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Key Points:
- Middle atmospheric winds show clear response to ozone variability in the Antarctic stratosphere
- Stratospheric thermal gradients and wind-filtering of gravity waves cause these changes
- Results show that the onset and duration of PMC/PMSE season can be affected by ozone recovery

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Observational evidence of the influence of Antarctic stratospheric ozone variability on middle atmosphere dynamics

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Abstract Modeling results have suggested that the circulation of the stratosphere and mesosphere in spring is strongly affected by the perturbations in heating induced by the Antarctic ozone hole. Here using both mesospheric MF radar wind observations from Rothera Antarctica (67°S, 68°W) as well as stratospheric analysis data, we present observational evidence that the stratospheric and mesospheric wind strengths are highly anti-correlated, and show their largest variability in November. We find that these changes are related to the total amount of ozone loss that occurs during the Antarctic spring ozone hole and particularly with the ozone gradients that develop between 57.5°S and 77.5°S. The results show that with increasing ozone loss during spring, winter conditions in the stratosphere and mesosphere persist longer into the summer. These results are discussed in the light of observations of the onset and duration of the Antarctic polar mesospheric cloud season.

1. Introduction

Solar radiative heating of the stratosphere is due primarily to the absorption of ultraviolet (UV) and visible radiation by ozone [*Dopplick*, 1972]. However, that heating can be perturbed by the large depletion in stratospheric ozone over the Antarctic during the southern springtime. Termed the ozone hole, it is caused by dynamical conditions that lead to catalytic destruction of ozone by heterogeneous reactions of atomic halogens (chlorine and bromine), themselves produced by photodissociation of anthropogenically produced chlorofluorocarbons on polar stratospheric cloud particles [*Farman et al.*, 1985; *de Laat and Van Wheele*, 2011]. This depletion can alter the planet's energy budget, temperature gradients, air chemistry, and circulation [*Kennicutt et al.*, 2014]. Consequently, the effects of the ozone hole and its possible recovery on global atmospheric circulation are important aspects that require clear understanding and demand an in-depth analysis [*Kennicutt et al.*, 2014].

Previous studies using reanalysis and ozone data as well as modeling have shown that the larger the ozone loss that occurs across the Antarctic polar vortex during spring, the longer it takes for the cold polar winter stratosphere to warm through the absorption of solar radiation by ozone. The result is that the latitudinal temperature gradients remain in a winter state longer into the spring and result in a persistence of winter lower stratospheric vortex conditions up to early December in Antarctica [*Waugh et al.*, 1999; *Randel and Wu*, 1999; *Waugh and Randel*, 1999; *Langematz et al.*, 2003; *Stolarski et al.*, 2006]. The effect of the year-to-year variations in the extent of the polar ozone loss drives a large interannual variability in the timing of the final warming and the strength and direction of the stratospheric wind speed, particularly during November.

The circulation and temperature of the mesosphere are controlled in large part by upward propagating gravity waves that carry momentum and energy into the mesosphere [*Fritts and Alexander*, 2003, and references therein]. Model simulations indicate that the forcing of the mesosphere is determined by the wind distribution of the underlying atmosphere [*Lindzen*, 1981; *Holton*, 1983; *Garcia and Solomon*, 1985], which alters the spectrum of gravity waves reaching the mesosphere. Indeed, the gravity wave momentum and forcing of the mesospheric wind have been measured to vary according to the strength and direction of the stratospheric winds [*Xu et al.*, 2011; *de Wit et al.*, 2014, 2015], as has the resultant mesospheric temperature field [*Gumbel and Karlsson*, 2011; *Lübken et al.*, 2014]. However, the connection of these observed mesospheric variations to changes in the springtime stratospheric ozone loss has not been explored.

