A study on zonally asymmetric structures of material circulation in the stratosphere using a formulation of three-dimensional residual mean flow

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The material circulation in the middle atmosphere is driven by momentum deposition of atmospheric waves such as gravity waves and Rossby waves propagating mainly from the troposphere as well as diabatic heating by radiative processes (Figure 1). This circulation largely affects the thermal and chemical structure of the middle atmosphere. The material circulation had mainly been studied in the two-dimensional (2-D) meridional cross section in the transformed Eulerian mean framework (Andrews and McIntyre 1976; 1978) because the Lagrangian mean flow, which represents the material circulation, is in good quantitative agreement with residual mean flow under certain conditions (Pendlebury and Shepherd, 2003). There is, however, increasing evidence that the material circulation has zonally asymmetric structures (Gabriel et al. 2011). This suggests necessity of a quantitative study on three-dimensional (3-D) material circulation in the middle atmosphere. Kinoshita and Sato (2013) derived formulae of 3-D residual mean flows applicable to both Rossby waves and gravity waves. The formulae should be a powerful tool to investigate longitudinal structures of the material circulation in the middle atmosphere.

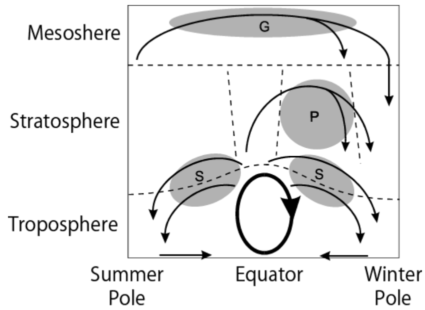

Figure 1: Schematic of the material circulation in the atmosphere. The shaded regions labeled S, P, and G denote regions of breaking synoptic-scale, planetary-scale, and gravity waves, respectively (Plumb 2002).

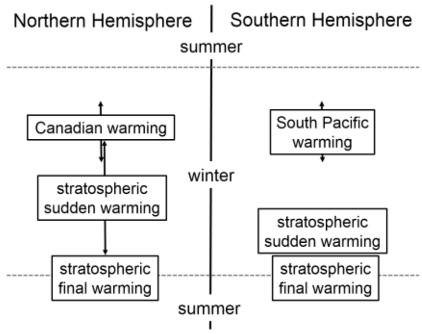

Figure 2: Summary of warming phenomena in the winter polar stratosphere and their occurrence period in both hemispheres.

During winter, the polar stratosphere is dominated by the polar vortex, which arises from radiative cooling in the absence of solar ultraviolet heating. But it can warm due to displacement of the polar vortex and/or anomalous adiabatic heating by downward residual mean flow. The warming phenomena have different characteristics according to their occurrence periods (Figure 2). In early winter, the polar vortex often displaces substantially from the Pole mainly in the middle and lower stratosphere. This warming phenomenon is called Canadian warming (CW; Manney et al. 2001) and South Pacific warming (Farrara et al. 1992) in the Northern Hemisphere (NH) and the Southern Hemisphere (SH), respectively. In the middle of winter, polar stratospheric temperature sometimes increases rapidly with time, accompanied by collapse of the polar vortex. Such an event is called stratospheric sudden warming (SSW). Its frequency after 1950s, when reanalysis data is available, is approximately 0.6 per year in the NH (Charlton and Polvani 2007). On the other hand, in the SH, SSW occurred only in 2002 (Roscoe et al. 2005). In the end of winter, a relatively sudden warming called stratospheric final warming (SFW) occurs every year, followed by summer state of the polar stratosphere. SFW dates are 1 month earlier in the NH than in the SH (Black et al. 2006; Hirano et al. 2016).

The big picture of our study is to investigate longitudinal structures of the residual mean flow during these warming phenomena in both hemispheres. Reanalysis data mainly used in our study is the Japanese 55-year Reanalysis (JRA-55). JRA-55 is the longest reanalysis whose data assimilation scheme is 4Dvar.

3-D structures of the material circulation during SFWs in the SH were revealed by Hirano et al. (2016). They examined interannual variability of SFW date in terms of wave activity by constructing early-minus-late SFW composites and showed in both two and three dimensions that potential temperature advection by residual mean flow is a main contributor to potential temperature increase before the SFW date, while contribution of diabatic heating by shortwave radiation, which is mainly attributable to ozone, is minor (Figure 3).

Our next focus is CWs, SSWs, and SFWs in the NH. Before moving on to analysis, we propose new definitions of CWs, SSWs, and SFWs by applying the momentum diagnostics (Waugh 1997) to the polar vortex, which is a main point of our presentation. Traditionally, zonal mean zonal wind is used to define SSWs and SFWs, for example, by Charlton and Polvani (2007) and Black et al. (2006), respectively. Although their definition is simple and easy to deal with, SSWs (SFWs) defined by them may include CWs and SFWs (SSWs). 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 momentum diagnostics, where the polar vortex is approximated as an

