The Antarctic ozone hole during 2008 and 2009

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The Antarctic ozone holes of 2008 and 2009 are reviewed from various perspectives, making use of a range of Australian data and analyses. In both years, ozone holes formed that were fairly typical of those observed since the late 1990s. The ozone hole of 2008 was somewhat larger than that of 2009. In 2009 the ozone hole developed more rapidly, but did not last as long as in 2008, particularly in the lower stratosphere.

Introduction

As a result of the enactment of the Montreal Protocol in 1987 and its subsequent Amendments and Adjustments, the global consumption and production of Ozone Depleting Substances (ODS) has been successfully controlled, leading to the situation today in which the atmospheric abundances of nearly all major ODSs are now in decline (Montzka et al. 2011). However, ozone depletion will continue to occur for several more decades. The most dramatic example is the annual Antarctic ozone hole, the region of severe ozone depletion which has been observed to form in the stratosphere over Antarctica every year since the early 1980s (Farman et al. 1985; Stolarski et al. 1986; Solomon 1999; Yang et al. 2008; Hoffman et al. 2009).

Tully et al. (2008) reported on the 2007 Antarctic ozone hole and provided some background information on the formation of the hole and projections of Antarctic ozone recovery, to which the reader is referred. As noted there, the impact of the ozone hole on Southern Hemisphere climate has been increasingly identified (Thompson and Solomon 2002; Arblaster and Meehl 2006; Cai 2006; Keely et al. 2007; Roscoe and Haigh 2007; Crook et al. 2008; Karpechko et al. 2008, 2010; Perlwitz et al. 2008; Son et al. 2008, 2009; Waugh et al. 2009a; Polvani et al. 2011a, 2011b; Arblaster et al. 2011). For example, changes to surface climate caused by ozone depletion may have increased Antarctic sea-ice extent (Turner et al. 2009), as well as influenced the ability of the Southern Ocean to absorb carbon dioxide from the atmosphere (Lenton et al. 2009).

Conversely, as the atmospheric concentrations of ODSs decline over coming decades, it is expected that changes in climate caused by anthropogenic emissions of long-lived greenhouse gases will play an increasing role in influencing stratospheric ozone abundance (Akiyoshi 2009; Waugh et al. 2009b, SPARC CCMVal 2010; Eyring et al. 2010; Oman et al. 2010).

The development of the ozone hole is also influenced by dynamical changes that have been observed in the Antarctic polar vortex (Grystai et al. 2007; Hassler et al. 2011).

The current estimate of the time when total stratospheric halogen concentration in Antarctica returns to its 1980
level is the year 2073 (Daniel et al. 2011), based on current atmospheric mixing ratios, projected production levels and existing bank sizes. However, it must be borne in mind that this calculation is sensitive to assumptions and scenarios regarding hypothetical future ODS production, and the projection would vary significantly under different choices of scenarios. As well, it does not take into account anticipated changes in atmospheric transport or atmospheric lifetimes, and more significantly, this date does not necessarily reflect the date when polar ozone returns to 1980 levels, since as noted above, ozone levels are projected to become increasingly influenced by other atmospheric changes.

In this paper, we analyse the Antarctic ozone holes of 2008 and 2009 from various perspectives and present a range of Australian and international data and analyses, including Bureau of Meteorology (BoM) meteorological analyses, ozone data from satellite instruments analysed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the Australian Antarctic Division (AAD), ozone profiles from Antarctica obtained from the AAD and BoM ozonesonde programme, Antarctic ultraviolet measurements from the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) biometer network and data from the OSIRIS instrument on board the ODIN satellite.

Meteorological conditions

On interannual timescales the Antarctic ozone hole exhibits considerable variability in severity, due to meteorological conditions in the Antarctic stratosphere, which is superimposed upon a much more slowly varying trend due to changes in stratospheric halogen loading. The temperature evolution above the South Pole during 2008 and 2009 was similar between the two years (Fig. 1), and overall slightly colder than the long-term average (by approximately 1 K at 50 hPa). Temperatures below 195 K (black contour in Fig. 1), which are typically cold enough for the formation of Type I Polar Stratospheric Clouds (PSCs), occurred from May to October, and had similar temporal and vertical evolutions in the two years. A notable difference between the two years occurred in October 2009 when a warming of approximately 5 K over a period of about two weeks occurred at pressures lower than 300 hPa (see Fig. 1(b)). Additionally, warming of the lower stratosphere progressed more rapidly in 2009, occurring approximately two weeks earlier than in 2008.

