P2.12 STRUCTURE AND EVOLUTION OF UPPER-TROPOSPHERIC JET STREAKS IN A STRATIFIED QUASIGEOSTROPHIC MODEL

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1. INTRODUCTION

Jet streaks are ubiquitous features of the extratropical upper troposphere and lower stratosphere that, in light of their well-documented association with cyclogenesis and severe weather, have received significant attention from the synoptic community (e.g., Bluestein 1993, Ch. 2). Nevertheless, relatively few investigations have addressed fundamental issues concerning the dynamics of jet streaks, such as their representation and their motion and evolution in different synoptic- and planetary-scale environments.

Several recent observational investigations suggest that many jet streaks may be associated with the superposition of large-amplitude, localized disturbances of mesoscale dimensions with the enhanced potential vorticity (PV) gradients that constitute the extratropical tropopause (e.g., Bosart et al. 1996; Lackmann et al. 1997; Pyle 1997; Hakim 2000a). Indeed, Pyle (1997) has identified such localized disturbances accompanying three of the four jet streaks examined. These disturbances typically have length scales of approximately 500 km (Hakim 2000a), appear as closed contours of Ertel PV (EPV) on isentropes that intersect the tropopause, and on occasion can be tracked unambiguously for periods in excess of two weeks (e.g., Bosart et al. 1996; Pyle 1997). The foregoing properties suggest that these disturbances may be coherent vortices, and in this regard it is noteworthy that an interpretation of jet streaks in terms of coherent vortices as identified by large-amplitude, localized PV anomalies is also consistent with interpretations of jet streaks found in several previous studies (e.g., Mattocks and Bleck 1986; Takayabu 1991; Davies and Rossa 1998).

Previous investigation into the possibility of interpreting jet streaks in terms of coherent vortices (Cunningham and Keyser 1999a,b) shows that a steady-state analytical vortex dipole solution applicable to the stratified quasigeostrophic (QG) system (Berestov 1979) provides a realistic dynamical representation of an isolated, straight jet streak. In particular, the dipole possesses an ageostrophic wind that is directed towards lower geopotential height in the entrance region of the wind speed maximum and towards higher geopotential height in the exit region. The rotational part of the ageostrophic wind dominates the divergent part, with the latter part being associated with a four-cell pattern of vertical velocity similar to that described in conceptual models of straight jet streaks [e.g., Fig. 6.6 in Uccellini (1990)].

Jet streaks are rarely straight or isolated, however, and typically are embedded in a larger-scale flow with both horizontal and vertical shear. Furthermore, observations suggest that the coherent vortices associated with jet streaks are generally either strongly asymmetric dipoles, with the cyclonic member much larger in magnitude than the anticyclonic member, or simply monopoles (e.g., Hakim 2000a; Cunningham 2000). The present study represents an attempt to account for these observed attributes of jet streaks, along with the time-dependent nature of these features.

An example of a jet streak associated with a large-amplitude, localized PV anomaly is depicted in Fig. 1, which shows both EPV and QGPV at 400 hPa for a jet streak that was located over the north central United States at 1200 UTC 3 November 1995. The data in this case are obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) 1.125°-resolution global analyses. It is apparent from Fig. 1 that associated with the localized maximum in the wind speed are localized maxima in the EPV and QGPV fields indicative of a coherent vortex. In addition, the striking similarity between the EPV and QGPV fields suggests that, to a first approximation, this feature may be well described by QG theory. This suggestion is verified through the diagnosis of three-dimensional ageostrophic circulations (not shown), which indicate that the divergent component of the ageostrophic wind is small in comparison to the rotational component, and that the QG vertical motion compares favourably with the vertical motion calculated using the kinematic method (Cunningham 2000). Moreover, it is emphasized that this study also represents the next step in the hierarchical investigation of jet streaks beyond the nondivergent barotropic model used by Cunningham and Keyser (2000), and in this regard the goal in this investigation is to provide a basic understanding of the dynamics of jet streaks in three dimensions. Consequently, it is suggested that the approximate nature of the QG system is appropriate and justifiable.

In the following section, we describe the stratified QG model to be employed in this investigation, and in section 3 we discuss numerical simulations using this model that address the interpretation of jet streaks in terms of coherent vortices and their interactions with baroclinic zonal background flows. Finally, we summarize the essential results of this investigation and suggest directions for future study.

