Q11 Is there depletion of the Arctic ozone layer?

Yes, significant depletion of the Arctic ozone layer now occurs in most years in the late winter and early spring period (January–March). However, Arctic ozone depletion is less severe than that observed in the Antarctic and exhibits larger year-to-year differences as a consequence of the highly variable meteorological conditions found in the Arctic polar stratosphere. Even the most severe Arctic ozone depletion does not lead to total ozone amounts as low as those seen in the Antarctic, because Arctic ozone abundances during early winter before the onset of ozone depletion are much larger than those in the Antarctic. Consequently, an extensive and recurrent "ozone hole", as found in the Antarctic stratosphere, does not occur in the Arctic.

Significant depletion of ozone has been observed in the Arctic stratosphere in recent decades. The depletion is attributable to chemical destruction by reactive halogen gases (see Q8), which increased in the stratosphere in the latter half of the 20th century (see Q15). Arctic depletion also occurs in the late winter/early spring period (January–March), however over a somewhat shorter period than in the Antarctic (July–October). Similar to the Antarctic (see Q10), Arctic ozone depletion occurs because of (1) periods of very low temperatures, which lead to the formation of polar stratospheric clouds (PSCs); (2) the large abundance of reactive halogen gases produced in reactions on PSCs; and (3) the isolation of polar stratospheric air, which allows time for chemical destruction processes to occur.

Arctic ozone depletion is much less than that observed each Antarctic winter/spring season. Extensive and recurrent ozone holes as found in the Antarctic stratosphere do not occur in the Arctic. Stratospheric ozone abundances during early winter, before the onset of ozone depletion, are naturally higher in the Arctic than in the Antarctic because transport of ozone from its source region in the tropics to higher latitudes is more vigorous in the Northern Hemisphere. Furthermore, ozone depletion is limited because, in comparison to Antarctic conditions, average temperatures in the Arctic stratosphere are always significantly higher (see Figure Q9-1) and the isolation of polar stratospheric air is less effective (see Q9). These differences occur because northern polar latitudes have more land and mountainous regions than southern polar latitudes (compare Figures Q10-3 and Q11-2 at 60° latitude), which creates more meteorological disturbances that warm the Arctic stratosphere (see box in Q10). Consequently, the extent and timing of Arctic ozone depletion varies considerably from year to year. In a few of the Arctic winters for the years shown in Figure Q11-1, PSCs did not form because temperatures were never sufficiently low. Ozone depletion in some winter/spring seasons occurs over many weeks, in others only for brief early or late periods, and in some not at all.

Long-term total ozone changes. Two important ways in which satellite observations can be used are to examine the average total ozone abundances in the Arctic region for the last half century and to contrast these values with Antarctic abundances:

- First, *total ozone averaged poleward of 63°N* for each March shows how total ozone has changed in the Arctic (see **Figure Q11-1**). The seasonal poleward and downward transport of ozone-rich air is naturally stronger in the Northern Hemisphere. As a result, total ozone values at the *beginning* of each winter season in the Arctic are considerably higher than those in the Antarctic. Before ozone depletion begins, normal Arctic values are close to 450 DU while Antarctic values are close to 330 DU. Decreases from pre-ozone-hole average values (1970–1982) were observed in the Arctic by the mid-1980s, when larger changes were already occurring in the Antarctic. The decreases in total ozone in the Arctic are generally much smaller than those found in the Antarctic and lead to total ozone values that are typically about 10 to 20% below normal. Maximum decreases in total ozone of about 30% observed in March 1997 and 2011 for considerable regions of the Arctic (see Figure Q11-2) are the most comparable to Antarctic depletion. In both of these Arctic winters, meteorological conditions inhibited transport of ozone-rich air to high latitudes, and in 2011 persistently low temperatures facilitated severe chemical depletion of ozone by reactive halogens (see Q8).