Temperature in the Antarctic stratosphere is strongly anti-correlated to preceding mid-latitude eddy heat flux (Fusco and Salby 1999; Newman and Nash 2000; Randel et al. 2002; Weber et al. 2003; Salby and Callaghan 2004; Huck et al. 2005). Daily eddy heat flux averaged between latitudes 65°S and 45°S as a function of pressure derived from the NCEP Reanalysis 2 assimilation (Kanamitsu et al. 2002) for 2008 (top) and 2009 (bottom) is shown in Fig. 2. Two episodes of strongly negative values (that is, significant poleward heat-flux) occurred in October 2009. This resulted in a weaker vortex and warmer temperatures.

The structures of the vortices during 2008 and 2009 are described using the potential vorticity gradient in equivalent latitude in Fig. 3 on the 500 K potential temperature isentrope. This isentropic level is near the top of the region of maximum springtime ozone loss. The vortex strength and location is similar between the two winters. Davis station (68.6°S, 78.0°E), which is located at the continental edge of East Antarctica and the site of Australian polar ozonesonde measurements, was inside the vortex for both seasons except during its final breakdown in December, although it remained inside for noticeably longer in 2008.

Further information on Antarctic atmospheric conditions can be found in WMO Antarctic Ozone Bulletins (http://www.wmo.int/pages/prog/arep/gaw/ozone/index.html) and Winter Bulletins of the National Oceanic and Atmospheric Administration (http://www.cpc.noaa.gov/products/stratosphere/winter_bulletins), the annual summaries of the National Climate Data Center (http://www.ncdc.noaa.gov/oa/
climate/research/monitoring.html) and annual instalments of the State of the Climate Report (http://lwf.ncdc.noaa.gov/oa/climate/research/state-of-climate/). Specific details of stratospheric conditions in 2008 can be found in Klekociuk et al. (2009).

**Satellite measurements of total column ozone**

In this section, a number of the standard metrics used for characterising the severity of the Antarctic ozone hole are presented, as computed by CSIRO Marine and Atmospheric Research (CMAR) using data from the Ozone Monitoring Instrument (OMI) onboard the National Aeronautics and Space Administration (NASA) Aura satellite, and the earlier Total Ozone Mapping Spectrometer (TOMS) instruments on board the Earth Probe (EP) and Nimbus-7 satellites. These metrics are all based on total column ozone, and as standard, we define the ozone hole as being the region over which total column ozone is less than 220 Dobson Units (DU). The data used here are processed with the TOMS version 8.5 algorithm; OMI data are used for years 2005–2009, and TOMS data are used for 1979–2005.

In June 2009, all of the OMI ozone data products were updated by NASA. These were subsequently processed by CSIRO, which has resulted in small changes in the ozone hole metrics reported for years 2005–2008 in Tully et al. (2008). In mid-2007, a corrected version of all the EP-TOMS data (1996–2005) was released. The correction addressed a degradation of the scanner mirror on TOMS that resulted in latitudinally dependent calibration errors. An empirical correction was applied based on the NOAA-16 SBUV/2 ozone record. The above-mentioned reprocessed and corrected datasets are used here. The analyses of the 2006–2009 Antarctic ozone holes are based on OMI data only, whereas the analysis of the 2005 hole is based on both OMI and TOMS data, and the analysis of 2004 and earlier holes is based on TOMS data only.
Daily values of the three most widely used ozone hole metrics are shown for July to December in Fig. 4: daily ozone hole area, the daily minimum column ozone observed south of 35°S, and the daily ozone mass deficit (the mass of ozone lost within the ozone hole compared to 220 DU). The slightly larger overall size of the 2008 ozone hole compared with that in 2009 can be gauged from Fig 4(a) and 4(c) (2008 values were generally higher than for 2009 particularly during September and October). Of additional note is the generally earlier start in depletion of 2009 compared with 2008 (comparing the changes in August between the two years, particularly in Figs 4(a) and 4(c)), and the earlier recovery in 2009 (comparing the December values in all panels of Fig 4). A feature of 2009 was the notable decline followed by partial recovery in the daily area deficit metrics during the middle of October (Figs 4(a) and 4(c); note also the increase in minimum ozone over the same period in Fig. 4(b)). This was a result of the strong episode of poleward heat flux mentioned above.

