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Contrasts between Antarctic and Arctic ozone depletion

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This work surveys the depth and character of ozone depletion in the Antarctic and Arctic using available long balloon-borne and ground-based records that cover multiple decades from ground-based sites. Such data reveal changes in the range of ozone values including the extremes observed as polar air passes over the stations. Antarctic ozone observations reveal widespread and massive local depletion in the heart of the ozone "hole" region near 18 km, frequently exceeding 90%. Although some ozone losses are apparent in the Arctic during particular years, the depth of the ozone losses in the Arctic are considerably smaller, and their occurrence is far less frequent. Many Antarctic total integrated column ozone observations in spring since approximately the 1980s show values considerably below those ever observed in earlier decades. For the Arctic, there is evidence of some spring season depletion of total ozone at particular stations, but the changes are much less pronounced compared with the range of past data. Thus, the observations demonstrate that the widespread and deep ozone depletion that characterizes the Antarctic ozone hole is a unique feature on the planet.

atmosphere | chemistry | stratosphere | trend

The observation and verification of extensive ozone depletion in the Antarctic ozone "hole" region has been a focus of considerable public and scientific attention for ≈2 decades (1, 2). It is well established that the ozone hole is mainly driven by human-made chlorofluorocarbons, through surface chemistry that takes place on polar stratospheric cloud particles that form at altitudes from ≈12 to 24 km under the very cold conditions that prevail in the Antarctic (3). It also has been demonstrated that significant ozone depletion can take place in other locations, particularly in the Arctic during cold winters (e.g., refs. 4–6). The question of whether Arctic ozone depletion can be as severe as that of the Antarctic is a matter of substantial interest to experts and both interest and confusion to the public. The primary focus of this work is to provide simple illustrations that can readily clarify the similarities and differences between the character of ozone depletion found at the two poles. In addition, we present probability distribution functions for ozone data and show how these provide insight into the observed changes in extreme values.

Polar ozone depletion is initiated through the combination of surface chemistry involving chlorine along with the action of sunlight, so that the maximum ozone losses are observed in the respective spring seasons in both hemispheres (2). Here we focus on a comparison of the behaviors observed in September, when ozone drops rapidly in the Antarctic, and the conjugate Arctic month of March.

Some studies of chemical ozone changes make use of satellite observations and correlations between ozone and other gases (5, 6), whereas others employ dense networks of local observations to examine the behavior of specific air parcels (4). Satellite data offer the possibility of more complete spatial coverage, but they are largely limited to the period after 1979 and hence are restricted in length. This work focuses on balloon-borne electrochemical ozonesonde data and ground-based total ozone records, some of which span >4 decades (refs. 2 and 7–9; see *Materials and Methods*). The locations of the records to be considered are depicted in Fig. 1. These cover the longest high-quality data sets available for both poles, with as wide a geographic area as possible on those time scales.

Our focus here is on comparing the amplitude and incidence of ozone depleted air in the Antarctic and Arctic stratosphere within long records spanning decades. Stratospheric airflow is largely in the east–west (zonal) direction around latitude circles, particularly in winter when a circumpolar vortex is established (e.g., refs. 10 and 11). Displacements or distortions of the circumpolar flow field occur mainly through wave-driven changes to the flow (11), which in turn are related in part to the underlying topography (distribution of oceans, continents, mountains, etc.). Such motions affect the local variability of ozone observed at any particular station, so that even those normally outside the vortex will sample from deep within the vortex at times. Thus, long records with frequent temporal sampling should be expected to reflect the range of values as air flows around latitude circles and within a distorted vortex.

It is not our purpose to analyze trends from these observations but rather to examine the character of the depletion and use that to provide a readily understandable descriptive analysis of the ozone depletion typically found in the Antarctic and the Arctic. In particular, the availability of many years of weekly (ozonesonde) and daily (total column ozone) data permits us to examine whether or not the dramatically reduced levels of ozone routinely found in the Antarctic are ever observed in Arctic records. It will be shown that such records reveal pronounced changes in the range of Antarctic ozone observations but considerably smaller Arctic depletion.

Balloon-Borne Ozone Observations

Fig. 2 presents balloon-borne observations of ozone at 70 mbar (≈18 km, in the heart of the region of maximum ozone depletion; ref. 12), for the Arctic for March and the Antarctic for September at many different stations. Fig. 3 presents the probability distribution function of the most temporally complete available multidecadal records among these (from Syowa in the Antarctic and Resolute in the Arctic).

