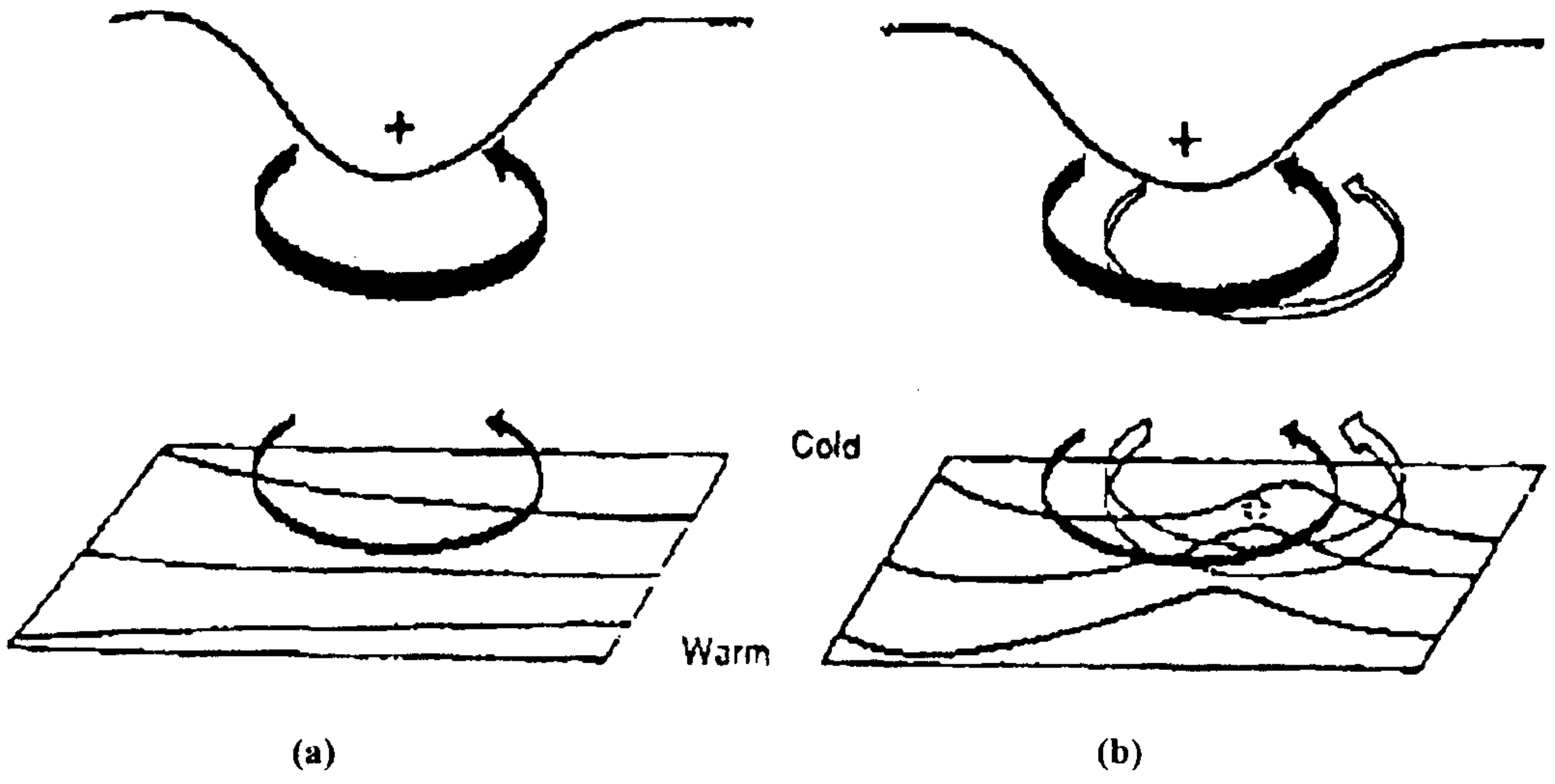


Figure 3. A schematic picture of cyclogenesis associated with the arrival of an upper-level PV anomaly over a low-level baroclinic region. In (a), the upper-level PV anomaly, indicated by a solid plus and associated with cyclonic circulation, has just arrived over a region of low-level baroclinicity. The circulation induced by the anomaly is indicated by solid arrows, and potential temperature contours are shown on the ground. A low-level PV anomaly can also induce a cyclonic circulation indicated by the open arrows in (b) that acts to reinforce the circulation pattern induced by the upper-level PV anomaly (Hoskins et al. 1985).

baroclinic cyclone in the context of "PV thinking". This mechanism, similar to that introduced in Petterssen type B development (Petterssen and Smebye 1971), involves the interaction of a PV anomaly on the dynamical tropopause with a comparable potential temperature disturbance near the ground (where in a quasi-geostrophic frame work a warm thermal anomaly can be viewed as equivalent to a positive concentrated PV anomaly in a thin surface layer, Bretherton 1966). Figure 3 shows schematically a cyclogenesis associated with the arrival of an upper-level PV anomaly over a low-level baroclinic region. In Figure 3a, the upper-level PV anomaly associated with the cyclonic circulation induces a weak circulation at the surface. The advection of potential temperature by the induced lower level circulation leads to a warm anomaly east of the upper-level anomaly (Figure 3b). This in turn will induce a cyclonic circulation in the upper level that will reinforce the original anomaly and can lead to amplification of the disturbance.

As discussed in Hoskins et al. (1985), a PV gradient on a θ surface and equivalently a θ gradient on a PV surface are associated with neutral Rossby waves. Therefore the interaction of an upper-level PV and surface θ anomalies can be interpreted in terms of mutual reinforcement of neutral Rossby waves at upper and lower boundaries.

The two fundamental principles of PV in Hoskins et al. are (1) the conservation of PV in the absence of diabatic heating and friction and (2) invertibility. The second principle states that, given proper boundary conditions and a balance condition, the meteorological fields (e.g. winds, temperature, and geopotential heights) can be obtained from the knowledge of PV distribution. As mentioned earlier, Hoskins et al. did not discuss in detail how diabatic heating and latent heat release affects cyclogenesis. Kleinschmidt, on the other hand, recognized that condensation heating produces non-conservative PV changes and that as a consequence, positive PV anomalies appear in the lower portion of frontal cloud masses. This PV anomaly induces cyclonic circulation, thus enhancing storm development. However this diabatically induced PV anomaly differs significantly from the other two ingredients at the tropopause level and ground surface. It is neither quasi-conservative nor PV advection by inviscid flow, but is generated by the passage of the air parcels through the region of diabatic heating.