Table 1 lists seven metrics for all 30 ozone holes recorded since 1979; 2008 was moderately severe in terms of maximum daily area (ranked 6th), and maximum daily deficit (also ranked 6th), compared with 2009 which ranked lower for these metrics (15th and 9th). While 2009 ranked markedly lower than 2008 for most of the metrics given in Table 1, the actual values of area and deficit were only approximately ten per cent smaller in 2009. Slightly lower minimum ozone values were observed in 2009.

The development of the three most widely used metrics from year to year is shown in Fig. 5. Also marked is a regression against polar Equivalent Effective Stratospheric Chlorine (EESC), which is a calculated measure of the total ozone-destroying effectiveness of chlorine and bromine compounds in the Antarctic stratosphere, based principally on ground-based measurements and assuming a mean transport time of five and a half years (Newman et al. 2006). While the values of these metrics would not be expected to be a simple linear function of EESC, in all three cases, a linear fit is able to match the decadal variation reasonably well and give a guide to the relative importance of meteorological variation, particularly in recent years when the halogen loading has been relatively constant.

Figure 5 also makes clear the overall similarity between the two years.

### Halley total column ozone

To place 2008 and 2009 into a longer perspective, monthly mean total column ozone values for September to November obtained from Dobson spectrophotometer measurements at Halley station (75.6°S, 26.5°W) by the British Antarctic Survey for 1957–2009 are shown in Fig. 6(a). The values for 2008 and 2009 are similar (particularly for September and October), and comparable to, though slightly larger, than values in the mid-to late-1990s. The October mean values are also shown in Fig. 6(b) with a regression to calculated Antarctic EESC, again as a guide to interpreting the variability.
Table 1. The ranking of various metrics that measure the severity of the Antarctic ozone hole: 1 = lowest ozone minimum, greatest area, greatest ozone loss etc.; 2 = second largest... Ozone hole depth is based on the minimum column ozone amount on any day during the ozone hole season. Fifteen-day average ozone hole depth is based on a fifteen-day moving average of the daily ozone hole depth. Minimum average ozone is the minimum daily average ozone amount (within the hole) on any day during the ozone hole season. Daily ozone hole area is the maximum daily ozone hole area on any day during the ozone hole season. Fifteen-day average ozone hole area is based on a fifteen-day moving average of the daily ozone hole area. Daily maximum ozone deficit is the maximum ozone deficit on any day during ozone hole season. Ozone deficit is the integrated (total) ozone deficit for the entire ozone hole season.

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Hassler et al. (2011) have recently studied the influence of dynamical changes in assessing long-term records of total ozone changes from Antarctic ground stations, and found that at Halley, dynamical changes to the vortex have not greatly influenced the interpretation of the ozone record.

**Vertically-resolved satellite measurements**

To investigate more closely the vertical structure of ozone depletion in 2008 and 2009, in Fig. 7, ozone hole area metrics are provided for three partial columns in the lower stratosphere, mid-stratosphere and full stratosphere (denoted as ‘low’, ‘mid’ and ‘full’ partial columns respectively) based on measurements by the Microwave Limb Sounder (MLS) instrument onboard the Aura spacecraft (Froidevaux et al. 2008). The MLS instrument provides height-resolved ozone information during day and night, and is thus able to measure the portion of the vortex that is within continuous darkness during winter and spring and outside the region measured by the OMI instrument. The black time series (full stratosphere) in Fig. 7 shows that the ozone hole in 2009...
began to rapidly expand on 10 August, approximately 10 days earlier than it did in 2008. At this time, the largest ozone change took place in the mid-stratosphere (blue time series). After the beginning of September, the size of the ozone hole in the mid-stratosphere showed similar evolution for the two years. In October 2009 heat flux bursts, as evident in Fig. 2 and noted earlier, resulted in a marked dip in both ‘low’ and ‘full’ ozone values. In the lower stratosphere (red time series), the ozone hole in 2009 was generally smaller and disappeared earlier than it did in 2008. Similar behaviour can be seen for the full stratosphere partial column (black time series). This is related to the small values of poleward heat flux late in the year in 2008. Overall, the main differences between the two years were the earlier development in 2009 because of more rapid decline of ozone in the mid-stratosphere, and a smaller overall size in 2009 because of less depletion in the lower stratosphere.