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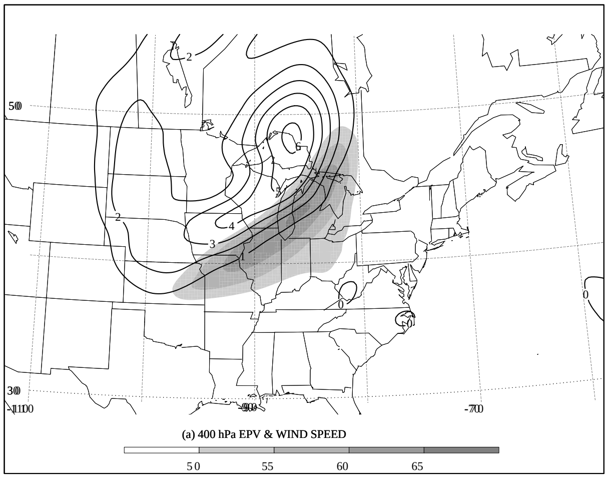

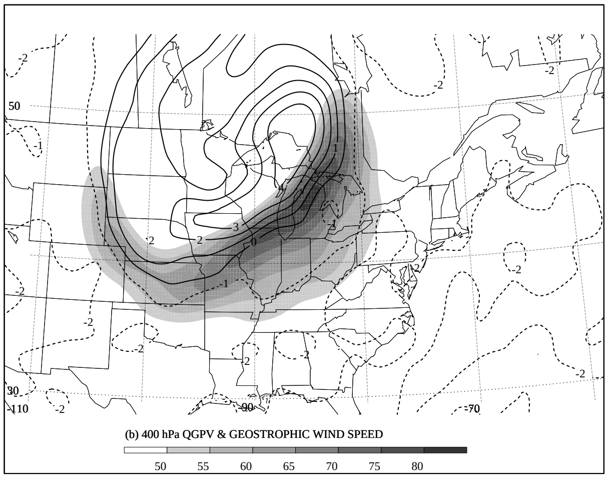

Figure 1. ECMWF analyses at 1200 UTC 3 November 1995 on the 400 hPa isobaric surface of: (a) EPV (contour interval 1 PVU) and total wind speed (values greater than 50 $\mathrm{m\,s^{-1}}$ shaded as indicated); (b) QGPV scaled by $-g\,d\theta_{ref}/dp$ (contour interval 1 PVU) and geostrophic wind speed (values greater than 50 $\mathrm{m\,s^{-1}}$ shaded as indicated).

2. STRATIFIED QUASIGEOSTROPHIC MODEL

The stratified QG model to be employed applies to a three-dimensional Boussinesq fluid on an *f* plane, confined between rigid horizontal boundaries at $z=0$ and $z=H$ that correspond to the surface and the tropopause, respectively. The model is expressed in terms of the conservation of QGPV, $f+q_*$, for $0<z<H$, where

$$q_* = \nabla^2\psi + \frac{f^2}{N^2}\frac{\partial^2\psi}{\partial z^2}, \tag{1}$$

and the conservation of perturbation potential temperature,

$$\theta' = \frac{f\theta_0}{g}\frac{\partial\psi}{\partial z}, \tag{2}$$

at $z=0$ and $z=H$. Here, $N^2 = (g/\theta_0)(d\theta_{ref}/dz)$ is the (constant) static stability and ψ is the geostrophic streamfunction.

The QG system is solved using an adaptation of the semigeostrophic model described by Snyder et al. (1991). The geometry is that of a midlatitude *f*-plane channel, with periodic boundary conditions in the zonal direction and solid-wall boundary conditions in the meridional direction. The model domain is a square region of side 8000 km and of depth $H=10\,\mathrm{km}$, and the horizontal and vertical grid spacings are 62.5 km and 0.625 km, respectively. It should be noted that only a portion of the model domain is shown in the subsequent figures. In all of the simulations to be described below, $f=10^{-4}\ \mathrm{s^{-1}}$ and $N=10^{-2}\ \mathrm{s^{-1}}$.

