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 is based on average and maximum noontime irradiance, as well as average and maximum daily dose. 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 erythemal 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 at McMurdo, Palmer Station, and South Pole can reach 80-100% of typical mid-summer San Diego conditions. Note that average daily erythemal 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 30%. 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, and the solar elevation is constant for 24 hours. Radiation levels at Ushuaia between November and January reach about 70% of San Diego values. Average daily erythemal dose at Barrow is 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. During the austral summer, average noontime irradiance at Palmer Station and Ushuaia is about 55% of the respective summer level for San Diego, which represents a significantly 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 erythemally-weighted irradiance values at the South Pole and McMurdo are a factor of 4.5 and 2.3, 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 erythemal weighted irradiance observed at Palmer Station in October and November can exceed maximum summer levels at San Diego by 25%, 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 and South Pole Station differ by roughly a factor of 1.5; the difference for Palmer is about a factor of 2. In contrast, average and maximum noontime levels for San Diego deviate by 12% only. The particularly high maximum levels at Palmer Station can be observed when the ozone hole starts to dissolve 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 erythemal doses at Palmer Station are up to 33% 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 20% difference for San Diego and a 25% difference for Barrow. Maximum daily doses at the four austral high-latitude sites are roughly 50-75% 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 erythemally weighted quantities. In contrast, Figure 7.7.5 shows a comparison between the sites based on average daily DNA-dose. The pattern presented in this figure is similar to Figure 7.7.1. However, there are also important differences. Since DNA-weighted irradiance is about a factor of two more sensitive to changes in ozone than erythemal irradiance (see Section 7.10.), ozone related features are more 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 40% during end of November whereas the drop in erythemal doses is only 20%. 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 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 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.

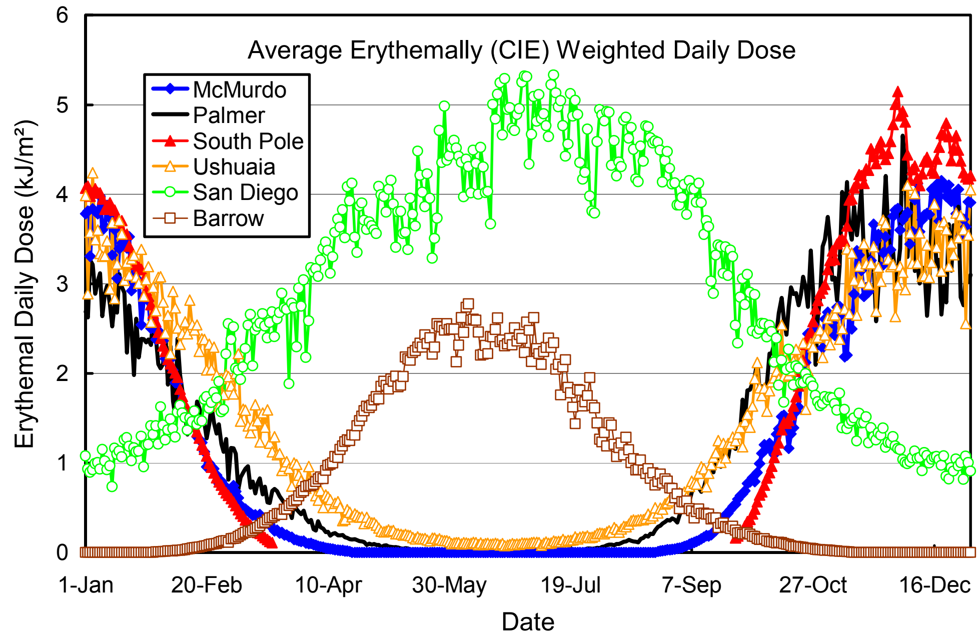

Figure 7.7.1. *Comparison of average daily erythemal dose from all network sites. The data is based on average daily doses from the years 1991 – 1999.*

