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Dynamical Aspects of the Life Cycle of the Mid-Latitude Cyclone

Objectives

The single most common weather element in the middle-latitudes is the frontal cyclone. As a consequence of this fact, the mid-latitude cyclone has been the subject of scientific scrutiny for well over 200 years. In this chapter we will employ the diagnostic tools and dynamical insights thus far developed and apply them to gain an understanding of the structure, evolution, and underlying dynamics of the mid-latitude cyclone life cycle.

This life cycle consists of various stages. We will pursue our investigation of several of these stages by adopting the perspective that the cyclone is the product of development initiated by finite, identifiable disturbances in the flow, not a manifestation of unstable growth of an infinitesimal perturbation. Consistent with this choice of perspective, we will make use of the quasi-geostrophic diagnostics developed in previous chapters to consider the dynamics of the cyclogenesis, post-mature, and decay stages of the cyclone life cycle. Examination of the post-mature stage will involve consideration of the structural and dynamical nature of the occlusion. Though research regarding the mid-latitude cyclone stretches back into the eighteenth century, we will begin our investigation by considering the broad structural characteristics of these storms starting with the synthesis of prior observations made manifest in the so-called polar front theory of cyclones.

8.1 Introduction: The Polar Front Theory of Cyclones

Much of the understanding of mid-latitude cyclones that existed before the turn of the twentieth century was fragmentary and lacked an organizing conceptual framework. Just after the end of World War I, meteorologists at the University of Bergen in

Norway, under the leadership of Vilhelm Bjerknes,¹ developed the polar front theory of the structure and life cycle of mid-latitude cyclones, now known colloquially as the Norwegian Cyclone Model (NCM). The essential genius of this conceptual model, which represented a grand synthesis of prior insights concerning the cyclone, was that it described the instantaneous structure of the cyclone while placing that structure into an identifiable life cycle. At the conceptual heart of the NCM was the existence of a globe-girdling, tropospheric deep, knife-like boundary known as the polar front which separated cold polar air from warm tropical air (Figure 8.1a). For reasons that were not discussed in the seminal paper by Bjerknes and Solberg (1922) that introduced the NCM, perturbation vortices occasionally developed along this polar front (Figure 8.1b). The existence of such vortices would then serve to deform the polar front, locally ushering tropical air poleward and polar air equatorward (Figure 8.1b). The precise mechanism by which the perturbation vortex would grow in intensity is not well explained in the NCM, but the continued growth of the perturbation was thought to lead to further deformation of the polar front (Figure 8.1c) and a lower sea-level pressure at the center of the perturbation. By this so-called mature stage of the life cycle, the deformation of the polar front had become so extreme as to lend the cyclone its now familiar characteristic frontal structure: a cold front extending equatorward and a warm front extending eastward from the sea-level pressure minimum. The region of homogeneous temperature between the two fronts was deemed the warm sector. Continued intensification of the cyclone compelled the cold front to encroach upon, and subsequently overtake, the warm front. Two important results of this process were that (1) the sea-level pressure minimum was removed from the peak of the warm sector and (2) an occluded front developed to connect the cyclone center to the peak of the warm sector (Figure 8.1d). It was thought that this process could result in the development of two varieties of occluded fronts in cyclones. One of these was the so-called warm occlusion in which the cold front would ascend the warm front upon overtaking it, leading to a vertical structure similar to that portrayed in Figure 8.2(a). Conversely, a so-called cold occlusion would result if the encroaching cold front was able to undercut the warm front and a vertical structure similar to that portrayed in Figure 8.2(b) would result. The warm (cold) occlusion was thought to occur when the air poleward of the warm front was more (less) dense than the air west of the cold front. Note that in either case, the development of the occluded front was associated with the denser air lifting the less

¹ Vilhelm Bjerknes was born on 14 March 1862 in Christiania, Norway (now Oslo). He was the son of a professor of mathematics and the father of Jacob Bjerknes whose seminal paper written with Halvor Solberg in 1922 established the Norwegian Cyclone Model. He earned an MS in 1888 and then moved to Bonn, Germany where he collaborated with Heinrich Hertz and received his Ph.D. in 1892. In 1897 he discovered the circulation theorem that bears his name and thereafter pursued research aimed at employing the circulation theorem to scientific weather forecasting. He was the driving force behind the establishment of the Bergen Geophysical Institute, colloquially known as the Bergen School, which eventually attracted such giants as Solberg, Bergeron, Petterssen, and Rossby. He died in 1951.

