

Response to Referee #1

The authors greatly acknowledge the Referee #1 valuable comments. We have extended our discussion following the Referee suggestions.

RC – Referee Comment; **AC** – Author Comment; New references – in *italic* throughout the text, are given at the end of the text.

RC: A disadvantage of the manuscript is that the authors did not present a clear physical interpretation of the link they have found and leave the reader with an unclear discussion about possible changes in the seasonal cycle or vertical profile.

AC: In our work we analyze relationships between the total ozone/vertically averaged stratospheric temperature and the quasi-stationary wave (QSW) amplitude considered with relatively low horizontal and vertical resolution. It is difficult to separate out the dynamical and chemical influences in the total ozone column (TOC) analysis. We attempted to partly explain the correlation distributions in Fig. 3 by 1) development of processes at polar stratospheric cloud (PSC) altitudes and 2) delayed impact on spring total ozone caused by anomalous Brewer-Dobson circulation (BDC) in the late winter. Both of these possible contributors are dependent on the planetary wave (PW) activity.

We noted in Sect. 4 that the wintertime PW activity is known to be positively correlated with spring polar ozone (Shindell et al., 1997; Salby and Callaghan, 2004; Weber et al., 2011). In general, this spring ozone response is explained by the cumulative effect of the BDC in the preceding winter and anomalous warming of the polar vortex due to anomalous BDC. The planetary wave activity driving the BDC is usually described by the vertical component of the Eliassen-Palm (EP) flux, which is proportional to the eddy heat flux and is a measure of the vertical propagation of planetary waves from the troposphere (when averaged over mid-latitudes or on a hemispheric scale). The EP flux into the upper stratosphere and mesosphere transmits momentum that drives a residual poleward circulation. The accompanying adiabatic warming in the downwelling air causes polar temperatures to be warmer than under conditions of radiative equilibrium.

Our results are largely consistent with the previous studies. However, a choice of the dynamical proxy (the QSW amplitude in the stratospheric temperature field) reveals some particular features of coupling between the QSW and ozone distribution in the Antarctic region. In order to explain clearer the possible sources of the preconditioning effects in our results (Fig. 3), we consider in more details the QSW amplitude variability in August, as suggested by the Referee, including the co-variability between the QSW and zonal mean temperatures in August which was not presented in the manuscript.

The distribution and strength of tropospheric PW activity influences the interannual variability in the amplitude of the QSW. Therefore, we first consider the seasonal climatology of the QSW amplitude in the Southern Hemisphere (SH) stratosphere which differs from that for the EP flux of the SH troposphere. The EP flux into the SH lower stratosphere increases almost monotonically during winter and spring and reaches a maximum level in October (e.g., Randel and Wu, 2002). However the seasonal tendency in the QSW amplitude in the Antarctic stratosphere is not monotonic and changes sign (from decreasing to increasing) around midwinter (Randel, 1988; *Hardiman et al.*, 2010). The climatological amplitude of stationary waves in the SH stratosphere has maxima in June and October, and is suppressed in the late winter and early spring during the period of strongest zonal winds ($70\text{--}80\text{ ms}^{-1}$ at 10 hPa in August; *Hardiman et al.*, 2010) by the Charney-Drazin criterion (*Charney and Drazin*, 1961). Climatologically, the QSW amplitude increases from August to October and it remains at high level in November (Randel, 1988;

Hardiman et al., 2010). Note that in the Arctic stratosphere, where the weaker zonal winds are more favourable for vertical wave propagation, a midwinter maximum in the QSW amplitude exists.

Based on the correlations shown in Figure 3, our hypothesis is that variability in the QSW amplitude (A_{QSW}) in August plays, to some extent, a preparatory role in the evolution of the ozone hole. Consistent with the QSW amplitude climatology, the poleward fluxes of heat and momentum in the SH stratosphere from the stationary wave number 1 (QSW1) component are weak in the winter and completely dominate the maxima during September–November (Randel, 1988). In the late winter (August), at the beginning of the rapid ozone losses, variability in the heat and easterly momentum deposition by the QSW could be possible factor influencing the Antarctic vortex temperature and strength that contribute to the preconditioning of the spring ozone hole. As the A_{QSW} variability in July exhibits the much weaker preconditioning effect than in August (Sect. 2), we consider in more details the zonally asymmetric temperatures in August.