**OSIRIS**

The Optical Spectrograph and Infra-Red Imager System (OSIRIS) instrument, launched in 2001 onboard the Odin satellite, produces vertical profiles of ozone number density from 6–8 km (or from cloud top) to 55–60 km with a 1 km step (Llewellyn et al. 2004). As Odin is on a polar synchronous orbit with a 98° inclination, the measurements are performed between 82.2°N and 82.2°S. The ozone number density profiles are retrieved from the OSIRIS spectral measurements of limb-scattered sunlight; thus no ozone data are available over polar regions during local winter when the solar zenith angle is greater than about 87°. The OSIRIS ozone retrieval algorithm and validation results, that suggest an uncertainty of five per cent, or less, at 15–25 km are described in detail in von Savigny et al. (2003), Petelina et al. (2004), and Roth et al. (2007).

Figure 8 shows vertical distribution of OSIRIS daily zonal mean ozone partial pressure averaged between 60° and 82.2°S during the Antarctic spring–summer periods of 2008 and 2009. For the 2008 ozone hole, clearly seen at around 15 km between September and January, the ozone partial pressure was overall much lower than that in 2009. As well, the 2009 ozone hole can be seen to have formed about two weeks earlier and nearly disappeared by November 22, while the 2008 hole lasted until about December 22, again relating to a markedly less disturbed polar vortex than usual at this time. As was evident in Fig. 7, the earlier development of the 2009 ozone hole was primarily due to more rapid ozone decline in the middle levels of stratosphere, while the greater persistence of the 2008 ozone hole was due to continued depletion in the lower levels.

**Ozonesondes**

Since 2003, BoM and AAD have conducted a program of ozonesonde releases from Davis station. Flights have been carried out at weekly intervals during winter and spring and monthly for the remainder of the year. Results of measurements during 2008 and 2009 are presented in Figs. 9–10. The time-height evolution of ozone partial pressure is shown in Fig. 9(a). The stratospheric ozone layer is apparent as the regions of ozone partial pressure greater than around 10 mPa. At Davis, the layer lies above approximately 20 km height at the start of the year and generally descends by approximately 5 km by the end of winter due to subsidence inside the polar vortex. Low ozone partial pressures in the height range 15–25 km in September and October are associated with Davis being inside the ozone hole. During 2008, the effects of the ozone hole can be seen to persist through to the end of the year, whereas during November–December 2009, the ozone partial pressure in the height range 15–25 km was distinctly higher by comparison. The relatively strong ozone layer at the end of 2009 was associated with the breakdown of the polar vortex and Davis being outside the vortex edge (compare Figs 3(a) and 3(b)). An excursion of the vortex to lie south of Davis also occurred in late October 2008 (near day 300), producing a short-lived increase in ozone partial pressure above 12 km height. A similar event occurred in early October 2009 (near day 275), resulting in the apparent increase in ozone concentration above 18 km height. The main differences between the two years are shown more clearly in the ozone mixing ratio anomaly plots of Fig. 9(b). Additionally, the two panels of this figure reveal that ozone in the upper troposphere was consistently lower after mid-winter in 2009 compared with 2008.

Ozone partial column time series for Davis are shown in Fig. 10. The 12–20 km and 20–25 km partial column values shown in Figs. 10(a) and 10(b), respectively, were generally lower in 2009 than those in 2008, particularly over the winter
and spring seasons (spanned by days 150–250). Short-lived increases in both years (near day 300 in 2008 and near day 275 in 2009) are also apparent. These increases are generally consistent with variability in other years.

Antarctic ultraviolet radiation

Solar ultraviolet (UV) radiation in Antarctica is measured by the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA), in collaboration with the Australian Antarctic Division (AAD). Broadband ultraviolet radiation (UVR) detectors (UVBiometer Model 501, Solar Light Co., Philadelphia USA) are located at the three stations on the Antarctic continent operated by AAD: Casey (66.3°S, 110.5°E), Davis (68.6°S, 78.0°E) and Mawson (67.6°S, 62.9°E). A description of the detectors and calibration methods used by ARPANSA in Antarctica has been published previously (Tully et al. 2008).