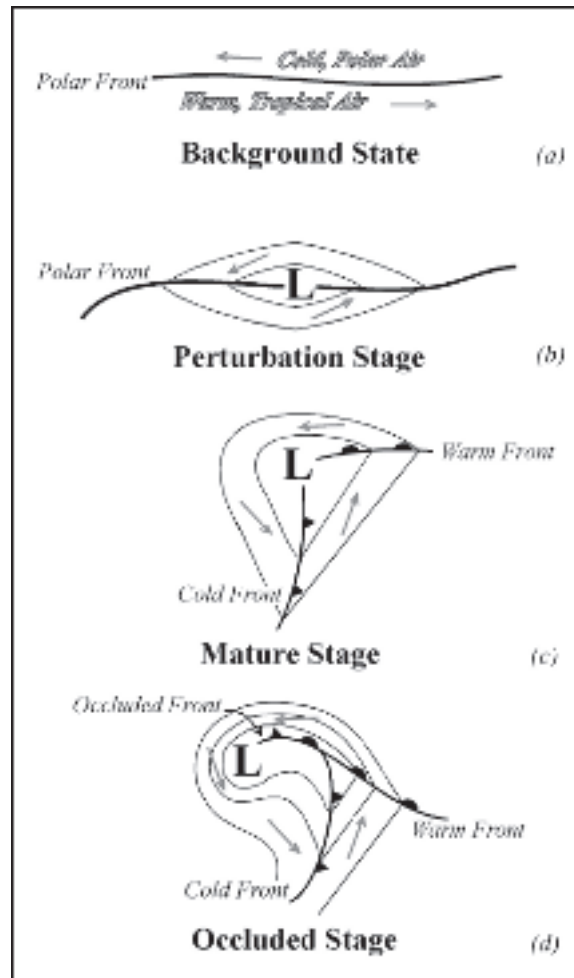


Figure 8.1 Evolution of a mid-latitude cyclone according to the Norwegian Cyclone Model. (a) The polar front as a background state. (b) The initial cyclonic perturbation. (c) The mature stage. (d) The occluded stage. The thin solid lines are isobars of sea-level pressure and the arrows are surface wind vectors

dense air aloft. In so doing, the horizontal density contrast originally characterizing the cyclone (manifest in the horizontal temperature gradient associated with the polar front) was reduced and a stable vertical stratification near the cyclone center was gradually put in place. As illustrated in Figure 8.3, transformation of an originally horizontal density contrast into a purely vertical one reduces the center of gravity of a fluid system gradually driving the system to its lowest potential energy state. Based upon this type of energetics argument, the NCM proposed that the development of the occluded front heralded the post-mature phase for a mid-latitude cyclone, a

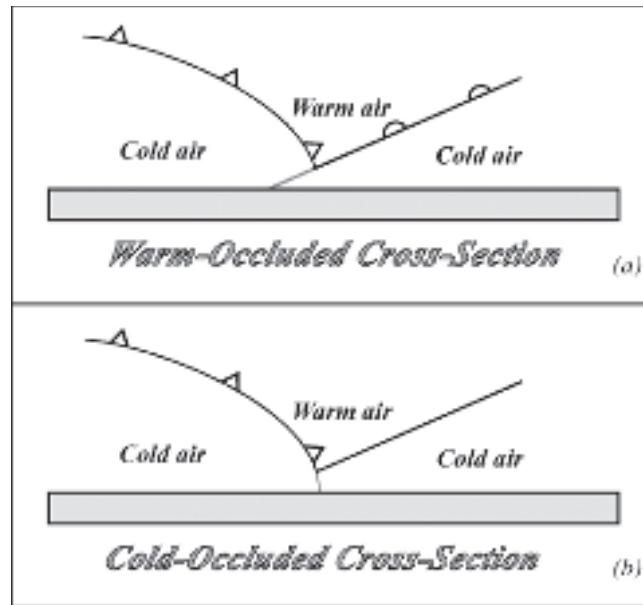


Figure 8.2 (a) Vertical cross-section through a warm occlusion in which the cold front ascends the warm front leaving a warm occluded front near the surface (gray line). (b) Vertical cross-section through a cold occlusion in which the warm front ascends the cold front leaving a cold occluded front near the surface (gray line)

cessation of intensification, and the commencement of cyclone decay. The nature of the cyclone decay was not described in the NCM beyond mention of the fact that the post-mature phase cyclone would eventually succumb to frictional dissipation associated with the surface of the Earth.

