11.1 EFFECTS OF CLOUDS, SURFACE ALBEDO AND OZONE VARIATIONS ON ULTRAVIOLET RADIATION CLIMATOLOGY AT STORM PEAK LABORATORY

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1. INTRODUCTION

Stratospheric ozone is declining in the northern latitudes (Herman *et a*l., 1997; Bojkov *et al*., 1998; Hansen and Chipperfield, 1999), the result of anthropogenic chlorine and bromine compounds released at the Earth's surface (Solomon, 1999). Even though halogen levels in the stratosphere are expected to level off in the early part of this century (WMO, 1998), increased greenhouse gases are predicted to cause cooling of the polar stratosphere resulting in greater frequency of Polar Stratospheric Clouds and further ozone reduction (Shindell *et al*., 1998a, 1998b).

Analysis of long-term observations of atmospheric column amount of ozone indicate that there has been a significant downward trend for the midlatitudes of the northern hemisphere, reaching 7% per decade in the winter and spring seasons, and up to 3% per decade in the summer and fall (Harris *et al.*, 1997). Depletion of stratospheric ozone increases the ultraviolet (UV) exposure to most organisms and ecological systems. Risks due to UVB (280-320 nm) exposure includes DNA damage, skin cancers, eye cataracts and immunosuppression. Biological damage is a function of the wavelength-dependant flux characteristics (Caldwell *et al.*, 1986), and calculations for the latitude zone 40°-50° N indicate a greater than 7% increase in plant-damaging UV-B flux over the period 1979-1989 (Madronich, 1992).

The effects of altitude on radiative extinction are typically much larger in the UV wavelengths than visible region (Barry, 1992), and plants and organisms which exist at higher altitude must adapt to much greater UV exposure simultaneously with less available sunlight and PAR. High risk is prevalent among human populations with outdoor occupations and recreation (Armstrong and Kricker, 1994) and is compounded for those who live or spend significant time at high elevation. Caldwell found an increase in UVB flux of 35% between 1.4 and 3.3 km altitude, as compared with a 5% increase in total solar irradiance. Vertical profiles of ozone concentration, aerosol and cloud cover change in response to seasonal circulation patterns, synoptic-scale air mass movement, and diurnal cycles in solar radiation and winds. While stratospheric ozone fluctuations are now closely monitored (Herman *et al*., 1999; CMDL, 1998), the mesoscale fluctuations in UV radiation received at the surface are still difficult to assess, due to the impacts of cloud cover (Frederick and Steele, 1995), aerosol extinction (Wenny *et al*., 1998), and ground reflectivity (Minschwaner, 1999).

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2. RADIATION MONITORING AT SPL

The Desert Research Institute (DRI) Division of Atmospheric Sciences operates the Storm Peak Laboratory (SPL), a mountain-top research facility (Figure 1) located at 3220 meters (10,525 ft) elevation within the Routt National Forest in the northwest corner of Colorado (location 40.45° N, 106.73° W). SPL is situated along a north-south ridge in an alpine forest environment, and is utilized to for research on alpine radiation climatology (Wetzel and Dillet, 1998) as well as cloud chemistry and orographic cloud processes (Borys and Wetzel, 1997).

Fig. 1. View of Storm Peak Laboratory at 3220 m elevation in Routt National Forest.

The USDA UV-B Monitoring Program (Bigelow *et al.*, 1998) provides continuous measurements of ultraviolet, visible and near-infrared diffuse and direct irradiance for evaluation of the climatology of ultraviolet radiation and ozone column amount (Slusser *et al*., 1999) in multiple ecological settings. The system at SPL (Figure 2) is the highest-elevation forest site in the USDA network.

Fig. 2. UV and solar filter radiometer system at Storm Peak Laboratory.

High altitude measurement sites for solar radiation are extremely valuable in monitoring the radiation budget of alpine ecosystems and in analysis of mid-tropospheric climate trends. Mountainous regions are zones in which all ecological components and human inhabitants are exposed to greater levels of UV radiation, and local production and destruction of ozone is controlled by vegetation, sources and transport processes which are higher in the troposphere. Orographic barriers also play a role in the downward mixing of stratospheric air, and the dispersion/destruction of stratospheric ozone, by orographically-induced turbulence and alteration of topopause fold structures (Ravetta *et al*., 1999).