3. The role of latent heat release in extratropical cyclones from a PV perspective

A review of studies concerning the effect of diabatically generated PV anomaly on mid-latitude cyclones will be given in this section. It is convenient to divide these studies into theoretical work, numerical simulations, and investigations of extratropical cyclogenesis using the interaction of three sources of PV anomalies associated with upper-level trough, latent heat release and surface θ gradient. The latter studies will also be presented in two parts. The first part, deals with those studies that reveal which latent heating, can be described as simply augmenting the cyclone intensity by superposing a positive PV anomaly near the cyclone center without significantly altering the PV structure elsewhere. The second part deals with the studies showing remarkable influences of latent heat release on the cyclone intensity and structure, to the extent of altering the whole dynamics of cyclogenesis.

3.1 Theoretical studies

Work in relation to condensation heating using the PV concept began in the late 1980s (except the studies of Kleinschmidt in 1950 and 1957). Much work has been done to extend the theory of baroclinic instability integrating the effects of nonlinearity and latent heat release. The semi-geostrophic model is usually used for numerical and analytical studies of the development into the nonlinear regime of the Eady wave instability with uniform shear in the vertical (e.g. Hoskins 1975). Unlike the quasi-geostrophic equations, this model is able to describe the formation of regions in which the vorticity is large, e.g. fronts and jet streams. Diabatic heating can also be parameterised in the model applying various schemes.

In connection with the effects of moist processes on baroclinic instability, Emanuel et al. (1987) have examined an Eady wave with parameterized latent heat release only in the ascending air. The basic underlying assumption of this parameterization is that the atmosphere adjusts itself to be almost neutral to moist slantwise ascent. As discussed by Bennetts and Hoskins (1979), neutrality to slantwise convection is equivalent to the condition of zero PV. Their results show the greatly enhanced growth rates and shortened wavelengths that are obtained as the moist PV approaches zero. Latent heat release produces a positive PV anomaly in the lower troposphere and a negative anomaly in the upper levels. These PV anomalies are advected through the baroclinic wave by the total wind field, reinforcing static stability and cyclonic vorticity at low levels and diminishing them at upper levels. They also demonstrate the region of updrafts intensifies and collapses to a thin ascending sheet in the moist case.

Craig and Cho (1988) used the Eady model of baroclinic instability with wave-CISK parameterization to study the effect of cumulus heating and the possibility of CISK in extratropical latitudes. The relation for cumulus heating was the same as that applied by Mak (1982) except that total vertical velocity, w, was used in their investigation. The idea behind conditional instability of the second kind, CISK, involves cooperative interaction between cumulus clouds and large-scale moisture convergence. Also, the pure CISK model denotes that the disturbance is driven entirely by latent heat release. Craig and Cho demonstrate the existence of a transition between two regimes in their model. For low ε, the heating rate, the modes were structurally similar to the dry wave; heating acts mainly to reduce the effective static stability, resulting in faster growth and shorter wavelengths. For larger ε, the diabatic energy conversion became dominant and the instability took on the characteristics of the pure CISK disturbance. In this regime, waves were structurally altered, with the maxima of geopotential fields determined by the heating boundaries rather than the physical boundaries. They stress that this solution does not have a well-defined growth rate and is difficult to interpret physically.

Snyder and Lindzen (1991) developed an extreme form of Craig and Cho's formulation by a highly simplified version of baroclinic wave-CISK in an unbounded fluid, without basic PV gradient and upper and lower boundaries. The CISK heating is bounded by two horizontal levels. The most basic result is that parameterized heating can act as a dynamical surrogate for the basic state PV gradients and produce "moist" baroclinic instability even in situations that are stable in the absence of heating. Their results suggest that moist baroclinic instability is not necessarily the result of a cooperative interaction between the parameterized heating and baroclinic instability, but rather that the presence of heating introduces distinct effects that may compete with dry baroclinic instability. Nevertheless they note that the unstable waves still result from the interaction of perturbation PV and the heating through the induced vertical motion and are not simply baroclinic waves with increased growth rates, due to a reduction in the effective static stability.

Using a two-dimensional semi-geostrophic model Montgomery and Farrell (1991) studied moist surface frontogenesis associated with interior PV anomalies. A widely accepted method in previous studies to parameterize the impact of latent heat release on baroclinic waves is to reduce the dry static stability. Therefore due to the sensitivity of the growth rate of most unstable mode to parameterized heating, they attempt to explore a variety of moist frontal processes applying various initial conditions with uniform and non-uniform interior PV as described below. The authors also stress the initial-value approach for understanding the cyclogenesis process in their study of polar low dynamics (1992).

The deviation from moist neutrality in the study of Montgomery and Farrell is either small and uniform, as used in Emanuel et al. (1987), or non-uniform, monotonically increasing with height. For the uniform interior PV, they reveal that as the ascent field due to the upper-level wave extends through the atmosphere a low-level positive PV anomaly is generated which subsequently couples baroclinically with the disturbance aloft. The local Rossby penetration depth is unchanged and coupling is strongest with longwave disturbances. It is shown that rapid surface frontogenesis occurs for the non-uniform interior PV case. The positive PV anomaly reduces the Rossby penetration depth and the baroclinic interaction is weakened and frontal collapse, as shown by Emanuel et al. (1987), occurs at a later time. A negative interior PV anomaly downstream of the positive anomaly also destabilizes surface disturbances by more heat transport poleward and an increase in the disturbance kinetic energy. They conclude that this frontogenesis is not primarily baroclinic and the source of energy is latent heat released in ascent regions. Development is slow in comparison with baroclinic frontogenesis but is not dependent on the presence of large amplitude perturbations. This configuration is also found, as diabatic destabilization stage, in their study of polar low dynamics (1992). Applying a three-dimensional geostrophic momentum model, they suggest that polar low development comprises an initial baroclinic growth phase followed by a slow intensification due to diabatic effects; called "induced self-development" and "diabatic destabilization" stages respectively. This result is confirmed by Nordeng and Rasmussen (1992) in a case study of a polar low development in the Bear Island region. Diabatic destabilization represents a simple mechanism for maintaining the intensity of these systems over water provided a suitable portion of the lower atmosphere is maintained nearly moist neutral. Montgomery and Farrell (1992) also point out that in exceptional instances of polar cyclogenesis with negligible upper-level forcing, diabatic destabilization can also describe the gradual intensification of small-scale vorticity in regions of sustained neutrality and surface baroclinicity.