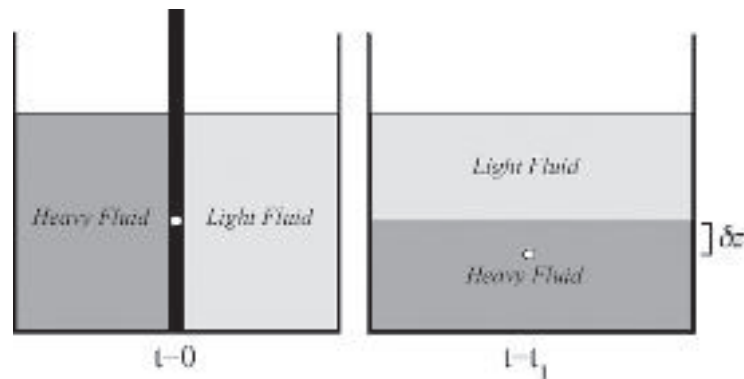


Figure 8.3 Fluids of different densities separated horizontally in a container by a dividing wall (thick black line) at $t = 0$. The white dot represents the height of the center of gravity of the two-fluid system. At $t = t_1$, after the divider has been removed, the height of the center of gravity of the fluid system has been lowered by an amount δz

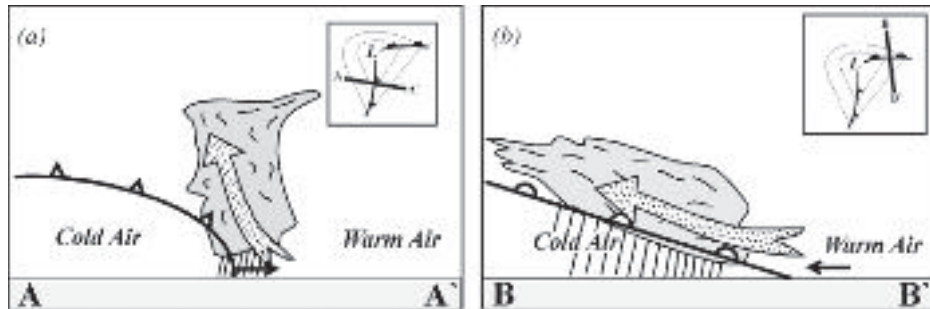


Figure 8.4 (a) Vertical cross-section through a cold front according to the NCM. Dotted arrow represents the updraft of air at the frontal boundary. Inset indicates the location of A–A', referring to Figure 8.1(c). (b) Vertical cross-section through a warm front according to the NCM. Inset indicates the location of B–B', referring to Figure 8.1 (c). Dotted arrow represents the updraft of air at the frontal boundary

The NCM accounted for the typical cloud and precipitation distribution associated with a mid-latitude cyclone with reference to the vertical structure of the fronts themselves. The cold front was described as a steeply sloped boundary between polar and tropical air masses that steadily advanced into the tropical air. The advance produced upgliding motions along the boundary itself and, as a consequence of its steep slope, the updrafts were vigorous and horizontally restricted leading to a narrow, sometimes squally precipitation distribution (Figure 8.4a). The warm front, on the other hand, was a less steeply sloped boundary between advancing tropical air and gradually retreating polar air (Figure 8.4b). The upgliding motions along the warm frontal surface were considered to be less intense as a consequence of the shallower slope. As a result, the cloudiness associated with the warm front was more horizontally widespread and the precipitation more benign.

Despite its great insights, the NCM, like all great conceptual leaps, certainly has its limitations. For instance, the nature of, and relationship between, the perturbations which grow into cyclones and the large-scale environment that promotes such growth are not addressed in the NCM and yet are clearly at the heart of understanding the mid-latitude cyclone life cycle. In addition, as discussed in Chapter 7, much more dynamically compelling arguments exist for explaining the production of vertical circulations at fronts. The fronts themselves, in fact, are not knife-like discontinuities as suggested by the NCM but zones of contrast across which temperature, density, and pressure are continuous. Neither are the frontal zones continuous through the depth of the troposphere. Note also that the NCM does not describe the physical mechanisms by which the cyclone intensifies from its incipient stage (Figure 8.1b) through its post-mature stage (Figure 8.1d). Also the development of the surface occluded front, though partly described through reference to the vertical frontal structure, is more correctly viewed as part of a process of occlusion that needs to be more comprehensively considered. Additionally, the decay of the cyclone is barely discussed in the NCM and yet clearly represents a major component of the cyclone