Thus, the locality of mountain ranges can have significantly different climatologies of ozone profile as well as UV flux. For example, people visiting mountainous areas for winter vacations often experience UV radiation exposure which is two to three times as great as they are accustomed to at sea level. One indicator of the potential for high UVB risk in the regional vicinity of Storm Peak Laboratory is that the counties of northwestern Colorado have an extremely high (10% of nation) incidence of death due to skin melanoma (Hartge *et al*., 1996).

The radiative monitoring site at the Storm Peak Lab, located in the Park Range, is the highest-elevation forested location in the USDA UV-B network. Sensors include (1) a Yankee Environmental Systems Ultraviolet Rotating Shadowband Radiometer (UV-MFRSR), with 7 narrowband (2-nm FWHM width) channels in the UVA/UVB wavelength region between 300 and 368 nm [at 300, 305, 311, 317, 325, 332 and 368 nm]; (2) a Yankee Multifilter Rotating Shadowband Radiometer (MFRSR), with six 10-nm channels in the range 415-940 nm [at 415, 500, 610, 665, 860 and 940 nm] and a broadband shortwave channel (400-1200 nm); and (3) the Yankee UVB-1 ultraviolet broadband pyranometer (280-360 nm).

The shadowband radiometers provide both direct and diffuse flux in the multiple narrowband channels, allowing the measurement of wavelength-specific UV irradiance components. The multi-spectral UV irradiances also provide retrieved values of column ozone amount (Slusser *et al*., 1999) and optical depths (Harrison *et a*l., 1994; Schmid *et al*., 1999).

3. SOURCES OF VARIABILITY IN UV FLUX

Annual variation in ozone column amount for 1999 at SPL is shown in Figure 3, as derived from the NASA satellite Total Ozone Mapping Spectrometer (TOMS). The characteristics of this time series closely match those from the ground-based Dobson spectrometer at NOAA's Climate Monitoring and Diagnostics Laboratory (CMDL) in nearby Boulder, Colorado, including the large variability during Spring, moderate and near-constant values during Summer, and minima from mid-October to mid-November.

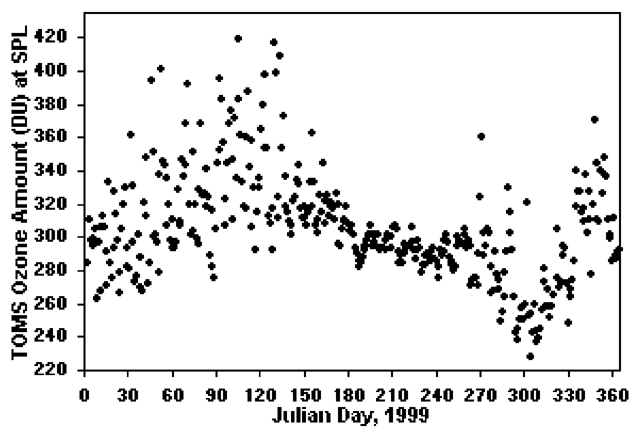

Fig. 3. Time series of NASA TOMS-derived daily values of ozone column amount over the SPL location during 1999.

Fioletov *et al.* (1999) report that the standard deviation in the differences between daily mean values of TOMS-estimated and ground-based Dobson ozone estimates was 2.4% or less. We have found that values of TOMS-derived ozone at SPL are usually about 2% larger than *in situ* amounts obtained by ozone retrievals from the UV-MFRSR instrument and the Solar Light MicroTOPS sunphotometer, but some overestimate is expected for the TOMS data due to the relatively high altitude of SPL and the terrain inhomogeneity within the sensor field of view and grid cell resolution of the TOMS data (1.0 deg latitude x 1.25 deg longitude). The MicroTOPS is a portable sunphotometer (Morys et al., 1990) which has a high accuracy when compared to precision ozone spectrophotometers (Kohler, 1999).

