Tellus (1985), *37A*, 132–155

Classification of mesoscale vortices in polar airstreams and the influence of the large-scale environment on their evolutions

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(Manuscript received April 5; in final form June 29, 1984)

ABSTRACT

Satellite imagery was used to detect and study 133 mesoscale cloud vortices which occurred in the northeastern Atlantic Ocean and adjacent seas between 1 December 1981 and 5 January 1982. Only vortices occurring in cold air, separate from synoptic-scale frontal cloud bands, were considered. The complete history of the evolution of each cloud vortex was recorded in terms of its location, size, cloud pattern, and cloud type (shallow or deep; stratiform or convective).

Once all vortices were documented, conventional meteorological data and analyses were consulted. One objective of the study was to determine whether satellite imagery could be used to estimate the central pressure of the cyclones accompanying the mesoscale vortices. Other objectives were to determine if there were significant differences in (1) the mesoscale cloud structure or (2) the large-scale environment of vortices which remained insignificant versus those that developed into polar lows.

Results indicate that the deficit pressure of the polar vortex could be estimated from satellite imagery and that there were recognizable differences between developing and non-developing vortices. Only a few cloud configurations accompanied polar lows, whereas the occurrence of certain other configurations at early stages in the vortex existence indicated that these vortices would remain insignificant. The synoptic-scale environment appeared to play a considerable role in determining which incipient vortices continued to develop. Moderate baroclinicity (horizontal temperature gradients and vertical wind shear), relatively weak winds, large lapse rates, and favorable vorticity advections accompanied developing polar lows. Non-developing vortices had unfavorable vorticity advections. Of these, some vortices were able to grow initially to moderate disturbances which remained steady thereafter. The apparent difference between these and insignificant vortices was that the steady vortices were more baroclinic and had steeper lapse rates.

1. Introduction

Despite decades of application of the Norwegian cyclone model (e.g. Bjerknes and Solberg, 1921) to weather analysis and forecasting, this classic conceptual model does not account for all of the cyclones on a weather map, nor does it account for all of the cloudiness detected on a satellite photograph—there are numerous areas of clouds separate from the polar front in both the warm and cold sectors. These clouds are frequently non-trivial; for example, Monteverdi (1976) has determined that 20–50% of the annual precipitation at San Francisco is non-frontal in nature. The non-frontal precipitation is often associated with isolated showers, but organized convective cloud systems frequently occur in the warm sector, and precipitation frequently occurs in association with pressure troughs (or depressions) in the cold sector.

This paper presents results of a systematic study of organized cloud systems in wintertime polar airstreams, such as those shown in Fig. 1. Many of the cloud systems were associated with disturbances which were insignificant in terms of accom-

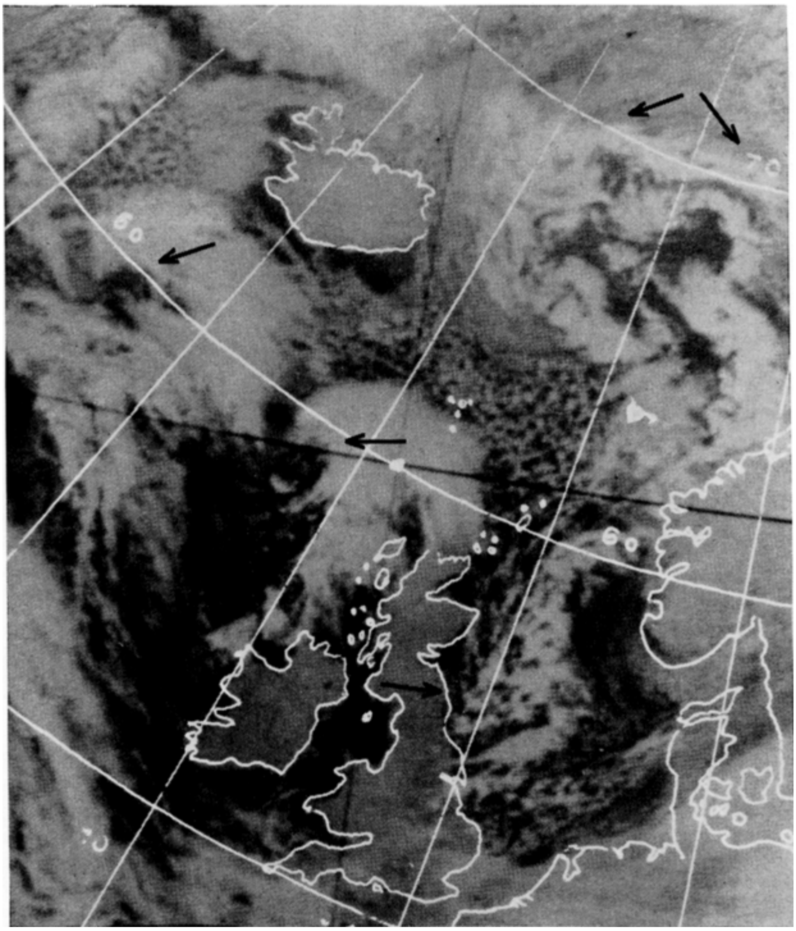

Fig. 1. Examples of cold-air organized cloud systems over the North Atlantic at 1900 GMT on 11 December 1981.

panying pressure and wind perturbations, and associated merely with enhanced showers of snow or small hail. Some of the disturbances, however, grew to become intense "polar lows". Past studies indicate that these disturbances can have pressure perturbations in excess of 20 mb and possess convergent, shifting winds which may be sustained at more than 25 m s^{-1} and gust to 60 m s^{-1} (Lyall, 1972; though in this case the polar low was not solely responsible for the strong winds—there was already a strong synoptic-scale flow over the region). Polar lows with mesoscale cloud systems resembling synoptic-scale comma clouds can bring continuous snow for a number of hours, and snowfalls of 28 cm (and up to 46 cm in a few spots) have been reported when polar lows moved across England (e.g. Stevenson, 1968; George, 1972).

There has been little discussion in the literature of the lesser insignificant cold-air disturbances, though a number of researchers have published studies of well-developed polar lows (e.g. Harrold and Browning, 1969; Reed, 1979; Seaman et al., 1982). Most of these were accompanied by comma-cloud configurations, though others have been accompanied by a spiral pattern of deep convective bands (e.g. Rasmussen, 1981). Two objectives of this paper, therefore, are to present a scheme for classification of mesoscale cloud vortices and to present empirical bases for deciding which types must be monitored as existing or developing intense polar lows. (It should be noted that there is presently little quantitative guidance regarding the threshold conditions which define a "polar low". This subject will be addressed in Section 4).

A third objective of this paper is to present some initial results of a study to determine if there are significant differences between synoptic-scale meteorological conditions accompanying polar vortices which develop into intense polar lows and those which remain insignificant (Section 5). Hypotheses are presented in Section 6. This research bears relevance to discussions regarding the relative roles played by baroclinicity and conditional instability of the second kind (CISK) in polar low development.

2. Data base and analysis procedure

Europe experienced a rather cold December, 1981, in association with cold air aloft accompanying a persistent mid-level trough having an axis located over Scandinavia. Accordingly, with the trough axis to the east of the major water bodies and the polar-front jet stream driven far to the south, cold-air vortices were more frequent than normal over the northeastern Atlantic during the period from early December through early January. A systematic study was performed for the period from 1 December 1981 through 5 January 1982, over oceanic areas and adjacent continental regions from 35° N to 75° N and roughly from Greenland to Europe and Scandinavia (54° W to 45° E). The Mediterranean region was excluded.

Imagery from each pass by the NOAA-6 and NOAA-7 satellites over the region was inspected for the existence of mesoscale cloud configurations, initially independently of other data. Because of the relative infrequency of visible imagery at the northern latitudes during winter, the study was based primarily upon infrared images (which were unenhanced and not particularly detailed). If a mesoscale cloud system showed signs of circulation at any time, it was counted as a cold-air vortex and its path was charted from the time that the circulation first appeared until its demise. Vortices evolving within or associated with a recognizable synoptic-scale frontal band were excluded from the study, as these vortices did not qualify as cold-air phenomena. Fig. 2 shows the location of a number of vortices relative to the 500 mb chart on one day of the study period.

Three classifications were made for each vortex at 12-hour intervals using the satellite imagery: (1) cloud category, based upon the depth, type, coverage, and configuration of clouds in the vortex; (2) maximum diameter of the vortex circulation, as

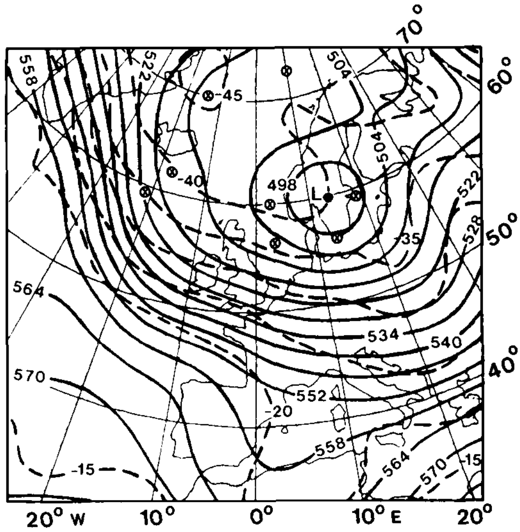

Fig. 2. Locations of polar vortices (dots) relative to the 500 mb height contours (solid in dam) and isotherms (dashed) at 0000 GMT on 8 December 1981.

determined from cloud bands, etc.; (3) maximum number of revolutions made by any cloud band about the circulation center. These classification parameters were chosen to incorporate the elements of the schemes developed by Junker and Haller (1980) and Dvorak (1975) for estimation of the central pressure of oceanic mid-latitude cyclones and tropical cyclones, respectively, using satellite imagery. The deficit pressures of polar vortices, as a function of the above classifications, are presented in Section 3.

Vortex nature (developing, steady, insignificant, dissipating comma) was also subjectively categorized from satellite imagery based upon the rates at which the circulation diameter and band revolution increased with time. A vortex was classified only once during its lifetime, according to its overall behavior. Developing vortices transformed from a state of initial minimal circulation into well-defined comma or spiral configurations. Non-developing vortices were categorized as steady if they appeared to be significant in terms of moderate amounts of circulation and moderate diameters and as insignificant if they were shallow, poorly-developed, or short-lived. Significant commas which were only observed during dissipation stages (i.e. satellite imagery was not available for early stages) were classified as dissipating commas.

