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Quasi-stationary planetary waves in late winter Antarctic stratosphere temperature as a possible indicator of spring total ozone

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Abstract

Stratospheric preconditions for the annual Antarctic ozone hole are analysed using the amplitude of quasi-stationary planetary waves in temperature as a predictor of total ozone column behaviour. It is found that the quasi-stationary wave amplitude in August is highly correlated with September–November total ozone over Antarctica with correlation coefficient as high as 0.83 indicating that quasi-stationary wave effects in late winter have a persisting influence on the evolution of the ozone hole during the following three months. Correlation maxima are found in both the lower and middle stratosphere. They are likely manifestations of wave activity influence on chemical ozone depletion and large-scale ozone transport, respectively. Both correlation maxima indicate that spring total ozone tends to increase in the case of amplified activity of quasi-stationary waves in late winter.

1 Introduction

For over three decades, significant depletion of stratospheric ozone has taken place each austral spring over Antarctica. During the 1990s and 2000s, the September mean ozone hole area, measured as the area where the total ozone column (TOC) was less than 220 Dobson Units (DU), was approximately 20–25 million square kilometres (Mkm^2) (NOAA, 2009). Over this time period, the September area grew during the 1980s and levelled off in recent years. However, in certain years this metric has been considerably smaller, being 17 Mkm^2 in 2004 and 11 Mkm^2 in 2002 (NOAA, 2009). Understanding the processes that influence interannual variability of the ozone hole metrics is important for comparison of observations with modelled ozone recovery scenarios.

Overall, it is clear that the level of year-to-year variability in the size of the ozone hole during the past two decades has been influenced more by fluctuations in dynamical forcing from planetary scale waves in the atmosphere and less by changes

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in stratospheric chlorine levels (Shindell et al., 1997; Randel et al., 2002; Salby and Callaghan, 2004; Weber et al., 2011). Years with stronger planetary wave activity at extratropical southern latitudes are generally associated with smaller ozone holes. Dynamical variability of the ozone hole has increased in the last decade. In addition to 2002 and 2004, the ozone holes of 2007 and 2010 were less severe than normal (Tully et al., 2008; WMO, 2010). In this regard, two processes which relate to the timing of the enhanced wave activity are important.

Firstly, planetary wave activity during the winter can warm and weaken the polar vortex, limiting the extent of halogen activation by Polar Stratospheric Clouds (PSC). This "preconditioning" lessens the overall severity of spring ozone loss, as demonstrated in observational and model studies (Allen et al., 2003; Huck et al., 2005; Weber et al., 2011). Secondly, the timing of the breakdown of the polar vortex has an important influence on the overall magnitude of ozone loss. The breakdown of the vortex, which may proceed rapidly through stratospheric warming episodes, is driven by planetary waves. As observed in 2002, both preconditioning and an unprecedented sudden stratospheric warming resulted in an anomalously small ozone hole for that year (Allen et al., 2003).

Preconditioning wave activity can influence stratosphere temperature not only from the upward flux of wave energy from the troposphere but also by ozone transport. Strong winter planetary wave forcing leads to larger transport of ozone in the stratospheric mean meridional circulation, known as the Brewer–Dobson circulation (BDC) that results in enriched ozone and higher stratospheric temperature in the extratropics (Randel et al., 2002; Salby and Callaghan, 2004; Hood and Soukharev, 2005; Weber et al., 2011). The co-action of dynamics, transport and chemistry is important, for example, in producing the fall–spring ozone correlation found in the Arctic (Kawa et al., 2005; Sinnhuber et al., 2006).

In this work, we statistically analyse the relationship between austral late-winter dynamical disturbances in the Antarctic polar vortex region and the behaviour of the ozone hole in spring. As an indicator of the dynamical activity in the late winter, the quasi-stationary wave (QSW) amplitude in the zonal stratospheric temperature distribution during August is used. It is known that the quasi-stationary planetary wave of zonal wave number 1 (QSW1) dominates the southern stratosphere (Randel, 1988; Wirth, 1993; Grytsai et al., 2007; Canziani et al., 2008) and therefore we focus here on the QSW effects. It has been shown by Grytsai et al. (2008) that the large increase of the QSW amplitude in August preceded anomalously diminished ozone holes in 1988 and 2002, whereas no preconditioning effects were observed in July.

We assume that the dynamical conditions in the vortex region in August (mainly due to QSW activity) affect both the early stage and further spring evolution of the ozone hole. Here we statistically analyse the association between the QSW amplitude in August and characteristics of the ozone hole over the 26 yr period 1985–2010. The paper is organized as follows. Section 2 describes the data sets and methods used, Sect. 3 presents the results, and Sect. 4 gives conclusions and brief discussion.

