7.7. Differences Between Sites

There are substantial differences in the UV climatology between the various sites of this network. A significant portion of the differences between the sites can be traced to their geographical locations, as lower latitudes experience higher sun elevations and thus more UV, all other factors being equal. However, the contention that insignificant levels of UV will occur in Polar Regions because of latitudinal differences does not appear to be true. In the following discussion, measurements from all six network sites are presented. The comparison includes average daily dose, maximum daily dose, average noontime irradiance, and maximum noontime irradiance. The results reveal that the observed differences between the sites very much depend upon the selection of the quantity used for the comparison.

Average daily dose is an appropriate quantity for investigating the cumulative UV exposures received over an extended time-period. It does not capture, however, the impact of transient high levels of UV that may occur during episodic combinations of clear skies and severe ozone depletion. Such incidents may have biological significance in systems that do not obey reciprocity in terms of exposure intensity versus duration. To study those effects, maximum daily dose is the more suitable measure. For some organisms high levels of UV radiation received during short time-periods, ranging from minutes to hours, may be even more detrimental. This also includes human beings who are usually exposed for few hours rather an entire 24-hour period. Since the highest levels of UV radiation are normally occurring around solar noon, average and maximum noontime irradiance are suitable quantities for studying short-term UV effects and for human risk assessment.

Figure 7.7.1 shows average daily DNA-dose for all sites. Summer doses in San Diego are highest because of the higher solar elevation at this low-latitude site. However, average November UV doses in Palmer Station can reach about 80% of typical mid-summer San Diego conditions. Daily average-DNA doses observed at McMurdo and South Pole during December and January are about half as high as in San Diego. Note that daily DNA-doses at McMurdo and South Pole Station are very similar between January and April but disagree significantly in November when doses at the South Pole exceed McMurdo levels up to 45%. The reason is that the influence of the ozone hole on UV-levels is more pronounced at the South Pole than at the Antarctic coast. Radiation levels at South Pole Station and Ushuaia during November are similar because the effect of low ozone levels at the South Pole, which leads to higher UV doses, is compensated for by the effect of the lower latitude of Ushuaia. On the other hand, when ozone levels at the South Pole are back to normal in January, daily DNA doses at Ushuaia exceed South Pole values by about 50-60%. Average daily DNA-doses at Barrow are the lowest of all network sites because of the high-latitude location of Barrow and the fact that ozone depletion in the northern hemisphere is less severe than over Antarctica.

All dose values discussed above represent irradiance values integrated over a period of 24 hours. Since McMurdo and South Pole have 24 hours of sunlight during summer, there is a significant contribution to the daily dose from the "midnight sun", which diminishes the difference to a site outside the Polar Circle. The additional contribution from the midnight sun is missing, when noontime values are compared, leading to higher inter-site differences. Figure 7.7.2 proves that differences between sites are indeed larger when average noontime irradiances, rather than daily doses, are compared. The figure depicts UV levels of all sites versus week of the year, e.g., for "week 1", observations between January 1 and January 7, for the years 1991-1999, were evaluated for each site. Average noontime irradiance at Palmer Station is about 60% of the respective level for San Diego, which represents a 20% higher difference between both locations compared to the difference seen for daily doses. The difference between sites further increases with their latitude differences: Average noontime summer DNA-weighted irradiance values at the South Pole and McMurdo are a factor of 9 and 4, respectively, lower than irradiance levels at San Diego.

The differences between sites show a completely different pattern when maximum rather than average values are compared. Figure 7.7.3 shows that maximum levels of noontime DNA-weighted irradiance observed at Palmer Station in October and November can exceed maximum summer levels at San Diego by 35%, whereas average values at Palmer are always lower than at San Diego. Maximum levels at Ushuaia are similar to San Diego conditions when maximum values are compared. Although maximum noontime values at McMurdo and South Pole are significantly smaller than in San Diego, the difference is smaller in comparison to average noontime values. By comparing Figure 7.7.2 with Figure 7.7.3 we see that average and maximum values for McMurdo, Palmer Station, and South Pole Station differ by roughly a factor of 3. In contrast, average and maximum noontime levels for San Diego deviate by 30% only. The particularly high maximum levels at Palmer Station can be observed when the ozone hole starts to dissolves in November and December. During this part of the year, the polar vortex becomes unstable and air masses with low ozone concentration may be centered over Palmer Station. In combination with the relatively high solar elevation, this leads to noontime UV levels that exceed San Diego summer levels.

The picture changes again when we compare maximum daily doses rather than maximum noontime irradiance values. Figure 7.7.4 shows that maximum daily DNA-weighted doses at Palmer Station are up to 70% higher than in San Diego. Maximum doses at McMurdo, South Pole Station, and Ushuaia are comparable to levels in San Diego. Note that the difference between McMurdo and the South Pole is also much smaller when maximum daily doses rather than maximum noontime values are compared. We attribute this to the difference in the diurnal cycle of the sun at these sites. At McMurdo, radiation levels peak at local solar noon whereas at the South Pole, there is virtually no change in solar elevation during a day.