Once all of the cold-air vortices were identified and classified using satellite imagery, surface charts were consulted in order to determine the magnitude of the pressure perturbation accompanying each vortex. In order to estimate the pressure deficit between the mesoscale vortex and its synoptic-scale surroundings, sequences of charts at 3-hour and occasionally 1-hour intervals were used. Owing to the small scale of the vortices and the sparsity of data over some oceanic regions, a deficit pressure estimate could not be made for all vortices at all times. Deficit pressures were estimated for vortices which passed over a station, and the pressure and pressure-tendency observations at the station were used to estimate the central pressure of the vortex. To obtain a deficit pressure, this central pressure was subtracted from the value obtained at that point from a smoothed isobaric analysis. The smoothed synoptic-scale analysis was drawn subjectively (by hand) by ignoring all observations in the vicinity of the polar vortex. Deficit pressures were tabulated at 12-hour intervals corresponding to times of upper-air analyses (0000 and 1200 GMT).

In order to obtain some information regarding whether there were differences in the synoptic-scale environment between vortices of different characteristics (cloud category and degree of eventual development), a synoptic-scale data base was archived. Sea-surface temperature at the center of each vortex was interpolated using operational analyses. Values of upper-air meteorological parameters were interpolated from the initial analysis fields of height and temperature at the 1000, 850, 700, and 500 mb levels obtained from the European Centre for Medium Range Weather Forecasts (ECMWF). Since the tropopause was generally near 400 mb in the cold-air regions of interest, analyses above 500 mb were not used.

Daily subjective comparisons of the ECMWF initial analyses with raw upper-air data, hand analyses and satellite imagery show that the ECMWF analyses are excellent for synoptic-scale features, but generally do not reveal the existence of mesoscale features such as polar vortices. Considering the spacing of the radiosondes over oceans, this is not surprising and is not detrimental to this study of the large-scale environment. ECMWF humidity analyses, however, were not used because it was evident that the presence or absence of mesoscale cloud systems (not adequately analyzed in the ECMWF model) was the key factor determining the variation of humidity in the cold air.

The ECMWF initial analysis data was available on a 1-degree latitude/longitude grid. Values at the vortex center were obtained through linear interpolation of this data. Values of a number of derived parameters involving gradients, listed in Table 1, were calculated using a grid length of 450 km. This grid spacing was chosen to be consistent with the density of upper-air observations and to help ensure that the calculated fields would reveal the synoptic-scale environment surrounding the

Table 1. *Synoptic-scale parameters calculated*

Sea surface temperature, T_S
By level: 1000, 850, 700, 500 mb
Geopotential height, h
Temperature, T
Departure from sea surface temperature, $T_S - T$
Horizontal temperature gradient, ∇T
Horizontal geopotential height gradient, ∇h
Geostrophic wind speed, $\lvert \mathbf{V}_g \rvert$
Geostrophic U and V components, u_g and v_g
Deviation of movement from geostrophic wind, MVMT − DIRVG
Temperature advection by geostrophic wind, $-\mathbf{v}_g \cdot \nabla T$
Thermal windspeed, $\lvert \mathbf{V}_T \rvert$
Thermal wind U and V components, u_T and v_T
Deviation of movement from thermal wind, MVMT − DIRVT
Relative geostrophic vorticity, ζ_g
Absolute geostrophic vorticity, $\zeta_g + f$
Vorticity advection by geostrophic wind, $-\mathbf{V}_g \cdot \nabla(\zeta_g + f)$
Thermal vorticity, ζ_T
Advection of thermal vorticity by thermal wind, $-\mathbf{V}_T \cdot \nabla\zeta_T$
By layer: 1000–850, 850–700, 700–500, 1000–500 mb
Lapse rate, γ
Average temperature, $\bar{T}$
Average geostrophic wind speed, $\overline{\lvert \mathbf{V}_g \rvert}$
Average U and V components, $\bar{u}_g$ and $\bar{v}_g$
Deviation of movement from average geostrophic wind, MVMT − AVGDIR
Magnitude of geostrophic shear vector, $\left\lvert \frac{\partial \mathbf{V}_g}{\partial z} \right\rvert$
Components of shear, $\frac{\partial u_g}{\partial z}$ and $\frac{\partial v_g}{\partial z}$
Deviation of movement from geostrophic shear, MVMT − DIRSHR
Richardson number, Ri

mesoscale polar vortices, rather than be affected by their presence.

Values of the parameters defined in Table 1 were calculated with respect to the centers of circulation of the vortices. Parameters were calculated from standard formulae (except that dry-bulb temperatures were used in place of virtual temperatures), e.g.,

$$u_g = -gf^{-1}\left.\frac{\partial h}{\partial y}\right)_p; \quad v_g = gf^{-1}\left.\frac{\partial h}{\partial x}\right)_p; \tag{1}$$

$$u_T = -gf^{-1}T^{-1}\left.\frac{\partial T}{\partial y}\right)_p; \quad v_T = gf^{-1}T^{-1}\left.\frac{\partial T}{\partial x}\right)_p; \tag{2}$$

$$\zeta_g = \hat{k}\cdot\nabla\times\mathbf{V}_g = gf^{-1}\nabla_p^2 h; \tag{3}$$

$$\zeta_T = \hat{k}\cdot\nabla\times\mathbf{V}_T \cong gf^{-1}T^{-1}\nabla_p^2 T; \tag{4}$$

$$R_i = g\theta^{-1}\left(\frac{\partial\theta}{\partial z}\right)\left(\frac{\partial|\mathbf{V}_g|}{\partial z}\right)^{-2}. \tag{5}$$

As discussed in Section 5, the values have been composited, and stratified by nature of the vortex. Statistical comparisons have been performed between the values for different vortex natures: (1) using observations during only early stages (first 18 hours) of the vortex lifetimes and (2) using all observations. Comparisons of early-stage and subsequent values have also been performed. Statistical significance was determined using two-sample t-tests. Other comparisons are planned, such as between values composited for different cloud categories.

3. Cloud categories and deficit pressures accompanying polar vortices

A total of 133 vortices were observed during the 36-day period. Fig. 3 shows the frequency of cold-air vortices by "box" (5-degree latitude by 5-degree longitude area). Just as the atmospheric conditions were much colder than normal, discussions with veteran European meteorologists led us to conclude that the vortex frequency shown in Fig. 3 was far greater than normal.

The average vortex lasted long enough that it could be evaluated with respect to more than two sets of upper-air analyses (stations shown by large dots on Fig. 3). Well-defined vortices often lasted

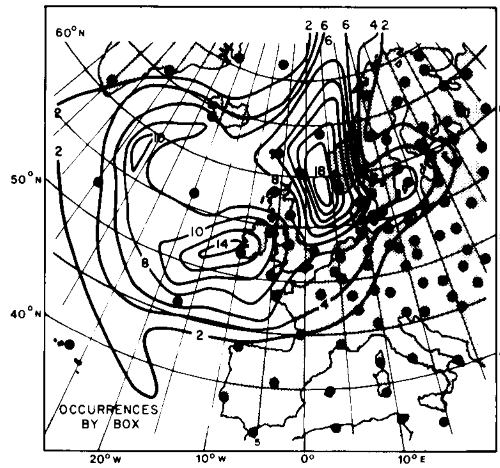

Fig. 3. Frequency of occurrence of cold-air vortices of all categories during the period from 1 December 1981 to 5 January 1982 by box (5 deg. latitude by 5 deg. longitude). Locations of upper-air stations are shown by dots.

for several days and the weakest of the vortex circulations sometimes were detected only for a few hours. The cloud clusters accompanying such short-lived vortices, however, usually persisted for a considerably longer period without showing signs of a circulation.

Cloud configurations accompanying the polar vortices were classified in *9 categories*, as listed in Table 2. These categories account for differences in cloud patterns, depth, and type—stratiform or convective. So many preliminary categories were selected, defined by the descriptions listed in Table 2, in order to show the variety of types of cold-air vortices which occur and to allow for possible differences in their evolutions. However, it will subsequently be shown (in Section 4) that, from an evolution standpoint, a number of these categories can be grouped together.

The various cloud configurations are illustrated in Fig. 4. The cloud patterns were of meso-alpha scale, having diameters ranging from about 100 to 1000 km. Category 1, 5, and 9 vortices were most common, as shown by the number of observations (one per 12-hour interval), listed in Table 2.

Vortices that were well-defined and resembled either synoptic-scale comma clouds (Carlson, 1980) or tropical storms were classified as Category 1. In order to allow for possible dif-

Table 2. *Observations by category of cloud pattern*

Category	Description	Totl # obs.	# with ΔP	Mean ΔP
1	Comma, deep spiral	84	54	10.1 ± 6.1 mb
2	"Merry-go-round" or ring of vortices	3	3	8.7 (± 3.2)
3	Crescent	17	13	3.5 ± 2.4
4	Oval, solid mass	10	3	5.7 (±1.2)
5	Multiple deep bands	108	34	4.0 ± 2.3
6	Multiple shallow bands	36	12	3.5 ± 2.2
7	Single deep band	2	2	4.0 (± 1.4)
8	Single shallow band	1	1	0.0
9	Swirl in cumulus streets	72	26	2.9 ± 2.1
Strong comma	(diameter > 3.5 deg. lat. or > 0.5 revolution)	44	27	12.7 ± 6.6
Minor comma	(diameter ≤ 3.5 deg. lat. and ≤ 0.5 revolution)	40	26	7.0 ± 3.5

ferences in accompanying meteorological conditions, however, category 1 vortices were further classified in sub-categories:

(1a) weak commas, stratiform in appearance but having a small, poorly-defined comma head;
(1b) well-defined, classic commas of chiefly stratiform cloud;
(1c) spiral configurations of deep convection, resembling tropical storms or comma clouds composed of convective cells;
(1d) "instant commas" of deep cirrus-topped cloud, developing suddenly from a virtually cloud-free environment;
(1e) occluded commas in which only streets of narrow convection identify the circulation center, but the deep stratiform cloud shield persists to the northeast.

It should be noted that the similar resemblances of a mesoscale comma cloud accompanying polar vortices and a synoptic-scale comma cloud do not necessarily imply that they have similar manners of development and evolution. The comma shape is just a fundamental characteristic of a vortex in a stratiform cloud field.

The frequency and the pressure perturbations of the various type 1 vortices are given in Table 3. It is not known, however, whether the relative frequencies of the various cloud configurations are the same in this sample as they are under less anomalous circumstances. All of the polar lows documented in the literature appear to be of category 1, particularly 1a, 1b, and 1c.