2 Data and method

Late winter zonal anomalies in stratospheric air temperature were examined with National Centers for Environmental Prediction – National Center for Atmospheric Research (NCEP – NCAR) Reanalysis data (Kalnay et al., 1996) from http://www.esrl.noaa.gov/psd/data/reanalysis. The monthly mean zonal temperature distributions in August were considered. We describe the total wave number effect of the QSW by the amplitude A_{QSW} calculated as one half of the difference between peak maximum and minimum as shown in Fig. 1. For our analysis, we created time series of A_{QSW} values for seven latitude circles between 50° S and 80° S with 5-degree steps and at the five pressure levels 150, 100, 50, 30 and 10 hPa (13–32 km) over the 1985–2010 period. The dominant QSW1 contribution is clearly seen from the single zonal maximum near 180° E on both curves in Fig. 1, which represent the extreme conditions in the winter southern stratosphere with weak (2002, solid curve) and strong (2006, dashed curve) stratospheric polar vortices.

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The A_{QSW} climatology for August is shown in latitude–altitude coordinates in Fig. 2. The amplitude tends to increase vertically and decrease poleward with maximum and minimum values of 8.1 K and 1.6 K, respectively. The maximum amplitude at 10 hPa (Fig. 2) relates to a general amplification of large-scale planetary waves between the lower and middle stratosphere (Matsuno, 1970; Randel, 1988). Peak values at 60° S correspond to the vortex edge region with a strong temperature gradient across it (Karpetchko et al., 2005). As planetary waves disturb the vortex shape and position, the zonal temperature deviations and, hence A_{QSW}, maximize around the mean position of the displaced vortex edge. The distribution of the standard deviation of the climatological mean A_{QSW} is similar to Fig. 2 with a deviation maximum of 4.6 K and a deviation minimum of 0.6 K (not shown). These climatological distributions are important in the interpretation of the spring ozone response to late-winter QSW activity (Sect. 4).

The ozone hole was characterised by monthly mean parameters of three types.

1. OH_a – the overall size of the ozone hole characterised by the monthly mean ozone hole area for September, October and November using data of (NOAA, 2009, Fig. 8) for 1985–2008 and data from http://www.cpc.ncep.noaa.gov/products/stratosphere/polar/polar.shtml for 2009 and 2010.

2. TOC_{zm} – the zonal mean total ozone column at latitudes of 60° S, 70° S and 80° S used to represent TOC variations at the edge of and inside the ozone hole. These values were collected from gridded satellite data obtained by Nimbus-7 Total Ozone Mapping Spectrometer (TOMS, 1979–1992; McPeters et al., 1996), Earth Probe TOMS (1996–2005; McPeters et al., 1998), and Aura Ozone Monitoring Instrument (2006–2010; Dobber et al., 2008) available at http://ozoneaq.gsfc.nasa.gov/measurements.md. Note that a data gap exists in TOC_{zm} at 80° S during September, when, on average, 18 days of measurements are available. Multi sensor reanalysis (MSR) data based on the TM3DAM assimilation scheme (van der A et al., 2010) were used for the 1993–1995 period (http://www.temis.nl/protocols/o3field/o3mean_msr.php).

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3. TOC_{SP} – the Amundsen-Scott total ozone column derived from ground-based measurements at South Pole (http://www.esrl.noaa.gov/gmd/ozwv/dobson/ams.html) and used as an independent ground-based time series showing the TOC variability in the vortex core. Ozone measurements here do not provide complete datasets of TOC_{SP} for October and November: The number of days when measurements were made was on average 14 and 25 in October and November, respectively, during 1985–2008. In September, the spectrophotometric ozone observations are impossible at the South Pole due to polar night and we have filled the data gap for this month using stratospheric temperature data as a proxy. It is known that stratospheric temperatures are highly correlated with total ozone (Wirth, 1993; Randel and Cobb, 1994; Solomon et al., 2005) and the temperature time series can therefore be used to infer the interannual TOC variability. The temperature time series for September at 90° S, T_{SP}, was created by averaging the NCEP–NCAR reanalysis temperatures over seven standard pressure levels 150, 100, 70, 50, 30, 20, and 10 hPa (13–32 km). Thus, this data set characterises interannual temperature variability over the South Pole in the partial column of the atmosphere between the lower and middle stratosphere, in the layer containing the maximum ozone amount.