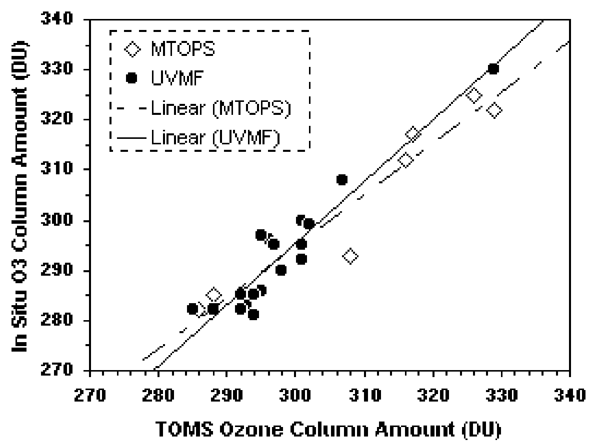

Fig. 4. Intercomparison of ozone column amount obtained from TOMS data with *in situ* retrievals by the UV-MFRSR and the MicroTOPS sunphotometer.

The TUV radiative transfer model (Madronich, 1992; Madronich and de Gruijl, 1993) is used to examine the sensitivity of UV spectral irradiance to local conditions of ozone amount, surface albedo, and other environmental characteristics. Figure 5 demonstrates the close agreement between this model and wavelength-specific measurements made at SPL by the UV-MFRSR instrument.

Sensitivity of UV spectral irradiance to ozone column amount and site elevation is demonstrated in Figure 6. The 300-nm channel is selected for discussion due to the peak of many biological UV-response curves near this wavelength. The maximum range in ozone column amount which might be expected at SPL during mid-Summer is 270 - 330 Dobson Units. Spectral UV irradiance for 270 DU is 195% of that for 330 DU. A change from the SPL site is also shown, first altering only the surface elevation (atmospheric column depth), and the more typical case of additional ozone column. Spectral irradiance at Boulder, Colorado with an ozone column of 340 DU is 24% less than at SPL with 330 DU. Both examples are indicative of the substantial variability in UV exposure in the Rocky Mountain environs of SPL.

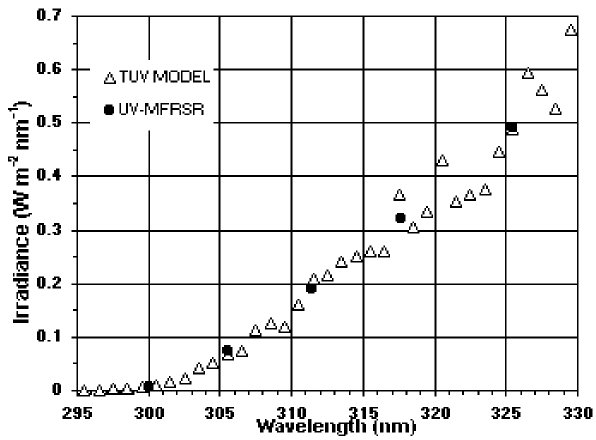

Fig. 5. Model and measurement data for UV-B spectral irradiance at SPL for solar noon on 07 Sep 1999. UV-MFRSR channels which span the UV-B range are shown (channels centered at 300, 305, 311, 317 and 325 nm).

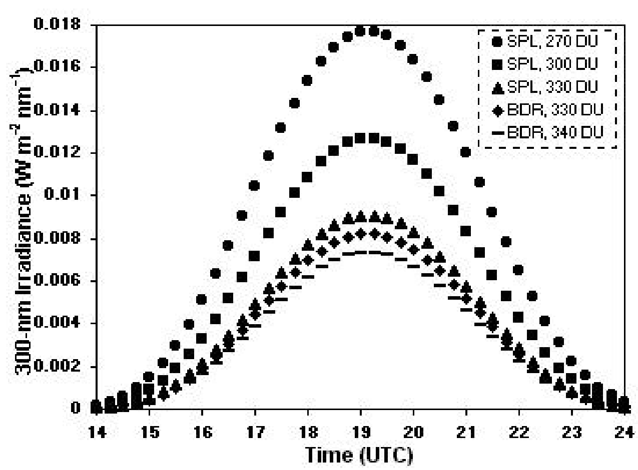

Fig. 6. Model-calculated time series of 300-nm irradiance for 20 June 1999, with variation in ozone column amount at Boulder, Colorado (1.6 km elevation) and at SPL (3.2 km).

