Evolution of the Arctic polar vortex during 2004/05 and 2005/06 winter seasons based on the analyses of MetO assimilated fields

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Abstract

The atmospheric polar vortex is a dominant feature of the winter middle atmosphere. Knowledge of Arctic polar vortex structure and behavior will provide information on the background atmosphere for chemical and dynamical studies at PEARL (Eureka, 80°N). To characterize polar vortices the MetO (UK Met Office) assimilated fields have been subjected to the Q-diagnostic. As a part of the diagnostic, potential vorticity, (PV), stream function, relative vorticity and the rate of strain and rotation in wind field (Q) have been calculated at several isentropic surfaces (~20-50 km). Evolution of the Arctic polar vortex is demonstrated for two winter seasons: 2004/05, with only a few relatively weak stratospheric disturbances; and 2005/06, with a major sudden stratospheric warming at the end of January. In addition data from 12 meteor and MF radars have been used to compare dynamical processes at mesospheric heights with the polar vortex structure. It is shown that the arrangement of radar wind vectors is consistent with cyclonic motion around the pole and they match the MetO winds well at corresponding locations during "quiet" days; while on occasions during the stratospheric disturbances radar and MetO winds demonstrate opposite directions.

Methodology

The Q-diagnostic includes calculation of the scalar quantity Q, which is "a measure of the relative contribution of strain and rotation in the wind field" [*Harvey et al.,* 2002], streamfunction (ψ), relative vorticity (ζ), and integration of Q, ζ and winds along ψ isopleths. The following description of the Q-diagnostic is a summary based on *Fairlie* [1995], *Harvey et al.* [2002], and *Malvern* [1969].

The motion is generally the combination of solid rotation and a "pure strain". In tensor notation Q is defined as $2Q=\mathbf{D}{:}\mathbf{D}-\mathbf{W}{:}\mathbf{W}$, where $\mathbf{D}=1/2(\mathbf{L}+\mathbf{L}^t)$ is "the rate of deformation" tensor with components

$$\frac{1}{2}\left(\frac{\partial u_i}{\partial X_j}+\frac{\partial u_j}{\partial X_i}\right)$$

$\mathbf{W}=1/2(\mathbf{L}-\mathbf{L}^t)$ is "the solid body spin" tensor,

$$\frac{1}{2}\left(\frac{\partial u_i}{\partial X_j}-\frac{\partial u_j}{\partial X_i}\right)$$

t denotes a transposed tensor,
$\mathbf{L}=\mathbf{u}\nabla$ is the velocity gradient tensor (its transpose is the matrix of ∇ **u**), and
the operator '**:**' represents the general tensor scalar product ($\mathbf{A}{:}\mathbf{B}=\mathbf{A}_{ij}\mathbf{B}_{ij}$).
For two-dimensional flow *Q* is given by

$$Q=\frac{1}{2}D:D-\frac{1}{4}\varsigma^2$$

$$=\frac{1}{2a^2}\left\{\left(\frac{1}{\cos\varphi}\frac{\partial u}{\partial\lambda}-v\tan\varphi\right)^2+\left(\frac{\partial v}{\partial\varphi}\right)^2+2\frac{\partial u}{\partial\varphi}\left(\frac{1}{\cos\varphi}\frac{\partial u}{\partial\lambda}+u\tan\varphi\right)\right\}$$

where φ is latitude, λ is longitude, *u* is zonal wind, *v* is meridional wind, and *a* is the radius of the Earth. In areas where *Q* is positive the strain dominates and fluid elements are stretched, and in regions with negative *Q* rotation dominates the flow.

The Ertel's Potential Vorticity (EPV) on a constant surface (isentropic or isobaric) is approximated as

$$PV=-g(\varsigma_z+2\Omega Sin\varphi)\frac{\partial\theta}{\partial p}$$

where the expression in the brackets is the component of the absolute vorticity ($\bar{\omega}_a$) perpendicular to the constant surface, ζ_z is the vertical component of the relative vorticity, and φ is the latitude [*McIntyre and Palmer,* 1983]. For adiabatic (the material derivative of the potential temperature Dθ/Dt=0) and frictionless flow PV is invariable, i.e. D(PV)/Dt=0: therefore, for time scales up to a week or so, PV and θ can be assumed to be constant following the motion.

Fairlie, T. D. A. (1995), Three-dimensional transport simulations of the dispersal of volcanic aerosol from Mount Pinatubo, *Q. J. R. Meteor. Soc., 121*(528), 1943-1980.

