

**A SYNOPTIC-CLIMATOLOGY AND COMPOSITE ANALYSIS OF
THE ALBERTA CLIPPER**

by

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ABSTRACT

Surface and upper-air analyses from the ECMWF TOGA dataset are used to construct a climatology of 177 Alberta Clippers over 15 boreal cold seasons (October-March) from 1986-87 to 2000-01. The Alberta Clipper (hereafter simply *Clipper*) occurs most frequently during December and January and substantially less frequently during October and March. These cyclones generally move southeastward from the lee of the Canadian Rockies toward or just north of Lake Superior before progressing eastward into southeastern Canada or the northeastern United States, with less than 10% of cases in the climatology tracking south of the Great Lakes.

Characteristics of the structure and evolution of Clippers during a 36-h period leading up to departure of the cyclone from the lee of the Canadian Rockies and a 60-h period after departure as the cyclone traverses central and eastern North America are examined through composite analyses. Over the course of the pre-departure period, a cyclone over the Gulf of Alaska approaches the west coast of North America, and through its interaction with the mountainous terrain of western North America spawns a surface lee trough, characterized by a thermal ridge at 850 hPa, to the east of the Canadian Rockies. This thermal ridge dampens considerably as the composite Clipper moves into central North America away from the immediate lee of the Canadian Rockies.

The composite Clipper system evolves from a lee cyclone with its non-classical thermal structures to a more classically structured midlatitude cyclone as it moves through central and eastern North America largely as a result of rotation of the low-level thermal gradient and the increasing westward tilt with height of the composite Clipper over the last 36 h of the post-departure period. The thermal gradient rotation is dynamically linked to

convergence of the along-isentrope component of the \mathbf{Q} vector (Q_s) and thus to the ascent that sustains the Clipper and creates some of its characteristic sensible weather elements. Such dynamical forcing is a direct consequence of the persistent westward displacement of the 500 hPa vorticity maximum with respect to the composite Clipper sea level pressure minimum that characterizes the post-departure period.

1. Introduction

One of the most significant synoptic-scale winter weather phenomena affecting central North America is the Alberta Clipper, defined in the *Glossary of Meteorology* (Glickman 2000) as “a low pressure system that is often fast moving, has low moisture content, and originates in western Canada (in or near Alberta province).”, Clippers¹ develop in the lee of the Canadian Rockies, a region characterized by a relative maximum in cyclogenesis events (Petterssen 1956, Reitan 1974, Chung et al. 1976, Zishka and Smith 1980, Whittaker and Horn 1981, Nielsen and Dole 1992). After initial formation, Alberta Clippers generally move southeastward into south-central Canada or the north-central United States, then progress eastward toward the east coast of North America (Hutchinson 1995). The Clipper track represents one of the major storm tracks for winter-season cyclones in the Northern Hemisphere (Petterssen 1956, Reitan 1974, Zishka and Smith 1980, Hoskins and Hodges 2002).

Most of the previous literature discussing the structure and evolution of the Alberta Clipper has focused on the formative, lee cyclogenesis stage of the Clipper (Henry 1925, Hess and Wagner 1948, Newton 1956, McClain 1960, Bonner 1961). Based upon this collective work, Palmén and Newton (1969) developed a conceptual model describing the development and evolution of northern Rocky Mountain lee cyclones and lee troughs. In this conceptual model, formation of the lee cyclone is preceded by the landfall of a cyclone from the Pacific Ocean along the west coast of North America. The lower-tropospheric wind flow

¹ The terms “Alberta Clipper,” and “Clipper,” will be used interchangeably during the course of this paper and highlight both the region of origin of such systems as well as their rapid movement, *a la* Clipper ships.

crossing the Rocky Mountains increases as the Pacific cyclone approaches the coast, resulting in the development of a lee trough. The trough generally remains fixed to the lee slopes of the mountains and broadens over time as air warmed by descent is advected eastward. The approach of an upper-level trough and its associated vorticity maximum produces cyclonic development within the lee trough. Palmén and Newton stated that the cyclone moves away from the lee of the Rocky Mountains when a cold front overtakes the lee trough, but more recent studies (e.g., Locatelli et al. 1989; Martin et al. 1990) have shown that movement of the lee cyclone away from the mountains is not dependent on such a circumstance.

Though lee troughing commonly occurs in association with cross-mountain flow in the lower troposphere, additional conditions are necessary for the development of a cyclone within the lee trough². Lee cyclogenesis often takes place when a region of strong ascent in the middle and upper troposphere associated with differential cyclonic vorticity advection is superimposed over a band of maximum descent in the lower troposphere (Newton 1956, Steenburgh and Mass 1994, Schultz and Doswell 2000). The resulting differential vertical motion generates cyclonic vorticity via column stretching. Differential cyclonic vorticity advection over an established low-level baroclinic zone in the lee of the Rockies also promotes the development of the lee cyclone (Steenburgh and Mass 1994; Davis 1997).

Within the spectrum of extratropical cyclones, Alberta Clippers are generally regarded as rather innocuous, small-scale systems. Their characteristic lack of available moisture and rapid movement conspire to produce relatively low precipitation amounts over

² Pierrehumbert (1986) and Tibaldi et al. (1990) emphasize that lee troughing is not synonymous with lee cyclogenesis.

a narrow path. Moderate precipitation generally occurs in areas up to a few hundred kilometers north of the system's track while lighter precipitation generally falls to the south of the track (Harms 1973, Beckman 1987, Hutchinson 1995). Relatively little moisture is necessary, however, for Clippers to produce snow accumulations of 80-150 mm (3-6 in) in 3 to 6 h given the very cold air and correspondingly large snow-to-liquid equivalent ratios (generally 20-to-1 or greater) associated with these systems (Harms 1973). Snowfall amounts can be enhanced through an influx of low-level moisture from the Great Lakes into the Clipper (Harms 1973, Vinzani and Changnon 1981, Silberberg 1990, Angel and Isard 1997) or as a result of locally intense upper-level forcing in the presence of low conditional stability (either potential or symmetric) (Smart and Carr 1986, Silberberg 1990, Gallus and Bresch 1997).

Often the most significant sensible weather element associated with Alberta Clippers is strong wind. Areas in the lee of the Rocky Mountains and Alberta are susceptible to frontal chinooks as a Pacific cyclone approaches the British Columbia coast and the Alberta Clipper develops within the lee trough (Price 1971; Oard 1993; Schultz and Doswell 2000). Over central and eastern North America, the strongest winds are usually located on the western side of the Alberta Clipper in the region between the surface cyclone and the often-intense anticyclone trailing the Clipper. Strong winds with Clippers can also arise from enhanced isallobaric winds associated with a substantial pressure rise-fall couplet, and a downward transport of high momentum air in regions of strong cold air advection and low static stability (Kapela et al. 1995, Schultz and Doswell 2000). The strong winds that follow the passage of a Clipper, coupled with preexisting or freshly fallen snow, can result in

considerable blowing and drifting of snow and the creation of ground blizzard conditions (Stewart et al. 1995, Schwartz and Schmidlin 2002).

Despite the acknowledged importance of the Alberta Clipper to the wintertime weather of central North America, few studies have considered the synoptic-scale structure and evolution of these disturbances beyond the cyclogenesis stage. Furthermore, nearly every study that has examined these systems beyond the cyclogenesis stage has employed a case study approach. This paper examines the synoptic-climatology of the Alberta Clipper by considering its composite structure and evolution throughout the Clipper life cycle. The paper is organized in the following manner. Section 2 contains a description of the dataset and analysis method used to construct a synoptic climatology of Alberta Clippers. Section 3 discusses the frequency, propagation characteristics, and intensity of these cyclones. An analysis of the composite structure and evolution of Alberta Clippers derived from all cases in the climatology is presented in Section 4. An examination of the quasi-geostrophic (QG) forcing for ascent throughout the Clipper is presented in Section 5, followed by discussion and conclusions in Section 6.

2. Data and Methodology

The climatology presented here was constructed using the European Centre for Medium-Range Weather Forecasts (ECMWF) Tropical Ocean Global Atmosphere (TOGA) surface and upper-air analyses for 15 boreal cold seasons (October-March) from 1986-87 to 2000-01. The ECMWF TOGA dataset consists of twice-daily (0000 and 1200 UTC) sea level and 14 (15 starting January 1992, 21 starting April 1999) unequally-spaced pressure

level analyses with 2.5° latitude-longitude grid spacing on a global domain. These data are directly interpolated from the ECMWF operational, full-resolution surface and pressure level data.³ The data were acquired from the National Center for Atmospheric Research (NCAR) in gridded binary (GRIB) format, then converted and transferred to General Meteorological Package (GEMPAK; desJardins et al. 1991) grids with a cylindrical equidistant grid projection. The GEMPAK grids were then accessed by FORTRAN 77 programs for the purposes of performing diagnostic computations using sea level pressure (SLP), geopotential height, temperature, and the zonal and meridional components of the wind.

For this study, a cyclone qualified as an Alberta Clipper if all of the following criteria were met:

- 1) The cyclone originated in the lee of the Canadian Rockies in Alberta, northeastern British Columbia, or far southwestern Northwest Territories.
- 2) The cyclone was defined by at least one closed isobar and/or a distinct local minimum in a SLP trough using a 2 hPa interval throughout its lifetime.
- 3) The SLP minimum progressed southeastward from its region of origin to south-central Canada or the north-central United States, and then continued eastward.
- 4) The surface cyclone had an association with a migratory 500 hPa vorticity maximum.
- 5) The SLP minimum moved east of 90°W longitude and remained a coherent feature for at least 60 h following its departure from the Canadian Rockies. The time of departure, adapted from Schultz and Doswell (2000), is defined as the last analysis time

³ The operational resolution of the ECMWF model during the period of this climatology was T63 through 16 September 1991, T213 from 17 September 1991 through 31 March 1998, T_L319 from 1 April 1998 through 20 November 2000, and T_L511 from 21 November 2000 onward.

before the SLP minimum makes appreciable movement away from the Canadian Rockies. This criterion excluded from the climatology cyclones that have short trajectories or exceptionally slow movement, characteristics common to about one-quarter of all cyclones originating in the lee of the Canadian Rockies (Chung et al. 1976). A total of 177 cases satisfied all of the above criteria (Table 1).

3. Distribution of Alberta Clippers

The cumulative monthly frequency of all Clippers during the 15-season climatology is shown in Fig. 1. The larger number of cases observed during the middle of the cold season is a consequence of the more southerly position of the jet stream that provides a more favorable upper-level flow pattern for Clipper development. Table 2 demonstrates that Clipper occurrence exhibits considerable intraseasonal and interannual variability.

a. Propagation characteristics

Figure 2 shows the track of each of the 177 Alberta Clippers in the climatology from the time of departure to 60 h after departure. Tracks for each case were constructed by finding the position of the SLP minimum at each 12-h analysis time from departure to 60 h after departure and connecting the position points with straight lines. Most of the Clippers moved southeastward toward or just north of Lake Superior before moving into southeastern Canada or New England, with only 15 of 177 cases tracking completely south of the Great

Lakes. Some Clippers moved at an especially fast rate, with 33 cases reaching the east coast of North America within 60 h of departure.

b. Intensity of Clippers

Though use of SLP as a measure of cyclone intensity is susceptible to a number of potential shortcomings (Sinclair 1994,1997; Mesinger and Treadon 1995; Pauley 1998), these are offset by the ease of access to SLP data in the ECMWF dataset and the ability to compare results from this study to other climatological studies that have used SLP to assess cyclone strength in regions traversed by Clippers (e.g., Hurley 1954; Harman et al. 1980; Angel and Isard 1998). Central SLP is therefore employed as a measure of cyclone intensity.

Following the lead of numerous other studies (e.g., Sanders and Gyakum 1980; Roebber 1989; Nielsen and Dole 1992; Angel and Isard 1997), cyclone intensification is appraised by examining the SLP tendency calculated for each 12-h period from the time of departure ($T=0$) to 60 h after departure ($T+60$). Following Roebber (1989), the SLP tendencies were adjusted by latitude using the formula $\Delta P_{\text{adj}} = \Delta P (\sin \varphi_{\text{ref}} / \sin \varphi)$, where ΔP_{adj} is the adjusted SLP tendency, ΔP is the SLP tendency, φ_{ref} is a reference latitude of 50°N , and φ is the mean latitude of the Clipper during the 12-h period. This adjustment to a reference latitude takes into account the fact that cyclones at different latitudes with similar pressure gradients will produce different geostrophic winds and thus should not be considered to have identical intensities. A reference latitude of 50°N is chosen since it is the mean latitude of Clippers in the 60-h post-departure period.

The distribution of central SLP values recorded at 12-h intervals from departure to 60 h after departure for all Clippers in the climatology is given in Fig. 3. The Clippers have a central SLP between 1000-1009 hPa during 46% of the total analysis times. A similar frequency of relatively high central SLP was found for winter cyclones moving east-southeast or south-southeast through the Midwest (Hurley 1954) and for winter cyclones over the Great Lakes (Harman et al. 1980; Angel and Isard 1998). Though the distribution is skewed toward lower pressure (largely an effect of the relatively high pressure at which the peak of the distribution is located), the central SLP of Clippers is ≤ 990 hPa in only 7% of the analyses. The relatively weak nature of most Clippers is further illustrated by the concentration toward higher values in the distribution of lowest central SLP attained for all Clippers during the 60-h post-departure period (Fig. 4). Only 28% of cases reach a central SLP ≤ 992 hPa, the benchmark used by Angel and Isard (1997) to define a “strong,, cyclone.

Changes in Clipper strength can be determined more explicitly by examining the distribution of adjusted 12-h SLP tendency (Fig. 5). Clippers experience minor SLP changes [$|\text{dp}/\text{dt}| \leq 2 \text{ hPa (12 h)}^{-1}$] during $\sim 37\%$ of all 12-h periods. Periods of moderate [$2\text{-}6 \text{ hPa (12 h)}^{-1}$] pressure rises outnumber periods of moderate pressure falls by about 10% (29% versus 19%), while the frequency of major [$\geq 6 \text{ hPa (12 h)}^{-1}$] pressure rises and falls, though nearly equal, are quite small ($\sim 7\%$).

The distribution of maximum 12-h deepening rates for Clippers during the post-departure period is shown in Fig. 6. The distribution is qualitatively similar to the maximum deepening rate distribution for continental cyclones presented in Roebber (1989, Fig. 2c). About 53% of the Clippers in the climatology have a maximum deepening rate of $2\text{-}6 \text{ hPa (12 h)}^{-1}$ (i.e., a moderate pressure fall). Only 10 of 177 Clippers experience a maximum

deepening rate $\geq 10 \text{ hPa (12 h)}^{-1}$, the approximate threshold rate for explosive cyclogenesis at 50°N (Sanders and Gyakum 1980). All but one of these explosive cyclogenesis periods occur either at 48 h or 60 h after departure time as rapidly-moving Clippers near or move over the Atlantic coast, where dynamic and thermodynamic conditions are generally most favorable for rapid cyclone development. Interestingly, the number of Clippers that experience filling throughout the 60-h post-departure period (15) is higher than the number of Clippers that undergo explosive cyclogenesis (10).