The difference in maximum and average daily DNA-doses can be seen by comparing Figure 7.7.1 and Figure 7.7.4. The comparison reveals a 30% difference for San Diego and a 50% difference for Barrow. Maximum daily doses at the four austral high-latitude sites are roughly a factor of 2.5 higher than average daily doses, reflecting again the important influence of ozone variability on UV in southern high latitudes.

All observations above were based on DNA-weighted quantities. In contrast, Figure 7.7.5 shows a comparison between the sites based on average daily erythemal dose. The pattern presented in this figure is similar to Figure 7.7.1. However, there are also important differences. Since erythemal irradiance is about a factor of two less sensitive to changes in ozone than DNA-weighted irradiance (see Section 7.10.), ozone related features are less pronounced in Figure 7.7.5. For example, the peak in the DNA-weighted data for Palmer Station in November is much less apparent in erythemal data. Similarly, average DNA-dose observed at the South Pole Station drops by about 50% during end of November whereas the drop in erythemal doses is only 16%. A comparison of Figure 7.7.1 and Figure 7.7.5 further reveals that summer-time erythemal doses from the high-latitude sites and from San Diego are more comparable than DNA-weighted doses. The reason is that erythemally weighted irradiance depends less on solar zenith angle than DNA irradiance. Therefore, the difference in latitude between the sites (which is directly linked to the difference in solar zenith angle) has a smaller impact on erythemal doses.

Figure 7.7.6 finally presents average daily irradiation for the 400-600 nm band from all sites. Since spectral irradiance in this band does not depend on atmospheric ozone concentrations, there are no significant ozone-related features in this figure; the curves appear smoother than for DNA and erythemal dose. Note that summer doses in the 400-600 nm interval are highest at the South Pole and McMurdo (the network sites with the highest latitudes), exceeding doses in San Diego. This is caused by 24 hours of sunlight, high surface albedo, and for South Pole, high altitude.

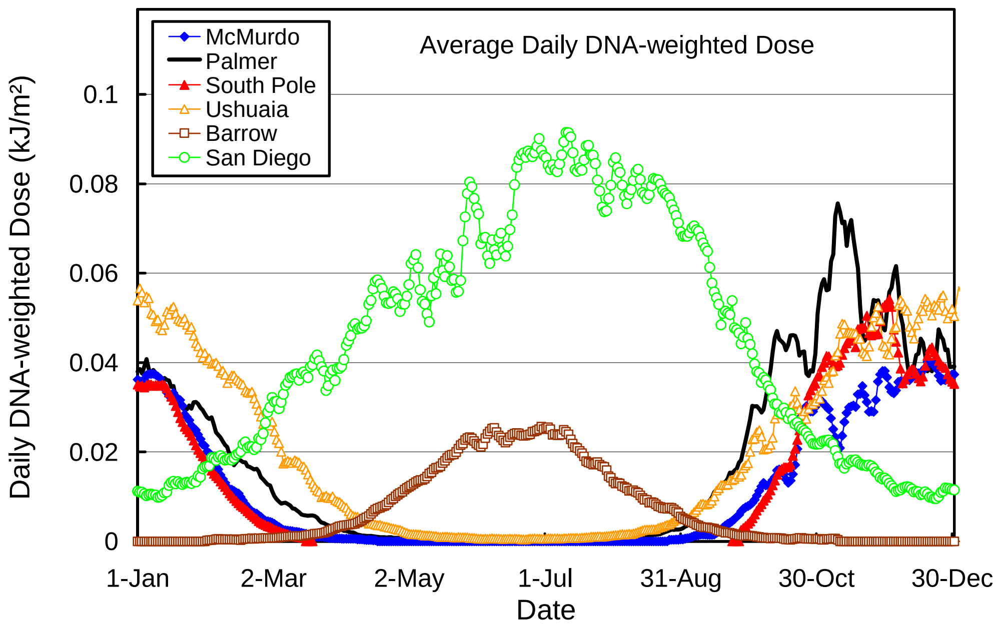

Figure 7.7.1. *Comparison of average daily DNA-weighted dose from all network sites. The data is based on average daily doses from the years 1991 – 1999. A five-day running average was applied to all curves for clearer presentation.*