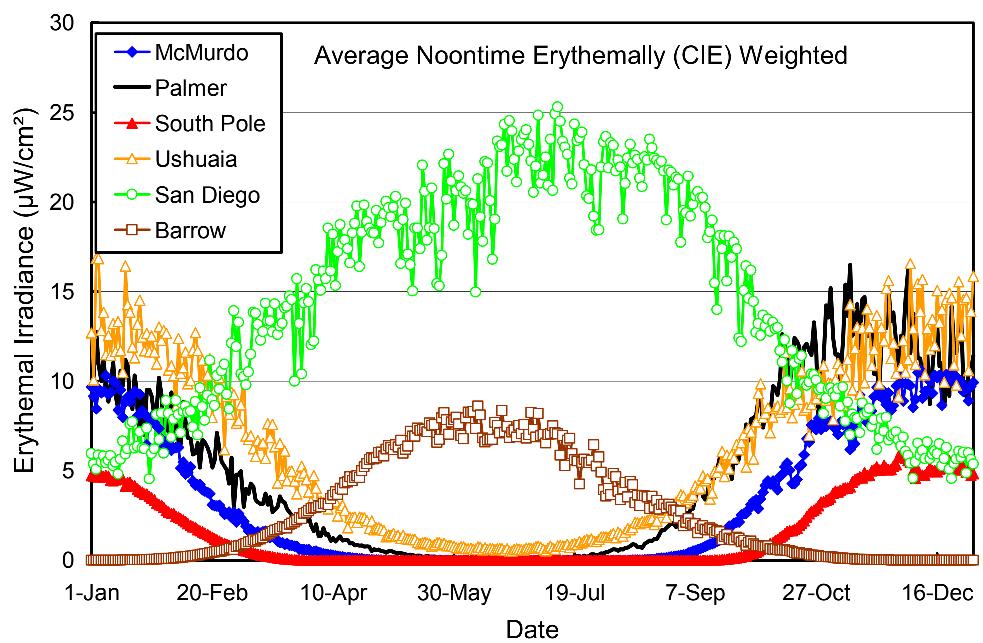

Figure 7.7.2. *Comparison of average noontime erythemal irradiance from all network sites. The data is based on measurements from the years 1991 – 1999.*

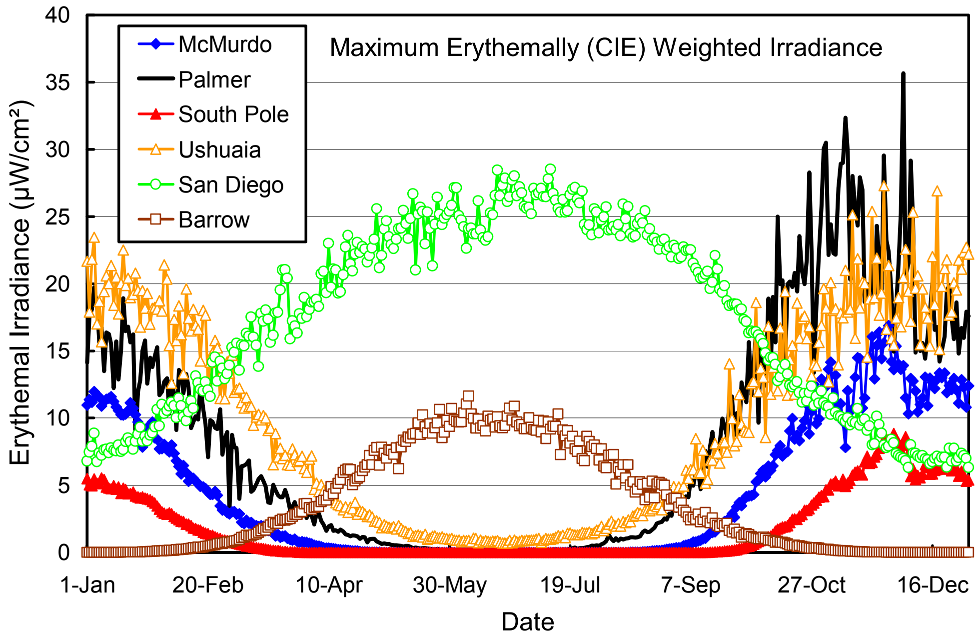

Figure 7.7.3. *Comparison of maximum noontime erythemal irradiance from all network sites. The data is based on measurements from the years 1991 – 1999.*