Recent modeling studies using both the Whole-Atmosphere Community Climate Model and the Canadian Middle Atmosphere Model suggest that ozone loss-induced changes in the stratospheric wind field change the spectrum of upward propagating gravity waves, which in turn changes the forcing on the mesosphere and affects the thermal structure and circulation of the polar mesosphere [*Smith et al.*, 2010; *McLandress et al.*, 2010; *Lossow et al.*, 2012]. However, up to now the effects of ozone loss on the mesospheric circulation have been studied using only model simulations. Here we use long-term mesospheric winds measured by a medium-frequency (MF) radar located at Rothera station (67°S, 68°W) on the Antarctic Peninsula, and stratospheric zonal winds from NASA's Modern-Era Retrospective Analysis for Research and Applications (MERRA) data set, to examine the changes in the mesospheric and stratospheric circulation in response to ozone hole variability during the Antarctic spring.

2. Data

2.1. Rothera MF Radar Data

In the present study, we use horizontal (zonal and meridional) winds measured by a medium-frequency (MF) spaced antenna radar located at Rothera station, Antarctica (67°S, 68°W) [*Hibbins et al.*, 2005]. The radar employs a single broad-beam transmit antenna and three receiver antennas spaced in a triangular array to observe D region partial reflection echoes. The radar operates at a frequency of 1.98 MHz with a transmitter power of 25 kW and full width half maximum pulse width of 25 μs. This corresponds to a height resolution of 4 km sampled at 2 km height intervals between 50 and 100 km. However, the majority of echoes occur at altitudes between 74 and 96 km, limiting the accuracy and temporal coverage of the derived winds below 74 km. The system utilizes a full correlation analysis [*Holdsworth and Reid*, 1995] to determine the wind field. However, since MF radars can underestimate the winds above ~94 km [*Cervera and Reid*, 1995; *Hall et al.*, 2005], we have only used winds between 74 and 92 km for this study. We use the wind measurements from January 2002 to December 2014 during which nearly continuous observations are available. The monthly mean zonal winds from this instrument are shown in Figure 1.

2.2. MERRA Zonal Winds Data

The stratospheric wind data used in the present study are taken from the Modern-Era Retrospective Analysis for Research and Applications (MERRA), whose derivation, quality, and validation are discussed in *Rienecker et al.* [2011]. The six zonal wind values available in MERRA for each day are formed into monthly means at each of the 42 pressure levels between 1000 hPa and 0.1 hPa at the $0.5° \times 0.75°$ grid point nearest to Rothera. The winds from 1979 to 2014 are used in the present study, although for comparison with the mesospheric winds only data from 2002 to 2014 are used. The annual cycle of the monthly mean winds over Rothera at an altitude of 30 hPa (~23 km), which is near the peak of the ozone concentration, is shown in Figure 2a for each of the years between 1979 and 2014.

2.3. Ozone and Ozone-Loss Metrics

The total column ozone (TCO) data used in this study are taken from the Solar Backscatter Ultraviolet Merged Ozone Data Set (SBUV MOD) version 8.6. The SBUV MOD is a monthly zonal-mean time series of total column ozone and ozone profiles spanning the period from January 1970 to July 2013, constructed from measurements made by the Nimbus 4 BUV, Nimbus 7 SBUV, and a series of SBUV(2) instruments [*Frith et al.*, 2014, and references therein]. The data are available on a 5° latitude grid between 87.5°N and 87.5°S. The SBUV MOD is a consistent, well-calibrated data set constructed using a simple average of SBUV data, and monthly means of the TCO were formed for each latitude grid. The data are available at ftp://toms.gsfc.nasa.gov/pub/MergedOzoneData/.

Ozone-hole area and the total ozone mass deficit used in this study are taken from the NASA Ozone Watch (http://ozonewatch.gsfc.nasa.gov/meteorology/SH.html) and are derived from observations from a variety of satellites. The ozone hole area is defined to be that region of ozone values below 220 Dobson units (DU) located south of 40°S. The ozone mass deficit is derived from the ozone hole area and combines the effects of changes in area and depth. It represents the total amount of ozone mass poleward of 40°S removed during the springtime ozone loss event relative to that present for a value of 220 DU.