RC (M1): Show in addition to figure 2 the variance of the amplitude because the annual variability contributes to the correlation not the climatologically mean, determine the dominant modes of inter-annual variability.

AC: We show the amplitude variance in new Fig. 2b, where the climatology of the standard deviation (SD) for August is presented. It is seen that the SD distribution is similar to the A_{QSW} distribution (Fig. 2a). A minor distinction is that there is a slightly wider latitude extension for the region of maximum variability (60° – 65° S in Fig. 2b) in comparison with the position of the A_{QSW} maximum (60° S in Fig. 2a). The latitudinal positions of both peaks in Fig. 2a and 2b are near the mean climatological position of the polar night jet axis in Antarctic winter (Waugh and Randel, 1999; Karpechko et al., 2005) as we noted in Sect. 2. However, these peak latitudes do not coincide with correlation maxima in Fig. 3 (except for November), nor with the correlation distributions for August (Fig. 2c–f), which were not presented in our manuscript. The four plots in Fig. 2c–f show the relationships between the A_{QSW} and vertically average (Sect. 2), zonal mean temperatures, T_{zm} , in August at latitudes between 60° S and 90° S. That behaviour of the vertical temperature profile in the lower stratosphere is related to the behaviour of the total ozone column as inferred from the similarity of the correlation patterns for the South Pole shown in Fig. 3d to those of other latitudes in Fig. 3a–c.

The correlation distributions in Fig. 2 c–f show the same details as in Fig. 3, particularly, in September (lower panel). This is evidence that, in the main features, a positive response to the QSW variations persists in the zonal means during four months, starting in August.

The correlation maxima in August (Fig. 2c–f) tend to locate around 70° S, similarly to those in Fig. 3 for September. The lower stratospheric maximum is absent for T_{zm} at 60° S (Fig. 2c), where strong ozone depletion does usually not occur (as this latitude is generally outside the ozone hole). This is in line with our assumption that, at higher latitudes, the QSW influence on the temperatures at the PSC altitudes could be important factor of the total ozone variations in September. In the zonally asymmetric temperature field, the temperature variability around the PSC threshold (-78° C, or 195 K) can occur at the different longitudes. It is known that the climatological east-west asymmetry of the Antarctic polar vortex and ozone hole exists with the typical displacement from the South Pole toward the Atlantic sector, 0° – 60° W (Wirth, 1993; Waugh and Randel, 1999; Grytsai et al., 2007; Agosta and Canziani, 2011).

Figure A1 illustrates the changes in the TOC field asymmetry in August under conditions of the strong polar vortex in 2006 (Fig. A1a) and the weak polar vortex in 2002 (Fig. A1b). The Multi Sensor Reanalysis (MSR) data (http://www.temis.nl/protocols/o3field/o3mean_msr.php) are used. These two years represent a range of dynamical variability in wave–ozone coupling in the Antarctic

stratosphere (Weber et al., 2001; their Fig. 4). The largest changes in the ozone field in 2002 occur between about 90° E and 240° E (Fig. A1b), corresponding to the maximum ozone accumulation due to the asymmetric BDC. The TOC minimum between about 0° E and 60° W (Fig. A1b) is the area of almost undisturbed TOC level in comparison with that in 2006 (Fig. A1a). We have compared the meridional temperature profiles for August 2002 and August 2006 at the individual pressure levels, 10 hPa and 50 hPa (Fig. A2a and A2b, respectively) using NCEP-NCAR reanalysis data. These pressure levels correspond to the correlation peaks in Fig. 2c and 2d. The asymmetry axis (longitudes of the temperature minimum and maximum) was taken in the meridional direction 45° W–135° E (dashed lines in Fig. A1). This differs from the asymmetry axis about 0°–180° E in the 100-hPa temperature in Fig. 1 because of westward tilt of the QSW phase with altitude (Randel, 1988; Gabriel et al., 2011). Temperature field (not shown) indicates also that the TOC maximum between 90° E and 180° E (Fig. A1b) is associated with the temperature maximum at 10 hPa within this sector.