Fig. 2 reveals the rapid ozone losses that are observed at all stations in the Antarctic during September over the past several decades, contrasting sharply with data taken in the 1960s and 1970s before the buildup of atmospheric chlorofluorocarbons led to the Antarctic ozone hole. Some of the early data were taken with methods believed to be less accurate than current

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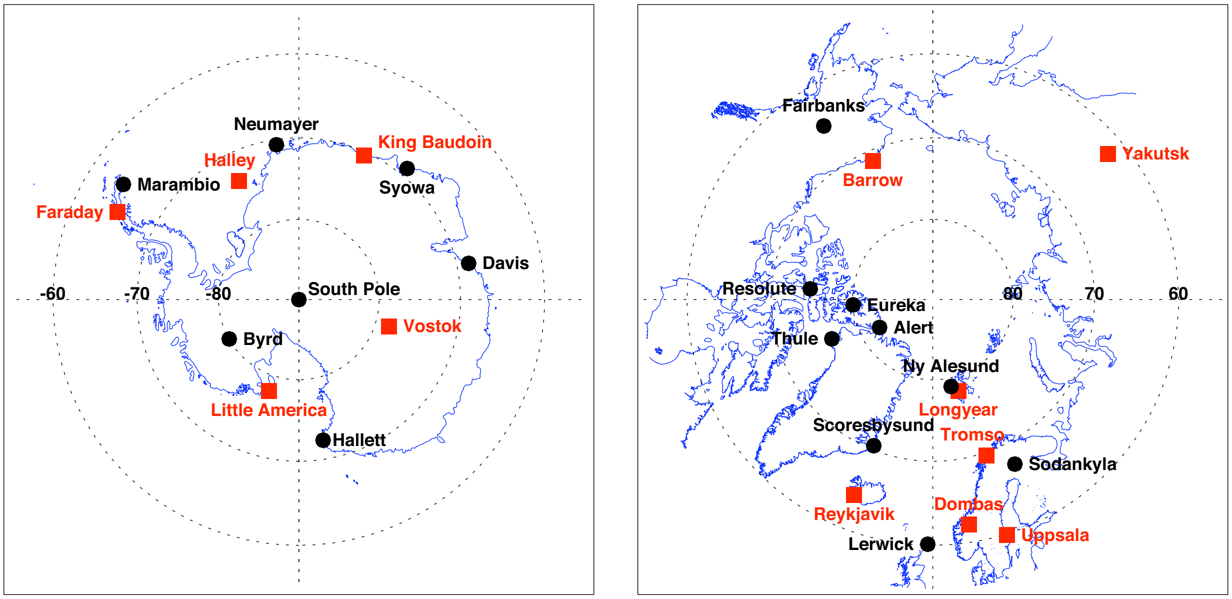

Fig. 1. Selected Antarctic (*Left*) and Arctic (*Right*) stations. Stations in red provide only total ozone data, whereas ozonesondes or both ozonesondes and total ozone are available for stations shown in black. The stations include those with the longest and earliest observations for each polar region.

observations, depicted by open symbols (see *Materials and Methods*). The figure makes clear that ozone losses in the Antarctic are, however, so severe that the long-term changes greatly exceed uncertainties related to the changes in methods, making examination of the historical data from stations such as Byrd, Hallett, and the South Pole of considerable interest. It is unfortunate that similar historical data exist from an even more limited number of locations in the Arctic (Resolute, Canada, and a very small number of observations in Alaska as shown). The observations before 1979 at Resolute were taken by using a less accurate method than the later observations and hence should not be used for trend analysis (13), but they allow comparison with the Antarctic data.