4. Structure and Evolution of the Composite Alberta Clipper

Although substantial intercase variability is found amongst the 177 cases selected for the Alberta Clipper climatology, a significant number of common elements in the structure and evolution of these storms were also evident. These common features will be highlighted through an analysis of the composite structure and evolution of the Clipper. The composite analysis will describe the evolution of the composite cyclone at 12-h intervals through two distinct stages: 1) a pre-departure period of 36 h leading up to the time of departure, and 2) a post-departure period of 60 h after departure.

a. Construction of the composites

The composite construction process began with the definition of a composite grid. The dimensions of the composite grid were chosen to be 40° latitude by 180° longitude. The composite grid was centered at the average position of the SLP minimum at departure time

($T=0$) for the pre-departure period and at the corresponding average position of the SLP minimum for each of the 12-h intervals in the post-departure period (Fig. 7). The number of grid points in the zonal and meridional directions in the composite grid (73 and 17 points, respectively) was fixed. The distance separating the grid points in the zonal direction is a function of grid row while the distance separating the grid points in the meridional direction is a constant, equivalent to the distance associated with a 2.5° increment in latitude. Having defined the composite grid, the procedure described by McLay and Martin (2002) was used to construct the composites for a given cyclone and analysis time. It should be kept in mind that the center of the composite domain remains at a fixed location from $T-36$ to $T=0$, but changes location from $T=0$ to $T+60$ as the composite Clipper follows the average storm track shown in Fig. 7. Therefore, tendencies of features away from the center of the composite domain should be considered from an Eulerian (Lagrangian) perspective during the pre-departure (post-departure) period.

b. Development of the composite Clipper in the pre-departure period

The pre-departure period for the composite Clipper is marked by three major features: a cyclone over the Gulf of Alaska, a tropospheric-deep ridge over western North America, and a lee trough developing east of the Canadian Rockies in British Columbia and Alberta. These features are reflected in the composite SLP field at $T-36$ (Fig. 8a) as a SLP minimum centered in the southwestern Gulf of Alaska, an anticyclone over the Intermountain West, and a weak trough of low pressure from northern British Columbia to southeastern Alberta. Associated with the Gulf of Alaska cyclone is a broad thermal ridge at 850 hPa over the

northeastern Pacific Ocean (Fig. 8b). A more subtle thermal ridge is located in the lee of the Canadian Rockies, with a strong northwest-southeast oriented baroclinic zone extending from northern Alberta to the western Great Lakes region (Fig. 8b). The Gulf of Alaska cyclone has prominent shortwave geostrophic relative vorticity maxima at 850 and 500 hPa (Figs. 8c,d) embedded within a larger-scale trough over the northern Pacific Ocean. Evidence for the lee trough in the vorticity⁴ field is seen only at 850 hPa (Fig. 8c).

At $T-12$, the center of the surface cyclone in the Gulf of Alaska is just south of the southern Alaska coast with little change in central SLP (Fig. 9a). The anticyclone over the Intermountain West has shifted slightly eastward and its central pressure has increased. The lee trough continues to broaden and become better defined. The axis of the 850 hPa thermal ridge connected with the Gulf of Alaska cyclone lies parallel to and just off the coastline with little change in its amplitude (Fig. 9b). Continuing cross-mountain flow has further increased the 850 hPa potential temperature over southern Alberta, enhancing the baroclinic zone over northeastern Alberta and Saskatchewan. As with the SLP minimum, the vorticity maxima at 850 and 500 hPa associated with the Gulf of Alaska cyclone are very close to the coast (Figs. 9c,d). The magnitude of the 850 hPa vorticity maximum has decreased slightly (Fig. 9c), a likely result of the interaction of the low-level flow with the coastal orography and the encroachment of the vorticity maximum upon the ridge to its east. The 500 hPa vorticity maximum experiences little change in its magnitude as it nears the coast (Fig. 9d). Only a slight indication of the lee trough is found in the 850 hPa geopotential height and vorticity fields (Fig. 9c), with no indication of the trough at 500 hPa (Fig. 9d).

⁴ For brevity, geostrophic relative vorticity will be referred to as simply “vorticity,” throughout this paper.

Substantial changes occur in the last 12 h before departure, as evidenced by the composite fields from $T=0$ (Fig. 10). The SLP minimum in the Gulf of Alaska has weakened dramatically as the center of the surface cyclone interacts with the orography along the coast (Fig. 10a). The center of the surface anticyclone in the Intermountain West has shifted slightly southeastward and weakened considerably. Broadening of the lee trough has continued, and an elongated area of low pressure links the Gulf of Alaska cyclone and the lee trough. Within the lee trough, a closed low pressure center has developed. With the landfall of the Gulf of Alaska cyclone, the amplitude of the 850 hPa thermal ridge (Fig. 10b) and magnitude of the 850 hPa vorticity maximum (Fig. 10c) associated with the Gulf of Alaska cyclone have greatly decreased. Over the lee of the Canadian Rockies, the 850 hPa thermal ridge has become more prominent with the thermal ridge axis positioned over the composite SLP minimum (Fig. 10b). A relatively strong 850 hPa vorticity maximum has formed within the lee trough, with the center of the vorticity maximum just east of the SLP minimum (Fig. 10c). The 500 hPa vorticity maximum associated with the Gulf of Alaska cyclone has nearly scaled the ridge over western North America (Fig. 10d), undergoing a decrease in its magnitude in the process. The 500 hPa ridge axis over western North America has shifted to a position just east of the SLP minimum.

c. Summary of the pre-departure period

The development of nearly every Clipper in the climatology is preceded by the landfall of a cyclone along the coastline of Alaska or British Columbia. These cyclones typically progress northeastward and fill as they approach the coastal mountain ranges

bordering the northeast Pacific Ocean. A strong northward component in movement and increase in central SLP is characteristic of almost all surface cyclones as they near major mountain ranges (e.g., Palmén and Newton 1969; Chung et al. 1976), with frequent dissipation of cyclones in the northeastern Pacific Ocean (Petterssen 1956; Zishka and Smith 1980; Roebber 1984; Bell and Bosart 1989; Lefevre and Nielsen-Gammon 1995). The composite results suggest the dissipation of a Pacific cyclone and the development of a new cyclone in the lee of the Canadian Rockies within the standing lee trough (Figs. 3.2-3.5a), contrary to the suggestions of Hess and Wagner (1948) and Bannon (1992).

The 850 hPa baroclinic zone to the east of the Canadian Rockies remains nearly stationary through the pre-departure period (Figs. 3.2-3.5b). As the Pacific cyclone nears the west coast of North America, cross-mountain flow strengthens and adiabatic warming from downslope flow in the lee of the Canadian Rockies increases. In the composite, the greatest adiabatic warming occurs to the south of the eventual position of the composite Clipper SLP minimum at departure time. The presence of a lee trough from $T-36$ to $T-12$ is manifest as a region of small 850 hPa vorticity on the east side of the Canadian Rockies (Figs. 8c and 9c). By $T=0$ (Fig. 10c), a more pronounced shortwave trough and substantially stronger vorticity maximum are shown over the lee of the Canadian Rockies. Though the composite does not unambiguously reveal whether the 850 hPa vorticity maximum associated with the Pacific cyclone propagates over the orography and the strong ridge or if a new vorticity maximum forms in the lee of the Canadian Rockies as a response to the development of the surface lee cyclone, the sudden increase in vorticity over the last 12 h of the pre-departure is most likely the result of differential vertical motion (i.e., descent at low levels, ascent at upper levels) and attendant column stretching.

It is clear from the composite that the 500 hPa vorticity maximum scales the ridge over western North America (Figs. 3.2-3.5d) during the pre-departure period. The magnitude of the vorticity maximum decreases as it interacts with the ridge through which it is moving. Though weakened by its passage over the ridge, the 500 hPa vorticity maximum is located well west of the SLP minimum at departure time. Encroachment of the upper-level trough axis on the lower tropospheric thermal ridge axis was identified by Carlson (1961) as the central characteristic of the transition from stationarity to mobility for a lee trough.

d. Structure and evolution of the composite Clipper in the post-departure period

At $T+12$ (Fig. 11), the center of the composite Clipper system has moved into far western Saskatchewan. The SLP minimum has deepened by about 1 hPa (Fig. 11a) with troughs of low pressure extending to the south-southeast and west-northwest of the surface cyclone center. The 850 hPa thermal ridge remains strongly amplified (Fig. 11b), with the thermal ridge axis collocated with the SLP trough south of the composite Clipper center. The thermal ridge is also collocated with the 850 hPa geopotential height trough (Fig. 11c), characteristic of a lee trough structure (e.g., Bluestein 1993, p. 13). The 850 hPa vorticity maximum has increased in magnitude while embedded in northwesterly flow and is centered directly over the SLP minimum (Fig. 11c). The magnitude of the 500 hPa vorticity maximum has also increased (Fig. 11d), but remains substantially less than that of the 850 hPa vorticity maximum. Importantly, the center of the 500 hPa vorticity maximum lies slightly to the west of the SLP minimum.

The central SLP of the composite Clipper is slightly higher at $T+24$ (Fig. 12a), with troughs of low pressure extending to the south and west-northwest from the SLP minimum. A surface anticyclone has become evident to the northwest of the composite Clipper. The amplitude of the thermal ridge at 850 hPa (Fig. 12b) has decreased slightly, and the thermal ridge axis has moved to just west of the SLP trough extending south from the composite Clipper center while taking on a southwest-northeast orientation. Colder air is beginning to filter southward to the west-northwest of the SLP minimum as evidenced by the subtle depression in the 850 hPa isentropes. The thermal ridge axis remains nearly collocated with the 850 hPa geopotential trough (Fig. 12c). The 850 hPa vorticity maximum continues increasing in magnitude within a compact shortwave trough, with the center of the vorticity maximum remaining almost directly over the SLP minimum. The strengthening 500 hPa vorticity maximum (Fig. 12d) continues to have a smaller magnitude than its counterpart at 850 hPa and remains west of the SLP minimum.

Filling of the composite SLP minimum continues through $T+36$ (Fig. 13a). The once well-defined troughs of low pressure emanating from the SLP minimum appear to have merged into one broad trough to the southwest of the surface cyclone center. The anticyclone to the northwest of the composite Clipper has shifted southeastward with little change in its intensity. The 850 hPa thermal ridge is substantially less amplified (Fig. 13b), and colder air to the west of the SLP minimum has continued to surge southward. The 850 hPa thermal ridge axis has rotated slightly counterclockwise and is positioned just east of the SLP minimum. The 850 hPa vorticity maximum has changed little in magnitude, but the center has moved slightly to the west of the SLP minimum (Fig. 13c). The 500 hPa vorticity

maximum has increased to a magnitude only slightly less than that of the 850 hPa vorticity maximum and remains centered to the west of the SLP minimum (Fig. 13d).

The SLP minimum continues its steady filling at $T+48$ with little evidence of distinct troughs extending from the center of the cyclone (Fig. 14a). A broad region of high pressure is in place west of the SLP minimum with the melding of the anticyclones from Canada and the northern United States Rocky Mountains. The 850 hPa thermal ridge maintains its smaller amplitude, but the thermal ridge axis has rotated counterclockwise to a north-south orientation (Fig. 14b). The 850 hPa vorticity maximum has decreased in magnitude and continues to be centered slightly west of the SLP minimum (Fig. 14c). The 500 hPa vorticity maximum has increased to a magnitude exceeding that of the 850 hPa vorticity maximum and remains centered well west of the SLP minimum (Fig. 14d).

The steady filling of the composite SLP minimum continues through $T+60$ (Fig. 15a). A broad anticyclone is now positioned over central North America. The 850 hPa thermal ridge axis has rotated to a northwest-southeast orientation with little change in its amplitude, and cold air continues pushing southward to the west of the composite Clipper center (Fig. 15b). The magnitude of the 850 hPa vorticity maximum continues its downward trend (Fig. 15c), while the 500 hPa vorticity maximum maintains its magnitude (Fig. 15d). A structure conducive for baroclinic development is exhibited by the composite Clipper as clear westward displacement of the vorticity centers with height is evident (Figs. 15c,d).

e. Summary of the post-departure period

The composite Alberta Clipper is not a particularly robust cyclone in terms of its central SLP or its size. In fact, the composite Clipper reaches its lowest central SLP (1002.4 hPa) at $T+12$, with a steady pressure increase of 0.7 to 0.8 hPa every 12 h through $T+60$ (Figs. 11-15a). Though the central SLP of the composite Clipper is relatively high, the system is flanked by anticyclones to its south and northwest that lead to relatively strong pressure gradients around the composite Clipper center.

The composite 850 hPa potential temperature field (Figs. 11-15b) undergoes substantial change during the post-departure period. Adiabatic warming from downslope flow creates an amplified thermal ridge in the first 24 h after departure. This enhanced thermal ridge maintains a strong baroclinic zone north and northeast of the composite Clipper center. The thermal ridge axis is collocated with the SLP trough early in post-departure period, with the peak of the thermal ridge near the composite SLP minimum. This structure clearly resembles a lee trough structure (e.g., Bluestein 1993, p. 13).

Substantial dampening of the thermal ridge occurs between $T+24$ to $T+36$ (Figs. 3.7-3.8b), a direct consequence of the cessation of adiabatic warming from downslope flow to the west of the composite Clipper center as the system moves farther away from the Rockies. The thermal ridge axis also shifts to a position slightly to the east of the SLP minimum and associated southward-extending SLP trough. Previously blocked by the higher terrain, colder air to the northwest of the composite Clipper center funnels southward as the system progresses away from the Rockies. The southward progression of the baroclinic zone to the west of the composite SLP minimum and the apparent merging of the two distinct pressure troughs at $T+24$ (Fig. 3.7a) into one broad trough at $T+36$ (Fig. 3.8a) mark the process of the cold front overtaking the lee trough. Over the last 24 h of the post-departure period, the

baroclinic zones take on an orientation resembling that of the cold and warm fronts in a classical cyclone (Bjerknes and Solberg 1922). Locatelli et al. (1989) and Steenburgh and Mass (1994) describe a similar transition in structure from a lee trough to a more classical midlatitude cyclone over approximately the same time frame as shown in this study.