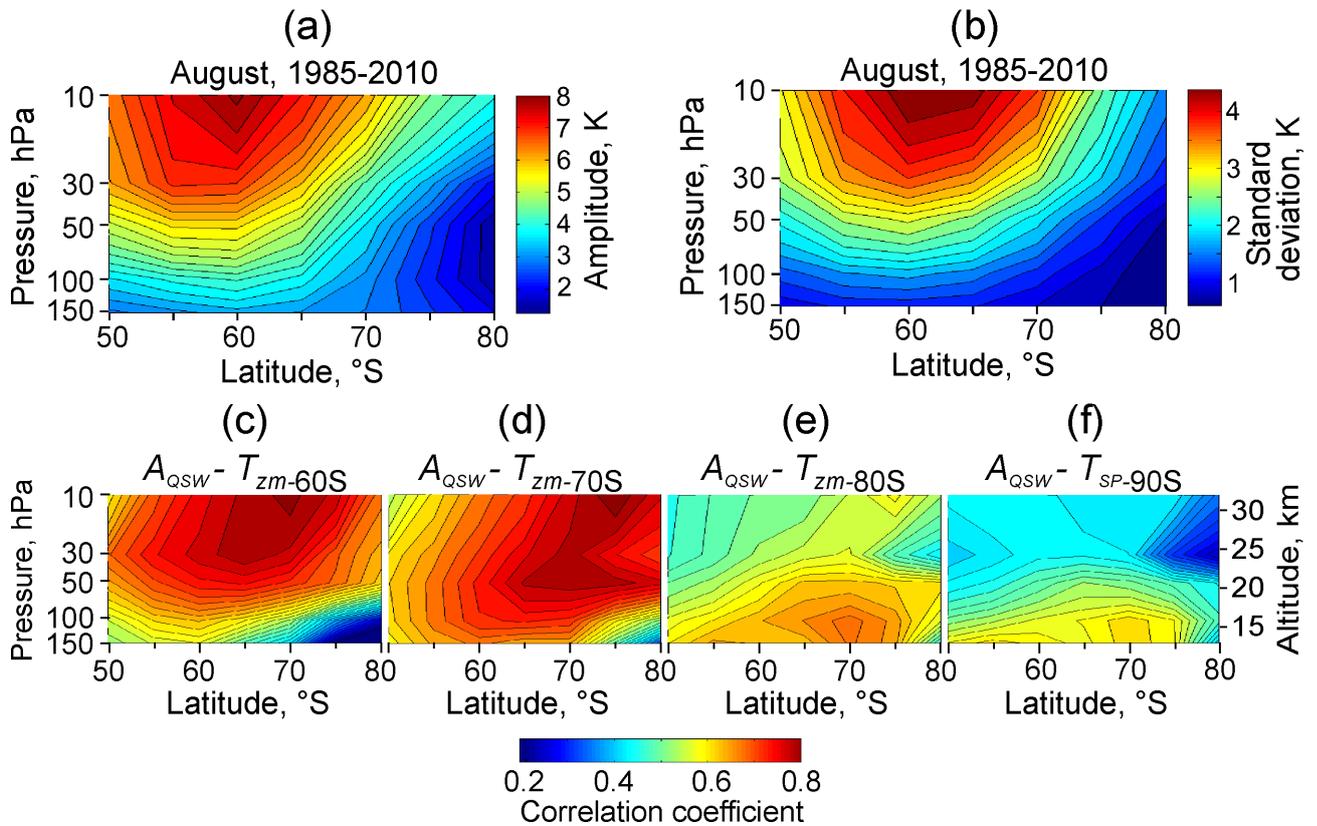


Fig. 2. Climatology of (a) the August QSW amplitudes and (b) amplitude standard deviations in Antarctic stratosphere temperature for the 1985–2010 period. (c–f) Correlation between the QSW amplitude and zonal mean stratospheric temperature (vertically averaged) in August at (c) 60° S, (d) 70° S, (e) 80° S and (f) 90° S.