Category 2 vortices were also well-defined, but were quite different in configuration. Fig. 4 shows an example, and a descriptive name of "merry-go-round" is suggested, as the vortex is comprised of several small category 5 vortices revolving about a relatively cloud-free center. Only one of the 133 polar vortices was of this category, and it formed directly beneath a 500 mb trough.

Most of the other 7 classifications of cloud category of Table 2 are relatively unambiguous, based upon the descriptions given in the table. However, category 3 and 1a vortices are somewhat similar in appearance. Both are stratiform but they differ in that the crescent configuration is bowed in the middle like a horseshoe whereas the curvature in the weak comma is asymmetric, with a more pronounced curvature in the comma head.

Category 9 vortices are like category 1e, except without a deep cloud shield nearby. Oerlemans (1980) has presented a case study of a vortex quite similar to these, though he indicated that the disturbance originated as a coastal phenomenon, rather than a disturbance over open ocean. Forbes and Merritt (1984) have described vortices over the United States Great Lakes which have a similar appearance.

Table 2 also lists for each cloud category the number of observations when deficit pressure estimates were obtained (one per 12-hour period) and the mean and standard deviation of the deficit pressure. A further breakdown of the cloud category-deficit pressure relationship is given in Table 4.

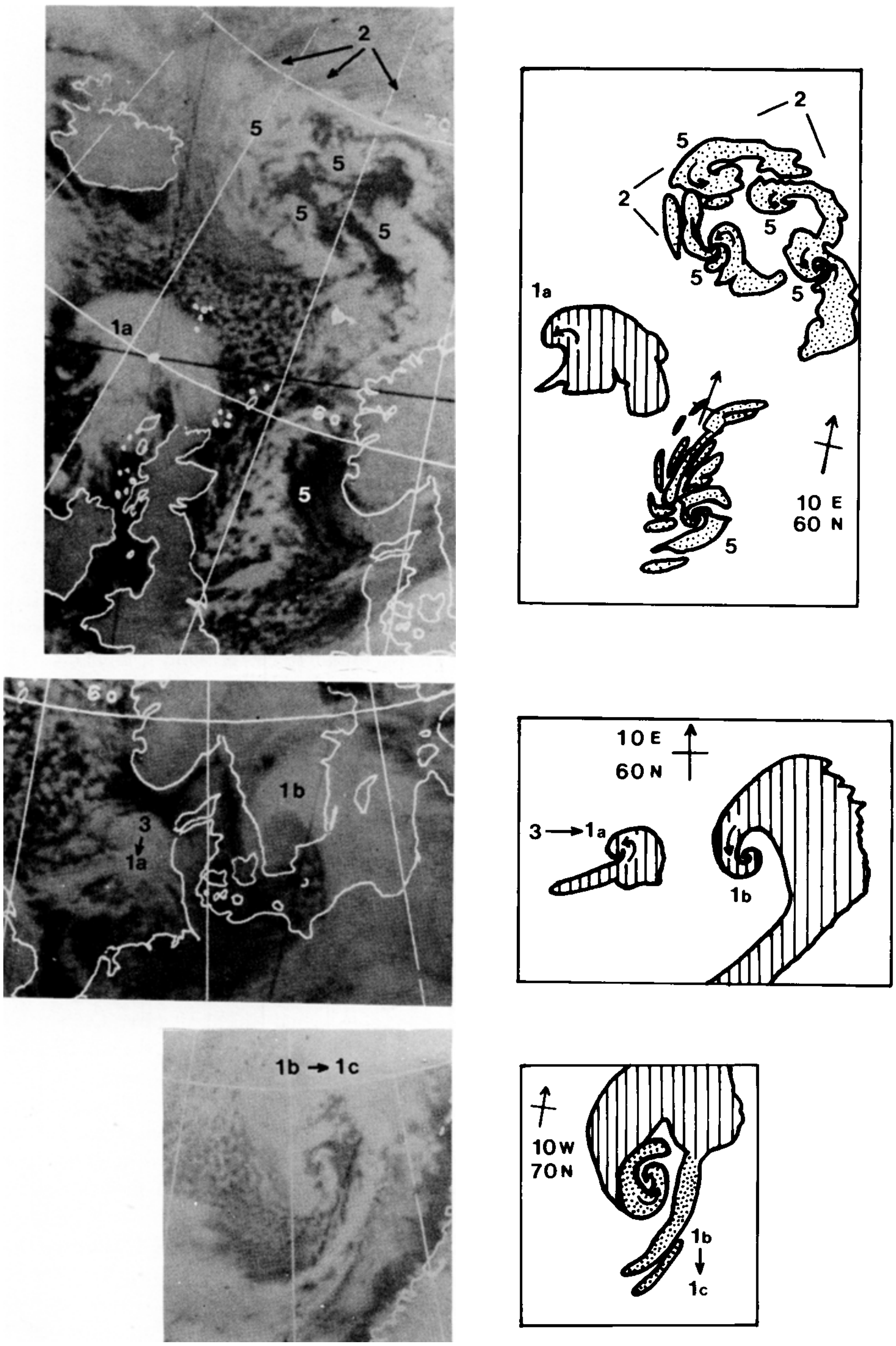

Fig. 4. Illustrations of the categories of cloud configurations. See text for details. Crosses are reference latitude/longitude intersections; arrowheads signify North.