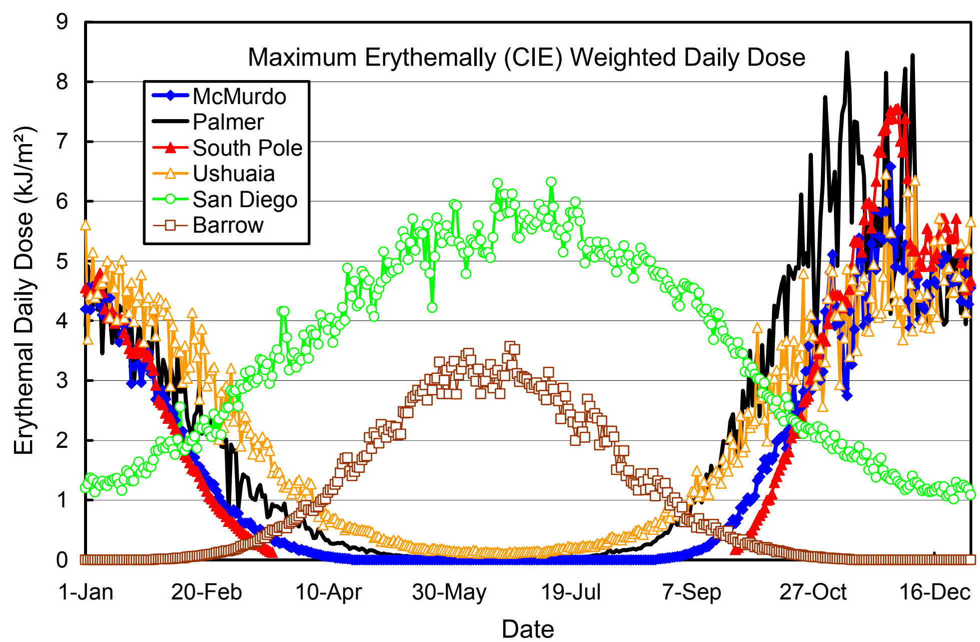

Figure 7.7.4. *Comparison of maximum daily erythemal dose from all network sites. The data is based on daily doses of the years 1991 – 1999.*

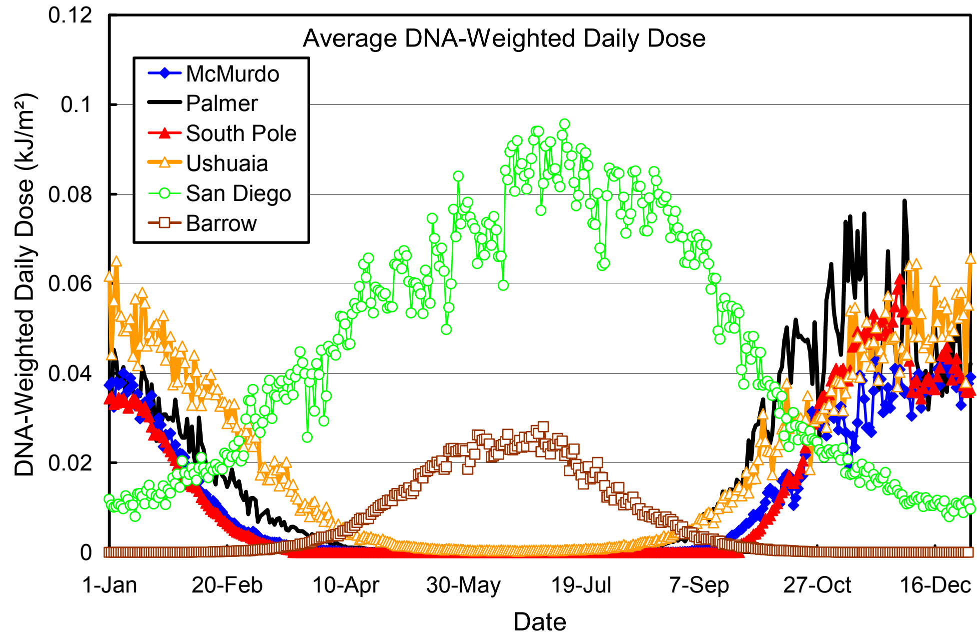

Figure 7.7.5. *Comparison of average daily DNA-weighted dose from all network sites. The data is based on average daily doses of the years 1991 – 1999.*

