1 Recent Changes in Surface Ultraviolet Solar Radiation and Stratospheric Ozone at a High Arctic Site

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1.1 Introduction

In 1888, photographic observations of the solar spectrum were made on top of Teide peak, Tenerife, Spain (Cornu 1890). Based on these measurements, the limit of the spectrum was set at 2922 Å. Cornu concluded that the lack of measurable radiation below this limit was due to strong absorption in the atmosphere above. Hartley (1880) suggested that the atmosphere contained ozone. This was later confirmed by Fabry and Buisson in 1913. They performed accurate measurements and concluded that the amount of ozone corresponded to a 3-mm-thick layer of pure ozone at standard temperature and air pressure. This corresponds to 300 Dobson Units (DU), which is the commonly used unit for total ozone amount in the atmosphere, i.e., the amount of ozone in a vertical column from the earth's surface to the "top" of the atmosphere. The pioneering work of G.M.B. Dobson (1889–1976) led to the construction of the famous Dobson spectrophotometer for accurate measurements of atmospheric ozone. Dobson instruments constitute the basis of the global network for measurements of atmospheric ozone and are still considered to be the most accurate instruments. After the discovery of the Antarctic ozone 'hole' in the mid-1980s there has been increased international interest in measurements of stratospheric ozone and surface UV radiation. Ozone depletion is not confined to high southern latitudes. Numerous ground-based and satellite measurements have confirmed a downward trend in the Northern Hemisphere as well. Unfortunately, the times series of high quality instruments for measurements of surface UV radiation at high northern latitudes are too short for trend estimates. The objective of this work is to describe the changes in surface solar UV radiation and total ozone during the last two decades at a high Arctic site, Ny-Ålesund, Spitzbergen, 79°N, by means of ozone data from satellites, ground-based ozone and UV instruments, and radiative transfer calculations.

1.2 Atmospheric Ozone

1.2.1 Natural Variations

Ozone is continuously destroyed and formed in the atmosphere. A photochemical theory was proposed by Chapman (1930) and involves oxygen only. A three-body process forms ozone:

$$O+O_2+M \rightarrow O_3+M \tag{1.1}$$

where M is another molecule, usually molecular nitrogen (N_2). Atomic oxygen, which is needed in the above process, is produced when molecular oxygen absorbs solar UV radiation at wavelengths below 242 nm:

$$O_2+h\nu \rightarrow O+O \tag{1.2}$$

On the other hand, ozone is destroyed by absorption of UV radiation below 310 nm:

$$O_3+h\nu \rightarrow O_2+O \tag{1.3}$$

and a two-body collision:

$$O+O_3 \rightarrow O_2+O_2 \tag{1.4}$$

The short wavelength UV radiation needed in Eq. (1.2) is mainly available in the stratosphere above the equatorial region and therefore the production of ozone is largest over the equator. However, the highest ozone columns are found at high latitudes in winter and spring, and the lowest values are in the tropics. This is a result of a meridional circulation in the stratosphere termed the Brewer-Dobson circulation. It is characterized by rising motion in the tropics and descending motion at mid and high latitudes (Dobson 1930; Brewer 1949). This transport is strongest towards the winter/spring hemisphere and explains the seasonal behavior of total ozone abundance at mid and high latitudes. Figure 1.1 illustrates the large day-to-day and the pronounced seasonal variations in total ozone at a high latitude site (60°N) and the small variations at an equatorial site. The large day-to-day variations at high latitudes, particularly in winter and spring, are a result of a dynamic active stratosphere.