Whitaker and Davis (1994) discussed the effect of latent heat release on cyclogenesis in a saturated environment using linear and nonlinear models. They used a parameterization of latent that assumed all rising air was saturated and all sinking air unsaturated (Is this what is meant?) The moist static stability increases with height, from near zero at the ground to values approaching the dry static stability in the middle and upper troposphere. This is different from the previous assumptions of interior PV in parameterization of heating (e.g. Emanuel et al. 1987, Montgomery and Farrell 1991). The most unstable mode of the Eady model grows only marginally faster than the corresponding mode of the dry problem (in contrast to results of Emanuel et al. (1987)). The vertical variation of moist static stability produces a gradient of moist PV in the rising air, eliminating the short-wave cutoff present in the dry Eady model. For short waves (which are neutral in the dry model), the instability results from the mutual amplification of the surface boundary temperature anomaly and interior PV anomaly through their induced horizontal and vertical velocity fields. Nonlinear simulations show that the moist cyclone grows faster than the linear growth rate at finite amplitude, while the dry cyclone grows at nearly the linear growth rate until maximum amplitude is reached. This enhanced growth rate is associated with the rapid amplification of a mesoscale PV anomaly generated by latent heat release at the warm front. The rapid amplification of the surface cyclone results from the superposition of the circulation associated with this mesoscale PV anomaly upon the circulation associated with the upper and surface boundary anomalies.

Following the work of Craig and Cho (1988), conditional convective heating in a baroclinic atmosphere was studied by Parker and Thorpe (1995). They point out that baroclinic instabilities can be dominated by the diabatic energy conversion and exhibit "solitary" properties, in that the dynamics is entirely determined by the PV anomalies in the vicinity of the region of convective heating. For high values of the heating parameter, ε, the modes reveal the solitary behavior and growth rate, phase speed, and local structure are independent of wavelength; at lower ε, the waves, like the dry mode, vary with wavelength. They also suggest that the PV tendencies due to diabatic heating can be interpreted in terms of interacting Rossby wave pairs, as proposed by Hoskins et al. (1985) for the dry Eady waves. The frontal structure that this model describes is dominated by latent heat release in the sense that frontogenesis is determined by a diabatic source of PV rather than by horizontal shear forcing. It is emphasized that a large-scale forcing is necessary, even if it is of a relatively small magnitude, as a catalyst to trigger low-level frontal convergence that leads to convection.

The effects of latent heat release on baroclinic dynamics as found in these studies can be summarized as:

- Enhancement of growth rates and shortening wavelengths via reduction in the effective static stability.
- Creation of a positive PV anomaly at low levels and a negative anomaly at upper levels.
- Intensification of updrafts and narrowing their regions.
- For a small and uniform interior PV: upper-level wave extends downwards and generates a low-level PV anomaly, which subsequently couples baroclinically

with the disturbance aloft.

- For a non-uniform interior PV: the positive PV anomaly reduces the Rossby penetration depth and the baroclinic interaction is weakened.
- For more realistic interior PV: linear simulations reveal the most unstable mode grows slightly faster than the dry Eady case, while in nonlinear models the moist cyclone grows faster than the linear growth rate.

As shown above, the main results of these theoretical studies in relation to the effects of latent heat release on extratropical cyclogenesis strongly depend on the models used, linear or nonlinear, and the parameterization of diabatic heating.

3.2 Numerical simulations

Using a hydrostatic, primitive equation model, with explicit condensation, Balasubramanian and Yau (1994) examined the effects of convection on a simulated marine cyclone. Their model produced an explosive moist cyclone with an intense bent-back warm front. They show that the thermal gradient in the bent-back warm frontal region is in agreement with observations. It is found that there is a positive PV anomaly along the regions of the warm front and bent-back warm front contributing 40% to the perturbation geopotential at 900 and 500mb over the cyclone centre. This contribution is twice that in the dry case. The individual circulation due to condensation produces cold advection in the moist cyclone while the dry cyclone shows a broad warm advection in the same region. They note that this cold advection acts to decrease the surface thermal anomaly and to enhance the upper-level wave deepening. Increased upper-level vorticity advection interacts with the low-level system, leading to explosive cyclogenesis. These results are confirmed in the same authors' study of the life cycle of a simulated marine cyclone from PV and an energetic point of view (1996). They also point out that, in contrast to the previous life cycle simulations of dry cyclones, the warm front is stronger than the cold front. It is concluded, except for the mesoscale structural differences and their associated interactions during the early stage that the moist cyclone appears dynamically similar to the dry cyclone from both view points.

Using extensive trajectory calculations, Wernli and Davies (1997) attempted to examine the space-time structure and dynamics of an extratropical cyclogenesis event. It is shown that there are many distinct moist ascending and dry descending trajectories. Three types of moist ascending airstreams associated with strong condensation are identified. One type which conveys moist air parcels from the warm sector's boundary layer to the upper troposphere is the main contributor to precipitation along the cold front during the early phase of development. Another type, distinguished by maximum water vapor flux, ascends to mid-tropospheric levels in the warm-frontal region and produces strong precipitation during the intensification stage. The third type, which is considered as a part of the first type, called W2 in the conveyor belt conceptual model, peels off and ascends into the cloud head (Young et al. 1987). This type of airstream ascends in the bent-back warm frontal region and influences cyclogenesis through the creation of a significant low-level PV anomaly close to the centre of the cyclone, as seen in previous studies. Three types of dry descending airstreams, as shown in Danielsen (1964), are also identified. The strongest descent occurs for moderately dry tropospheric air parcels, which are initially located upstream of the upper-level trough. At a later time, this descending motion is split into a major anticyclonic and a weak cyclonic branch, and the position of the parcels is very close to a region of strong convective activity. The second type originates within a tropopause-fold region. During the descent to low-levels the dry air parcels stay on a cyclonically curved path and their mean PV value decreases to below 1PVU. This air stream represents a turbulent mass exchange from the stratosphere to the troposphere. The third type reveals a stratospheric intrusion overrunning the surface fronts whilst approaching the mature cyclone.

Bresh et al. (1997) discussed a polar low development over the Bering Sea. A series of fine-mesh (20 km) experiments are performed to study the structure of the cyclone and to determine the physical processes important for its development. In an experiment with both surface fluxes and latent heating withheld, the low pressure at the initial time weakened and died away. Their discussion shows that the low formed in a region of moderate low-level baroclinity when an upper-level trough, associated with anomalously large PV, advanced into the region. It is suggested that in order to form a polar low of the observed type and intensity, it is essential to have modification of the boundary layer before and during the development. Also, the existence of latent heating is essential. They remark that baroclinic growth was able to proceed only when static stability was reduced at low-levels, otherwise the baroclinity was not sufficiently strong to permit wave amplification. It is also pointed out that in the experiments with reduced stability, the downward penetration of the upper-level anomaly was enough to induce a low-level thermal anomaly that through mutual interaction was able to form an intense low-level circulation and create a low-level PV anomaly by condensation heating.

