UV index climatology over the United States and Canada from ground-based and satellite estimates

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[1] Long-term monthly mean UV index values for Canada and the United States were calculated using information from two sources: from noon erythemal UV estimated from Total Ozone Mapping Spectrometer (TOMS) total ozone and reflectivity data and from UV index values derived from observations of global solar radiation, total ozone, dew point, and snow cover. The results are presented as monthly maps of mean noon UV index values. Mean UV index values in summer range from 1.5 in the Arctic to 11.5 over southern Texas. Both climatologies were validated against spectral UV irradiance measurements made by Brewer spectrophotometers. With snow on the ground the TOMS-based data underestimate UV by up to 60% with respect to Brewer measurements and UV derived from global solar radiation and other parameters. In summer, TOMS UV index climatology values are from 10 to 30% higher than those derived from global solar radiation and other parameters. The difference is probably related to aerosol absorption and pollution effects in the lower troposphere that are not currently detected from space. For 21 of 28 midlatitude Brewer sites, long-term mean summer UV measured values and UV derived from global solar radiation and other parameters agree to within +5 to −7%. The remaining seven sites are located in "clean" environments where TOMS estimates agree with Brewer measurements while UV derived from global solar radiation and other parameters is 10–13% lower. Brewer data also demonstrate that clean and "typical" sites can be as little as 70–120 km apart. *INDEX TERMS:* 0360 Atmospheric Composition and Structure: Transmission and scattering of radiation; 3359 Meteorology and Atmospheric Dynamics: Radiative processes; 0394 Atmospheric Composition and Structure: Instruments and techniques; 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); *KEYWORDS:* UV index, Brewer, TOMS, pyranometer, climatology, ozone

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1. Introduction

[2] The UV index was introduced in Canada in 1992 [*Kerr et al.*, 1994; *Burrows et al.*, 1994] in response to growing concerns about the increase of UV radiation due to ozone depletion and was later adopted by the World Meteorological Organization (WMO) and *World Health Organization* [2002]. The UV index was designed to represent UV irradiance in a simple form, as a single number, and it is an indicator of potential skin damage. It is proportional to the wavelength integral of the downward spectral UV irradiance weighted according to the erythemal action spectrum [*McKinlay and Diffey*, 1987] of the Commission Internationale de l'Éclairage (CIE). The UV index is nondimensional, obtained by dividing the CIE-weighted integral by 25 mW m^{-2}, and it ranges from 0 at night to ~10 on a clear summer day at northern midlatitudes near sea level.

[3] The UV index is currently used in ~30 countries for monitoring and forecasting of UV irradiance [*Long*, 2003]. There has recently been considerable progress toward harmonization of the UV index programs in different countries under the guidance of the WMO and the World Health Organization (WHO) (Global solar UV index, a practical guide, available online at http://www.who.int/uv/publications/globalindex/en/). It is planned to introduce the same way of reporting the UV index in the United States and Canada by the spring of 2004. However, methods of UV index measurement or estimation vary from country to country, which may result in a bias between respective UV index values. Estimation and comparison of long-term mean UV index values facilitate detection and analysis of the

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discrepancies between the outputs of different methods. We use the term "UV index climatology" for convenience meaning the geographical distribution of long-term mean UV values, although the time span of available data is far less than the 30 years typically required for climatology calculations [*Intergovernmental Panel on Climate Change*, 2001].

[4] Long-term characteristics of the UV index distribution can be derived directly from UV measurements. There are a number of sites with records of spectral [e.g., *Zerefos et al.*, 1997; *McKenzie et al.*, 1999; *Lakkala et al.*, 2003] as well as broadband and multifilter UV measurements [*Kerr et al.*, 2003, and references therein] suitable for estimating UV climatology and long-term changes at these sites. Both the United States and Canada run networks of Brewer spectrophotometers. A network of 21 Brewers, owned by the U.S. Environmental Protection Agency and operated by the University of Georgia, is measuring UV spectral irradiances throughout the United States [*Sabburg et al.*, 2002; *Kimlin et al.*, 2003]. The UV monitoring network run by Environment Canada comprises Brewers making spectral UV measurements at 12 sites. The limited spatial extension of available spectral UV measurements militates against production of UV climatology maps directly from Brewer UV data.

[5] Climatology of spectral UVB irradiance can also be constructed from long-term records of other geophysical parameters, primarily total ozone and cloud cover. Ground-based and satellite total ozone measurements are the sources of ozone data. Cloud cover or sunshine duration can be considered as proxies for cloud transmission in UV calculations [e.g., *Bais et al.*, 1993; *Josefsson and Landelius*, 2000; *Lindfors et al.*, 2003]. Global shortwave solar radiation measured by pyranometers can also be used as a parameter for estimating the UV attenuation not due to ozone, and UV irradiance can be derived from global solar radiation and total ozone data [*Bordewijk et al.*, 1995; *Bodeker and McKenzie*, 1996]. The presence of aerosols with strong absorption in the UV part of the spectrum, as for example, from forest fires, causes overestimation in the UV derived from pyranometer data. However, cases of large loading of these aerosols are relatively rare [*McArthur et al.*, 1999]. Solar radiation measurements have a history of similar length to that of ground-based ozone measurements, and there are many sites with long-term records. These measurements have been used to reconstruct climatology and to estimate long-term changes in surface UV over Canada [*Fioletov et al.*, 2001, 2003] and New Zealand [*Bodeker et al.*, 2002].

[6] UV climatology can be estimated from radiative transfer calculations that use climatology or actual measurements of ozone, clouds, and other characteristics of the atmosphere measured by satellites as input parameters [e.g., *Lubin et al.*, 1998]. The accuracy of the model estimates largely depends on how well the values of input parameters are known. It has been estimated at ±10% for clear skies and ±20% for all sky conditions with climatology values of ozone, cloud, surface pressure, surface albedo, temperature, and a rudimentary representation of aerosols as input parameters [*Sabziparvar et al.*, 1999]. Direct measurements of these parameters allow improved estimation. NASA's Total Ozone Mapping Spectrometer (TOMS) instruments onboard Nimbus 7 and Earth Probe satellites provide one of the longest records of simultaneous global observations of several of the key parameters affecting the UV. Calculation of erythemal UV irradiance from extraterrestrial solar spectral irradiance and TOMS measurements of total column ozone, aerosols, and surface reflectivity and their application for UV retrievals have been described in the literature [*Herman et al.*, 1996, 1999; *Krotkov et al.*, 1998, 2002], including estimates of errors from various sources. It has been found that TOMS typically produces systematically higher UV irradiance values than are measured at the ground for snow-free conditions [e.g., *McKenzie et al.*, 2001; *Fioletov et al.*, 2002; *Kimlin et al.*, 2003] and underestimates UV in the presence of snow at the ground [*Krotkov et al.*, 2001]. It has also been found that there are two sites, one in New Zealand and one on the west coast of Canada, where the measurements and TOMS-derived data demonstrate near-zero bias.

[7] In this study, UV irradiance derived from global solar radiation, total ozone, dew point temperature, and snow cover, along with UV estimates from TOMS data, were analyzed in order to establish the UV climatology of Canada and the United States. The results are presented in the form of monthly maps. UV irradiance measurements at the Canadian and U.S. Brewer networks were used for verification of the results. Possible sources of discrepancies between different estimates of UV index climatology are discussed.

2. Data Sets and UV Index Climatology Estimates

[8] The duration of available data was different for the three sources considered here. At the time of this study, TOMS UV estimates were available for the period 1980–1992 (Nimbus 7) and 1996–2000 (Earth Probe). Available pyranometer and satellite total ozone data make it possible to estimate UV for the period 1979–1990; gridded satellite total ozone data were not available prior to 1979. Quality-controlled 1 hour resolution pyranometer data from the U.S. network were not available after 1990. Thus 1980–1990 was the longest duration over which the required input data were available for both methods of estimation (ground-based and TOMS-based). The period of available Brewer data ranges from 13 years at Toronto to 2 years at Chicago. Ozone values averaged over the 1990s period were 1–3% lower (depending on the season) than those for the 1980–1990 period used for UV climatology estimates from TOMS and pyranometer-based UV index data. This introduces a bias between the UV climatology values estimated from Brewer measurements and from the other sources; however, the bias is small compared to the natural year-to-year variability.