The modeled global distribution of ozone is overestimated if only Chapman's reactions are used. Since Chapman's oxygen theory were introduced, a number of compounds and reactions have been included: hydrogen
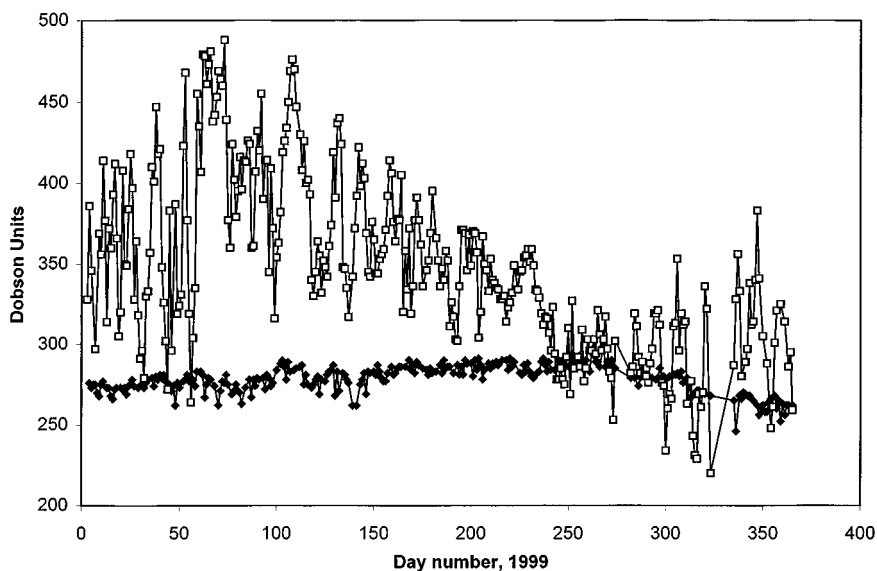
Fig. 1.1. Daily variations in total ozone at a high latitude site (*open squares*; 60°N, 0°E) and at an equatorial site (*filled diamonds*; 0°N, 0°E) in 1999 measured by the TOMS instrument aboard the Earth Probe satellite

species (Bates and Nicolet 1950), nitrogen oxide chemistry (Crutzen 1970, 1971; Johnston 1971), chlorine (Molina and Rowland 1974; Stolarski and Cicerone 1974) and bromine (McElroy et al. 1986). The different compounds take part in a catalytic cycle and can be written in a general form:

$$X+O_3 \rightarrow XO+O_2 \tag{1.5}$$

$$XO+O \rightarrow X+O_2 \tag{1.6}$$

The net result is:

$$O+O_3 \rightarrow O_2+O_2 \tag{1.7}$$

X corresponds to NO, OH, H, Cl, Br and I. All these compounds are present in the unperturbed atmosphere. These reactions, the Chapman reactions and the circulation patterns explain the natural global distribution of ozone in time and space.

Dobson (1968) noted that there is less ozone naturally present over Antarctica than over the Arctic in winter and spring. The difference is due to different surface topography. Antarctica is a continent covered with ice and

surrounded by ocean while the Arctic consists of sea/ice surrounded by landmasses. This is of importance for the different circulation patterns in the stratosphere over the two polar regions. In wintertime the absence of solar radiation leads to cooling over the poles and hence a large temperature gradient in the north-south direction develops. This temperature gradient creates a strong flow of air in the west-east direction in the stratosphere known as the polar vortex. Air inside the vortex is relatively isolated from the air outside. This prevents ozone-rich air from lower latitudes to flow into the polar regions in winter and spring. Over Antarctica a strong vortex breakup in late spring and an increase in total ozone is observed. The Arctic polar vortex is generally more disturbed due to airflow over a more variable topography. This leads to increases in the natural wintertime Arctic ozone abundance by bringing down ozone-rich air from above and also warms the lower stratosphere. The climatological differences between the two polar regions described here are due to natural processes and should not be confused with the abrupt decline in ozone that started in the mid-1970s.

1.2.2 Long-Term Ozone Changes at High Latitudes

Large losses of stratospheric ozone in Antarctica were first documented at the British Antarctic Survey station Halley by Farman et al. (1985). This seasonal depletion of springtime ozone is known as the ozone 'hole'. The Antarctic ozone 'hole' is not a true hole but the depletion is limited to altitudes between approximately 12 and 25 km. Even in the most extreme depletion observed in the 1990s, ozone remained undisturbed below and above this altitude region. However, some ozone soundings have shown that virtually all ozone is absent between 15 and 20 km (Hoffman et al. 1997). In the 1990s, the October averages at Halley were 100–150 DU, while the October averages before the ozone hole developed (before mid-1970s) were around 300 DU.