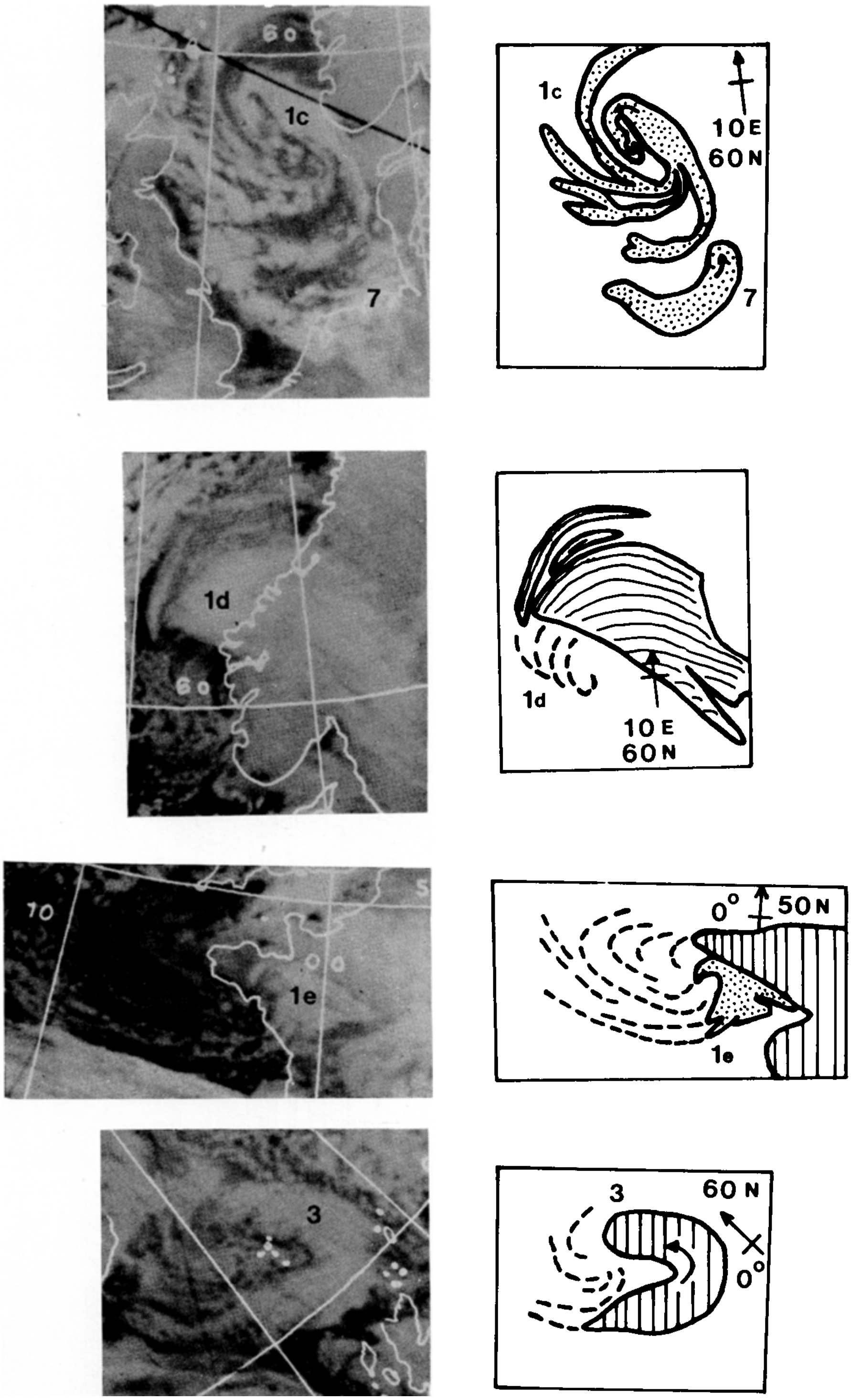

Fig. 4—cont

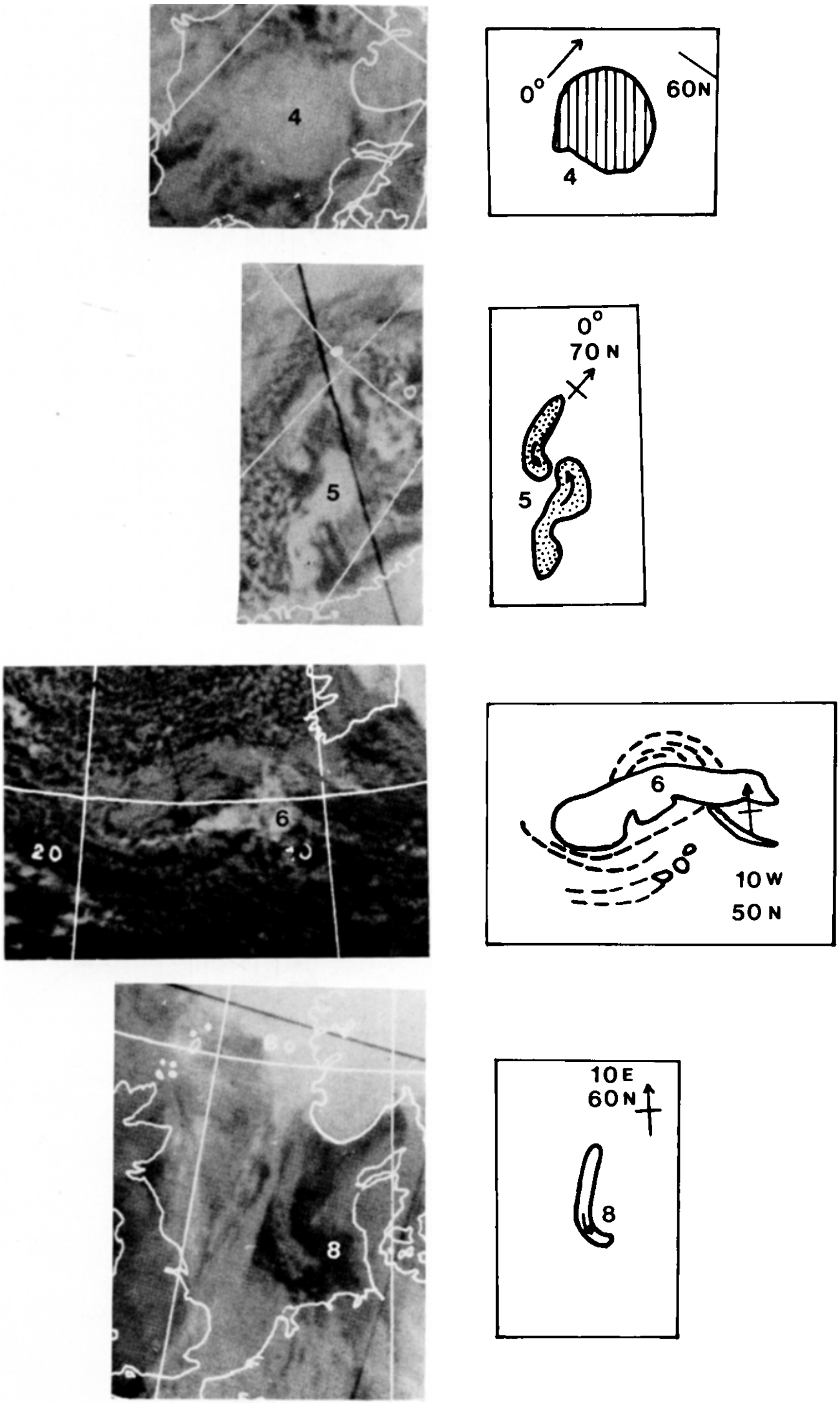

Fig. 4—cont

Fig. 4—cont

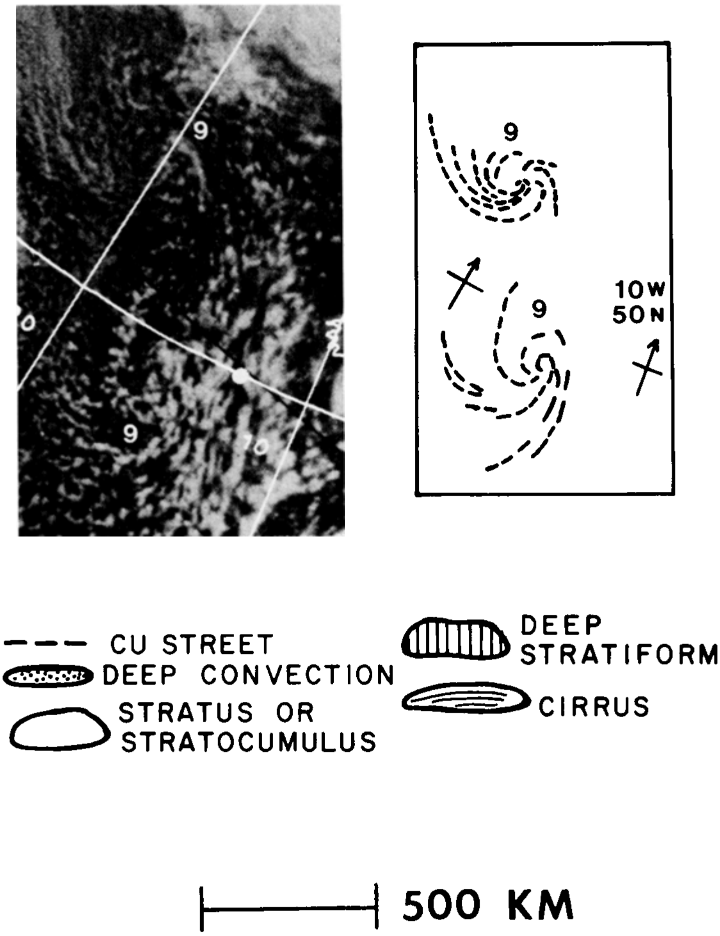

Fig. 4—cont

Table 3. *Observations of category 1 vortices*

Nature	Total # obs.	% of obs.	# of vortices	% of vortices	# of obs. with ΔP	Mean ΔP (mb)	Range (mb)
1a Weak comma	13	16	12	44	9	6.6 ± 3.5	2–14
1b Classic comma	38	46	15	56	27	13.1 ± 6.1	5–23
1c Convective spiral	5	6	5	19	1	5.0	
1d Instant comma	2	2	2	7	2	3.5 (±2.1)	2–5
1e Occluded comma	25	30	14	52	15	8.0 ± 5.1	2–14

Category 1 vortices were not only the most sensational in appearance but were also associated with the largest deficit pressures. One deficit pressure reached 23 mb. Configurations of deep convective bands (such as category 5) exhibited modest pressure perturbations, but only became intense polar lows when reaching the form of category 1c. Circulations in shallow convection (such as category 9) possessed minimal pressure perturbations.

Overall, the vortices behaved somewhat similarly, in terms of deficit pressure, to either

Table 4. *Relationship between cloud category and pressure perturbation*

Category	# obs. with ΔP	⩾2	⩾4	⩾6	⩾8	⩾10	⩾12	⩾14	⩾16	⩾18	⩾20	Range
1	54	100%	93%	74%	56%	37%	33%	28%	24%	20%	13%	2–23
2	3	100	100	67	67	67	0	0	0	0	0	5–11
3	13	77	46	23	0	0	0	0	0	0	0	0–7
4	3	100	100	33	0	0	0	0	0	0	0	5–7
5	34	79	56	29	6	0	0	0	0	0	0	1–9
6	12	75	50	17	0	0	0	0	0	0	0	1–7
7	2	100	50	0	0	0	0	0	0	0	0	3–5
8	1	0	0	0	0	0	0	0	0	0	0	0
9	26	73	27	12	8	0	0	0	0	0	0	0–8
Strong comma	27	100	100	85	67	56	48	44	44	37	22	4–23
Minor comma	26	100	85	62	42	15	15	8	0	0	0	2–14

tropical cloud systems or oceanic mid-latitude cyclones. Curved banded convective configurations had deficit pressures that were generally largest when (a) the convection was in the form of a broad cluster of deep, large-diameter elements and (b) the bands made considerable fractions of a full revolution about the circulation center. This is similar to the behavior of tropical storms (Dvorak, 1975). The vortices with more stratiform appearances seemed to generally follow the guidelines of Junker and Haller (1980) for oceanic cyclones: the deficit pressure increased as the deep cloud system became progressively a spiral, as a deep band revolved about the circulation center. The rate of increase of deficit pressure appeared to be only half of that specified by Junker and Haller, however, and was also a function of the diameter of the circulation.

Tables 2 and 4 show that *strong commas*—having either a large circulation diameter (> 3.5° latitude) or a band spiralling more than one-half revolution about the circulation center—had significantly larger deficit pressures than *minor* (i.e. lesser) *commas* (at the 99.9% confidence level). It should be noted here that "strong" commas and "classic" category 1b commas are not necessarily the same, as a few 1b vortices failed to meet the size requirements and a few 1e vortices satisfied the size and circulation requirements. Similarly, "minor" commas and "weak" category 1a commas are not necessarily the same.

4. Identification of existing or potential polar lows via satellite imagery

"Polar lows" have apparently been given special attention in the literature primarily because of their unusual (i.e., cold-air) manner of occurrence. Though some were quite intense, intensity does not appear to have been a major consideration. A survey of the literature, making estimates from published charts when deficit pressures were not listed, indicates that the previously-documented "polar lows" had deficit pressures ranging from about 4 to 24 mb. Apparently, "polar lows" were studied provided that they were of sufficient intensity (or were accompanied by sufficiently-drastic weather) to capture the scientist's interest. For purposes of suggesting which of the vortices in the present study were sufficiently intense to merit the title of "polar low", we have used a threshold deficit pressure of about 6 mb.

The results of the cloud category-deficit pressure comparison, summarized in Tables 2–4, have shown which vortices in this sample generally possessed significant deficit pressures. That is, the presence of a cloud configuration of category 1 or 2 indicated the presence of a cold-air disturbance with better than a 50% chance of having a deficit pressure exceeding 8 mb. Thus, it can be stated that the detection of a category 1 or 2 vortex in satellite imagery usually signified the existence of a "polar low". Conversely, any other type of cloud configuration had very little likelihood of being a polar low at that instant.

Most of the polar lows in this sample, however, did not suddenly appear in the form of category 1 or 2 vortices—only 21% of the vortices which developed into polar lows first exhibited circulation while in these configurations. The other polar lows formed as category 3 (14%), 4 (21%), or 5 (43%) and evolved into category 1 or 2. As discussed subsequently, however, the existence of categories 3, 4, and 5 did not guarantee eventual evolution into a polar low.

Rather than classify the cold-air vortices as "polar lows" and "other" vortices, we have adopted a different terminology. We have called all cold-air vortices "polar vortices" and further classified them on the basis of their nature—developing, steady, or insignificant. Using our terminology, such vortices evolve into significant, moderate, and weak disturbances, respectively. After reaching a significant intensity, weakening disturbances were classified as having a "dissipating comma" nature.

It was generally possible, independently of pressure observations, to monitor the evolution of the polar vortices and determine their nature—developing, steady, insignificant, or dissipating comma—by observing the changes in their degree of organization (ideal organization being like a comma cloud or tropical storm), the change of circulation diameter, and the strength of the circulation (number of revolutions made by the cloud bands). After viewing the satellite imagery thoughout its entire lifetime, the vortex nature classification was given.