The linear (Pearson) correlation coefficient, r, between the A_{QSW} time series and ozone hole parameters, OH_a, TOC_{zm}, TOC_{SP} and T_{SP}, was calculated. The correlation significance was estimated with a Student's t-test and without accounting for the lag-1 autocorrelation of the correlated time series, as is usually done in climate-related studies (e.g. Ciasto and Thompson, 2008). Spring total ozone usually has low correlation to ozone anomalies in the previous calendar year in both hemispheres (Fioletov and Shepherd, 2003). Besides, by our estimate, autocorrelation in the A_{QSW} time series is also too low ($r < 0.1$ in most cases under consideration) to take into account an effective sample size reduction in significance testing.

Using the QSW climatology at 100 hPa, Grytsai et al. (2008) noted that QSW amplitudes in July and August have a similar latitudinal distribution between 50° S and

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80° S. The strong QSW activity in August was the only preconditioning effect in the occurrences of small ozone holes in 1988 and 2002. We have compared the preconditioning potential of A_{QSW} in July and August using time series for 65° S, 100 hPa, over the 1985–2010 period. Correlations between A_{QSW} and ozone hole area averaged over September–November are $r = -0.19$ (statistically insignificant) for QSW in July and $r = -0.64$ (significant at the 1 % level) for QSW in August.

This obvious difference is confirmed also by the r-values in Table 1. It is seen that, in contrast to July, variations of the QSW amplitude in August and ozone hole area in spring months are closely coupled ($r < -0.5$ in five cases, all significant at the 1 % level). At 100 hPa (10 hPa) the correlation reaches a negative value of $r = -0.65$ ($r = -0.76$). For July, a single value of $r = -0.43$ is statistically significant at the 5 % level.

The comparison shows that stratospheric disturbances associated with QSW anomalies in August result in a noticeably stronger response in the spring ozone hole than those in July. In the next section, we analyse quantitative relationships between late-winter QSW anomalies at selected latitudes and pressure levels and the spring ozone hole parameters indicated above.

3 Results

The August QSW amplitudes, A_{QSW}, were correlated with ozone hole parameters in September, October and November, namely, with: (1) ozone hole area, OH_a, (2) zonal mean total ozone, TOC_{zm}, at 60° S, 70° S and 80° S, and (3) South Pole total ozone, TOC_{SP} (October and November), and stratosphere temperature, T_{SP} (September), averaged between 10 hPa and 150 hPa (see Sect. 2). The correlation analysis is restricted to 26 yr from 1985 to 2010 (with the exception of TOC_{SP} limited by 2008) to examine the available principal ozone hole years. Linear (non-linear with polynomial 3 fitting) trends were subtracted from the A_{QSW} and T_{SP} (OH_a, TOC_{zm} and TOC_{SP}) time series. (Nonlinearity in the long-term changes of the Antarctic total ozone in spring is

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due to a transition from relatively monotonic TOC decrease during the 1980s – first half of 1990s to a leveling off after the mid-1990s; corresponding changes in the ozone hole area have occurred; e.g. Newman et al., 2004).

Figure 3 summarises the correlation distributions. The axes represent the latitude–altitude ranges for the preconditioned QSW amplitude anomalies, A_{QSW} (50° S–80° S, 10 hPa–150 hPa). Correlation dependences of the ozone hole parameters in September, October and November on A_{QSW} are presented in Fig. 3 in the bottom, middle and top panels, respectively. Negative correlation for the ozone hole area (Fig. 3e) is shown in the same colour scale as positive correlations for TOC (Fig. 3a–d). The data set size used in this study (26 yr) produces correlation coefficient values $|r| \geq 0.47$ that are statistically significant at the 1 % level and less, based on the Student's t-test.

One can see from Fig. 3, that the contours of $r = 0.5 - 0.8$ (for simplicity, we give modulus of the correlation coefficients hereafter) cover much or all of the individual plots except for Fig. 3a, top plot. This is evidence of the high wave–ozone dependence in the region under consideration. Clear correlation maxima are seen in Fig. 3. They indicate the latitudes and altitudes where the QSW anomalies have the strongest influence on spring total ozone. Correlation peaks in Fig. 3 are shown with two decimal places. The highest correlation is seen in the relationship between A_{QSW} at 10 hPa, 75° S, and TOC_{zm} at 70° S in September ($r = 0.83$; bottom plot in Fig. 3b).

