Temperature Advection

Recall the First Law of Thermodynamics:

$$c_p \frac{dT}{dt} - \alpha \frac{dp}{dt} = \dot{q} \qquad \text{where } \dot{q} \text{ is heating rate.} \qquad (1)$$

Recall that $\alpha = \frac{RT}{p}$ and that in pressure coordinates,

$$\frac{dp}{dt} = \omega \quad \text{(vertical motion) by definition}$$

We can write (1) as a prediction equation for temperature; i.e., - following a parcel:

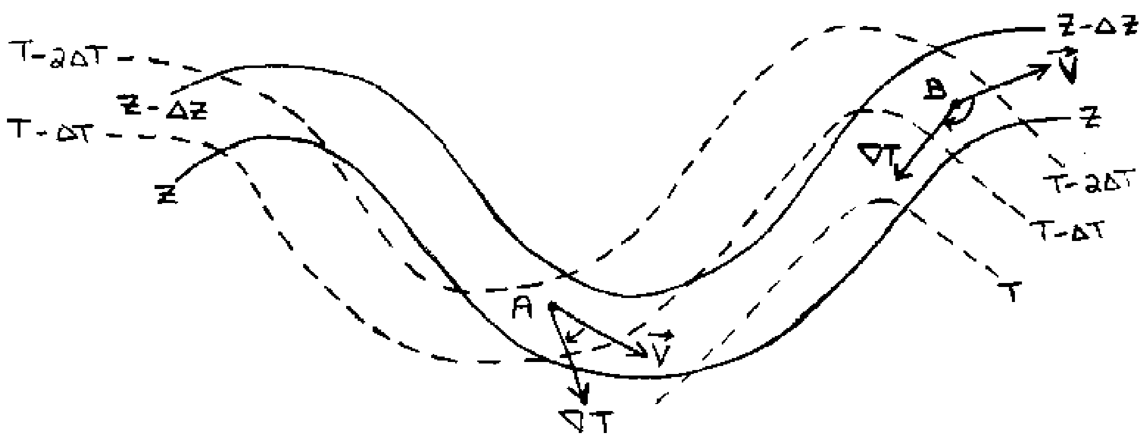
$$\frac{dT}{dt} = \underbrace{\frac{RT}{c_p p}\omega}_{\text{adiabatic heating or cooling}} + \underbrace{\frac{\dot{q}}{c_p}}_{\text{diabatic heating or cooling}} \qquad (2)$$

For example, if $\omega < 0$ (rising motion), $\frac{dT}{dt} < 0$; (cooling by adiabatic expansion).

We can write (2) in Eulerian form:

$$\frac{\partial T}{\partial t} = \underbrace{-\vec{V} \cdot \nabla T}_{\text{horizontal advection of temperature}} \underbrace{- \omega \frac{\partial T}{\partial p}}_{\text{vertical advection of temperature}} + \frac{\alpha}{c_p}\omega + \frac{\dot{q}}{c_p} \qquad (3)$$

To physically interpret horizontal temperature advection, we draw a pattern of isotherms lagging contours that one might see for a developing wave cyclone:



Consider point A: $\vec{V} \cdot \nabla T > 0$ since $\theta < 90°$ and $-\vec{V} \cdot \nabla T < 0$; i.e., - negative horizontal temperature advection. Therefore, the temperature at point A cools with time (due to this term). Now since A is behind the trough axis, $\omega > 0$ (sinking); since $\frac{\partial T}{\partial p} > 0$ (except in inversions), then $-\omega \frac{\partial T}{\partial p} < 0$ which is negative vertical temperature advection (i.e., - subsidence is bringing cold air from higher to lower levels).

But if $\omega < 0$, then $\alpha/c_p\ \omega > 0$ and we have adiabatic warming at point A due to this term. The latter effect is larger, however, than the $-\omega \frac{\partial T}{\partial p}$ cooling because α/c_p is the dry adiabatic lapse rate while $\frac{\partial T}{\partial p}$ is the actual or observed lapse rate which is usually smaller. Thus, $-\omega\left(\frac{\partial T}{\partial p} - \frac{\alpha}{c_p}\right)$ is positive at point A, and $\frac{\partial T}{\partial t} > 0$ at point A. This means that the cooling due to horizontal advection is opposed by adiabatic warming at point A.

The student should verify that at point B, we have warm temperature advection which is opposed by adiabatic cooling due to rising motion.

The horizontal advection effects are usually larger but one should be aware that adiabatic effects may occasionally dominate where vertical motions are large and/or the stability is large.

Recall that the First Law may also be written with potential temperature as the dependent variable:

$$\frac{d\theta}{dt} = \frac{\theta}{c_p T}\dot{q} \tag{4}$$

and if diabatic heating = 0

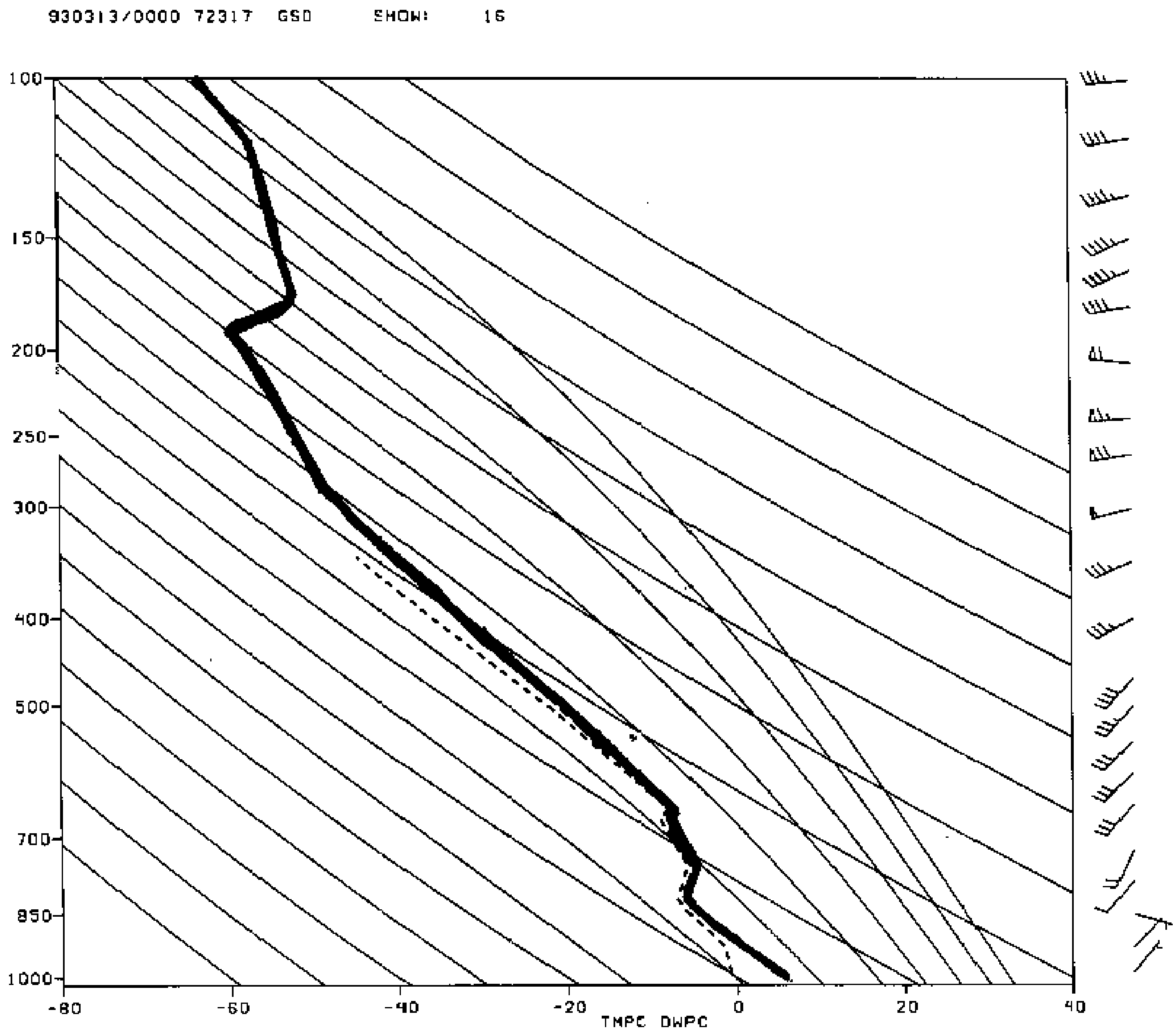
$$\frac{d\theta}{dt} = 0 \tag{5}$$

Here we say that the motion is adiabatic, θ is conserved following the parcel, and the parcel travels on an isentropic surface. Expanding (4) into Eulerian form,

$$\frac{\partial \theta}{\partial t} = -\vec{V} \cdot \nabla_p \theta - \omega \frac{\partial \theta}{\partial p} + \frac{\theta}{c_p T}\dot{q} \tag{6}$$

Here $-\omega \frac{\partial \theta}{\partial p}$ corresponds to the $-\omega\left(\frac{\partial T}{\partial p} - \frac{\alpha}{c_p}\right)$ term, and since $\frac{\partial \theta}{\partial p}$ is usually < 0, we have warming for sinking motion ($\omega > 0$), and cooling for rising motion ($\omega < 0$), as deduced above. The student should be able to obtain (3) from (6) and vice versa.