Though the central SLP of the composite cyclone is relatively high, the cyclonic circulations associated with the composite system are well-defined at both 850 and 500 hPa as evidenced by the magnitude of the geostrophic relative vorticity (Figs. 11-15c,d). The magnitude of the 850 (500) hPa vorticity maximum is largest during the early (late) stages of the post-departure period (Figs. 11-15c,d), suggesting that the lower tropospheric circulation of the Clipper is strongest early in the life cycle, while the upper tropospheric circulation strengthens throughout the life cycle. The positioning of the vorticity maxima with respect to the SLP minimum also sheds light on the nature of the evolving Clipper system. The 850 hPa vorticity maximum center is located directly above the SLP minimum through the first 24 h of the post-departure period, shifting slightly to the west of the SLP minimum over the last 36 h of the post-departure period. At 500 hPa, the center of the vorticity maximum remains well west of the SLP minimum throughout the post-departure period, a configuration most favorable for cyclone development and propagation. Thus, analysis of the evolving thermal and geopotential height fields suggests that the composite Clipper acquires a structure more favorable for baroclinic growth (e.g., Holton 1992) as time progresses.

5. Composite QG forcing for ascent

Additional insight into the nature of the Alberta Clipper can be gleaned by considering the QG forcing for ascent throughout the Clipper life cycle. The characteristic precipitation pattern of the Clipper is directly related to the distribution of vertical motion which is driven by both synoptic-scale and frontogenetical processes. Many studies have stressed the importance of the upper-level vorticity maximum and associated vorticity advection on the development and evolution of cyclones originating from the Canadian Rockies (e.g., Hess and Wagner 1948; McClain 1960; Palmén and Newton 1969; Steenburgh and Mass 1994). Frontal-scale processes also can contribute greatly to forcing for vertical motion in cyclones that are generated in the lee of the Canadian Rockies (Locatelli et al. 1989; Martin et al. 1990; Steenburgh and Mass 1994; Kapela et al. 1995). The forcing produced by synoptic-scale and frontogenetical processes can be separately diagnosed from a QG perspective by considering the \mathbf{Q} -vector form of the QG omega equation,

$$(\sigma^2 - f_o \frac{d}{dt}) \nabla^2 \bar{\mathcal{Q}} \quad (1)$$

(Hoskins et al. 1978). For adiabatic, geostrophic flow, \mathbf{Q} represents the rate of change of the potential temperature gradient vector ($\nabla\theta$) on an f -plane along a geostrophic trajectory:

$$\bar{\mathcal{Q}} = f_o \frac{d}{dt_g} \nabla_p \theta \quad (2)$$

where $\frac{d}{dt_g} = \frac{R}{f p_o} \left(\frac{p_o}{p}\right)^{\frac{c_v}{p}} \frac{d}{dt} + u_g \frac{\partial}{\partial x} + v_g \frac{\partial}{\partial y}$, the subscript g denotes geostrophic and the subscript p denotes differentiation on an isobaric surface. Keyser et al. (1992) showed that a partition of \mathbf{Q} into across- and along-isentrope components describes changes in the magnitude and direction of $\nabla\theta$, respectively. Employing the natural coordinate system adopted by Martin (1999), the across-isentrope component of \mathbf{Q} is given by

$$\bar{Q}_n = \frac{\bar{Q} \cdot \hat{n}}{|\hat{n}|} = Q_n \hat{n} \quad (3)$$

and is physically related to changes in the magnitude of \hat{n} . Note that the scalar function Q_n is identically equal to the QG frontogenesis function ($\mathcal{F}_g = \frac{d}{dt_g} |\hat{n}|$), thus \bar{Q}_n represents the forcing for vertical motion associated with frontogenetical processes. The along-isentrope component of \mathbf{Q} is given by

$$\bar{Q}_s = \frac{\bar{Q} \cdot \hat{s}}{|\hat{s}|} = Q_s \hat{s} \quad (4)$$

and is related to the rate of change of direction of \hat{n} . Keyser et al. (1992) referred to \bar{Q}_s as the “wave scale,, forcing for \hat{n} . Support for this assertion arises from a recent study of cyclones from the QG perspective that identifies \bar{Q}_s as the predominant forcing associated with synoptic-scale development (Martin 2005). Given their relationships to \hat{n} , examination of each component of \mathbf{Q} provides insight into the dynamical processes that underlie the changes in the thermal structure of the composite Clipper during the post-departure period.

Figure 16 shows the 850 hPa composite potential temperature and \mathbf{Q}_n vectors of the composite⁵ at $T+12$, $T+36$, and $T+60$. Recalling that $\mathbf{Q}_n = \mathcal{F}_g \hat{n}$, the evolution of the geostrophic frontogenesis throughout the Clipper life cycle is reflected in the distribution and direction of \mathbf{Q}_n . At $T+12$ (Fig. 16a), the strongest geostrophic frontogenesis is located well east of the composite SLP minimum along the broad northwest-southeast oriented baroclinic

⁵ The components of the \mathbf{Q} -vector, \mathbf{Q}_n and \mathbf{Q}_s , are calculated using the composite geostrophic wind and potential temperature. Thus, \mathbf{Q}_n and \mathbf{Q}_s vectors shown are not *composite* \mathbf{Q}_n and \mathbf{Q}_s vectors, but rather \mathbf{Q}_n and \mathbf{Q}_s vectors of the composite.

zone, while geostrophic frontolysis is occurring to the northwest of the SLP minimum. Geostrophic frontogenesis continues to the east and northeast of the composite SLP minimum at $T+36$ (Fig. 16b), though its magnitude is slightly less than it was 24 h earlier. Geostrophic frontogenesis is also occurring west of the composite SLP minimum along the southward-propagating cold front that was previously blocked by the orography. The thermal structure has taken on a more classical appearance with a warm-frontal baroclinic zone extending east and a cold-frontal baroclinic zone running west-southwest from the center of the cyclone. The more classical structure of the thermal field is maintained at $T+60$ (Fig. 16c) with distinct areas of geostrophic frontogenesis along the apparent warm and cold fronts. The strongest geostrophic frontogenesis remains along the warm front, though the magnitude of the frontogenesis along both fronts is slightly less than it was at $T+36$.

The 850 hPa composite potential temperature and \mathbf{Q}_s vectors of the composite are shown in Fig. 17. Throughout the post-departure period, \mathbf{Q}_s vectors with the greatest magnitude are located near the thermal ridge axis. As a result, the greatest rotation of the thermal gradient vector will occur in the baroclinic zone near the thermal ridge axis. From $T+12$ to $T+36$ (Figs. 17a,b), the baroclinic zone along the top portion of the thermal ridge rotates counterclockwise from a northwest-southeast orientation to a largely west-east orientation. As the composite Clipper moves into eastern North America between $T+36$ and $T+60$ (Figs. 17b,c), the baroclinic zone and the thermal ridge axis undergo a considerable counterclockwise rotation. Slight amplification of the thermal trough to the west of the composite SLP minimum is also apparent between $T+36$ and $T+60$, a result of \mathbf{Q}_s divergence centered within the thermal trough. The rotation of the thermal gradient described by \mathbf{Q}_s leads to the development of a more classical thermal structure in the composite Clipper.

The \mathbf{Q}_n and \mathbf{Q}_s components of \mathbf{Q} and their respective divergences computed from the 500-850 hPa layer-averaged composite geostrophic wind and potential temperature at $T+12$, $T+36$, and $T+60$ are shown in Fig. 18. At $T+12$, the convergence of \mathbf{Q}_n and \mathbf{Q}_s are comparable in magnitude and located well east of the SLP minimum (Figs. 18a,b). The distribution of $\nabla \cdot \vec{\mathbf{Q}}_n$ (Fig. 18a) clearly depicts a circulation along the warm-frontal baroclinic zone to the east of the composite SLP minimum. The east-west couplet of $\nabla \cdot \vec{\mathbf{Q}}_s$ along the mean flow greatly resembles regions of cyclonic and anticyclonic vorticity advection about a vorticity maximum (Fig. 18b). By $T+36$, the Clipper has acquired more classical frontal features as evidenced by the warm-frontal circulation to the east and cold-frontal circulation to the west of the center of the composite Clipper depicted in the $\nabla \cdot \vec{\mathbf{Q}}_n$ field (Fig. 18c). The magnitude of $\nabla \cdot \vec{\mathbf{Q}}_s$ has increased considerably (Fig. 18d), a reflection of the increased strength of the upper-level vorticity maximum in the composite. The collocation of relatively strong \mathbf{Q}_n and \mathbf{Q}_s divergence to the west of the composite SLP suggests that fairly strong subsidence occurs in that region. This subsidence, and its attendant downward transfer of momentum, likely contributes to the strong winds often experienced over central North America following the passage of cold fronts associated with Clippers (Kapela et al. 1995). The magnitudes of $\nabla \cdot \vec{\mathbf{Q}}_n$ and $\nabla \cdot \vec{\mathbf{Q}}_s$ have decreased over all areas by $T+60$ (Figs. 18e,f), an indication of the slight weakening of the composite Clipper. The frontal circulations about the composite SLP minimum (Fig. 18e) remain evident, though slightly weaker than 24 h earlier. Synoptic-scale processes continue to be the dominant contributor to QG forcing for vertical motion as the divergence and convergence of \mathbf{Q}_s (Fig. 18f) remain considerably larger than the \mathbf{Q}_n counterparts.

The composites provide compelling evidence of the evolution of the Alberta Clipper from the lee trough to a more classically structured midlatitude cyclone. Orographic processes play an essential role in the building and maintenance of a prominent low-level thermal ridge early in the post-departure period. As the Clipper moves away from the immediate lee of the Rockies, the effects of orography are quickly lost and the thermal ridge undergoes rapid dampening. At the same time, synoptic-scale forcing becomes more dominant with the incorporation of the upper-level vorticity maximum into the Clipper structure. The positioning of the 500 hPa vorticity maximum upstream of the SLP minimum allows for cyclonic vorticity advection by the thermal wind, a considerable portion of \bar{Q}_s (Martin 1999), to occur over the surface cyclone. Q_s is responsible for the geostrophic rotation of the thermal ridge that results in the development of a more classical thermal structure in the composite Clipper. Thus, the thermal gradient rotation necessary for the composite Clipper to acquire a more classical thermal structure is dependent upon the upstream displacement of the 500 hPa vorticity maximum with respect to the surface cyclone center which, in turn, fosters middle tropospheric ascent associated with the Clipper.

6. Conclusions

The Alberta Clipper is one of the most prominent cold season weather phenomena affecting central and eastern North America. Though often considered innocuous as a result of its rather weak signature in the SLP field and its associated meager precipitation amounts, the Clipper can bring hazardous weather in the form of strong winds, blowing and drifting snow, and bitterly cold temperatures. Even with their frequent occurrence and acknowledged

potential for producing dangerous weather, only a few studies have examined the Clipper in detail. The present paper partially fills this surprising void by investigating the Clipper via synoptic-climatological and composite analyses.

Many common characteristics were evident in the 177 Alberta Clippers selected for the climatology. These common features were addressed through an analysis of the structure and evolution of the composite Clipper. The first part of the analysis investigated the development of the composite Clipper in the 36 h leading up to its departure from the lee of the Canadian Rockies. This pre-departure period is marked by the following characteristics:

- 1) The approach and landfall of a Pacific cyclone whose mean sea level pressure minimum and 850 hPa geopotential height minimum weaken considerably along the coastal mountain ranges of Alaska and British Columbia.
- 2) The development and eastward expansion of a standing lee trough in response to increasing cross-mountain flow and associated adiabatic warming with the approach of the Pacific cyclone toward the coast.
- 3) The development and amplification of a thermal ridge at 850 hPa in the lee of the Rockies primarily south of the departure point of the composite Clipper resulting from increased adiabatic warming from persistent downslope flow.
- 4) The scaling of the ridge centered over the west coast of North America by the 500 hPa shortwave trough and associated vorticity maximum connected to the landfalling Pacific cyclone which leads to their incorporation as part of the composite Clipper structure at the time of departure.
- 5) The development of a closed surface circulation in the lee trough at the time of departure.

The evolution of the variables above resembles findings shown in previous studies of lee cyclogenesis in the Canadian Rockies (e.g., Hess and Wagner 1948; Palmén and Newton 1969; Chung et al. 1976).

The second part of the analysis examined the structure and evolution of the composite Clipper in the 60-h period following departure. Key features of note during post-departure period include the following:

- 1) The central SLP of the composite Clipper remains relatively high throughout the post-departure period, with the lowest SLP reached 12 h after departure followed by a steady rise in central SLP through the end of the post-departure period.
- 2) The once-prominent 850 hPa thermal ridge formed primarily by adiabatic warming from downslope flow early in the post-departure period dampens considerably as the composite Clipper moves into central North America away from the immediate lee of the Canadian Rockies.
- 3) Cold air to the west of the composite Clipper SLP minimum begins to filter southward starting 24 h after departure as a cold front, previous blocked by higher terrain, rotates counterclockwise around the Clipper. The cold front appears to overtake the lee trough ~36 h after departure.
- 4) The geostrophic relative vorticity maximum at 850 (500) hPa reaches its maximum magnitude early (late) in the post-departure period which suggests that the lower- (upper-) level circulation in the composite Clipper is strongest early (late) in the life cycle.
- 5) Synoptic-scale processes are the dominant contributor to QG forcing for vertical motion in the composite Clipper throughout the post-departure period, while QG forcing from frontogenetical processes is relatively weak and decreases over time.

6) An initially vertically-stacked system at low levels acquires more westward tilt with height as the post-departure period progresses. The 500 hPa shortwave trough and associated vorticity maximum always remain to the west of the composite SLP minimum throughout the post-departure period.

As a whole, the composite Clipper evolves from a lee trough to a more classical midlatitude cyclone as it moves through central and eastern North America. This evolution is largely accomplished through the counterclockwise rotation of the 850 hPa thermal ridge axis and the increasing westward tilt with height of the composite Clipper over the last 36 h of the post-departure period. The thermal gradient rotation is dynamically linked to cyclonic vorticity advection by the thermal wind and convergence of the along-isentrope (i.e., Q_s) component of the Q -vector made possible by the persistent westward displacement of the 500 hPa vorticity maximum with respect to the composite Clipper SLP minimum. The nature and timing of the composite Clipper evolution resembles the conceptual model of lee trough evolution described in Steenburgh and Mass (1994).

Finally, two conspicuous types of Alberta Clippers emerged in this climatology; those that maintain a coherent surface signature over eastern North America and those that do not. In a companion study we will present results of an examination of these “sustained,, (SUS) and “diminishing,, (DIM) cases and suggest that large-scale circulation features play a significant role in determining the duration of a given Alberta Clipper event.

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FIGURE CAPTIONS

Fig. 1. Cumulative monthly Alberta Clipper frequency from the climatology.

Fig. 2. Storm tracks of all Alberta Clippers in the climatology out to 60 h after departure.

Fig. 3. Distribution of central sea level pressure recorded at every 12-h analysis time during the 60-h post-departure period for all Clippers in the climatology. A total of 1062 sea level pressure values were recorded.