life cycle. Finally, given the lack of available upper air observations at the time of its development, the NCM does not describe the vertical structure of cyclones and the manner in which that vertical structure supports the cyclone and evolves throughout its life cycle. In the remainder of this chapter we will investigate (1) the nature of cyclogenesis (the intensification of a cyclone), (2) the process of occlusion, and (3) the nature of cyclolysis (the decay of a cyclone). In order to provide a broad background to these discussions, and to illuminate some characteristics of a basic hydrodynamic instability that underlies the existence of mid-latitude cyclones, we first explore the basic environmental conditions that prevail at middle latitudes and then explore the characteristic vertical structure of a developing mid-latitude cyclone building our model literally from the ground up.

8.2 Basic Structural and Energetic Characteristics of the Cyclone

The uneven heating of the spherical Earth results in a pole-to-equator temperature gradient on the planet. As a consequence of the dominance of the thermal wind balance outside of the tropics, such a temperature gradient is manifest as a baroclinic westerly vertical shear at middle latitudes. If we consider the rather hypothetical situation in which the mid-latitude flow is purely zonal and in thermal wind balance, then at some middle or upper tropospheric level the geopotential height lines and isotherms would be everywhere parallel. Imagine that a wave-like perturbation were introduced into this flow and that the speed of the wave exactly equaled the speed of the background zonal flow. In such a case, only the meridional motions associated with the perturbation would be discernible. Those meridional motions would promote warm air advection downstream of the trough axis and cold air advection upstream of the trough axis as shown in Figure 8.5, eventually producing a wave in the thermal field that would lag the wave in the momentum field by one-quarter

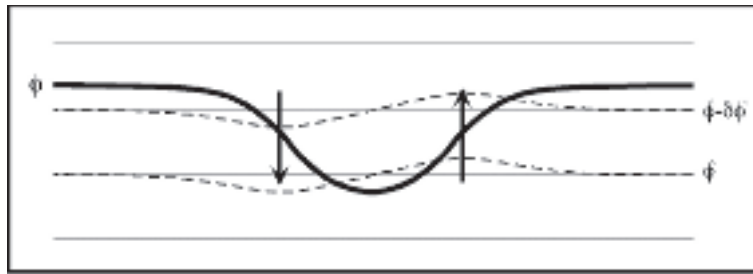


Figure 8.5 Effect of introducing a wave in the momentum field into a zonally oriented bundle of column-averaged isotherms. Light gray lines are undisturbed thickness isopleths of the mean state. Dashed lines are the disturbed thickness isopleths after the meridional motions of the wave (arrows) have distorted them. The thick black line shows a schematic geopotential height line. Note that the resulting thickness wave is a quarter wavelength out of phase with the wave in the geopotential height

wavelength. In order for this wave-like perturbation to grow, two conditions must be met: (1) the positive and negative zonal temperature anomalies must become larger, and (2) the kinetic energy associated with the wave motions must increase.

The pole-to-equator temperature gradient represents a horizontal density contrast conceptually analogous to that shown in the left panel of Figure 8.3. If, by some mechanism, the dense fluid ends up beneath the less dense fluid (as shown in the right panel of Figure 8.3) then the center of mass of the fluid system has been reduced and there has been a conversion of *some* of the initial potential energy into the kinetic energy of the fluid motions involved in the rearrangement. That fraction of the total potential energy that can be converted into kinetic energy is known as the **available potential energy** (APE). Were our hypothetical wave-like disturbance able to convert the APE of the background zonal baroclinic shear into the kinetic energy of its own motions then the wave-like perturbation would grow at the expense of the basic flow. In such a case, we would designate the background flow as unstable to the introduction of such a disturbance.

Mid-latitude cyclones and anticyclones are wave phenomena. As a result, any regional sea-level pressure analysis, such as the example shown in Figure 8.6, will display an alternating sequence of surface high- and low-pressure disturbances. In order that a surface low- (high-) pressure system remain a region of relative low (high) pressure, air must be extracted from (stuffed into) the atmospheric column above the surface. Thus, an alternating sequence of highs and lows, each associated with sinking or rising air in their respective columns, characterizes a mid-latitude wave train as shown in Figure 8.7(a). Recall that based on simple curvature arguments alone, we know that upward (downward) vertical motions occur downstream of trough (ridge) axes at upper tropospheric levels. Consequently, regions of low (high) geopotential height must be located to the west of the rising (sinking) air columns as shown in Figure 8.7(b). Thus, we know that for developing mid-latitude disturbances, the geopotential height axes tilt westward, into the vertical shear, with increasing height.