Harvey, V. L., R. B. Pierce, T. D. Fairlie and M. H. Hitchman (2002), A climatology of stratospheric polar vortices and anticyclones, *J. Geophys. Res., 107*(D20), 4442-doi:10.1029/2001JD001471.

Malvern L. E. (1969), Introduction to the mechanics of a continuous medium, 713 pp., Prentice-Hall, Englewood Cliffs, NJ.

Data

To characterize the stratospheric dynamics, the MetO (from the United Kingdom Meteorological Office, also well-known as UKMO) temperatures and horizontal wind components are used. From October 2003 until middle of March 2006 daily temperatures, geopotential heights and wind components have been produced using the New Dynamics version of the stratospheric Unified Model at 25 standard UARS pressure levels from the surface up to 0.1 hPa (0-64 km):

p(i)=1000*10^{-i/6}, i=0, 1,…, 24.

The generated data fields have global coverage with 2.5° and 3.75° steps in latitude and longitude, respectively (72 by 96 grid size).

Starting March 2006 the datasets are outputs of the extended operational NWP (Numerical Weather Prediction) model. The "new" products have smaller grid size (640 by 480) with 0.5625° and 0.375° steps in latitude and longitude, respectively. Data are available at 27 pressure levels (different from UARS levels). For the purpose of this study only the new data at "old" grid points (72 by 96) have been used.

To study dynamics at mesospheric heights (60-100 km), the meridional (NS) and zonal (EW) components of the winds obtained by MFR (Medium Frequency Radar) and MWR (Meteor Wind Radar) were used. The daily mean wind data from selected heights were provided by 12 mid- and high-latitude stations. The coordinates of the stations, main parameters and references that contain more detailed description of these radars are given in the Table below.

Station	Longitude, deg. East	Latitude, deg. North	Radar type	Frequency, MHz	Heights, km	References
Collm	13	51.3	SKiYMET	32.6	82-97 (3)	*Jacobi et al.* [2005]
Andenes	16	69.3	MFR(ATRAD)	1.98	82-96 (2)	*Singer et al.* [1997]
Svalbard	16	78	VHF (ATRAD)	31	82-97 (3)	*Hall et al.* [2003]
Tromso	19.7	69.3	MFR	2.78	55-97 (3)	*Hall* [2001]
Esrange	20.4	67.9	SKiYMET	32.5	82-97 (3)	*Mitchell et al.* [2002]
Obninsk	36	52	MWR beam	33.3	~94	*Portnyagin et al.* [2006]
Wakkanai	142	45	MFR(ATRAD)	1.9585	60-96 (2)	*Murayama et al.* [2000]
Poker Flat	212.5	65.1	MFR(ATRAD)	2.43	60-96 (2)	
Yellowknife	245.5	62.5	SKiYMET	35.65	82-97 (3)	*Hocking* [2004]
Saskatoon	252	52	MFR	2.219	55-97 (3)	*Manson et al.* [1973]
Platteville	255	40	MFR	2.219	55-97 (3)	*Manson et al.* [2003]
Resolute Bay	265	74.5	SKiYMET	51.5	82-97 (3)	*Hocking* [2004]

Note on the "Old" and "New" MetO

Availability of both "old" (October 2003 – March 2006) and "new" (after March, 2006) MetO products over a few days in March allows their intercomparison. For example two longitudinal cross-sections (16°E and 253°E) of the zonal (EW) wind profiles (solid and dashed lines) and Q values (light and dark grey shadings) calculated using "old" (left) and "new" (right) data products are shown in Figure 1 for March 10, 2006. Although there are some differences in initial fields (such as zonal wind component) as well as in the Q-diagnostic and PV (not shown), the changes do not affect results and conclusions of the analyses such as used in this study.

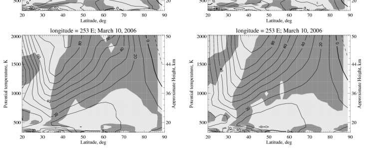
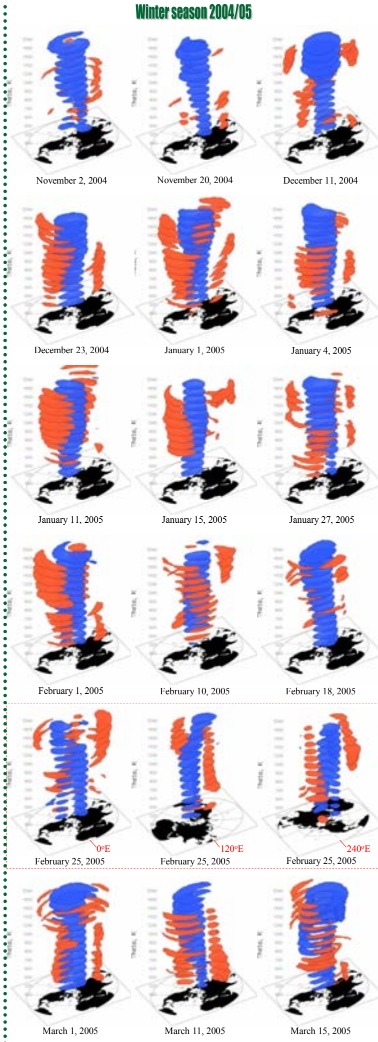


