Observed Cyclone–Anticyclone Tropopause Vortex Asymmetries

GREGORY J. HAKIM AND AMELIA K. CANAVAN

University of Washington, Seattle, Washington

(Manuscript received 30 September 2003, in final form 28 June 2004)

ABSTRACT

Relatively little is known about coherent vortices near the extratropical tropopause, even with regard to basic facts about their frequency of occurrence, longevity, and structure. This study addresses these issues through an objective census of observed tropopause vortices. The authors test a hypothesis regarding vortex-merger asymmetry where cyclone pairs are repelled and anticyclone pairs are attracted by divergent flow due to frontogenesis. Emphasis is placed on arctic vortices, where jet stream influences are weaker, in order to facilitate comparisons with earlier idealized numerical simulations.

Results show that arctic cyclones are more numerous, persistent, and stronger than arctic anticyclones. An average of 15 cyclonic vortices and 11 anticyclonic vortices are observed per month, with maximum frequency of occurrence for cyclones (anticyclones) during winter (summer). There are about 47% more cyclones than anticyclones that survive at least 4 days, and for longer lifetimes, 1-day survival probabilities are nearly constant at 65% for cyclones, and 55% for anticyclones. Mean tropopause potential-temperature amplitude is 13 K for cyclones and 11 K for anticyclones, with cyclones exhibiting a greater tail toward larger values.

An analysis of close-proximity vortex pairs reveals divergence between cyclones and convergence between anticyclones. This result agrees qualitatively with previous idealized numerical simulations, although it is unclear to what extent the divergent circulations regulate vortex asymmetries.

1. Introduction

Extratropical tropopause disturbances may be classified as waves or coherent vortices according to whether their dynamics are essentially linear or nonlinear, respectively. Although a great deal is known about waves near the tropopause, relatively less is known about coherent vortices, even with regard to basic facts about their frequency of occurrence, longevity, and structure. This study addresses these issues through an objective census of observed tropopause vortices. In particular, we explore cyclone–anticyclone asymmetries in terms of vortex population, structure, and dynamical interaction.

Aspects of cyclone–anticyclone asymmetry are seemingly well understood through concepts such as gradient-wind balance and vortex stretching. For example, steady-state axisymmetric solutions to the gradient-wind equation feature well-known asymmetries in pressure and wind due to centrifugal accelerations that are absent from geostrophic balance (e.g., Holton 1992, section 3.2.5). These classical solutions have been ex-

tended numerically to steady axisymmetric vortices in a stratified fluid by applying potential vorticity (PV) inversion to assumed PV distributions (Thorpe 1986; Wirth 2001). Although the centrifugal acceleration is undoubtedly important for cyclone–anticyclone asymmetry, the gradient-wind equation provides only a kinematic diagnostic relationships for velocity given pressure (or vice versa); the same interpretation applies to PV inversion, where other fields are recovered from the PV. These relationships do not provide any insight into how the given pressure or PV distributions are determined; such insight requires dynamics.

Similarly, it is clear from stretching of absolute vertical vorticity by vertical motion, $(\zeta + f)\partial w/\partial z$, that the contribution from stretching of relative vorticity, ζ , by vertical motion, w , is important to breaking vortex symmetry¹; specifically, this effect is usually believed to favor cyclones by the following argument. For a given magnitude of $\partial w/\partial z$, there is a larger magnitude vertical-vorticity tendency when ζ has the same sign as the Coriolis parameter, f (i.e., cyclones). Conversely, the fact that vertical motion depends inversely on the absolute vorticity (e.g., Hakim and Keyser 2001) suggests an asymmetry favoring anticyclones. Therefore, the

Corresponding author address: Gregory J. Hakim, Department of Atmospheric Sciences, University of Washington, Box 351640, Seattle, WA 98195-1640.
E-mail: hakim@atmos.washington.edu

¹ This term is absent in quasigeostrophic theory, which has only cyclone–anticyclone symmetry.

vortex-stretching argument is ambiguous and depends on the dynamical evolution of the interplay between vorticity and divergence in conditioning vortex asymmetries. The fact that both cyclone and anticyclone biases have been discovered in idealized numerical solutions for balanced² turbulence (Polvani et al. 1994; Yavneh et al. 1997; Hakim et al. 2002, hereafter HSM) underscores the fact that the simple explanations given above are incomplete.