  Overall, Arctic total ozone values exhibit larger year-to-year variability than those in the Antarctic. Ozone differences from the 1970–1982 average value are due to a combination of chemical destruction by halogens and meteorological (natural) variations. In the last quarter century, these two

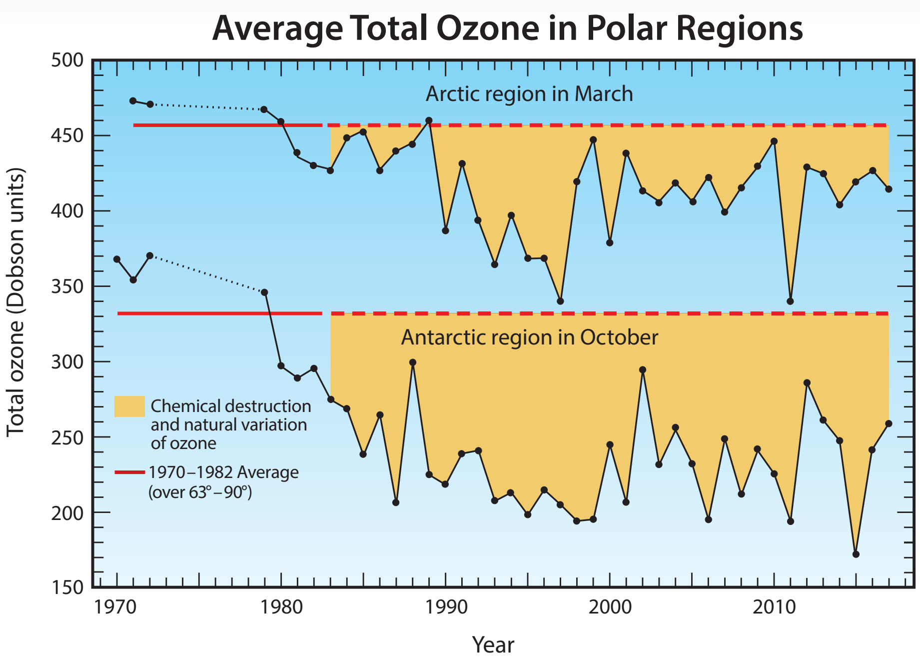

Figure Q11-1. Average total ozone in polar regions. Long-term changes in average total ozone are shown for the Antarctic and Arctic, defined by latitudes poleward of 63°. Total ozone is measured with satellite instruments. The reference values (red lines) are averages of springtime total ozone from observations acquired between 1970 and 1982. Each point represents a monthly average for October in the Antarctic or March in the Arctic. After 1982, significant ozone depletion is found in most years in the Arctic and all years in the Antarctic. The largest average depletions have occurred in the Antarctic since 1990. The ozone changes arise from a combination of chemical destruction and natural variations in meteorological conditions that influence the year-to-year values of ozone, particularly in the Arctic. The influence of natural variations on Antarctic ozone has increased since 2000. For example, an increase in stratospheric particles following the volcanic eruption of Calbuco in southern Chile coupled with a cold, stable polar vortex played a prominent role in the low values of total ozone observed over Antarctica in October 2015, whereas the 2017 ozone hole was less extensive than prior years due to the presence of a less stable polar vortex. Essentially all of the ozone decrease in the Antarctic and usually about 50% of the decrease in the Arctic each year are attributable to chemical destruction by reactive halogen gases. In the Arctic, the other 50% is attributable to natural variations in the amounts of ozone transported towards the northern polar region before and during winter. Average total ozone values over the Arctic are naturally larger than over the Antarctic at the beginning of each winter season because, in the preceding months, more ozone is transported poleward in the Northern Hemisphere than in the Southern Hemisphere.

aspects have contributed about equally to observed ozone changes. The amount of chemical destruction depends in large part on stratospheric temperatures. Meteorological conditions determine how well Arctic stratospheric air is isolated from ozone-rich air at lower latitudes and also influence the extent and persistence of low temperatures.