Despite being subjective, the classification was remarkably accurate when subsequently compared to deficit pressures. Table 5 shows the mean (average of all observations) and peak (average of all individual case maxima) deficit pressures and their standard deviations for each vortex nature. There was little overlap of values. Since developing vortices had the longest lives, and spent only a portion of their lives in the mature stage, the mean deficit pressure shown includes pressure values during the initial development stages. Thus, the mean deficit pressure of 9.6 mb is considerably less than the typical peak value of 13.2 mb, and the indicated standard deviation is large. Dissipating commas were associated with diminishing deficit pressures.

It is impressive that the standard deviations of deficit pressure accompanying steady and insignificant vortices were so low, generally lower than those of the individual cloud categories of Table 2. This indicates that the histories of the vortices, their diameters, and their amounts of circulation affected the deficit pressures accompanying vortices of a particular cloud category.

To generalize, developing vortices had deficit pressures which almost always exceeded 8 mb, and typically reached about 13 mb, sometime during their lifetime, whereas steady vortices did not. Steady vortices had deficit pressures which increased initially and then remained near 5 or 6 mb, whereas insignificant vortices usually did not attain more than a 3 mb deficit pressure.

Without scrutinizing the history of evolution of a vortex—only knowing its current cloud category, diameter, and degree of circulation—it was difficult in this sample to predict the nature of the vortex. Weak commas (Category 1a) were sometimes associated with steady (rather than developing) vortices, developing vortices in early stages were often in the form of category 3, 4, or 5, and dissipating commas sometimes evolved into cumulus swirls (category 9). However, as shown in Table 6, commas and the merry-go-round vortices were normally developing (significant), whereas shallow features (categories 6 and 8) and cumulus street swirls (category 9) were normally insignificant (weak).

An inspection of this sample suggests that it is

Table 5. *Observations by nature of vortex*

Nature	Estimated # cases	Estimated # obs.	# obs. with ΔP	Mean ΔP	Peak ΔP
Developing commas	16	101	61	9.6 ± 6.0	13.2 ± 5.8
Steady	18	73	42	4.8 ± 1.8	5.8 ± 1.8
Insignificant	96	155	41	2.1 ± 1.7	2.6 ± 2.0
Dissipating commas	3	10	4	$4.0 (\pm 2.5)$	6.0

Table 6. *Relationship between cloud category and vortex nature*

Category	Significant (developing or dissipating comma)	Steady	Insignificant
1	79%	21%	0%
2	100	0	0
3	47	24	29
4	40	10	50
5	19	26	55
6	0	33	67
7	0	50	50
8	0	0	100
9	13	13	74
Strong comma	91	9	0
Minor comma	65	35	0

Table 7. *Probability of vortex nature based upon cloud category, if category 1 or 2 has not yet been reached*

Category	Developing	Steady	Insignificant
3	50%	19%	31%
4	40%	10%	50%
5	10%	28%	62%
6	0%	25%	75%
7	0%	33%	67%
8	0%	0%	100%
9	0%	15%	85%

possible to use the observed cloud configuration in a predictive sense if one aspect of vortex history is taken into account—a record of whether or not the vortex has yet attained category 1 or 2. This eliminates the dissipating comma stages and gives the probabilities of Table 7. It can be seen that crescent configurations (category 3) and solid circular cloud masses (category 4) merited continued scrutiny, whereas other cloud configurations were unlikely to become polar lows. Multiple bands of deep convection (category 5) occasionally developed into polar lows, and convective circulations of several types (categories 5, 6, 7, 9) sometimes became (or were already) steady moderate-intensity disturbances, but such circulations most frequently remained insignificant.

Pragmatically, as for an operational classification scheme, the results of this section indicate that there can be considerable grouping of the original nine categories (plus sub-categories) of polar vortex cloud configurations. (1) Categories 1 and 2 indicate the presence of a well-defined circulation in a pattern of deep clouds, and are likely to accompany a *significant* disturbance (polar low). (2) Categories 3, 4, and 5 exhibit some circulation in a pattern of deep clouds, and indicate the potential for a fraction of the cases to develop to *moderate or significant* intensity. (3) Categories 6, 7, and 8 (and 9, when not a result of dissipating comma) signify shallow or non-clustered cloud patterns which accompany disturbances which remain *weak*.

5. Synoptic-scale environments of vortices of different natures

5.1. *General conditions accompanying polar vortices*

Cold air was entrenched over the study area at all levels for most of the period. An anomalously-strong mid-tropospheric trough was anchored near Scandinavia, and an anomalously-strong ridge persisted over Greenland (Taubensee, 1982). Winds were relatively weak over the study area, with more of a northeasterly component than normal, and the jet stream was driven well to the south of the area to about 15 degrees south of its normal position.

The days on which polar vortices were numerous over the area were typically days when the Scandinavian trough was either shifted or broadened toward the west to extend over the study area. This was sometimes in association with short-wave disturbances propagating southeastward on the west side of the quasi-stationary Scandinavian trough. In any event, polar vortices were prevalent on days when the heights and temperatures were below average for the study period and, thus, well below the climatological normals. Vortices typically began developing about one day after a fresh cold-air mass invaded the region.

Table 8 presents mean values for selected meteorological parameters at 1000, 850, 700, and 500 mb levels. The means are averages of values interpolated at the center of each vortex at 12-hour

Table 8. *Mean values of selected parameters, all vortex observations*

Parameter	1000 mb	850 mb	700 mb	500 mb
T_{sea} (K)	280.0			
T (K)	274.6	264.2	254.0	237.2
h (m)	8	1291	2766	5186
$\|\mathbf{V}_g\|$ (m s^{-1})	8.6	8.3	9.0	12.8
u_g (m s^{-1})	−0.3	1.6	3.9	8.3
v_g (m s^{-1})	−3.9	−4.0	−4.1	−4.8
$\|\nabla T\|$ (K m^{-1})	7.6×10^{-6}	7.0×10^{-6}	6.9×10^{-6}	7.6×10^{-6}
$\|\mathbf{V}_T\|$ (s^{-1})	2.2×10^{-3}	2.1×10^{-3}	2.1×10^{-3}	2.6×10^{-3}
u_T (s^{-1})	1.4×10^{-3}	1.4×10^{-3}	1.7×10^{-3}	2.0×10^{-3}
v_T (s^{-1})	-0.2×10^{-3}	0.0×10^{-3}	-0.1×10^{-3}	-0.4×10^{-3}
$-\mathbf{V}_g \cdot \nabla T$ (K s^{-1})	-1.9×10^{-5}	-2.0×10^{-5}	-1.9×10^{-5}	-1.5×10^{-5}
ζ_g (s^{-1})	2.2×10^{-5}	1.9×10^{-5}	2.0×10^{-5}	3.1×10^{-5}
$-\mathbf{V}_g \cdot \nabla(\zeta_g + f)$ (s^{-2})	1.1×10^{-10}	0.5×10^{-10}	-0.1×10^{-10}	-0.8×10^{-10}
ζ_T (s^{-1} m^{-1})	-3.5×10^{-9}	-1.2×10^{-9}	2.9×10^{-9}	4.4×10^{-9}
$-\mathbf{V}_T \cdot \nabla\zeta_T$ (s^{-2} m^{-1})	3.3×10^{-18}	4.1×10^{-18}	2.5×10^{-18}	-2.1×10^{-18}
Deviation from $\mathbf{V}_g$ (deg.)	−17	−10	−2	7
Deviation from $\mathbf{V}_T$ (deg.)	16	20	22	18
	1000–850 mb	850–700 mb	700–500 mb	1000–500 mb
γ (K m^{-1})	8.1×10^{-3}	6.9×10^{-3}	7.0×10^{-3}	7.2×10^{-3}
Thickness (m)	1283	1475	2420	5178
Ri	119	94	137	160

intervals, and represent the large-scale environment rather than internal details of the developed vortices. Only a brief summary of the observations will be presented here. Differences in values between vortices of different natures are discussed in section 5.2.

The polar vortices were typically found over warm waters topped by considerably colder air. The 500 mb temperature accompanying the vortices averaged 237.2 K and the 850 mb temperature (264.2 K) was about 5 K below the climatological normal. Lapse rates were conditionally unstable below 850 mb and slightly stable in the layer above. (The moist adiabatic lapse rate is about 7–8 × 10^{-3} K m^{-1} at these temperatures).

Heights of the pressure surfaces were rather low, with the 700 mb heights about 100 m below climatological normal and about 50 m below the average for the study period. The 500 mb heights at the vortex center were about 160 m below the climatological normal.

Geostrophic wind speeds accompanying the polar vortices were fairly weak and backed with height. The wind directions were variable between northeast, north, northwest, and west; this resulted in a very weak mean u component. Because of the variable wind direction, the mean u and v components failed to yield the mean speed.

The air masses in which polar vortices formed were moderately baroclinic, having horizontal temperature gradients of about 7 K per 1000 km throughout the troposphere. This value is approximately the climatological normal over the region, but is considerably smaller than a value in a well-defined synoptic-scale frontal zone, which would be about 20 K per 1000 km. There was, therefore, a moderate amount of vertical wind shear—a thermal wind of about 2 m s^{-1} per km from the west-northwest. Again, the mean u_T and v_T do not produce the mean thermal wind speed because of variable thermal wind directions. The relatively weak wind shears contributed to large Richardson numbers.

The polar vortices were occurring in regions of weak large-scale cold advection at all levels, at rates equivalent to a cooling of about 1.5 K per day. It is not uncommon for values to be 5 times larger within the frontal zones of synoptic-scale cyclones.

The vortices were associated with synoptic-scale positive geostrophic relative vorticity of about 2–3 $\times$ 10^{-5} s^{-1}. By contrast, an intense short-wave trough may be associated with a relative vorticity of 8–10 $\times$ 10^{-5} s^{-1}. Overall, vorticity advection accompanying the vortices was quite weak, $\pm$ 1 $\times$ 10^{-10} s^{-2}. Vorticity advections accompanying well-defined synoptic-scale waves are frequently $10 \times 10^{-10}\,s^{-2}$)

The thermal vorticity, ζ_T, is a measure of the horizontal thermal pattern accompanying the vortices (see eq. (4) of Section 2). The negative values indicate that the vortices occurred within a large-scale warm pocket at low levels; positive values indicate a cold pocket in the upper troposphere. Advection of thermal vorticity by the thermal wind, an indicator of cyclogenesis when positive in the layer between the surface and the level of non-divergence (e.g. Haltiner and Martin, 1957), indicates that the overall thermal configuration below 500 mb was weakly favorable for cyclogenesis.