Finally, model studies have shown that changes in middle atmospheric circulation due to ozone loss should be most prominent between 60°S and 70°S [*Smith et al.*, 2010; *McLandress et al.*, 2010; *Lossow et al.*, 2012], close to the latitude of Rothera. Since these changes are driven by the latitudinal temperature gradients in the stratosphere, themselves related to the latitudinal gradients in ozone, we also considered the TCO difference between 57.5°S and 77.5°S. This should characterize the thermal gradients above Rothera that drive the zonal winds in the stratosphere and is used as a measure of ozone changes during springtime that can affect the circulation.

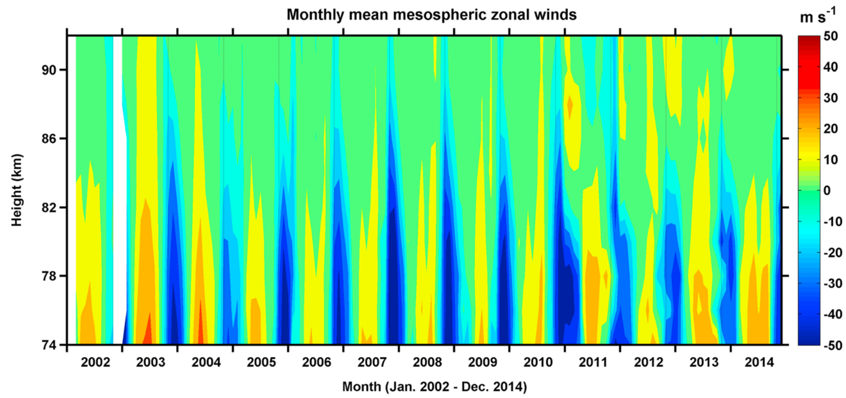

Figure 1. Interannual variability of the monthly mean zonal winds in the mesosphere between 74 km and 92 km.

3. Results

Figure 1 shows the year-height climatology of monthly mean mesospheric zonal winds between 74 and 92 km as measured by the MF radar at Rothera from 2002 to 2014. As can be seen in Figure 1, the westward wind regime over Rothera, characterized by the dark blue contour, qualitatively shows a generally increasing trend in altitude extent from 2002 to 2007 before decreasing after 2011. This interannual variability is examined below in light of changes in the stratospheric wind fields and ozone during late spring.

The linkage between the mesospheric and stratospheric winds at mid-to-high latitudes has been well established [*Xu et al.*, 2011; *de Wit et al.*, 2014, 2015]. Thus, to localize the timing of the mesospheric wind variability seen in Figure 1, the superposition of 36 years (1979–2014) of monthly mean zonal winds at 30 hPa from the MERRA reanalysis data set at Rothera's location is shown in Figure 2a. Here we use winds at 30 hPa as these are near the peak of the ozone concentration and most likely to be affected by ozone loss. As can be seen