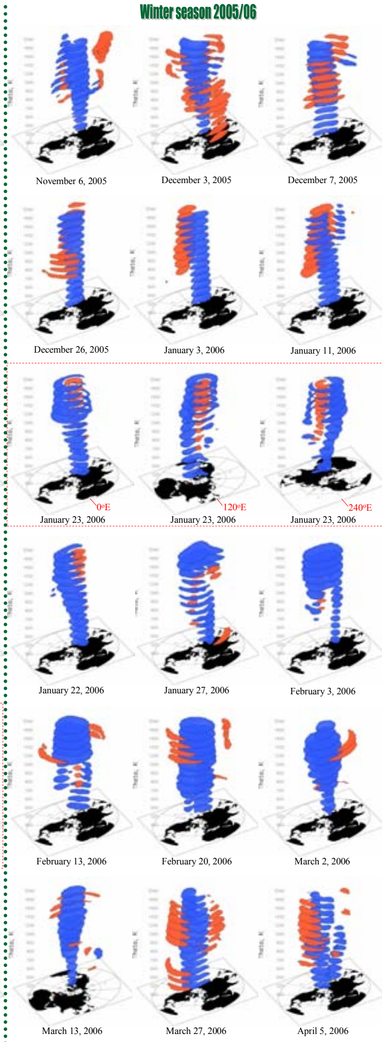
Figure 1: Latitude-altitude cross sections of the Q parameter (dark grey is negative, light grey is positive) at 16°E (top) and 253°E (bottom) longitudes on March 10th, 2006. The calculations using "old" and the "new" MetO data are shown on the left and right sides respectively. Solid and dashed lines are positive (eastward) and negative (westward) MetO zonal winds (m/s).

Winter season 2004/05



The Q values have been calculated from MetO data at 24 isentropic surfaces (from 300 to 2000 K) for each day of the winter of 2004/05 (November 1, 2004 - March 31, 2005). The identified edges of vortices have been used to color the cyclonic polar vortex with blue and anticyclones with orange; and then they are contoured as overlapping projections for isentropic surfaces from 500 to 2000 K (~20-50 km). The results are shown above for several days. The Arctic winter of 2004/05 was relatively cold, especially in the lower stratosphere. The vortex started to form in autumn, and by December it became strong. December 23, 2004 is a typical example of a cold vortex: the blue area has a cone-shape reflecting the increase of the vortex area with height. During most of the Arctic winter of 2004/05 the polar vortex exhibited similar characteristics except for three time intervals when it was disturbed: two short-lived and weak disturbances occurred around January 1 and February 1 of 2005. The vortex became elongated and twisted with height. The anticyclones then occupied larger areas. The strongest disturbance for this winter occurred at the end of February. For example the vortex structure for February 25: in the lower stratosphere the polar vortex splits into two parts, while at the upper levels the vortex is just strongly elongated and displaced from the pole. Again, the whole structure is elongated and rotated westward with height. The vortex began to re-form again in the beginning of March, but quickly became strongly distorted (e.g. March 15).

