Response to Referee #1

Manuscript acp-2016-537
Evolution of the eastward shift in the quasi-stationary minimum of the Antarctic total ozone column.
A.Grytsai et al.

RC – Referee comments, **AC** – Author comments.
The changes, additions and corrections are in blue.

We thank Referee #1 for the helpful comments and suggestions. We have added citation and have extended discussion accordingly to **RC**. Additional citation and discussion will be included in the revised text of the manuscript.

RC: Page 1, L 34-35: There are earlier papers on the field and should be cited, e.g.: Chubachi, Shigeru. Preliminary result of ozone observations at Syowa station from February 1982 to January 1983. Memoirs of National Institute of Polar Research. Special issue 34 (1984): 13-19.
AC: We have included this paper in the citation in Chapter 1 (L 34–35). Additionally, one of the earliest publications on the Antarctic ozone decrease based on satellite data (Stolarski et al., 1986) has been also included in the citation.
L 34–35: (Chubachi, 1984; Farman et al., 1985; Chubachi and Kajiwara, 1986; Stolarski et al., 1986; Solomon, 1999).

RC: Page 1, L 37-38: This has already been published 20 years before Solomon et al., (2005). See for instance Chubachi, (1984) and read the fourth result in the Summary of this paper and the discussion presented in it.
AC: The paper Chubachi (1984) has been cited in L 38.
L 38: (Chubachi, 1984; Solomon et al., 2005).

RC: Page 2, L 48-53: The fundamental citations on the field of first major sudden stratospheric warming over Antarctica in Sept 2002 and the vortex split are missing.
AC: The three earliest papers on the event 2002 have been included in the citation.
L 46–47: The role of planetary waves was especially important in the unusual SH stratospheric warming in 2002 (Varotsos, 2002; Allen et al., 2003; Hoppel et al., 2003).
L 52–53 (wave 1 and wave 2 activity):
… September 2002 (Varotsos, 2002; Nishii and Nakamura, 2004; Newman and Nash, 2005; Peters et al., 2007; Grassi et al., 2008; Peters and Vargin, 2015).

RC: Page 3, L 123-124: In both formulas insert space between $m\lambda$ and $d\lambda$.
AC: corrected

RC: Page 5, L 174: Add a note that *r* stands for the correlation coefficient and briefly discuss its statistical significance
AC: L 173-176: … The linear correlation between the two variables is positive and r = 0.49–0.57 for the seven latitude circles between 50°S and 80°S with maximum at 60°S. The correlation coefficient r was calculated for the time series length N = 35 (1979–2013, Fig. 4) and the value r = 0.39 is significant at the 99% confidence limit based on Student's *t*-test. Hence, an eastward shift of the QSW minimum in the ozone distribution with high probability corresponds to a greater ozone mass deficit (larger ozone loss).

RC: In addition, discussion on the plausible contribution of El Nino events in 1988 and 2002 should be made. For instance, the existing literature on this subject suggests that El Nino characteristics in 1988 and 2002 may not have been similar. Brief discussion on it should be added. Furthermore, it has been suggested often that the delayed SSWs in Antarctica are being directly and primarily caused by the ozone destruction by CFCs. It would be worthwhile short discussion on this for the years 1988 and 2002 to be incorporated.
AC: We have added a short comment on the events 1988 and 2002.
L 177: Simultaneous negative deviations are observed in the years of large (1988) and major (2002) stratospheric warmings (vertical lines in Fig. 4). Both anomalous events in the SH stratosphere were associated with enhanced planetary wave activity (Varotsos, 2003a; Allen et al., 2003; Baldwin et al., 2003; Grytsai et al., 2008). As seen from Fig. 4, relatively small ozone mass deficit …