In the vertical, two correlation maxima are noted. At lower altitudes (100–50 hPa, or 16–21 km), the localized maximum around 70° S is seen in September (Fig. 3b–e, bottom plots). Correlation maximum at higher levels, near 10 hPa (32 km), exists predominantly at 75° S in September, at 60° S in November and takes intermediate latitudes in October (Fig. 3, bottom, top and middle panels, respectively). Clear vertical separation of the maxima is evidence for two different sources of the preconditioning effect in the lower and middle stratosphere.

The existence of a correlation maximum in the lower stratosphere shows that the late winter QSW anomalies here cause a relatively short-term response (September) in the ozone hole parameters (bottom plots of Fig. 3b–e). In September, these

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parameters (high-latitude TOC, South Pole stratosphere temperature and ozone hole area) characterise the region of rapid ozone depletion inside the stratospheric polar vortex. The largest ozone losses occur in the lower stratosphere at the altitudes of about 15–20 km where most of the ozone column normally resides and where PSCs provide reactive chlorine species for catalytic destruction of ozone (Solomon et al., 2005; Salby, 1996; Randel and Wu, 1999; Tully et al., 2008). Note that this correlation maximum is absent in TOC_{zm} at the latitude circle 60° S (Fig. 3a) which is usually outside the ozone hole. It can therefore be inferred that, in the lower stratosphere (50–100 hPa; Fig. 3b–e, bottom plots), the QSW variability in August and ozone loss variability (and resulting column ozone variability) inside the ozone hole in September are tightly coupled.

The ozone amount in the lower stratosphere usually reaches a minimum level in October, when mid-stratospheric ozone dominates the vertical ozone profile and column ozone (Randel and Wu, 1999; Solomon et al., 2005). Any coupling between the QSW anomalies and ozone loss should cease after September (see further discussion in Sect. 4). This could be a possible cause of disappearance of the correlation maximum in the lower stratosphere in October and November (Fig. 3, middle and top panels).

It is interesting that very similar correlation patterns in September are observed in stratospheric temperatures over the South Pole, T_{SP} (bottom plot of Fig. 3d), zonal mean total ozone at high latitudes, TOC_{zm} at 70° S and 80° S (bottom plots of Fig. 3b–c) and ozone hole area, OH_a (Fig. 3e, bottom plot). This is evidence of the close ozone–temperature relation mentioned in Sect. 2. It is important to note the high positive correlation between A_{QSW} and T_{SP} ($r = 0.6 - 0.7$; bottom plot of Fig. 3d). This indicates that the stratosphere over the South Pole in September is generally warmer if the quasi-stationary wave amplitude in August is larger. Taking into account the ozone–temperature coupling, the same conclusion can apply to the whole results of Fig. 3: The larger preconditioned QSW amplitude, the higher TOC levels and stratospheric temperatures in the latitudinal zone 60° S–90° S in spring.

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A common and more persistent feature of the correlation patterns in Fig. 3 is the correlation increase with altitude. Correlation maxima in the middle stratosphere near 10 hPa are observed in all correlated pairs and exist from September to November. In September, they are about equal in magnitude to those in the lower stratosphere, but occur at somewhat higher latitudes as noted above (Fig. 3, bottom panel). The poleward shift of upward increasing correlation is also observed in October and November (Fig. 3, middle and top panels). This tendency forms a diagonal pattern in the shape of the contours on Fig. 3.

If Fig. 3 is compared to Fig. 2, one sees that the correlation distribution in November (Fig. 3, top panel) resembles the QSW climatological distribution in August (Fig. 2). Both distributions tend to maximize at the pressure level of 10 hPa with peak magnitudes at 60° S. Diagonal patterns on both distributions (the minima at higher latitudes and lower altitudes with an inverted combination for the maxima) are also similar. This similarity can indicate that the climatological increase of A_{QSW} with altitude (and the increase of A_{QSW} variability, as noted in Sect. 2) contributes to the correlation maximum in the middle stratosphere (Fig. 3). Continuation of this maximum during spring months shows that the late winter QSW anomalies could be associated with ozone/temperature anomalies near 10 hPa, which are able to persistently influence the total ozone column.

Dominance of the QSW1 in the Southern Hemisphere (Sect. 1) leads to steady displacements of the stratospheric polar vortex relative to the pole (Waugh and Randel, 1999) that, in turn, result in zonal asymmetry of the ozone and temperature fields (Wirth, 1993; Grytsai et al., 2007; Canziani et al., 2008). Because the QSW amplitude, A_{QSW}, is also determined mainly by QSW1 (Fig. 1), it could be considered as an approximate measure of the quasi-stationary vortex displacement off the pole in August. In this approximation, the results of Fig. 3 suggest that the preconditioned vortex asymmetry is positively correlated with the zonal mean ozone and temperature in spring and is in inverse proportion with the ozone hole area.