If $\dot{q} > 0$ (diabatic heating), $\frac{d\theta}{dt} > 0$ and the parcel moves to a higher θ-level in the atmosphere.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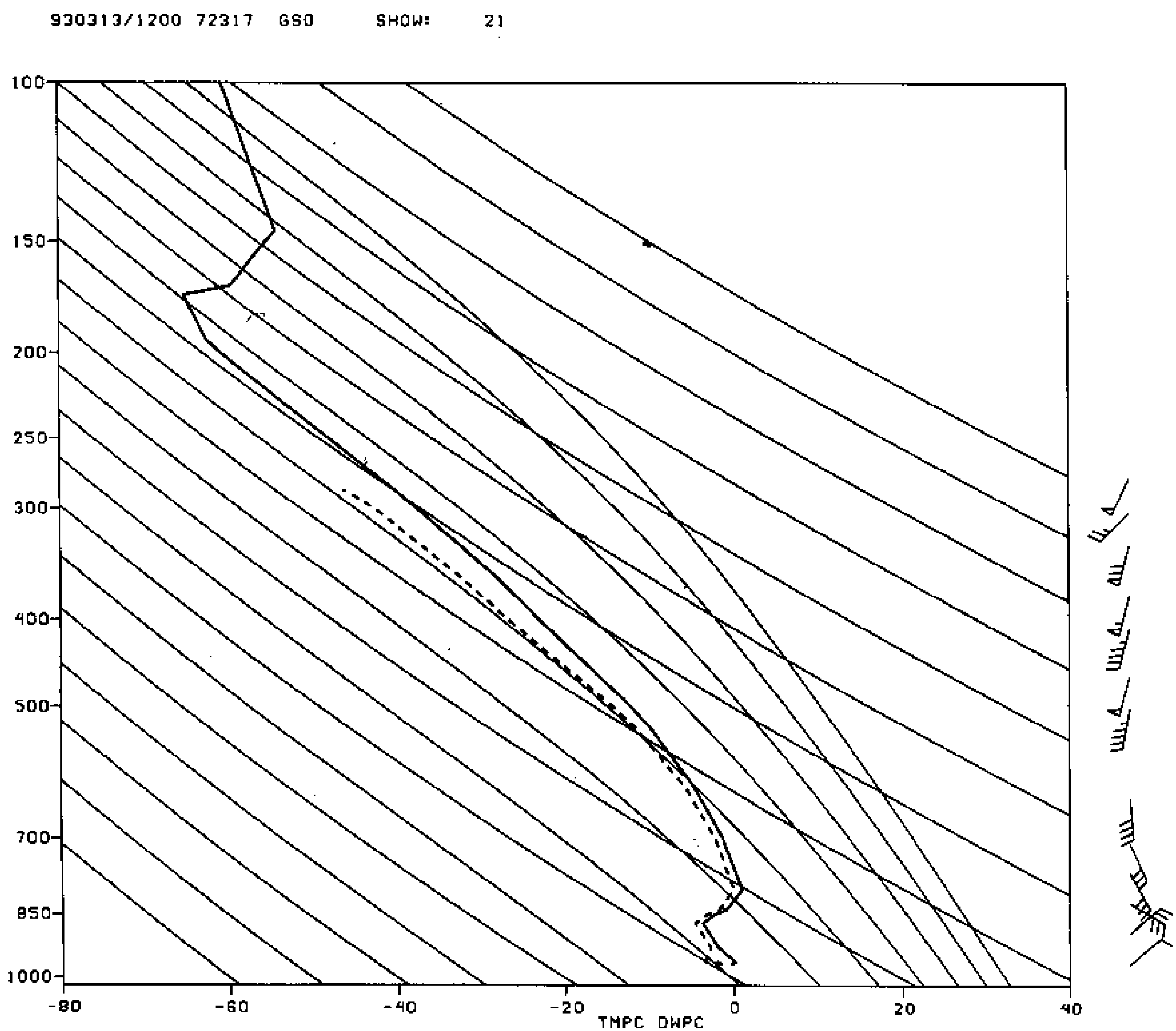
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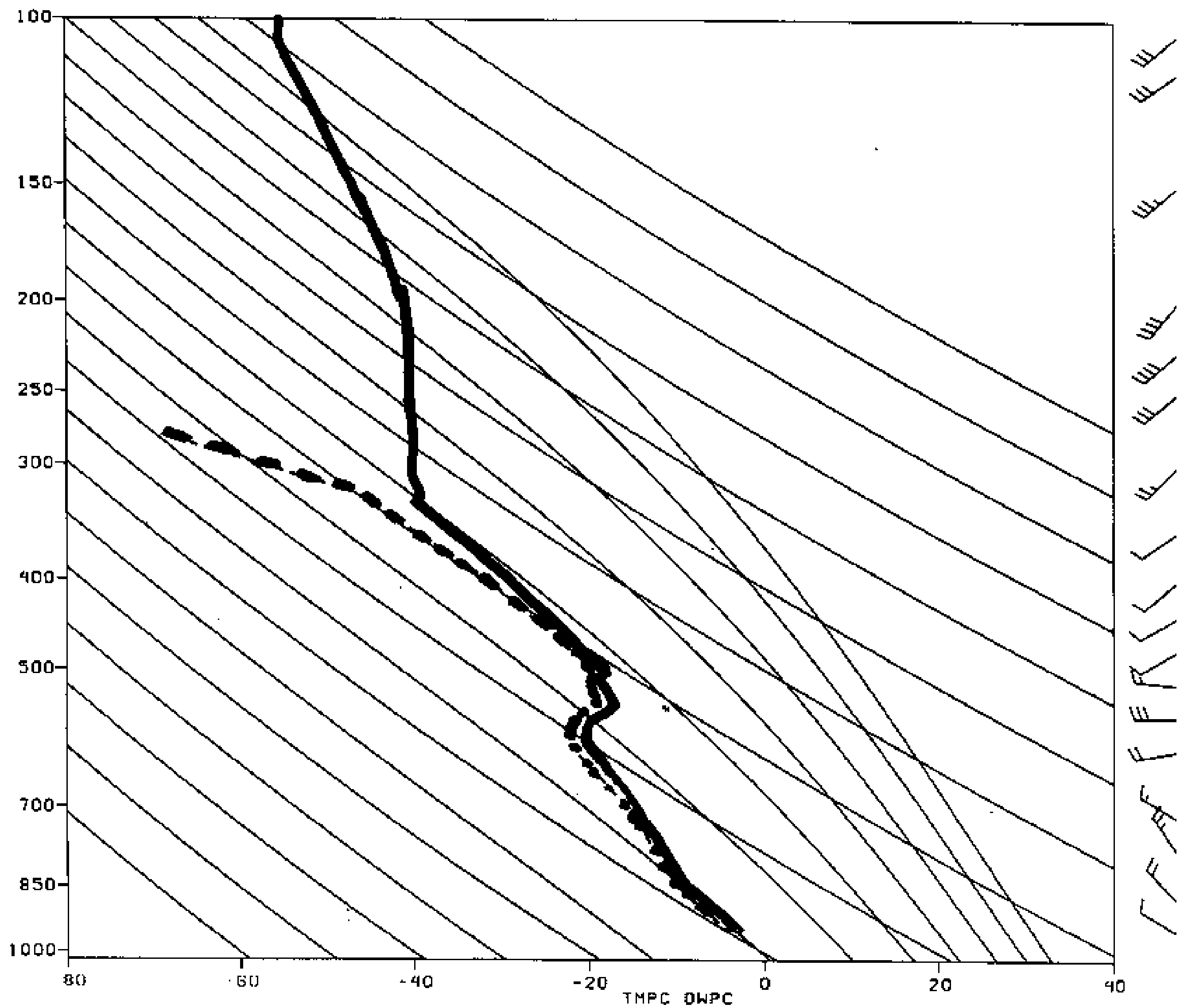