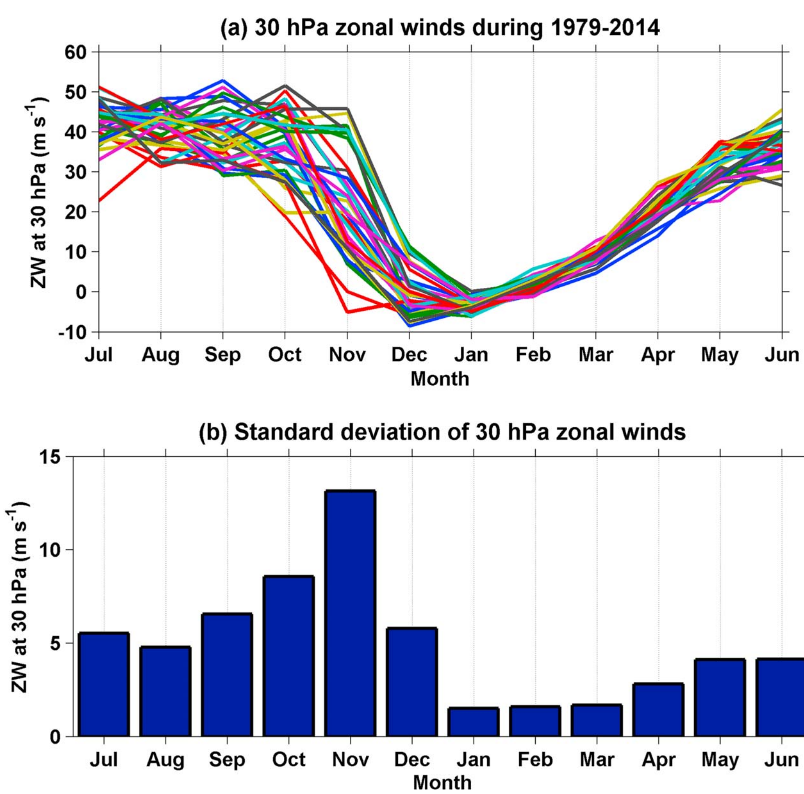

Figure 2. (a) The superposition of 36 years (1979–2014) of monthly mean stratospheric zonal winds at 30 hPa nearest to Rothera's location; (b) monthly standard deviation of these 30 hPa zonal winds.

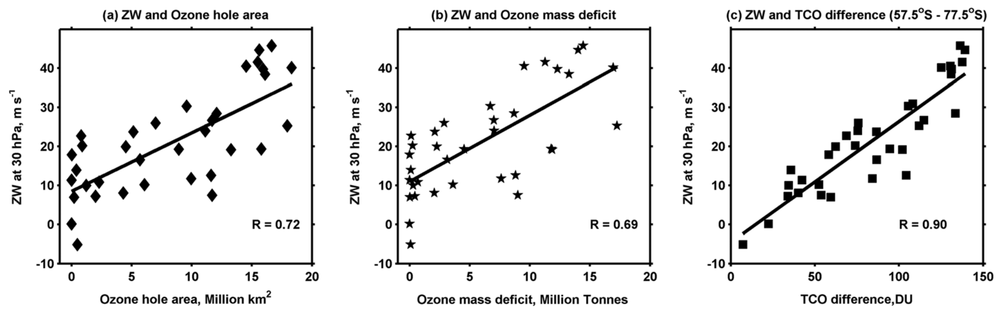

Figure 3. Correlation between zonal winds at 30 hPa with (a) ozone hole area, (b) ozone mass deficit, and (c) difference of total column ozone between 57.5°S and 77.5°S. Note that all these values correspond to the month of November. "R" in each panel indicates the cross-correlation coefficient.

in the figure, the transition from winter to summer conditions varies between October and December (Figure 2a), and as a consequence the largest, year-to-year wind variability occurs in the month of November (Figure 2b).

During November, the winds around 30 hPa represent the largest eastward winds in the column below the mesosphere and provide the main filtering of the upward propagating gravity waves that link the winds in these two regions [e.g., *Smith et al.*, 2010; *de Wit et al.*, 2014, 2015]. The large interannual variability of these November winds should therefore provide the largest changes in the gravity wave filtering, and hence, the greatest variability in the mesospheric winds should also occur then. Therefore, in the following we focus on the variability of stratospheric and mesospheric winds for November, corresponding to late spring in the southern hemisphere (SH).