Fig. 2 shows that the character of Antarctic ozone has dramatically changed since the development of the Antarctic ozone hole, with >90% local depletion in ozone being seen in

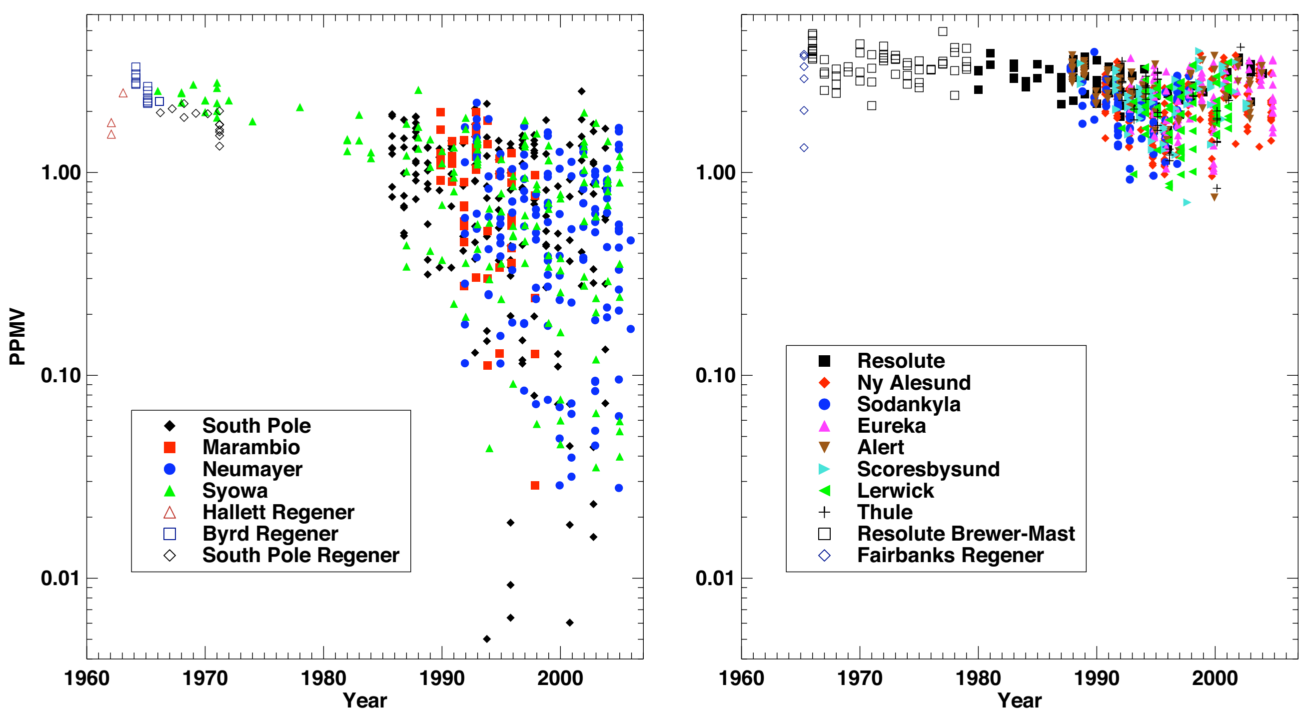

Fig. 2. Observations of the ozone mixing ratio in September in the Antarctic (*Left*) and March in the Arctic (*Right*) averaged for a pressure level of 70 (±2) mbar (≈18 km in the heart of the region of ozone depletion). Historical data taken with less accurate methods (Brewer–Mast and Regener; see *Materials and Methods* and references cited therein) are shown using open symbols. PPMV, parts per million by volume.

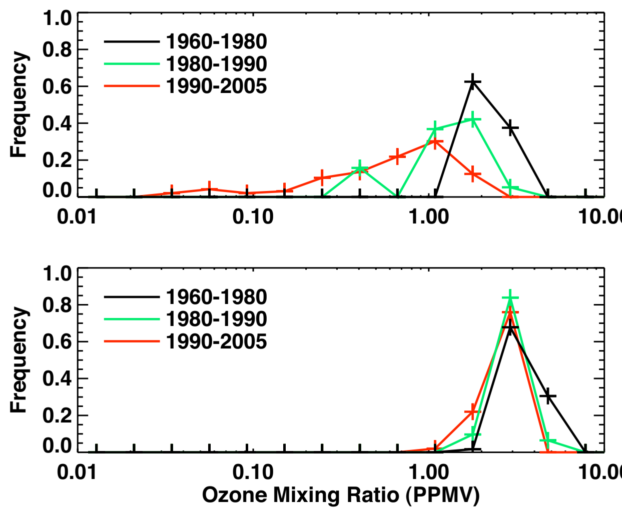

Fig. 3. Changes in the distribution of ozone at available sites with the longest Antarctic (Syowa; *Upper*) and Arctic (Resolute; *Lower*) records at 70 (±2) mbar (≈18 km as in Fig. 2) for September and March since 1960. Symbols show the midpoints of bins for each grouping of data in these probability distributions. PPMV, parts per million by volume.