Results from one such turbulence experiment applied to the tropopause suggests that a fundamental asymmetry due to mesoscale frontogenesis may be important for tropopause vortex asymmetries (HSM). Stirring of tropopause potential temperature inevitably results in a cascade to smaller scales and the formation of filaments of warm and cold air (Jukes 1994). Frontogenesis along thinning filament edges provokes divergent circulations to maintain thermal wind balance (e.g., Holton 1992), with warm air rising and cold air sinking, so that cold³ (warm) filaments experience accelerated (decelerated) contraction (Fig. 1). Note that the potential temperature patterns in Fig. 1 apply explicitly to the tropopause, and are reversed from those shown in HSM (they studied a surface with upward decay; i.e., an “upside down” tropopause). These circulations have also been found for deformation fields applied to two-dimensional semigeostrophic filaments (Davies and Müller 1988), and axisymmetric tropopause vortices (Wirth 2000).

HSM went on to hypothesize that divergence associated with filaments in strain may play a role in determining tropopause vortex population asymmetries through the vortex-merger process. This process involves the combination of two like-signed vortices into a single, larger vortex; merger is completely symmetric for two-dimensional (barotropic) and quasigeostrophic turbulence. In contrast, vortex merger symmetry is broken for balanced tropopause turbulence due to the frontogenesis mechanism discussed previously. For example, cyclones are associated with relatively cold air at the tropopause (e.g., Thorpe 1986) so that a pair of cyclones is separated by a filament of relatively warm air. Under the strain of the vortical flow, the edges of the warm filament experience frontogenesis, causing warm air to rise in the center of the filament. This rising air is associated with divergence at the tropopause (Fig. 1b, gray lines), which may act to repel the vortices and delay, or prevent, merger. In contrast, anticyclones are associated with relatively warm air at the tropopause so that a pair of anticyclones is separated by a filament of relatively cold air that produces convergence in the vortex strain (Fig. 1a, gray lines). This asymmetry in the merger process suggests that anticyclones are favored

FIG. 1. Schematic illustration of the divergent-flow response to tropopause (a) cold and (b) warm filaments in deformation. Black arrows depict the ambient deformation acting to thin the filaments (thick gray lines) and increase horizontal temperature gradients along the filament edges. This frontogenesis produces a divergent-flow response in the vertical plane normal to the filaments, which is illustrated by arrow heads and arrow tails, showing rising and sinking motion in the troposphere, respectively. The net effect of the horizontal divergence that accompanies these vertical circulations, given by the gray arrows, is to accelerate the contraction of cold relative to warm filaments. By extension, close-approach tropopause cold vortices (cyclones) stretch a warm filament between them and are repelled by divergent winds, whereas close-approach warm vortices (anticyclones) are attracted. Figure adapted from Hakim et al. (2002).

to merge and build to larger horizontal scales relative to cyclones. The frontogenetical circulations may also be important in determining vortex structural asymmetries, although the specific processes are less clear.

Goals of the present paper include objectively determining tropopause cyclone and anticyclone vortex population number and structural properties, and testing the divergence-effect hypothesis. The analysis is conducted on the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis dataset, with an emphasis on vortices occurring over high latitudes of the Northern Hemisphere. This region is chosen for study because the complicating influence of the jet stream is weaker. Horizontal and vertical shears associated with the jet stream may condition vortex asymmetries, so avoiding the jet provides a closer approximation to the idealized solutions of HSM. The vortex census, which involves objective identification and tracking algorithms, is described in section 2. Results related to vortex population and structural asymmetries are described in section 3, and the dynamical asymmetry hypothesis is tested in section 4. A summary is provided in section 5, along with ideas for future research.

2. Vortex census methodology

Previous studies have identified and tracked upper-tropospheric “disturbances” by subjective (Sanders

² Dynamics free of gravity waves.

³ “Cold” and “warm” are used here in a relative sense with regard to tropopause potential temperature.

1988) and objective algorithms (Bell and Bosart 1989; Lefevre and Nielsen-Gammon 1995; Dean and Bosart 1996); however, only Bell and Bosart tracked both cyclones and anticyclones. An essential difference between our research and these earlier studies is that we identify and track only tropopause vortices; the earlier studies tracked both waves and vortices in the upper troposphere. Tropopause vortices are defined by closed material contours and, therefore, are easily identified as local extrema of potential temperature when the tropopause is taken to be a PV surface under the assumption of adiabatic and frictionless conditions. Here we define the tropopause as the $1.5 \times 10^{-6} \text{ m}^2 \text{ K kg}^{-1} \text{ s}^{-1}$ [or 1.5 potential vorticity units (PVU)] surface, which is established every 6 h for the period 1948–99 from the 2.5° NCEP–NCAR reanalysis dataset (Kalnay et al. 1996) by searching downward from the stratosphere; other fields are then interpolated linearly in log pressure to the tropopause. Given tropopause fields every 6 h over this 52-yr period, we first establish a database of vortex locations as described in section 2a, and a database of vortex tracks as described in section 2b.