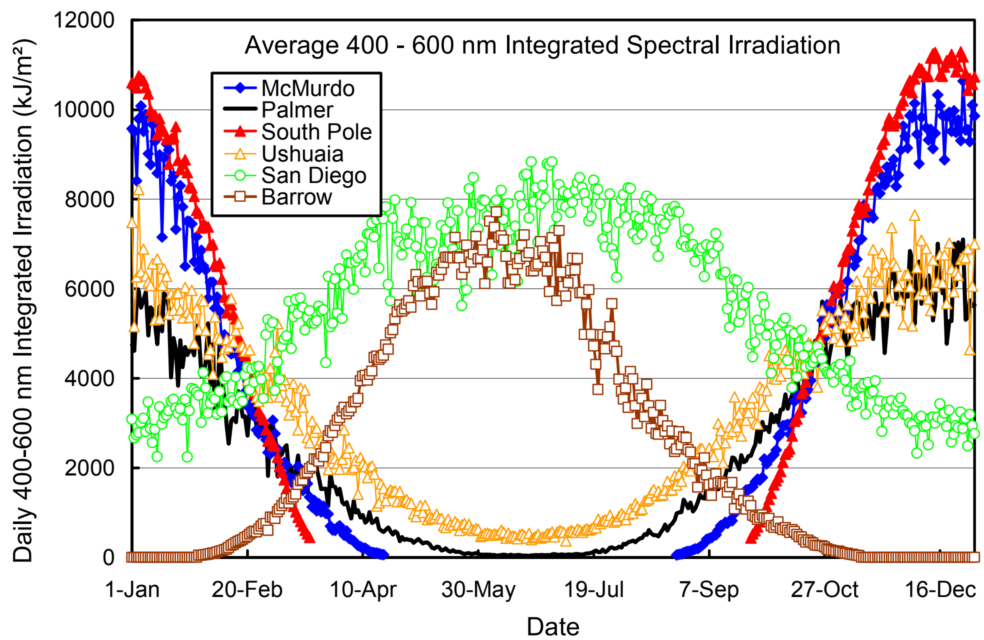

Figure 7.7.6. *Comparison of average daily irradiation of the 400-600 nm band from all network sites. The data is based on measurements from the years 1991 – 1999.*

7.8. Trends in UV

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.

In order to determine trends in UV from the data of the NSF network, the monthly means of the daily erythemal and DNA-doses were calculated for the months September through October when data from the network were available (months with more than five days missing were discarded from the analysis). Trends were determined by linear regression analysis. A trend is regarded significantly different from zero when

$|s / s_{err}| > t(y-2, 0.0455)$ with:

s	= Scale factor of linear regression
s_{err}	= Standard deviation of scale factor
y	= Number of years included in regression
$t(y\text{-}2, 0.0455)$	= Value of Student t-distribution with degree of freedom y-2 and probability 0.0455

Note that $t(y\text{-}2, 0.0455)$ is approximately 2 for large y. Significance of trends is therefore tested on the 2σ-level. Note further that regression statistics, assuming normal distribution, may not be the most appropriate model to estimate trends in environmental data. The application of more realistic, but far more complicated statistical models, which consider also the existence of autocorrelation, natural cycles, instrument drift, etc., may lead to trend estimates with different significance.

Trend estimates for all austral sites and months are compiled in Table 7.8.1, together with the correlation coefficients r^2. Trends range between –40±55% / decade (daily DNA dose for Ushuaia in October) and +162±180% % / decade (daily DNA-dose for South Pole in November). Largest positive trends are generally observed in November, with the exception of Ushuaia. However, most trends are not significant at the 2σ-level, primarily due to the large year-to-year variability in total column ozone; the second reason is cloud variability. The only exceptions of significant trends are the trends in daily CIE dose for Palmer in November and South Pole in October.

Figure 7.8.1 shows the values of average daily DNA-weighted dose for Palmer Station that were calculated for the months September – December from data recorded between 1988 and 2000. Note that the trend for November would be significant if the measurements from 1998 and 1999 had been excluded. We want to point out that the comparatively low DNA-dose value for November 1998 and 1999 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. 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 followed 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.

The example above shows that extreme caution has to be applied when trends are estimated using data from 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. In addition, network operation started in 1988 when the phenomenon of the ozone hole was already developed. Unfortunately it is not possible to compare UV levels in the late 1990s with pre-ozone hole levels from the 1970s.

Table 7.8.1: Trend estimates in daily Erythemal and DNA-doses. Shaded fields mark trends that are significant at the 2σ-level.

Site	Month	Daily erythemal dose		Daily DNA dose	
		Trend (% per decade)	R^2	Trend (% per decade)	R^2
McMurdo	September	28±31	0.40	55±60	0.42
	October	11±45	0.05	23±80	0.06
	November	38±55	0.25	96±122	0.03
	December	14±29	0.19	27±53	0.22
Palmer	September	38±48	0.27	74±86	0.31
	October	11±57	0.02	15±79	0.02
	November	59±54	0.38	94±105	0.29
	December	25±42	0.18	34±67	0.14
South Pole	October	41±39	0.54	88±89	0.51
	November	67±73	0.41	162±80	0.40
	December	34±38	0.45	76±93	0.42
Ushuaia	September	11±23	0.14	16±46	0.08
	October	-20±34	0.26	-40±55	0.35
	November	-1±41	0.00	1±71	0.00
	December	11±15	0.31	19±24	0.35