3. NUMERICAL SIMULATIONS OF JET STREAKS REPRESENTED BY COHERENT VORTICES

As discussed previously, it is apparent that jet streaks and the coherent vortices that accompany them invariably are embedded in a larger-scale flow with both horizontal and vertical shear. In an effort to extend the interpretation of jet streaks in terms of coherent vortices to include background flows characteristic of the extratropical upper troposphere and lower stratosphere, the interactions between vortices and background flows possessing horizontal and vertical shear are examined via numerical simulations of the QG model described in section 2. These simulations investigate the evolution of a monopolar vortex in the presence of a hierarchy of zonal background flows. The initial vortex in the simulations consists of a Gaussian distribution of QGPV for $0<z<H$, along with a Gaussian distribution of perturbation potential temperature at $z=H$ and zero perturbation potential temperature at $z=0$. The background flows examined include: a zonal flow with uniform vertical shear and zero interior QGPV (Eady 1949); a zonal flow with nonuniform horizontal and vertical shear and zero interior QGPV (Hoskins and West 1979); and a zonal jet with nonuniform interior QGPV (a baroclinic Bickley jet). Because of space considerations, only the case of a monopolar vortex in the baroclinic Bickley jet is shown here, since this simulation represents the closest idealized analogue to the observationally motivated interpretation of jet streaks as resulting from the superposition of a coherent vortex with a band of locally enhanced PV gradients; however, the broad aspects of the interactions between the vortex and the background flows are similar in all cases.

It can be shown that a monopolar vortex in a uniform zonal flow is associated with a localized wind speed maximum arising simply from the superposition of the vortex with the zonal flow. Nevertheless, such a configuration is steady and vertical circulations are absent. The addition of vertical shear not only results in vertical circulations that are qualitatively in accord with observations of jet streaks associated with short-wave troughs, but also introduces complex time dependence to the structure, motion, and evolution of the vortex. Moreover, the presence of vertical shear allows the possibility of baroclinic growth excited by the vortex

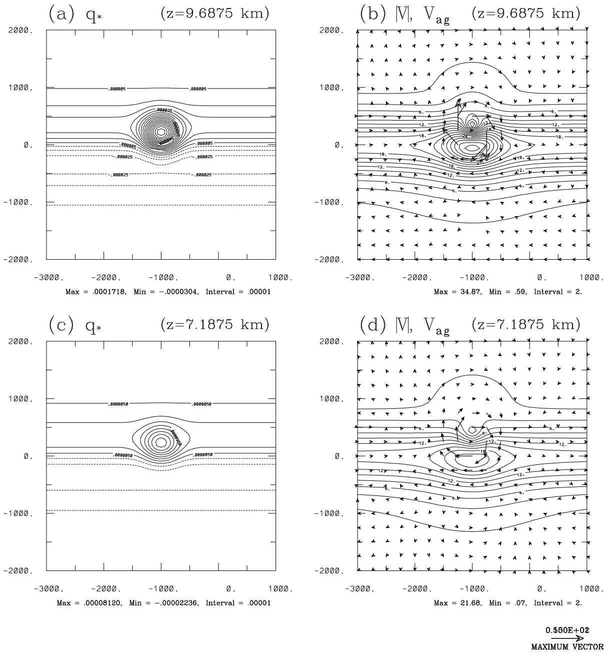

Figure 2. Fields in the $x-y$ plane at $t=0$ associated with the simulation of a monopolar vortex in the baroclinic Bickley jet (3): (a) q_* at $z=9.6875$ km (contour interval 1×10^{-5} s^{-1}); (b) total geostrophic wind speed (contour interval 2 m s^{-1}) and ageostrophic wind (magnitude of reference vector is 15 m s^{-1}) at $z=9.6875$ km; (c) q_* at $z=7.1875$ km (contour interval 1×10^{-5} s^{-1}); (d) total geostrophic wind speed (contour interval 2 m s^{-1}) and ageostrophic wind (magnitude of reference vector is 5 m s^{-1}) at $z=7.1875$ km.

(e.g., Montgomery and Farrell 1992; Hakim 2000b), potentially accounting for the close link between jet streaks and cyclogenesis noted in the Introduction.

The profile of the baroclinic Bickley jet is given by

$$\bar{u}(y,z)=\frac{U_0 z}{H}\operatorname{sech}^2\left(\frac{y}{\delta}\right), \tag{3}$$

where $U_0 = 20$ m s^{-1} and $\delta = 500$ km for the simulation shown herein. Aspects of the horizontal and vertical structure of the initial conditions for the simulation are shown in Figs. 2 and 3, respectively. There is an along-jet wind speed maximum on the equatorward side of the vortex, with an associated ageostrophic wind field directed towards the cyclonic shear side of the jet in the entrance region of the jet streak and towards the anticyclonic shear side in the exit region (Figs. 2b,d). In the vertical, the vortex is initially upright (Figs. 3a,b), and there is a two-cell pattern of vertical motion with descent upshear of the vortex and ascent downshear (Fig. 3d). The initial perturbation potential temperature at $z=H$ (not shown) consists of a localized cold anomaly superposed on a meridionally localized temperature gradient.