Since our primary interest involves vortices poleward of 65°N, we shall make a few comments regarding data quality and resolution in this region. Observation density in this region is relatively sparse in terms of direct observations, but it is not a “data void” (e.g., Serreze et al. 1993). Although analyses may depart from “truth” in this region more than over the middle of the North American continent, for example, a benefit of the reanalysis dataset is that it provides dynamically consistent analyses. Further reassurance is provided by the fact that the vortex statistics exhibit no obvious trends during the 52-yr period of study. Regarding data resolution, mean vortex diameters are approximately 1600 km, which are resolved by about 18 grid points in the zonal direction at 70°N and 7 grid points in the meridional direction. Although higher-resolution data is of course always preferable, we believe that the available data resolution is adequate for this study; previous related studies used gridded data of comparable or coarser resolution.

a. Vortex identification

Tropopause vortices are identified in terms of local extrema in tropopause potential temperature. A grid point is accepted as a local extremum if the grid value exceeds the values of all other points located within 650 km,⁴ although the results are not sensitive to this cutoff distance. Hereafter, the grid point associated with the potential-temperature extremum will be referred to as the vortex *core*. Once identified, vortex properties are determined by the following statistical method.

The bounding isentrope is identified by scanning outward from the vortex core along eight equally spaced radials (on a latitude–longitude grid) until the radial gradient changes sign; the minimum of these eight potential-temperature values defines the bounding isentrope. Vortex potential-temperature amplitude is defined as the difference between the core value and the bounding contour.⁵ A vortex *centroid* may then be defined statistically by a center-of-mass calculation:

$$x_c = \frac{\sum \theta (x - x_0)}{\sum \theta}, \quad y_c = \frac{\sum \theta (y - y_0)}{\sum \theta}, \quad (1)$$

where x and y denote longitude and latitude, respectively, subscripts “ c ” and “0” denote the centroid and core coordinates, respectively, and summation is taken over all points within the bounding isentrope. Similarly, a vortex radius, r , may be defined as

$$r = \frac{\sum \theta r_c}{\sum \theta}, \quad (2)$$

where summation again applies to all points located within the bounding potential-temperature contour, and r_c is the great-circle distance from the centroid. Vortex pressure amplitude is defined as the difference between the core pressure and the pressure on the radial defining the bounding potential-temperature contour where that contour is crossed. Note that pressure extrema are typically not collocated with potential-temperature extrema, and the bounding pressure contour is not a dynamically meaningful quantity; therefore, this definition is arbitrary, and is chosen for simplicity.

In order to assess the sensitivity of the results to the definition of the tropopause, the vortex identification algorithm was performed on the 3.0-PVU surface during 1995–99. Results for vortices poleward of 65°N show that there are 19% more cyclones and 24% more anticyclones for the 3.0-PVU tropopause relative to the 1.5-PVU tropopause. Vortices common to both datasets were identified by searching outward from each vortex in the 1.5-PVU dataset up to a radius of 500 km for a matching vortex in the 3.0-PVU dataset; matches are found for 60% of cyclones and 64% of anticyclones. For these matching vortices, the mean radius is the same for both tropopause definitions: 760 km for cyclones and 830 km for anticyclones. The mean potential-temperature amplitude is 6.9 K for cyclones in both cases, and 5.6 K (5.9 K) for anticyclones on the 1.5-PVU (3.0 PVU) tropopause.

⁴ An exception was made when points adjacent to the extremum location shared the same value.

⁵ This definition is dynamically motivated by the fact that vortices are material eddies, and therefore can be usefully defined by conservative material quantities like PV and potential temperature. Other amplitude definitions, such as departures from climatology, lack this dynamical link.

b. Vortex tracking

Given a database of vortex locations, vortex tracks are defined by a simple proximity algorithm. A vortex track is extended from time t_0 to $t_0 + 6$ h if at time $t_0 + 6$ h another vortex is located within 600 km of a vortex at time t_0 . Vortices at time $t_0 + 6$ h that go unmatched with vortex tracks at t_0 are genesis events representing the start of new tracks. Vortex tracks that fail to extend to $t_0 + 6$ h are retested at $t_0 + 12$ h; failure to extend the track at his point defines a lysis event, and the track is ended.