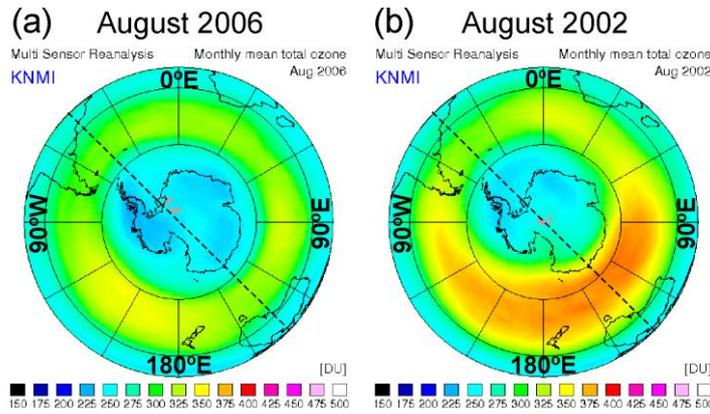


Fig. A1. Total ozone fields from Multi Sensor Reanalysis data for (a) strong and zonally symmetric vortex in August 2006 and (b) weak and zonally asymmetric vortex in August 2002.

Fig. A2 shows low zonal asymmetry in August 2006 (dashed curves) and high zonal asymmetry in August 2002 (solid curves) in agreement with Fig. A1. The changes in the temperature profiles in 2002 are mainly due to temperature increase over the eastern Antarctic (135° E, right half of the solid curves). These changes are accompanied by the poleward shift of the meridional temperature gradients here. Over the western Antarctic (45° W, left half of the plots), the temperature profiles are not significantly different. Such the asymmetric contribution to zonal mean temperature variability is obviously related to the asymmetric ozone accumulation (Fig. A1) due to asymmetries in the residual circulation (e.g., Salby and Callaghan, 2004; Gabriel et al., 2011).

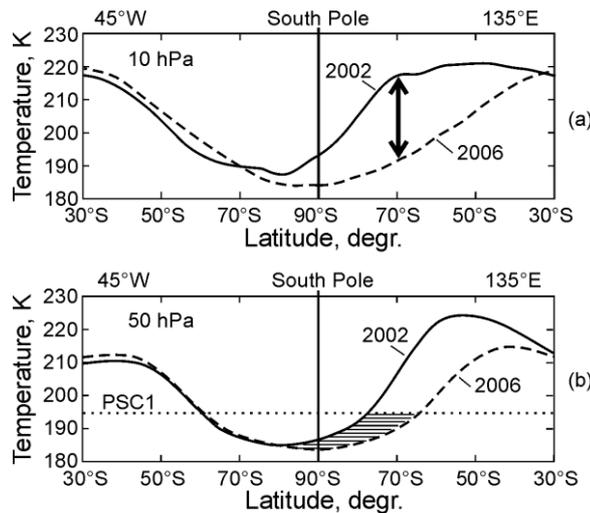


Fig. A2. Stratospheric temperature profiles in the meridional plane 45° W– 135° E at the pressure levels of (a) 10 hPa and (b) 50 hPa for August 2002 (large vortex asymmetry, solid curves) and August 2006 (small vortex asymmetry, dashed curves).

From Salby and Callaghan (2004), the interannual changes of the wintertime tendency in the 50 hPa geopotential height related to the changes in the vertical component of the EP flux, show the similar asymmetric patterns: the maximum response in geopotential height is seen in the Eastern Hemisphere. This maximum is located at higher latitudes (with the steepest meridional gradient poleward of 60° S) in winters of strong PW activity than in winters of weak PW activity (Salby and Callaghan, 2004; their Fig. 13). The latitudinal changes at opposite longitudes are insignificant. Taking into account the climatology (east-west asymmetry in the ozone accumulation), the changes are typically small in the west segment of the Antarctic stratosphere and they do not contribute significantly to the zonal mean changes. It seems that the positive correlation in Fig. 2c–f is mainly

due to direct proportion between interannual temperature variations in the east Antarctic stratosphere and the zonal mean temperatures.

It should be noted that the zonal mean meridional ozone flux in the SH polar region is typically low over the whole year except for a peak in October and November (Miyazaki *et al.*, 2005; Monier and Weare, 2011). Similarly, Figs. A1 and A2 suggest that the changes in the zonal means consist of relatively small component independent of the changes in the asymmetric ozone accumulation. The latter relates to the vertical component of the eddy ozone flux (Miyazaki and Iwasaki, 2005) and is in agreement with observed zonal asymmetry in the vertical velocity in the Antarctic stratosphere (Sato *et al.*, 2009; Gabriel *et al.*, 2011).