- Second, *total ozone maps* over the Arctic and surrounding regions (see **Figure Q11-2**) show year-to-year changes in total ozone during March. In the 1970s, total ozone values were near 450 DU when averaged over the Arctic region in March. Beginning in the 1990s and continuing into the mid-2010s, values above 450 DU were increasingly absent from the March average maps. A comparison of the maps in the 1970s and early to mid-2010s, for example, shows a striking reduction of total ozone throughout the Arctic region. The large geographical extent of low total ozone in the maps of March 1997 and March 2011 represent exceptional events in the Arctic observational record of the last four decades as noted above in the discussion of Figure Q11-1. The high values of total ozone observed throughout the Arctic during March 2018 followed a meteorological warming event in late February that disrupted the polar vortex circulation and transported large amounts of ozone to high northerly latitudes. The large-scale differences between Arctic ozone distributions observed in March 2011, 2014, and 2018 are a prime example of the influence of meteorology in driving year-to-year variations in Arctic ozone depletion.

Altitude profiles of Arctic ozone. Arctic ozone is measured using a variety of instruments (see Q4), as in the Antarctic, to document daily to seasonal changes within the ozone layer. Spring Arctic and Antarctic balloon-borne measurements are shown in Figure Q11-3. Arctic profiles were obtained from the Ny-Ålesund research station at 79°N. For 1990–2018, the March average reveals a substantial ozone layer, contrasting sharply with the severely depleted Antarctic ozone layer in the October average over a similar time period. This contrast further demonstrates how higher stratospheric temperatures and more variable meteorology have protected the Arctic ozone layer from the greater ozone losses that occur in the Antarctic, despite similar abundances of reactive halogen gases (see Q7) in the two regions.

The Arctic profiles shown in Figure Q11-3 for 29 March 1996 and 1 April 2011 are two of the most severely depleted in the 30-year