Fig. 4. Distribution of lowest central sea level pressure during the 60-h post-departure period for all Clippers in the climatology.

Fig. 5. Distribution of adjusted sea level pressure tendency [$\text{hPa (12 h}^{-1})$] during the 60-h post-departure period for all Clippers in the climatology.

Fig. 6. Distribution of maximum Clipper deepening rates [$\text{hPa (12 h}^{-1})$] during the 60-h post-departure period.

Fig. 7. Gray dots represent the average position of all Alberta Clippers in the climatology at the given time (in hours) after departure. The black line connecting the dots represents the average track of the Alberta Clippers in the climatology.

Fig. 8. Composite analyses for all Alberta Clippers at $T-36$. (a) Composite sea level pressure. Isobars are labeled in hPa and contoured every 2 hPa. (b) Composite 850 hPa potential temperature. Isentropes are labeled in K and contoured every 3 K. (c) Composite 850 hPa geopotential height (solid lines) and 850 hPa geostrophic relative vorticity (shading). Geopotential height is labeled in dam and contoured every 3 dam. Shading for geostrophic relative vorticity begins at $5 \times 10^{-6} \text{ s}^{-1}$ with a shading interval of $10 \times 10^{-6} \text{ s}^{-1}$. (d) As in (c), except at 500 hPa. Geopotential height is contoured every 6 dam.

Fig. 9. As for Fig. 8 except for $T-12$.

Fig. 10. As for Fig. 8 except for $T=0$. Values in the lower right corner of (a), (c), and (d) are the minimum sea level pressure (hPa), maximum 850 hPa geostrophic relative vorticity ($\times 10^{-6} \text{ s}^{-1}$), and maximum 500 hPa geostrophic relative vorticity ($\times 10^{-6} \text{ s}^{-1}$), respectively. The X symbol in (b)-(d) corresponds to the location of the sea level pressure minimum of the composite Clipper.

Fig. 11. As for Fig. 10 except for $T+12$.

Fig. 12. As for Fig. 10 except for $T+24$.

Fig. 13. As for Fig. 10 except for $T+36$.

Fig. 14. As for Fig. 10 except for $T+48$.

Fig. 15. As for Fig. 10 except for $T+60$.

Fig. 16 Composite 850 hPa potential temperature and 850 hPa Q_n vectors of the composite at (a) $T+12$, (b) $T+36$, and (c) $T+60$. Potential temperature is labeled in K and contoured every 3 K. The X symbols as in Fig. 10.

Fig. 17 As in Fig. 16 except for 850 hPa Q_s vectors of the composite. The thick dashed line represents the 850 hPa thermal ridge axis.

Fig. 18 (a) 500-850 hPa layer-averaged Q_n vectors and Q_n divergence of the composite at $T+12$. Q_n divergence (convergence) is labeled in units of $10^{-16} \text{ m}^2 \text{ s}^{-1} \text{ kg}^{-1}$, indicated by dark (light) shading, and contoured every $2 \times 10^{-16} \text{ m}^2 \text{ s}^{-1} \text{ kg}^{-1}$ starting at 1 (-1) $\times 10^{-16} \text{ m}^2 \text{ s}^{-1} \text{ kg}^{-1}$. (b) As in (a), except for Q_s vectors and Q_s divergence at $T+12$. (c) As in (a), except for $T+36$. (d) As in (b), except for $T+36$. (e) As in (a), except for $T+60$. (f) As in (b), except for $T+60$. The X symbols as in Fig. 10.

Cumulative Monthly Alberta Clipper Frequency (1986-2001)

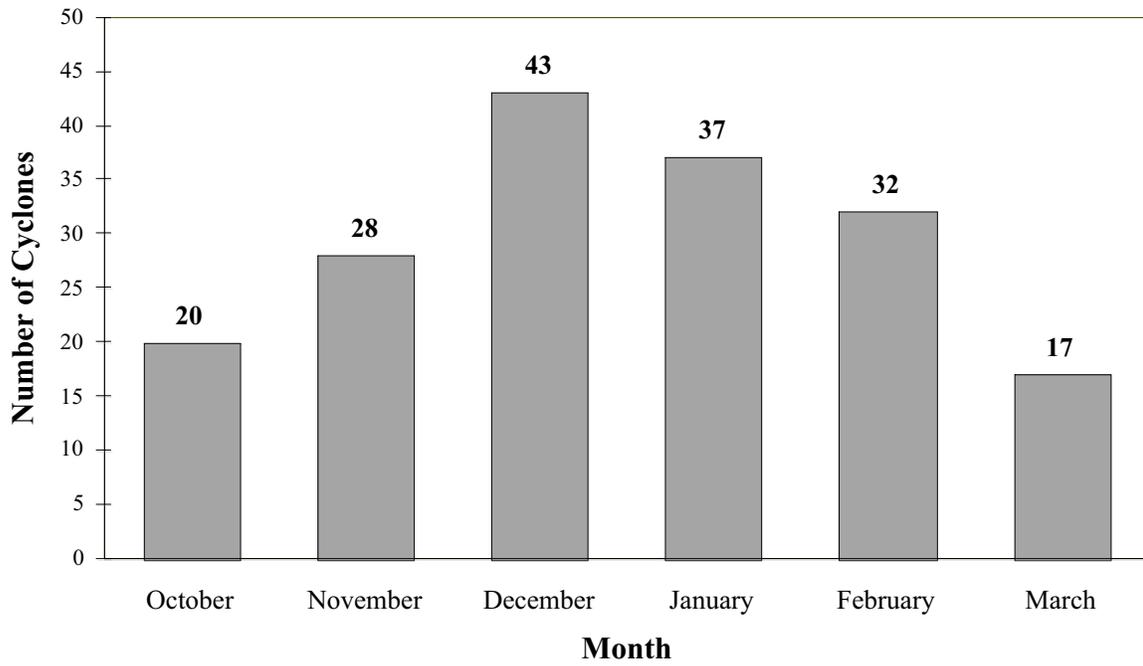


Fig. 1. Cumulative monthly Alberta Clipper frequency from the climatology.

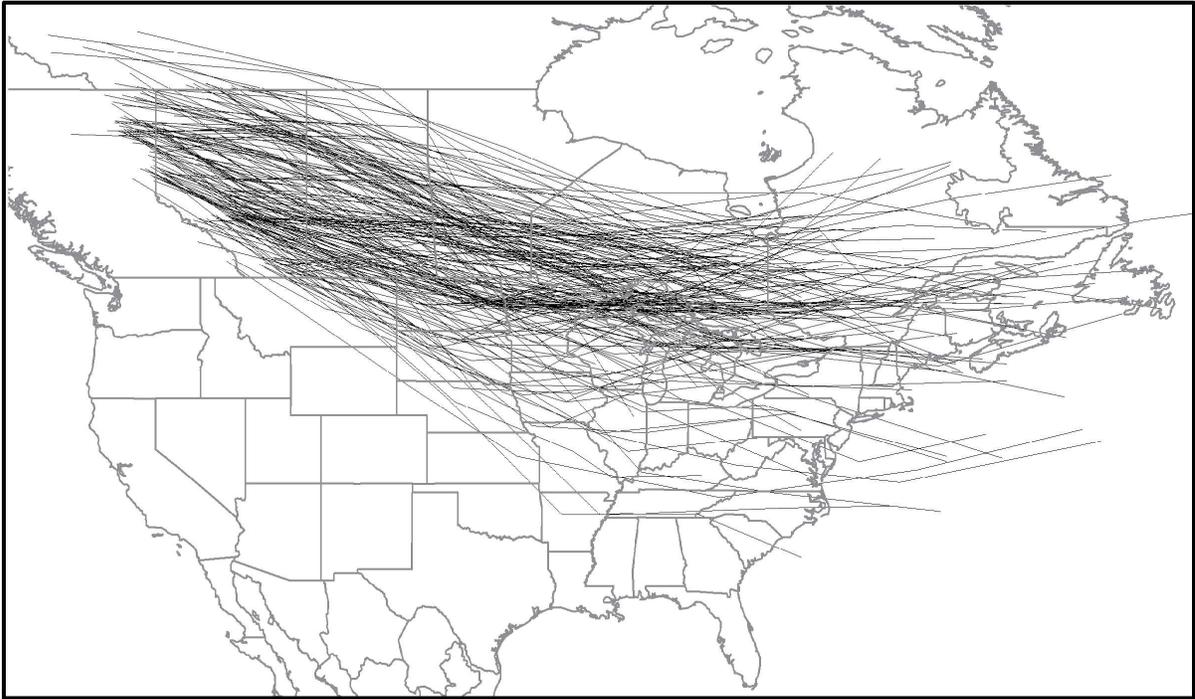


Fig. 2 Storm tracks of all Alberta Clippers in the climatology out to 60 h after departure.

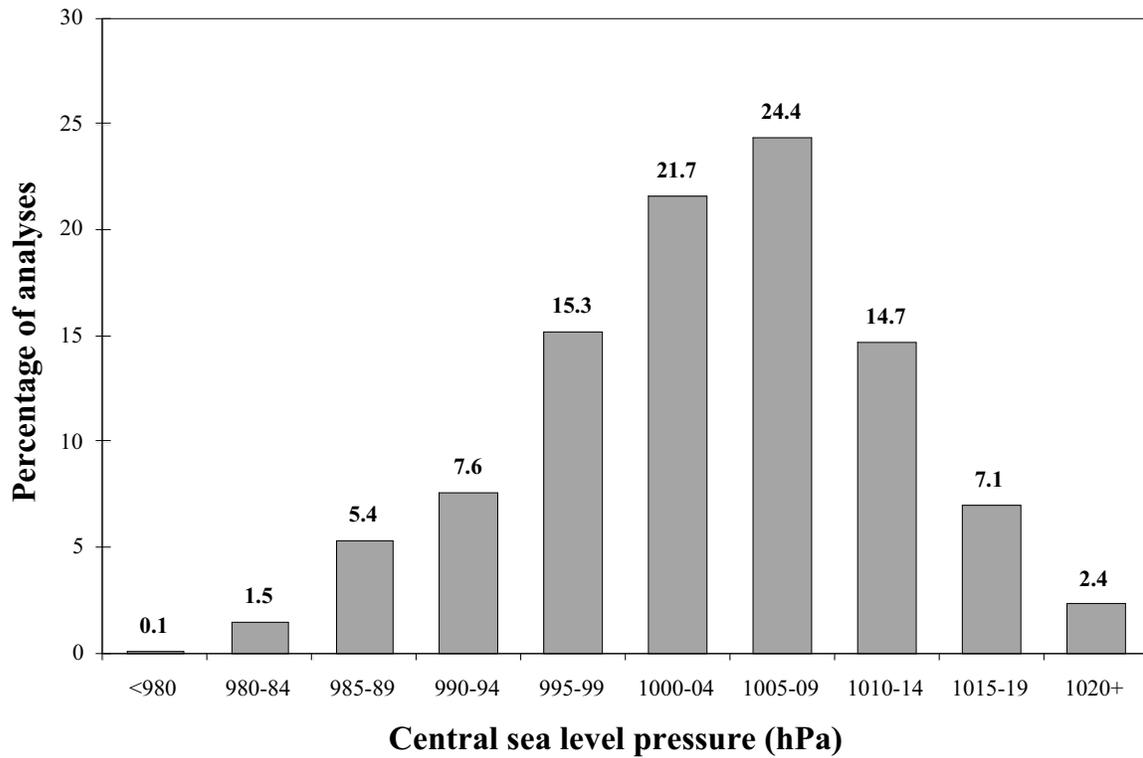


Fig. 3 Distribution of central sea level pressure recorded at every 12-h analysis time during the 60-h post-departure period for all Clippers in the climatology. A total of 1062 sea level pressure values were recorded.

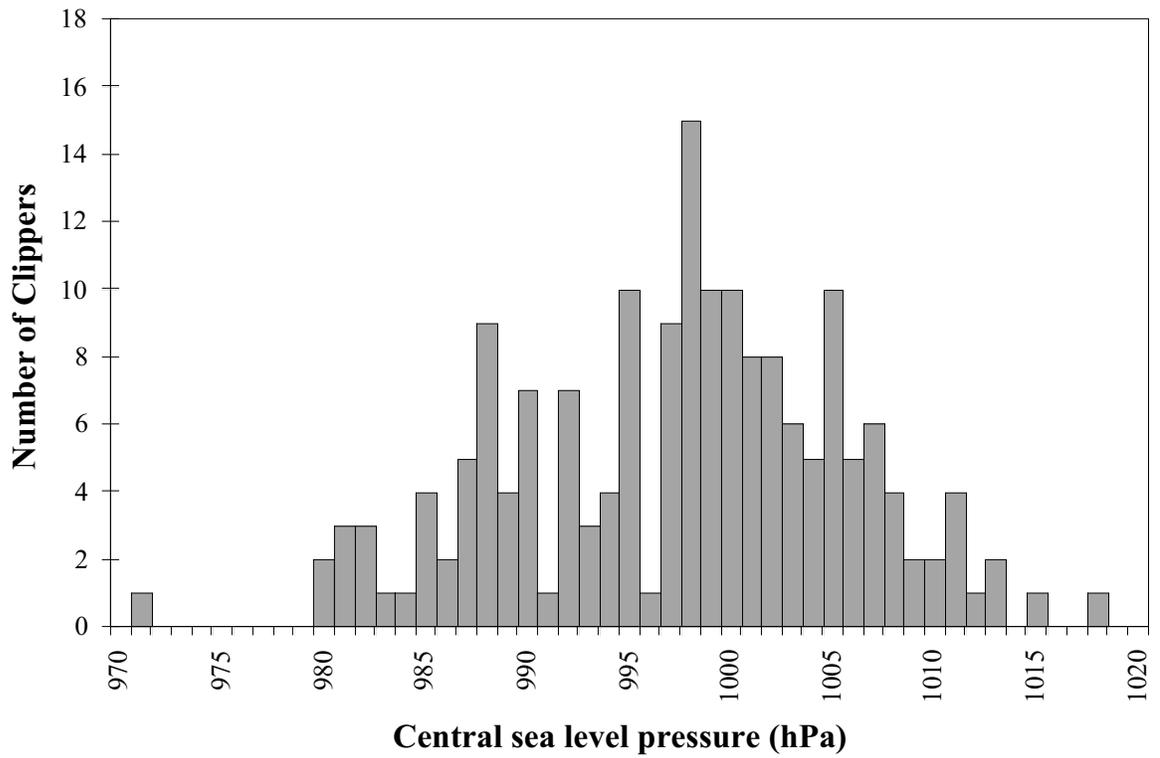


Fig. 4 Distribution of lowest central sea level pressure during the 60-h post-departure period for all Clippers in the climatology.