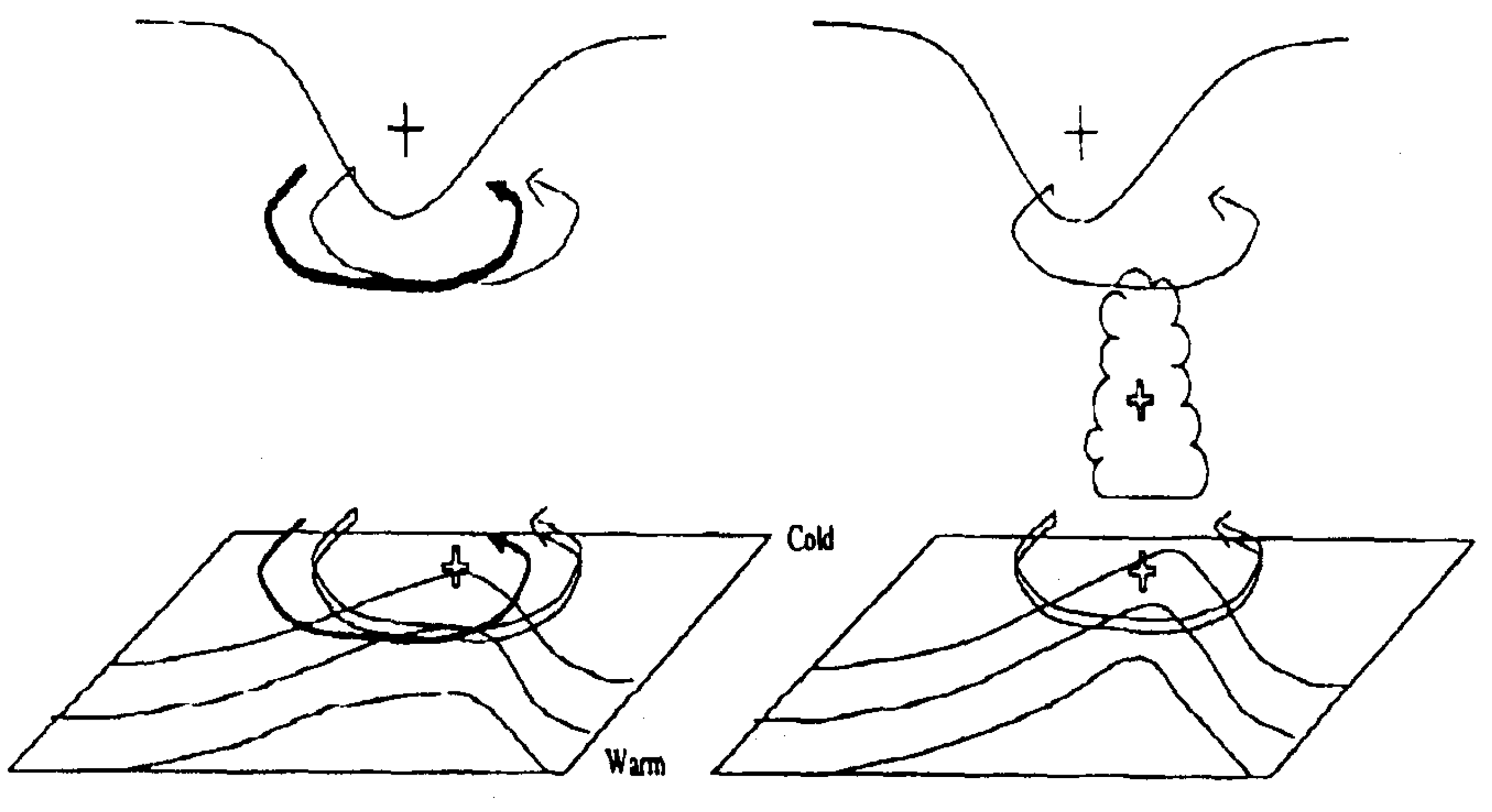
Birkett (1998) studies the existence and role of reduced upper-level PV anomaly due to latent heat release in extratropical cyclones. The first intensive observing period, IOP 1, from FASTEX (the Fronts and Atlantic Storm Track Experiment) was chosen as the case study in this work. Using trajectory calculations, she defines this anomaly objectively and then applies PV inversion to quantify the instantaneous fields of flow and temperature that could be attributed to the negative PV anomaly. Numerical experiments, with modified initial conditions, are also performed to determine the temporal implications of removing the objective PV anomaly. It is shown that correlation between the magnitudes of the PV anomaly and induced fields is nonlinear and negative anomalies produce proportionally larger fields than positive ones. Background PV and density fields are also fundamental to the fields induced. She concludes that the instantaneous fields induced by the negative upper-level PV anomaly are comparable in magnitude to those induced by a positive anomaly while over time its influence is relatively small with maximum impact at the early stages of low development. Numerical experiments also illustrate a downstream negative PV anomaly delaying the development of the cyclone and reducing its overall strength, suggesting that it is not valid to neglect the role of the negative anomaly in comparison to the positive anomaly.

Mallet et al. (1999) discuss the effect of diabatic heating on the early development of the IOP 17 cyclone from the FASTEX experiment. Three phases of development are identified in this cyclogenesis event but only the first development phase is investigated in detail. The results of two numerical simulations, one with full physics and the other excluding cloud processes, and a few diagnostics are used in their study. It is shown that the latent heat release along the warm front modifies the upper-level winds and splits the jet into two separate jet streaks during the first development phase of the storm. There is also a positive feedback between the storm's dynamics and the diabatic processes. Their results suggest that the baroclinic forcing is detached from the storm at a later time due to slow propagation whilst diabatic forcing remains collocated with the warm-frontal ascent and the storm evolves towards a purely diabatic deepening regime. It is pointed out that the threshold values of the heating rate, in this case, are significantly larger than those obtained by the previous studies (Craig and Cho 1988, Snyder and Lindzen 1991, Parker and Thorpe 1995). They suggest that the diabatic unstable CISK waves discussed in the previous studies are not restricted to small-scale systems such as polar lows, or comma clouds but can also overtake the baroclinic growth in larger-scale systems.

In all, the main results of these studies concerning the effects of latent heat release are consistent with the theoretical studies discussed earlier. They are: the existence of a positive PV anomaly at low levels and a negative PV anomaly at upper levels; positive PV anomaly along the regions of the warm and bent-back warm front contributes significantly to the low-level cyclogenesis; production of cold advection at low levels which increases the upper-level wave deepening; the existence of a positive feedback between the baroclinic dynamics and diabatic heating; rapid amplification of the surface cyclone due to superposition of the circulation associated with the diabatically produced PV anomaly upon the circulation associated with the upper and surface anomalies.