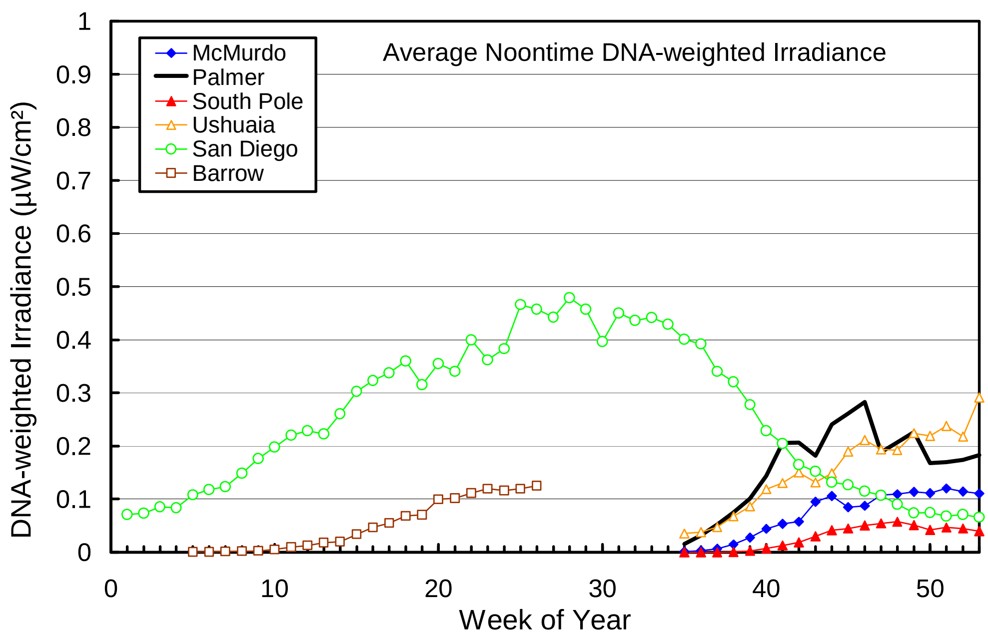

Figure 7.7.2. *Comparison of average noontime DNA-weighted irradiance from all network sites. The data is based on average daily doses of the years 1991 – 1999. For the high-latitude sites, only spring-time values are shown.*

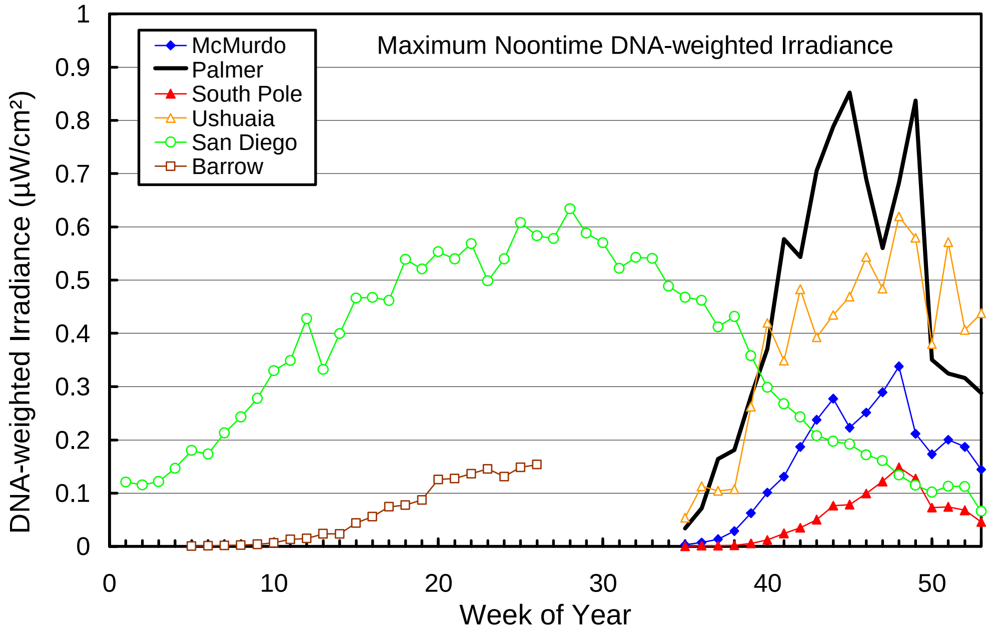

Figure 7.7.3. *Comparison of maximum noontime DNA-weighted irradiance from all network sites. The data is based on daily doses of the years 1991 – 1999. For high-latitude sites only spring-time values are shown.*

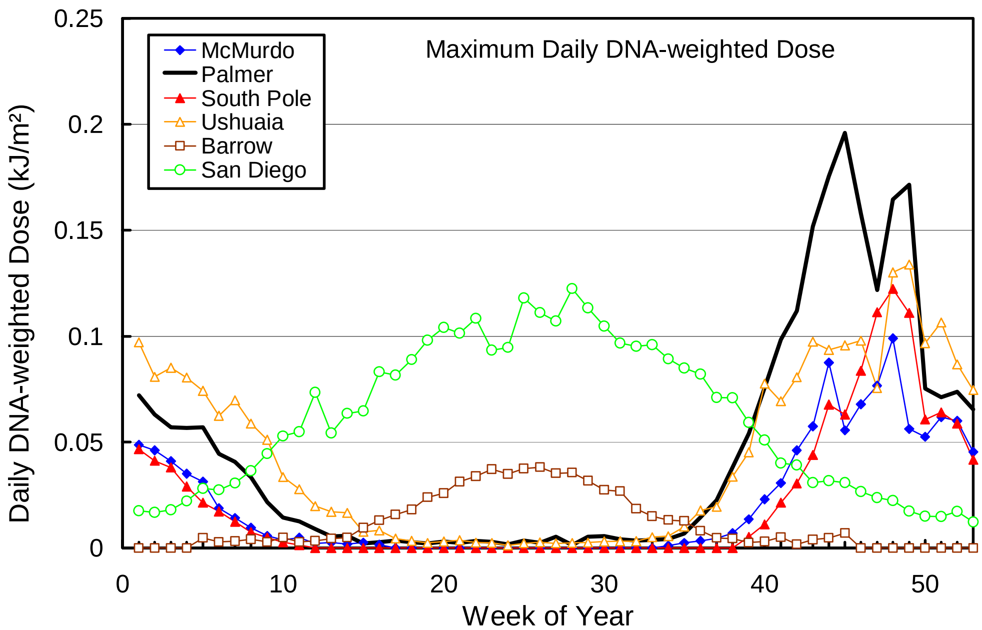

Figure 7.7.4. *Comparison of maximum daily DNA-weighted dose from all network sites. The data is based on daily doses of the years 1991 – 1999.*

