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Report

Report on the method for determining the location of the polar vortex boundary region

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Abstract: To determine the boundary region of the polar vortex objectively using the PV distribution on isentropic surfaces, the equivalent latitude (Eql) of the polar vortex boundary was calculated using a slightly modified form of the technique of E.R. Nash *et al.* (J. Geophys. Res., **101D**, 9471, 1996). Using the NCEP/NCAR reanalysis data, the Eql of the polar vortex boundary region in the winter of 1999/2000 was calculated, and compared with the ozone mixing ratio in the lower stratosphere over Eureka observatory (80°N, 86°W). The results indicate that this method determines the boundary region of the polar vortex well.

key words: polar vortex, equivalent latitude, ozone, boundary region

1. Introduction

The boundary region of the polar vortex is the region where the potential vorticity (PV) rises steeply from mid-latitude to the polar region. It is marked by strong circumpolar winds, and is a barrier for material transport. To study the stratospheric ozone loss over the polar region, for example, measured ozone profiles need to be classified according to their position relative to the polar vortex boundary (*e.g.,* Kreher *et al.,* 1999). Nash *et al.* (1996) defined the boundary region of the polar vortex as the location of the large gradient of PV, and suggested an objective technique for determining the polar vortex boundary and its width using the distributions of PV on isentropic surfaces. The advantage of this technique is that it can provide the polar vortex boundary region with finite width. For that purpose, the equivalent latitude (Eql) is calculated from the PV distribution over the hemispheric scale. The PV increases monotonically with increasing Eql, and steeply increases at the boundary region of the polar vortex.

In this report, to improve the temporal continuity and extent of the boundary region, the technique of Nash *et al.* (1996) is slightly modified, and to ascertain the adequacy of the technique, the Eql of the Arctic polar vortex boundary region in the lower stratosphere in the winter of 1999/2000 is compared with the ozone mixing ratio over Eureka observatory (80°N, 86°W) (Hirota *et al.,* 2003). The calculation is based on Ninomiya *et al.* (1998) and the NCEP/NCAR reanalysis data (Kalnay *et al.,* 1996) was used as the objective analysis data.

2. Calculation of the Eql of the Arctic polar vortex boundary region

The Eql of the Arctic polar vortex boundary region is calculated as follows:

1) Using the objective analysis data, the PV ($1\,\mathrm{PVU}=10^{-6}\,\mathrm{m^2\,kg^{-1}\,s^{-1}\,K}$) on the 475 K isentrope is calculated. The objective analysis data are on a 2.5° longitude–latitude grid (144×73).

2) With a trapezoidal approximation, the area from the pole to each latitude is calculated. At the pole, a triangle of 88.75°–90° is assumed.

3) Calculation of the Eql:

PV values are contoured on an equivalent area map projection. The areas enclosed by isolines are calculated. Expressed as a fraction of the total hemispheric surface area, these areas are rearranged on the hemisphere. The transformed PV isolines are symmetrical around the pole. The latitude on this transformed map projection is referred to as the Eql. Actually the Eql was calculated at every 1 PVU.

4) Mean wind speed along the PV isolines:

For a given PV value, some grid points, which have larger or smaller PV values, are selected. From these points around the PV value, two points which have the smallest PV gradient are found. From the data at these two points, u and v are calculated on a proportional allotment, and the wind velocity $U=(\sqrt{(u^2+v^2)})$ for a certain PV value is calculated. Then the mean wind velocity along an Eql is obtained.

5) The edge of the polar vortex:

The vortex edge is defined as the location of the maximum gradient of PV constrained by the location of the maximum wind jet calculated along PV isolines, i.e., the PV gradient multiplied by the mean wind speed along PV isolines. A sloping filter that ranges between 1 at 80° and 0 at 90° Eql is applied after Nash *et al.* (1996).