A simple picture for latent heat release in the PV conceptual model, based on the findings of theoretical and numerical studies, is shown schematically in Figure 4. The basic mechanism in this conceptual model involves the overtaking of a surface baroclinic zone by an upper-level PV anomaly, resulting in mutual intensification as long as the system maintains the proper condition (Figure 4a). The effect of latent heat release on the surface cyclogenesis is that the diabatically generated PV anomaly reinforces the warm anomaly, leading to a strong surface cyclone, and enhances the upper-level PV anomaly by advection (Figure 4b).

The main shortcomings of these numerical studies are related to their limitations in providing quantitative information on the relative importance of diabatic heating and baroclinic dynamics involved at different stages of cyclogenesis and the interaction with each other.



(a) (b)

Figure 4. (a) schematic illustration of circulations associated with upper-level PV and surface warm anomalies, acting to reinforce each other (From Hoskins et al. 1985); (b) simple picture for diabatically produced PV anomaly, acting to re-enforce warm anomaly and to enhance advection of upper-level PV anomaly.

3.3 Case studies of extratropical cyclones using PV conceptual model

A large number of case studies have used the PV conceptual model to gain a better understanding of extratropical cyclogenesis. The PV concept is especially attractive to use because of the principles of PV conservation and invertibility. Using the invertibility property of PV these studies have attempted to quantify the contribution of upper- and lower-level PV anomalies to low-level circulation and the interactions between them. Some results suggest that latent heating influences the baroclinic dynamics simply by superposing a positive PV anomaly near the cyclone centre without significantly altering the PV structure elsewhere. On the other hand, a few studies reveal that latent heat release can enhance largely the cyclone intensity and alter significantly the structure of upper-level PV and surface thermal anomalies. Therefore, based on the weak or strong impact of diabatically produced PV anomaly on the baroclinic dynamics as found in the previous studies, their results are presented in two parts.

3.3.1 Weak contribution to cyclogenesis from latent heat release

The development of the storm of 15-16 October 1987 based on the feature of isentropic and PV surfaces was discussed by Hoskins and Berrisford (1988). It is shown that high PV stratospheric air and, to its east, a tongue of low PV sub-tropical tropospheric air exists on the 350 K isentropic surface. There is also large baroclinity and the regions of PV greater than 1.5 PVU (1PVU = 10^{-6} K m^2 kg^{-1} s^{-1}) surrounded by low values of PV. They suggest that all the features above are important but the lower-level PV maximum is crucial in the intensity of the low-level wind maximum. It is concluded that a cooperative interaction between a trough in the tropopause and low-level baroclinity was present in this case, but an extra important feature was the lower tropospheric PV maximum.

The piecewise PV inversion concept was first used by Davis and Emanuel (1991) to investigate the dynamics of extratropical cyclones in a potential vorticity framework. They developed a diagnostic system based on the conservation and invertibility properties of Rossby-Ertel PV. It is used to calculate contributions from individual PV anomalies to the overall geopotential height and wind fields of the cyclone. A particular case of cyclogenesis is examined to demonstrate the insight that can be gained by this method. They speculate that the low-level PV anomaly seems to result from the condensation of water vapor rather than from advection and contributes to about 40% of the low-level cyclonic circulation in the mature storm. It is also found that the upper-level wavelike perturbation amplified mostly from advection by the circulations associated with the lower PV and boundary θ anomalies, suggesting a mutual reinforcement of tropopause and surface Rossby waves, although the low-level PV anomaly enhances the growth of the θ anomaly. The PV destruction aloft is computed from the ω-equation and is suggested that some of the rapid downstream ridge development may have been due to the PV destruction that occurred above the maximum heating region in the upper troposphere. They emphasize that further investigation is needed regarding the overall effect of the low-level PV anomaly on the evolution of the upper-level PV anomaly.

Using the PV inversion method introduced by Davis and Emanuel (1991), the role of initial structure and condensation heating in a cyclone development over the United States on 15 December 1987 was studied by Davis (1992). This case is also compared with a different cyclogenesis event (4-5 February 1988), characterized by an initially small amplitude upper-level wave and relatively fixed structure during growth, which was studied by Davis and Emanuel. It is found that a large amplitude tropopause perturbation initiates low-level cyclogenesis and creates a localized warm thermal anomaly in the baroclinic zone. Davis points out that latent heating plays a small role in this case and superposition of upper and lower level PV anomalies is responsible for this short-lived development. The results reveal that the low-level PV anomaly and distribution of precipitation is controlled by the tropopause perturbation. It is also shown that condensation accelerated cyclonic wrapping of the upper-level PV anomaly and hastened the eastward propagation of the surface thermal wave. Davis stresses the importance of further studies in relation to the influence of latent heating on the upper-level structure. In contrast to the December case, it is concluded that in the February case, the low-level PV anomaly assisted in amplifying the surface thermal wave early in the development and the upper-level wave during the later stage of growth.

Following previous studies, Davis et al. (1993) investigated the effect of latent heating on the structure and evolution of three simulated extratropical cyclones. They use the PV inversion method along with performing numerical simulations both with and without latent heating. The cases include one continental cyclone development and two cyclones over the Western Atlantic Ocean. They conclude that condensation acts primarily to superpose a PV anomaly onto a given baroclinic structure. The structure of upper-level PV and θ anomalies is influenced by the low-level PV anomaly, but the horizontal scale of changes is too small to affect the interaction between the upper and surface anomalies. Hence, dynamical feedback from latent heating appears to be minor, even though the effect of condensation may be locally large. It is noted that indirect effects of latent heating are: an increase in the translation speed of the surface θ anomaly, intensification of the downstream ridge aloft, and an enhanced upper-level cyclonic wrapping of positive and negative PV anomalies. They stress that the basic development mechanism in the absence of condensation involves the interaction of upper-level PV and θ anomalies.

Davis et al. (1996) discuss the synoptic-scale evolution of a rapidly intensifying oceanic cyclone from the perspective of balanced dynamics. They note that the balance equations are reasonably accurate during the rapid deepening phase and also capture much of the height tendency and wind fields (nondivergent and irrotational parts). The cyclone intensification is not dominated by unbalanced processes, as suggested by Uccellini (1990). It is stressed that the existence of balanced flow consolidates the foundation of "PV thinking" which has been applied to the problem of cyclogenesis by many investigators. In their case study they also show that the largest contributions to the cyclonic circulation come from the motion of the upper level and diabatically produced PV anomalies. It is suggested that the region of negative PV anomaly is developed within the amplifying short-wave ridge and also sharp tropopause gradients to the north and west of this region are attributed to latent heat enhanced outflow. They speculate that the rapid growth in this case may be attributed to 1) the large initial amplitude of the upper-level anomaly, 2) nonlinear effects, 3) heat and moisture fluxes from the ocean in addition to a destabilized lower troposphere.