Summing up, the two correlation maxima in Fig. 3 indicate a sensitivity of the ozone hole to late-winter QSW disturbances. The QSW amplitudes in two stratospheric

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layers, 50–100 hPa and near 10 hPa, have a certain predictive ability for the ozone hole parameters: When larger QSW anomalies in the lower (middle) stratosphere in August are observed, larger anomalies in ozone hole parameters in September (September–November) can be expected.

4 Conclusions and discussion

In this work, we argue that the amplitude of quasi-stationary planetary waves in the stratospheric temperature distribution, A_{QSW}, during late winter month, August, allows for the quantitative analysis of preconditioning of ozone hole parameters in spring. Although the spatial resolution is not very high (~500 km in the meridional direction and on average 5 km by altitude), it seems to be quite enough for a representation of the main features of the correlation between planetary waves and ozone hole parameters (Fig. 3).

The correlation coefficients are in the range of 0.5–0.8 (negative in the case of the ozone hole area) and they are statistically significant at the <1 % level. This is evidence of the strong response of spring Antarctic ozone to dynamical activity in late winter. Although, in general, 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), our study accentuates the effects of the QSW component of the planetary waves in this correlation. We have demonstrated the existence of two correlation maxima, which differ in the duration of the total ozone response to preconditioning QSW activity.

The QSW anomalies, A_{QSW}, in the lower stratosphere (50–100 hPa) influence strongly the polar total ozone and stratospheric temperature, as well as ozone hole area, in September (Fig. 3b–e, bottom panel). In the middle stratosphere (10 hPa) they cause the TOC anomalies of the same sign in September–November (Fig. 3). The QSW anomalies in these stratospheric layers can be used as an indicator of ozone hole behaviour in spring months: the larger the preconditioned QSW amplitude, the higher TOC and temperature in the Antarctic stratosphere and the smaller the ozone hole. Below, we briefly discuss some processes and tendencies inherent in the Antarctic

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stratosphere that seem to be related to the observed dependences between the quasi-stationary wave amplitudes and the ozone hole parameters.

4.1 Seasonal ozone cycle

The seasonal cycle of total ozone in the extratropics is closely related to the enhanced meridional ozone transport in winter–spring due to the BDC with corresponding ozone maximum in spring in both hemispheres (Salby, 1996; Fioletov and Shepherd, 2003). In the precondition analysis for Antarctic ozone, it is important to take into account the specific shape of the annual ozone cycle in the winter–spring season. The natural ozone cycle has been modified at high southern latitudes due to ozone hole development since the 1980s. Observations at Antarctic stations show that the spring ozone maximum no longer appears because ozone depletion starts as early as July with the following TOC minimum in September–October and ozone recovery in late November–December (Randel and Wu, 1999; Lee et al., 2001; Solomon et al., 2005; Shanklin et al., 2009a, 2009b). This forms the ozone hole season which can last about half of the annual ozone cycle (July–December) since the late 1990s.

The difference between the natural and modified annual ozone cycles, as seen from observations at Antarctic stations in the pre-ozone hole years and ozone hole years, respectively, increases rapidly in August and September (Salby, 1996; Randel and Wu, 1999; Solomon et al., 2005). This is in accordance with typical changes in the ozone loss rate. For example, satellite measurements during 2002–2009 have shown that, inside the polar vortex, the ozone loss rates at the isentropic level 475 K (about 20 km) are larger in August and September than in October, when the chemical ozone loss stops (Sonkaew et al., 2011). For the polar region, we have calculated relative percent differences between monthly mean TOC in 1979–1983 and 1999–2008: $\Delta TOC = (TOC_{1979-1983} - TOC_{1999-2008}) \times 100\,\% / TOC_{1979-1983}$. The MSR zonal mean data (see Sect. 2) area weighted between 70° S and 90° S were used. The first 5 yr period includes the earliest years of the ozone hole development and the second 10 yr period covers the decade of the largest ozone hole area. Figure 4 shows that, indeed, the difference in the annual ozone cycle grows rapidly from July to September and decreased TOC levels exist later during October–December.