2.1. Brewer Spectral UV Measurements

[9] The Brewer instrument measures the spectral UV irradiance on a horizontal surface with a spectral resolution of ~0.55 nm, full width at half maximum. In its normal UV routine in the Canadian network the Brewer scans from 290 to 325 nm and then back to 290 nm,

Table 1. Locations of the Brewer Instruments

Station	Latitude, °N	Longitude, °W	Elevation, m	Data Available Since
Everglades	25.39	80.68	15	1997
Big Bend	29.31	103.18	1131	1997
Atlanta	33.75	84.42	315	1997
Riverside	34.00	117.35	597	1996
Albuquerque	35.09	106.29	1615	1999
Great Smokey	35.60	83.78	566	1997
Research Triangle Park	35.89	78.87	134	1997
Sequoia	36.49	118.82	420	1999
Canyonlands	38.47	109.82	1298	1997
Shenandoah	38.52	78.44	1096	1997
Gaithersburg	39.13	77.22	130	1997
Rocky Mountains	40.03	105.53	2896	1998
Boulder	40.13	105.24	1689	1997
Chicago	41.79	87.60	156	2000
Toronto	43.78	79.47	198	1989
Acadia	44.38	68.26	122	1998
Halifax	44.70	63.60	50	1992
Montreal	45.47	73.74	31	1993
Theodore	46.90	103.38	562	1999
Olympic	48.14	123.40	8	1998
Glacier	48.51	113.87	976	1998
Saturna	48.78	123.13	178	1991
Winnipeg	49.90	97.24	239	1992
Regina	50.21	104.67	592	1996
Saskatoon	52.11	106.71	530	1991
Goose Bay	53.31	60.36	40	1998
Edmonton	53.55	114.10	766	1992
Churchill	58.74	94.07	35	1992
Denali	63.73	148.97	839	1998
Resolute	74.72	94.98	40	1991
Eureka	80.05	86.18	315	1997
Alert	82.50	62.32	62	1995

while the Brewers at the U.S. network use a single scan from 286.5 to 363 nm. The integration time is ~1 s for each wavelength, the sampling interval is 0.5 nm, and the spectral scan takes ~8 min. There are normally from one to four such measurements performed every hour throughout the day from sunrise to sunset. Spectral UV measurements are weighted using the erythemal action spectrum and integrated to calculate the UV index. The spectral interval of Brewer measurements in the Canadian network is too short to include all of the integration, and the Brewer algorithm for this spectral integral assigns a higher weight to the measurement at 324 nm wavelength to compensate for the missing contribution of wavelengths longer than 325 nm. It has been found that this interpolation method introduces an error typically <2% in the UV index value for solar zenith angles <70°. A similar but much smaller correction for the unmeasured spectrum 363–400 nm is made for the U.S. Brewer measurements.

[10] The U.S. and Canadian Brewer measurements were corrected for instrument-related systematic errors using slightly different procedures. The Brewer instruments are calibrated using a 1000 W standard lamp traceable to the National Institute of Standards and Technology. The calibrations are performed annually for the U.S. network and once every 1–2 years for the Canadian network. The response function of the instruments is calculated for each day on the basis of a linear interpolation between the two temporally closest response functions. The U.S. network data are corrected for instrument angular response as described by *Sabburg et al.* [2002]. The correction is based on angular response measurements of each instrument and the estimated typical aerosol optical depths for each site. The angular response correction for the Canadian network is based on measurements of the angular response of Brewer 14 but takes into account the actual cloud/aerosol conditions at the sites [*Fioletov et al.*, 2002]. The correction is from +3 to +12% for clear sky conditions depending on the solar zenith angle and about +9% for the diffuse irradiance (cloudy conditions).

[11] The overall random uncertainty for Canadian Brewer field measurements has been estimated at 6% (2σ) [*Fioletov et al.*, 2001]. That estimation includes a small, probably insufficient, contribution from not correcting for the variation of responsivity with temperature. Most Brewer instruments exhibit temperature dependence in response to the UV index in the range −0.1 to −0.4% per degree Celsius [*Weatherhead et al.*, 2001]. Meanwhile, the internal instrument temperature is typically above +10°C because of the internal heater, and it can get as high as 45°C on hot summer days particularly at high altitudes. The U.S. data in this study are corrected for temperature on the basis of the individual characterization of all the U.S. instruments. The Canadian data have not yet been corrected, partly because not all the instruments have been characterized for temperature. Field calibrations are normally done in the summer and, consequently, data for very hot days and those for the winter months will likely overestimate and underestimate, respectively, the true values by up to 4%. It will be noted that this range is roughly half of what can be inferred from the above responsivity and temperature ranges,

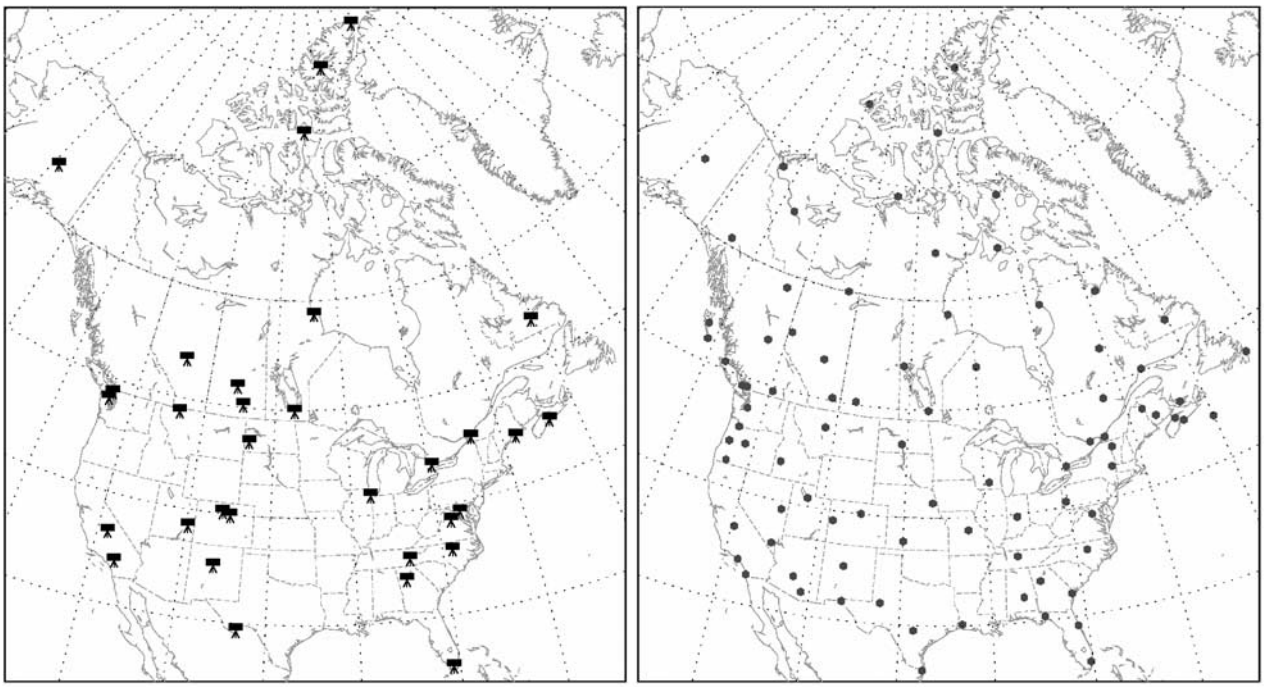

Figure 1. Map of (left) Canadian and U.S. Brewer and (right) pyranometer stations used in this study.

which is primarily due to smaller responsivity variations in the Canadian instrument characterizations obtained to date. The data from the two networks were also screened for different types of errors in individual spectra using identical data quality control procedures. Table 1 provides information on Brewer instrument locations and data availability, and the map of Brewer stations is shown in Figure 1.