The measured daily UV Index values for each of the sites along with the daily total column ozone value derived from OMI satellite observations for the 2008 and 2009 seasons are shown in Fig.11(a)–(c) and 11(d)–(f), respectively. Superimposed on the seasonal variation of UV Index due to solar zenith angle changes and effects of local weather conditions (cloud), strong anti-correlation between the measured UV Index and OMI satellite measurements of total column ozone is observed for clear sky days.

The World Health Organization (WHO 2002) classifies solar UVR exposure risk on the basis of UV Index as Low (2 or less), Moderate (3 to 5), High (6 to 7), Very High (8 to 10) or Extreme (11 or more). Peak UV Index levels recorded at the edge of the Antarctic continent occasionally reach Extreme levels when clear skies combine with low total column ozone levels.

Table 2 shows the number of days for which the OMI satellite total column ozone value was less than 220 DU, indicating the presence of the ozone hole, for each of the Australian stations in Antarctica for 2007–2009.

2008 season

Despite the persistence of the 2008 season’s ozone hole, there were fewer occasions when it passed over the AAD stations in December and a similar number of times in November compared with 2007. All of the Antarctic stations recorded
Fig. 9  Time-height sections obtained from ozonesonde measurements at Davis station. (a) Ozone partial pressure in 2008 (left) and 2009 (right), interpolated to a uniform grid at 500 m (vertical) by 8 days (horizontal) resolution. The time of the measurements is shown by the vertical lines near the top of each panel. The location of the thermal tropopause (WMO definition) is shown by the black dots connected by white lines. (b) Ozone mixing ratio anomaly with respect to the Fortuin-Kelder ozone climatology (Fortuin and Kelder, 1998).

Fig. 10  Partial column ozone derived from ozonesonde measurements at Davis station. (a) 12–20 km partial column. (b) 20–25 km partial column. The solid grey line in each panel is the seasonal variation of the Fortuin and Kelder climatology (Fortuin and Kelder, 1998).
Fig. 11 Total column ozone in Dobson units (left axis) and daily UV Index (right axis) for (a, d) Casey (66.3°S, 110.5°E), (b, e) Davis (68.6°S, 78.0°E) and (c, f) Mawson (67.6°S, 62.9°E) in (2008, 2009) respectively. Also shown is the line for 220 Dobson units, where ozone values lower than this are defined as being part of the ozone hole (left axis).
Table 2. Number of ozone hole events (defined as total column ozone less than 220 DU based on OMI satellite measurements) over each of the Australian Antarctic stations by month for 2007-2009—Casey (66.3°S, 110.5°E), Davis (68.6°S, 78.0°E) and Mawson (67.8°S, 62.9°E).

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extreme UV Index levels (11 or greater) in 2008, once each at Casey and Davis and on three occasions at Mawson.

There were significantly more ozone hole events at Casey during this year, 27 in 2008 compared with only nine in 2007, most of which occurred in September and October. The final ozone hole event for Casey occurred over the days of 7 to 10 November 2008. Although skies were overcast throughout this period, the clearest of these days was the 10th which combined with the very low total column ozone reading of 172 DU gave the highest UV Index for the season of 11 (Fig. 11(a)).

At Davis there were four fewer ozone hole events in 2008, with more occurrences in September, fewer in October and none in December. The highest UV Index for the season was recorded in early November. Three clear sky days from 7 to 9 November 2008 coincided with an ozone hole event and produced an extreme UV Index of 11+ on the 9th (Fig. 11(b)).

There was very little difference in the number or timing of ozone hole events over Mawson station during the 2008 season compared to 2007. The final ozone hole event (209 DU) occurred on 4 December 2008 when the measured UV Index reached extreme levels 11+ (Fig. 11(c)).

2009 season
There was little difference in the number of ozone hole events recorded over the AAD stations in the 2009 season compared to 2008. However there were significantly more ozone hole events in October and fewer in November 2009 compared to the previous year. The most noteworthy aspect of the 2009 ozone hole is the abrupt end of its influence above the AAD stations in the first days of November. Simultaneously, the measured UV Index dropped dramatically. At Davis and Mawson the ozone was higher than the long-term average for virtually all of November while for Casey the ozone values returned to long-term average levels by mid-November. Only two days of Extreme UV were recorded in 2009, one each for Casey and Mawson. The UV Index did not exceed 10 (Very High) at Davis during the 2009 season.