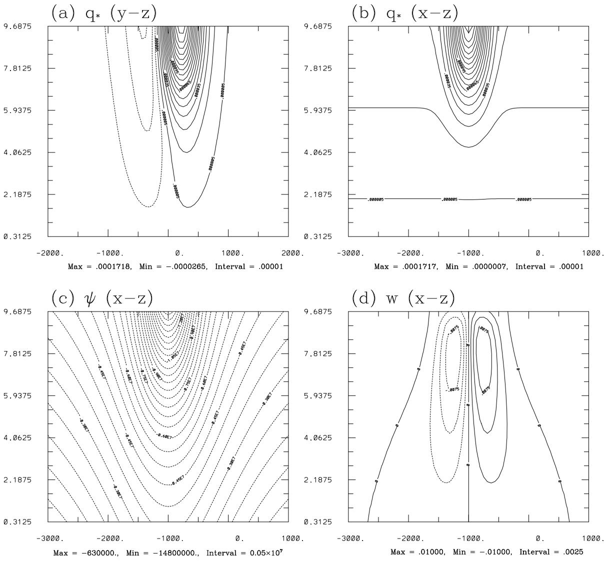

Figure 3. Fields at $t=0$ associated with the simulation of a monopolar vortex in the baroclinic Bickley jet (3): (a) q_* in the $y-z$ plane at $x=-1000$ km (contour interval 1×10^{-5} s^{-1}, negative values dashed); (b) q_* in the $x-z$ plane at $y=187.5$ km (contour interval 1×10^{-5} s^{-1}, negative values dashed); (c) ψ in the $x-z$ plane at $y=187.5$ km (contour interval 5×10^{5} m^2 s^{-1}, negative values dashed); (d) vertical velocity in the $x-z$ plane at $y=187.5$ km (contour interval 2.5×10^{-3} m s^{-1}, negative values dashed).

As the simulation proceeds, the vortex distorts the QGPV gradient, particularly on the downshear side of the vortex, while simultaneously being subject to the horizontal and vertical shear of the jet. The structure at $t=50$ h is illustrated in Figs. 4 and 5. The maximum in wind speed (Figs. 4b,d) is located along the jet in conjunction with the vortex and has developed an along-jet asymmetry, whereby the exit region is more compact than the entrance region; consistent with this asymmetry, the ageostrophic wind is larger in magnitude in the exit region than in the entrance region. (Figs. 4b,d). The vortex has developed a vertical structure exhibiting a tilt that, although small near the lid, is significant in the upper to middle levels (Figs. 5a,b). The midlevel tilt appears to be beneath the jet in the meridional direction (Fig. 5a) and upshear in the zonal direction (Fig. 5b). The former is reminiscent of a tropopause fold, whereas the latter is consistent with cyclonic growth at the surface observed in this simulation (compare Figs. 3c and 5c), with the maximum surface cyclonic vorticity beneath the maximum ascent in the exit region of the jet streak. It is noteworthy, however, that cyclonic development is considerably stronger in the cases of the Eady basic state and Hoskins–West jet (not shown). It is hypothesized that this difference is related to the stronger horizontal shear associated with the Bickley jet, since the presence of horizontal shear generally

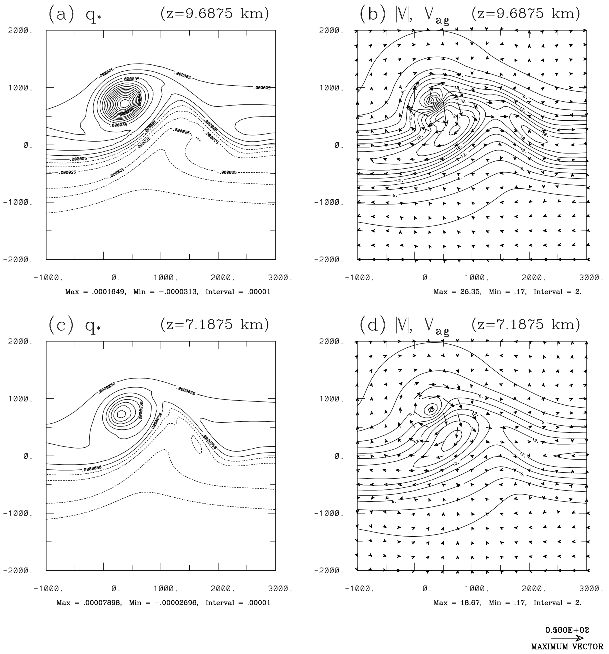

Figure 4. As in Fig. 2, except at $t = 50$ h .