[12] All available Brewer data were used to calculate mean noon UV index values for each month of the year. The means were calculated for each day from all Brewer measurements taken between 1100 and 1300 solar time (ST), and then the daily values for each month of the year were averaged. Figure 2 shows the map of mean UV index values at the Brewer sites for January, March, May, July, September, and November. Colors of the circles indicating the sites reflect the UV index values and were selected according to the WHO-recommended standard color scale for the UV index representation (WHO, Global solar UV index, a practical guide, available online at http://www.who.int/uv/publications/globalindex/en/). The same color scale is used in Figures 3, 5, and 6.

[13] As one would expect, summer UV index values are typically higher at low latitudes owing to the lower solar zenith angle there than those at high latitudes. However, the latitude is clearly not the only factor affecting UV. For example, mean UV index values for July are higher at Theodore, located at 47°N, than over southern Florida (26°N) owing to difference in altitude, cloud conditions, and, perhaps, absorbing aerosols. There are also longitudinal differences. Summer values over the West Coast are typically higher than the values over the east coast at the same altitudes.

[14] Mean UV index values in summer range from 1.5 in the Arctic to 11.5 over southern Texas. Summer UV values over North America are similar to those observed over Europe at the same latitudes [*Seckmeyer et al.*, 1995]. For comparison, UV index values at the high-altitude Mauna Loa observatory are typically 17–18 in August–September [*Tarasick et al.*, 2003]. Also, mean UV index values over North America are lower than those for South America and New Zealand at the same latitudes because of higher climatological total ozone, greater Earth-Sun distance, and higher concentration of absorbing aerosols [*McKenzie et al.*, 1999; *Cede et al.*, 2004]. The UV index over Lauder, New Zealand, located at 45°S, frequently exceeds 11 and can be as high as 12 [*McKenzie et al.*, 1999], while over North America it rarely exceeds 9 at the same latitude.

2.2. TOMS-Estimated UV

[15] The new TOMS UV version 8 data became available in 2004. A new data product, erythemally weighted noon UV irradiance, i.e., UV index multiplied by 25 mW m^{-2}, is included in the version 8 data set. The TOMS UV algorithm is based on corrections to clear-sky UV irradiance calculated by a radiative transfer model. The algorithm accounts for UV absorption by ozone and scattering by clouds and aerosols [*Herman et al.*, 1996, 1999]. Absorption by aerosols in the free troposphere and stratosphere can be detected as positive aerosol index data [*Krotkov et al.*, 1998]. However, pollution aerosols in the boundary layer at midlatitudes tend to produce negative aerosol indexes, and, consequently, there is no attempt to correct for pollution aerosol absorption in the current version of the TOMS UV algorithm [*Krotkov et al.*, 2002]. The nonabsorbing aerosols (negative aerosol index) are approximately taken into account as increased cloud reflectivity relative to the ground reflectivity climatology. The UV climatology maps were calculated from

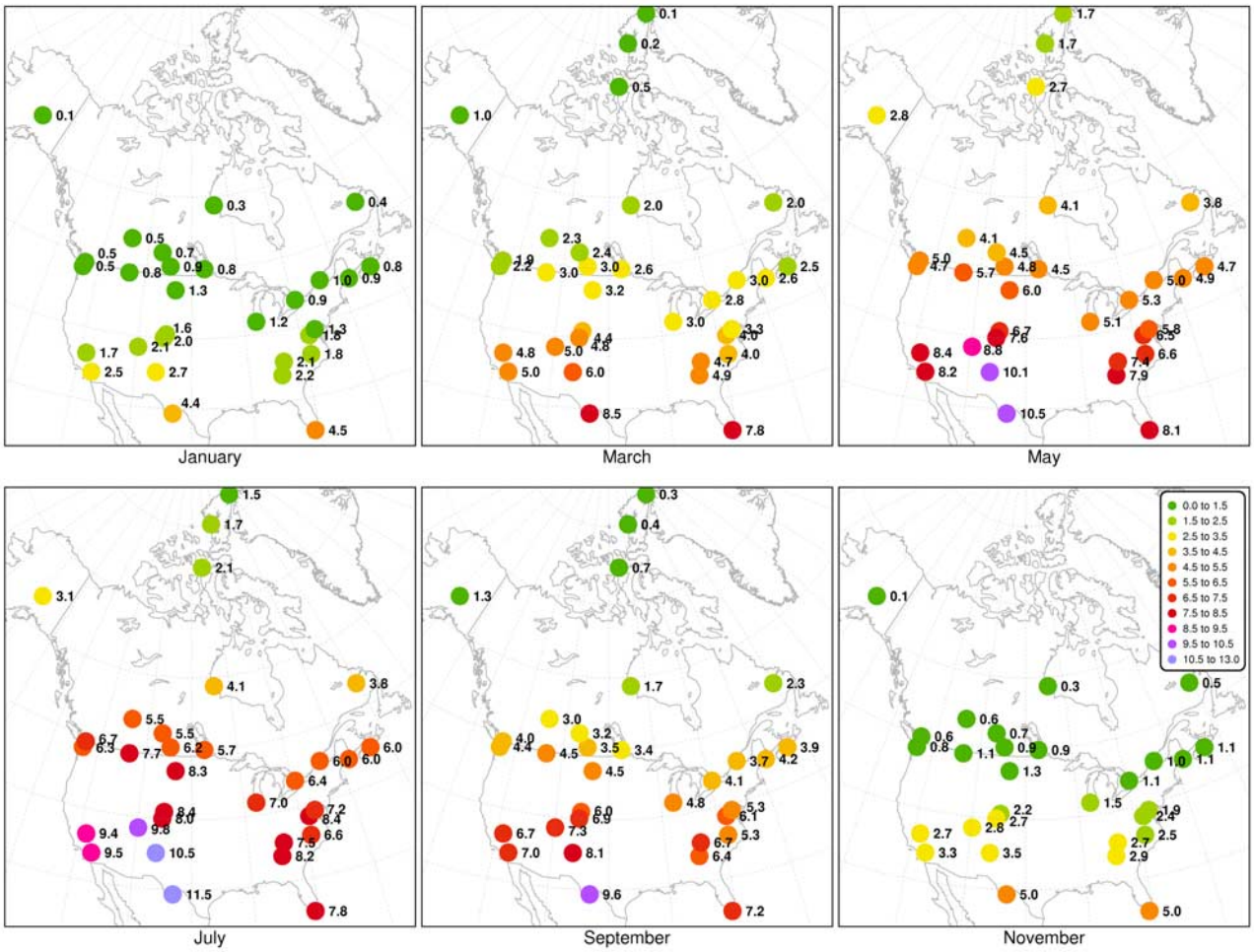

Figure 2. Maps of mean noon (1100–1300 solar time (ST)) UV index values for 6 months estimated from Brewer measurements.

Nimbus 7 TOMS 1° by 1.25° noon erythemal UV gridded data available from http://toms.gsfc.nasa.gov/. Long-term monthly mean values were calculated for each cell of the grid from the TOMS erythemal UV noon values. The results are presented for January, March, May, July, September, and November in Figure 3.

[16] The present TOMS UV algorithm estimates surface albedo using the lowest reflectivity measured by TOMS for each month of the year for each pixel during the period from 1979 to 1993 [*Herman and Celarier*, 1997]. This approach works well for snow-free conditions. The TOMS algorithm does not use the actual snow information. Instead, if snow is anticipated, the current TOMS algorithm [*Krotkov et al.*, 2002] uses a climatological snow/ice flag (probability of the presence of snow on a given day at a given location) to estimate the presence of snow. The algorithm first determines a snow albedo threshold (SAT). Currently, the SAT is simply the observed monthly minimum reflectivity value bounded from below by a constant value of 0.4. The value 0.4 was selected as appropriate for snow-covered urban-/suburban-populated areas containing at least moderate densities of roads, houses, and trees. The daily estimation of albedo (A_s) is based on comparison of SAT with the actual TOMS measured reflectivity at 360 nm. If the reflectivity is less than (SAT + 0.05), the cloud-free conditions are assumed, and A_s is set equal to reflectivity. Otherwise, A_s is set equal to SAT, and all additional measured SAT plus reflectivity is assigned to a cloud above the snow surface. High reflectivity values caused by snow under clear sky conditions may be interpreted by the TOMS algorithm as a combination of snow and clouds, resulting in underestimation of UV indexes. Because of this effect, climatological UV index values in winter, spring, and autumn at high latitudes from TOMS data are typically lower than those from Brewer measurements, as is discussed below in section 3.