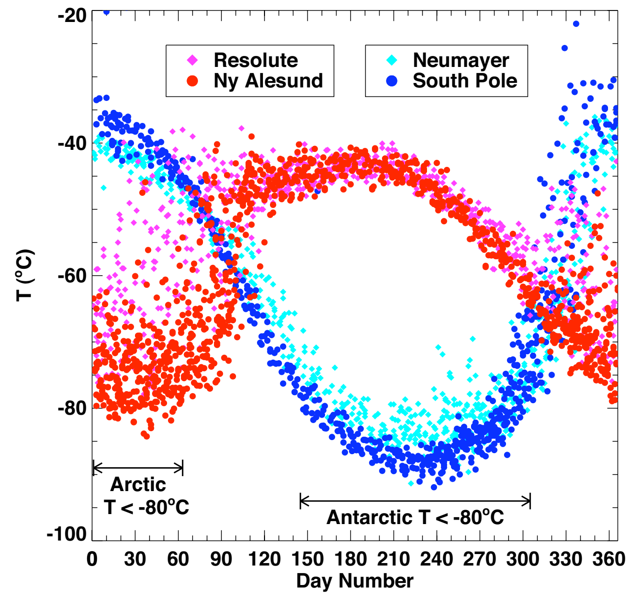

Fig. 4. Observations of temperatures at 70 (±2) mbar (≈18 km) during ozonesonde ascents in the 1990s for Resolute and Ny Alesund in the Arctic as compared with Neumayer and South Pole in the Antarctic. The portions of the year when temperatures fell below −80°C (the conditions for which ozone depletion chemistry is expected to be most rapid) are also shown.

many air parcels and often >99%. Such losses are seen throughout the Antarctic, including at stations near the edge of the South Polar Region such as Marambio and Neumayer. Even a few years of Antarctic data are sufficient to reveal severe ozone depletion because of its large influence on the range of observations as air from deep within the polar vortex or air outside the vortex is sampled at each of the stations shown.

Some depletion is also evident in the Arctic in the conjugate month of March, particularly in certain years such as 1995, 1996, 1997, and 2000, when local changes of >50% are evident at this pressure level. A few Arctic air parcels have been shown to exhibit local losses of ≈70% (14). The largest Arctic depletions are observed most frequently in the European sector, because of a tendency for the coldest part of the Arctic vortex to be shifted toward these longitudes.

Fig. 3 shows that the distribution of measurements in the Antarctic has both shifted and dramatically broadened, whereas