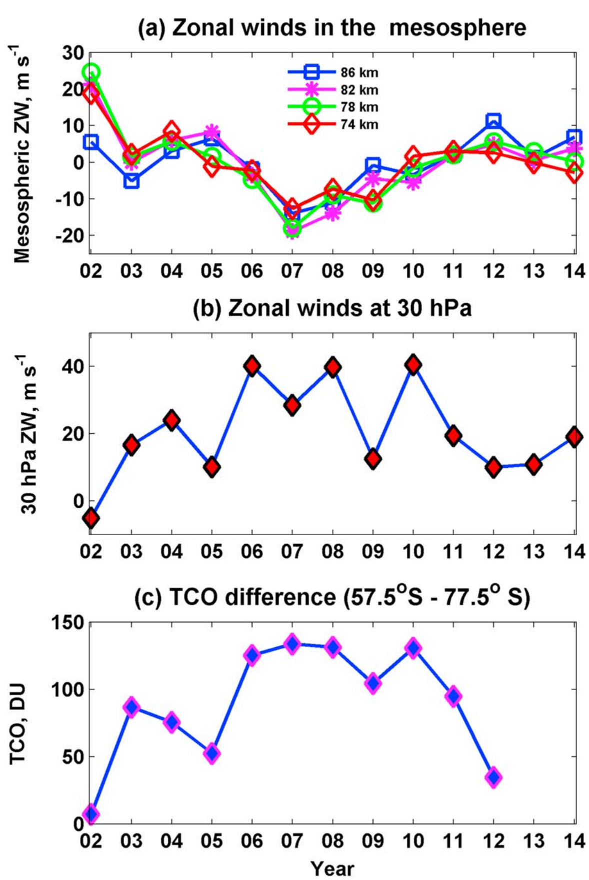

Figure 4. Interannual variability of the monthly mean (a) zonal wind anomalies in the mesosphere at 74 km, 78 km, 82 km, and 86 km; (b) the stratospheric zonal winds at 30 hPa; and (c) the TCO difference. All values correspond to the month of November.

Comparisons of the 30 hPa zonal winds during November from 1979 to 2014 with different measures of ozone loss are shown in Figure 3. The scatterplots in Figure 3 show the correlations of the stratospheric winds at 30 hPa with (a) ozone hole area, (b) ozone mass deficit, and (c) the TCO difference between 57.5°S and 77.5°S. The zonal winds at 30 hPa show a good correlation with ozone hole area (correlation coefficient, $R = 0.72$), ozone mass deficit ($R = 0.69$), and TCO difference ($R = 0.90$), in keeping with previous studies. The large correlation with TCO difference, compared to other ozone loss parameters, indicates that the latitudinal gradients in ozone play an important role in driving the stratospheric zonal circulation. However, note that the TCO difference itself is predominantly driven by ozone loss and recovery at the southern pole.

To examine whether the mesospheric winds are affected by these ozone loss-induced changes in the stratospheric wind field, we compare the November mesospheric winds from Rothera at several altitudes with both the stratospheric winds at 30 hPa and the ozone gradients during 2002–2014. Figure 4a

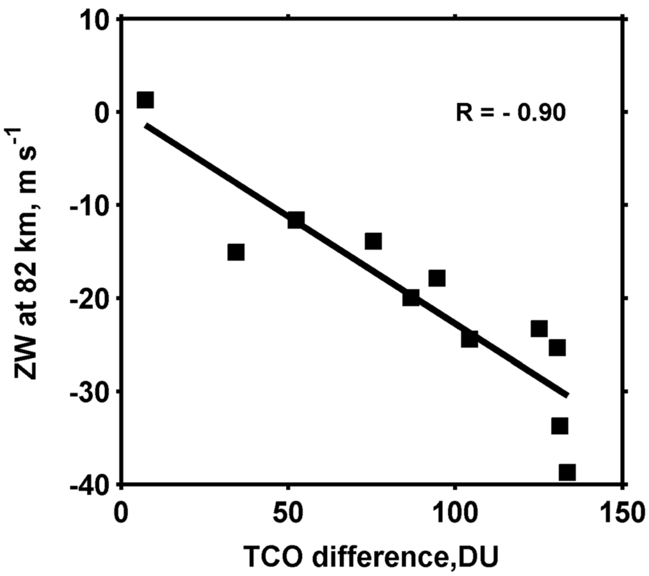

Figure 5. Correlation between the monthly mean zonal wind anomaly at 82 km and the TCO difference during November. R indicates the correlation coefficient.