[17] There is some difference in the timing used for the UV index climatology estimates from ground-based and satellite data. TOMS estimates are calculated exactly for the solar noon, while the global solar radiation-based and Brewer climatologies represent the UV index averaged over the period from 1100 to 1300 ST. This results in TOMS being systematically higher than the two other data sources. The bias is 1.5–2.5% in summer months (higher in tropics, lower at high latitudes) and up to 3% in the spring and autumn. This bias in percent is higher at high latitudes in the winter, but it is negligible compared to the difference introduced by snow effects

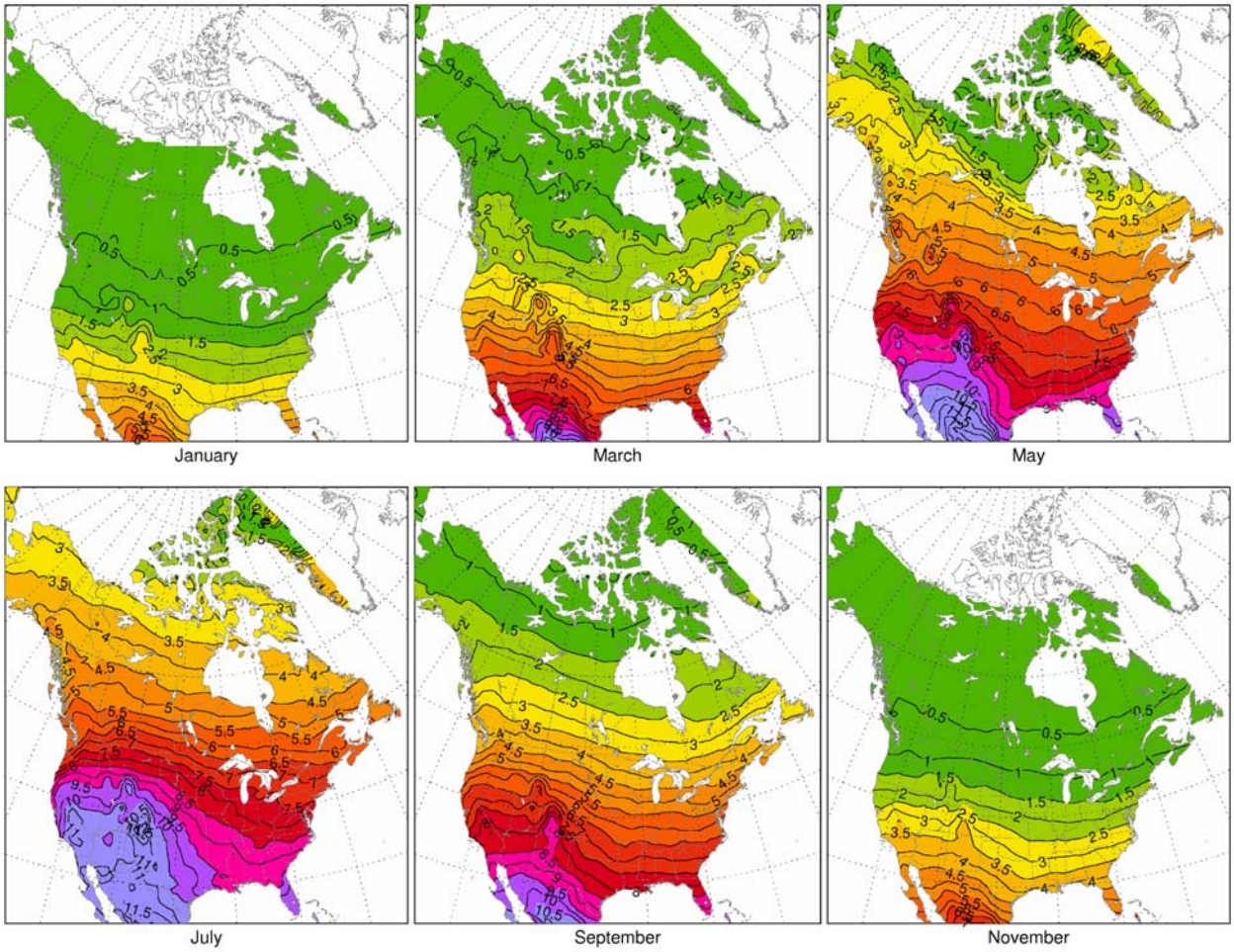

Figure 3. Maps of mean noon UV index values for 6 months estimated from TOMS data for the period 1980–1990.

there at that time of year. The bias is <0.3 units of the UV index for typical conditions.

2.3. UV Derived From Global Solar Radiation, Total Ozone, Snow, and Dew Point Temperature

[18] The link between different characteristics of UV irradiance and global solar radiation, total ozone, and other geophysical parameters is well established [*Bordewijk et al.*, 1995; *Bodeker and McKenzie*, 1996; *McArthur et al.*, 1999; *Kaurola et al.*, 2000; *Feister et al.*, 2002; *Diaz et al.*, 2003]. The approach previously developed for estimating the UV climatology for Canada [*Fioletov et al.*, 2003] was used here. The parameterizations have been described by *McArthur et al.* [1999] and *Fioletov et al.* [2001]; the input parameters are TOMS total ozone, global solar radiation measured by pyranometers, snow depth, dew point temperature, solar zenith angle, and altitude. Direct comparisons of resulting "pyranometer-based" UV data with Brewer measurements at seven Canadian sites for the period in the 1990s, when both pyranometer and spectral UV data were taken, have been reported [*Fioletov et al.*, 2003]. An agreement to within 2–3% was demonstrated except during periods of melting snow when local and temporal variations in snow albedo yield larger discrepancies.

[19] Global solar radiation data from the National Oceanic and Atmospheric Administration (NOAA) solar and meteorological surface observation network and from the Canadian National Solar Radiation network were used in this study. The Canadian data were available for the period 1960–2000 from 45 sites as hourly (solar time) integrated global solar radiation. Estimated uncertainties of individual pyranometer measurements were 4–7% (95% confidence level), depending on the absolute level of the global radiation [*McArthur et al.*, 1999]. It should be mentioned that a 5% error in pyranometer data for clear sky in summer translates into a 2% error in derived UV irradiance. The U.S. data from the SOLRAD network were reported for the period 1961–1990 as hourly (local standard time) integrated values and were interpolated to 1 hour solar time averages [*National Solar Radiation Data Base*, 1992]. The reported uncertainties for hourly values of global solar radiation measured under optimum conditions were ±5%. This network was closed between 1990 and 1995 because of National Weather Service modernization. The available U.S. database contains solar radiation data from 237 sites; however, reported global solar radiation for the majority of the sites was derived from other meteorological parameters. Only U.S. stations

Table 2. UV Enhancement Due to Snow Albedo Estimated From Brewer Measurements and Derived From TOMS Reflectivity Under Clear Sky[a]

Station	Enhancement, Brewer Data	Enhancement, TOMS Data
Toronto	16	14
Halifax	7	8
Montreal	23	22
Winnipeg	31	31
Goose Bay	18	21
Edmonton	25	26
Churchill	36	40
Resolute	36	50

[a]Sites are sorted by latitude. Enhancement is in percent.

that actually have global solar radiation measurements were used in this study, reducing the total number of available U.S. sites to 48. It should be noted that about half of all data reported from these 48 stations carried *E* and *F* flags [*National Solar Radiation Data Base*, 1992, Table 3–6]: "Modeled solar radiation data using inputs of observed or interpolated sky cover (cloud amount) and aerosol optical depths derived from direct normal data collected at the same location." It was necessary to use these modeled data because the number of actual measurements is not enough to estimate climatology for most of the sites. The reported uncertainty of these modeled data is ±7% for monthly values [*National Solar Radiation Data Base*, 1992]. The map of pyranometer stations is shown in Figure 1.