6) The boundary region of the polar vortex:

The vortex boundary region is defined between the local maximum convex and concave curvature in the PV distribution surrounding the vortex edge (confined in the range between ±15° in Eql). In case where the vortex is greatly distorted from a circle, multiple peaks often appear in the plot of the PV gradient multiplied by the mean wind speed along a PV isoline with respect to the Eql (Ninomiya *et al.,* 1998). To reduce the appearance of multiple peaks, the Eql was smoothed by averaging PV in the range of ±3 PVU. Then, the maximum value of the second derivative of the PV is found outside the polar vortex edge. Furthermore, to suppress the effect of multiple peaks, the Eql at the outermost value equal to the maximum value×0.7 is defined as the outer edge of the boundary region. The minimum value of the second derivative of the PV is also found inside the polar vortex edge. The Eql at the innermost value equal to the minimum value×0.7 is defined as the inner edge of the boundary region. The coefficient 0.7 was chosen so that the outer edge of the boundary region would not extend extraordinary toward the lower Eql. Around 0.8 to 0.7, the variation of Eql for the outer edge is rather small, and 0.7 was adopted. In addition, the boundary region is constrained between 40° and 80° in Eql.

From the PV at Eureka, its Eql is obtained.

3. Results of the Eql calculation

In many cases, there were multiple peaks in the plot of PV gradient multiplied by the mean wind speed along a PV isoline. As an example, plots of PV, PV gradient multiplied by the mean wind speed along PV isoline and the second derivative of PV on January 1, 2000 are shown in Fig. 1a and 1b. The Eql at both edges of the polar vortex boundary and Eureka from the middle of December 1999 to the end of March 2000 are shown in Fig. 2a. The open and solid circles show the daily inner and outer edges of the boundary region, respectively. The solid and dashed thick lines are 5-day running means of the daily inner and outer edges, respectively. Open triangles show the Eql of Eureka. Figure 2b shows those when the Eql at the maximum and minimum values of the second derivative of PV are used to determine both edges of the boundary region.

In this winter, the polar vortex was not developed until early December, but became clearly defined by the end of December (Manney and Sabutis, 2000). The vortex was split into two sub-vortexes in the middle of March with one substantial remnant present well into April (Harris *et al.,* 2001). In accordance with this, the vortex area was rapidly decreasing in March. Figure 2a indicates that the unusual narrow boundary regions are not seen around February 20, and in the middle and the end of March. The mean width of the boundary region from the middle of December to the end of March was 6.2° in Eql. In the case of Fig. 2b, it was 4.3°. Without smoothing the Eql in the

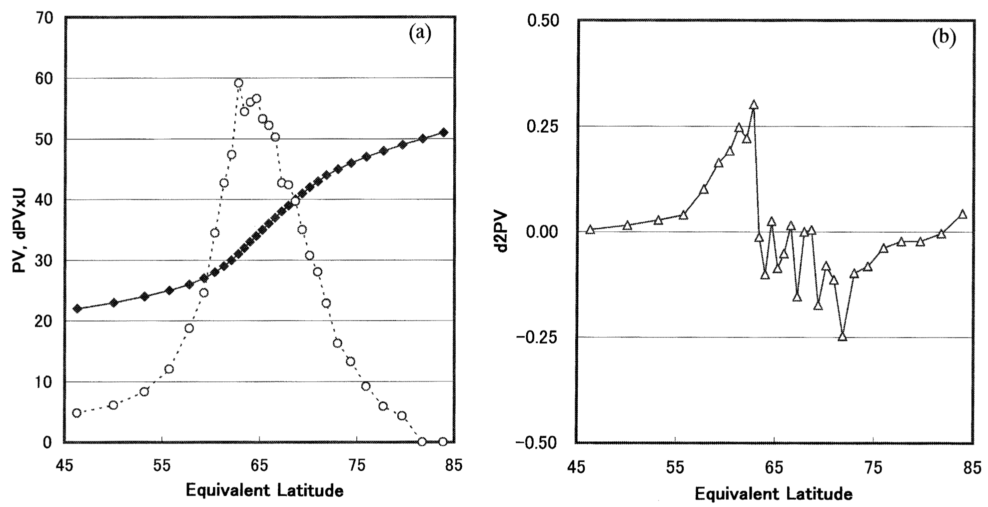

Fig. 1. (a) Potential vorticity (PV), PV gradient multiplied by the mean wind speed along PV isolines (dPV×U) and (b) second derivative of PV (d^2PV) with respect to the equivalent latitude (Eql) in the Northern Hemisphere on January 1, 2000. NCEP/NCAR reanalysis data were used. PV (◆) : $\times 10^{-6}$ m^2 kg^{-1} s^{-1} K. dPV×U (○) : $\times 10^{-6}$ m^2 kg^{-1} s^{-1} K deg^{-1}. d^2PV (△) : $\times 10^{-6}$ m^2 kg^{-1} s^{-1} K deg^{-2}.