UV-B flux to the surface is a strong function of snow cover (Krotkov *et al.*, 1997). Snow cover is typically present on the Park Range from October through June. Even during mid-summer, surface albedo in this mountainous region is enhanced by the presence of high-altitude snow fields and occurrence of valley fog. Areally-averaged surface albedo is highest in winter due to the frequent snowfall and riming of trees by orographic cloud. Figure 7 provides an example of the large effect of a surface albedo variation. This range of surface albedo could even be experienced within a one day period in late Spring or early Fall, due to unseasonal snowfall events. The alteration of albedo from 0.2 to 0.8 causes a 17% increase in mid-day clear-sky irradiance at 300 nm for this case.

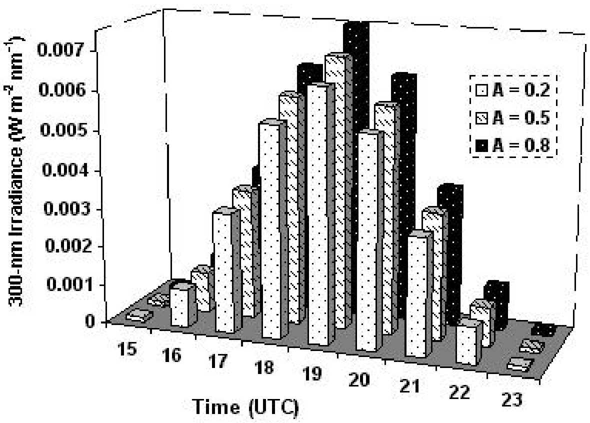

Fig. 7. Model-calculated spectral irradiance time series for 21 September 1999 showing sensitivity to surface albedo.

Local enhancement over clear-sky values can be caused by cloud reflection (McCormick and Suerhcke, 1990; Estupinan *et al.*, 1996), particularly when surface albedo is large. Measurements made on 21 April 2000 for an orographic wave cloud band (Figure 8) indicate downward spectral irradiance which is 18% above the clear-sky model-calculated values during late morning.

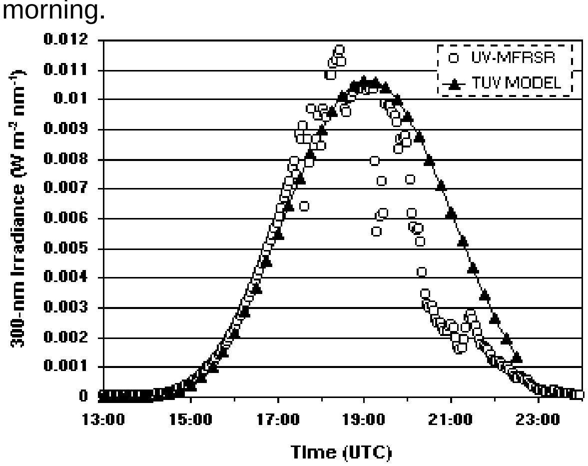

Fig. 8. Comparison of model (TUV) clear-sky and measured (UV-MFRSR) spectral irradiance at 300 nm for 21 April 2000.

The magnitude of this effect is comparable to (and additional to) the effect of having snow cover (c.f. Figure 7). The UV-MFRSR sensor obtains both diffuse and direct flux measurements in each channel, which are useful in quantifying the influence of cloud reflection.

Flux enhancement by cloud reflection in the other UV-B wavelength channels measured by the UV-MFRSR were: 16% (for 305 nm), 19% (311 nm), 18% (317 nm) and 18% (325 nm). Cloud-induced increases such as shown in Figure 8 are observed very frequently, and a relatively short period of enhanced exposure can produce a signficant increase in sunburn risk and other biological damage.

4. COMPARISON TO SATELLITE DATA

Mountainous regions offer a challenge for satellite-estimation of UV flux and ozone column amount, due to common occurrence of valley fog and orographic cloud, and spatial inhomogeneity in surface albedo as well as elevation.

The TOMS ozone column amounts closely track the values obtained from the UV-MFRSR channel irradiances at SPL (Figure 9). The TOMS values are typically lower, as discussed in Section 3 (c.f. Figure 4).