[20] Dew point temperatures measured at the beginning of each hour (local standard time) and daily snow depth available from the National Climate Data Archive of Canada and from the NOAA National Climatic Data Center were used in addition to global solar radiation and total ozone to estimate the UV index. Water vapor affects the transmission of global solar radiation and therefore must be considered in the relationship between global radiation and UV. In the calculation the surface dew point temperature is a proxy for the total column water vapor. Snow depth was used as an indicator of the presence of snow on the ground in order to account for UV enhancement due to high snow albedo. Snow and dew point data were obtained from the nearest available station to the point of the radiation measurement, within a radius of 50 km.

[21] There are, however, two major improvements to the previously developed algorithm related respectively to the snow enhancement correction and the interpolation over areas of high elevations. In the previous study by *Fioletov et al.* [2003] the UV enhancement due to snow was estimated from measurements under clear sky at Canadian Brewer sites. The results were interpolated assuming that the enhancement is a function of latitude. Although this approach can capture the major features of the surface albedo distribution, it does not reflect real effects of the terrain and landscape on UV. In this study, high-resolution satellite measurements were used to derive mean snow albedo. The regional albedo over snowy areas was estimated from TOMS reflectivity measurements at 360–380 nm. The mean TOMS reflectivity under cloud-free conditions with snow was calculated for each point of the TOMS grid. The European Centre for Medium-Range Weather Forecasts data archive provided information on snow and cloud conditions. The factor $(1 - R_s S_b)^{-1}$ quantifies the effect of UV enhancement due to snow, where R_s is the TOMS surface reflectivity, and $S_b = 0.4$ is the fraction of reflected radiation backscattered by the atmosphere [e.g., *Krotkov et al.*, 1998]. Table 2 shows that these satellite-derived estimates of the UV enhancement and those from ground-based Brewer measurements agree very well, typically within 1–2%.

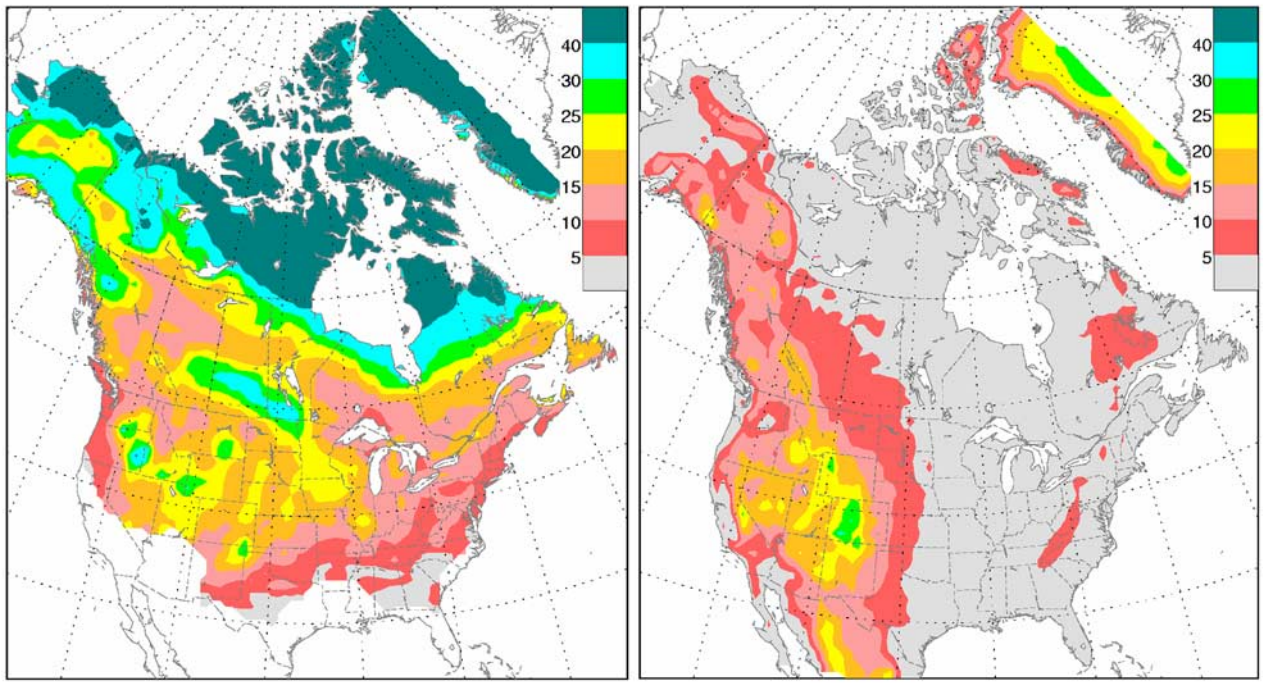

Figure 4. UV enhancement due to (left) snow albedo and (right) altitude in percent.

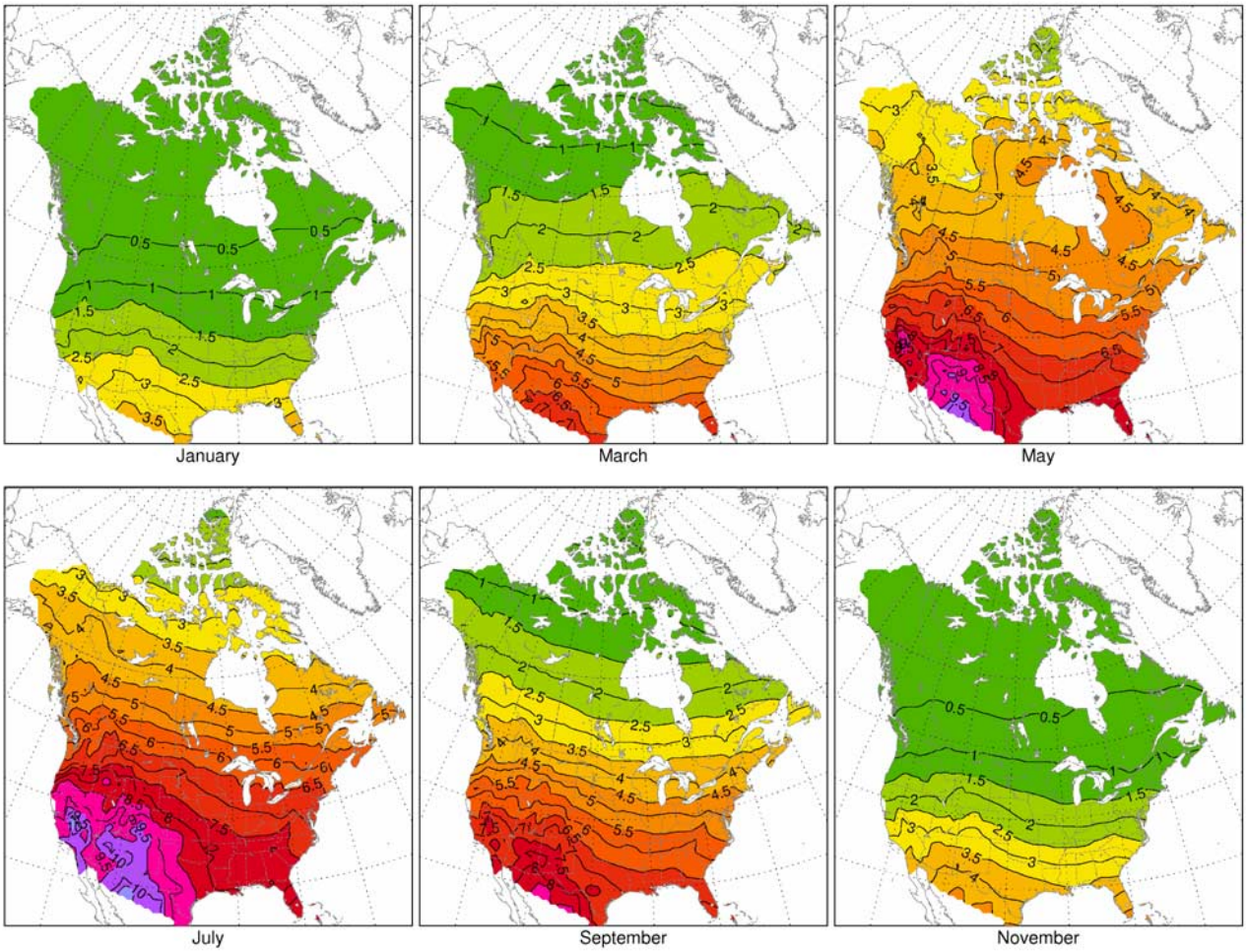

Figure 5. Maps of mean noon (1100–1300 ST) UV index values for 6 months estimated from global solar radiation, total ozone, snow, and dew point temperature data for the period 1980–1990.