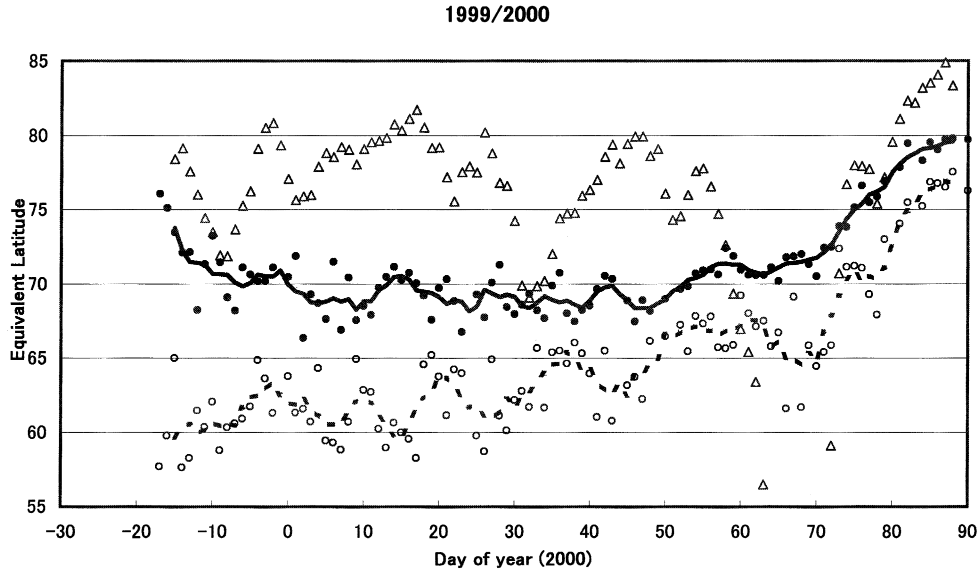

Fig. 2a. *Equivalent latitude of the polar vortex boundary region on the 475 K isentrope in the Northern Hemisphere in 1999/2000.*
The solid and open circles show the daily inner and outer edges of the boundary region, respectively. The solid and dashed thick lines show 5-day running means of the daily inner and outer edges, respectively. Open triangles show Eureka station (5-day running mean).

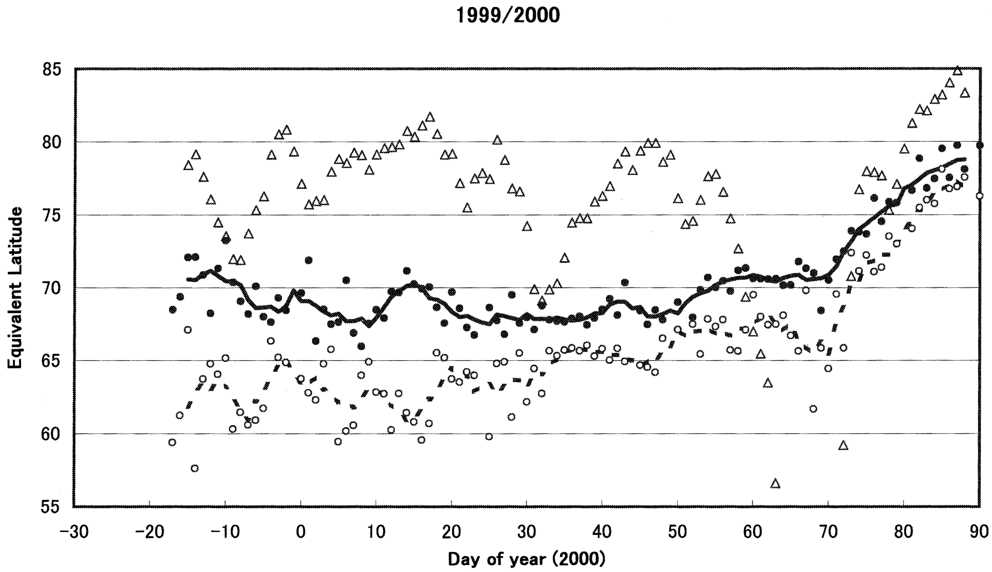

Fig. 2b. *Equivalent latitude of the polar vortex boundary region on the 475 K isentrope in the Northern Hemisphere in 1999/2000.*
The Eql at the maximum and minimum values of the second derivative of PV is used to determine both edges of the boundary region. The same symbols as in Fig. 2a are used.