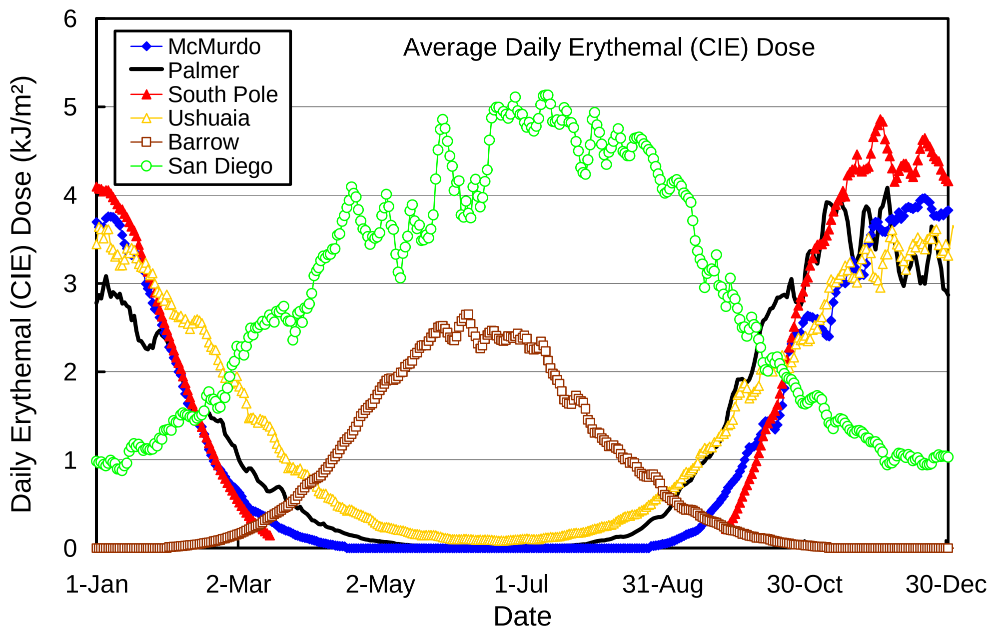

Figure 7.7.5. *Comparison of average daily erythemal dose from all network sites. The data is based on average daily doses of the years 1991 – 1999. A five-day running average was applied for clearer presentation.*

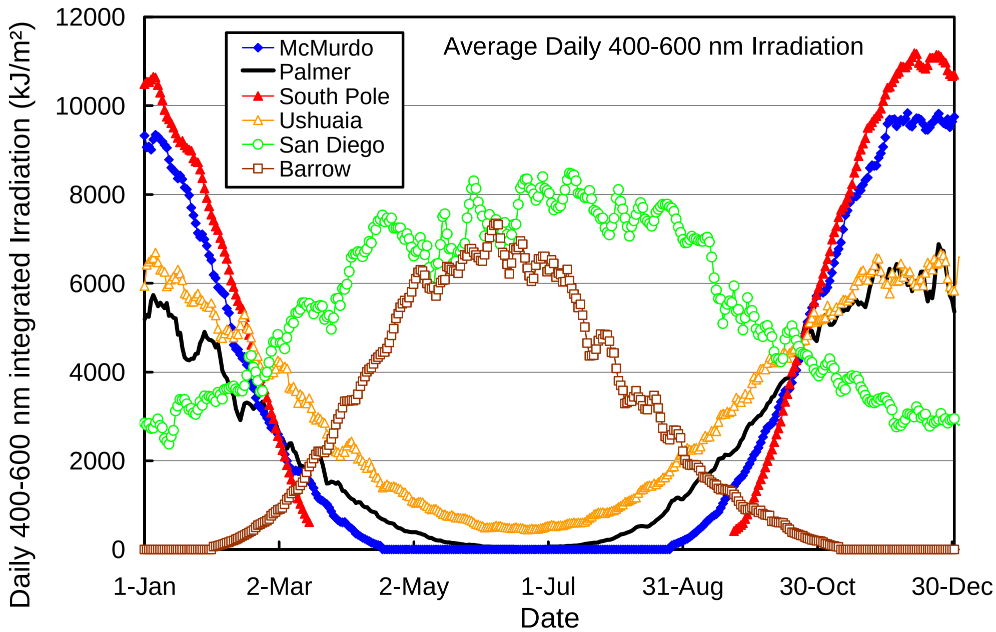

Figure 7.7.6. *Comparison of average daily irradiation of the 400-600 nm band from all network sites. The data is based on average daily doses of the years 1991 – 1999. A five-day running average was applied for clearer presentation.*

7.8. Are there UV Irradiance Trends?

The assessment of trends in UV is affected by numerous factors, including the magnitude of the trend to be detected, and the variability and autocorrelation of the noise in the data (e.g. Weatherhead et al., 1998). Another important factor is the time span of available data. The influence of this important parameter is shown below with data from Palmer Station. The monthly average daily DNA-weighted doses were computed for each month and year between 1988 and 1999, as far as data is available. The resulting doses are shown in Figure 7.8.1. For each month, a correlation of monthly average DNA doses versus year was computed and a linear trend estimated.