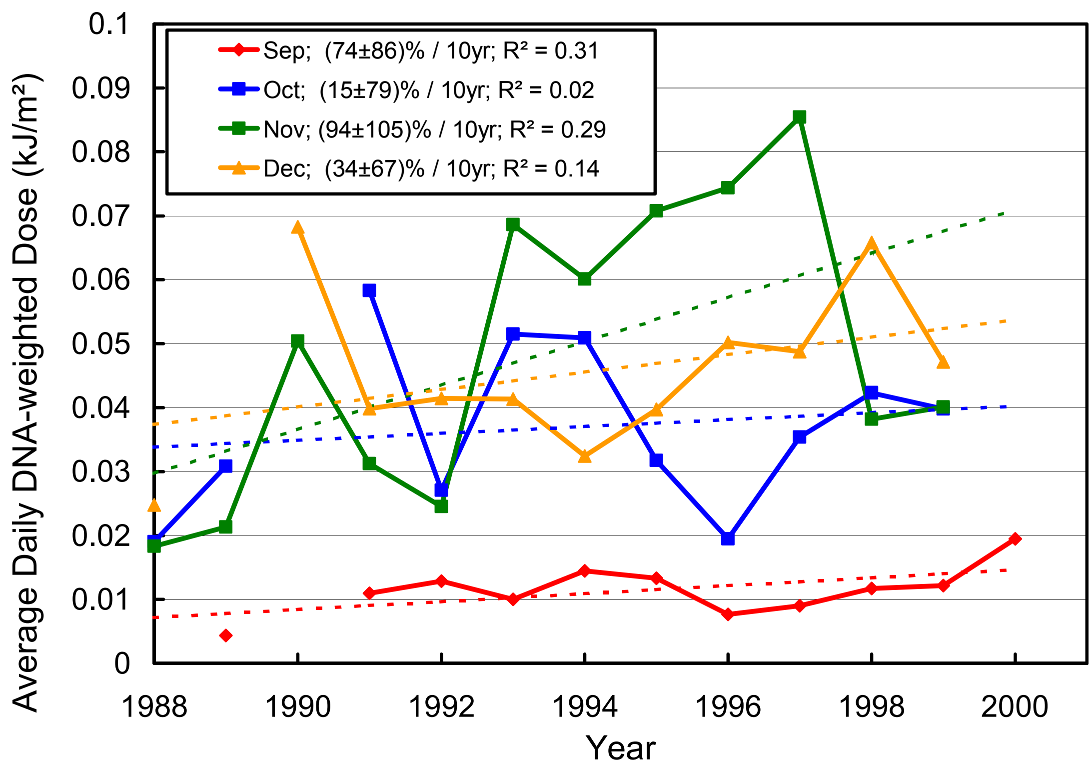

Figure 7.8.1. *Monthly average daily DNA-weighted dose at Palmer Station. The broken lines are the least square fit.*

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.