The effect of UV enhancement is even stronger under cloudy conditions [e.g., *Krotkov et al.*, 1998]. However, the difference in UV enhancement due to snow between clear sky and cloudy conditions has little impact on the UV climatology and was neglected here.

[22] Figure 4 (left) illustrates the mean UV enhancement by snow estimated from the TOMS reflectivity data under assumption that the UV enhancement by snow is the same for all seasons. The enhancement is clearly linked to terrain and vegetation. The flat terrain of the Arctic tundra enhances UV by up to 50%, i.e., just slightly below the theoretical maximum of ~66% for 100% surface albedo. The enhancement declines sharply to 10–20% over northern boreal forests and then increases again to 25–35% south of the tree line over the prairies. There is also relatively high snow enhancement at parts of the southwestern United States corresponding to areas of flat treeless terrain. Figure 4 (left) and the map of global tree cover fraction [*DeFries et al.*, 2000] show definite similarity. Snow in the areas with 70–100% tree cover enhances UV by only 10–15%, while the enhancement is 20–25% where the tree cover is ~30%.

[23] The second improvement is that altitude is now taken into account when interpolating estimated UV climatology from measuring sites to the grid. The solar radiation network has a relatively low spatial resolution. Results of the UV estimation for the stations were interpolated to a grid with resolution of ~65 km to produce the maps. Results of the interpolation may have substantial errors for areas with mountainous terrain between the pyranometer sites that are typically located in valleys at relatively low elevations. To account for altitude effects, UV estimates at the sites were converted to UV at sea level and then interpolated to the grid. For each grid point the interpolated value was calculated as a weighted average on 8–16 (depending on data density) nearest sites with weights inversely proportional to the distance with some adjustments based on the position of interpolated sites [*Shepard*, 1968]. To reduce effects of the latitudinal gradient, a least squares plane was calculated to fit all interpolated data. The entire surface was tilted accordingly before the interpolation, and the tilting was reversed afterward. Then, an altitude adjustment was applied to the gridded data using actual elevations for the 1° by 1.25° TOMS grid. These corrections are based on the assumption that erythemal UV increases by 0.8% for each 10 hPa decrease in pressure [see, e.g., *Krotkov et al.*, 1998]. Figure 4 (right) illustrates the UV enhancement due to elevation calculated under this assumption. It should be stressed that this altitudinal correction does not affect UV estimates at the pyranometer sites, but it does affect the interpolation between the sites.

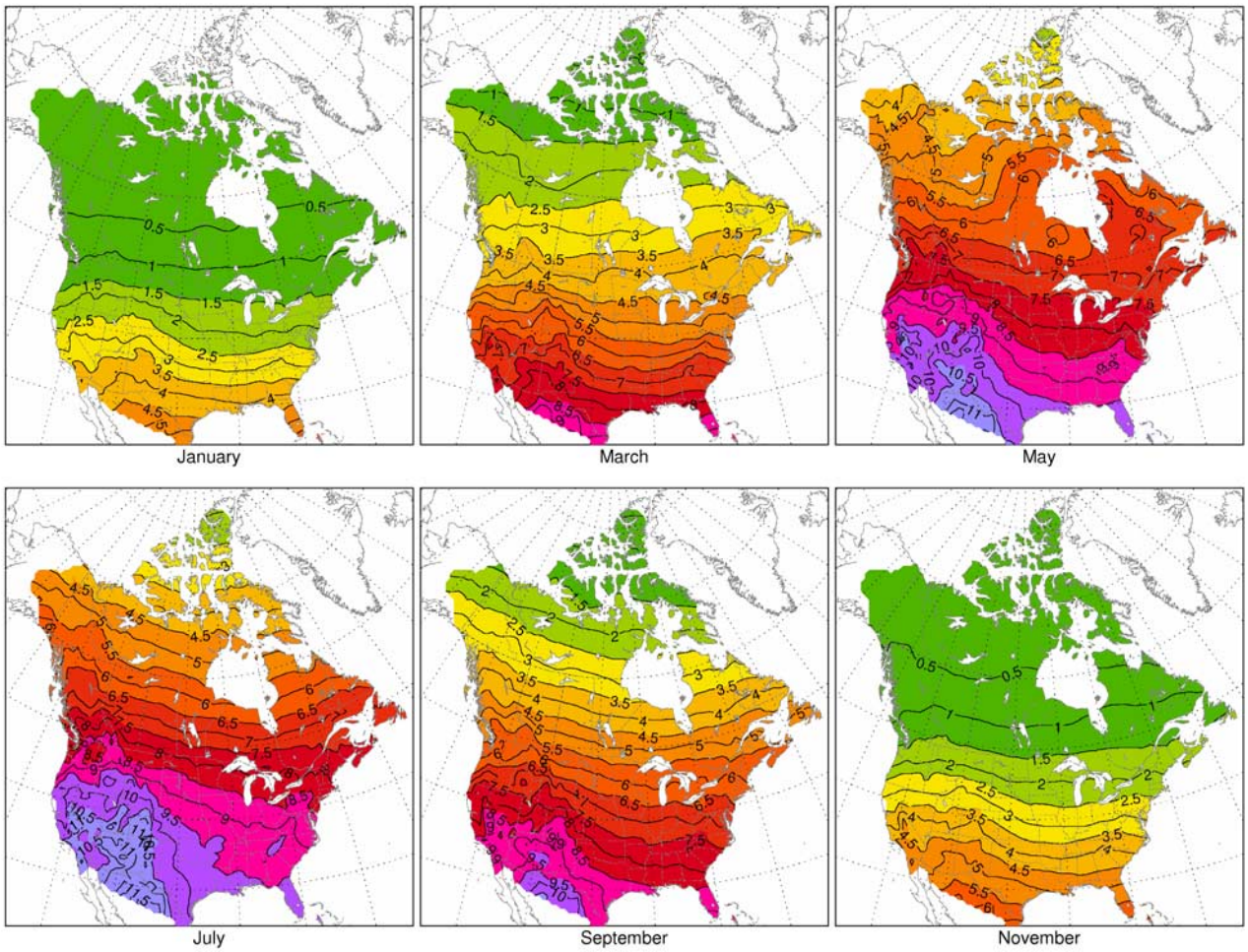

Figure 6. Maps of the 95th percentile of noon (1100–1300 ST) UV index values for 6 months estimated for the period 1980–1990 using global solar radiation, total ozone, snow, and dew point temperature data.

[24] Figure 5 shows maps of the mean UV index values at solar noon for January, March, May, July, September, and November. As mentioned, the noon UV index values were calculated as averages of two hourly integrals: from 1100 to noon and from noon to 1300 ST. Figure 6 gives information about extreme levels of the noon UV index values. It shows the 95th percentile of derived noon (1100–1300) ST UV index values; that is, only 5% of days have a higher level than shown in Figure 6. Maps for other months are available from http://exp-studies.tor.ec.gc.ca/e/ozone/uv.htm.