This simple algorithm was subjectively determined to work well, particularly in the main region of interest poleward of 65°N . This method may not perform as well in situations of persistent strong winds, such as near jet streams, because the separation criteria implies a maximum vortex speed of approximately 28 m s^{-1} . Of course, more sophisticated tracking schemes could be employed; however, the simple scheme is desirable not only because it works for the intended region, but also because it is easily reproduced.

In addition to the *full set* of vortex tracks, we define an *arctic set* of vortex tracks that satisfy the additional requirements that the vortices survive at least two days (eight 6-h time periods) and spend at least 60% of their lifetime poleward of 65°N .

3. Vortex population statistics

We begin with an overview of the full set and arctic set of tropopause vortices for the purpose of establishing cyclone–anticyclone differences in geographical frequency of occurrence and longevity, and for comparison with previous studies. Subsequently, we summarize structural asymmetries for arctic vortices, which leads to the dynamical test for close-approach vortex pairs that is described in section 4.

Figure 2 summarizes the geographical distribution for the full set of identified tropopause cyclones and anticyclones. A grand total of 1 576 732 cyclones and 1 878 667 anticyclones are identified, which correspond to 310 605 cyclone tracks and 571 628 anticyclone tracks. Preferred cyclone locations include the poleward side of the climatological locations of the Atlantic and Pacific jet streams, the Canadian Arctic, the Mediterranean Sea through the Middle East, and Russia; local minima are found on the equatorward side of the jet streams, near the North Pole and near regions of high terrain such as the Rocky Mountains, the Himalaya Plateau, and northern Greenland (Fig. 2a). These locations are in good agreement with those found by Dean and Bosart (1996) for 500-hPa troughs. Comparing tropopause cyclones with preferred regions for surface cyclones, we find that they coincide over the storm tracks (e.g., Hoskins and Hodges 2002). An interesting difference occurs upstream of the main surface-cyclone storm tracks, where local maxima in tropopause cy-

FIG. 2. Total number of tropopause (a) cyclonic and (b) anticyclonic vortex events occurring in a 2.5° – 10° lat–lon box centered at a point; a cosine-latitude normalization has also been applied for equal-area weighting.

clone frequency occur near central Russia and Baffin Island, perhaps acting to seed the development of surface cyclones at the entrance to the Pacific and Atlantic storm tracks, respectively. Over the Arctic, we find that the strongest correspondence between surface and tropopause cyclone frequency occurs from Iceland to the Barents Sea (Serreze et al. 1993).

Preferred anticyclone locations include the subtropical side of jet streams, Greenland, and an elongated band that continues downstream from the subtropical side of the Atlantic jet stream across Europe and Russia; local minima are found near the North Pole, eastern Canada, and a band stretching from the Mediterranean

Sea and North Africa to Asia and across the storm track region of the North Pacific Ocean (Fig. 2b). With the exception of the Greenland maximum, these locations are in general agreement with those found by Bell and Bosart (1989) for closed-circulation geopotential highs at 500 hPa. In contrast to cyclones, tropopause anticyclones show little correspondence to regions of surface anticyclone occurrence (Serreze et al. 1993; Hoskins and Hodges 2002).

There is a distinct asymmetry in vortex life span toward longer-lived cyclones (Fig. 3). For short lifetimes, there is an anticyclone bias, and both cyclones and anticyclones exhibit steep declines for longer lifetimes. There are 47% more cyclones than anticyclones that survive at least 4 days, and longer lifetimes are well approximated by exponentially decaying distributions. These distributions imply constant probabilities for surviving an additional 6 hours (24 hours) of 90% (66%) for cyclones and 86% (55%) for anticyclones; distributions and survival probabilities for arctic vortices are similar to those for the full population (not shown). The cyclone figure is comparable to the 24-h survival rate of 75% that Lefevre and Nielsen-Gammon (1995) found for cyclonic disturbances at 500 hPa. In order to assess the dependence of survivability on vortex strength, we calculate 24-h survival probabilities for tracks lasting at least 4 days as a function of vortex potential-temperature amplitude. Survival probabilities for cyclones increase from 62.5% for amplitudes of 0–5 K to 71.2% for amplitudes of 25–30 K; anticyclones show little dependence of survival probability on amplitude.