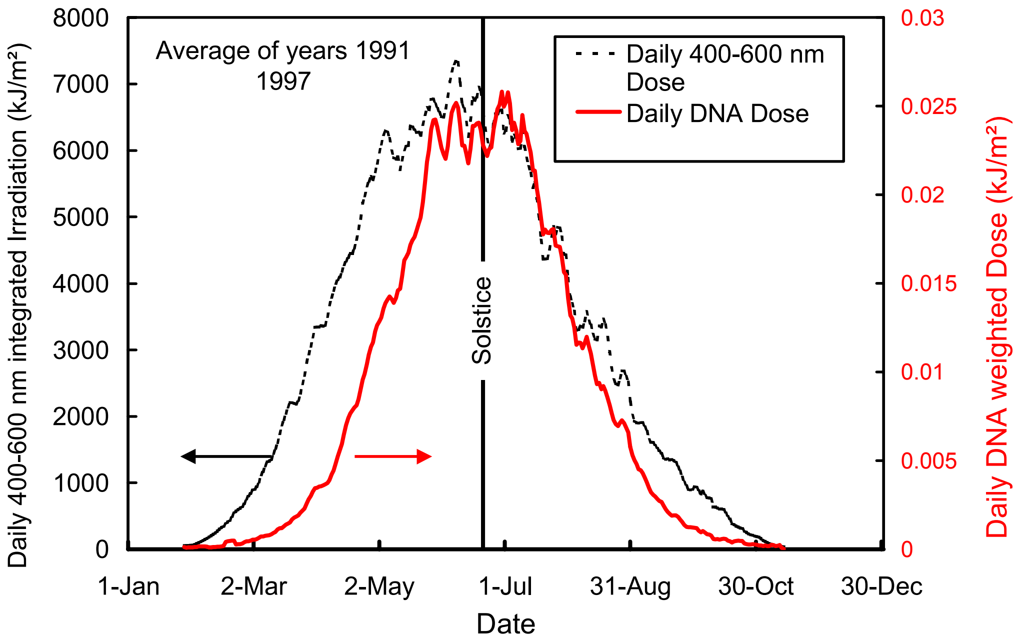

Figure 7.9.1. *Daily doses at Barrow, averaged for 1991-1997. The dotted line (left axis) is the average daily dose of the 400-600 nm band; the solid line (right axis) is average daily DNA-weighted dose.*

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.

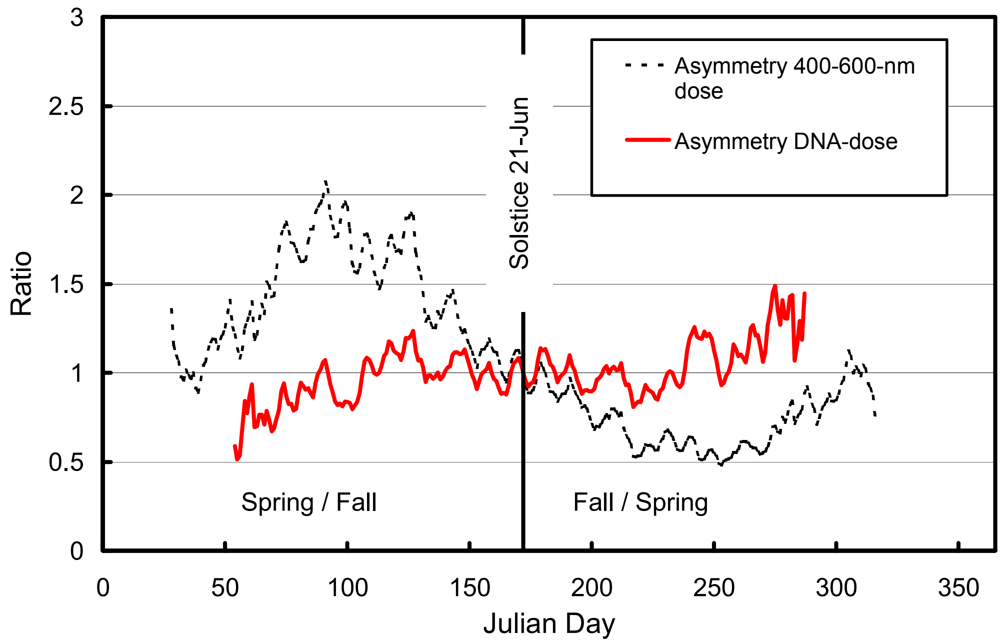

Figure 7.9.2. *Spring-fall asymmetry of the radiation doses at Barrow. The doted line is the spring-fall ratio for the 400-600 nm dose; the solid gray line is the analogous ratio for DNA-weighted dose.*

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.