shows the mesospheric zonal winds at four heights (74 km, 78 km, 82 km, and 86 km). Here the average November mean wind at each height, derived from the 13 year climatology, has been removed so that the wind anomalies at all the heights have the same mean. Figure 4b shows the stratospheric zonal winds at 30 hPa during the period for which mesospheric winds are available, and Figure 4c shows the TCO difference, representing the difference in TCO values between 57.5°S and 77.5°S latitudes, over the same time period. From the figure it is clear that the anomalously strong eastward winds in the stratosphere during November, driven by the polar ozone loss that delays the springtime warming of the pole, are accompanied by strong westward wind anomalies in the mesosphere.

The relation between the mesospheric zonal wind anomaly and the spring ozone loss itself is shown in Figure 5, which gives the correlation analysis between the November mesospheric wind anomaly at 82 km and the TCO difference. The zonal wind anomaly at 82 km shows a strong anticorrelation with the TCO difference ($R = -0.90$). Thus, the November winds in the stratosphere and mesosphere show their largest correlation and anticorrelation, respectively, with the TCO difference, suggesting that the latitudinal gradients in ozone driven by ozone loss play an important role in the mesospheric dynamics at southern high latitudes during spring time. Although these effects are also observed in December (figures not shown), the ozone gradients and subsequent changes in the stratosphere and mesosphere zonal winds are smaller than in November.

4. Discussion and Conclusions

Long-term (2002–2014) measurements of horizontal winds in the mesosphere measured by an MF radar at Rothera (67°S, 68°W) have been combined with stratospheric zonal winds from the MERRA reanalysis data set and total column ozone observations from the SBUV satellite to show the relationship between circulation changes in the polar mesosphere and stratosphere and the ozone loss in the Antarctic. During the late southern spring (November), Antarctic ozone shows large interannual variability. Associated with these ozone changes, the zonal winds in the stratosphere and mesosphere also show large interannual variability. With increased ozone loss during the spring, winter conditions of strong eastward winds in the stratosphere persist into November and December, and these are associated with a large westward wind anomaly in the mesosphere.

The observed persistence of the wintertime eastward stratospheric polar vortex with increased polar ozone loss is consistent with previous observations and modeling studies [*Waugh et al.*, 1999; *Randel and Wu*, 1999; *Waugh and Randel*, 1999; *Langematz et al.*, 2003; *Stolarski et al.*, 2006; *Smith et al.*, 2010; *Lossow et al.*, 2012]. These investigations have found that with increased ozone loss, temperatures in the polar stratosphere remain colder as the heating by solar absorption is reduced. This leads to a prolongation of the large wintertime pole-to-equator temperature gradients, which, through thermal wind balance, maintain the strong wintertime eastward winds in the lower stratosphere longer into the early summer.

The direction of the mesospheric wind anomalies are found to be in antiphase with that of the stratosphere. That is, while the November stratospheric winds show a positive (eastward) anomaly with increases in the ozone loss, the mesospheric winds show a negative (westward) anomaly. This is consistent with the observational results of *Xu et al.* [2011] and *de Wit et al.* [2014, 2015], who find that the strength and direction of the stratospheric wind varies the gravity wave filtering in the stratosphere, with stronger eastward winds

