Polar Vortex Oscillation Viewed in an Isentropic Potential Vorticity Coordinate

REN Rongcai\(^1\) and Ming Cai\(^2\)

\(^{1}\)State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG), Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029
\(^{2}\)Department of Meteorology, Florida State University, Tallahassee, Florida 32306, USA

(Received 16 January 2006; revised 14 August 2006)

ABSTRACT

The stratospheric polar vortex oscillation (PVO) in the Northern Hemisphere is examined in a semi-Lagrangian \(\theta\)-PVLAT coordinate constructed by using daily isentropic potential vorticity maps derived from NCEP/NCAR reanalysis II dataset covering the period from 1979 to 2003. In the semi-Lagrangian \(\theta\)-PVLAT coordinate, the variability of the polar vortex is solely attributed to its intensity change because the changes in its location and shape would be naturally absent by following potential vorticity contours on isentropic surfaces. The EOF and regression analyses indicate that the PVO can be described by a pair of poleward and downward propagating modes. These two modes together account for about 82% variance of the daily potential vorticity anomalies over the entire Northern Hemisphere. The power spectral analysis reveals a dominant time scale of about 107 days in the time series of these two modes, representing a complete PVO cycle accompanied with poleward propagating heating anomalies of both positive and negative signs from the equator to the pole. The strong polar vortex corresponds to the arrival of cold anomalies over the pole and vice versa. Accompanied with the poleward propagation is a simultaneous downward propagation. The downward propagation time scale is about 20 days in high and low latitudes and about 30 days in mid-latitudes. The zonal wind anomalies lag the poleward and downward propagating temperature anomalies of the opposite sign by 10 days in low and high latitudes and by 20 days in mid-latitudes. The time series of the leading EOF modes also exhibit dominant time scales of 8, 7, 16, 9, and 33.8 months. They approximately follow a double-periodicity sequence and correspond to the 3-peak extratropical Quasi-Biennial Oscillation (QBO) signal.

Key words: polar vortex oscillation, semi-Lagrangian \(\theta\)-PVLAT coordinate, poleward and downward propagation

doi: 10.1007/s00376-006-0884-6

1. Introduction

The wintertime stratospheric circulation is dominated by the cyclonic vortex centered over the polar area. It has been recognized that the annular mode, the leading climate variability pattern of large-scale circulation anomalies, is intimately related to the oscillation between a weak and strong stratospheric polar vortex (Baldwin and Dunkerton, 1999; Waugh and Randal, 1999; Thompson et al., 2002; Limasawan et al., 2004). In general, a quasi-annular circulation is associated with a strong polar vortex. However, a strongly zonally asymmetric circulation may not necessarily always correspond to a weak polar vortex. For example, a strongly zonally asymmetric circulation can be associated with a strong polar vortex that is not centered over the polar area. Therefore, the regular zonal average along latitude circles may not be able to reflect the intensity of the polar vortex in all cases. To faithfully capture the intensity variability of the polar vortex, one has to do the averaging in a Lagrangian coordinate.

Isentropic potential vorticity (\(\Omega\)) can be approximately regarded as material lines because it can be altered only by irreversible mixing and diabatic/frictional processes (Hoekins et al., 1985; Haynes and McIntyre, 1987). Many weather phenomena, such as cyclones, cut-off lows, blocking highs, and jet streams can be vividly identified on daily isentropic \(\Omega\).
maps (Hoskins et al., 1985). The zone of the strongest $\Omega$ gradient outlines the location of the westerly jet surrounding the polar vortex. Many basic features such as the intensity, geographical location, geometric shape, and size of the polar vortex can be simultaneously tracked using a few key $\Omega$ contours (Baldwin and Holton, 1988; Waugh and Randel, 1999).