An important consequence of the asymmetric temperature increase in 2002 (Fig. A2, solid curves) is the noticeable poleward shift of the meridional temperature gradients in the Eastern Hemisphere. The gradient is less shifted but is steeper in the lower stratosphere (50 hPa, Fig. A2b) than in the middle stratosphere (10 hPa, Fig. A2a).

In the lower stratosphere (Fig. A2b), as seen from the hatched area below the PSC threshold (dotted line), the poleward shift of the temperature gradient could be the main cause of the PSC area decrease in August 2002 in comparison with August 2006. Since the western part of the profile is much less variable, the interannual temperature variability near 70° S in its eastern part could give the largest contribution to the temperature-dependent PSC occurrence. The asymmetric PSC area variations, in turn, result in the related ozone losses (e.g., Gabriel *et al.* (2011), who assume that the feedback of temperature-dependent chemistry could enhance the amplitudes of the stationary wave patterns in ozone in the case of a zonally asymmetric configuration of the cold winter polar vortex) and their contribution to the ozone and temperature variations in the zonal means. This could be a possible cause of the correlation maximum appearance in the lower stratosphere near 70° S (Fig. 2d).

At the upper levels, the PSC do not affect the ozone/temperature variability. However, the large poleward shift of the temperature gradient at 135° E indicates the higher temperature change again near 70° S (double arrow in Fig. A2a). Such changes could provide a large contribution to the vertically averaged temperatures and could be a possible explanation of the correlation maximum occurrence at upper level near 70° S (Fig. 2c–f), not at 60° S, the mean latitude of the night jet axis and the A_{QSW} itself.

While this conclusion is made from the two-year comparison, similar asymmetric changes in the August ozone/temperature fields (not shown) occur always in the cases of the weak polar vortex (1988, 2002, 2004, 2007, 2010) relative to the strong polar vortex (1996, 2001, 2003, 2006, 2011; see the MSR data at <http://www.temis.nl/protocols/O3global.html> for the TOC fields). In general, the larger QSW disturbances suggest the larger poleward shift of the temperature gradient in the Eastern Hemisphere stratosphere so that co-variability between A_{QSW} and T_{zm} would also tend to be shifted to the A_{QSW} values at the higher latitudes, than the climatological position of the A_{QSW} itself and its variance (Fig. 2a and 2b).

Note, that ‘diagonal patterns’ in the correlation distributions (Sect. 3), which are similar in Fig. 2c–f and Fig. 3, are reminiscent of the vertical structure of the temperature – wave relationship in Antarctic stratosphere shown by Salby and Callaghan (2004). They have analyzed the anomalous wintertime tendencies in the Antarctic stratosphere temperature corresponding to a 1 SD increase in vertical component of the EP flux. From Salby and Callaghan (2004), the location of the maximum in the lowermost stratosphere at ~65° S, to the north relative to that above 30 hPa (~80° S, their Fig. 11), suggests an influence by the Antarctic continent. The radiative impact of Antarctica leads to anomalous cooling of the lower stratosphere and would damp the positive temperature anomaly that

is introduced by anomalous ozone downwelling. In the lowermost stratosphere this effect covers the area approaching the continent boundary latitudes ($\sim 70^\circ$ S in Eastern Antarctica). Note that the correlation maxima for T_{zm} at 80° S and 90° S (Fig. 2e and 2f, respectively) take the lowermost altitudes and this may also be associated with radiative influence of Antarctica.

Summing up, Figs. A1 and A2 combined with the climatological data indicate that the interannual variations of the meridional temperature gradients caused by the QSW are significantly larger over the east Antarctic, than over the west Antarctic. These variations give main contribution to the zonal mean temperature variations (positive coupling between A_{QSW} and T_{zm} in Fig. 2c–f) and to localization of the correlation maxima in Fig. 2c–f; radiative influence of the Antarctic continent on the correlation distribution is also possible.