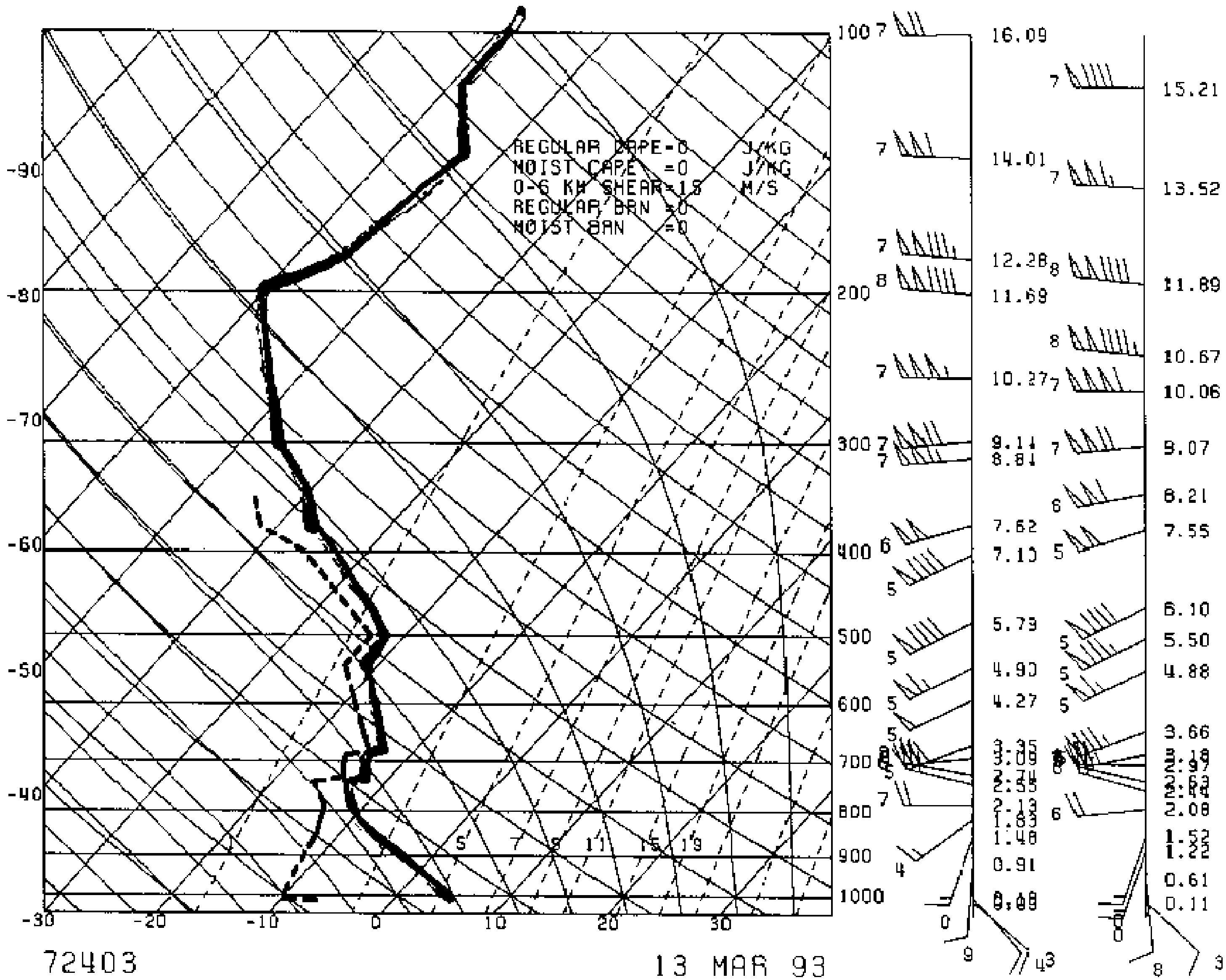

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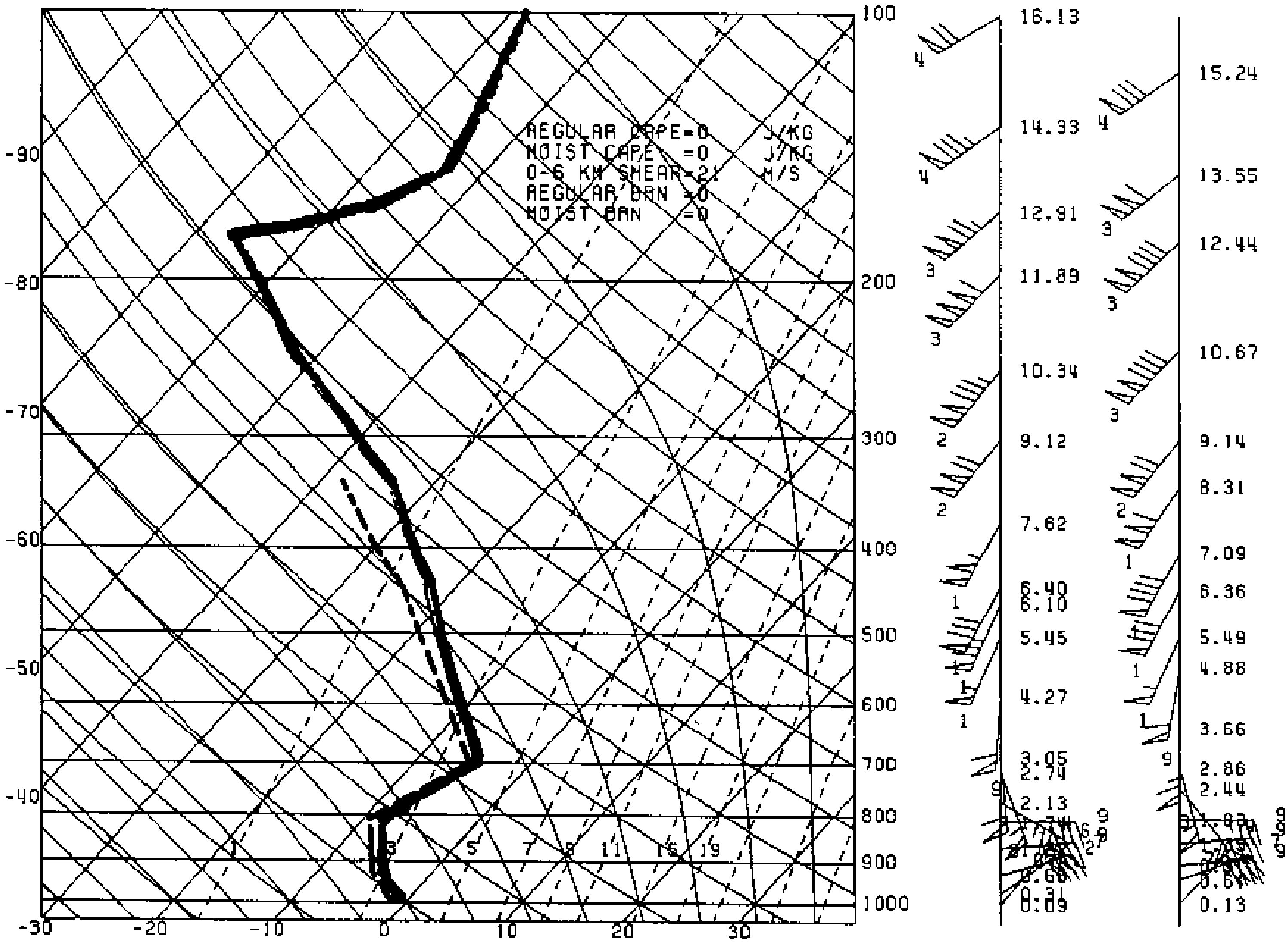