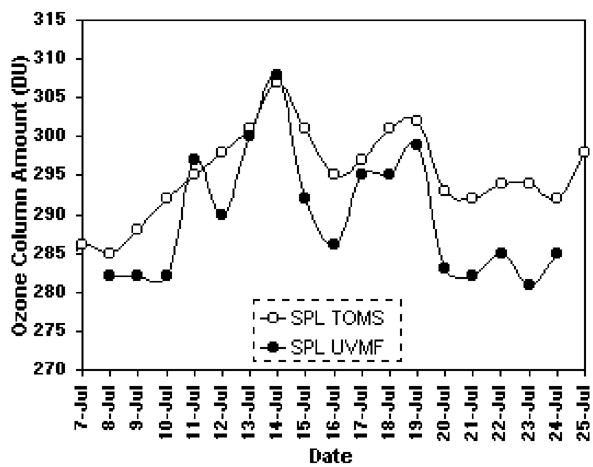

Fig. 9. Time series of ozone column amount estimated from the TOMS satellite data and the UV-MFRSR ozone multichannel measurements at SPL during July 1999.

Comparison of TOMS-derived ozone amounts and direct Dobson instrument measurements at CMDL in Boulder, Colorado (Figure 10) displays this influence in the opposite direction. The Dobson values are taken at a relatively low elevation with respect to the terrain to the immediate west. The distance between

SPL and Boulder is 132 km, which places the two sites in adjacent TOMS grid cells, and much of the intervening terrain is above 3 km elevation. Thus, the terrain effects is evident in TOMS ozone trends, and it is advantageous to use ozone amounts obtained from the UV-MFRSR or MicroTOPS instruments at SPL when sky conditions are suitable, or to adjust TOMS estimates of ozone amount when *in situ* values are not available.

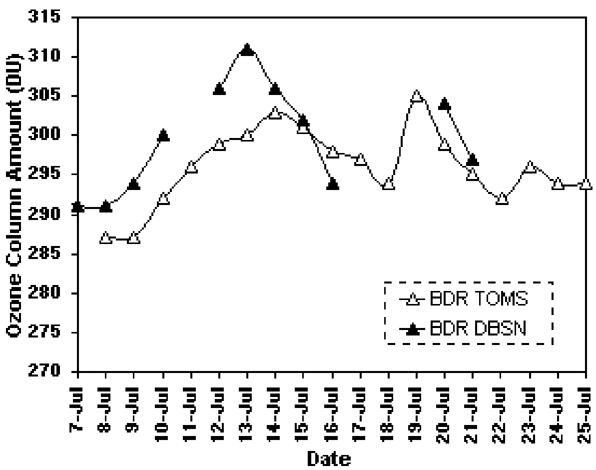

Fig. 10. Time series of ozone column amount estimated from the TOMS satellite data and NOAA CMDL Dobson measurements at Boulder, Colorado during July 1999.

5. CONCLUSIONS

Monitoring environmental exposure to UV radiation is a critical component in the link between global change and biological impacts. Exposure to UV radiation typically increases as the total column amount of ozone decreases, but the overall variability in downward UV irradiance due to cloud cover fluctuations is comparable to that caused by the observed seasonal and decadal trends in ozone column amount (Blumthaler *et al*., 1994). Dramatic increases in short-term UV dosage due to local enhancement in excess of clear-sky values can be caused by cloud reflection (Mims and Frederick 1994; Schafer *et al*., 1996), particularly over areas with high surface albedo. Measurements of UV-B flux at SPL have shown that surface downward fluxes can significantly exceed clear-sky values due to the effects of snow cover and broken cloud which allow multiple reflection.

Improvement in UV trend analysis for alpine regions will be pursued through continuing analysis of data from SPL in conjunction with additional satellite products such as UV reflectivity (Eck *et al*., 1995; Krotkov *et al.*, 1998, 1999; Herman *et al.*, 1999) and higher-resolution image data in near-infrared channels, to aid detection of cloud over snow and to improve characterization of cloud albedo (Wetzel, 1995; Wetzel *et al*., 1996).

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