Recall that at the mature stage of the mid-latitude cyclone, the low-pressure center is located at the peak of the warm sector. The surface anticyclone lies to the west of the surface cyclone with its center close to the center of minimum temperature at sea level. Now, since the hypsometric equation relates thickness to column-averaged temperature, upper tropospheric geopotential minima (maxima) must lie atop relatively cold (warm) columns. Thus, as shown in Figure 8.7(c), the thermal axes of developing mid-latitude waves tilt eastward with increasing height. Finally, note that since the air is rising through the warm column and sinking through the cold column, developing mid-latitude disturbances are characterized by thermally direct vertical circulations which convert the APE of the background baroclinicity, which is itself manifest in the westerly vertical shear of the large-scale flow, into the kinetic energy of the disturbances.

The fact that the structure of the mid-latitude cyclone results in spontaneous conversion of APE to kinetic energy implies that the background zonal baroclinic

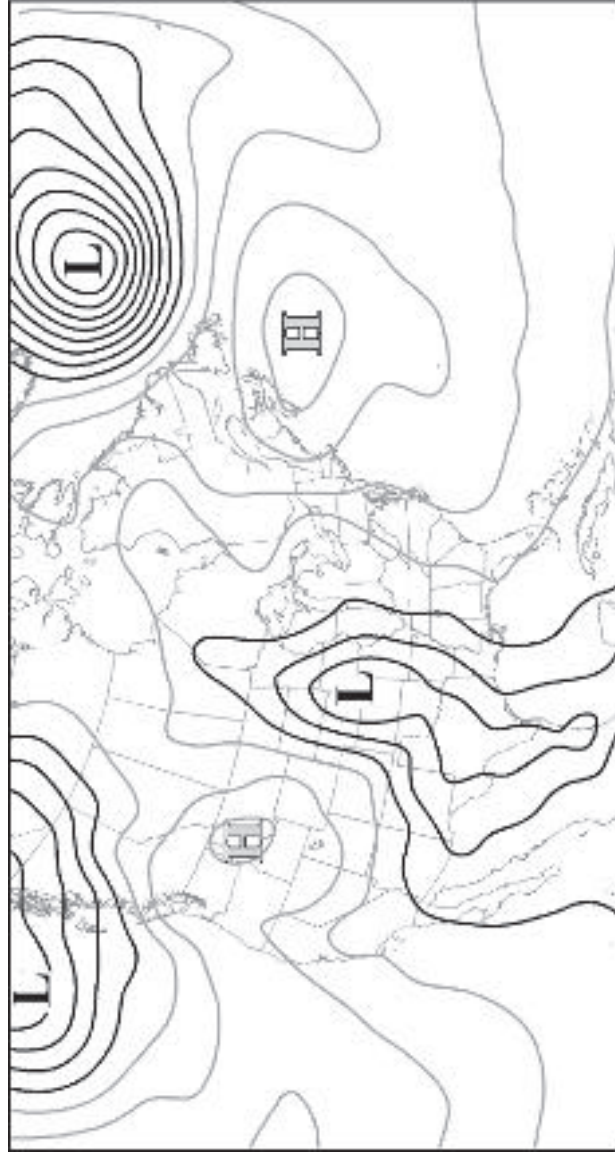


Figure 8.6 Sea-level pressure analysis over North America at 1200 UTC 16 April 2004. Solid lines are isobars contoured every 4 hPa with black (gray) lines corresponding to pressures less than (greater than) or equal to 1012 (1016) hPa. The L and H identify centers of surface low- and high-pressure systems, respectively