A similar analysis was already presented in the Volume 7 UV network report, based on data from the years 1988-1997. At that time, the largest correlation coefficient was found for November doses. Assuming a linear upward trend, the increase in DNA dose was expressed by:

$$\text{DNA-dose} = 0.0077 \times \text{year} - 15.33.$$

This trend estimate suggests a sixfold increase in DNA-dose between 1988 and 1998 (solid line in Figure 7.8.1). The standard deviation of the slope of 0.0077 is 0.0015, and the regression coefficient R^2 is 0.79, indicating that the upward trend is statistically significant.

When data from 1998 is also included in the analysis the picture changes fundamentally, as the average daily DNA-weighted dose in 1998 was very similar to radiation levels at the beginning of the time series. The resulting linear trend estimated from November doses of the years 1989-1998 is:

$$\text{DNA-dose} = 0.0047 \times \text{year} - 9.36$$

The trend is indicated by a dotted line in Figure 7.8.1. The standard deviation of the slope of 0.0047 is 0.0021, and the regression coefficient R^2 is 0.39. Hence, with the inclusion of 1998 data, the upward trend becomes almost insignificant.

We want to point out that the comparatively low DNA-dose value for November 1998 are no indication that UV levels at Palmer may already come back to pre-ozone-hole conditions. In fact, dose levels in December 1998 (around 12/5/98) were the highest observed by the NSF UV spectroradiometer at Palmer since the start of network operation in 1988 (see also Figure 7.2.6). UV levels at Palmer Station are usually highest when the ozone hole starts to dissolve and ozone depleted air masses move towards lower latitudes. The comparatively low UV-dose values in November, which were replaced by record high levels in December 1998, may therefore indicate that the ozone hole was in fact more stable in 1998 than it was in previous years. A more comprehensive analysis in support of this observation is still needed before final conclusions can be drawn.

The example above shows that extreme caution has to be applied when trends are estimated from data of the network. A time span of 12 years of network operation still appears to be too short for solid trend assessments, considering the large natural variability of UV irradiance at high-latitudes.

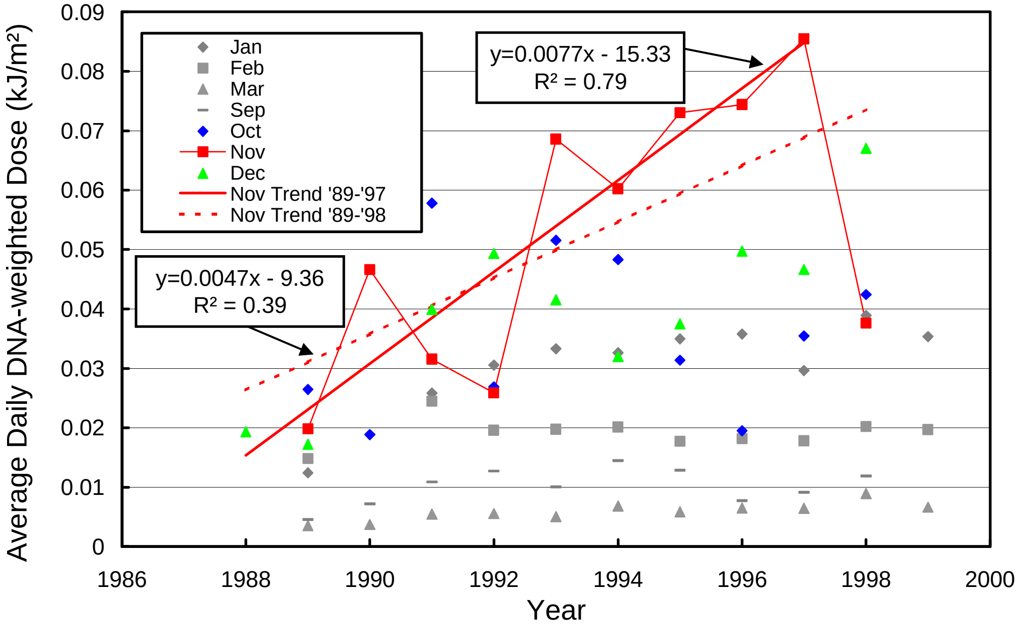

Figure 7.8.1. *Monthly average daily DNA-weighted dose at Palmer Station and trend lines for November.*

7.9. Factors Affecting UV Radiation

Solar UV radiation at the Earth's surface is affected by various parameters including the position of the sun, the constituents of the atmosphere (i.e., air molecules, clouds, ozone, aerosols, and other trace gases) and the reflectance properties of the ground (i.e., albedo). An example of this complex interaction presented in the following is the influence of column ozone, cloud cover, and ground albedo on daily doses at Barrow. The analysis was part of a presentation given at the XXV General Assembly of the European Geophysical Society, Nice, France, April 25-29, 2000. The complete set of viewgraphs from the talk are available from the Biospherical Instruments website at www.biospherical.com.