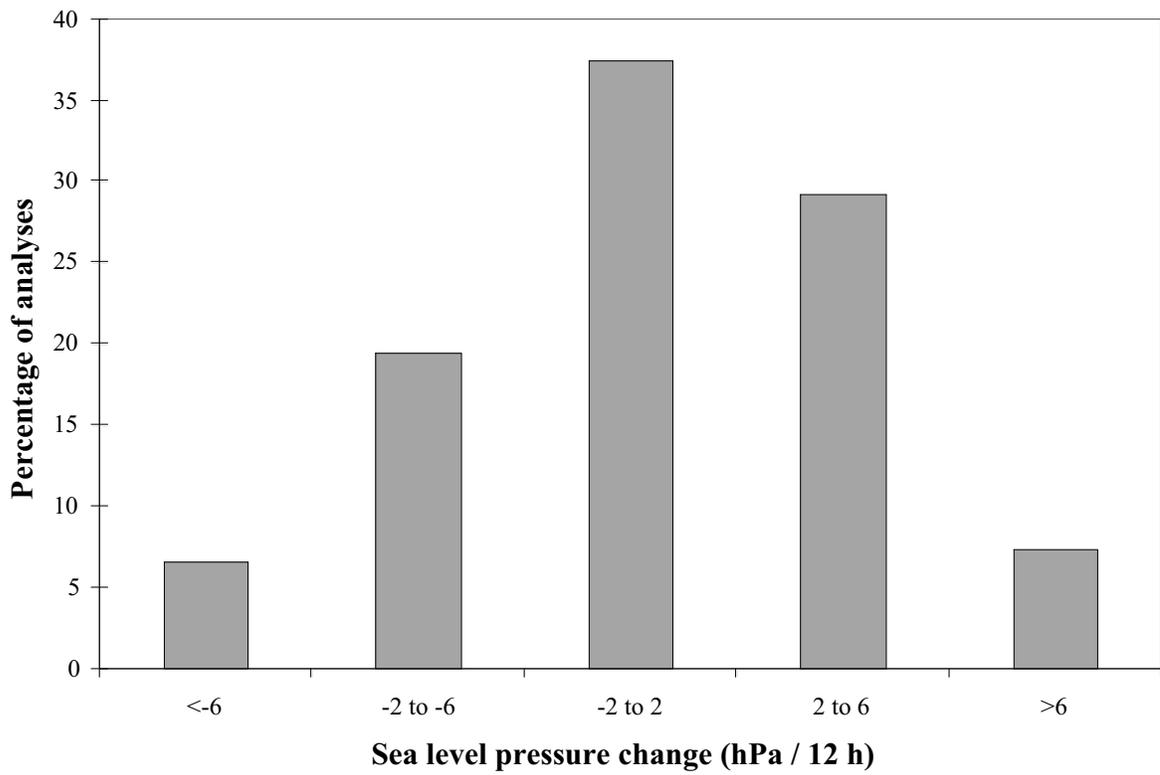


Fig. 5 Distribution of adjusted sea level pressure tendency [hPa (12 h⁻¹)] during the 60 h post-departure period for all Clippers in the climatology.

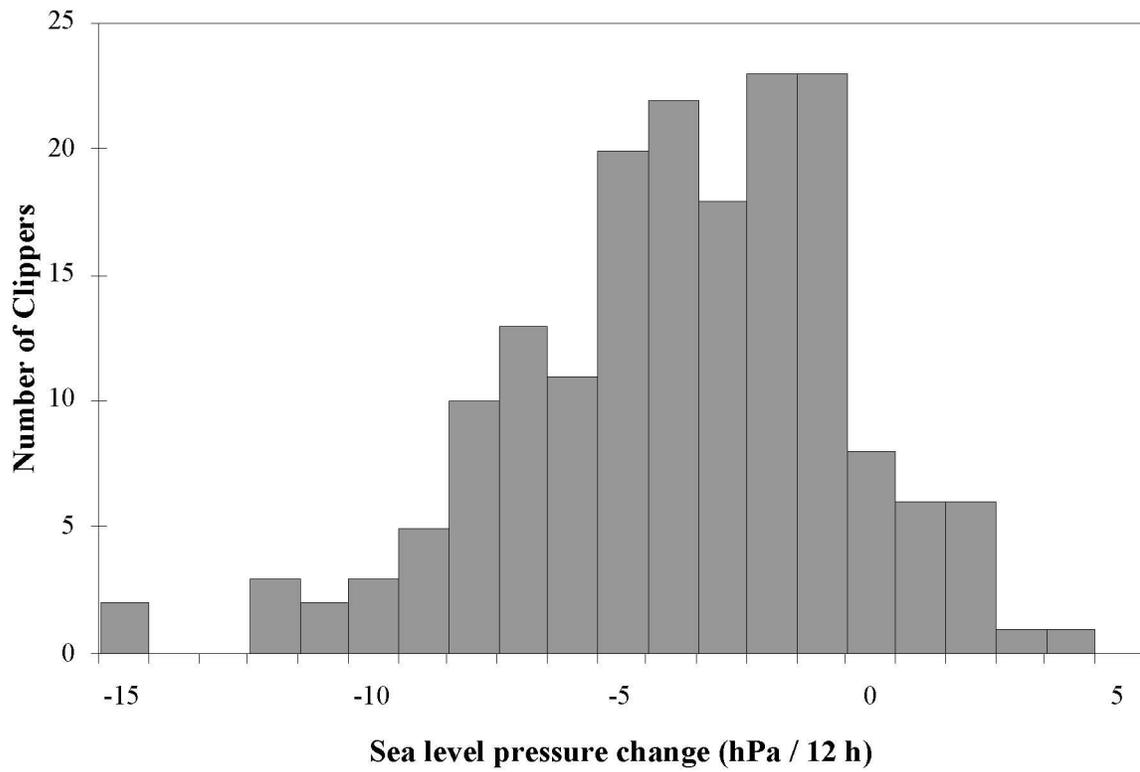


Fig. 6 Distribution of maximum Clipper deepening rates [hPa (12 h)^{-1}] during the 60-h post-departure period.

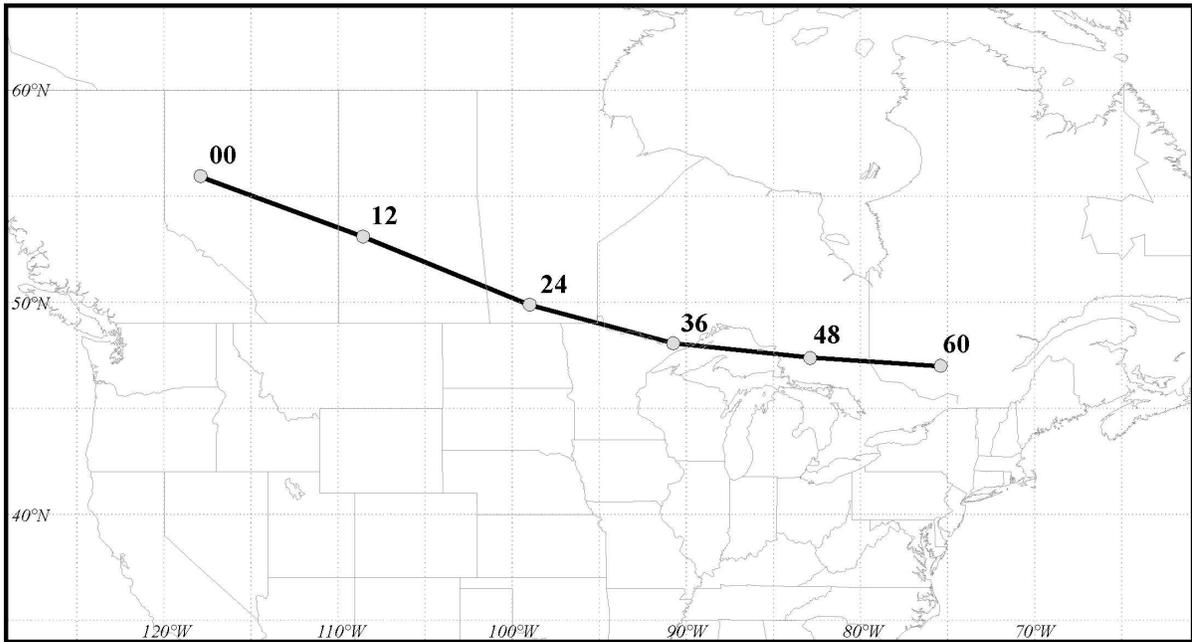


Fig. 7 Gray dots represent the average position of all Alberta Clippers in the climatology at the given time (in hours) after departure. The black line connecting the dots represents the average track of the Alberta Clippers in the climatology.

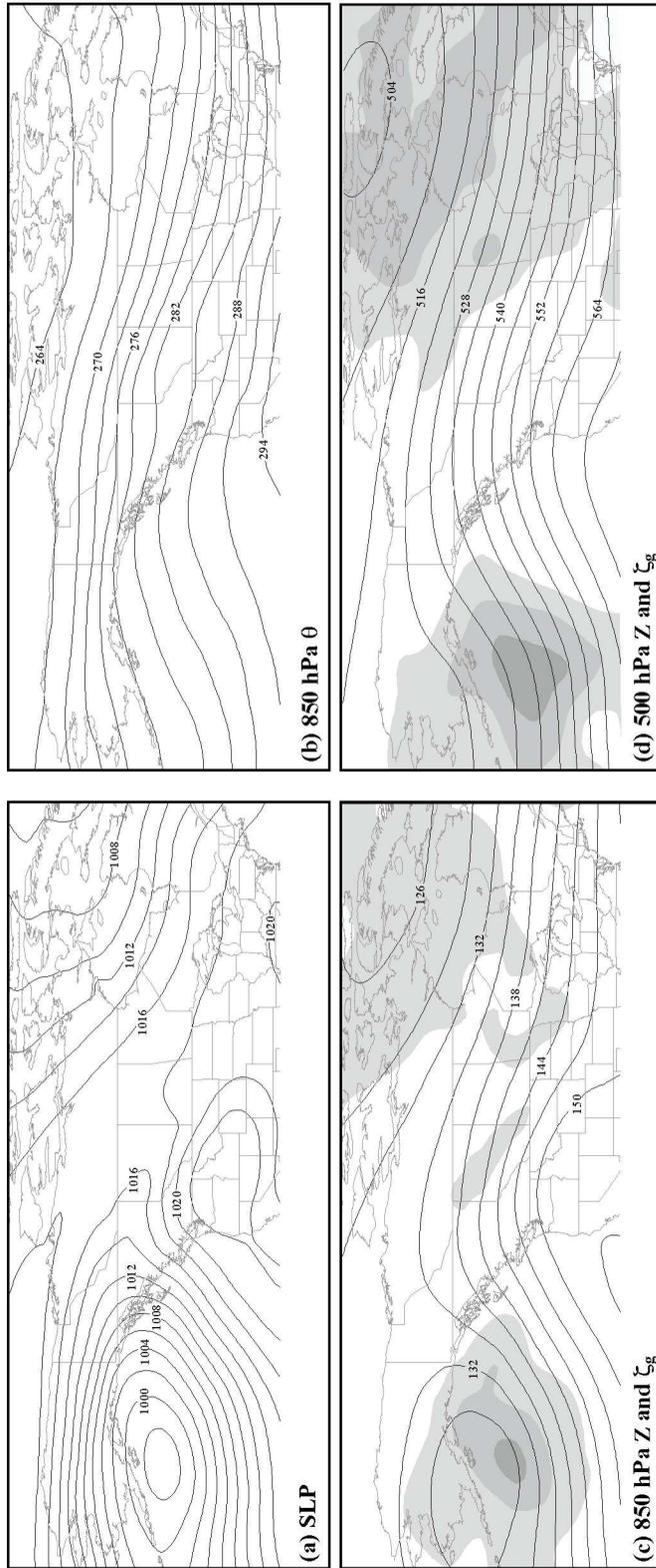


Fig. 8 Composite analyses for all Alberta Clippers at 7-36. (a) Composite sea level pressure. Isobars are labeled in hPa and contoured every 2 hPa. (b) Composite 850-hPa potential temperature. Isentropes are labeled in K and contoured every 3 K. (c) Composite 850-hPa geopotential height (solid lines) and 850-hPa geostrophic relative vorticity (shading). Geopotential height is labeled in dam and contoured every 3 dam. Shading for geostrophic relative vorticity begins at $5 \times 10^{-6} \text{ s}^{-1}$ with a shading interval of $10 \times 10^{-6} \text{ s}^{-1}$. (d) As in (c), except at 500 hPa. Geopotential height is contoured every 6 dam.

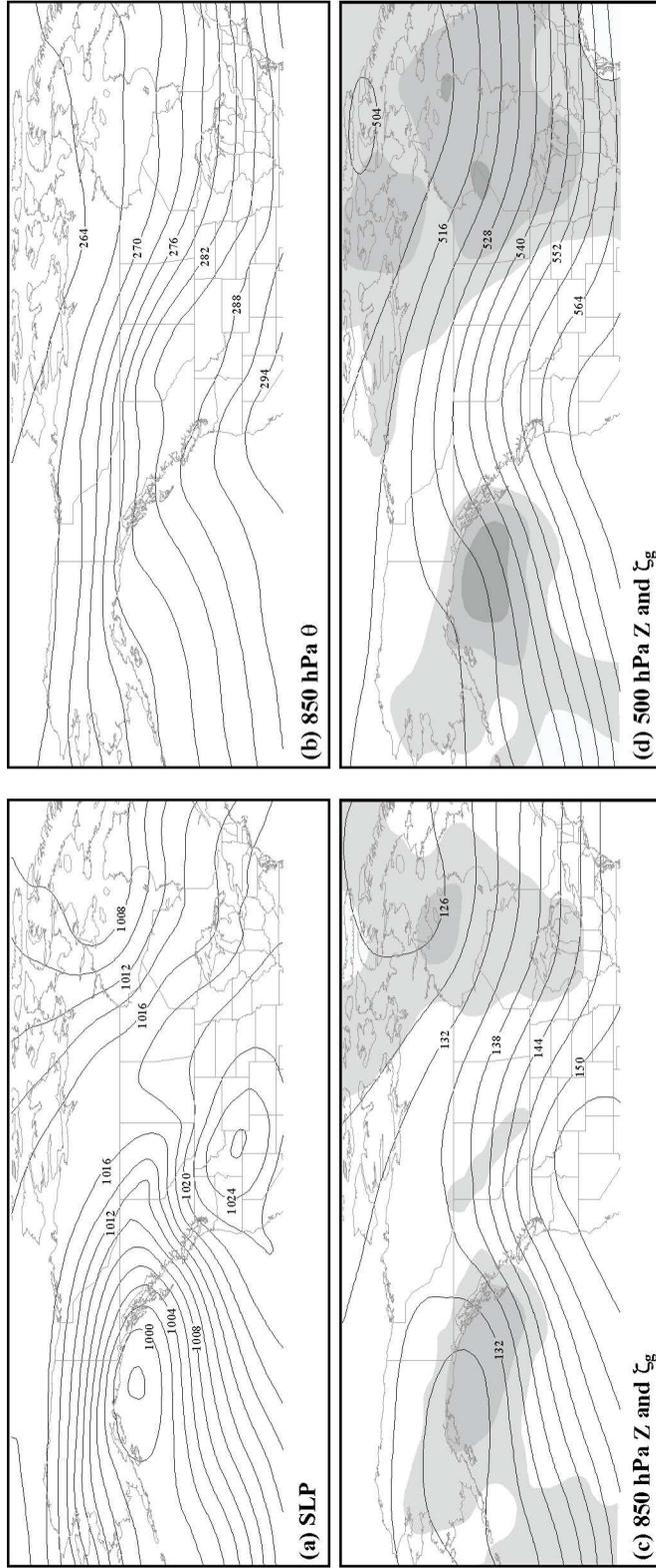


Fig. 9 As for Fig. 8 except for T -12.