3. Comparison of UV Index Values From Different Data Sources

[25] Figure 7 shows the difference between UV index climatology estimates from TOMS (Figure 3) and pyranometer-based data (Figure 5) for January, March, May, July, September, and November. TOMS-based values are up to 60% lower than the pyranometer-based estimates over snow-covered areas. The largest negative bias is observed over flat treeless terrain of the Arctic with high snow albedo. It can be clearly seen, for example, in May west of Hudson Bay, where pyranometer-estimated UV index values are 4–4.5, while TOMS estimates are ~2. Brewer measurements at Churchill with an average of 4.1 confirm that the pyranometer-based estimates are correct. There is a similarity between the snow enhancement map (Figure 4) and the difference map (Figure 7) for March. Agreement between TOMS- and pyranometer-based climatological UV values is better over areas of low albedo (boreal forests) and worse over the prairies and tundra. It can be argued that this occurs because the snow enhancement correction of pyranometer data is based on Figure 4 results. However, Figure 3 for March shows that TOMS UV estimates are also lower over areas of high snow albedo compared to surrounding regions. Relatively low TOMS UV index values can be seen, for example, over the prairies west of Lake Winnipeg or the Saint Lawrence River valley. This is due to the TOMS surface albedo determination and the difficulty in distinguishing between snow and clouds from TOMS reflectivity measurements described in section 2. The situation is opposite in January over the area west of Great Slave Lake where TOMS UV is higher than pyranometer-based climatology by 30%. Snow albedo there is lower than the SAT (see Figure 4), and the snow probability in January is nearly 100%. Clouds there could be interpreted as snow by the TOMS algorithm yielding overestimation of the UV.

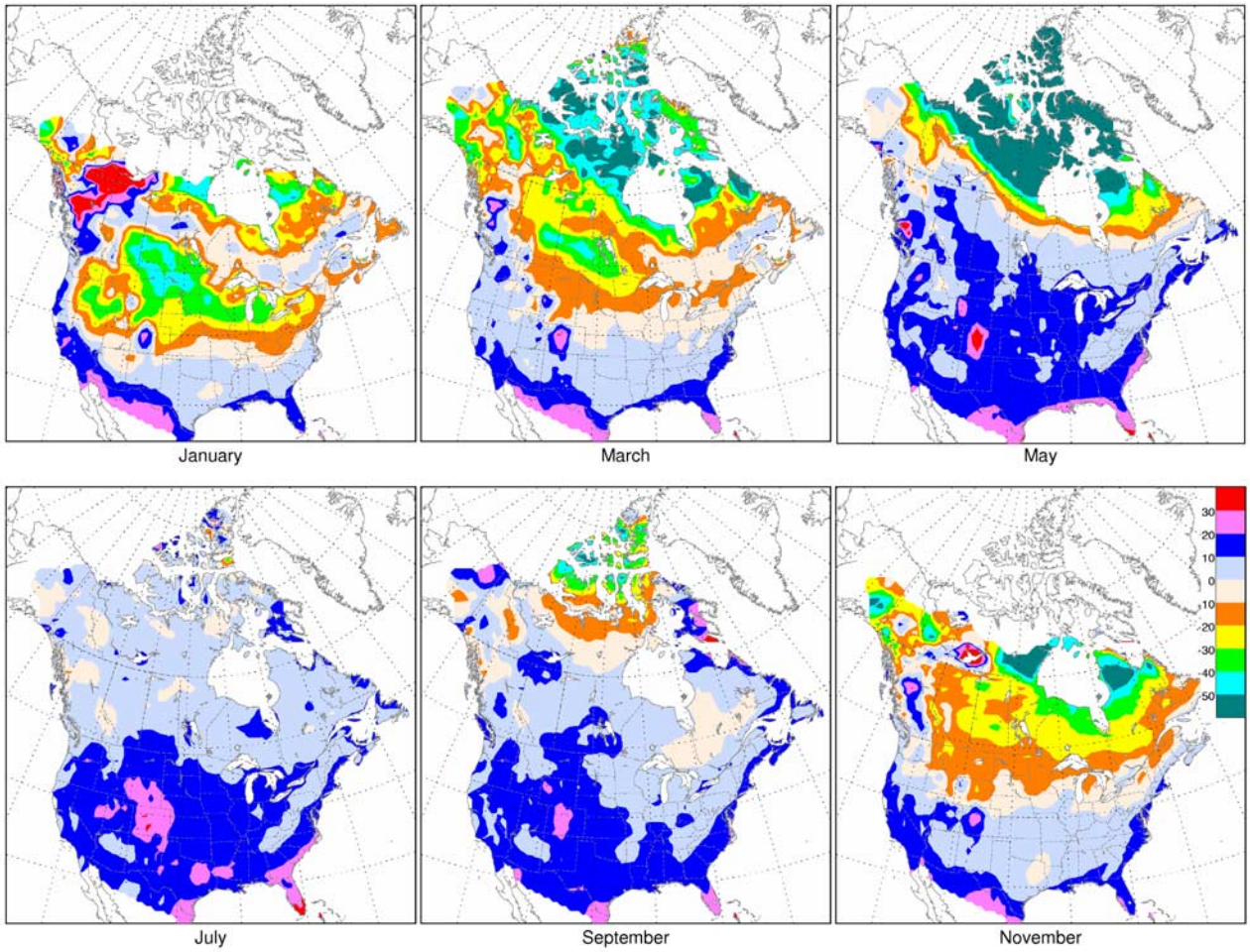

Figure 7. Maps of the difference in percent between noon UV index values for 6 months estimated from global solar radiation, total ozone, snow, and dew point temperature data and values from TOMS data for the period 1980–1990. Difference is positive if TOMS UV estimates are higher.

[26] In the absence of snow in summer, TOMS-based UV index estimates typically demonstrate 10–30% higher values of the UV index than pyranometer-based UV climatology. The difference is particularly high at low latitudes. For example, it is clearly evident over Florida in July, where TOMS-estimated mean UV index values are 9.5–10, while the estimates from pyranometer-based data are only 8–8.5.

[27] Climatological noon UV index values at the Brewer sites were extracted from the maps shown in Figures 3 and 5 and were compared with the actual Brewer mean values shown in Figure 2. The extracted data were weighted averages of four nearest grid points with weights inversely proportional to the distance. As mentioned, the period of Brewer measurements is different from that used for the climatology estimates. It was therefore expected that the estimated climatological mean summer noon values would be 1–3% lower than direct Brewer measurements as a result of the difference in the time spans and the ozone decline. The duration of Brewer measurements is relatively short, and the natural ozone and cloud cover variability introduces an uncertainty of 3–4% (2σ) for summer mean values estimated from Brewer measurements. However, it is still much less than a 10–30% difference between the UV index climatological values from pyranometer-based and TOMS data discussed here. Figure 8 shows the difference between mean noon UV index climatological values measured by Brewer spectrophotometers at 32 sites and estimated from the two sources for summer months with no snow (July and August for Resolute, Eureka, and Alert; June–August for Churchill and Denali; May–August for all other sites).

[28] The difference between the pyranometer- and Brewer-based summer climatological values is between +5 and −7% (a negative difference means pyranometer-based UV index values are lower than Brewer ones) for 21 of the 28 midlatitude sites located between 25° and 59°N with an average of −0.2%. These differences are larger than 2–3% differences reported by *Fioletov et al.* [2003] when simultaneous Brewer and pyranometer measurements were used. The majority of these 21 sites demonstrate a negative bias of 10–30% with TOMS. For example, Brewer measurements at Everglades, Florida, agree with pyranometer-based estimates and are ~30% lower than UV derived from TOMS. There was no obscuration of the horizon that could contribute to the TOMS-Brewer bias that may be found at some sites. The Brewer at Everglades is located on a 15 m tower, the terrain is flat, and the field of view is unobstructed in all directions. At the remaining 7 sites the difference is between −10 and −13%. All these sites demonstrate a relatively low

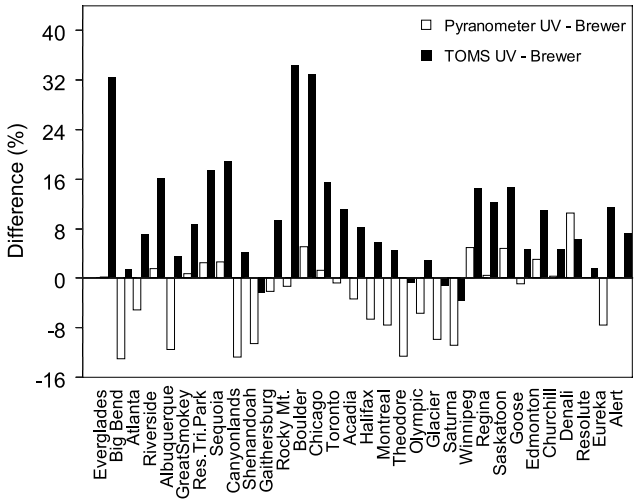

Figure 8. Difference between pyranometer-based and Brewer-measured UV climatology (open bars) and TOMS-estimated and Brewer-measured UV climatology (solid bars) in percent of Brewer values for 32 Brewer sites estimated for summer months with no snow (July and August for Resolute, Eureka, and Alert; June–August for Churchill and Denali; May–August for all other sites). Stations are sorted by latitude. There are no pyranometer-based UV estimates for Alert.

bias (from −1 to +6%) with TOMS. Five of them are located at high elevations (between 980 and 1600 m above sea level) with mountain terrain and glaciers. Estimates of UV climatology for the Arctic are less reliable than for midlatitudes because of high solar zenith angles. Records of Brewer measurements are also relatively short there for all sites except Resolute. Four Arctic Brewer sites demonstrated from +2 to +11% bias with TOMS UV and from −7% to +10% bias with pyranometer-based estimates. These differences are within ±0.2 UV index units.