This more detailed consideration suggests that eddy vertical ozone flux is an important source of variability in the zonal mean ozone and temperature in the late winter Antarctic stratosphere that, in turn, can contribute to the preconditions to the zonal means in spring (Fig. 3). Precondition effects could be realized through asymmetric changes in the meridional temperature gradients (Fig. A2) and related changes in strength of the polar night jet via thermal wind equation (*Andrews et al.*, 1987). As the planetary wave penetration into stratosphere is sensitive to the zonal wind anomalies, seasonal enhancement of the PW activity in spring could be dependent on a level of such the anomalies in the late winter. Referring to McCormack et al. (2011) we noted the possibility that the strength of the vortex is potentially influenced by zonally asymmetric ozone (ZAO). The Referee has drawn our attention to *Albers and Nathan* (2011), who discuss that zonal wind changes due to ZAO can have contributions from planetary wave drag, ozone heating and Newtonian cooling.

RC M2: Split the section 4 into two new sections starting with the discussion in 4 and then finally in section 5 present the conclusions with an overall summary.

AC: We will introduce section 5 (conclusions) in the revised manuscript.

RC M3: focus the discussion on the link you have found, give answers to following questions, Why does such a link exist? Start with the mean residual transport equation like equation 9.4.13 on page 357 in the textbook of Andrews, Holton, McIntyre: Middle atmosphere dynamics, AP 1987, which described the zonal mean total ozone tendency as function of the residual advection including Eulerian flow and wave heat fluxes as well as sources and turbulent wave fluxes plus diffusion. Further take both pathways of wave influences on the mean ozone field into account as well described recently in Albers et al. JAS 2011 (<http://dx.doi.org/10.1175/JAS-D-11-0126.1>).

AC: Our preconditioning indicator, the QSW amplitude, describes the stratospheric temperature field disturbances in late austral winter over the altitude range 13–32 km. This where the horizontal transport and horizontal eddy mixing is negligible due to the mixing barrier near the strong polar jet axis (*Holton et al.*, 1995; *Miyazaki et al.*, 2005). Low QSW activity and low zonal mean ozone transport, as noted above, result in relatively high contribution of the eddy vertical ozone flux associated with the asymmetric BDC (*Miyazaki et al.*, 2005; *Gabriel et al.*, 2011) to the zonal mean ozone and temperature in August. Variability in the eddy vertical ozone flux, most likely, underlies the general positive coupling between eddy and zonal mean temperature in Fig. 2c–f and, in turn, could contribute to preconditioning of the spring ozone (Fig. 3).

Asymmetric ozone/temperature increase (Figs. A1 and A2) due to the asymmetric BDC enhancement can contribute to the decrease of the zonal-mean meridional temperature gradient across the vortex edge that, through thermal wind balance, leads to zonal wind weakening. The heat and easterly momentum deposition related to the QSW could also contribute to the preconditioning vortex warming and weakening as noted above. Assumed response in the seasonal PW amplification will cause the changes in the total PW activity in the spring including the higher QS

wave numbers (QSW2 and QSW3) and transient planetary and gravity waves. Although these QSW-related influences on the seasonal evolution of the Antarctic polar vortex and ozone hole are in general agreement with the effects of the zonally asymmetric ozone in the model studies (*Albers and Nathan, 2011; McCormack et al., 2011*), they show strong altitudinal dependence in the stratosphere layer under analysis.

From *Albers and Nathan (2011)*, ZAO contributes to zonal wind via planetary wave drag (their pathway 1) and via ozone heating (pathway 2). In their numerical experiment based on coupled equations for wind, temperature and ozone, ZAO causes a slightly weaker and warmer vortex in the dynamically controlled region, below ~35 km, i.e., in the altitude range analyzed in our work. The authors note that “it is plausible that the model employed in this study actually underestimates the impact of pathway P2 on the zonal mean circulation”. Because of the differences between the two polar regions in the climatologies and seasonal tendencies, effects of ZAO in the SH polar region in late winter can differ from those in the NH winter discussed by *Albers and Nathan (2011)* and *McCormack et al. (2011)*. For example, low QSW activity and strong zonal wind in the austral late-winter stratosphere suggest that a relationship between planetary wave propagation and damping could differ from that in the boreal winter conditions.