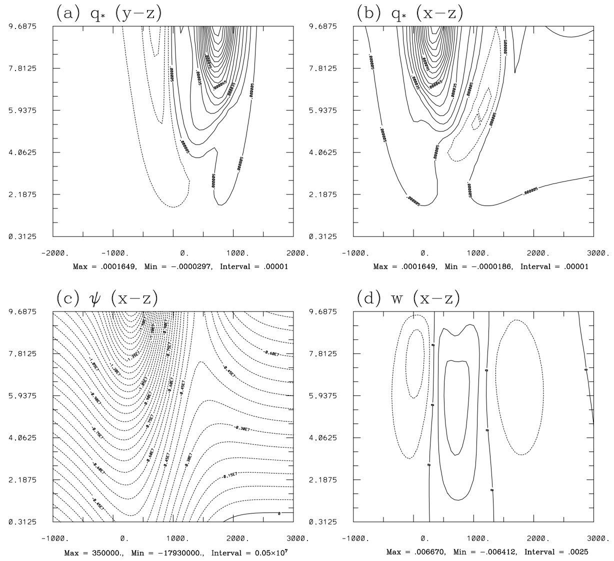

Figure 5. As in Fig. 3, except at $t = 50$ h . Panel (a) is in the $y - z$ plane at $x = 375$ km , and panels (b), (c), and (d) are in the $x - z$ plane at $y = 687.5$ km .

reduces the rate of baroclinic growth (e.g., James 1987).

The observation that the vortex is capable of maintaining vertical coherence even in the presence of significant vertical shear is a consequence of the so-called alignment process. In this regard, it is of interest that the combined effects of vertical shear and alignment result in a tilted vertical structure in the simulations that is in accord with observations of jet streaks and short-wave troughs (e.g., Sanders 1988).

4. SUMMARY AND DISCUSSION

Although simulations of the interactions between monopolar vortices and a hierarchy of zonal background flows with horizontal and vertical shear display complex time-dependent behaviour, several aspects of these simulations provide idealized analogues to the behaviour of observed jet streaks. In particular, the jet streaks in these simulations display: (i) an along-jet asymmetry, with elongated entrance regions and compact exit regions; (ii) a two-cell pattern of vertical motion, in which the maximum ascent is located beneath the cyclonic-shear side of the exit region of the jet streak, consistent with the along-jet asymmetry noted in (i); (iii) an ageostrophic wind that is directed towards lower geopotential height in the entrance region and towards higher geopotential height in the exit region, and that is stronger in the exit region than in the entrance region (also consistent with the along-jet asymmetry); and (iv) a deepening surface cyclone beneath the region of maximum ascent. Furthermore, in the simulations the QGPV field exhibits a vertical tilt that is upshear in the zonal direction, consistent with the observed cyclonic growth, and that is beneath the jet in the meridional direction, reminiscent of a tropopause fold.

Despite the apparent success of this study in describing aspects of the nature and behaviour of jet streaks, several limitations of the approach are evident. These limitations include the assumption of a preexisting vortex and the restriction to balanced (specifically QG) dynamics in a domain with a rigid upper boundary representing the tropopause. With respect to the former limitation, it is suggested that the present approach is appropriate for the present study, since the coherent vortices that are associated with jet streaks appear to originate in locations well removed from where the jet streak is observed (Pyle 1997). Nevertheless, the origin of coherent vortices in the upper troposphere and lower stratosphere is an important issue deserving of further investigation.

With respect to the latter limitation, it is well known that jet streaks frequently are characterized by large Rossby numbers and strong ageostrophic winds such that QG dynamics may not even be qualitatively accurate. Indeed, observations indicate that jet streaks are invariably associated with tropopause undulations of significant amplitude. Moreover, many studies have shown evidence suggesting that jet streaks may be a focal point for the generation of unbalanced flow phenomena such as gravity waves. In light of the foregoing limitations, several extensions to the present study are under consideration; these involve the use of higher-order balance and primitive equation models to examine the entire life cycles of jet streaks and the associated coherent vortices, as well as the possible coupling between these features and gravity waves.