The polar vortices generally moved in the direction of the 700 mb wind and about 20 degrees to the right (south) of the thermal wind. This is similar to the movement of travelling, non-developing synoptic-scale waves. The developing polar vortices behaved more like developing baroclinic waves, however, moving to the left of the mean wind and more nearly along the thermal wind.

In summary, Table 8 shows the meteorological conditions which accompany the average polar vortex. These values are representative of the large-scale environment surrounding the vortex, rather than revealing internal details of the vortex structure. No consideration has yet been given to differences between developing and non-developing vortices; this is treated in Section 5.2. The results document the fact that the polar vortices in this sample occurred under conditions often quite different from those of synoptic-scale cyclones. They occurred away from the jet stream and on its cold side. Temperatures were anomalously cold; heights were well below climatological normals and even below average for this anomalous study period; wind speeds and vertical wind shears were rather weak. Also evident is that the vortices occurred in regions of cold advection, not normally favorable for cyclogenesis. Other conditions, if not in opposition to cyclogenesis, were weaker than those normally accompanying cyclogenesis. At the approximate level of non-divergence (700 mb) in these regions of low tropopause (400 mb), thermal vorticity advection was weakly positive and absolute vorticity advection was near zero and became more negative with height.

Thus, the polar vortices occurred under circumstances considerably less baroclinic than those of polar front wave cyclogenesis, but markedly colder temperatures promoted large lapse rates and air–sea temperature differences. Such conditions suggest that a larger role was played by diabatic heating and CISK in at least the early stages of vortex development, and that polar lows should develop on scales (wavelengths) smaller than the polar front wave cyclone (see Section 6). That was indeed the case in this sample, with the diameter of the polar vortex cloud circulation being only about 250 km, though the clouds sometimes extended to a diameter of about 800 km. By contrast, synoptic-scale comma clouds frequently span 2500 km.

5.2. *Differences in the environments of developing, steady, and insignificant vortices*

The research performed on this topic is viewed as the first stage of an experiment to deduce whether polar vortex development can be predicted statistically. The crucial meteorological question is whether there are differences in the synoptic-scale environments of vortices of different natures, or whether sub-grid-scale processes within the vortex, including latent and sensible heating, are crucial. The results presented below indicate that there are statistically-significant differences between a number of parameters in the synoptic-scale environments of developing and non-developing polar vortices. However, it is also clear that in an absolute sense the differences are not great. For example, the differences in temperatures and heights of the pressure surfaces between vortices of different natures are only about half of the magnitude of the departures of these parameters from climatological normals for that time of year.

Thus, in studying the remainder of Section 5, the reader should keep in mind the fact that most parameters were only slightly different between vortices of different natures, whereas the pattern over the entire region was markedly abnormal. We will ultimately hypothesize that it was not so much the difference between values, but instead the location of occurrence of the vortices relative to the large-scale pattern, that distinguished between developing and non-developing vortices. The data presented below provides the basis for this hypothesis, which must be tested on other samples, particularly those drawn from less anomalous periods.

Values of the parameters were composited for three periods: (1) the early or initiation stage—the first 18 hours of the vortex lifetime; (2) the subsequent period—from 18 hours to demise; (3) the entire period of vortex lifetimes. There are some statistically-significant differences in parameters measured during the early stage, but many more significant differences when all stages are considered. This suggests that the values of the parameters may, in later stages, reflect the existence of the intensified vortices rather than give an indication of forthcoming change of intensity. Research on the potential for statistical prediction is continuing.

The results presented here are communicated primarily for their potential to shed some observational light on the issue of the mechanism(s) for polar low development. Some discussion of the implication of the observations is given as they are presented, and a conceptual model of the vortex evolution process is proposed in Section 6.

5.2.1. *Early stages.* Of the parameters listed in Table 1, Table 9 lists the values of those which showed statistically-significant differences during the first 18 hours of vortex lifetime. Checks indicate which observations were significantly different from those of the developing vortex. Owing to the relatively small number of observations for the steady vortices (for most parameters, 15) and developing vortices (20) versus insignificant vortices (103), there were fewer statistically-significant differences between developing and steady vortices than between developing and insignificant vortices. Impressively, however, there was only one parameter (850 mb u_T) that was significantly different between steady and insignificant vortices (indicated by the asterisk in Table 9).

Mean values were termed significantly different if it could be concluded, with at least 95% confidence using a two-sample t-test (Panofsky and Brier, 1958), that the true means would not be expected to have identical values. In other words, calculated means have an inherent uncertainty related to the variance and size of the sample; thus, two calculated means that appear to be slightly different might truly be identical. Checked values can be judged not equal with at least 95% confidence. The following discussion summarizes the significant differences during the early stages of vortex lifetimes.

Developing vortices originated at more northern latitudes (62° N) than the other vortices (57° N).

Table 9. *Significance results—initiation stage*

Parameter	Developing	Steady	Insignificant
Sea surface temperature (K)	278.6 ± 2.4	√280.5 ± 2.5	√280.3 ± 2.6
500 mb temperature (K)	235.9 ± 5.3	236.0 ± 6.1	√238.8 ± 6.7
Average temperature, 1000–500 mb (K)	254.6 ± 3.5	254.5 ± 5.9	√257.0 ± 5.7
Lapse rate, 700–500 mb (K km^{-1})	7.1 ± 1.1	6.7 ± 0.8	√6.7 ± 0.8
700 mb geostrophic wind speed (m s^{-1})	6.8 ± 4.5	9.7 ± 5.1	√9.6 ± 5.6
Average windspeed, 700–500 mb (m s^{-1})	7.8 ± 5.8	11.9 ± 6.1	√11.2 ± 6.7
Average windspeed, 1000–500 mb (m s^{-1})	7.1 ± 4.3	10.2 ± 6.0	√10.0 ± 6.0
1000 mb u_g (m s^{-1})	−5.4 ± 4.8	√−0.0 ± 7.5	√0.6 ± 7.0
850 mb u_g (m s^{-1})	−3.8 ± 5.8	√2.6 ± 7.3	√2.1 ± 7.0
700 mb u_g (m s^{-1})	−0.4 ± 5.7	√5.8 ± 7.4	√3.9 ± 7.4
1000 mb u_T (10^{-3} s^{-1} m^{-1})	1.9 ± 1.0	1.6 ± 1.6	√1.1 ± 1.2
850 mb u_T (10^{-3} s^{-1} m^{-1})	1.9 ± 1.0	*1.9 ± 1.0	√1.1 ± 1.2
850 mb absolute vorticity (10^{-5} s^{-1})	14.7 ± 1.6	13.9 ± 2.8	√13.3 ± 2.8
500 mb thermal vort. adv. by thermal wind (10^{-17} m^{-1} s^{-2})	0.7 ± 1.6	−0.7 ± 1.5	0.0 ± 2.3
Deviation of movement from 700 mb thermal wind (deg. az.)	66.0 ± 87.0	51.0 ± 91.0	√25.0 ± 68.0
Deviation of movement from 1000–500 mb geostrophic shear (deg. az.)	65.0 ± 88.0	47.0 ± 86.0	√19.0 ± 73.0

This explains the otherwise-paradoxical cold sea-surface temperatures accompanying these vortices. It also explains why their 850 mb absolute vorticity (owing to the larger Coriolis parameter) was significantly larger than that of insignificant vortices, whereas the differences of relative vorticity were not statistically significant. It is suggested, however, that stretching of ambient absolute vorticity by inflow to the disturbance may have been important in initiating circulation in the vortices, especially those undergoing development. It is further noted that the more northerly initiation may have allowed the developing vortices a longer fetch over warm water, maximizing the time-integrated contribution of diabatic heating and CISK.

Developing vortices were accompanied by colder temperatures at 500 mb than their insignificant counterparts. This was also portrayed in the values of 1000–500 mb average temperature and steep 700–500 mb lapse rate.

Developing vortices were also associated with weak winds in the upper troposphere (700–500 mb), also manifested in the 1000–500 mb average wind. The weak upper-tropospheric winds arose as a combination of two statistically-significant differences. First, the low-level (1000–700 mb) u component was negative and significantly different from that of the non-developing vortices. Second, the low-level (1000–850 mb) shear, as manifested by the thermal wind component u_T, was significantly more positive than that of the insignificant vortices. Since the shear vector was opposite the low-level wind vector, the upper-tropospheric winds were weak. This reversed shear accompanying polar lows has been noted by Duncan (1978), and is discussed further in Section 6.

The developing vortices were accompanied by weak 500 mb positive vorticity advection, whereas the advection was weakly negative for non-developing vortices. The difference was not statistically significant (at the 95% confidence level) for absolute vorticity advection, but the advections of thermal vorticity by the thermal wind at 500 mb were significantly different. Developing vortices showed small positive values; insignificant vortices had small negative values. Together with the larger 1000–850 mb u_T values, this gives some indication that baroclinic processes were important for vortex development. At this stage the vortex movement, deviating significantly to the right of the 700 mb thermal wind, would seem to contradict this assertion, though this deviant movement disappeared at later stages.

The early-stage data, in summary, suggests that vortex development was enhanced by these factors: (1) stretching of low-level absolute vorticity, inducing a circulation which can subsequently produce a favorable pattern of thermal advections within the moderately-baroclinic vortex; (2) convection enhanced through a steepened lapse rate near 500 mb and through reduced winds at that level; (3) weak positive absolute and thermal vorticity advection; (4) steepened lapse rates and slightly increased vertical wind shears which promote cyclogenesis at short wavelengths (see Section 6).

Steady vortices in early stages had environments which were in many respects like those of developing vortices. Temperatures were just as cold, baroclinicity (temperature gradients and thermal wind) was essentially identical, and lapse rates were almost the same—though slightly more stable above 700 mb. The steady vortices had slightly *lower* heights at all levels and slightly *larger* relative vorticity at 500 mb.

There were some apparent differences in the environments of steady and developing vortices, though most were not statistically significant (see Table 9). Due to a more southern occurrence, the sea-surface temperatures were significantly warmer, and the air–sea temperature differences larger, than those of developing vortices. This suggests that steady vortices may have been more convective at low levels. Another significant difference was that the 500 mb thermal vorticity advection was negative, suggesting that steady vortices were inhibited from developing by an adverse thermal pattern. The thermal pattern differences are borne out by values of thermal vorticity, though not statistically significant. The thermal vorticity was more positive than vortices of other natures, revealed either as larger positive values at 850, 700, and 500 mb or as a smaller negative value at 1000 mb, suggesting that steady vortices occurred nearer the center of the cold pocket.