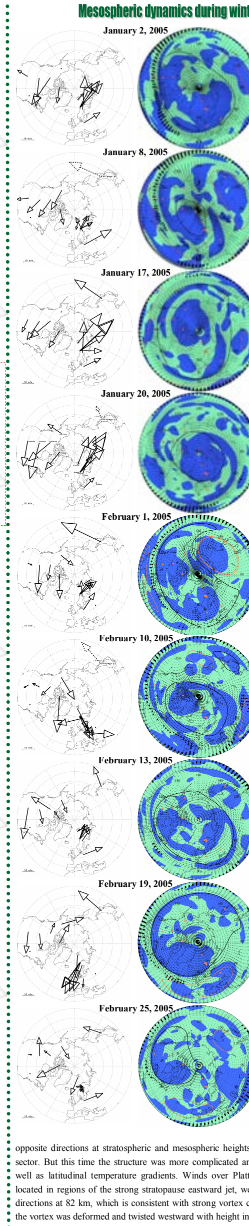
Winter season 2005/06



Similar analysis has been conducted for the Arctic winter of 2005/06. The results obtained show that during the NH winter season 2005/06 the polar vortex behaved differently compared to the previous winter. The vortex also started to form in autumn but had a relatively small area even at the beginning of December. Most of December it was shifted off-pole toward Eurasian continent by 2 anticyclones, which occupied areas over the Pacific at middle latitudes and the Atlantic at the tropics. The whole structure (cyclone and anticyclone) were tilted westward with height. Also, areas with negative potential vorticity were present at the upper levels, which could indicate the intrusion of the tropical air into the high latitudes. A Major Sudden Stratospheric Warming (SSW) occurred at the end of January of 2006 (e.g. see January 23): the anticyclonic air has been surrounded by a cyclonic ring. The vortex began to re-establish itself in February from the top down. However the latitudinal PV gradient was relatively weak (not shown). By the beginning of March the vortex area started to decrease at the top levels (see for ex. March 2). Although the vortex was disturbed (elongated, shifted off the pole, or/and "comma"-shaped) it had organized structure until April, which is significantly longer compared with the spring of 2005.

Note that there are three plots shown for three different position (rotated: 0°E, 120°E and 240°E) for each of February 25, 2005 and January 23, 2006.

Mesospheric dynamics during winter of 2004/05



The daily MetO winds at the 2000K (~ 50 km) isentropic surface (right column) along with the 3-day mean wind vectors at 82 km (left column) are shown for a sequence of days throughout January and February of 2005. The plots on the right are the stereographic projections (15-90°N) of the Q-diagnostic over the NH with the blue areas where Q is negative (rotation dominates the flow) and green areas where Q is positive (strain is dominant). Black arrows are winds, red stars are locations of the radar stations, and black/red lines are estimated edges of cyclones/anti-cyclones. Black filled dots are assigned to the areas with the negative PV. As can be seen in the figure, at the upper strato-spheric heights the vortex does not have "solid" or continuous shape as it usually has in the middle stratosphere. The NS wind component is often strong, and there is significant divergence from the cyclonic eastward flow. On the left column vectors of the radar mean wind at 82 km measured at 12 locations (the same loca-tions that are shown by red stars on the left column) are plotted on top of a stereogra-phic map (30-90°N). In January arrangement of radar wind vectors is consistent with cyclonic motion around the pole, and they match well the MetO winds at corresponding locations. Often, especially when negative areas of Q have consistent large circular shapes with little or no shear (green) zones inside (e.g. January 20), the stratospheric and meso-spheric vectors show very close similarity in their direc-tions. On February 1st, the time of the weak stratospheric disturbance, radar and MetO wind vectors over high-latitudinal stations (>60°N) demonstrate opposite direc-tions and have strong meri-dional components. This sug-gests an existence of a boundary between cold and warm regions across the pole, and strong poleward/equator-ward flows in the 30-60°E and 210-240°E longitudinal seg-ments, respectively. The winds were weak at North American stations (Platteville, Saskatoon, & Yellowknife) situated away from this region of strong temperature gradients. During the first half of February the stratospheric vortex became stronger. This is reflected in the plots for February 10 and 13: the stratospheric and meso-spheric winds are again similar in directions. On February 19 the warming has begun and as in February 1 wind vectors have opposite directions at stratospheric and mesospheric heights over the European-Scandinavian sector. But this time the structure was more complicated and involved strong longitudinal as well as latitudinal temperature gradients. Winds over Platteville, Saskatoon and Wakkanai, located in regions of the strong stratopause eastward jet, were not affected and had eastward directions at 82 km, which is consistent with strong vortex conditions. Finally by February 25 the vortex was deformed and twisted westward with height in the upper stratosphere, so that the stronger cyclonic area was located over North America. At mesospheric heights winds were also weak and completely disorganized. Later in March the cyclonic flow was partially re-stored at 50 and 82 km, before it disappeared during the transition to the summer circulation.

Data comparison

Meridional (left) and zonal components (right) of the MetO (bottom panels) and MFR (top panels) horizontal winds are shown in Figure 2. There is very good general agreement for the transition heights between the two data sets: the winds are westward in summer and eastward in winter with clear equinox transitions. Strong dynamical events, such as those associated with stratospheric warmings, are also evident in both data sets: during the "stratwarm" that occurred from the end of January to the beginning of February 2000 ("stratalert" information at ftp://strat50.met.fu-berlin.de/pub/stratalert/ 1999_2000) both MetO and MFR data sets show a reversal in the zonal and meridional winds. On the other hand, the speeds near 55 km from MetO and MFR did not initially agree well. The speeds measured by MF radars are thought to be systematically low by factors of up to 1.5. To account for possible bias, the MFR winds for this figure have been multiplied by a 1.5 factor before plotting. With this adjustment, the speeds recorded by the two systems are quite similar.