According to the OMI satellite data, the minimum total column ozone over Casey occurred on 20 – 27 September 2009 when the ozone was 152 – 163 DU. However, the UV Index over these dates was only 4 (Moderate) due to cloud cover and the relatively large minimum solar zenith angle at this time of year. A few days later on 30 September the skies were clear over Casey and yet the UV Index was only 2 (Low) as the ozone measured by OMI soared to 420 DU. This was the result of the ozone hole being displaced off the pole in the direction of South America and an accompanying movement of ozone-rich mid-latitude air over the Australian sector of the Antarctic coast. The majority of ozone hole events over Casey occurred from mid-October to the first week of November 2009, during which time there were few clear-sky days and the UV Index was Very High on twelve occasions. On 1 November the OMI total column ozone value was 170 DU and with a mostly clear sky afternoon the UV Index reached 11+ (Extreme) (Fig. 11(d)). Due to the ozone levels returning to long-term average levels soon after this time the UV Index level of Very High was not reached again until mid-December.

One notable aspect of this year’s record of UV Index at both Davis and Mawson was that the maximum recorded UV levels occurred in October, earlier than is typical. The highest UV Index recorded at Davis was 10 (Very High) on the 30th and 31st of October (Fig. 11(e)) and for Mawson it was 11+ (Extreme) on the 31st of October (Fig. 11(f)). In addition, the monthly average UV Index for October was well above the levels recorded in the previous few years while for November they were significantly lower and in December they were only slightly lower.

Mid-latitude effects
During the period of the breakup of the 2009 Antarctic ozone hole, unusually low ozone values were recorded by the Bureau of Meteorology’s long term ozone monitoring program at Macquarie Island (158.9°E, 54.5°S). Observations of total ozone with a Dobson spectrophotometer were first made at this site in 1957; however data prior to 1987 are currently under review. Two episodes of very low ozone were observed on 5 November 2009 (daily average 266 DU) and then 15–16 November (272 and 278 DU). The lowest single value was 256 DU measured by Direct-Sun observation at
2:46 pm on the 5th. The daily average of 266 DU was the lowest for this time of year recorded since at least since 1987 (Fig. 12).

Figure 13 shows potential vorticity for 5 November 2009 at the 450 K potential temperature isentrope, revealing that on this date the polar vortex had become distorted in an almost wave-2 pattern, and was unusually stretched in the direction of the Tasman Sea.

Figure 14 shows the location of Macquarie Island in terms of potential vorticity plotted for winter and spring of 2009, along with the inner and outer edge of the polar vortex, at the 500 K potential temperature isentrope. On both 5 November and 15 November, Macquarie Island was situated poleward of the central vortex edge, resulting in ozone-depleted air from the polar vortex being directly overhead.

It is unusual for such substantial remnants of the ozone hole to extend so far from Antarctica in the Australian sector, as usually elongations tend to occur more in the direction of the Antarctic Peninsula and South America, and this episode warrants further investigation.

Conclusions

In summary, the Antarctic ozone holes that formed in 2008 and 2009 were both fairly typical of those that have been observed since the mid-1990s. In terms of maximum daily area they ranked 6th (26.9 million square kilometres) and 15th (24.4 million square kilometres) respectively. The ozone hole of 2008 developed more slowly than in 2009 and lasted well into December. This is essentially a reflection of the greater overall strength of the polar vortex in 2008, which led to a more circular and less elongated shape than usual in August, in turn resulting in less area being exposed to sunlight initially to instigate ozone depletion. However, by September and the end of the polar night, the strength of the vortex caused a larger and more persistent ozone hole, particularly evident in the lower levels of the stratosphere.

Fig. 13  Polar map of potential vorticity (expressed in negative potential vorticity units (PVU; 1 PVU = 10⁻⁶ K m² kg⁻¹ s⁻¹)) on 2009 November 5 and the 450 K potential temperature isentrope, obtained from GASP analysis.

Fig. 14  Analysis of the polar vortex edge for the 500 K potential temperature isentrope (around 20 km altitude), derived from the United Kingdom Meteorological Office (UKMO) stratospheric assimilation. Plotted as a function of time are the equivalent latitudes of the ‘inner’ (blue line), ‘central’ (black line), and ‘outer’ (orange line) limits of the vortex edge as defined by Nash et al. (1996). The equivalent latitude of Macquarie Island (54.5°S, 159.0°E geographic) is shown by the red line. Note the excursions on 5 and 15 November during which Macquarie Island was situated poleward of the central vortex edge.
Acknowledgments

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