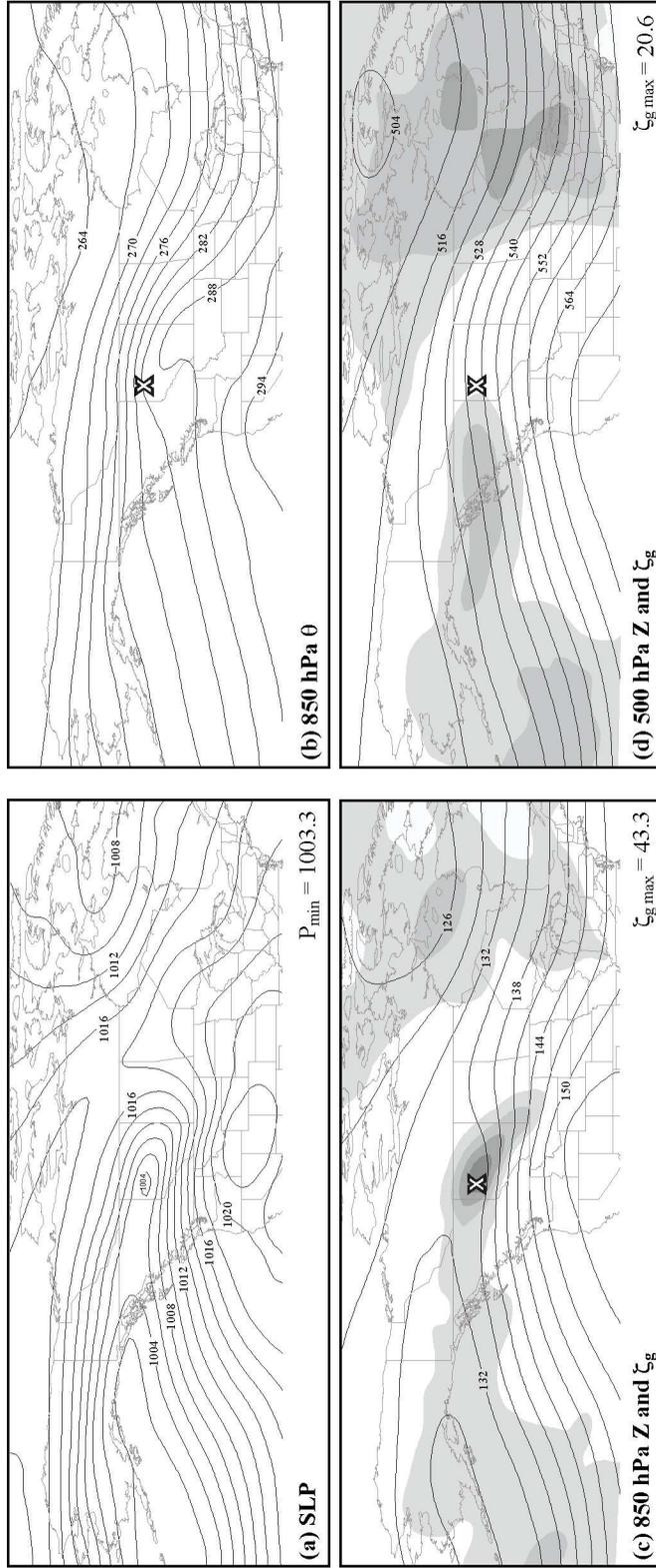


Fig. 10 As for Fig. 8 except for $T=0$. Values in the lower right corner of (a), (c), and (d) are the minimum sea level pressure (hPa), maximum 850-hPa geostrophic relative vorticity ($\times 10^{-6} \text{ s}^{-1}$), and maximum 500-hPa geostrophic relative vorticity ($\times 10^{-6} \text{ s}^{-1}$), respectively. The X symbol in (b)-(d) corresponds to the location of the sea level pressure minimum of the composite Clipper.

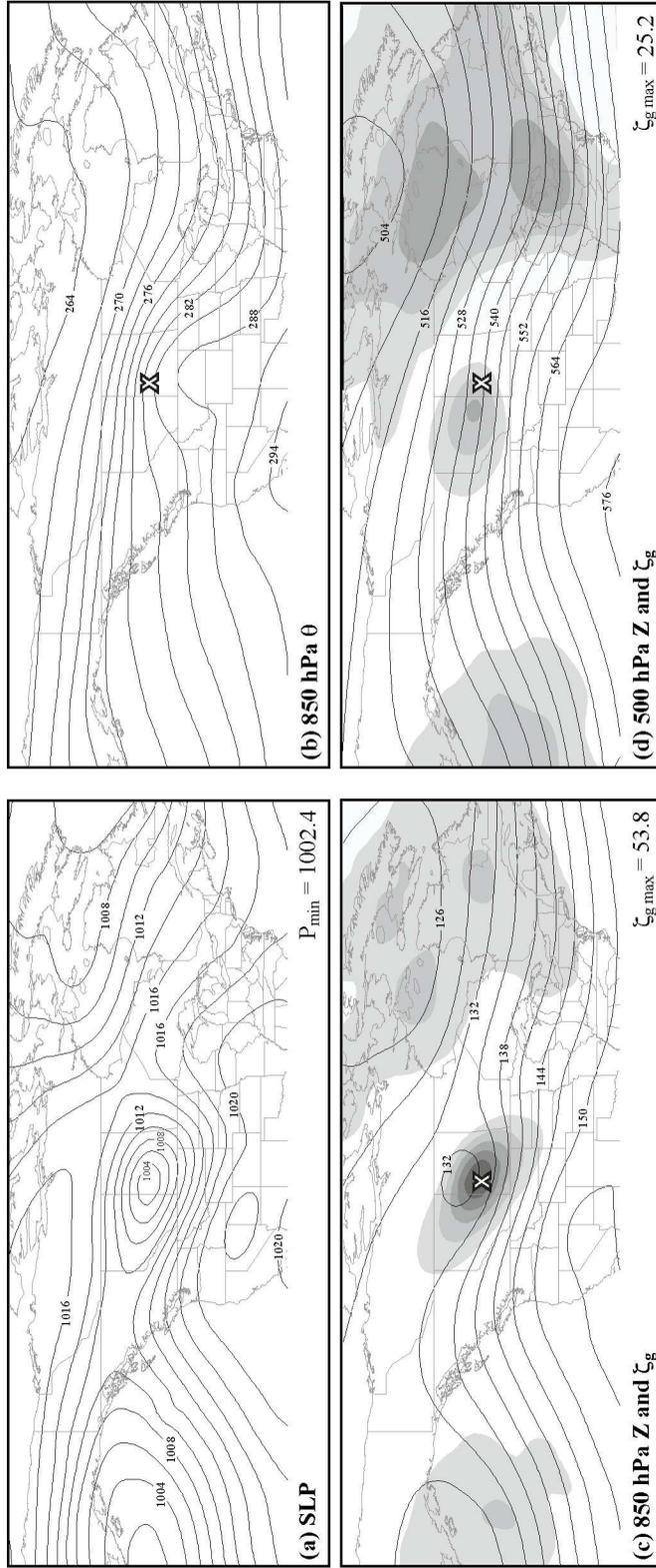


Fig. 11 As for Fig. 10 except for $T+12$.

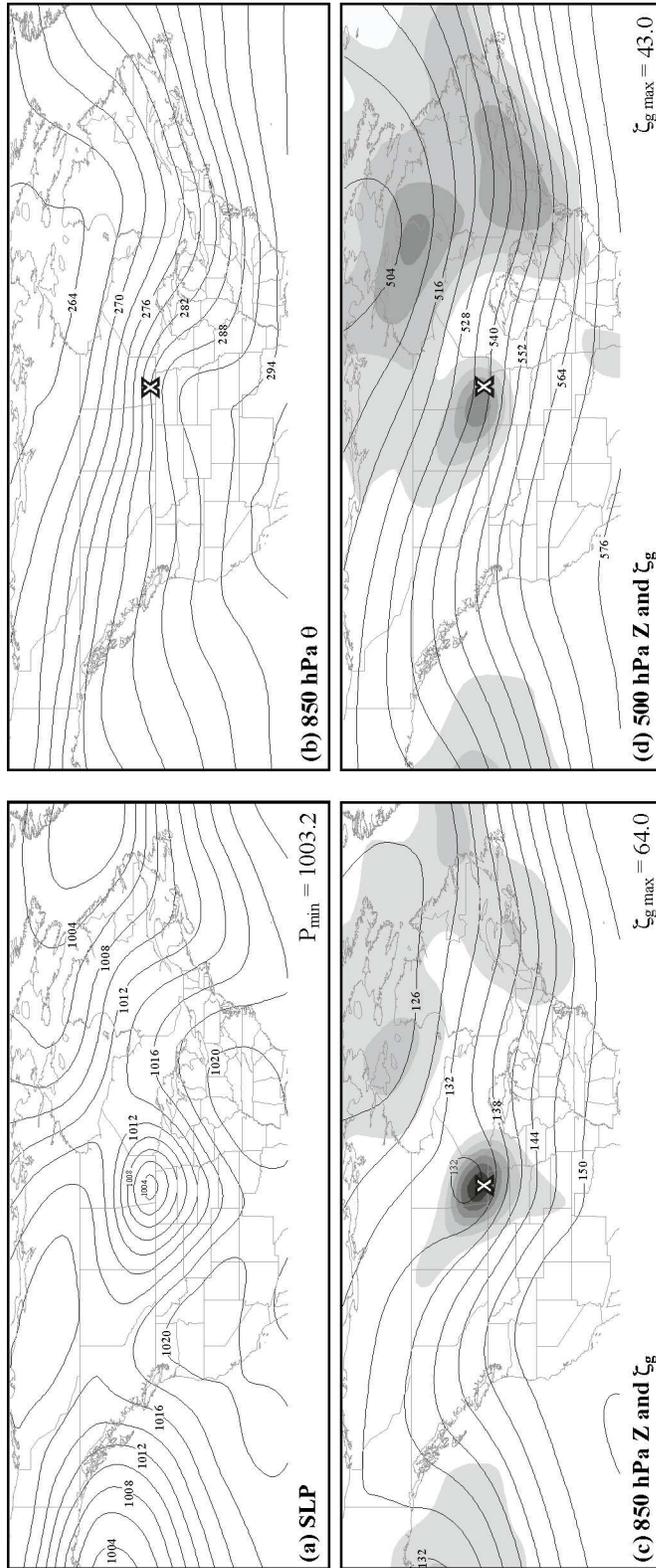


Fig. 12 As for Fig. 10 except for T+24.

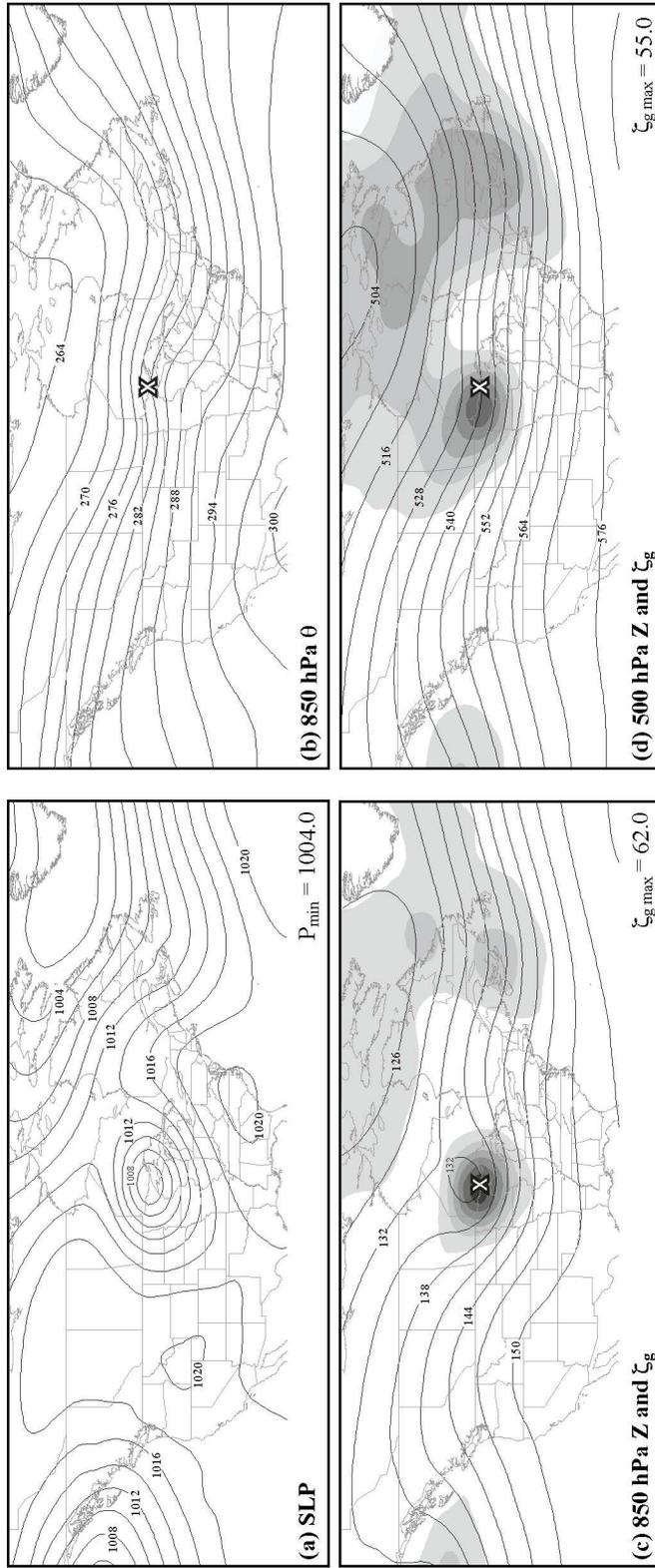


Fig. 13 As for Fig. 10 except for $T+36$.