Figure 7.9.1 shows daily doses calculated from both DNA-weighted irradiance data and irradiance measurements in the 400-600 nm band. In order to reduce apparent year-to-year variability, both doses were averaged over the period 1991-1997.

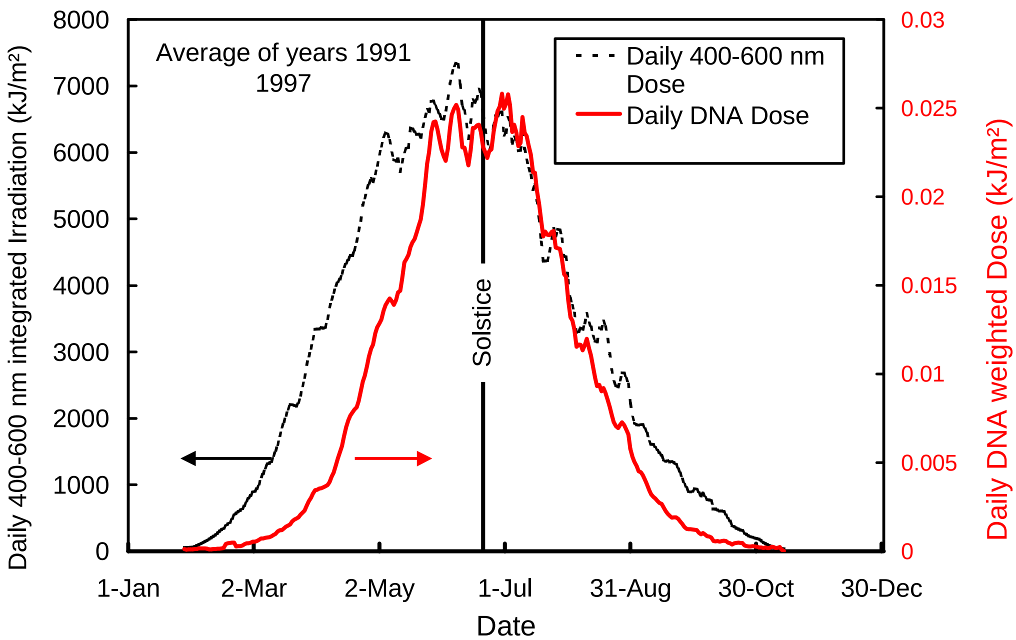

Figure 7.9.1. *Daily doses at Barrow, averaged for 1991-1997. The dotted line (left axis) is the average daily dose of the 400-600 nm band; the solid line (right axis) is average daily DNA-weighted dose.*

Figure 7.9.1 indicates that average daily DNA-weighted dose is quite symmetrical with respect to the solstice (Jun 21st). Average daily dose in the visible band, however, appears to be shifted approximately 14 days toward spring. Figure 7.9.2 shows this asymmetry more clearly. Here, both doses were mirrored at the solstice, and the ratio of spring to fall values was formed. The resulting ratios depicted in Figure 7.9.2 are therefore independent from solar zenith angle dependence and unity normalized at the solstice. Average doses in the 400-600 nm band appear to be a factor of two higher in spring than in fall. DNA-weighted doses, on the other hand, do not show a clear spring-fall asymmetry.

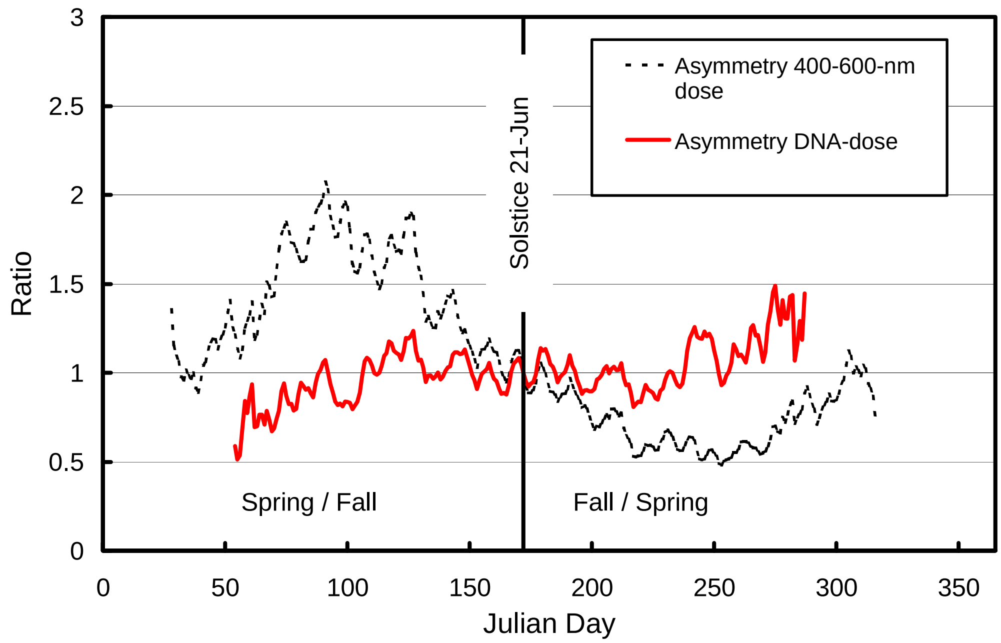

Figure 7.9.2. *Spring-fall asymmetry of the radiation doses at Barrow. The doted line is the spring-fall ratio for the 400-600 nm dose; the solid gray line is the analogous ratio for DNA-weighted dose.*