We focus now on documenting properties of Arctic vortices. A total of 127 552 cyclones and 78 677 anticyclones are identified, which correspond to 9032 cyclone

tracks and 6861 anticyclone tracks, or about 15 cyclones and 11 anticyclones per month. There is weak seasonality for numbers of Arctic vortices, with a peak for cyclones from late autumn through early spring, and a peak for anticyclones during summer (Fig. 4). Cyclones exhibit a peak in potential-temperature amplitude during winter, whereas anticyclones exhibit little seasonal variation in potential-temperature amplitude. Both vortex lifetime and radius exhibit little seasonal variation from their mean values given below. Comparing the annual cycle in Arctic tropopause vortex population number with arctic surface cyclones and anticyclones reveals that the number of both surface disturbances peaks in summer (Serreze et al. 1993), whereas only tropopause anticyclones peak in summer. Surface disturbance amplitude, as measured by mean sea level pressure, peaks in winter for both cyclones and anticyclones, which agrees with tropopause cyclones.

The seasonal cycle of vortex amplitude also indicates that, on average, cyclones are stronger than anticyclones. A composite average of Arctic vortex amplitude over a 5-day period starting with vortex origin confirms that cyclones tend to be stronger than anticyclones at all times when measured in terms of tropopause potential temperature and pressure, although the pressure asymmetry is greater (Figs. 5a,b); 5-day mean values are 13.0 K for cyclones and 11.4 K for anticyclones. These vortices exhibit a characteristic life cycle of growth and decay, with potential-temperature amplitude increasing by about 50% during the first 48–72 h (Fig. 5a). Although growth is comparable for cyclones and anticyclones, anticyclones decay faster. Moreover, the period of growth occurs while the cyclones (anticyclones) move equatorward (poleward) (Fig. 5d). In

FIG. 3. Vortex lifetime distributions for cyclones (circles) and anticyclones (squares). Heavy lines depict linear fits to exponential distributions for lifetimes of 4–15 days, with $R^2 = 0.994$ for cyclones and 0.969 for anticyclones. These distributions imply constant probabilities for surviving an additional 6 h (24 h) of 90% (66%) for cyclones and 86% (55%) for anticyclones.

FIG. 4. Number of unique arctic vortex tracks (heavy lines) and potential-temperature amplitude (thin lines) as a function of month of year. Solid lines depict cyclones and dashed lines depict anticyclones. All monthly values are normalized to 30-day months.

FIG. 5. Ensemble-mean Arctic vortex properties with time: (a) tropopause potential-temperature amplitude, (b) tropopause pressure amplitude, (c) radius, and (d) latitude. Cyclones are depicted by circles and anticyclones by squares. Solid lines show third-order polynomial fits through the data. All vortices survive a minimum of 5 days so that the population is constant for all times displayed.

terms of vortex radius, we find that anticyclones are larger than cyclones, with typical values of 875 and 775 km, respectively (Fig. 5c). Although anticyclone radius varies little over the 5-day period, exhibiting perhaps a slight increase, cyclone radius increases from approximately 700 to nearly 800 km during the first 48–72 h. These cyclone radius values agree well with values of 500–800 km as determined by Hakim (2000) for a sample of midlatitude (40°N) vortices.

During the period of strengthening (0–60 h), mean core potential temperature values change from 284.6 to 281.5 K for cyclones and 328.5 to 327.3 K for anticyclones; the implied tendencies of -1.2 and -0.5 K day^{-1} , respectively, are typical values for infrared radiative clear-sky cooling rates near the subarctic upper troposphere (Liou 2002, p. 163). This evidence suggests that vortex strengthening is occurring primarily due to changes in vortex structure near the bounding poten-

tial-temperature contour, consistent with the observed cyclone radius changes. We note that an estimate based on climatology for the change in potential-temperature values outside the vortices due to their meridional motion (Fig. 5d) only amounts to about 1.3 K; that is, meridional motion alone appears insufficient to account for the observed strengthening.