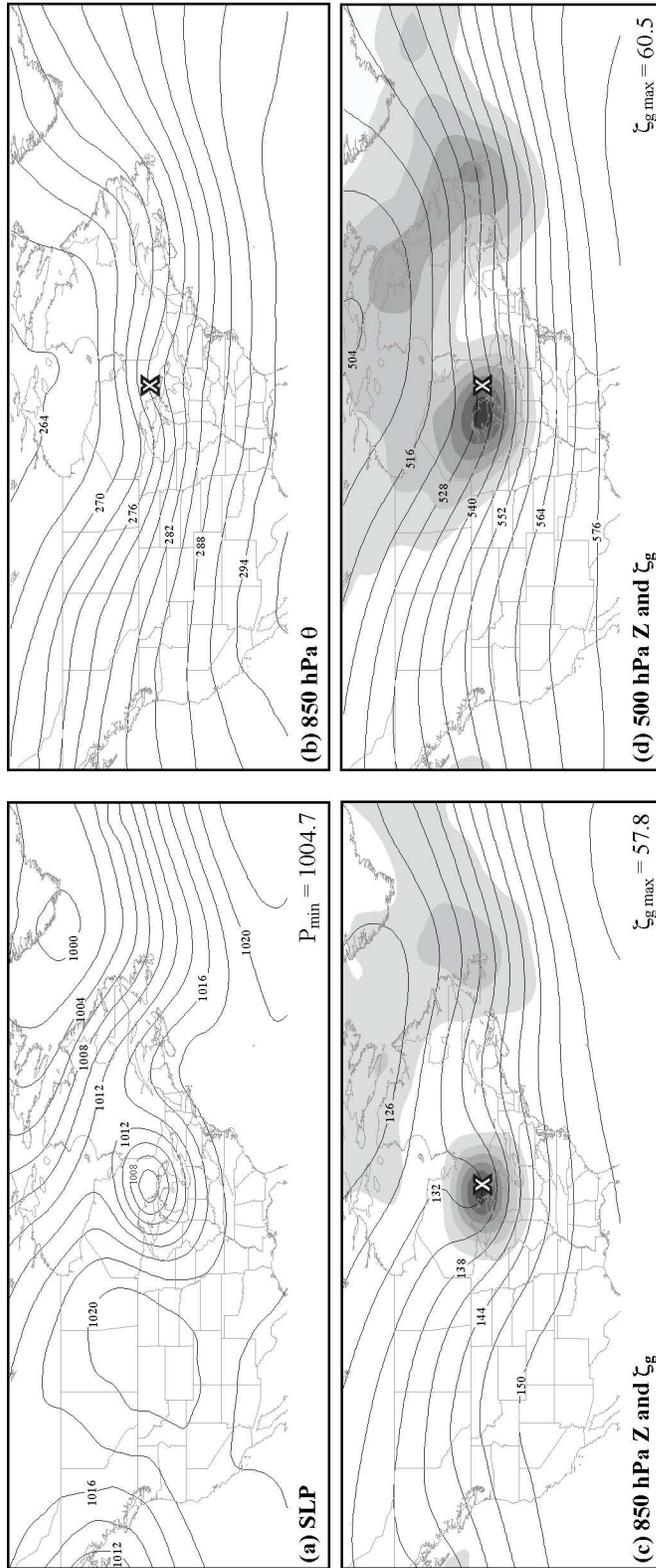


Fig. 14 As for Fig. 10 except for $T+48$.

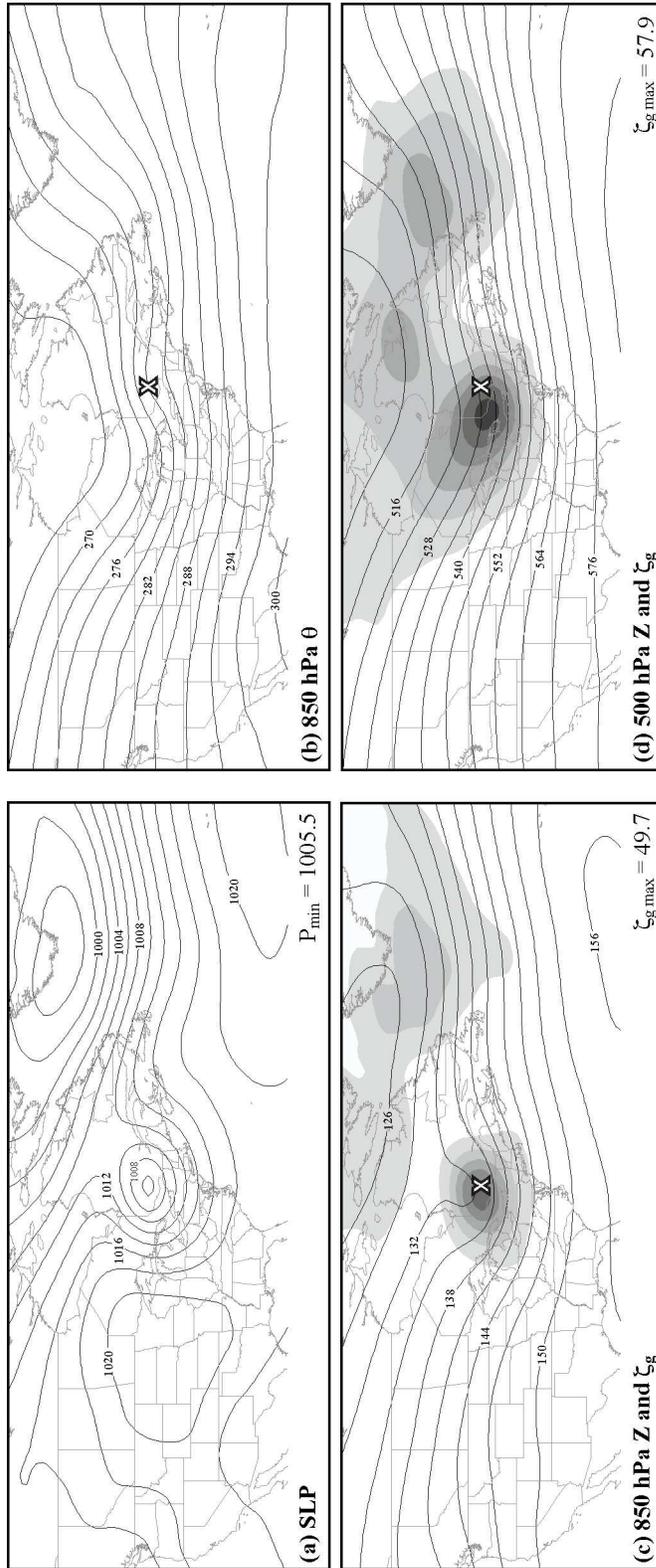


Fig. 15 As for Fig. 10 except for $T+60$.

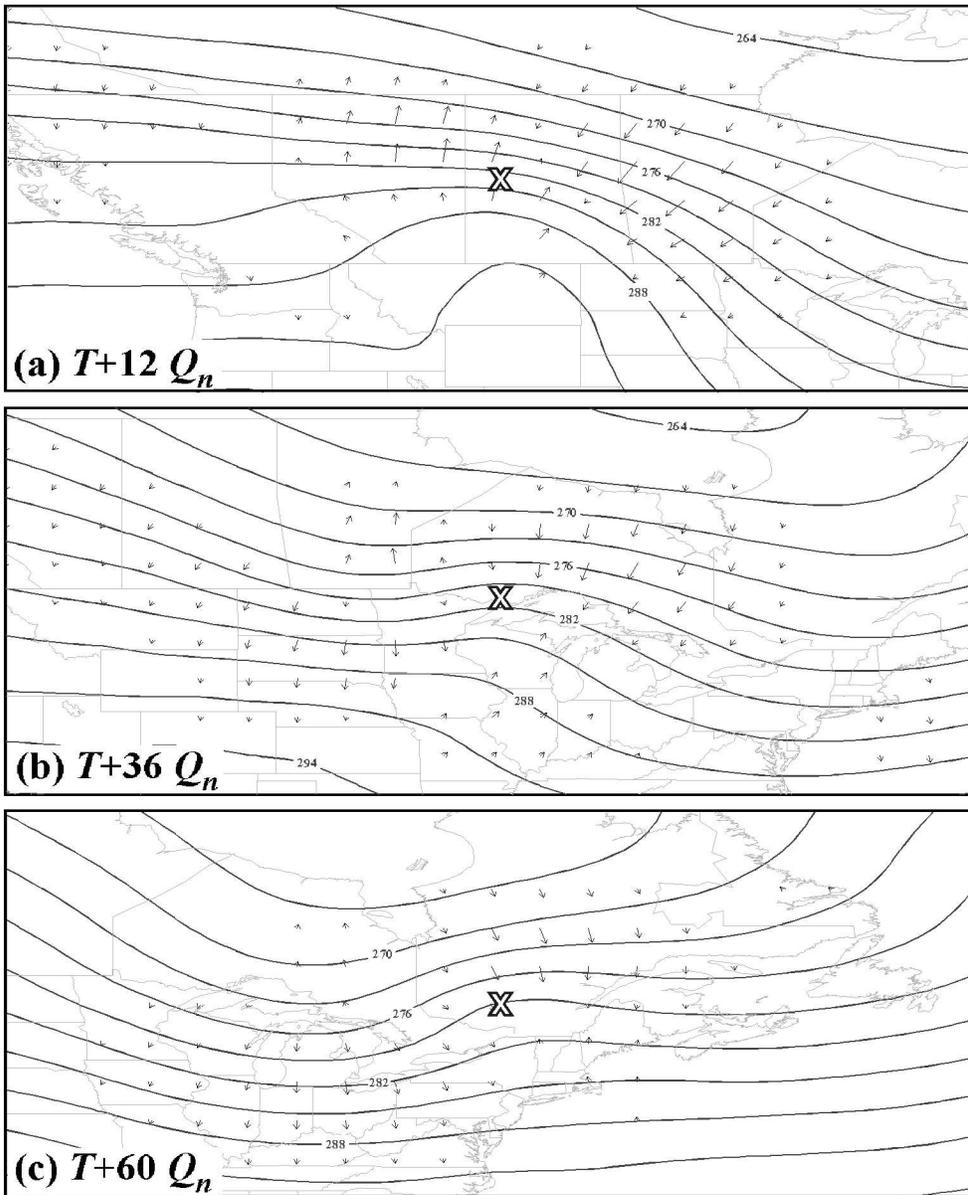


Fig. 16 Composite 850-hPa potential temperature and 850-hPa Q_n vectors of the composite at (a) $T+12$, (b) $T+36$, and (c) $T+60$. Potential temperature is labeled in K and contoured every 3 K. The X symbols as in Fig. 10.

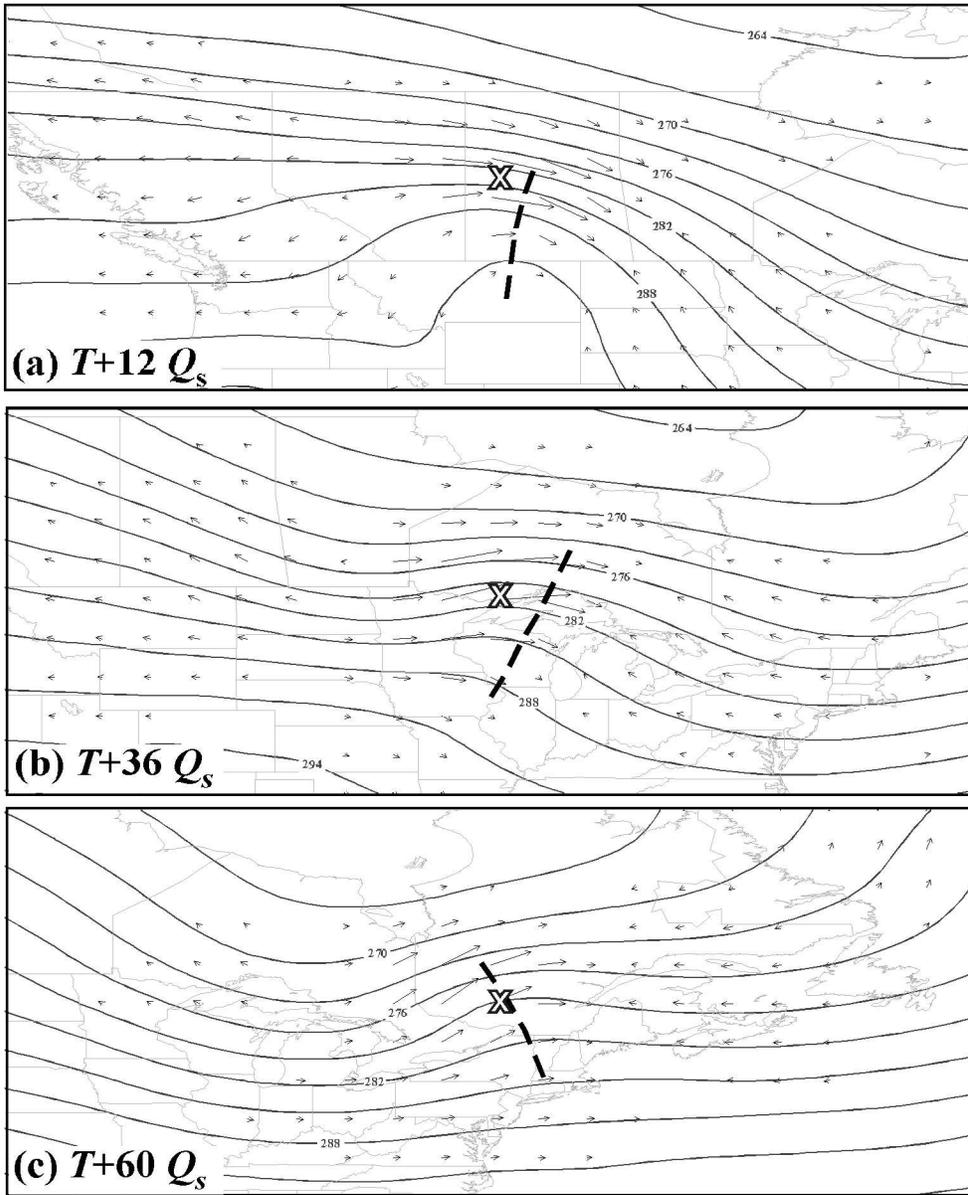


Fig. 17 As in Fig. 16 except for 850-hPa Q_s vectors of the composite. The thick dashed line represents the 850-hPa thermal ridge axis.