The significance of PV anomalies and their relative role in a frontal-wave cyclogenesis was examined by Fehlmann and Davis (1998). They identify two distinct upper-level PV anomalies on the 310 K isentropic surface and two lower level anomalies at 850 mb. A set of experiments with modified initial conditions, after removal of one (or more) PV anomalies, is performed. It is shown that removal of the low-level anomalies is compensated by the subsequent rapid regeneration of similar features through cloud diabatic process. This suggests that the initial configuration and amplitude of the low-level PV features is not a central or unique aspect of the development. On the other hand, cyclognesis is eliminated with the removal of upper-level PV anomalies. Their simulations indicate that the two upper-level PV anomalies interact strongly with one another, influence the surface thermal wave and the low-level PV anomaly, and yield an upper-level cut-off over the surface cyclone. They conclude that the presence and structure of the upper-level PV anomaly is intrinsic to the cyclogenesis while diabatic effects and the low-level PV anomaly play only a modulating role in this case.

As a summary, the results of the above case studies fit properly the classic picture of a baroclinic instability augmented by latent heat release as shown in Figure 4. The other noteworthy features concerning the effects of latent heat release can be summarized as: playing a small and modulating role in the interaction between the upper level and surface anomalies; control and generation by the upper disturbance; amplification of upper-level ridge downstream of the upper trough which leads to PV destruction; enhancement of cyclonic wrapping of upper-level PV anomaly and hastening the eastward propagation of the surface thermal wave.

As a main result, these studies suggest that cyclogenesis is basically driven by baroclinic dynamics and latent heat release plays the secondary role. It is also pointed out that the feedback from latent heating to the upper level and surface anomalies is minor, even though the effect of condensation may be large locally. However, these results are limited to a few case studies associated with relatively weak latent heating. They do not describe cyclogenesis events involving intense latent heat release in which this process might have profound impacts on the intensity and structure of the cyclone. Also, the overall effect of latent heating on upper level and surface anomalies has not been discussed thoroughly.

3.3.2 Intense influence of latent heating on extratropical cyclogenesis

A few studies have investigated an explosive extratropical cyclone involving intense convection to understand how the baroclinic dynamics interact with diabatic process. Craig and Cho (1992) used the semi-geostrophic approximation along with a simple parameteriza-tion for cumulus heating to study the linear stability of two comma-cloud cyclogenesis events. They attempt to describe the instabilities in terms of the interaction of PV anomalies from three sources: advection of PV gradients on isentropic surfaces, surface θ gradients, which were unimportant in each case, and PV anomaly generated by the release of latent heat. It is shown that the most important source of anomalies for the fastest growing baroclinic modes is convective heating. The modes are also characterized by short wavelengths along the jet associated with their small vertical scale that are determined by the depth of the heating region rather than by the tropopause height. They point out that some details of the model structure are influenced by the choice of parameterization for heating and the predicted wavelengths tended to be shorter than observed, largely due to errors in the specified vertical distribution of heating.

In relation to the remarkable effects of physical processes on extratropical explosive cyclones, Reed et al. in two companion papers. (1993) studied the development of the ERICA IOP 5 storm, occurred during 18-20 January 1989, The second paper describes the results of sensitivity tests along with further diagnostics such as PV-based ones. An experiment with latent heating withheld reveals an extreme sensitivity of the storm development, in both intensity and structure, to release of latent heat. It is shown that there is no noticeable difference of the surface thermal anomaly in full physics control and dry experiments, but the low-level PV field illustrates a large source of PV anomaly in the control run. The upper-level PV anomaly is also intensified significantly within 24 h. In contrast to Davis et al. (1993), they attribute this process to the enhanced vertical circulation produced by the interaction of upper and lower PV anomalies, as described in Hoskins et al. (1985), though in this case the diabatically produced PV anomaly becomes the replacement for surface θ anomaly. Reed et al. emphasize the necessity of carrying out a PV inversion to investigate this process more precisely and also the effect of an upper-level PV anomaly on the low-level circulation. Low PV values, surrounded by a narrow zone of high PV, were also found to the east of the upper-level PV anomaly.

Using the PV framework Stoelinga (1996) examined comprehensively the roles of latent heat release and surface friction in the "Scamp" storm, which occurred during 23-25 February 1987 in the Western Atlantic. His methodology involved a full physics mesoscale model, partitioned PV integration and the piecewise PV inversion technique of Davis and Emanuel (1991). Two sensitivity tests were performed removing latent heat release, and also removing surface fluxes of heat, moisture, and momentum. Using these techniques, he attempts to quantify both the accumulation of PV to particular non-conservative processes and the wind and temperature fields associated with each PV anomaly. As discussed in Balasubramanian and Yau (1994), he notes a significant positive PV anomaly above the surface warm and bent-back warm fronts at the level of maximum heating which contributed about 70% to the strength of the mature surface cyclone. He discusses how the upper-level divergence indirectly enhanced by latent heating helps prevent the primary upper-level PV anomaly from moving too rapidly downstream and thereby decoupling from the low-level disturbance. The non-divergent wind field due to the negative PV anomaly also helped to prevent decoupling by slowing down the eastward propagation of the upper-level wave and accelerating the eastward propagation of the lower level wave. He points out that the surface θ anomaly is very weak in this particular case, suggesting that cyclogenesis appears to result from superposition and mutual enhancement between the upper-level PV anomaly and the diabatically generated PV anomaly. He also stresses that this interaction cannot be easily examined through PV inversion alone.

One weakness of these studies is related to the role of surface thermal anomaly in cyclogenesis, which has not been discussed precisely. In particular, the studies of Craig and Cho (1992) and Reed et al. (1993) do not provide quantitative information about the relative importance of PV anomalies at different stages of cyclogenesis. They suggest that the thermal anomaly is very weak, but at the same time the results reveal that the baroclinic dynamics is still significant and low-level PV anomaly acts to enhance this mechanism. Also, little attention has been paid to the overall effect of latent heat release on the upper-level PV anomaly, especially the diabatic reduction of the upper-level PV anomaly.