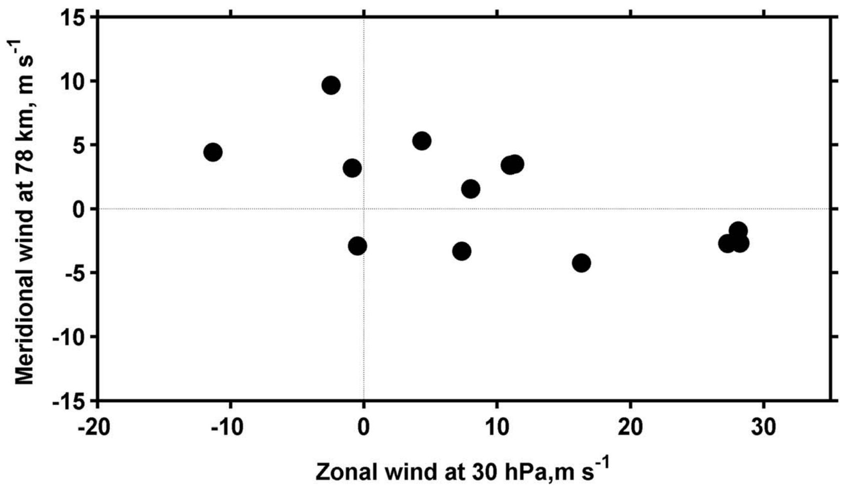

Figure 6. Scatterplot of the November 30 hPa zonal wind anomaly versus the November 78 km meridional wind above Rothera for the years 2002 to 2014. Poleward flow in the upper mesosphere (wintertime conditions) typically occurs during years with high eastward stratospheric zonal winds (and vice versa).

removing the eastward gravity waves and their momentum. The resultant westward momentum reaching the mesosphere forces the mesospheric wind toward the west. However, here we show that the strength and direction of the mesospheric wind anomalies during November are directly proportional to the ozone gradients that force the stratospheric wind anomalies, experimentally confirming previous modeling results [*Smith et al.*, 2010; *McLandress et al.*, 2010; *Lossow et al.*, 2012]. The correlation coefficients of the ozone gradient with stratospheric and mesospheric winds are both 0.90, clearly indicating that the variability in the circulation of both the stratosphere and mesosphere during early summer is driven by the ozone loss occurring in the Antarctic stratosphere.

The influence of the ozone hole on the dynamics of the middle atmosphere is multifold. In the present study we note a large westward anomaly in the mesospheric winds during years when large polar stratospheric ozone loss and eastward stratospheric winds persist into the early summer. To confirm that this mesospheric wind anomaly is due to the enhanced westward gravity wave forcing caused by the stratospheric winds, we show in Figure 6 the November 30 hPa zonal wind plotted against the November 78 km meridional wind above Rothera for the years 2002 to 2014. During years when the winter conditions of strong eastward winds persist into late spring in the stratosphere (a consequence of increased stratospheric ozone gradients), a poleward (southward) residual circulation is observed in the upper mesosphere. This convergent residual circulation is characteristic of the winter conditions of westward gravity wave forcing in the mesosphere, and this extended wintertime mesospheric circulation will reduce upwelling in the polar mesosphere and lead to higher temperatures in the mesopause region [*Espy et al.*, 2003; *Smith et al.*, 2010]. In addition, the reduced upwelling affects the upward transport of water vapor to the mesopause region. All these effects should lead to a delay in summertime conditions needed for polar mesospheric cloud (PMC) formation. Indeed, previous studies have shown a clear relationship between the stratospheric polar vortex variability and the onset of the PMC season [*Karlsson et al.*, 2011; *Benze et al.*, 2012] but have not made the connection to the causal agent, the polar ozone loss. For example, *Karlsson et al.* [2011] showed that the PMC onset was delayed in 2007–2008 and 2008–2009 summers (SH) compared to the 2009–2010 summer. Here we can see from Figure 4c that the stratospheric ozone gradient is greater in the first 2 years than in the third, indicating that the ozone loss in the stratosphere in springtime delays the onset of the occurrence of PMCs. The ozone loss may also affect the occurrence of polar mesospheric summer echoes (PMSE) as these phenomena are also dependent on cold summer temperatures and the upward transport of water vapor [*Rapp and Lübken*, 2004].

The variability in spring time ozone loss provides a plausible explanation for the enhanced variability of the PMC season onset in the SH compared to its northern hemisphere counterpart [*Karlsson et al.*, 2011]. Based on the results presented here, future scenarios of polar stratospheric ozone recovery [e.g., *Eyring et al.*, 2007] should make the onset of polar mesospheric summer conditions occur earlier and more regularly, thus extending the PMC/PMSE observation season in the southern hemisphere.

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