As follows from comments and illustrations above, variability in the late winter ZAO caused by variability in the asymmetric BDC (eddy vertical ozone flux) results not only in the positive correlation between the QSW amplitude and zonal mean temperatures in Fig. 2c–f, but also in the altitude-dependent structure of the correlation. Main features of this relationship remain in the correlation distribution in Fig. 3. This means that the preconditioning effects could be mainly attributed to the altitude-dependent modification of the late-winter SH stratosphere by the QSW. Note that the altitude-dependent response in the zonal mean ozone and temperature to the QSW variations seems to be distinctive features of the dynamically controlled stratosphere in the SH polar region.

For example, altitude-dependent changes in the meridional temperature gradients in late winter (Fig. A2) could be precondition factor for horizontal eddy transport and mixing in spring. *Miyazaki and Iwasaki (2005)* use ozone transport diagnosis based on mass-weighted isentropic zonal means which offer advantages over the transformed Eulerian mean (TEM) formalism of *Andrews et al. (1987)*. *Miyazaki and Iwasaki (2005)* have provided analysis for the austral winter (JJA). *Miyazaki et al. (2005)* extend this work and examine other seasons. They show that the mean and eddy components of ozone transport vary with time and height in both hemispheres. We noted above, that zonal mean ozone transport in the SH is usually low in all seasons and the eddy ozone flux has maximum in spring (*Miyazaki et al., 2005; Monier and Weare, 2011*). Horizontal diffusion coefficient for ozone mixing, by *Miyazaki et al. (2005)*, maximizes in the SH middle stratosphere (20 hPa) in November–December (their Fig. 7). It is important to note that the strength of the eddy ozone flux depends on not only wave breaking activity but also on the meridional ozone gradient: a steep meridional ozone gradient enhances the eddy meridional ozone flux as well (*Miyazaki et al., 2005*). This gives ground to include the changes in the meridional temperature gradients to concomitant factors of the preconditioning.

Overall, the poleward eddy transport compensates for the chemical ozone losses associated with the ozone hole, and provides an important contribution to the total column during the recovery phase of the ozone hole. Observations at the Antarctic stations Syowa and Davis located in the Eastern hemisphere near 70° S (40° E and 78° E, respectively) show that ozone maximum at 20–25 km in the vertical ozone profile in the spring can exceed that at 15–20 km in the undisturbed winter profile (*Sato et al., 2009, their Fig. 2; Tully et al., 2008, their Figs. 20–22*). Because the typical ozone maximum at 15–20 km disappears usually in the spring ozone hole, the upper-level ozone becomes the main contributor to column ozone. As spring progresses, the influence exerted on the

meridional gradients by the strength of the QSW in August could contribute to the stronger eddy mixing higher in the stratosphere (correlation maximum near 10 hPa in Fig. 3).

The typically large vortex displacements in the middle stratosphere can also contribute to coupling between the upper-level ozone accumulation and column ozone, without irreversible transport or mixing. This is illustrated in Fig. A2 for August (see also Fig. 33 by Tully et al. (2009), where, for September 2007, progressive poleward shift with increasing altitude is seen in the ozone maximum in the Eastern Hemisphere; by Kondragunta et al. (2005), in a case of the ozone hole 2002, the offset between the vortices in the lower stratosphere and middle stratosphere masked the ozone depletion in the lower stratosphere and resulted in higher total column ozone and a smaller ozone hole estimate). Therefore, preconditioned QSW variations and the further seasonal PW amplification can contribute to the TOC variations through the altitude-dependent horizontal displacements of the Antarctic vortex. Note also that the anomalies in the mid-stratospheric ozone accumulation in August can persist in spring due to low descent rate of stratospheric anomalies as we noted in Subsect. 4.2. Overall, in the upper levels of the ozone hole, the QSW controls in-fill, while in the lower levels it limits the overall amount of chemical loss and the size of the ozone depleted area and, thus, contributes to the correlation patterns in Fig. 2c–f and Fig. 3.