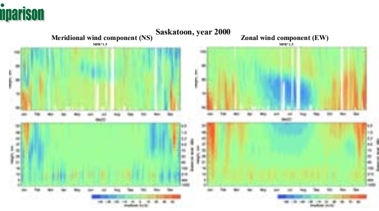


Figure 2: The contour plots of meridional (NS) and zonal (EW) wind components from MetO (the bottom panel, 0-55 km) and MF radar (the top panel, 58-103 km) for Saskatoon during 2000.

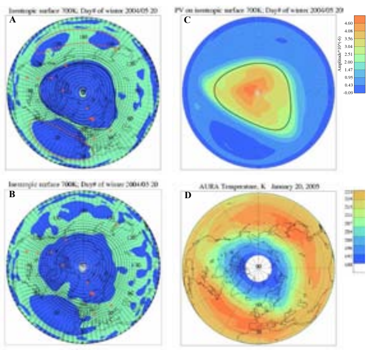


Figure 3: The Q-diagnostics calculated using MetO (A) and NCEP (B) datasets, Potential Vorticity distribution (C) for the isentropic surface 700 K (~27 km), and temperatures measured by Aura satellite (D) at 21hPa over the Northern Hemisphere on January 20, 2005. Also on the Q-plot, the stratospheric winds are shown by black arrows; red stars indicate the locations of mesospheric radars for which data are available; and thick black and red contour lines indicate the edges of the polar vortex (cyclones) and anticyclones, respectively.

Figure 3 demonstrates good agreements between Q-diagnostic calculated from MetO (A) and NCEP (B) datasets; between Q-diagnostic and PV calculations (C); and between Q-diagnostic calculated from MetO data and temperature observations obtained by Aura, MLS (D). All plots are shown over the Northern Hemisphere for January 20, 2005. The Q-diagnostic and PV plots are demonstrated at the same isentropic surface (700 K), while Aura temperatures are given at 21 hPa pressure level.

- The comparison of plots A (calculated from MetO) and B (from NCEP) of Figure 2 demonstrates very good agreement between results (vortex location and shape) obtained using two different sources of assimilated temperature and wind fields. The differences can be partly explained by spatial longitude resolution: the Q contours calculated from the more "coarse" (2.5°×3.175°) MetO data look smooth, while Q areas obtained from NCEP data (2.5°×2.5°) show more detail.
- There is also good agreement between PV (plot C) and Q contours (plots A&B). The vortex edge estimated from the Q-diagnostic (black line) corresponds well to the region where the meridional gradient of PV increases, while edges of anticyclones (red contour on plot A) are located in areas of low PV.
- The Aura temperature field is shown on plot D. It can be seen that the distribution of the cold and warm areas is very similar to the locations of cyclones and anticyclones. In particular, the identified polar vortex (black thick contour) resembles the shape of the cold polar region (blue shadings of the bottom plot) very well.

Summary

The evolution of the polar vortex during the Arctic winter seasons 2004/05 and 2005/06 has been studied using MetO assimilated fields and data from meteor and MF and MW radars at 12 mid- and high-latitude locations.

- Assimilated global data products, such as MetO, are very valuable for studies of the global atmospheric dynamics.
- The Q-diagnostic was used to characterize the dynamics of the middle and upper stratosphere. The winter of 2004/05 was shown to be relatively cold with a few weak disturbances at low stratospheric levels and no major mid-winter stratospheric warmings (SSW). In contrast, during the winter of 2005/06 the polar vortex exhibited strong variability throughout the season and SSW occurred in late January. Therefore the winters considered here are examples of two different Arctic regimes.
- The Q-diagnostic is a beneficial technique to investigate the longitudinal as well as latitudinal differences in observed atmospheric parameters.
- An attempt to compare winds from the upper stratospheric (~50-60 km) heights with those from the mesospheric heights (82 km) was made with the emphases on the vortex structure. The results show that the winds can have similar as well as completely opposite behavior throughout the stratosphere and mesosphere depending on the time and position of the radar station relative to the vortex edge. The comparison is difficult mostly due to the lack of mesospheric observations. An extension of the existing models with data assimilation to the mesospheric heights will be very desirable for investigations of stratospheric-mesospheric coupling processes.
- Additional data from a MWR, which was installed at PEARL (Eureka, 80°N) and produces data starting mid-February 2006, is a valuable addition to a similar study (in progress) for winter season 2006/07.

Acknowledgement

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