The difference change in Fig. 4 suggests that dynamical impacts during July–September can produce especially strong effects on the general severity of the ozone hole. By our results, the significant preconditioning effects of the stratospheric QSW appear as early as August and are observed in the TOC response until November (Table 1 and Fig. 3). These preconditioning effects, hence, differ in timing and duration from those in total tropospheric wave forcing of the stratosphere. As shown by Shindell et al. (1997), midwinter (July) tropospheric wave activity is critical in determining ozone loss behaviour in the springtime, approximately two months later (September). The high correlation between the winter cumulative extratropical 100 hPa eddy heat flux and the ozone ratio with respect to fall ozone levels at high latitudes persists well into the summer months (Weber et al., 2011). A distinctive feature in our results is also a vertical differentiation of the correlation in Fig. 3 that implies a specific relationship between the QSW amplitude and the vertical ozone profile.

4.2 Vertical ozone profile

The QSW climatology alone (Fig. 2) does not reveal the large A_{QSW} variations in the lower stratosphere (Sect. 2). Nevertheless, the correlation maximum in lower stratosphere (Fig. 3b–e, bottom) indicates a high sensitivity of high-latitude total ozone in September to the QSW anomalies in August even if they are of typical magnitude in this stratospheric layer. It has been inferred in Sect. 3 that this sensitivity can appear due to a strong dependence of rapid ozone losses in the lower stratosphere (15–20 km) on the large-scale dynamical disturbances associated with the late winter QSW.

Ozone depletion in the ozone hole grows rapidly from July to September (Fig. 4). Starting in July near the vortex edge, 60° S–70° S, almost complete ozone depletion occurs in September in the lower stratosphere at polar latitudes 70° S–90° S, as known from many observational and model studies (e.g. Lee et al., 2001; Solomon et al., 2005; Tully et al., 2008). So, a tendency of the growing ozone depletion is limited in time (July–September, Fig. 4), by altitude (15–20 km) and latitude (70° S–90° S).

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Unlike ozone loss, ozone accumulation due to the BDC persists during austral winter and spring and covers the middle and high latitudes (Salby, 1996; Randel et al., 2002; Salby and Callaghan, 2004; Weber et al., 2011). Ozone/temperature anomalies in the middle stratosphere associated with anomalous BDC transport can reside persistently in the stratosphere due to a low descent rate of stratospheric air during winter and spring (1–3 km month^{-1}; e.g. Sato et al., 2009).

Therefore, ozone loss and ozone buildup are the most important processes influencing the TOC level via changes in the vertical ozone distribution and they both can be sensitive to the QSW anomalies. We noted in Sect. 3 that the QSW1 dominance results in a displacement of the Antarctic vortex relative to the pole. As shown in other studies, ozone accumulation in the Antarctic stratosphere during winter and spring is asymmetric due to zonal asymmetry in mean meridional transport with an ozone maximum in the Eastern Hemisphere (Salby and Callaghan, 2004; Sato et al., 2009; Gabriel et al., 2011). On the other hand, effective PSC formation inside the Antarctic vortex suggests concentricity of the vortex and long-term air exposure at low temperatures (Maturilli et al., 2005 and references therein). A contribution of vortex asymmetry to the wave number one pattern in ozone via zonal asymmetries in PSC is also suggested by Gabriel et al. (2011).

The QSW anomalies, A_{QSW}, can possibly be indicative of ozone/temperature anomalies in August caused by asymmetry in both BDC- and PSC-related processes and result in correlation maxima in the middle and lower stratosphere, respectively (Fig. 3).

It should be noted that recent model studies show a difference in the asymmetry effects on the stratosphere in the Southern and Northern Hemispheres. Zonally asymmetric ozone heating tends to produce a colder (warmer) winter polar stratosphere in the Southern (Northern) Hemisphere. However, physical mechanisms have not yet been fully explained (McCormack et al., 2011; and references therein). In the case of the precondition analysis, our results suggest likely positive relation between late-winter asymmetry of the Antarctic vortex and zonal mean total ozone and temperature inside the ozone hole in spring. This agrees with the results of Salby and

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Callaghan (2004) who have shown that the BDC-related tendency of asymmetric ozone increase in austral winter is accompanied by positive anomalies in zonal mean temperature in the stratosphere (their Figs. 17 and 18).

Further details of the correlations between quasi-stationary waves and Antarctic ozone, as well as assumed coupling between vortex asymmetry, PSC-related ozone loss and BDC-related ozone accumulation, should be analysed with higher spatial resolution, including layer-wise distribution of the ozone amount in the stratosphere.

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Table 1. Correlation coefficients (r) of the QSW amplitude at 65° S in July and August with the monthly mean ozone hole area in September–November. The r-values that are significant at the 1 % level (5 % level) are in bold (in italics).