Steady vortices were also apparently inhibited from developing by cold advection, which was stronger at all levels than that of other vortices, and by absolute vorticity advection at 500 mb that was negative (like that of insignificant vortices). The advections were associated with winds that were stronger at all levels, especially aloft, than those of developing vortices. The wind components were also anomalous, with stronger westerly components (especially above 850 mb) and larger northerly components (especially below 700 mb) than with other vortices.

The data indicates that steady vortices occurred somewhat closer to the upper-air pressure and thermal trough axes than other vortices. The steady vortices also occurred on the *upwind* side of the axes, unlike developing vortices, which promoted negative absolute and thermal vorticity advections which would act to suppress development even though baroclinicity and steep lapse rates were present. The vortices were apparently initiated at these unfavorable locations because of anomalously-large low-level lapse rates and air–sea temperature differences which arose after the tropospheric cold pocket moved southeastward over warm waters.

Like steady vortices, insignificant vortices were also initiated after cold air aloft moved over warm waters, and were apparently inhibited from developing by negative advections of absolute and thermal vorticity in mid-troposphere. A position upstream of the pressure and thermal trough axes is indicated, but the thermal vorticity values are more like those of developing vortices. This indicates that the insignificant vortices occurred farther from the center of the cold pocket, consistent with warmer temperatures aloft and smaller lapse rates. This suggests that convection was somewhat suppressed. Baroclinicity (horizontal temperature gradient) was also reduced, suggesting that insignificant vortices were inhibited from developing even into steady vortices by: (1) reduced lapse rates; (2) reduced baroclinicity; (3) adverse vorticity advections.

5.2.2. Vortex evolutions. Table 10 presents values of parameters which showed statistically-significant changes (at the 95% confidence level) between the early (first 18 hours) and subsequent stages of the vortex lifetimes. A number of parameters changed significantly for developing vortices, though this may have been due to their presence becoming more readily detected by the observation network as they developed. Steady vortices did not show any significant changes (owing partially to small sample sizes and partly to

Table 10. *Parameters showing significant changes during vortex evolution*

Parameter	1st 18 hours	Subsequent
Developing vortices		
1000 mb height (m)	27	−33
850 mb height (m)	1304	1251
700 mb height (m)	2772	2726
500 mb height (m)	5182	5136
1000 mb relative vorticity ($\times 10^{-5}$ s^{-1})	2.2	4.0
850 mb relative vorticity ($\times 10^{-5}$ s^{-1})	1.8	3.5
700 mb relative vorticity ($\times 10^{-5}$ s^{-1})	1.8	3.2
500 mb relative vorticity ($\times 10^{-5}$ s^{-1})	2.3	3.8
1000 mb absolute vorticity ($\times 10^{-5}$ s^{-1})	15.1	16.4
850 mb absolute vorticity ($\times 10^{-5}$ s^{-1})	14.7	15.9
Deviation from 700 mb thermal wind (deg.)	66	6
Deviation from 500 mb thermal wind (deg.)	45	−2
Deviation from 850–700 mb shear (deg.)	62	15
Deviation from 1000–500 mb shear (deg.)	65	5
1000 u_g (m s^{-1})	−5.4	−0.8
850 u_g (m s^{-1})	−3.8	1.6
700 u_g (m s^{-1})	−0.4	4.0
Steady vortices		
None		
Insignificant vortices		
1000 mb ∇T ($\times 10^{-6}$ K km^{-1})	7.8	6.1

their steady nature). Only one parameter changed significantly for the insignificant vortices—1000 mb baroclinicity (temperature gradient) decreased.

Developing vortices were characterized by decreasing heights of all pressure surfaces, by increasing values of relative vorticity (less defined in absolute vorticity as they moved to more southern latitudes), by a movement becoming more nearly parallel to the thermal wind, and by increasing westerly geostrophic wind components (as the initial easterly components disappeared).

Of these changes, the deflection of the movement to become nearly parallel to the thermal wind seems to be most illuminating, and suggests that baroclinic processes played a significant role in the development. Other parameters, however, gave contradictory suggestions. Vortex development was accompanied (non-significantly) by decreases of baroclinicity at all levels and a decrease of 500 mb vorticity advection.

An inspection of the non-significant parameters (not shown) suggests that there was considerable latent heating accompanying vortex development. Despite persisting but diminishing cold advection at all levels, there was a temporal warming at all levels. The warming was largest (1.4 K) at 1000 and 850 mb, and the increasing negative values of thermal vorticity at these levels indicate that there was an intensifying warm pocket there. In response to the differential warming, lapse rates remained constant and large below 850 mb and increased aloft.

In summary, the data suggest that development proceeded (1) with an initial but diminishing contribution from absolute vorticity advection, (2) with substantial contribution from thermal vorticity advections associated with system baroclinicity, and (3) with considerable contribution from latent heating which reduced the system static stability. Thus, the evidence is consistent with a model of polar low development presented by Sardie and Warner (1983), involving both baroclinicity and CISK. Further discussion is given in Section 6.

5.2.3. *Vortex differences, all observations.* When all observations (first 18 hours and subsequent period combined) were considered, *most* parameters had values that showed statistically-significant differences between developing and one or both forms of non-developing vortices. Rather than tabulate the values, a brief descriptive summary is given in Table 11. The results are similar to those discussed in sections 5.2.1 and 5.2.2.

Table 11. *Summary of significant differences between vortices of different natures, all observations*

Developing vortices:	Moderate baroclinicity
	Smallest air–sea T difference
	Coldest 500 mb T
	Largest lapse rates above 850 mb
	Greatest 850 mb negative thermal vorticity
	Smallest wind speeds, all levels
	Largest vorticity, 1000–700 mb
	500 mb positive vorticity advection
	500 mb positive thermal vorticity advection
	Movement left of 1000–500 mb mean wind
Steady vortices:	Largest baroclinicity, all levels
	Coldest T, 1000–700 mb
	Largest air–sea T differences
	Positive 850 mb thermal vorticity
	Moderate low-level wind speed
	Largest 500 mb wind speed
	Moderate mid-tropospheric vorticity
	500 mb negative thermal vorticity advection
Insignificant vortices:	Smallest baroclinicity
	Warmest T, all levels
	Moderate air–sea T difference
	Smallest 850–700 mb lapse rate
	Largest wind speeds 1000–850 mb
	Largest heights, all pressure levels
	Smallest vorticity, all levels
	Greatest 500 mb negative vorticity advection
	Negative thermal vorticity advection, 1000–700 mb

Insignificant vortices had minimal potential for development: (1) mid-tropospheric layers were slightly stable and low-level wind speeds were strong, suppressing substantial latent heating and CISK; (2) baroclinicity was small; (3) vorticity advections were adverse. *Steady* vortices had some factors favorable for development—substantial baroclinicity and cold air extending upward to 700 mb, which favored convective heating—but vorticity advections were adverse. *Developing* vortices had a blend of moderate baroclinicity, large lapse rates at all levels, and favorable vorticity advections.

Following further discussion of these results in section 6, in comparison with other studies, a conceptual model of polar vortex evolution is proposed.

6. Discussion

6.1. *Comparison with other studies*

There have been a number of studies of cold-air vortices and polar lows reported in the literature. It is the purpose here to comment on similarities and differences between these studies and the research reported in the previous sections.

Several researchers have examined post-cold-frontal comma clouds occurring over the eastern Pacific Ocean during winter (e.g., Reed, 1979; Mullen, 1979; Locatelli et al., 1982). A common characteristic of these vortices is that they occurred sufficiently close to the frontal zone that a wave was usually induced on the front. Such vortices were observed by the lead author over the North Atlantic during the spring of 1982, and a frontal wave was induced when the center of the vortex moved to within approximately 450 km of the edge of the frontal cloud band. None of the developing vortices during the winter sample discussed in this paper, however, occurred this close to the front. Instead they were of type 2 of Locatelli et al. (1982), occurring farther back in the cold air (though not all were more convective there, as Locatelli et al. have suggested). Insignificant and steady vortices sometimes occurred nearer the polar front, but did not apparently induce frontal waves. Similarly, vertical wind shears were only $\frac{1}{3}$ to $\frac{1}{2}$ of those of Mullen's (1979) composites, as his Pacific cases were more baroclinic and occurred nearer the jet stream axis.

Mullen (1983) has indicated that Pacific polar vortices sometimes deepen at rates of more than the 24 mb per 24 hours proposed by Sanders and Gyakum (1980) as a designator of explosive cyclogenesis. There was no evidence that any of the Atlantic vortices in this study developed at such vigorous rates over a 24-hour period, though three deepened at rates exceeding 1 mb h^{-1} for 12 hours.

Mullen (1982) has reported that cyclones similar to polar lows can develop over the wintertime continent, and concludes that such occurrences rule out the necessity of CISK for polar low development. The prevalence of polar vortices over water, as reported in this paper, would seem to argue otherwise, however. Vortices sometimes developed near shorelines (e.g. Norway), but the vast majority of the polar vortices intensified over open water. By contrast, the polar lows characteristically met their demise upon making landfall; see Fig. 5. Polar lows

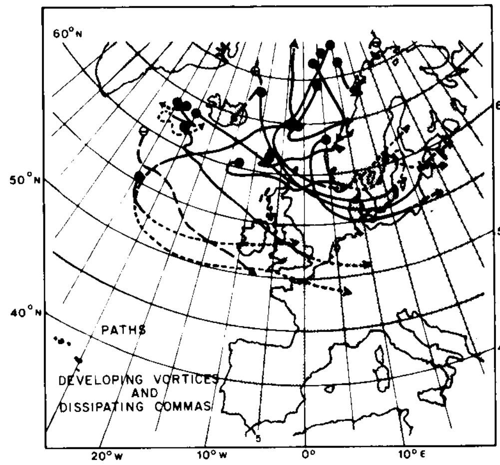

Fig. 5. Paths of the developing vortices (solid dots show locations of initiation) and dissipating commas (open circles reveal location of first detection). Previously-developing vortices have reached peak intensity and begun to dissipate where the paths become dashed.

appear able to survive the relatively-short trip across England, and showed some preference in this study for a path revolving around the large-scale trough from the North Sea into the Baltic Sea (which encountered Denmark and southern Sweden), but typically lost their cloud circulation and pressure deficit within 24 hours of moving completely and continuously over land. This is consistent with the observations of Økland (1977), and must surely argue that the oceans play a momentous (if not always necessary) role in the initiation and intensification of most polar vortices.