case of Fig. 2a, it was 4.1°. This is because, without the coefficient less than 1.0 or without smoothing the Eql, both edges of the boundary region are calculated closer to the center due to the large effect of multiple peaks near the center of the polar vortex boundary region.

4. Comparison with the ozonesonde data

In order to check the adequacy of the method, the Eql of the polar vortex boundary region was compared with the ozone mixing ratio in the lower stratosphere over Eureka in the winter of 1999/2000.

Judging from Fig. 2a, Eureka was inside the polar vortex in the lower stratosphere (on the 475 K isentrope) from the middle of December to the end of March except on December 21 and 22, between February 28 and March 14 and on March 19. Figure 3 shows the ozone volume mixing ratio on the 475 K isentrope over Eureka in the same period as shown in Fig. 2a. From late December to the end of January, the ozone mixing ratio was almost constant. This is because the ozone mixing ratio was almost the same inside and outside the vortex without the ozone destruction in the early stage of vortex formation (December 21 and 22). From early February to the end of March, the ozone mixing ratio inside the polar vortex decreased from 3.2 ppmv to 1.0 ppmv. Inside the polar vortex, significant chemical ozone loss did occur in the lower stratosphere over Eureka from early February to the end of March, following the diabatic descent (Hirota *et al.,* 2003). The time evolution of the ozone mixing ratio shown in Fig. 3 would reflect this ozone loss process. However, between February 26 and

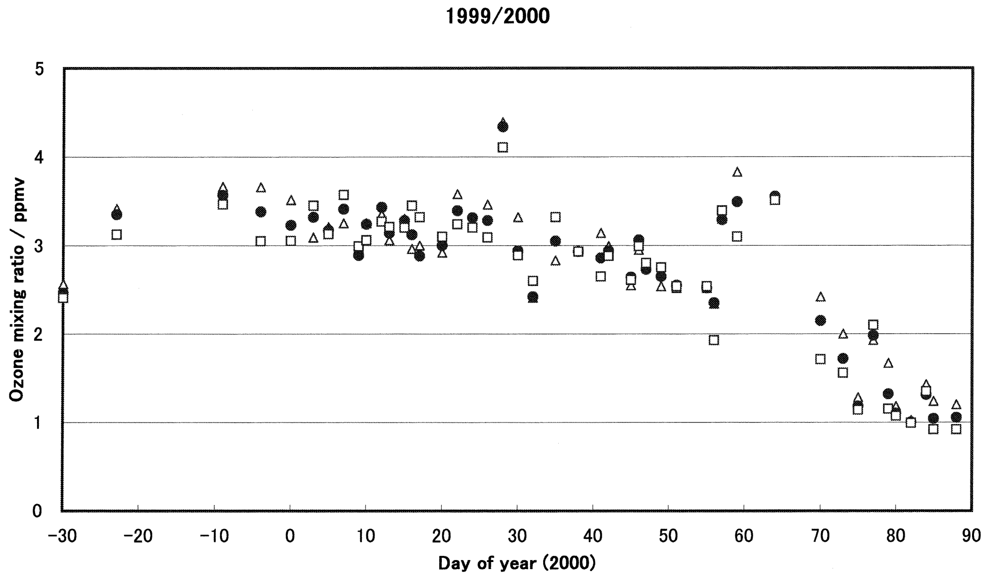

Fig. 3. Ozone volume mixing ratios in the lower stratosphere over Eureka in 1999/2000. Solid circles, open triangles and open squares show mixing ratios on 475 K, 480 K and 470 K isentropes, respectively.