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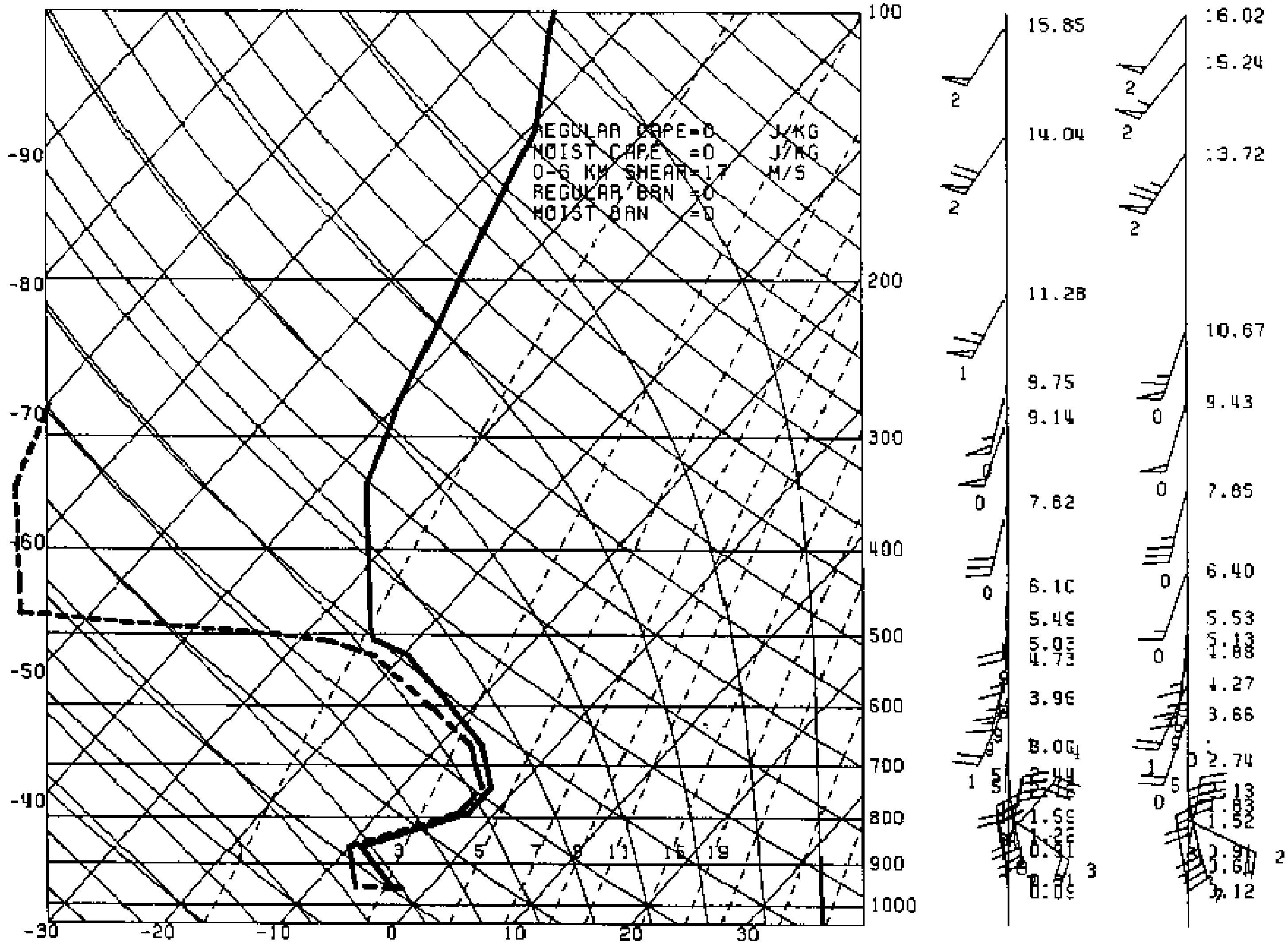

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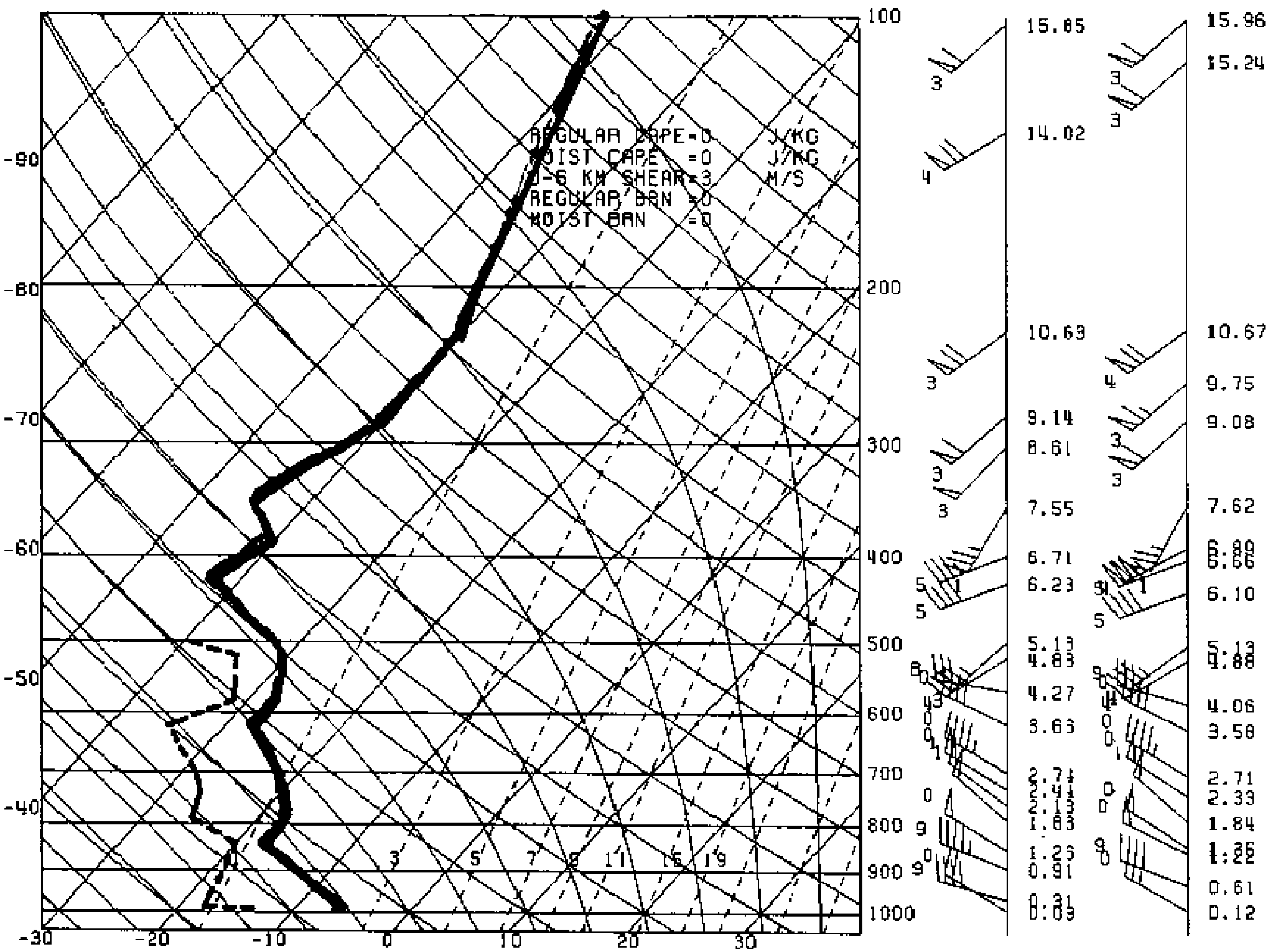