Using conventional synoptic analysis, piecewise PV inversion, and numerical simulations Ahmadi-Givi and Craig (2001) have attempted to investigate qualitatively and quantitatively the relative contribution of different PV anomalies to the low-level circulation and interaction between them. To do this, an intensive observing period, IOP 18, of FASTEX involving intense latent heat release has been examined. Figure 5 displays the magnitude of the geopotential-height perturba-tions at 850 mb associated with the surface thermal anomaly (Theta), the upper-level PV (UPV) and diabatically generated PV (LPV) anomalies every 6 hours for a period beginning at the incipient stage and ending at the mature stage (from 0600 UTC 22 February to 1800 UTC 23 February 1997). In contrast to previous case studies, the results of PV inversion (Figure 5) and sensitivity tests (not shown) reveal that the contribution of the Theta anomaly is much weaker than those associated with the UPV and LPV anomalies, which contribute equally to the intensity of the mature cyclone. Another interesting result in Figure 5 is that the magnitude of the low-level geopotential-height perturbation associated with the UPV anomaly is substantially increased by the end of the intensifying stage when latent heating is removed throughout the simulation (UPV (L02)). This implies that latent heat release acts to considerably weaken the low-level attributed fields associated with the UPV anomaly. In general, it is shown that latent heat release has contradictory effects on the UPV anomaly. On the one hand, latent heating tends to destroy the UPV anomaly by inhibiting its downward penetration as well

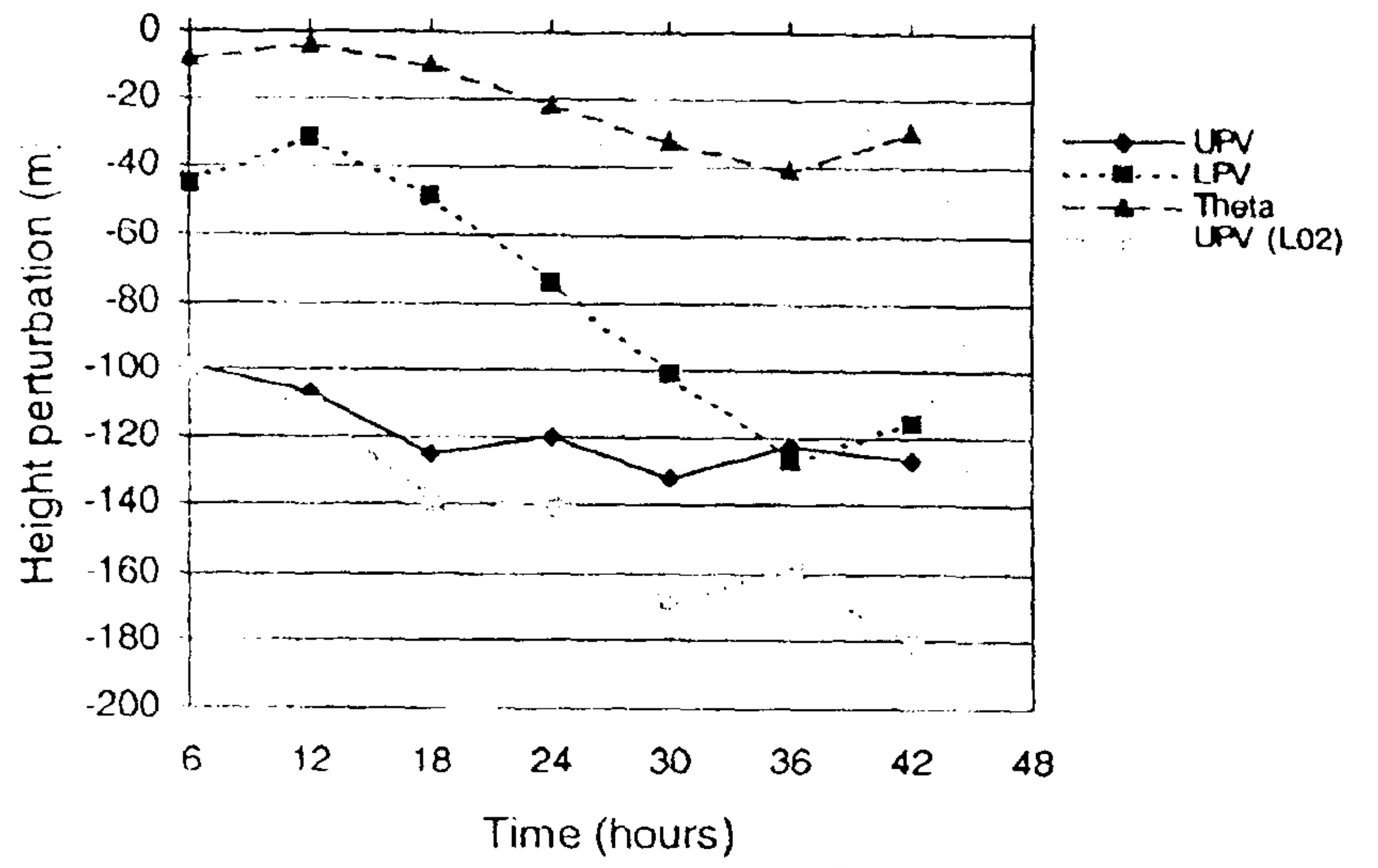


Figure 5. The contributions to the 850 mb geopotential-height perturbation from upper-level PV anomaly (UPV), diabatically produced PV anomaly (LPV), surface thermal anomaly (Theta), and upper-level PV anomaly in experiment L02, in the absence of latent heat release (UPV (L02)). Time period starts at 0600 UTC 22 February and ends at 0000 UTC 24 February 1997 (Ahmadi-Givi and Craig 2001).

as reducing its horizontal extent; on the other, it acts to enhance the effect of the UPV anomaly on the low-level cyclogenesis by amplifying the downstream ridge aloft. Figure 6 shows schematically the various effects of latent heat release on the UPV anomaly. In magnitude, it is found that the negative feedback from latent heating on the UPV anomaly is much stronger than the positive impact. They show that the LPV anomaly is controlled mainly by the UPV anomaly with a very weak contribution from surface heat fluxes.

In contrast to the case studies mentioned in section 3.3.1, the above results reveal the important effect of latent heat release on baroclinic dynamics and surface cyclogenesis. These results do not fit the simple picture of a baroclinic instability augmented by latent heat release (Figure 4). The main results of foregoing studies relevant to latent heat release are: significant contribution to the strength of the mature cyclone, intense interaction with the upper-level PV anomaly and thereby substantial effects on its magnitude and structure, becoming the replacement for surface θ anomaly.