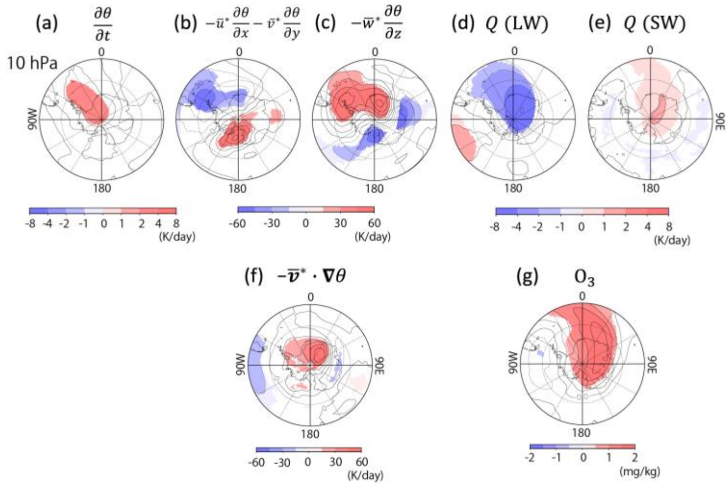

Figure 3: Polar stereographic projection maps of early-minus-late SFW composites of (a) tendency of potential temperature, potential temperature advection by (b) the horizontal and (c) vertical components of residual mean flow, heating rate by (d) longwave and (e) shortwave radiation, (f) potential temperature advection by all the components of residual mean flow, and (g) ozone mass mixing ratio for the time period from 1 to 15 October at 10 hPa. Contours representing 0, ±1, ±2, ±4, and ±8 K/d are drawn in Figures 3a, 3d, and 3e. Contour interval in Figures 3b, 3c, and 3f is 15 K/d and that in Figure 3g is 0.5 mg/kg. Only areas with 95% confidence level for a two-sided *t* test are colored (Hirano et al. 2016).

equivalent ellipse. The momentum diagnostics enable them to define displacement and splitting SSWs separately by using centroid latitude and aspect ratio, respectively, of the equivalent ellipse as a criterion. However, their SSWs may include CWs and SFWs. Moreover, there is almost no clear definition of CWs.

CWs, SSWs, and SFWs are clearly distinguished in our analysis, and new definitions for them are proposed based on momentum diagnostics to investigate longitudinal structures of the polar vortex and material circulation during CWs, SSWs, and SFWs. The validity of our new definition will be guaranteed in terms of mixing by an analysis based on equivalent latitude (Nash et al. 1996).

References

Andrews, D. G., and M. E. McIntyre, Planetary waves in horizontal and vertical shear: The generalized Eliassen-Palm relation and the mean zonal acceleration, J. Atmos. Sci., 33(11), 2031–2048, 1976.

Andrews, D. G., and M. E. McIntyre, Generalized Eliassen-Palm and Charney-Drazin theorems for waves on axisymmetric mean flows in compressible atmospheres, J. Atmos. Sci., 35(2), 175–185, 1978.

Black, R. X., B. A. McDaniel, and W. A. Robinson, Stratosphere-troposphere coupling during spring onset, J. Clim., 19(19), 4891–4901, 2006.

Charlton, A. J., and L. M. Polvani, A new look at stratospheric sudden warmings. Part I: Climatology and modeling benchmarks, J. Clim., 20(3), 449–469, 2007.

Farrara, J. D., M. Fisher, C. R. Mechoso, and A. O'Neill, Planetary-scale disturbances in the southern stratosphere during early winter, J. Atmos. Sci., 49(18), 1757–1775, 1992.

Gabriel, A., H. Körnich, S. Lossow, D. H. W. Peters, J. Urban, and D. Murtagh, Zonal asymmetries in middle atmospheric ozone and water vapour derived from Odin satellite data 2001–2010, Atmos. Chem. Phys., 11(18), 9865–9885, 2011.

Hirano, S., M. Kohma, and K. Sato, A three-dimensional analysis on the role of atmospheric waves in the climatology and interannual variability of stratospheric final warming in the Southern Hemisphere, J. Geophys. Res. Atmos., 121(14), 8429–8443, 2016.

Kinoshita, T., and K. Sato, A formulation of three-dimensional residual-mean flow applicable both to inertia-gravity waves and to Rossby waves, J. Atmos. Sci., 70(6), 1577–1602, 2013.

Manney, G. L., J. L. Sabutis, and R. Swinbank, A unique stratospheric warming event in November 2000, Geophys. Res. Lett., 28(13), 2629–2632, 2001.

Mitchell, D. M., L. J. Gray, J. Anstey, M. P. Baldwin, and A. J. Charlton-Perez, The influence of stratospheric vortex displacements and splits on surface climate, J. Clim., 26(8), 2668–2682, 2013.

Nash, E. R., P. A. Newman, J. E. Rosenfield, and M. R. Schoeberl, An objective determination of the polar vortex using Ertel's potential vorticity, J. Geophys. Res. Atmos., 101(D5), 9471–9478, 1996.

Pendlebury, D., and T. G. Shepherd, Planetary-wave-induced transport in the stratosphere, J. Atmos. Sci., 60(12), 1456–1470, 2003.

Plumb, R. A., Stratospheric transport, J. Meteorol. Soc. Jpn., 80(4B), 793–809, 2002.

Roscoe, H. K., J. D. Shanklin, and S. R. Colwell, Has the Antarctic vortex split before 2002?, J. Atmos. Sci., 62(3), 581–588, 2005.

Seviour, W. J., D. M. Mitchell, and L. J. Gray, A practical method to identify displaced and split stratospheric polar vortex events, Geophys. Res. Lett., 40(19), 5268–5273, 2013.

Waugh, D. N., Elliptical diagnostics of stratospheric polar vortices, Q. J. R. Meteorol. Soc., 123(542), 1725–1748, 1997.