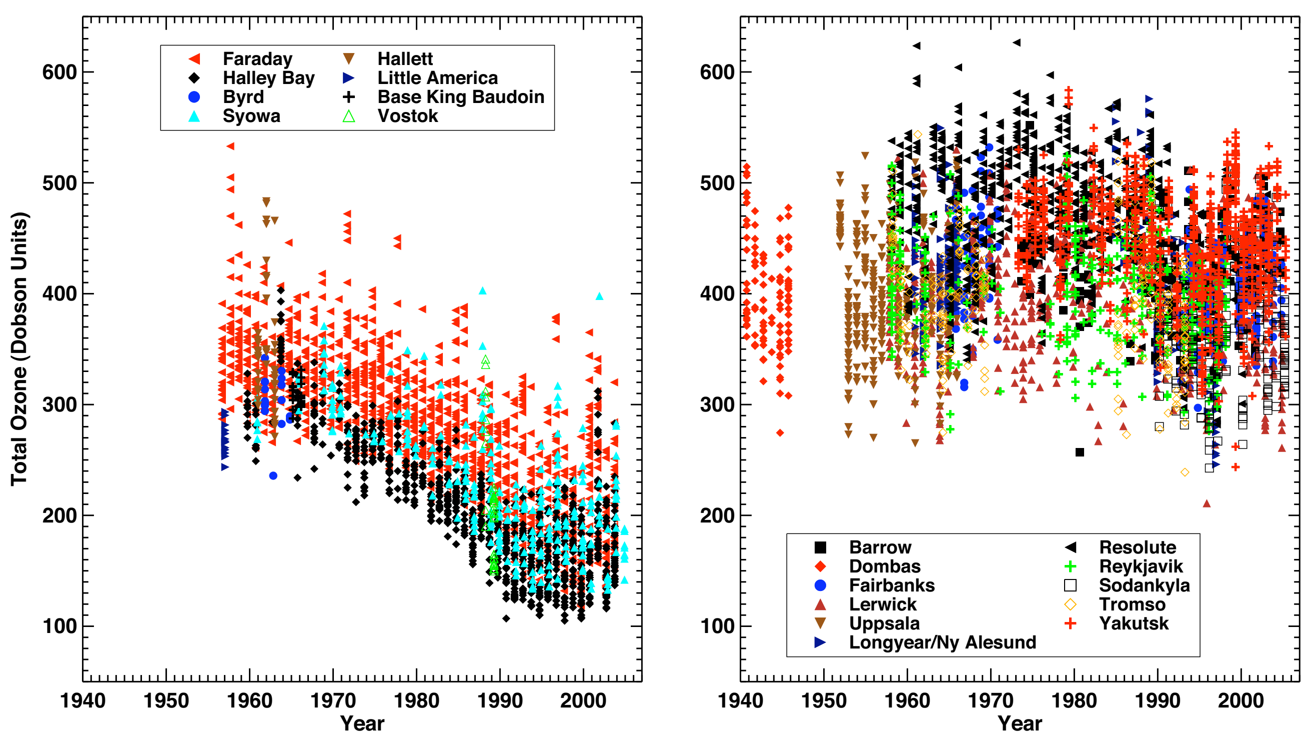

Fig. 5. Observations of daily total column ozone in Antarctica in September (*Left*) and in the Arctic in March (*Right*). Some records have been offset in time slightly for clarity.

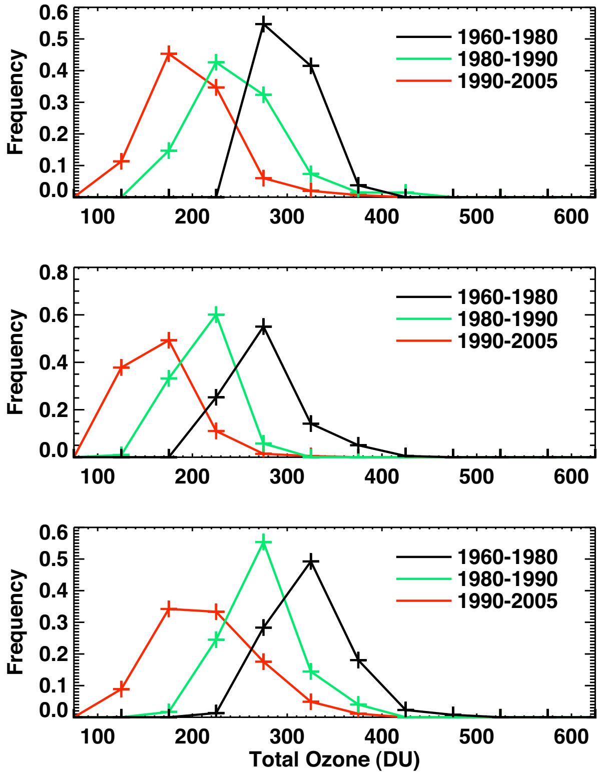

Fig. 6. Observations of changes in the frequency distribution of total column ozone (DU, Dobson units) in Antarctica in September for Syowa (*Top*), Halley Bay (*Middle*), and Faraday (*Bottom*), which are stations with long records since 1960. Symbols show the midpoints of bins used. DU, Dobson units.

the available long-term Arctic changes reflect much less broadening. Figs. 2 and 3 make clear that extensive ozone losses as large as those routinely found in the Antarctic are not observed at any Arctic station (nor are they found in other months or at other pressure levels; data not shown). Thus, the amplitude of the depletion in the two polar regions has been markedly different to date, even for those years with the largest Arctic ozone losses.