L 182: is opposite. The anomalies in 1988 and 2002 are the largest relatively mean tendencies in Fig. 4. Sources of anomalous planetary waves in these years have been identified in both the tropical Pacific (Kodera and Yamazaki, 1989; Grassi et al., 2008) and the SH extratropics (Nishii and Nakamura, 2004). It has been noted that the evolution of sea surface temperatures (SST) in the tropical Pacific in the spring months of 1988 and 2002 were different (Varotsos et al., 2003b) with strong La Niña and emerging El Niño conditions, respectively (see for example the monthly time series for the indices Niño 3 and Niño 4 at http://www.esrl.noaa.gov/psd/data/climateindices/). As has been identified by Lin et al. (2012), stronger stratospheric planetary wave activity is generally seen in the SH when SST anomalies exhibit La Niña–like and central-Pacific El Niño–like patterns. These authors find that a westward phase shift is seen in SH stationary planetary waves for La Niña conditions, and an eastward phase shift for warm central Pacific sea surface temperatures. Figures 3 and 5 show westward phase shift in TOC minimum and maximum longitudes in both 1988 and 2002, which in the case of 2002 is counter to the expectation from Lin et al. (2012) based on prevailing central Pacific SSTs, and which we take up further in Section 3.2. Possibly, extratropical wave sources (Nishii and Nakamura, 2004) could contribute to observed phase shift in this case. Generally, planetary wave activity contributes significantly to the interannual variability of the ozone hole size, depth and duration (Kodera and Yamazaki, 1989; Allen et al., 2003; Varotsos, 2002, 2004). On the other hand, decadal changes of the ozone hole metrics seem to be influenced by ozone depletion itself. For example, the delay in the final warming of the Antarctic vortex and seasonal disappearance of the ozone hole in 1980s–1990s appears influenced by increasing overall ozone loss (Haigh and Roscoe, 2009).

AC:
L 183: A general eastward shift in the TOC zonal minimum longitude in the Antarctic region occurred during 1980s–1990s.

L 287-289: However, the easternmost longitudes in Fig. 7f show also a negative anomaly in the central Pacific, as distinct from a positive one (Lin et al., 2012). Note that Fig. 7f shows also significant negative SST anomaly in the South Pacific and positive SST anomalies in the western tropical Pacific and in the Atlantic. Their combined influences could result in other phase shift direction in the SH stratosphere planetary waves than from positive anomaly in the central tropical Pacific in (Lin et al., 2012).

RC: Finally, comments on the discrepancies observed in the ozone vertical distribution along with TOC variability would be very informative. For example, the cases in 2001 and 2002 would be very interesting to be added.
AC: As the changes in the vertical ozone distribution during the austral spring influence the column ozone from year to year, we would prefer not to focus on the cases 2001 and 2002 and comment briefly these influences in terms of interannual variability.

L 344: the QSW3 pattern below the tropopause ($r_{max} \approx 0.5$) is seen. The strong correlation in the stratosphere (between 200 hPa and 20 hPa, or 12 km and 26 km, respectively, in Fig. 10) demonstrates close coupling between the QSW_{min} longitude and ozone loss in their interannual variations. The vertical ozone profile in the austral spring undergoes the largest ozone decrease at this altitude range (Chubachi, 1984; Varotsos, 2003b; Solomon et al., 2005). Dynamical activity changes the extent of ozone depletion from year to year and enhances the TOC variability in the conditions of zonal asymmetry of the polar vortex. The role of zonal asymmetry becomes more important due to vertical non-alignment of the vortex structure (Varotsos, 2004). The vortex appears progressively shifted with height towards South America and high ozone in the middle stratosphere (around 30 km) within the Australian sector masks ozone depletion in the lower stratosphere (Kondragunta et al., 2005; Tully et al., 2008) resulting in additional variability of stratospheric temperature, column ozone and ozone hole characteristics. In this way, vertical changes in the wave 1 and wave 2 impacts on the ozone profile over Antarctica can contribute to the strong correlation between zonal structure in ozone distribution (QSW_{min} longitude) and stratospheric temperature in Fig. 10.

References

Allen, D. R., Bevilacqua, R. M., Nedoluha, G. E., Randall, C. E., and Manney, G. L.: Unusual stratospheric transport and mixing during the 2002 Antarctic winter, Geophys. Res. Lett., 30, 1599, doi:10.1029/2003GL017117, 2003.