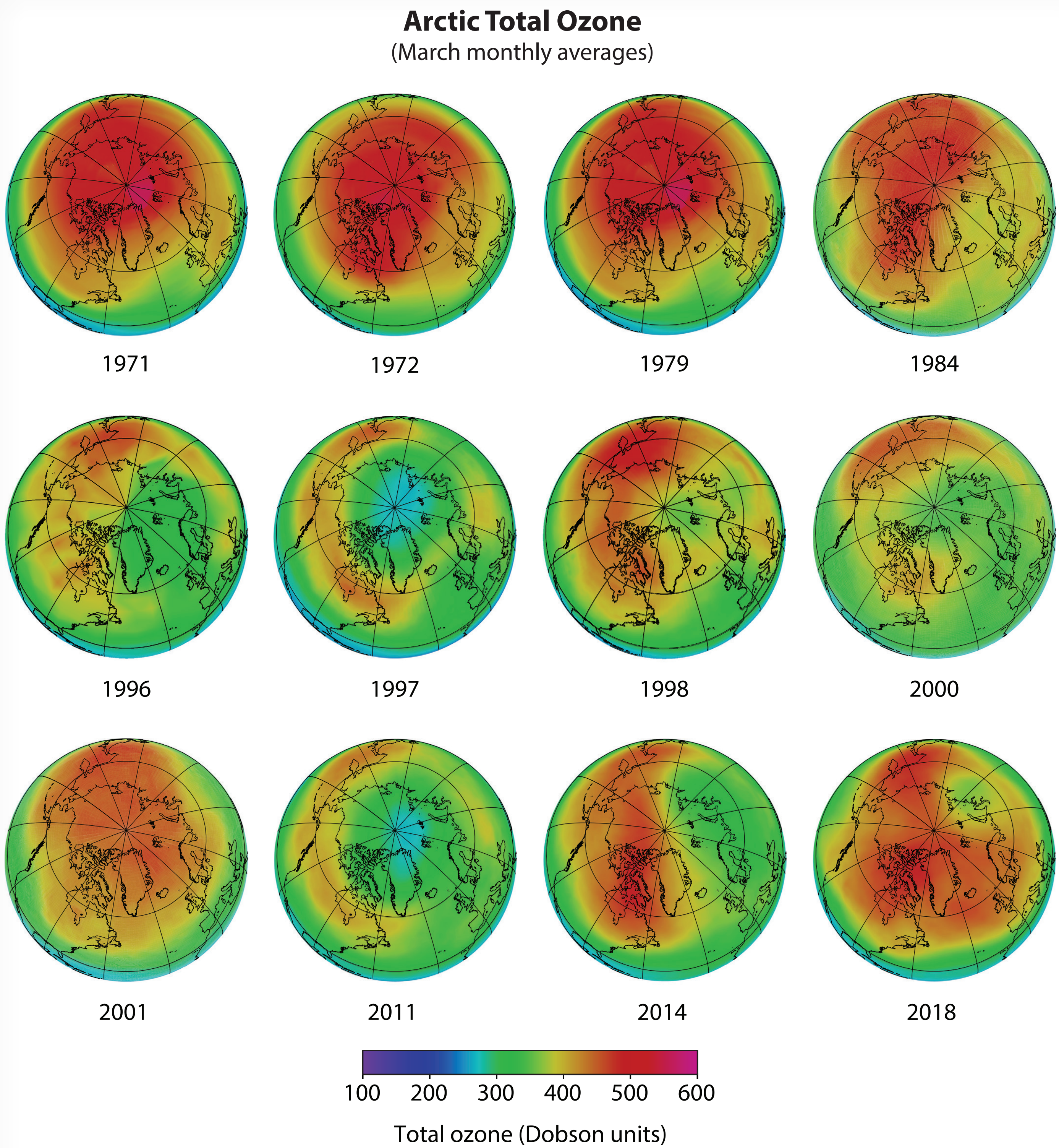

Figure Q11-2. Arctic total ozone. Long-term changes in Arctic total ozone are evident in this series of total ozone maps derived from satellite observations. Each map is an average during March, the month when some ozone depletion is usually observed in the Arctic. In the 1970s and 1980s, the Arctic region had normal ozone values in March, with values of 450 DU and above (red colors). Ozone depletion on the scale of the Antarctic ozone hole does not occur in the Arctic. Instead, late winter/early spring ozone depletion has eroded the normal high values of total ozone. For most years starting in the 1990s, the extent of ozone values of 450 DU and above is greatly reduced in comparison with the 1970s. The large regions of low total ozone in 1997 and 2011 (blue colors) are unusual in the Arctic record, although not unexpected. Meteorological conditions led to below-average stratospheric temperatures and a strong polar vortex in these winters, conditions favorable to strong ozone depletion.