[29] Near-zero bias was previously reported for Lauder, New Zealand [*McKenzie et al.*, 2001] and Saturna, Canada [*Fioletov et al.*, 2002]. It was suggested that relatively high levels of UV at these sites could be explained by clean atmospheres with low concentrations of boundary layer absorbing aerosols. Relative to TOMS, Saturna data are 5–7% higher than Olympic data in summer, though the Olympic site is located 74 km south of Saturna. The Brewer at Saturna is located on a hill 170 m above sea level, while the Olympic elevation is 8 m. This suggests that the additional UV absorption not accounted for in the TOMS algorithm occurs in the first 100–200 m above the ground.

[30] The Shenandoah Brewer site provides an example of how local conditions and elevation affect UV climatology. Figure 2 demonstrates that UV index values at Shenandoah are higher than at Gaithersburg, located 125 km northeast, and at Research Triangle Park, located 300 km south of Shenandoah. The mean noon UV at Shenandoah is 8.4 in July, compared to 7.2 at Gaithersburg and 6.6 at Research Triangle Park. UV index values >11 were observed 367 times at Shenandoah (where the bias with TOMS is 0.1%) compared to 9 times at Research Triangle Park (21% bias), and 28 times at Gaithersburg (12% bias). It is unlikely that the bias is caused by Brewer calibration errors. The comparison with TOMS demonstrates that the bias shows little change with time. Shenandoah is ~950 m higher than Gaithersburg and Research Triangle Park sites, which clearly contributes to the higher UV index values. TOMS gridded data used here have a 1° by 1.25° resolution, and the average height was used to estimate UV. For the grid cell containing Shenandoah, the average elevation is ~300 m, and this yields underestimation of the TOMS UV index at that particular site by ~5%.

[31] The effect of the site elevation alone is not enough to explain all the difference between pyranometer-derived and Brewer-measured values at Saturna, Shenandoah, and five other sites. The parameterization for UVA calculation from global solar radiation was empirically established using Toronto data [*McArthur et al.*, 1999], where the additional UV absorption is significant. If the factors causing the additional UV absorption affect global solar radiation to a much smaller extent, results of UV estimations will be biased at the clean sites. It is suggested that this is why UV climatology estimates from pyranometer data are lower than the Brewer measurements at these seven sites.

[32] TOMS UV estimates are 30% higher than pyranometer-based values over the Rocky Mountains in western Colorado. This feature was not seen in version 1 of the TOMS UV algorithm and is related to the snow and cloud corrections introduced in version 8. It is likely due to the high albedo of several mountain peaks above 4200 m located there and covered by snow. As a result, surface albedo in the TOMS algorithm is high for that area, and this contributes to high UV index values estimated from TOMS. Pyranometer stations are located at lower altitudes where snow cover is less frequent. Brewer measurements at Boulder and Rocky Mountains also demonstrate a 30–35% bias compared with TOMS gridded data. However, the bias is only 20% if the comparison is limited to the occasions when the center of the TOMS pixel is located within 30 km of the Brewer site.

[33] Obscuration of the horizon at some ground sites, variations in the cloud cover that are not seen from TOMS measurements, that are taken only once per day, the large size of the TOMS pixel, difference in altitude between the center of the TOMS pixel and the ground-based site, and difference in terrain and cloud cover within the pixel are among other sources of the bias between TOMS UV and ground measurements. They make it difficult to interpret the bias at individual sites, especially when TOMS gridded data are used. A detailed validation of the TOMS UV algorithm using Brewer measurements will be the subject of a separate study.

4. Summary and Discussion

[34] UV index climatology over Canada and the United States for the period 1980–1990 was calculated using satellite UV estimates from TOMS total ozone and reflectivity data, and UV index values which were derived from ground-based global solar radiation, total ozone, snow, and dew point temperature measurements. Brewer UV measurements at 32 sites in Canada and the continental United States were used for the validation. The TOMS-based method underestimates UV compared to pyranometer-based UV in the presence of snow on the ground. The new

version 8 of the TOMS UV algorithm has an improved method of UV estimation over snow-covered areas. However, TOMS-derived UV is still substantially lower than the measurements over snow-covered surfaces. The difference is larger, more than 50%, over the areas of high snow albedo (tundra, prairies) and smaller, ~10–20%, where albedo is low (forests) (Figures 4 and 7). These differences are largely caused by inaccurate assumptions about surface albedo and the ineffectiveness of the current TOMS algorithm in distinguishing between snow and clouds. It is expected that future versions of the TOMS UV algorithm will estimate surface albedo more realistically [e.g., *Tanskanen et al.*, 2003]. Snow and cloud data from additional data sources could improve the TOMS UV estimation. For example, *Romanov et al.* [2003, Figure 11] demonstrated high correlation between maximum snow fraction estimated from geostationary satellites and tree cover fraction, and the latter is linked to the UV enhancement by snow. The snow cover fraction data produced by the National Environmental Satellite Data and Information Service could be used in the TOMS UV algorithm as a source of snow albedo information. Accounting for snow depth could further improve estimates of UV enhancement by snow [*Arola et al.*, 2003].

[35] UV index climatology estimates from TOMS measurements for snow-free conditions in summer are 10–30% higher than those from pyranometer-based estimates. They are also higher than estimates from Brewer measurements. It is likely that the bias between TOMS UV estimates and Brewer measurements is caused by boundary layer absorbing aerosols, whose effects are not accounted for by the TOMS algorithm. The bias does not exist at sites with exceptionally clean local environments and/or at sites located above that absorbing aerosol layer.

[36] TOMS UV climatology estimates in summer are higher than those from Brewer data, except for several sites where the bias between the two sources is nearly zero. Pyranometer-based UV climatology estimates are in agreement with the Brewer-based estimates at 21 of 28 Brewer midlatitude sites with the difference between +5 and −7%. Seven sites demonstrated a larger bias (between −10 and −13%). These sites are located in clean environments and/or at high elevations, and the bias between Brewer and TOMS-derived climatological values is low there. This suggests the following interpretation of the UV climatology maps (Figures 3 and 5): These pyranometer-based UV climatology maps provide UV index values for sites with a typical level of boundary layer absorbing aerosol, while TOMS UV estimates are more suitable for clean environment. Brewer data demonstrate that clean and typical sites can be as little as 70–120 km apart and that accurate UV climatology maps require a high spatial resolution.

[37] Little is yet known about the spatial and temporal distribution of UVB absorption by aerosols, although climatology of absorbing aerosols at longer wavelengths is being developed from network measurements of aerosol optical depth and sky radiance [*Holben et al.*, 2001]. From the results discussed here, it appears that if aerosol absorption in the UVB is not properly accounted for in radiative transfer models used to predict the UV index in operational weather forecasting, then the 10–30% systematic difference between radiative transfer-based UV index forecasts and real measurements or forecasts based on empirical relationships with UV measurements can be expected. Long-term changes and trends in these absorbers may yield effects on UV that are comparable to and even stronger than those from ozone depletion.

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