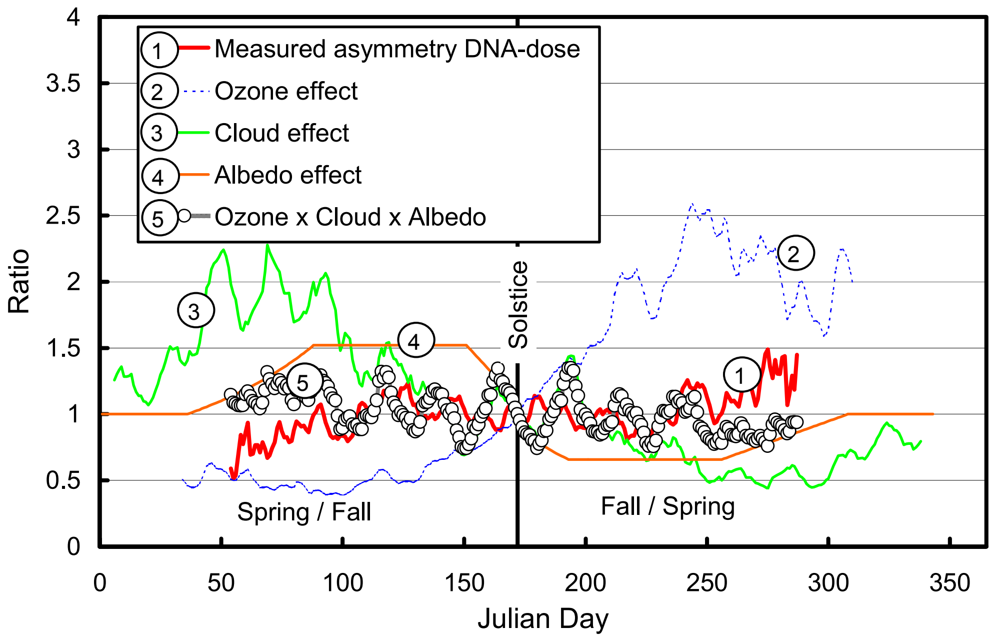

Figure 7.9.3. *Explanation of spring-fall differences in average daily DNA-dose at Barrow. Line 1: Measured spring-fall ratio of DNA-dose. Line 2: Calculated spring-fall ratio due to the annual cycle in total column ozone. Line 3: Expected ratio due to the seasonal cycle in cloud cover. Line 4: Expected 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 shows no significant asymmetry between spring and fall like the measured DNA-dose (Line 1). This indicates 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. Relationship between total column ozone and UV

The relationship between total column ozone and DNA-weighted (Setlow) irradiance was calculated from measurements at all network sites and is illustrated in Figure 7.10.1. The graph was constructed by comparing pairs of scans with identical (or very similar) solar zenith angle, but different ozone column. Note that these datasets usually pair observations before and after summer solstice at the same solar angles to help isolate the impact of springtime ozone depletion. The springtime data at Antarctic sites normally have substantially lower ozone due to the "ozone hole."

According to Booth and Madronich (1994), the relationship between column ozone and UV can be approximated by

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

Here, E^* and E refers to values of DNA-weighted irradiance measured at different days, and O_3^* and O_3 are the corresponding ozone levels. For our analysis, NASA/TOMS ozone values were used. Radiation amplification factors (RAF) are unitless sensitivity coefficients that relate changes in total column ozone to changes in UV. We determined RAF values for each site with a least square fitting routine. The results show that RAF values depend only slightly on site and range between 2.02 and 2.30. For small changes in ozone, a RAF value of 2 means that a 1% decrease in ozone will lead to a 2% increase in DNA-weighted irradiance. For larger changes in ozone, the relationship can no longer be considered linear, and the power formulation of the RAF as displayed above has to be applied (Booth and Madronich ,1994).

The fact that the difference between sites is small suggests that RAF values depend only slightly on solar zenith angle and total column ozone. With the help of the UVSPEC/libRadtran radiative transfer model (see the website www.libradtran.org) we studied this dependency in more detail. Model spectra calculated for solar zenith angles between 0° and 90°, and ozone values between 100 and 500 DU were convolved with the action spectra for erythema and DNA-damage. By correlating the biologically weighted UV values with ozone, RAF values were determined in dependence of SZA and total column ozone. The result is shown in Figure 7.10.2. RAF values for erythemal weighting vary between 1 and 1.2 for SZAs below 70°. When the sun is lower, erythemal RAF values tend to decrease. For DNA-weighting, RAF values range typically between 2 and 2.4, and are only lower for low ozone values and small SZA. RAF values determined theoretically agree well with RAF values determined with the data from the NSF network. For example for South Pole, RAF=2.3 was determined experimentally, and this values matches well the theoretically derived RAF values for high SZAs, which is depicted in Figure 7.10.2.