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gated by several authors, notably Palmen [22] and Hsieh[23]. The initial disturbance can usually be identified with a trough in the isotherms which is situated upwind from the trough in the contours at, say, the 500-mb level. There is then cold advection in the rear of the trough and warm advection further upwind. This stage is shown in Diagram A of Fig. 12.8.4. These advections appear to be favorable for growth of the contour wave, with the result that the next stage will be shown in Diagram B.

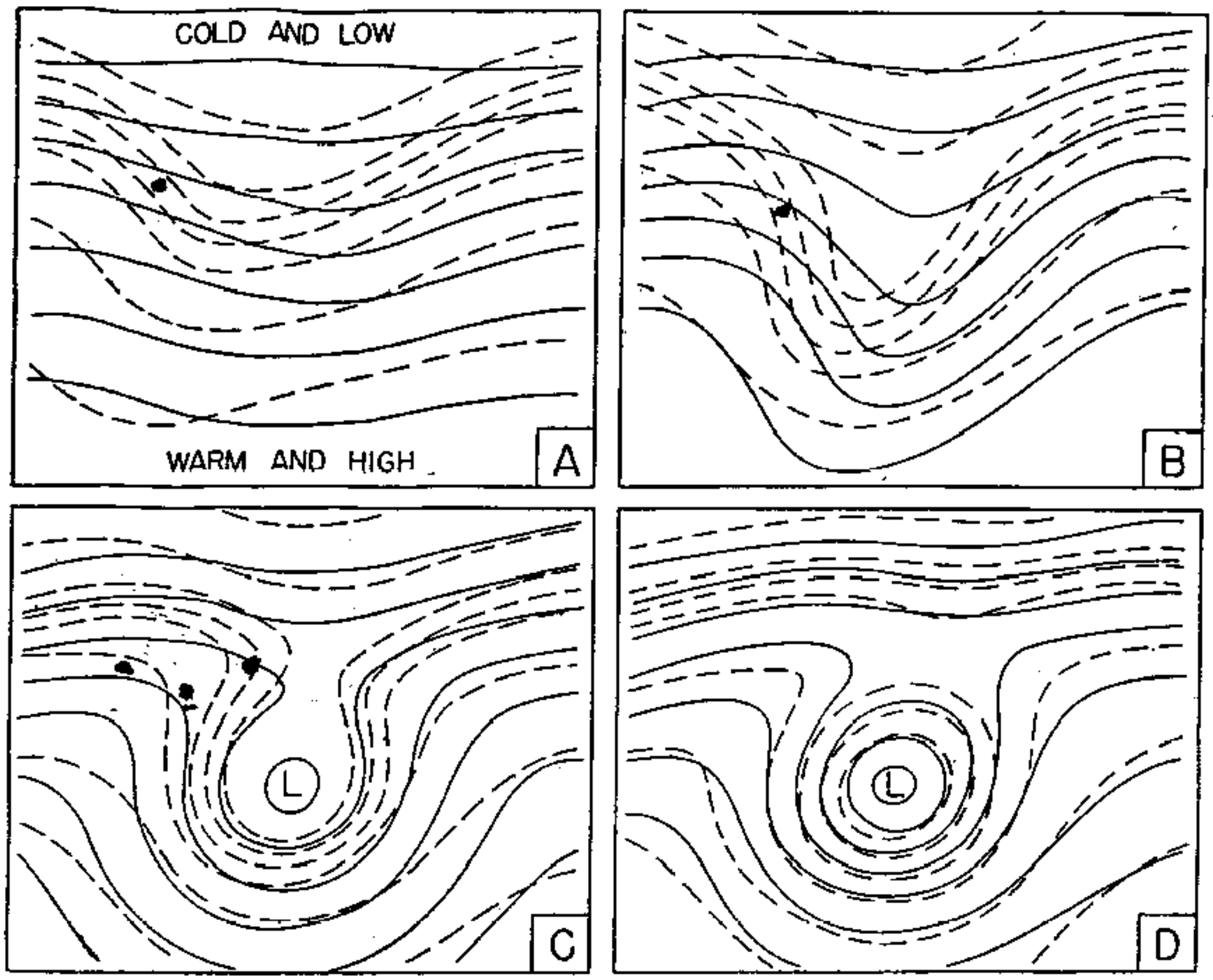

Fig. 12.8.4. Typical features of the development of a cutoff low. (*Mainly after Hsieh [23].*)

In the third stage (Diagram C) the warm air from the west begins to merge with the warm air to the east of the trough; a ridge of high pressure builds across the trough, thus cutting off a dome of cold air and a closed cyclonic circulation to the south. In the final stage of development (Diagram D), a ribbon of isotherms has been established to the north and the cutoff low has acquired a high degree of thermal symmetry.