   A clear and measurable decline in ozone has also been observed in the Arctic during the last two decades. The decline, however, is much smaller than observed over the Antarctic continent. Figure 1.2 shows the large difference in springtime total ozone between an Antarctic site (Halley Bay, October averages) and an Arctic site (Ny-Ålesund, April averages) in the period 1979–1999. Figure 1.3 shows monthly averages in total ozone for Ny-Ålesund for April, June and August and illustrates that the decline is a springtime phenomenon. The linear trend for April in the period 1979–1997 is −11.0 %/decade ±5.6 % (2σ uncertainty). Note the low April average in 1997 followed by high averages in 1998 and 1999. This reduced the trend in April to −6.1±5.8 % based on the period 1979–1999 and showed that adding a few years may change the trend considerably. The corresponding trend for April in Tromsø (69°N) is −5.4±5.0 % and in Oslo (60°N) −4.8±4.4 %. This illustrates
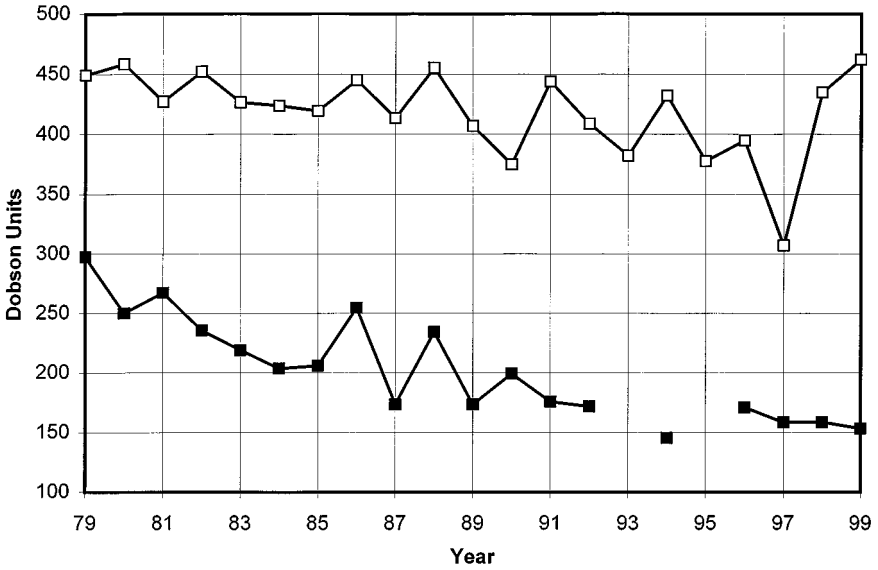
Fig. 1.2. Springtime column ozone at an Antarctic and Arctic site 1979–1999. The Ny-Ålesund data (*open squares*) are April averages. The Halley Bay data (*filled squares*) are October averages. The averages are based on TOMS measurements except the 1994–1995 data from Ny-Ålesund, which are based on Dobson and GUV measurements
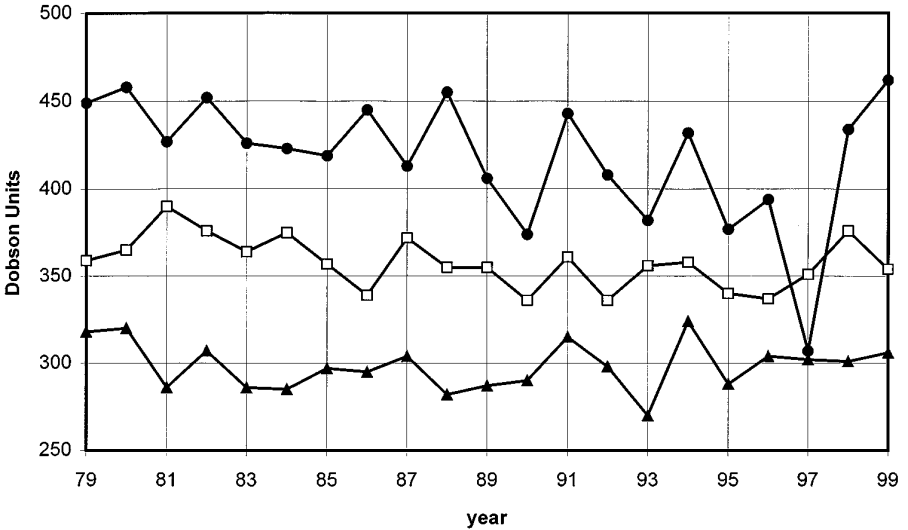

Fig. 1.3. Monthly average ozone for April (*upper curve*), June (*middle*) and August (*lower*) at Ny-Ålesund 1979–1999