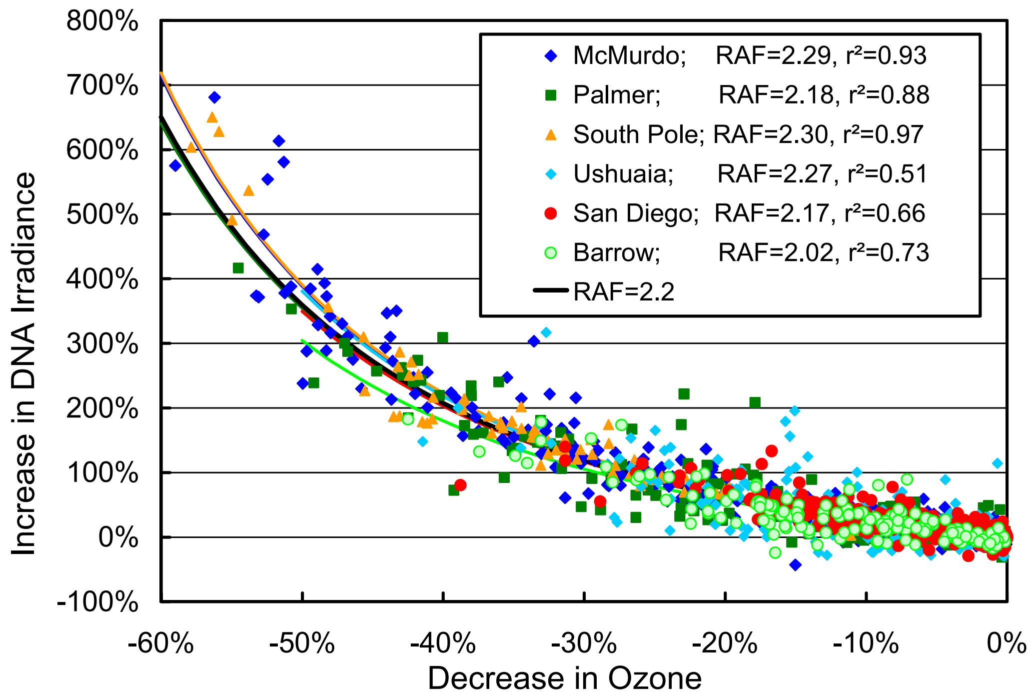

Figure 7.10.1. *Relationship between total column ozone and DNA-weighted irradiance. For each site, radiation amplification factors (RAF) were calculated by least square fit.*

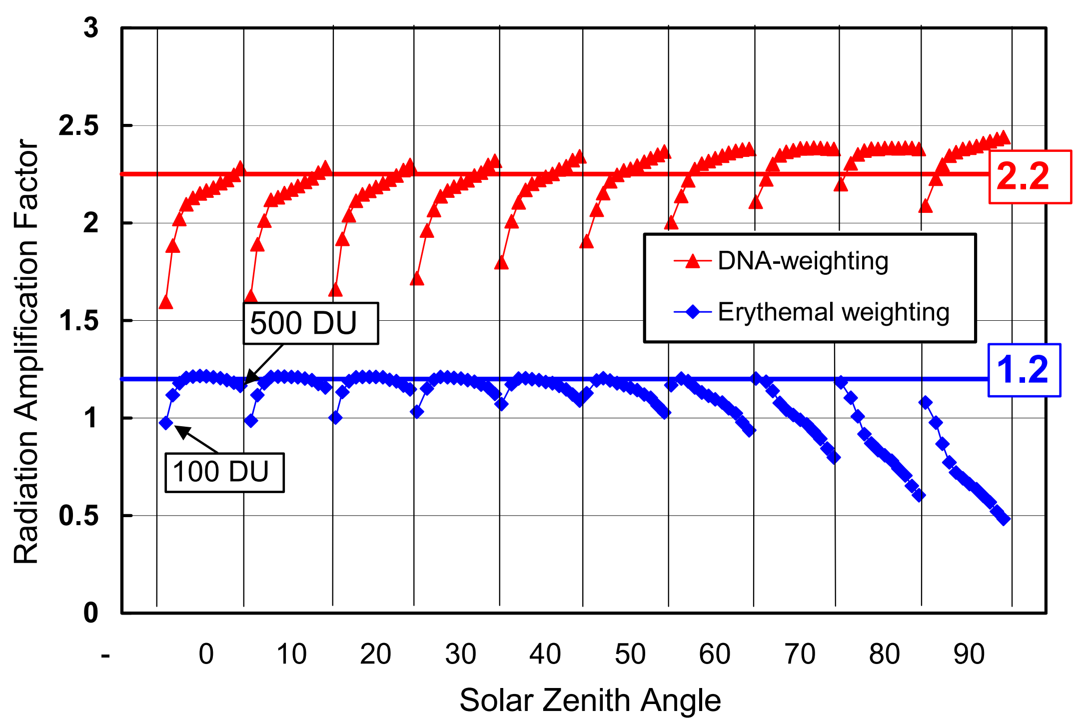

Figure 7.10.2. *Radiation amplification factor for DNA-weighted and erythemally weighted irradiance in dependence of SZA and total column ozone. The first value in each SZA-bin refers to a ozone column of 100 DU; the last value refers to 500 DU.*