No systematic attempt was made to examine the vortex substructure, so it is not known what fraction of the Atlantic vortices in this study were accompanied by mesoscale fronts similar to those described by Locatelli et al. (1982). However, other studies of Atlantic polar lows (e.g. Harrold and Browning, 1969; Harley, 1960) have indicated that mesocale fronts sometimes exist.

Not surprisingly, the large-scale conditions accompanying the polar vortices in this paper are similar to those previously reported in the literature for polar lows in this geographic region. Mansfield (1974) considered only shallow disturbances (i.e., not accompanied by a discernible 500 mb trough) located entirely within the cold air mass. Nine of his 12 cases had surface wind speeds ≤ 5 m s^{-1}, and it was reported that development was rare on the east flank of cold-air outbreaks. His model further indicated that polar lows are expected to develop in regions where a shallow baroclinic zone coincides with weak surface winds flowing essentially perpendicularly to isotherms of sea-surface temperature.

Duncan (1978) presented evidence that polar lows can develop under synoptic-scale wind shear conditions that are quite different from those of typical mid-latitude cyclones. Instead of an environment where westerly winds increase with height ("normal" shear), polar lows sometimes develop under large-scale conditions of reversed vertical wind shear. In such a situation the thermal wind vector is oriented in a direction opposite to the wind at the steering level. That is, the low moves parallel to, but in a direction opposite from, the mid-tropospheric thermal wind.

An examination of the thermal wind vectors and vortex movement for the cases examined in this paper gave the interesting results of Table 12. More than two-thirds of the developing vortices and comma clouds in dissipating stages were accompanied by reversed shear, whereas two-thirds of the steady and insignificant vortices had normal shear. The angular separation was not typically 180°, however, and any value larger than 90° was considered reversed shear.

Polar lows were traditionally viewed as developing by process relating to sea-surface sensible and latent heating and convective heating (Meteorological Office, 1962). Økland (1977) and Rasmussen (1979, 1981) have advocated the CISK mechanism for development of Atlantic polar lows. Others (e.g. Harrold and Browning, 1969; Mansfield, 1974; Duncan, 1977, 1978; Reed, 1979; Blumen, 1980) have viewed polar low development as essentially baroclinic, with small scale attributed to small static stability. However, a study by Sardie and Warner (1983) indicates that a model incorporating both moist baroclinicity and CISK gives the best results for Atlantic polar lows, whereas moist baroclinicity alone is sufficient to explain development of Pacific polar lows. The observations in this paper, though perhaps not definitive regarding mechanisms, are consistent with the Sardie and Warner (1983) results. It is impressive that their model predicts the observed scale (wavelength) of the vortices.

Table 12. *Vertical wind shear and vortex nature*

Nature	Normal shear	Reversed shear
Developing	21%	79%
Steady	67%	33%
Insignificant	68%	32%
Dissipating comma	33%	67%

It is at this juncture, however, that we must return to the point made previously—that the absolute differences in values of parameters between developing and non-developing vortices in this study were not large. The differences were sufficiently small that models for predicting growth rates and preferred wavelengths (e.g. Sardie and Warner, 1983; Staley and Gall, 1977; Duncan, 1977) would give nearly the same preferred wavelengths and growth rates for the developing and non-developing vortices. The basic tendencies shown by these models—short-wavelength development favored by large low-level lapse rates, large low-level vertical wind shears, shallow disturbances, and weak upper-level wind shears (steady vortices may have had their development hampered by large vertical wind shears above 700 mb)—are in agreement with the polar vortex data presented in this study. However, the models would require far larger differences between the environments of vortices of different natures in order to predict such dramatic differences in vortex evolution. Thus, the different natures of these vortices are not apparently explained solely by differences in their environmental lapse rates and vertical wind shears, the parameters used in the models.

The maximum growth rates predicted by these models will be for cyclonic disturbances growing at the most favorable position slightly downwind of the pressure and thermal trough axes. The growth rates, however, are quite sensitive to both the phase separation of the thermal and height patterns and the position of the disturbance relative to these patterns (e.g., Sanders, 1971; Sanders and Gyakum, 1980; Carlson, 1982). Further, disturbances do not always occur at the location most favorable for development (e.g. Sanders and Gyakum, 1980). Hence, for identical values of lapse rate and wind shear, two vortices can have quite different growth characteristics depending upon their positions relative to the patterns of height and temperature in their large-scale environment.

6.2. *Hypotheses regarding vortex evolution*

It is hypothesized here, based upon the above discussion and consistent with the observations presented in Section 5, that a major difference between developing and non-developing vortices in this study was their location of occurrence relative to the height and thermal trough and ridge axes. This hypothesis is supported by the observations of negative advections of absolute and thermal vorticity accompanying non-developing vortices, whereas values were positive for developing vortices. The advections were rather weak on average, suggesting an average vortex position near the trough axes.

It is further hypothesized that the disturbances were initiated by diabatic heating associated with large air–sea temperature differences and convection embedded within layers of conditional instability at low levels. Both developing and non-developing vortices were initiated in this way, at an assortment of locations relative to the trough and ridge axes but at quite similar air temperatures. Once initiated, those vortices in favorable locations developed through moist baroclinicity and CISK, whereas development of vortices in unfavorable positions was suppressed by adverse absolute and thermal vorticity advections. Fig. 6 is a schematic diagram which illustrates the positions of the developing, steady, and significant vortices relative to the large-scale wave patterns.

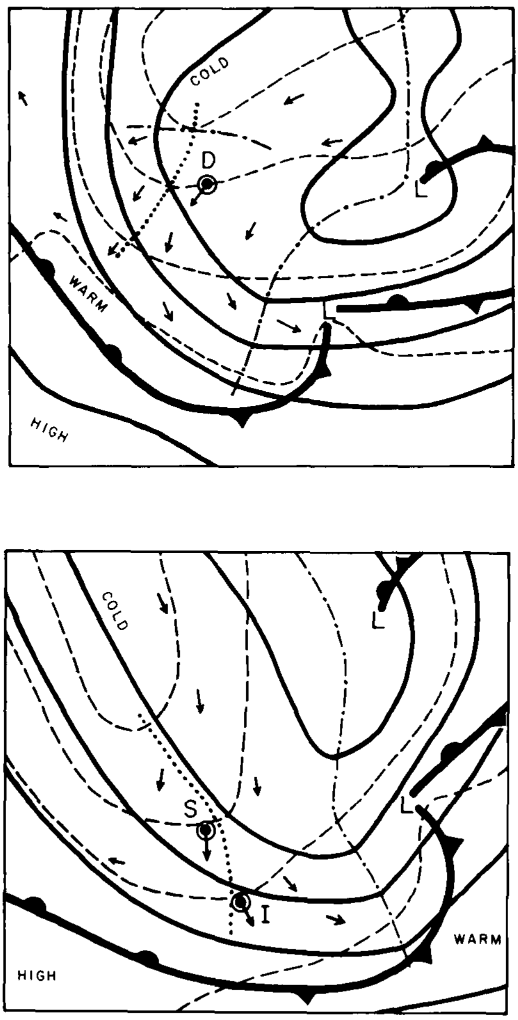

Fig. 6. Schematic diagram showing the mean position of the developing (D), steady (S), and insignificant (I) vortices relative to the large-scale environment. Contours of the 500 mb pressure surface are solid, 1000–500 mb thicknesses are dashed, and surface geostrophic winds are shown by vectors.

7. Summary

The observations presented in this paper have shown that satellite imagery can be used to identify and distinguish between existing polar lows and insignificant polar vortices, and to estimate their deficit pressures. The cloud configurations in early stages of the vortex lifetimes give some clues regarding which vortices will subsequently develop (see Table 7), but many forecast failures could be expected from such a practice.

There were differences in the environments of developing, steady, and insignificant vortices, though (1) the differences between the environments of vortices of different natures were not usually as large as the departure of the overall pattern from climatological normal, and (2) conditions were not as baroclinic as those associated with synoptic-scale cyclogenesis. It is hypothesized, therefore, that the occurrence of polar vortices entails two steps. First, cloud systems are initiated at a number of locations with similar air temperatures and lapse rates on days following the arrival of a cold air mass over the region. The development of an initial circulation (vorticity) is dominated by processes related to diabatic heating and CISK. In the second phase, however, baroclinic processes become quite important. It is during the early part of this phase that the different natures of the vortices arise, as vortices initiated at favorable locations (relative to the height and thermal trough and ridge patterns of the large-scale environment) develop through moist baroclinicity and CISK. Because of the comparatively weak baroclinicity, polar cyclogenesis in this sample did not proceed at the explosive rates often accompanying large-scale cyclogenesis over oceans when strong baroclinicity is present. By contrast, steady and insignificant vortices showed progressively less development during phase 2 because of near-zero or negative vorticity and thermal vorticity advections linked to their "abnormal" positioning relative to the large-scale pattern. It is expected that during latter parts of the second stage the internal details of the vortex circulation also become important in relation to continued development.

It is recognized that compositing techniques sometimes tend to obscure the details recognizable in a case study approach. Having now obtained a composite picture, case studies are planned. Nevertheless, it is felt that the composite observations presented here, though exhibiting considerable variance about means, portray a consistent and plausible conceptual model of polar vortex evolution. The conceptual model, and the hypotheses which comprise it, must be tested against other samples.

8. Acknowledgements

This research was begun while G. Forbes was a Visiting Scientist at the Royal Netherlands Meteorological Institute (KNMI), whose support is gratefully acknowledged. Satellite photos were provided by the KNMI, and the author benefited from discussions with their meteorologists. A special thanks is extended to Kees Lemcke of the KNMI for compiling a data tape of analyses which the European Centre for Medium Range Weather Forecasts graciously made available. Discussions with Erik Rasmussen, Joe Sardie, and Richard Reed better enabled the authors to draw contrasts between our cases, other polar lows, and synoptic-scale cyclones. Thanks are extended to Mike Fritsch, Nelson Seaman, Keith Browning, and Frank Hill for their useful comments and suggestions. Thanks are also extended to Delores Corman and Nancy Warner who typed the manuscript. The research was supported in part by the Air Force Geophysics Laboratory under Contract F19628-82-K-0023 and by the Office of Naval Research under Contract N00014-80-C-0954, Naval Environmental Prediction Research Facility, Monterey, CA.

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