Baldwin, M., Hirooka, T., O'Neill, A., and Yoden, S.: Major stratospheric warming in the Southern Hemisphere in 2002: Dynamical aspects of the ozone hole split, SPARC Newsletter, 20, 24–27, http://www.sparc-climate.org/publications/newsletter/, 2003.

Chubachi, S.: Preliminary result of ozone observations at Syowa station from February 1982 to January 1983, Mem. Natl. Inst. Polar Res., Spec. Issue Jpn., 34, 13–19, 1984.

Grassi, B., Redaelli, G., and Visconti, G.: Tropical SST preconditioning of the SH polar vortex during winter 2002, J. Climate, 21, 5295–5303, doi: 10.1175/2008JCLI2136.1, 2008.

Grytsai, A. V., Evtushevsky, O. M., and Milinevsky, G. P.: Anomalous quasi-stationary planetary waves over the Antarctic region in 1988 and 2002, Ann. Geophys., 26, 1101–1108, doi:10.5194/angeo-26-1101-2008, 2008.

Haigh, J. D. and Roscoe H. K.: The final warming date of the Antarctic polar vortex and influences on its interannual variability, J. Climate, 22, 5809–5819, doi:10.1175/2009JCLI2865.1, 2009.

Hoppel, K., Bevilacqua, R., Allen, D., Nedoluha, G., and Randall, C.: POAM III observation of the anomalous 2002 Antarctic ozone hole, Geophys. Res. Lett., 30, 1394, doi:10.1029/2003GL016899, 2003.

Kodera, K. and Yamazaki, K.: A possible influence of sea surface temperature variation on the recent development of ozone hole, J. Meteorol. Soc. Jpn., 67(3),465–472, 1989.

Kondragunta, S., Flynn, L. E., Neuendorffer, A., Miller, A. J., Long, C., Nagatani, R., Zhou, S., Beck, T., Beach, E., McPeters, R., Stolarski, R., Bhartia, P. K., DeLand, M. T., and Huang, L.-K.: Vertical structure of the anomalous 2002 Antarctic ozone hole, J. Atmos. Sci., 52, 801–811, doi:http://dx.doi.org/10.1175/JAS-3324.1, 2005.

Nishii, K. and Nakamura, H.: Tropospheric influence on the diminished Antarctic ozone hole in September 2002, Geophys. Res. Lett., 31, L16103, doi:10.1029/2004GL019532, 2004

Stolarski, R. S., Krueger, A. J., Schoeberl M. R., McPeters, R. D., Newman, P. A., and Alpert, J. C.: Nimbus 7 satellite measurements of the springtime Antarctic ozone decrease, Nature, 322, 808–811, doi:10.1038/322808a0, 1986.

Tully, M. B., Klekociuk, A. R., Deschamps, L. L., Henderson, S. I., Krummel, P. B., Fraser, P. J., Shanklin, J. D., Downey, A. H., Gies, H. P., and Javorniczky, J.: The 2007 Antarctic ozone hole, Aust. Meteorol. Mag., 57, 279–298, 2008.

Varotsos, C.: The Southern Hemisphere ozone hole split in 2002, Environ. Sci. Pollut. Res., 9, 375–376, doi:10.1007/BF02987584, 2002.

Varotsos, C.: What is the lesson from the unprecedented event over Antarctica in 2002? Environ. Sci. Pollut. Res., 10, 80–81, doi:10.1007/BF02980093, 2003a.

Varotsos, C.: Why did a "no-ozone-hole" episode occur in Antarctica? Eos, 84, 183–185, doi:10.1029/2003EO190007, 2003b.

Varotsos, C.: The extraordinary events of the major, sudden stratospheric warming, the diminutive Antarctic ozone hole, and its split in 2002, Environ. Sci. Pollut. Res., 11, 405–411, doi:htto://dx.doi.org/10.1065/esor2004.05.205, 2004.