In the absence of the specific analysis, and applying the results of studies cited above in the context of our work, we suggest that the late-winter effects of the QSW in the vertical eddy ozone flux have controlling aspects in the correlations presented in Fig. 3. Firstly, the QSW most strongly and promptly controls the ozone amount in the lower stratosphere through its influence on the temperature near the PSC threshold (Fig. A2b) and, hence, on the ozone depleted area. This can be seen by the peak correlations in the lower stratosphere in August (Fig. 2d–f) and September (lower panel of Fig. 3), the two months when ozone loss rate at the PSC altitudes is the highest (Fig. 4). Second, the meridional temperature gradient variability in late winter can be controlling factor of the zonal mean wind and PW propagation and the eddy ozone transport and mixing in spring, especially, in the middle stratosphere (correlation maxima near 10 hPa in Fig. 3). Besides, the heat and easterly momentum deposition caused by the late winter QSW is also possible component of the preconditioned warming and weakening of the Antarctic vortex. These effects are combined with climatological structure of the Antarctic vortex and ozone hole in the late winter and spring (east-west asymmetry) that suggests significance of the altitude-dependent vortex displacements for the column ozone variability. Relative importance of the possible precondition factors should be examined in the model experiments. Note also that the precondition effects discussed above is not fully analogous to the cumulative effect of the wintertime activity of the total PW (Shindell et al., 1997; Salby and Callaghan, 2004; Weber et al., 2011). The A_{QSW} variability in July exhibits the much weaker precondition effect than in August (Sect. 2), i.e. the one-month QSW component of the wave activity is only considered in the context of the preconditions in this work.

RC M3: What is the cause for the temporal shift in the correlation? Take into account the role of vacillation as described by the Holton-Mass model, where for wave-1, they found about 60 days as a typical time scale of oscillation between planetary wave activity and the mean flow?

AC: Stratospheric vacillations described by *Holton and Mass* (1976) could affect the seasonal weakening and warming of the polar vortex. This was clearly observed in austral winter-spring 2002 (*Scaife et al.*, 2005). From *Scaife et al.* (2005), zonal wind vacillations, with maximum amplitude in upper stratosphere in winter, descended with time following seasonal descent of polar night jet down through the stratosphere. The vacillation regime was associated with substantial reduction of the polar vortex area and increased refractive index for planetary waves in the lower stratosphere. These preconditions favoured major stratospheric warming in September 2002. Vacillations could contribute to seasonal persistence of the correlations in Fig. 3 taking into account their slow descent rate through the stratosphere. However, there is a little observational evidence of

the vacillation development in the Antarctic stratosphere in other years (*Scaife et al.*, 2005, their Fig. 6).

RC M3: Why is the phase of QSPW unimportant? This needs also a discussion because wave flux depends on phase shift.

AC: QSW1 phase influence on the Antarctic stratosphere was considered for example by *Agosta and Canziani* (2011) in the context of locations of the tropospheric wave sources. It is shown, that westward rotation of the QSW1 phase in TOC is associated with a predominantly single poleward tropospheric jet structure in midlatitudes and with wave energy propagation from the tropical central Pacific into higher latitudes. Possible effects in preconditioning of the spring behaviour are under study (*Agosta and Canziani*, 2011). *Grytsai et al.* (2008) have shown that the weak Antarctic polar vortices and high TOC levels in springs 1988 and 2002 are associated with a westward shift in the zonal QSW minimum relative to its longitude in the stronger and colder vortices in 1987 and 2001. These and some other works confirm dependence of the Antarctic vortex evolution on the QSW phase due to possible modulation of the wave heat and momentum flux through the stratosphere. Taking into account the comments above, in addition to the QSW amplitude and phase, the asymmetric temperature gradients across the vortex edge and, possibly, other stratospheric characteristics (for example, the altitude-dependent asymmetry in the zonal winds; e.g., *Grytsai et al.*, 2008) could be considered as accompanying factors of the preconditions.

In conclusion, we have presented extended comments on the possible causes of the altitudinal dependence in the relationship between the zonally asymmetric (induced by the QSW) and zonal mean stratospheric temperatures in the late austral winter and how these effects of the QSW could contribute to the preconditions of the spring total ozone and to the correlation distribution in Fig. 3. To answer some questions more specifically, additional analysis of the observation and reanalysis data should be carried out and modeling targeted to the winter-spring transition in the SH stratosphere dynamics and chemistry is necessary.

Minor revisions: we will introduce the corrections suggested by **RC m1–m3** in the revised manuscript.

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