5. ACKNOWLEDGEMENT

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6. REFERENCES

Berestov, A. L., 1979: Solitary Rossby waves. *Izv. Acad. Sci. USSR Atmos. Oceanic Phys.*, **15,** 443–447.

Bluestein, H. B., 1993: *Synoptic–Dynamic Meteorology in Midlatitudes. Vol. II*. Oxford University Press, 594 pp.

Bosart, L. F., G. J. Hakim, K. R. Tyle, M. A. Bedrick, W. E. Bracken, M. J. Dickinson, and D. M. Schultz, 1996: Large-scale antecedent conditions associated with the 12–14 March 1993 cyclone (“Superstorm ‘93”) over eastern North America. *Mon. Wea. Rev.*, **124,** 1865–1891.

Cunningham, P., 2000: Coherent vortices in the extratropical upper troposphere: A dynamical interpretation of jet streaks. Ph.D. dissertation, University at Albany, State University of New York, 152 pp.

Cunningham, P., and D. Keyser, 1999a: Tropopause-based mesoscale coherent vortices: A dynamical interpretation of jet streaks. Preprints, *Twelfth Conf. on Atmospheric and Oceanic Fluid Dynamics*, New York, NY, Amer. Meteor. Soc., 59–63.

Cunningham, P., and D. Keyser, 1999b: The dynamics of jet streaks in the upper troposphere: Observations and idealized modeling. Preprints, *Eighth Conf. On Mesoscale Processes*, Boulder, CO, Amer. Meteor. Soc., 203–208.

Cunningham, P., and D. Keyser, 2000: Analytical and numerical modelling of jet streaks: Barotropic dynamics. *Quart. J. Roy. Meteor. Soc*., **126,** 3187–3217.

Davies, H. C., and A. M. Rossa, 1998: PV frontogenesis and upper-tropospheric fronts. *Mon. Wea. Rev.*, **126,** 1528–1539.

Eady, E. T., 1949: Long waves and cyclone waves. *Tellus*, **1,** 33–52.

Hakim, G. J., 2000a: Climatology of coherent structures on the extratropical tropopause. *Mon. Wea. Rev.*, **128,** 385–406.

Hakim, G. J., 2000b: Role of nonmodal growth and nonlinearity in cyclogenesis initial-value problems. *J. Atmos. Sci.*, **57,** 2951–2967.

Hoskins, B. J., and N. V. West, 1979: Baroclinic waves and frontogenesis. Part II: Uniform potential vorticity jet flows—Cold and warm fronts. *J. Atmos. Sci.*, **36,** 1663–1680.

James, I. N., 1987: Suppression of baroclinic instability in horizontally sheared flows. *J. Atmos. Sci.*, **44,** 3710–3720.

Lackmann, G. M., D. Keyser, and L. F. Bosart, 1997: A characteristic life cycle of upper-tropospheric cyclogenetic precursors during the Experiment on Rapidly Intensifying Cyclones over the Atlantic (ERICA). *Mon. Wea. Rev.*, **125,** 2729–2758.

Mattocks, C., and R. Bleck, 1986: Jet streak dynamics and geostrophic adjustment processes during the initial stages of lee cyclogenesis. *Mon. Wea. Rev.*, **114,** 2033–2056.

Montgomery, M. T., and B. F. Farrell, 1992: Polar low dynamics. *J. Atmos. Sci.*, **49,** 2484–2505.

Pyle, M. E., 1997: A diagnostic study of jet streaks: Kinematic signatures and relationship to coherent tropopause disturbances. M.S. thesis, University at Albany, State University of New York, 169 pp.

Sanders, F., 1988: Life history of mobile troughs in the upper westerlies. *Mon. Wea. Rev.*, **116,** 2629–2648.

Snyder, C., W. C. Skamarock, and R. Rotunno, 1991: A comparison of primitive-equation and semigeostrophic simulations of baroclinic waves. *J. Atmos. Sci.*, **48,** 2179–2194.

Takayabu, I., 1991: “Coupling development”: An efficient mechanism for the development of extratropical cyclones. *J. Meteor. Soc. Japan*, **69,** 609–628.

Uccellini, L. W., 1990: Processes contributing to the rapid development of extratropical cyclones. *Extratropical Cyclones, The Erik Palmén Memorial Volume*, C. W. Newton and E. O. Holopainen, Eds., Amer. Meteor. Soc., 81–105.