Quite frequently, the development of a cutoff high is accompanied by the formation of one or more cutoff lows in neighboring regions. It is typical of these developments that the initial state may be identified with upper-air troughs and wedges which are out of phase with the thermal pattern.

The typical features of a developing cutoff high are shown in Fig. 12.8.6. In the early stage (Diagram A), appreciable amounts of warm advection are found to the windward of the wedge aloft. The wedge, which usually moves very slowly, gradually expands northward, and after some considerable time the stage shown in Diagram B is reached. The flow around the wedge has changed from a wave-shaped to an Ω-shaped pattern. At this stage the meandering zonal current begins to split; the main current swinging around the wedge, while the secondary current begins to penetrate along the base of the Ω-shaped pattern. In favorable circumstances the cutoff high acquires appreciable dimensions and intensity; the zonal current develops two distinct branches; sharp troughs or cutoff lows develop to the southwest and southeast, as shown in Diagram C. On occasions the trough may assume the shape of a shear line.

The most striking example in recent years of development of a cutoff high with neighboring cutoff lows is, perhaps, the one that commenced about February 12, 1948, developed into a major circulation system, and dominated the conditions over western Europe for more than 2 weeks.

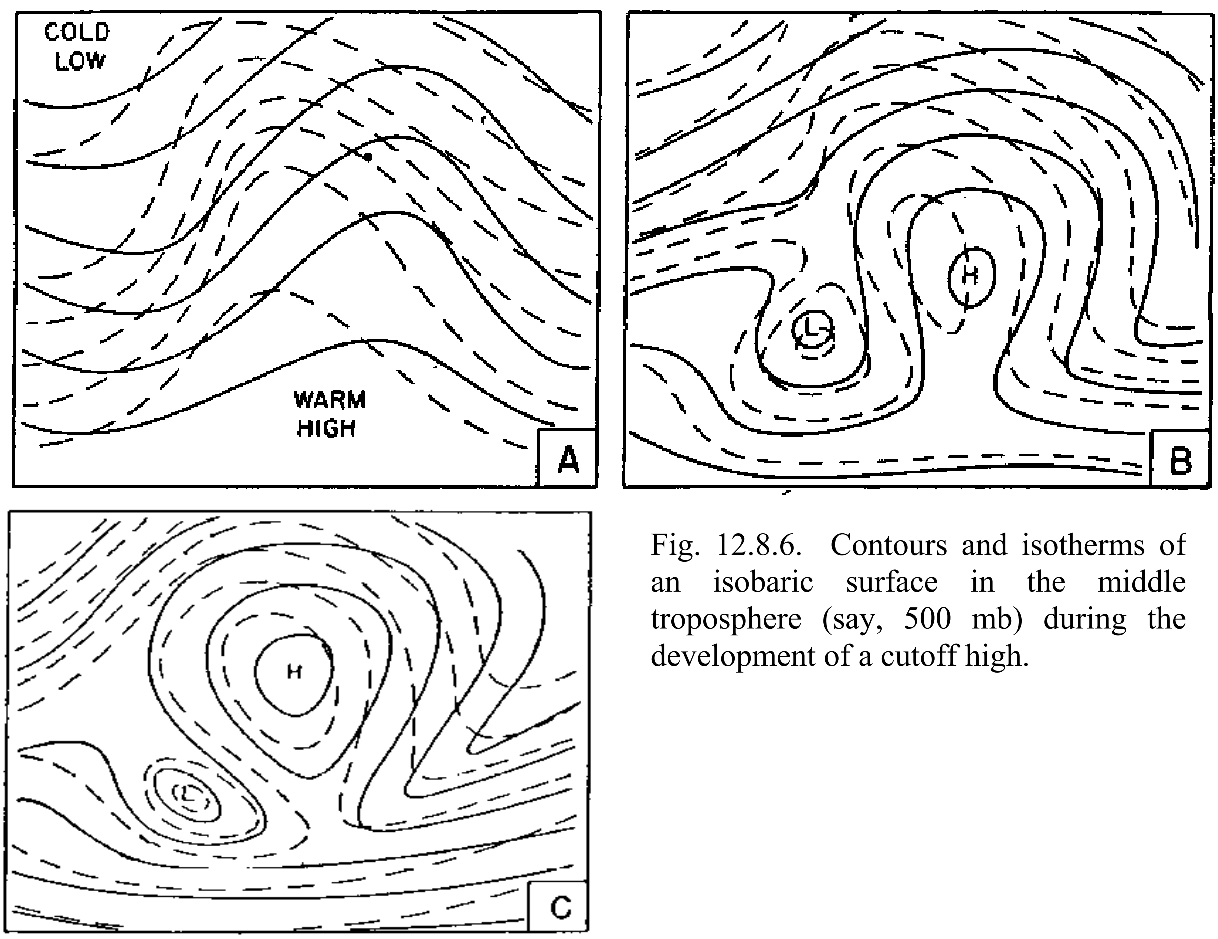

Fig. 12.8.6. Contours and isotherms of an isobaric surface in the middle troposphere (say, 500 mb) during the development of a cutoff high.