New definition of stratospheric warming events in the Northern Hemisphere based on geometry of the polar vortex

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It is known that a few kinds of warming events occur in the Northern Hemisphere (NH) winter polar stratosphere. (Labitzke 1982). In early winter, the polar vortex often displaces substantially from the Pole mainly in the middle and lower stratosphere, which is called Canadian warming (CW; Manney et al. 2001) in the NH. In the middle of winter, polar stratospheric temperature sometimes increases rapidly, accompanied by collapse of the polar vortex. Such an event is called stratospheric sudden warming (SSW; Scherhag 1952). In the end of winter, a relatively sudden warming called stratospheric final warming (SFW; Black et al. 2006) occurs every year, followed by the summer state of the polar stratosphere. Traditionally, zonal mean zonal wind is used to define SSWs (Butler et al. 2015) and SFWs (Black et al. 2006). Although their definition is simple and easy to deal with, CWs, SSWs, and SFWs may be confused. Moreover, the polar vortex has notable horizontal structure during SSWs and SFWs, which cannot be captured by the definition based on zonal mean quantities. Mitchell et al. (2013) and Seviour et al. (2013) proposed new definition of SSWs based on moment diagnostics, where the polar vortex is approximated as an equivalent ellipse (Hu 1962; Waugh 1997). The moment diagnostics allow them to define displacement and splitting SSWs separately by using centroid latitude and aspect ratio of the polar vortex. However, SSWs in their definition may include CWs and SFWs. Note also that there is almost no clear definition for CWs.
In our study, CWs, SSWs, and SFWs are defined by applying moment diagnostics to geopotential height field at 3, 10, and 30 hPa in the polar region. The three kinds of warming events are clearly distinguished in our definition.
First, displacement, splitting, and disappearance events are defined at each altitude. To detect displacement events, centroid latitude is used as in the previous studies. Displacement events are categorized into major and minor ones according to how far the polar vortex displaces from the Pole. Splitting events are defined using kurtosis, which is measure of bipolarity (Mattewman et al. 2009). If geopotential height at all the lattice points in the polar region is larger than background value in the moment diagnostics, the events are defined as disappearance events.
Next, CWs, SSWs, and SFWs are defined based on the events identified above. Displacement-SFWs (D-SFWs) and splitting-SFWs (S-SFWs) are first defined if displacement and splitting events are followed by disappearance events, respectively. SSWs and CWs are then distinguished according to at which altitude the polar vortex is more perturbed. If the polar vortex displaces further from the Pole in the lower stratosphere than in the upper stratosphere, the events are defined as D-CWs. Otherwise, the events are defined as D-SSWs. If splitting events occur only in the lower stratosphere, the events are defined as S-CWs. Other splitting events are defined as S-SSWs.
We performed composite analysis in each category of each warming phenomenon. It is shown that the definition based on geometry of the polar vortex is consistent with a dynamical aspect of each warming phenomenon. We will investigate longitudinal structures of the polar vortex and material circulation during CWs, SSWs, and SFWs, using formulae of three-dimensional residual mean flows applicable to both Rossby waves and gravity waves derived by Kinoshita and Sato (2013).

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