The spring-fall ratio for DNA-weighted dose derived from the measurements was compared with analogous ratios that have been computed from the influence of ozone, cloud cover and surface albedo on DNA-weighted dose. Figure 7.9.3 shows the results. Line 1 in Figure 7.9.3 is identical to the measured DNA-ratio of Figure 7.9.2. Line 2 reflects the spring-fall DNA-ratio that would be expected if the seasonal cycle in total column ozone were the only parameter affecting DNA-dose. This curve was calculated with TOMS total ozone data and a parameterization of the anti-correlation of ozone and UV suggested by Booth and Madronich (1994), using a radiation amplification factor (RAF) of 2.2 (see Section 7.10.). With the presumption that all atmospheric parameters, except ozone, were constant throughout the year, Line 2 indicates that DNA-weighted dose is a factor of 2.5 higher in fall than in spring. This large difference can be explained as total column ozone at Barrow is about 150 DU lower in fall than in spring.

Line 3 in Figure 7.9.3 shows the spring-fall DNA-ratio that would be expected from the annual cycle in cloud cover if clouds were the only parameter affecting UV. Cloud cover data was provided by the National Climatic Data Center. The relationship between cloud cover and attenuation of DNA-weighted irradiance was parameterized according to Thiel et al. (1997), using the assumption that Stratocumulus clouds were prevailing. Line 3 indicates that DNA-doses can be expected to be higher in spring by about a factor of two because of fewer clouds in the first part of the year. Thus the annual cycle in cloud cover partially cancels out the influence of the ozone cycle.

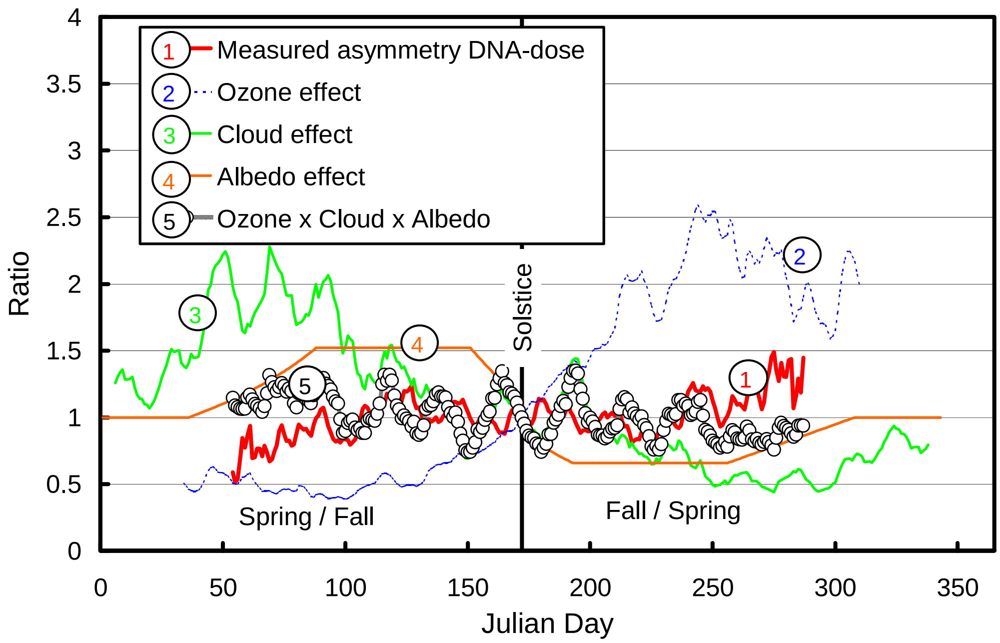

Figure 7.9.3. *Explanation of spring-fall differences in average daily DNA-dose at Barrow. Line 1: Measured spring-fall ratio of DNA-dose. Line 2: Calculated spring-fall ratio due to the annual cycle in total column ozone. Line 3: Expected ratio due to the seasonal cycle in cloud cover. Line 4: Expected ratio from the seasonal differences in albedo. Line 5: Product of ozone, cloud, and albedo influence. Line 5 is similar to Line 1, indicating that the measurements can be explained by the influence of the three factors.*

Variability in surface albedo is another important parameter affecting DNA-irradiance at Barrow. Albedo measurements performed by NOAA's Climate Monitoring and Diagnostics Laboratory (CMDL) observatory in Barrow indicate that the ground is completely covered by snow between the beginning of November and end of May (Dutton and Endres, 1991). According to data from the National Ice Center (www.natice.noaa.gov), the adjoining ocean is covered by sea ice during approximately the same period, causing high albedo beyond the immediate vicinity of the measurement site. Comparisons of SUV-100 spectral measurements with radiative transfer model calculations show that during this period the effective UV albedo is 0.85, causing an increase of DNA-weighted irradiance by about 52% when compared with snow-free conditions that prevail in Barrow between the beginning of July through mid-September. Line 4 in Figure 7.9.3 indicates the spring-fall ratio in DNA-dose that can be expected from the albedo variability.