Probability density functions (PDFs) of Arctic cyclone–anticyclone structural asymmetries are shown in Fig. 6. In terms of the core value of tropopause potential temperature, we find that cyclones tend to be colder than anticyclones, with PDF expected values of 279 and 317 K, respectively (Fig. 6a). These distributions have non-Gaussian tails toward extreme values, but cyclones have a greater departure from Gaussianity for cold vortices (note the “shoulder” around 230–250 K). In terms of potential-temperature amplitude, the distributions for both cyclones and anticyclones peak at small values,

FIG. 6. Arctic vortex tropopause structural properties: (a) core-value potential temperature, (b) potential-temperature amplitude, (c) radius, and (d) pressure amplitude. Cyclones are given by solid lines and anticyclones by dashed lines. The thin lines in (a) show Gaussian PDFs having the same mean and variance as the observed distributions. Note that the ordinate in all panels is logarithmic.

with the primary asymmetry occurring near large-amplitude tails of the distributions as a bias for stronger cyclones (Fig. 6b). The amplitude asymmetry is more dramatic as measured by tropopause pressure perturbations (Fig. 6d).⁶ The sharp drop in pressure amplitude at very large values (~ 600 hPa) may reflect the fact that cyclones are capable of spanning nearly the entire troposphere and, therefore, are bounded above in pressure amplitude by the surface pressure. Finally, a concise summary of cyclone–anticyclone structural asymmetries is given by the radius–amplitude joint PDF (Fig. 7). In particular, the PDF difference plot exhibits a clear bias for weak and large anticyclones as compared with strong and small cyclones (Fig. 7b).

⁶ Regarding negative pressure-amplitude values, recall that pressure amplitude is ambiguous and was defined for simplicity by the locations that determine potential-temperature amplitude.

4. Vortex dynamical asymmetry

We proceed now to testing the hypothesis concerning an asymmetrical repulsive (attractive) frontogenetical force between cyclone (anticyclone) vortex pairs. This predicted effect is a specific example of a general asymmetry concerning the forward cascade of potential temperature variance (HSM; see also Fig. 1). Therefore, because vortex pairs are reasonably well resolved by the NCEP–NCAR reanalysis dataset, we believe that testing the specific hypothesis also provides important evidence regarding the general asymmetry due to the forward cascade of potential-temperature variance to the mesoscale.

Vortex pairs are derived from the filtered Arctic dataset by requiring that the vortex cores be separated by 1400–1800 km and that both vortices have potential-temperature amplitudes of at least 5 K; no minimum lifetime criteria is required. The separation criteria was

FIG. 7. (a) Arctic vortex radius-amplitude joint PDF and (b) anticyclone PDF minus the cyclone PDF. Contours in (a) are shown every 1×10^{-3} from 1×10^{-3} to 5×10^{-3} and in (b) every 3×10^{-4} from -1.5×10^{-3} to 1.7×10^{-3} ; the zero contour is suppressed. Dashed contours depict positive values in (b), that is, an anticyclonic bias.

selected based on the probability of finding two vortices separated by a specified distance, which shows a sharp drop below 1400 km and a gradual increase for larger separation distances (not shown). The selected range provides a large sample of close, and comparably spaced, vortex pairs. It proves useful to introduce coordinates along a great-circle arc defined by the vortex cores. For all pairs, the origin is defined by the vortex with greatest amplitude, and unit nondimensional distance by the second vortex. Data are interpolated to a regular grid along this arc with the understanding that the coordinates are always fixed relative to the vortex centers; figure axes may be labeled in dimensional distance (km) because the variability in vortex separation distance is small by design: 1600 ± 110 km. Horizontal divergence is interpolated to the arc after being computed from tropopause winds, and vertical motion is interpolated to the cross section along the arc.

For close-approach cyclone pairs (11 881 cases), the calculation reveals divergence between the cores, as predicted (cf. Figs. 1b and 8a, heavy solid line). When the full sample is filtered to include only pairs that have moved closer together during the prior 6 h, the effect is stronger (Fig. 8a, thin solid line); the reverse is true for cyclone pairs moving apart (Fig. 8a, thin dashed line). These results also show convergence within the vortex, although it is unclear if this effect is directly related to the circulation between the vortices, or indirectly related through adjustment of the vortices to perturbations in their structure due to vortex-vortex interaction.

For close-approach anticyclone pairs (6037 cases), the calculation reveals weak convergence between the cores, as predicted (cf. Figs. 1a and Fig. 8b, heavy solid

FIG. 8. Arctic vortex-pair divergence ($\times 10^{-6} \text{ s}^{-1}$) along the great circle connecting the vortex cores: (a) cyclone pairs and (b) anticyclone pairs. The gray line gives the potential-temperature amplitude relative to the stronger (left) vortex; the zero crossing marks the bounding isentrope for the stronger vortex. Black lines show horizontal divergence of tropopause winds. The thick solid line applies to all vortex pairs, the thin solid line to vortex pairs moving closer together, and the thin dashed line to vortex pairs moving farther apart. Horizontal distance along the great circle is shown relative to the core of the stronger vortex.

line). When the full sample is filtered to include only pairs that have moved closer together during the prior 6 h, the effect is stronger (Fig. 8b, thin solid line); the reverse is true for anticyclone pairs moving apart (Fig. 8b, thin dashed line). As in the cyclone-pair case, the results also show the reverse signal inside the vortex core (divergence).