March 11 and on March 18, ozone mixing ratios were rather high. In comparison with the results shown in Fig. 2a, high ozone mixing ratios are due to the presence of air masses in the boundary region of and outside the polar vortex, in which severe ozone loss did not occur. These results indicate that the method of Eql well determines the boundary region of the polar vortex. The movement of the polar vortex boundary in the lower stratosphere over Eureka, however, was not exactly in agreement with the variation of ozone mixing ratio. There was a time lag of one or two days between variation in ozone mixing ratio and the position relative to the polar vortex boundary (February 26 and March 18). On January 28, the ozone mixing ratio was also high. Figure 2a shows that the lower stratosphere over Eureka was inside the polar vortex on that day. Though the temperature on the 475 K isetrope was less than -80°C during December 30 and January 26, it rose by 6 degrees from January 26 to 28. The high ozone mixing ratio on January 28 would not have been caused by the movement of the polar vortex boundary in the lower stratosphere over Eureka.

5. Summary

To determine the boundary region of the polar vortex objectively using the PV distribution on isentropic surfaces, the equivalent latitude (Eql) of the polar vortex boundary was calculated using a slightly modified form of the technique of Nash *et al.* (1996). Using the NCEP/NCAR reanalysis data, the Eql at both edges of the polar vortex boundary in the winter of 1999/2000 was calculated. In cases where the vortex is greatly distorted from a circle, multiple peaks often appear in the plot of PV gradient multiplied by the mean wind speed along a PV isoline with respect to the Eql. To suppress the effect of multiple peaks, the Eql was smoothed by averaging PV in the range of ± 3 PVU. Furthermore, the Eql at the outermost value equal to $0.7\times$the maximum value of the second derivative of the PV is defined as the outer edge of the boundary region. Similarly, the Eql at the innermost value equal to $0.7\times$the minimum value is defined as the inner edge of the boundary region.

The results were compared with the ozone mixing ratio in the lower stratosphere over Eureka observatory (80°N, 86°W). Inside the polar vortex, due to the significant chemical ozone loss in the lower stratosphere over Eureka, ozone decreased from early February to the end of March. However, on a few days in the same period, ozone mixing ratios were rather high. The position of Eureka relative to the polar vortex boundary suggests that high ozone mixing ratios result from the air masses in the boundary region of and outside the polar vortex, in which severe ozone loss did not occur. The results indicate that this method determines the boundary region of the polar vortex well.

References

Harris, N.R.P., Guirlet, M., Newman, P.A. and Adriani, A. (2001): SOLVE-THESEO 2000 science meeting. SPARC Newsletter, **16**, 27–29.

Hirota, M., Miyagawa, K., Yoshimatsu, K., Shibata, K., Nagai, T., Fujimoto, T., Makino, Y., Uchino, O., Akagi, K. and Fast, H. (2003): Stratospheric ozone loss over Eureka in 1999/2000 observed with

ECC ozonesondes. J. Meteorol. Soc. Jpn., **81**, 295–304.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woolen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K.C., Ropelewski, C., Wang, J., Leetmaa, A., Reynolds, R., Jenne, R. and Joseph, D. (1996): The NCEP/NCAR 40-year reanalysis project. Bull. Am. Meteorol. Soc., **77**, 437–471.

Kreher, K., Bodeker, G.E., Kanzawa, H., Nakane, H. and Sasano, Y. (1999): Ozone and temperature profiles measured above Kiruna inside, at the edge of, and outside the Arctic polar vortex in February and March 1997. Geophys. Res. Lett., **26**, 715–718.

Manney, G.L. and Sabutis, J.L. (2000): Development of the polar vortex in the 1999–2000 Arctic winter stratosphere. Geophys. Res. Lett., **27**, 2589–2592.

Nash, E.R., Newman, P.A., Rosenfield, J.E. and Schoeberl, M.R. (1996): An objective determination of the polar vortex using Ertel's potential vorticity. J. Geophys. Res., **101D**, 9471–9478.

Ninomiya, M., Nakane, H., Sasano, Y., Kurnosenko, S. and Bodeker, G. (1998): Improvement of the method for determining the location of the polar vortex boundary region. Abstracts for Spring Conf. of the Meteorol. Soc. Jpn., 127 (in Japanese).