4. Summary and conclusions

This paper has reviewed the effect of latent heat release on extratropical cyclones dynamics within the concept of "PV thinking". Based on the previous studies, it is generally agreed that release of latent heat is the most important diabatic process among the various physical processes, particularly in the explosive maritime cyclones. The use of potential vorticity as a diagnostic variable can be the most fundamental approach to the study the effect of latent heat release on cyclone development. Since the original paper of Hoskins et al. (1985), a large number of studies have used the PV concept to gain a better understanding of extratropical cyclones and processes leading to cyclogenesis. The study of diabatic processes in baroclinic cyclogenesis was less emphasised in Hoskins et al. (1985). They did not go into detail on how release of latent heat affects cyclogenesis, except to say that the reduced static stability in saturated air increases the vertical penetration of the induced fields, thus amplifying the feedback. Numerous investigations have examined the diabatic effect applying "PV thinking" to observed cyclones, and opinions vary as to its significance. Some results indicate that latent heat release may not only have profound impact on both the intensity and basic structure of a cyclone but also in some special cases, such as polar lows, may even determine whether or not cyclogenesis occurs at all. Perhaps the greatest difficulty with interpreting observations of extratropical cyclones is the enormous case-to-case variability of properties such as structure, motion, and intensity. Hoskins (1990) states that there is no unique framework for understanding the growth and decay of extratropical cyclones. This is mostly because of the freedom involved in the nonlinear interactions between the baroclinic dynamics and the various physical processes (Uccellini 1990 and Kuo et al. 1991).

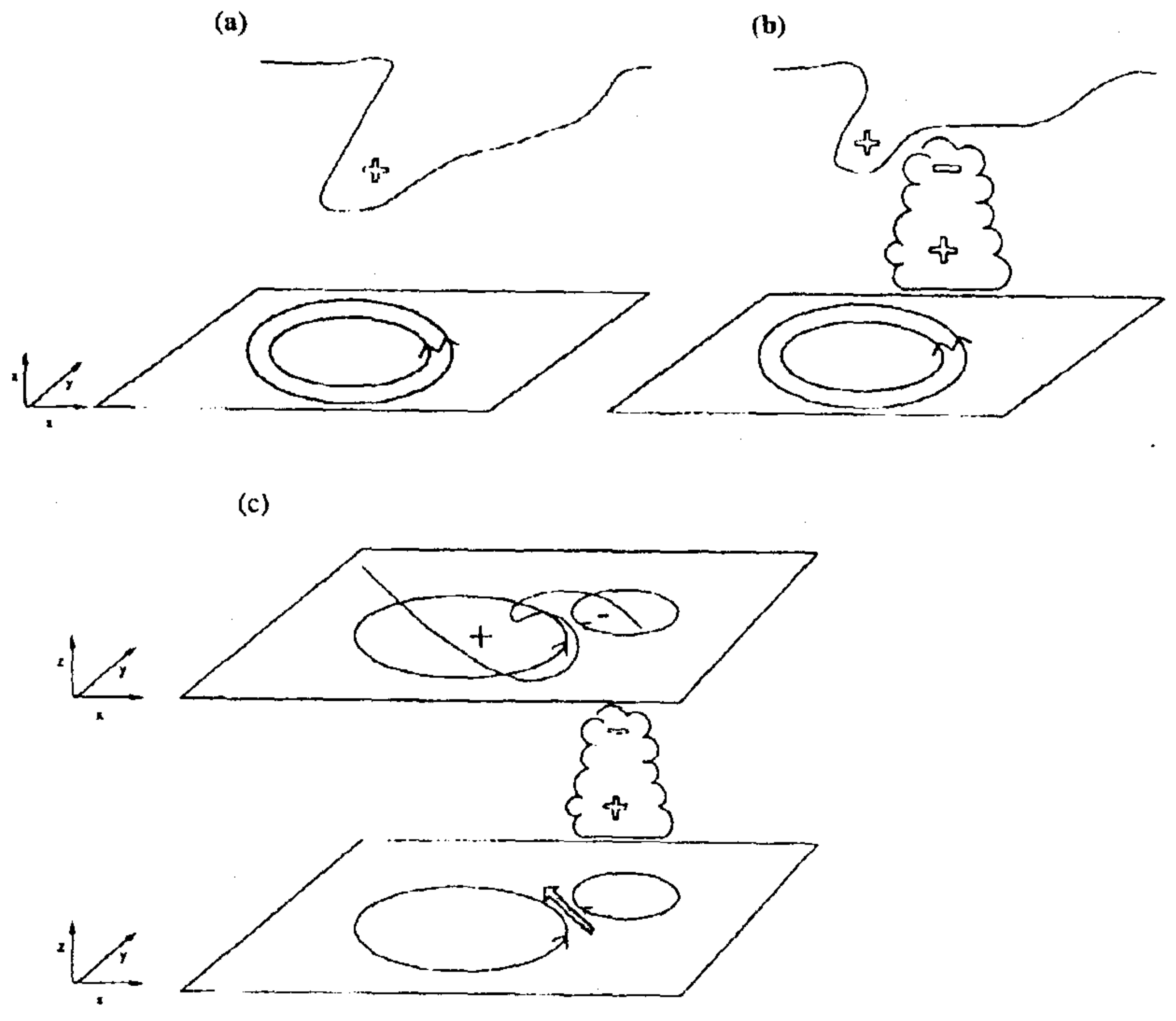


Figure 6. Schematic illustration of the various effects of latent heat release on the low - level circulation associated with the UPV anomaly; (a) with no latent heat release, (b) the negative effect, and (c) the positive effect. See text for explanation (Ahmadi-Givi and Craig 2001).

Using the invertibility principle of PV, a large number of case studies have attempted to quantify the contribution of upper- and lower-level PV anomalies to the low-level cyclone, and to show how these anomalies interact. Their results can be divided into two categories, depending on the weak or strong impact of diabatically generated PV anomaly on the baroclinic dynamics. In the weak cases, cyclogenesis is basically driven by baroclinic dynamics and latent heat release plays a secondary role. The results of these studies fit properly the classic picture of a baroclinic instability augmented by latent heat release (Figure 4). The primary effect of latent heat release is to produce a positive PV anomaly above the surface warm anomaly. The cyclonic circulation associated with the diabatic PV anomaly reinforces that of the surface warm anomaly and enhances the upper-level PV anomaly by advection. Latent heat release also produces a negative PV anomaly in the upper troposphere that can amplify the upper-level ridge downstream of the cyclone center, but this effect appears to be less significant. In contrast to the weak cases, some results reveal the important effect of latent heat release on baroclinic dynamics and surface cyclogenesis. The dynamics of these cases are not adequately described by the conventional baroclinic instability theory, possibly modified by latent heat effects. Release of latent heat makes a very large contribution to the intensity of the surface cyclone, particularly when the surface thermal anomalies are weak. The low-level diabatically produced PV anomaly becomes the replacement for the surface warm anomaly. It is also suggested that diabatically generated PV anomaly has a considerable negative impact on the upper-level PV anomaly, reducing both its downward penetration and its horizontal extent (Figure 6). This leads to a significant decrease in the low-level winds and height perturbations induced by the upper-level PV anomaly.

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