Understanding of these differences is aided by consideration of the typical differences in temperature between the two poles in the spring. It is well established that Antarctic ozone losses are associated with cold temperatures that lead to polar stratospheric cloud surfaces (below approximately $-80°C$) along with the presence of sunlight (e.g., refs. 1, 2, and 15). Such cold temperatures are observed more frequently in the Antarctic than in the Arctic and over a greater portion of a typical season. Fig. 4 shows temperature differences as observed for illustrative Arctic and Antarctic ozonesonde stations and includes data from stations that are typically deep within the vortex as well as on the edge. A more comprehensive analysis of the differences in temperature between the two polar regions across a broader range of available observations is given in ref. 2. The availability of extremely cold air in the Antarctic is likely to be particularly important to maintaining ozone losses that can extend over broad regions in altitude and latitude and can last for many weeks, despite mixing of ozone-rich air. Limited depletion generally occurs in air that has not yet been exposed to much sunlight, particularly before mid-September or mid-March, when much of the winter polar stratosphere is still too dark for much ozone loss.

Total Column Ozone Measurements

Fig. 5 displays daily total ozone column records for September in the Antarctic and March in the Arctic, as in Fig. 2. Total column depletion is the integral over ozone loss as a function of altitude. Total ozone depletion leads to increases in UV light reaching the surface of the Earth and hence is critical to the biological impacts of ozone depletion. Much of the Antarctic ozone loss occurs over a particular range of altitudes. Near-complete removal of ozone (>90 or even 99% as shown in Fig. 2) occurs in the Antarctic over altitudes ranging from ≈12 to 24 km, which correspond to the coldest parts of the Antarctic stratosphere. At warmer altitudes above and below these levels, ozone is much less depleted if at all, limiting the remaining column to ≈100 Dobson units (1 Dobson unit = 2.6×10^{16} molecules·cm^{-2}). Thus, the changes in the total ozone column are less pronounced than those at the discrete level of 70 mbar shown in Fig. 2.

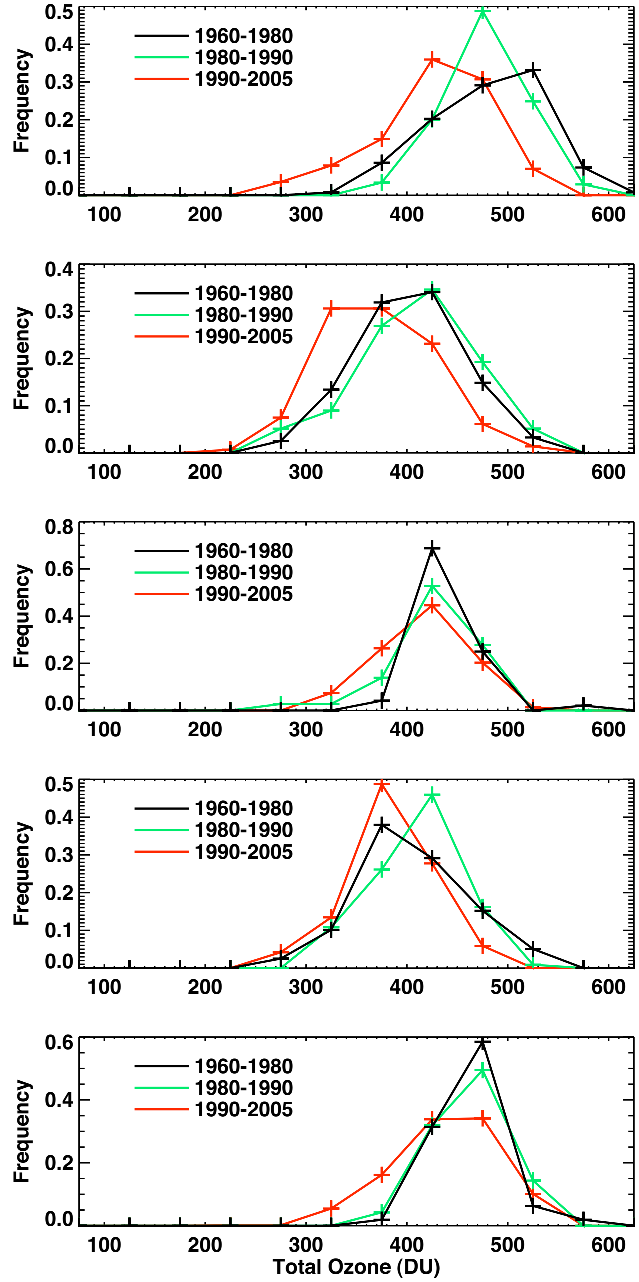

Fig. 7. Observations of changes in the frequency distribution of total column ozone in the Arctic in March for several stations with long records since 1960. From top to bottom, stations are Resolute, Lerwick, Barrow, Reykjavik, and Yakutsk. Symbols show the midpoints of bins for each grouping of data in these probability distributions. DU, Dobson units.