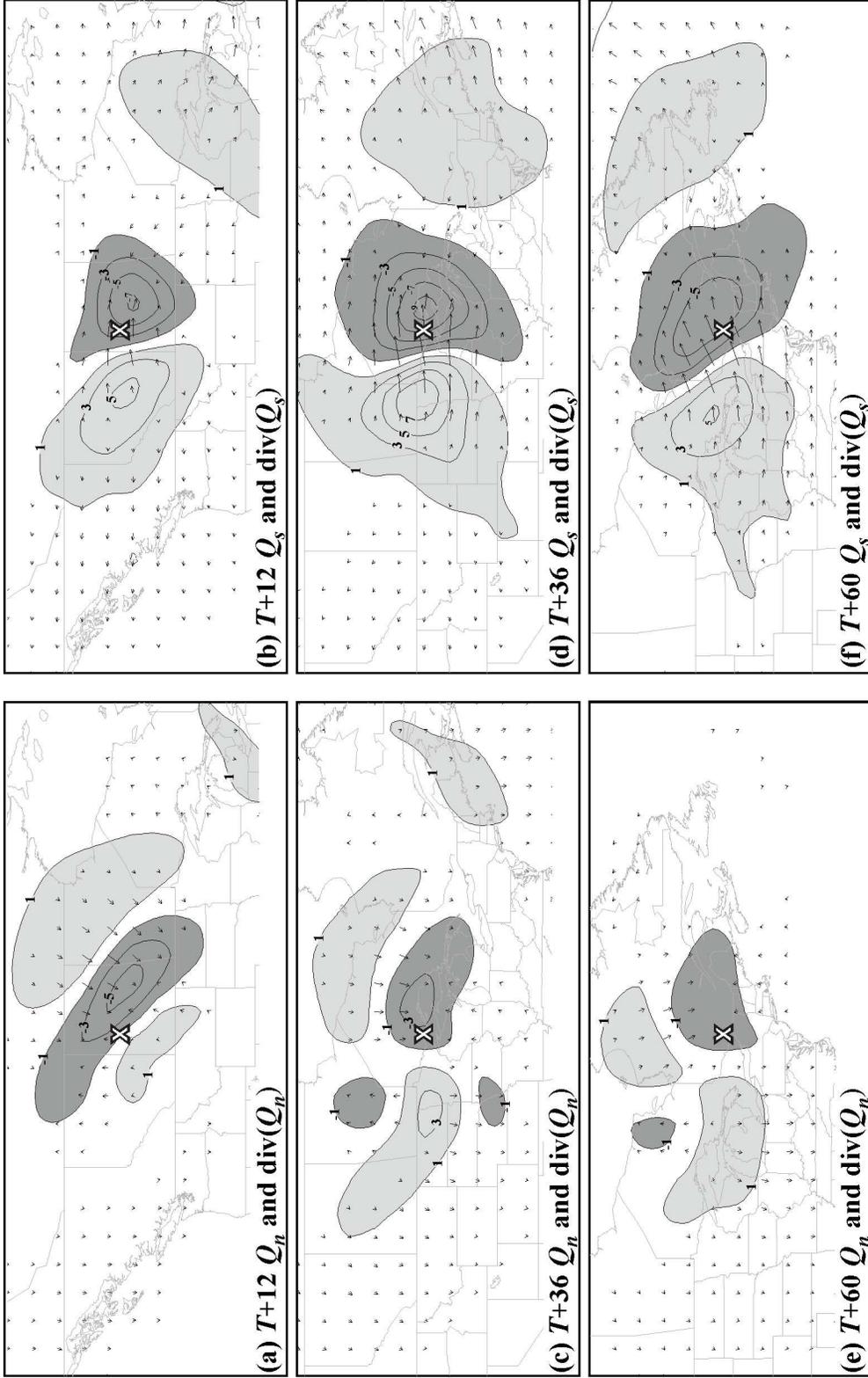


Fig. 18 (a) 500-850 hPa layer-averaged Q_n vectors and Q_n divergence of the composite at $T+12$. Q_n divergence (convergence) is labeled in units of $10^{-16} \text{ m}^2 \text{ s}^{-1} \text{ kg}^{-1}$, indicated by dark (light) shading, and contoured every $2 \times 10^{-16} \text{ m}^2 \text{ s}^{-1} \text{ kg}^{-1}$ starting at 1 (-1) $\times 10^{-16} \text{ m}^2 \text{ s}^{-1} \text{ kg}^{-1}$. (b) As in (a), except for Q_s vectors and Q_s divergence at $T+12$. (c) As in (a), except for $T+36$. (d) As in (b), except for $T+36$. (e) As in (a), except for $T+60$. (f) As in (b), except for $T+60$. The X symbols as in Fig. 10.

Table 1. Alberta Clipper cases in the climatology. Listed in the “Date,, column is the departure time for each case. In the “Type,, column, “SUS,, represents a sustained case, “DIM,, represents a diminishing case, and “IND,, represents an indefinite case. A *sustained* case is a Clipper that maintains a coherent surface signature over eastern North America, a *diminishing* case is a Clipper that does not, and an *indefinite* case is a Clipper whose coherence over eastern North America cannot be determined conclusively.

<u>Date</u>	<u>Type</u>	<u>Date</u>	<u>Type</u>
1200 UTC 20 Oct 1986	SUS	1200 UTC 04 Jan 1990	DIM
0000 UTC 02 Nov 1986	IND	0000 UTC 06 Jan 1990	SUS
1200 UTC 13 Nov 1986	IND	0000 UTC 10 Jan 1990	IND
1200 UTC 15 Nov 1986	SUS	1200 UTC 18 Jan 1990	SUS
1200 UTC 01 Dec 1986	DIM	1200 UTC 20 Jan 1990	IND
1200 UTC 04 Dec 1986	SUS	1200 UTC 22 Jan 1990	DIM
0000 UTC 06 Dec 1986	SUS	1200 UTC 05 Feb 1990	SUS
1200 UTC 07 Dec 1986	SUS	0000 UTC 08 Feb 1990	DIM
0000 UTC 10 Dec 1986	SUS	1200 UTC 22 Feb 1990	SUS
0000 UTC 30 Dec 1986	DIM	0000 UTC 05 Oct 1990	IND
0000 UTC 18 Jan 1987	DIM	1200 UTC 21 Oct 1990	DIM
1200 UTC 20 Jan 1987	DIM	0000 UTC 31 Oct 1990	IND
1200 UTC 01 Feb 1987	IND	0000 UTC 24 Nov 1990	SUS
1200 UTC 06 Feb 1987	IND	1200 UTC 06 Dec 1990	DIM
1200 UTC 25 Mar 1987	DIM	1200 UTC 23 Dec 1990	SUS
1200 UTC 07 Oct 1987	IND	1200 UTC 12 Jan 1991	DIM
1200 UTC 28 Oct 1987	SUS	1200 UTC 18 Jan 1991	IND
0000 UTC 10 Dec 1987	DIM	1200 UTC 21 Jan 1991	IND
0000 UTC 21 Jan 1988	DIM	1200 UTC 20 Feb 1991	SUS
0000 UTC 23 Jan 1988	DIM	1200 UTC 04 Mar 1991	IND
0000 UTC 08 Feb 1988	IND	1200 UTC 07 Mar 1991	DIM
0000 UTC 29 Feb 1988	IND	0000 UTC 20 Oct 1991	SUS
1200 UTC 30 Oct 1988	DIM	0000 UTC 20 Nov 1991	DIM
0000 UTC 02 Dec 1988	SUS	1200 UTC 25 Nov 1991	IND
1200 UTC 13 Dec 1988	IND	1200 UTC 04 Dec 1991	SUS
1200 UTC 29 Dec 1988	SUS	0000 UTC 06 Dec 1991	SUS
0000 UTC 16 Jan 1989	SUS	0000 UTC 25 Dec 1991	SUS
0000 UTC 17 Jan 1989	DIM	1200 UTC 13 Jan 1992	SUS
1200 UTC 18 Jan 1989	SUS	1200 UTC 18 Jan 1992	SUS
1200 UTC 21 Jan 1989	IND	1200 UTC 21 Jan 1992	SUS
0000 UTC 23 Feb 1989	SUS	1200 UTC 24 Jan 1992	SUS
1200 UTC 10 Nov 1989	SUS	1200 UTC 28 Jan 1992	DIM
0000 UTC 16 Nov 1989	SUS	1200 UTC 04 Feb 1992	DIM
0000 UTC 19 Nov 1989	SUS	1200 UTC 19 Feb 1992	SUS
1200 UTC 21 Nov 1989	DIM	0000 UTC 27 Feb 1992	SUS
0000 UTC 24 Nov 1989	DIM	0000 UTC 19 Oct 1992	IND
1200 UTC 28 Nov 1989	SUS	1200 UTC 26 Oct 1992	IND
1200 UTC 30 Nov 1989	IND	1200 UTC 15 Nov 1992	IND
1200 UTC 08 Dec 1989	DIM	0000 UTC 09 Dec 1992	DIM
0000 UTC 12 Dec 1989	DIM	0000 UTC 24 Dec 1992	IND
0000 UTC 24 Dec 1989	SUS	0000 UTC 27 Jan 1993	SUS

<u>Date</u>	<u>Type</u>	<u>Date</u>	<u>Type</u>
0000 UTC 06 Mar 1993	SUS	0000 UTC 20 Mar 1997	SUS
1200 UTC 08 Mar 1993	DIM	0000 UTC 23 Mar 1997	DIM
1200 UTC 18 Mar 1993	SUS	1200 UTC 25 Mar 1997	IND
1200 UTC 09 Oct 1993	IND	1200 UTC 26 Mar 1997	SUS
1200 UTC 22 Oct 1993	SUS	1200 UTC 28 Mar 1997	DIM
0000 UTC 27 Oct 1993	SUS	1200 UTC 30 Oct 1997	DIM
0000 UTC 03 Nov 1993	SUS	1200 UTC 17 Dec 1997	SUS
0000 UTC 20 Nov 1993	IND	0000 UTC 27 Dec 1997	DIM
0000 UTC 18 Dec 1993	DIM	1200 UTC 29 Dec 1997	IND
0000 UTC 20 Dec 1993	DIM	0000 UTC 31 Dec 1997	SUS
1200 UTC 27 Dec 1993	DIM	0000 UTC 30 Jan 1998	IND
1200 UTC 30 Dec 1993	SUS	0000 UTC 08 Oct 1998	DIM
1200 UTC 22 Jan 1994	SUS	1200 UTC 13 Nov 1998	IND
0000 UTC 05 Feb 1994	SUS	1200 UTC 15 Nov 1998	SUS
1200 UTC 13 Feb 1994	DIM	1200 UTC 24 Nov 1998	DIM
0000 UTC 13 Mar 1994	DIM	0000 UTC 08 Dec 1998	SUS
1200 UTC 25 Mar 1994	DIM	0000 UTC 17 Dec 1998	SUS
0000 UTC 23 Nov 1994	SUS	0000 UTC 30 Dec 1998	SUS
0000 UTC 01 Dec 1994	SUS	1200 UTC 02 Feb 1999	IND
1200 UTC 08 Dec 1994	DIM	1200 UTC 07 Feb 1999	DIM
1200 UTC 26 Dec 1994	SUS	0000 UTC 23 Feb 1999	DIM
0000 UTC 09 Feb 1995	DIM	0000 UTC 19 Mar 1999	DIM
1200 UTC 15 Feb 1995	SUS	1200 UTC 03 Oct 1999	DIM
0000 UTC 21 Feb 1995	SUS	0000 UTC 17 Oct 1999	DIM
0000 UTC 02 Mar 1995	IND	0000 UTC 24 Oct 1999	SUS
0000 UTC 18 Oct 1995	DIM	0000 UTC 08 Nov 1999	SUS
1200 UTC 11 Nov 1995	DIM	0000 UTC 25 Nov 1999	DIM
1200 UTC 21 Nov 1995	IND	1200 UTC 28 Dec 1999	SUS
1200 UTC 29 Nov 1995	SUS	1200 UTC 29 Dec 1999	DIM
1200 UTC 01 Dec 1995	SUS	1200 UTC 30 Dec 1999	IND
1200 UTC 12 Jan 1996	SUS	1200 UTC 04 Jan 2000	IND
0000 UTC 16 Jan 1996	SUS	0000 UTC 07 Jan 2000	SUS
0000 UTC 06 Feb 1996	SUS	0000 UTC 21 Jan 2000	DIM
0000 UTC 09 Feb 1996	SUS	1200 UTC 01 Feb 2000	DIM
1200 UTC 13 Feb 1996	IND	1200 UTC 18 Feb 2000	SUS
0000 UTC 15 Mar 1996	DIM	1200 UTC 13 Nov 2000	DIM
1200 UTC 25 Mar 1996	DIM	0000 UTC 27 Nov 2000	SUS
0000 UTC 12 Oct 1996	SUS	1200 UTC 06 Dec 2000	SUS
1200 UTC 08 Nov 1996	IND	0000 UTC 19 Dec 2000	DIM
0000 UTC 20 Dec 1996	IND	1200 UTC 27 Dec 2000	DIM
0000 UTC 31 Dec 1996	DIM	0000 UTC 01 Jan 2001	SUS
1200 UTC 01 Jan 1997	DIM	0000 UTC 04 Jan 2001	DIM
0000 UTC 14 Jan 1997	IND	1200 UTC 05 Jan 2001	IND
1200 UTC 30 Jan 1997	IND	0000 UTC 03 Feb 2001	DIM
0000 UTC 31 Jan 1997	SUS	0000 UTC 21 Feb 2001	DIM
1200 UTC 12 Feb 1997	SUS		
0000 UTC 15 Feb 1997	IND		
0000 UTC 17 Feb 1997	SUS		
1200 UTC 21 Feb 1997	SUS		
1200 UTC 24 Feb 1997	SUS		

<i>Season</i>	<i>October</i>	<i>November</i>	<i>December</i>	<i>January</i>	<i>February</i>	<i>March</i>	<i>Total</i>
1986-1987	1	3	6	2	2	1	15
1987-1988	2	0	1	2	2	0	7
1988-1989	1	0	3	4	1	0	9
1989-1990	0	7	3	6	3	0	19
1990-1991	3	1	2	3	1	2	12
1991-1992	1	2	3	5	3	0	14
1992-1993	2	1	2	1	0	3	9
1993-1994	3	2	4	1	2	2	14
1994-1995	0	1	3	0	3	1	8
1995-1996	1	3	1	2	3	2	12
1996-1997	1	1	2	4	5	5	18
1997-1998	1	0	4	1	0	0	6
1998-1999	1	3	3	0	3	1	11
1999-2000	3	2	3	3	2	0	13
2000-2001	0	2	3	3	2	0	10

Table 2. The number of Alberta Clippers that developed during each individual month and year in the climatology.