QSW amplitude, month, pressure level	Ozone hole area, month Sep	Oct	Nov
July, 10 hPa	−0.28	*−0.43*	−0.35
July, 100 hPa	−0.07	−0.15	−0.26
August, 10 hPa	**−0.51**	**−0.76**	**−0.61**
August, 100 hPa	**−0.59**	**−0.65**	−0.32

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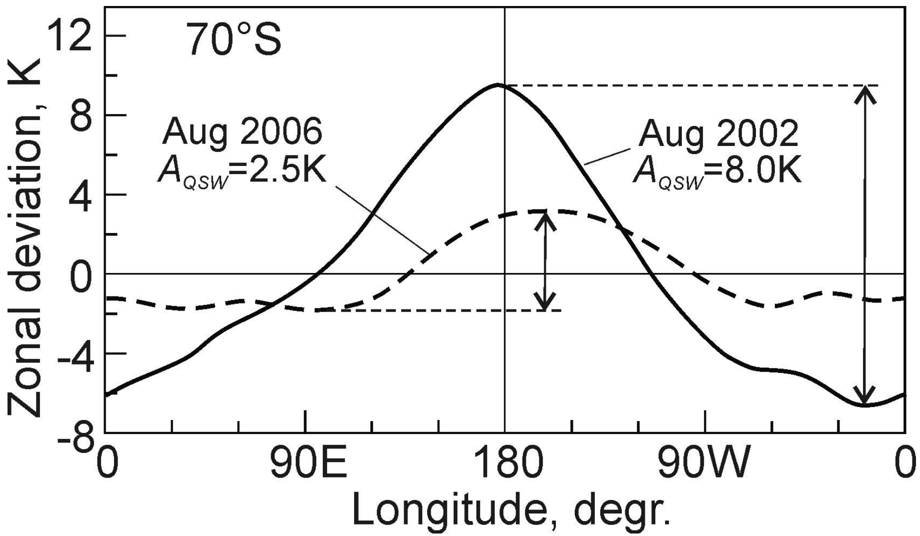

Fig. 1. Zonal anomalies of 100 hPa temperature at 70° S in August 2002 (solid curve) and August 2006 (dashed curve) as an illustration of weak and strong vortex conditions, respectively.

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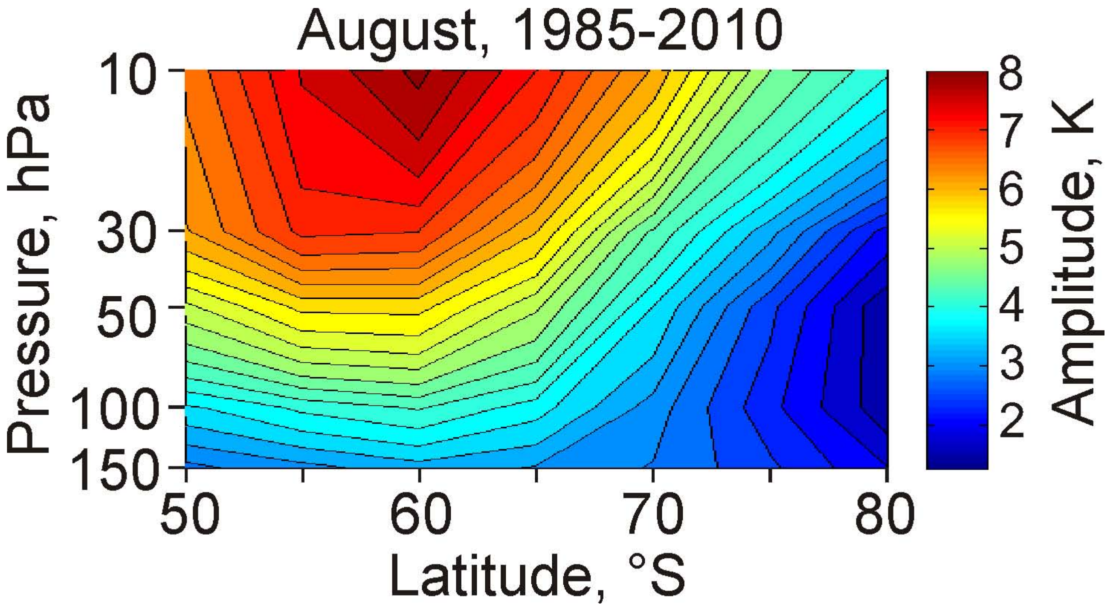

Fig. 2. Climatology of the August QSW amplitude in stratosphere temperature along the seven latitude circles between 50° S and 80° S for the 1985–2010 period.