Fig. 5 shows that observations of total ozone of the past few decades are markedly different in the Antarctic spring from data taken earlier. Since at least the 1980s, many Antarctic observations display total ozone values that fall considerably below those ever measured earlier. Indeed, the data suggest that the tendency for increasingly low ozone minima may have begun in the 1970s. The observation of unprecedented minima in total ozone in recent decades and throughout the polar region is a clear indication of substantial ozone losses inside Antarctic ozone hole. For the Arctic, there are some daily values in certain years that fall below those observed in earlier decades, especially in the mid-1990s. However, Fig. 5 makes it clear that the changes in the Arctic spring total ozone column are considerably less pronounced than those of the Antarctic, not only in the mean but also in the extremes.

Figs. 6 and 7 expand on this picture by showing the changes in the distribution of daily total ozone measurements in the two polar regions, illustrating the dramatic and systematic changes not only in the mean but also in the extremes in the Antarctic. Changes are less evident in the Arctic, and at some stations there is a great deal of interdecadal variability rather than systematic shifts indicative of chemical depletion. There is evidence that the lowest values of ozone have decreased at many stations since 1990, but the changes are much less pronounced relative to typical variability seen, for example, over 1960–1980, than in the Antarctic.

Summary

The longest and earliest ozone records in both polar regions (dating back to the 1960s or earlier) allow a comparison of the nature and extent of ozone depletion in the Arctic and Antarctic. In this work, both the spring season ozone losses in the heart of the ozone depletion region near 18 km and the total ozone column decreases have been considered. The use of numerous stations and the longest available records has allowed a clear picture to be drawn of the unique nature of the Antarctic ozone hole and its contrasts with Arctic ozone depletion.

The comparisons show that the two polar regions display fundamentally different character. Observations of the ozone abundance at 70 mbar ($\approx$18 km) show that some local ozone depletion has occurred in the Arctic. However, the extreme anomalies associated with the springtime Antarctic ozone hole as observed in many records (frequent removal of $>$90% of the ozone at this level and sometimes $>$99%) are not observed in any of the available long-term Arctic records.

Similar differences between the hemispheres are observed in the total column changes. The depletions observed in the total ozone column in the Antarctic in September fall much farther outside of the range of past variability than is ever observed in the Arctic in March, even in the most depleted years. For Antarctic stations, daily minima in total ozone that are far below historical data are often observed in September at stations throughout the Antarctic since at least 1980, whereas in the Arctic only a few observations for the conjugate month of March fall below the historical ranges. Thus, whereas some Arctic ozone losses are evident and are well documented in some years, the data make it clear that the massive depletion of ozone associated with the Antarctic ozone hole has not been mirrored in the Arctic.

Materials and Methods

Unless otherwise noted, ozonesondes used the electrochemical method (7, 13). Data quality has been checked, including the identification of observations with errors in the background currents that can lead to spurious values. Total ozone observations generally employed the Dobson UV absorption approach (2, 8), and where information on the light source was available, we included only those data taken by using the direct sun, blue sky, or thin cloud. Data from Yakutsk employed the filter ozonometer method, whereas the recent data from some stations employed the Brewer method (see refs. 8 and 9 for a discussion of the methods and the uncertainties for the indicated stations, including reanalysis of the earliest Dobson records). Such data are subject to limitations of spatial sampling. Uncertainty in the ozonesonde data is typically of the order of 5–10%, although a few early measurements employing the less-accurate Regener or Brewer–Mast methods can be subject to larger error bars (7, 13). Typical recent total ozone observations are accurate to better than 5% (8), and reanalyzed early total ozone records are also likely to be accurate to better than 10% in clean polar regions, although offsets of up to 10–20 Dobson units have been reported in some early records (8, 9).

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