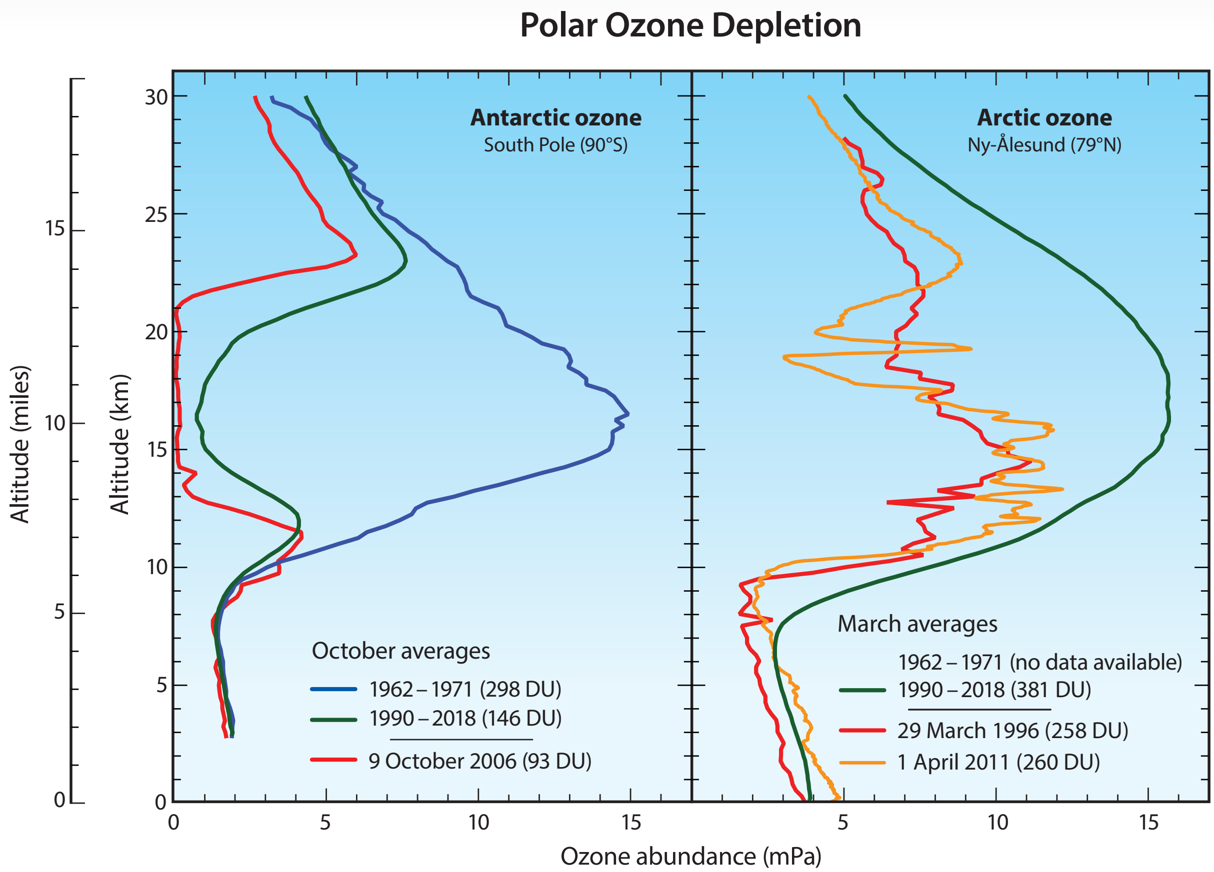

Figure Q11-3. Vertical distribution of Antarctic and Arctic ozone. At high latitudes during winter and spring, most stratospheric ozone resides between about 10 and 30 km (6 to 19 miles) above Earth's surface. Long-term observations of the ozone layer with balloon-borne instruments also allow vertical profiles of ozone during winter to be compared between the Antarctic and Arctic regions. In the Antarctic at the South Pole (left panel), a normal ozone layer was observed to be present between 1962 and 1971. As shown here, ozone was almost completely destroyed between 14 and 21 km (9 to 13 miles) over the South Pole on 9 October 2006. Average October values of ozone in the last three decades (1990–2018) are 90% lower than pre-1980 values at the peak altitude of the ozone layer (16 km). The Arctic ozone layer is shown by the average March profile for 1990–2018 obtained over the Ny-Ålesund research station (right panel). No data from Ny-Ålesund are available for the 1962–1971 period. Some profiles reveal significant depletion, as shown here for 29 March 1996 and 1 April 2011. In such years, winter minimum temperatures are generally lower than normal, allowing for formation of PSCs and increases in ClO over longer periods of time. The number in parentheses for each profile is the total ozone value in Dobson units (DU) (see box in Q4). On 9 October 2006 at the South Pole, the total ozone value of 93 DU was less than one-third of the October average ozone measured at the South Pole between 1962 and 1971. Depletion of ozone of this magnitude has never been observed in the Arctic. Ozone abundances are shown here as the pressure of ozone at each altitude using the unit "milli-Pascals" (mPa) (100 million mPa = atmospheric sea-level pressure).

record from Ny-Ålesund. Although significant, the depletion during both events is smaller in comparison to that routinely observed in the Antarctic, such as in the profile from 9 October 2006. In the Antarctic stratosphere, near-complete depletion of ozone over many kilometers in altitude and over areas almost as large as North America is a common occurrence. Ozone depletion of this magnitude has never been observed in the Arctic stratosphere.

Restoring ozone in spring. As in the Antarctic, ozone depletion in the Arctic is largest in the late winter/early spring season. In spring, temperatures in the polar lower stratosphere increase (see Figure Q9-1), halting the formation of PSCs, the production of ClO, and the chemical cycles that destroy ozone. The breakdown of the polar vortex ends the isolation of air in the high-latitude region, allowing more ozone-rich air to be transported poleward where it displaces or mixes with air in which ozone may have been depleted. As a result of these large-scale transport and mixing processes, any ozone depletion at high northern latitudes typically disappears by April or earlier.