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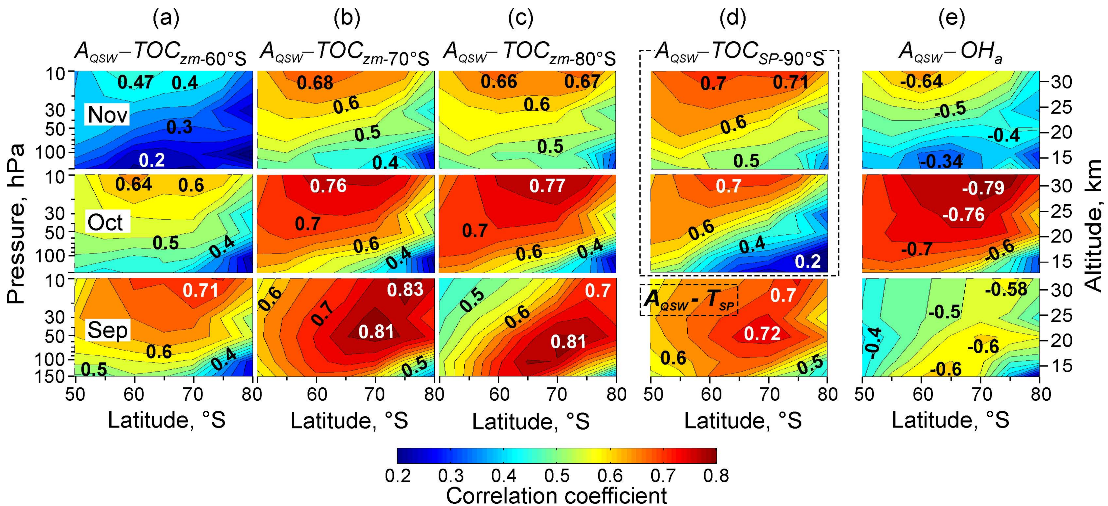

Fig. 3. Latitude–altitude distributions of the correlations between the QSW amplitude, A_{QSW}, in August and TOC_{zm} at **(a)** 60° S, **(b)** 70° S and **(c)** 80° S; **(d)** South Pole total ozone, TOC_{SP}, and temperature, T_{SP}, and **(e)** ozone hole area, OH_a (note the opposite sign of the correlation here).

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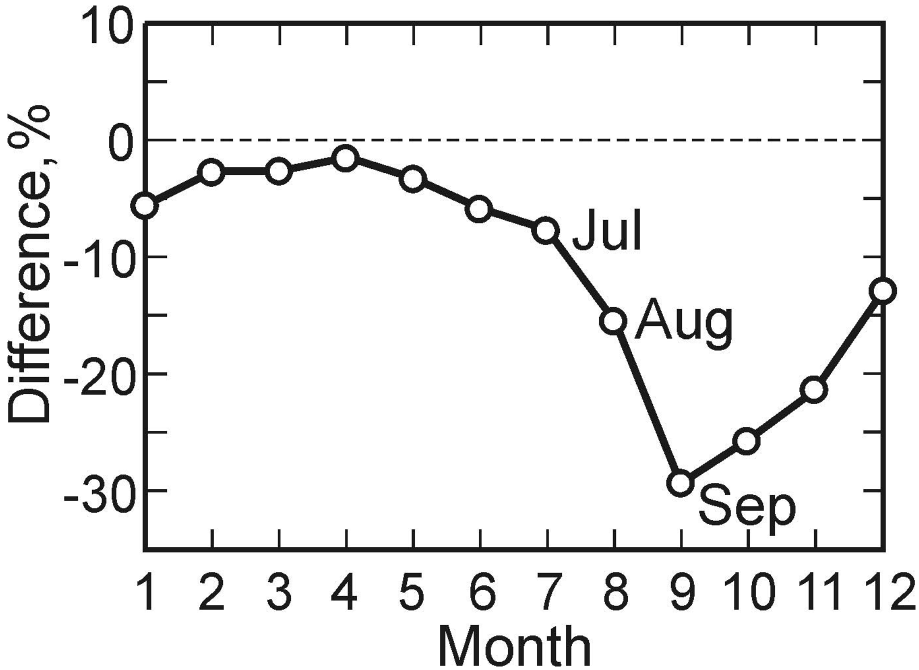

Fig. 4. Relative percent difference between monthly mean total ozone in the periods 1979–1983 and 1999–2008 averaged over the Southern polar region (70° S–90° S). The zonal mean MSR data are used.

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