Recently, Cai and Ren (2006a, b') examined the climate variability of atmospheric anomalies in a semi-Lagrangian coordinate constructed using constant isentropic ($\theta$) and potential vorticity ($\Omega$) surfaces. Instead of just following a few key isentropic $\Omega$ contours to outline the polar vortex itself as in Baldwin and Holton (1988) and Waugh and Randel (1999), they constructed the semi-Lagrangian coordinate system by converting the area of the spherical cap encircled by each $\Omega$ contour on an isentropic $\Omega$ map to its equivalent latitude referred to as the PVLAT. Unlike the regular Eulerian longitude-latitude coordinate system, the semi-Lagrangian “longitude-PVLAT” coordinate system itself evolves in time because it follows the $\Omega$ contours. The 2-D flow in the $\theta$-PVLAT coordinate (PVLAT as the meridional axis and $\theta$ the vertical axis) is obtained by averaging the original 2-D field along PVLAT (or $\Omega$ contours), rather than along latitude circles. Because of the conservation property of the potential temperature and potential vorticity, the grids in the $\theta$-PVLAT coordinate can be regarded as natural boundaries separating air masses of different properties. The “zonal mean” along the PVLAT is very close to a “Lagrangian averaging”, capturing both the thermodynamic and dynamic properties of the same air mass more accurately compared to the conventional zonal mean along the geographical latitudes.

In this paper, we wish to examine the climate variability of the polar vortex in such a semi-Lagrangian coordinate system that constantly evolves with time. Because the variability of the polar vortex in the semi-Lagrangian $\theta$-PVLAT coordinate can be solely attributed to its intensity variability, we are able to isolate the most fundamental underlying dynamic/thermodynamical processes associated with the Polar Vortex Oscillation (PVO).

The paper is organized as follows. The next section describes the data used in this study and concepts of PVLAT coordinate. Reported in section 3 are the characteristics of the PVO index derived from the Empirical Orthogonal Function (EOF) analysis of $\Omega$ anomalies in the $\theta$-PVLAT coordinate. Section 4 discusses the temporal evolution of the PVO index and its association with a systematic simultaneous poleward and downward propagation of circulation anomalies of both signs from the tropics to the pole and from the stratosphere to the troposphere. We will also show that in the regular latitude coordinate, the poleward propagation signal is diluted, appearing more like a quasi-stationary seesaw oscillation between the subtropics and extratropics because the averaging is not along the material coordinate. Section 5 discusses the interannual variability of the poleward and downward propagation associated with the PVO. The summary and discussion are given in section 6. The Appendix documents the algorithm for constructing the semi-Lagrangian coordinate from daily isentropic $\Omega$ maps.

2. Data and the $\theta$-PVLAT coordinate

The data used in this study are derived from the daily isentropic analysis (00Z) of the NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research) reanalysis II dataset from 1 January 1979 to 31 December 2003 (Kalnay et al., 1996). The isentropic analysis includes the zonal and meridional winds, potential vorticity, temperature, Montgomery potential, relative humidity, and Brunt-Väisälä frequency square. There are 11 isentropic surfaces (the standard NCEP/NCAR reanalysis isentropic levels: $\theta$=270, 250, 200, 300, 315, 330, 350, 400, 450, 500, and 650 K), extending from the lower stratosphere to the mid-stratosphere approximately around 20 hPa. On each of the isentropic surfaces, the data are defined on $144 \times 73$ grids (or $2.5^\circ \times 2.5^\circ$ resolution) covering the entire spherical surface from the South Pole to the North Pole.

Daily isentropic $\Omega$ fields are used to construct the semi-Lagrangian $\theta$-PVLAT coordinate with $\theta$ representing the vertically increasing constant potential temperature surfaces and “PVLAT”—the “meridional coordinate”—representing northward increasing $\Omega$ by assigning individual $\Omega$ contours on an isentropic surface to a latitude value that the area of the spherical cap encircled by the $\Omega$ contour is identical to that encircled by the latitude circle (Norton, 1994). Readers may refer to the Appendix for the details of the algorithm used to convert $\Omega$ contours to PVLAT in this paper.

Using the algorithm outlined in the Appendix, we have created maps of PVLAT from IPV maps on daily basis. Figure 1 shows an example of such a mapping from $\Omega$ contours (contours) to PVLAT (shadings),