In order to estimate the number of individual vortex pairs that are associated with the appropriate divergence field between them, the divergence is averaged in each case for points within 300 km of the midpoint of the great circle connecting the vortex cores. For cyclone pairs, 60% of all cases are associated with mean divergence. Similarly, 60% of all anticyclone pairs are associated with mean convergence. Although this simple measure is perhaps not ideal for assessing the presence of these circulations, it does suggest considerable case to case variability.

To confirm that these signals are not an artifact of computing divergence at the tropopause and to explore the vertical scale of these circulations, we consider cross sections of vertical motion for the full set of vortex-pair samples (Fig. 9). These cross sections confirm the tropopause divergence calculation, in that there is rising (sinking) air beneath tropopause divergence (convergence). Although the vertical motion is weak, with maximum rising motion of -0.15 dPa s^{-1} (approximately 0.15 cm s^{-1}) between cyclones and maximum sinking motion of 0.30 dPa s^{-1} (approximately -0.30 cm s^{-1}) between anticyclones, the circulations span the troposphere.

5. Summary

A census of tropopause vortices is used to document cyclone–anticyclone asymmetries in vortex population, structure, and dynamics. Emphasis is placed on arctic vortices, which are relatively well removed from the westerly jet streams in middle latitudes. These vortices facilitate comparisons with earlier idealized modeling experiments of balanced tropopause turbulence. In particular, we have focused on quantifying the population and structural differences between cyclonic and anticyclonic vortices, and on testing a hypothetical asymmetrical vortex “force” for vortex pairs, where cyclone pairs are repelled and anticyclone pairs are attracted.

The vortex census results reveal that there are about 32% more unique cyclone than anticyclone tracks that last at least two days in the Arctic region (poleward of 65°N). The number of cyclone (anticyclone) tracks peaks in winter (summer) at about 16 (14) per month, and cyclone amplitude peaks in winter at about 14 K while anticyclone amplitude is nearly constant at about 8 K. These properties may reflect a larger-scale cyclonic bias due to the polar vortex, which is strongest in winter. Regarding vortex lifetime, cyclones are found to last longer than anticyclones with nearly time-indepen-

FIG. 9. Distance–height cross section of vertical motion (in pressure coordinates) for Arctic vortex pairs along the great circle connecting the vortex cores: (a) cyclones and (b) anticyclones. Contours are shown every 0.05 dPa s^{-1} , with solid lines for negative values (rising air) and dashed lines for positive values (sinking air).

dent 24-h survival probabilities of 65% and 55%, respectively, for lifetimes greater than four days. Vortex structural asymmetries can be summarized as a bias for stronger and smaller cyclones, compared with weaker and larger anticyclones (Fig. 7). Mean radii for cyclones and anticyclones are about 750 and 850 km, respectively, and mean amplitudes are about 13 and 11 K, respectively. Pressure-amplitude results suggest that tropopause distortion in some cyclonic vortices may be large enough to reach the earth’s surface, a possibility that has been hinted at in a case of intense surface cyclogenesis (Hakim et al. 1995).

An examination of vortex dynamical asymmetry is limited in scope to testing the hypothesis that cyclone

pairs in close proximity are repelled from merging into a single vortex by divergent flow produced by frontogenesis; vortex attraction is predicted for anticyclones due to convergent flow (Hakim et al. 2002). A diagnosis of vortex pairs confirms these predictions and also reveals the opposite patterns of divergence within the vortex cores, perhaps as part of the same vertical circulation. Although these circulations appear weak relative to those associated with midlatitude cyclones, they are roughly comparable to Ekman circulations for decaying vortices (Holton 1992, p. 135). The existence of these circulations provides supporting evidence for the important hypothesis that two-dimensional turbulence near the tropopause acts to pump heat upward. The contribution of this process to the general circulation of the polar vortex remains unclear, and is an interesting subject for future research.