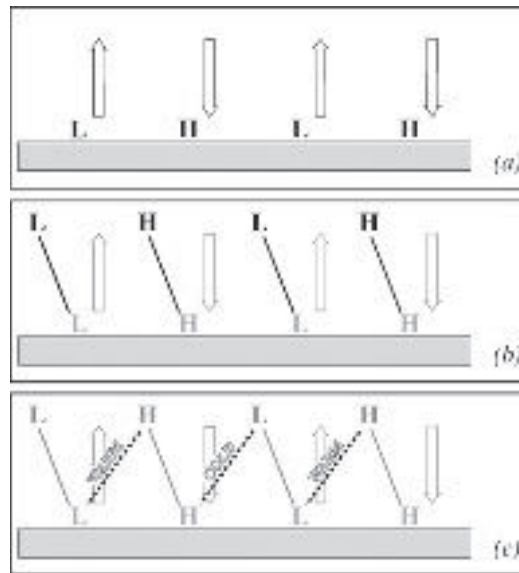


Figure 8.7 Vertical structure of a developing mid-latitude cyclone. (a) Alternating sequence of surface high- and low-pressure systems with ascent (descent) slightly downstream from the lows (highs). (b) Upper tropospheric lows and highs are displaced to the west with height (see text for explanation). Thick solid lines represent geopotential axes connecting surface and upper tropospheric features. (c) Thick dashed lines are thermal axes which tilt slightly to the east with height (see text for explanation). Note that warm air is ascending and cold air is descending in this wave train

shear is, indeed, unstable to certain wave-like perturbations and that mid-latitude cyclones are a primary manifestation of this instability. A more fully developed version of this baroclinic instability² theory suggests that disturbances of the scale of mid-latitude short waves (3000 to 4500 km in wavelength), in environments characterized by observed values of vertical shear, are those that exhibit the most efficient growth by this mechanism.

Though elements of the foregoing characteristic vertical structure of cyclones were known in the late nineteenth century, almost no mention was made of the vertical wave structure of cyclones in the NCM. The goal in the subsequent sections will not be to provide a comprehensive review of the theory and supporting observations regarding the various stages of the mid-latitude cyclone life cycle,³ but instead to demonstrate that the diagnostic tools we have developed thus far can be gainfully employed in developing an understanding of the basic elements of that life-cycle evolution.

² Baroclinic instability theory was discovered independently by Jule Charney (1947) and Eric Eady (1949) using approaches to the problem that were significantly different from one another. Charney was also the first to derive rigorously the quasi-geostrophic system of equations upon which much of this book is based.

³ A vast literature exists on the related subjects and to review it is an enormous job. A number of seminal references from that literature are given at the end of the chapter.

8.3 The Cyclogenesis Stage: The QG Tendency Equation Perspective

Cyclogenesis is the process by which a surface cyclone initially develops and subsequently intensifies. Intensification is often measured in terms of sea-level pressure decreases following the cyclone center. A consequence of this semi-Lagrangian negative pressure tendency is an increase in the low-level geostrophic vorticity. Thus, cyclogenesis can be viewed as a process of low-level vorticity production. Vorticity production necessitates the presence of divergence and vertical motions, as we have already seen. Consideration of the isobaric form of the continuity equation leads to

$$\int_0^{p_s} \partial \omega = - \int_0^{p_s} (\nabla \cdot \vec{V}) \partial p \quad \text{or} \quad \omega_{p_s} = - \int_0^{p_s} (\nabla \cdot \vec{V}) \partial p. \quad (8.1)$$

Now, since

$$\omega = \frac{dp}{dt} = \frac{\partial p}{\partial t} + \vec{V}_a \cdot \nabla p + w \frac{\partial p}{\partial z}$$

and both w and $\vec{V}_a \cdot \nabla p$ are nearly zero *at the surface of the Earth*,⁴ then (8.1) can be rewritten as

$$\frac{\partial p_s}{\partial t} \approx - \int_0^{p_s} (\nabla \cdot \vec{V}) \partial p. \quad (8.2)$$

This expression, known as the pressure tendency equation, dictates that the surface pressure tendency at a point is a consequence of the total convergence of mass into the vertical column of atmosphere above that point. Thus, net mass divergence (convergence) in the column is responsible for sea-level pressure falls (rises) at a given location. As we have already seen, however, measuring the divergence cannot be done with a great degree of accuracy. Thus, approximations to (8.2) must be made in order to render useful results. The simplest set of approximate equations are the quasi-geostrophic set that we derived in Chapter 5. Recall that the quasi-geostrophic vorticity and thermodynamic energy equations were given by

$$\begin{aligned} \frac{\partial \zeta_g}{\partial t} &= -\vec{V}_g \cdot \nabla (\zeta_g + f) + f_0 \frac{\partial \omega}{\partial p} \\ \frac{\partial}{\partial t} \left(-\frac{\partial \phi}{\partial p} \right) &= -\vec{V}_g \cdot \nabla \left(-\frac{\partial \phi}{\partial p} \right) + \sigma \omega, \end{aligned}$$

⁴ Ageostrophic pressure advection ($\vec{V}_a \cdot \nabla p$) can be different from zero just above the surface, however.