By multiplying the spring-fall ratios that have been calculated above for the effects of ozone, clouds, and albedo on DNA-dose, the combined influence of all three parameters was determined. The resulting product is Line 5 in Figure 7.9.3. This curve is very similar to the measured spring-fall asymmetry in DNA-dose (Line 1), indicating that the measurement can be explained by the seasonal cycles of the three factors. Remaining deviations are partly due to the simple parameterizations applied. For example, non-linear interference of albedo and cloud reflections were not taken into account. In addition not all time-series were complete for the 1991-1997 period; e.g., no TOMS data exists for 1995.

7.10. Amplification of UV Radiation Correlated with Ozone Depletion

As reported by Booth and Madronich (1994), the relationship between ozone depletion and ultraviolet radiation does not simply obey a linear rule such as "for a 1% decrease in ozone, a 2% increase in UV is expected." The relationship between ozone depletion and UV increase is illustrated in Figure 7.10.1. Both a linear and a power application of the concept of Radiation Amplification Factors (RAF) is applied and contrasted with observations taken at the South Pole Station. The power formulation is seen below where E^* and E are the pre-solstice and post-solstice UV irradiances, respectively, and O_3^* and O_3 are the corresponding ozone levels.

$$\frac{E^*}{E} = \left(\frac{O_3}{O_3^*}\right)^{RAF}$$

Note that these datasets pair observations before and after summer solstice at the same solar angles to help isolate the impact of springtime ozone depletion. The springtime data normally have substantially lower ozone due to the "ozone hole."

Radiation amplification factors (RAF) are unitless sensitivity coefficients that relate the decreases in total column ozone in the atmosphere to increases (normally) in some defined measures of irradiance, usually in the UV-B. These factors are increasingly used to convey the relative increase in harmful UV radiation with decrease in ozone concentration. However, the indiscriminate use of simple linear RAF extrapolation may lead to serious underestimates of UV radiation when large changes of ozone concentration are involved. For example, Figure 7.10.1 uses spectral irradiance data measured at the South Pole during 1990 and 1991 austral summers to contrast a traditional linear RAF formulation with a nonlinear alternative. As shown, significant discrepancies occur where ozone depletion exceeds 25%. The nonlinear formulation indicates a much higher increase in UV irradiance. This power-based function is much more accurate than the linear function. Failure to use this formulation in place of the linear one could result in significant underestimates of the resulting impact of exposure.

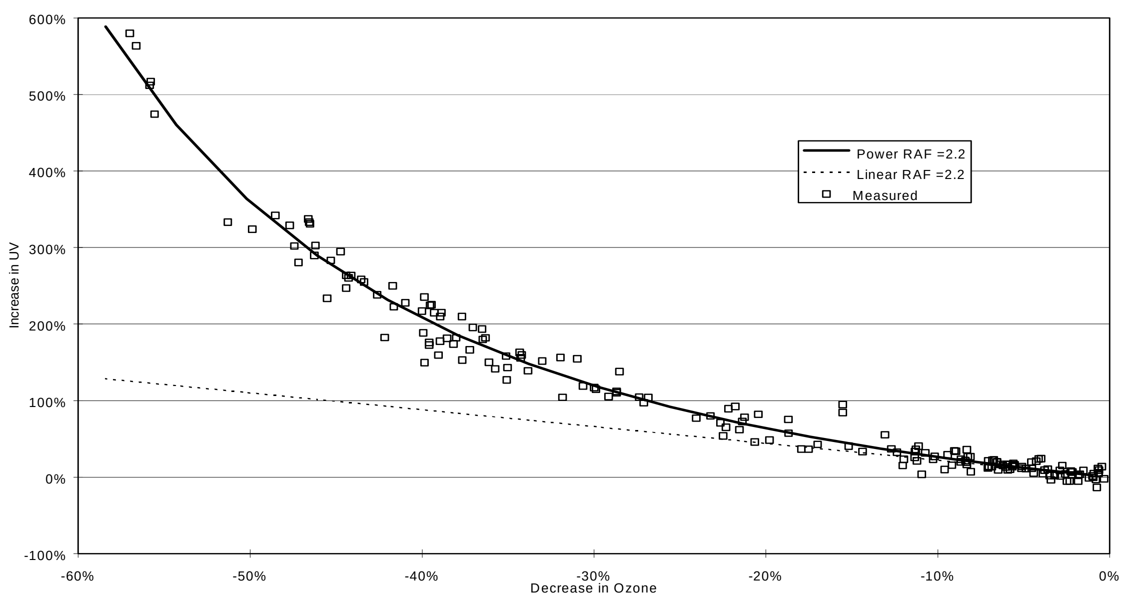

Figure 7.10.1. *Radiation Amplification for DNA-weighted irradiance due to ozone depletion at South Pole Station. The averaged observation per day from 1 February 1991 and 12 December 1992 was used, providing the solar zenith angle was less than 80°. The power-based formulation is much more indicative than the linear function of the true increase in UV due to ozone depletion.*