This study raises a number of additional questions that require future research. For example, it would be interesting to examine vortex statistics for the midlatitudes and subtropics and to compare the results with the polar region. Another interesting problem concerns the dominant vortex-genesis mechanisms and whether they are shared by both cyclones and anticyclones. Similarly, general factors contributing to the growth and decay of vortices need to be isolated. Another problem concerns the merging of vortices, which is an essential process to the phenomenology of two-dimensional turbulence, but it is unclear whether this process is important for the genesis and growth of arctic vortices. Attempts at reliable objective classification of this process will likely require higher-resolution data than that used here.

Acknowledgments. This paper is based in part on the second author's M.S. thesis, and was sponsored by the National Science Foundation through NSF Grants ATM-9980744, ATM-0228804, and CMG-0327658 awarded to the University of Washington. We thank Volkmar Wirth and two anonymous reviewers for comments that helped clarify portions of the manuscript.

REFERENCES

- Bell, G. D., and L. F. Bosart, 1989: A 15-year climatology of Northern Hemisphere 500 mb closed cyclone and anticyclone centers. *Mon. Wea. Rev.*, **117**, 2142–2163.
- Davies, H. C., and J. C. Müller, 1988: Detailed description of deformation-induced semi-geostrophic frontogenesis. *Quart. J. Roy. Meteor. Soc.*, **114**, 1201–1219.
- Dean, D. B., and L. F. Bosart, 1996: Northern Hemisphere 500-hPa trough merger and fracture: A climatology and case study. *Mon. Wea. Rev.*, **124**, 2644–2671.
- Hakim, G. J., 2000: Climatology of coherent structures on the extratropical tropopause. *Mon. Wea. Rev.*, **128**, 385–406.
- , and D. Keyser, 2001: Canonical frontal circulation patterns in terms of Green's functions for the Sawyer–Eliassen equation. *Quart. J. Roy. Meteor. Soc.*, **127**, 1795–1814.
- , L. F. Bosart, and D. Keyser, 1995: The Ohio Valley wave-merger cyclogenesis event of 25–26 January 1978. Part I: Observations. *Mon. Wea. Rev.*, **123**, 2663–2692.
- , C. Snyder, and D. J. Muraki, 2002: A new surface model for cyclone–anticyclone asymmetry. *J. Atmos. Sci.*, **59**, 2405–2420.
- Holton, J. R., 1992: *An Introduction to Dynamic Meteorology*. Academic Press, 511 pp.
- Hoskins, B. J., and K. I. Hodges, 2002: New perspectives on the Northern Hemisphere winter storm tracks. *J. Atmos. Sci.*, **59**, 1041–1061.
- Jukes, M., 1994: Quasigeostrophic dynamics of the tropopause. *J. Atmos. Sci.*, **51**, 2756–2768.
- Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.*, **77**, 437–471.
- Lefevre, R. J., and J. W. Nielsen-Gammon, 1995: An objective climatology of mobile troughs in the Northern Hemisphere. *Tellus*, **47A**, 638–655.
- Liou, K. N., 2002: *An Introduction to Atmospheric Radiation*. Academic Press, 577 pp.
- Polvani, L. M., J. C. McWilliams, M. A. Spall, and R. Ford, 1994: The coherent structures of shallow-water turbulence: Deformation-radius effects, cyclone/anticyclone asymmetry and gravity-wave generation. *Chaos*, **4**, 177–186.
- Sanders, F., 1988: Life history of mobile troughs in the upper westerlies. *Mon. Wea. Rev.*, **116**, 2629–2648.
- Serreze, M. C., J. E. Box, R. G. Barry, and J. E. Walsh, 1993: Characteristics of arctic synoptic activity, 1952–1989. *Meteor. Atmos. Phys.*, **51**, 147–164.
- Thorpe, A. J., 1986: Synoptic scale disturbances with circular symmetry. *Mon. Wea. Rev.*, **114**, 1384–1389.
- Wirth, V., 2000: Thermal versus dynamical tropopause in upper-tropospheric balanced flow anomalies. *Quart. J. Roy. Meteor. Soc.*, **126**, 299–317.
- , 2001: Cyclone–anticyclone asymmetry concerning the height of the thermal and the dynamical tropopause. *J. Atmos. Sci.*, **58**, 26–37.
- Yavneh, I., A. F. Shchepetkin, J. C. McWilliams, and L. P. Graves, 1997: Multigrid solutions of rotating, stably stratified flows: The balance equations and their turbulent dynamics. *J. Comput. Phys.*, **136**, 245–262.