Validation of Environment Canada and NOAA UV Index Forecasts with Brewer Measurements from Canada

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ABSTRACT

Ground-based ultraviolet (UV) irradiance measurements by Brewer spectrophotometers at 10 sites across Canada are compared with UV index forecasts for the same locations from Environment Canada (EC) and NOAA. For the EC forecast validation, summertime (May–August) data for the period from 1996 to 2009 are used. Comparison with NOAA forecasts is made for the more limited period of May–August 2006 and 2007. Several statistical measures are used, including the mean and the standard deviation of differences, correlation coefficients, and the probability of detection and false-alarm rate for prediction of high (UV index of 6 or above) values. For most conditions, only modest differences are found between the two forecasting systems; that is, UV index forecasts reported in the United States and Canada for Canadian sites are compatible. In general, the physically based NOAA system, which started operation in 2005, performs better than the semiempirical EC model, developed in the mid-1990s. The difference in model performance is not large under clear-sky and light-cloud conditions, but the EC model underperforms relative to the NOAA model under heavy-cloud and rainy conditions. Both the EC and the NOAA forecast models tend to overestimate UV under clear-sky and light-cloud conditions. Under heavy-cloud and rainy conditions, the EC model underestimates UV values, with about 30% of all forecasts under these conditions being 2 or more units below observations. NOAA forecasts tend to overestimate UV index values under these conditions.

1. Introduction

The UV index program was developed by Environment Canada (EC) in 1992 to give information on surface UV radiation (280–400 nm) to the general public. Its goal was to provide an easily understood number that would quantify the UV radiation levels that were expected for the following day. UV exposure continues to be a health concern, as skin cancers are expected to cause approximately 1300 deaths in Canada in 2012 (Canadian Cancer Society 2012). The index is based on erythemal (skin reddening) exposure, since this has the most immediate short-term impact on humans. The UV index is defined as the integral of the solar spectral irradiance across the ultraviolet region multiplied by the erythemal action spectrum (McKinlay and Diffey 1987; CIE 1998), divided by 25 mW m$^{-2}$ (Kerr et al. 1994; Burrows et al. 1994). The UV index is a nondimensional parameter that rarely reaches a value of 10 in Canada but can reach 20 or even higher in high-altitude locations in the tropics. The scale was established from analysis of spectral UV data measured by Brewer spectrophotometers at Toronto, Ontario, Canada, between 1989 and 1992 (Kerr and McElroy 1993; Kerr et al. 1994). In 1994 a UV index program was introduced in the United States by the National Weather Service (NWS; Long et al. 1996), which was replaced by the current forecast system in 2005. The UV index is now in operational use in more than 100 countries worldwide, including all of the countries of Europe, the United States, Canada, Taiwan, Thailand, Israel, Australia, New Zealand, Brazil, Argentina, Chile, and South Africa (e.g., Long 2003; Staiger and Koepke 2005; Sudhibrabha et al. 2006; Kerr and Fioletov 2008; Lee et al. 2008). It has been defined as the standard public awareness program for UV protection and has been used to inform the public about the risk of sunburn and skin cancer, as well as the need for sun protective behavior.

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As a part of the UV index program, daily forecasts of noon UV radiation throughout Canada for clear-sky conditions began in May of 1992 (Burrows et al. 1994). The forecast was based on an empirical relationship between total ozone and UV index, in which total ozone was predicted by a statistical model that relates total ozone to several meteorological variables output by the operational weather forecast model. In 1996 a nonlinear tree-based regression model, Classification and Regression Trees (CART), was added to the UV forecast scheme to achieve a more accurate adjustment of clouds and precipitation (Burrows 1997). Since then, that UV forecast model has been used in EC operation with only minor changes.

Although many countries now issue UV index forecasts using various forecasting methods, relatively little attention has been paid to validation of their accuracy, except for brief (generally initial) periods. This study provides the first systematic validation, over an extended period of time, of the EC UV index forecast.

The performance of the EC UV index forecast under different weather conditions is evaluated by comparison with the reference UV index values measured by Brewer spectrophotometers across Canada (e.g., Tarasick et al. 2003). A similar validation approach, although on a shorter time interval, is performed for National Oceanic and Atmospheric Administration (NOAA) UV index forecasts. Unlike the semiempirical EC model, the NOAA model (developed 10 years later) is based on ozone column amounts from a physical model, coupled with a radiative transfer model. The EC and NOAA forecasting models’ comparative performance for this common period is also evaluated.

2. Brewer UV measurements

Ground-based spectral UV irradiance measurements by Brewer spectrophotometers have been collected in Canada since 1989. The Brewer instrument measures UV irradiance incident on a horizontal surface with a spectral resolution of approximately 0.55 nm. In its normal UV routine, the Brewer scans from 290 to 325 nm and then back to 290 nm. The integration time is approximately 1 s for each wavelength, the sampling interval is 0.5 nm, and the double scan takes about 8 min. The reported units of UV irradiance are milliwatts per meter squared per nanometer. The UV irradiance is weighted by the erythemal action spectrum and then is integrated over wavelength to produce an erythemal dose rate, which is divided by 25 mW m$^{-2}$ to give the nondimensional UV index. There are normally from one to four such measurements performed every hour throughout the day from sunrise to sunset.

The spectral interval of Brewer measurements in the Canadian network does not cover the entire range of the erythemal action spectrum, which extends to 400 nm. The Brewer algorithm assigns a higher weight to the measurement at 324-nm wavelength to compensate for the missing contribution of wavelengths that are longer than 325 nm (which is known to correlate strongly with the 324-nm intensity). It has been found that this extrapolation introduces an error that is typically less than 2% in the UV index value for solar zenith angles of less than 70° (Fioletov et al. 2004).

The Brewer instruments are calibrated using a 1000-W standard lamp traceable to the National Institute of Standards and Technology. The calibrations are performed once every 1–2 yr. The response functions of the instruments are calculated for each day on the basis of a linear interpolation between the two temporally closest response functions.

UV irradiance measurements made by Brewer spectrophotometers at 10 Canadian ozone and UV monitoring network stations between 1996 and 2009 are used in this study. Most Brewer instruments that provided data were single monochromators, either MKII or MKIV models. One instrument (No. 111) was a double monochromator, with better stray light rejection. Data from single monochromators were corrected for stray light from information derived from instrument laser scans as discussed by Fioletov et al. (2000). Site coordinates and instrument numbers are given in Table 1, and the station map is shown in Fig. 1. The Saskatoon, Saskatchewan, site was closed in October of 2002. Three other sites—Winnipeg, Manitoba; Montreal, Quebec; and Halifax, Nova Scotia—were closed in May of 2004, December of 2004, and April of 2005, respectively.

All data are available online from the World Ozone and Ultraviolet Radiation Data Center (http://www.woudc.org/). All Brewer data have been corrected for instrument-related systematic errors, including angular response error (Bais et al. 1998; Fioletov et al. 2002), following which the overall uncertainty due to changing instrument responsivity, temperature dependence, and other factors has been estimated at about 6% (Fioletov et al. 2001; Kimlin et al. 2005; Lakkala et al. 2008). The noontime UV index values analyzed in this study are the averages of all Brewer measurements taken between 1100 and 1300 local solar time; each is thus typically an average of from two to eight measurements. The analysis is limited to the summer months (May–August), during which period the variation of the noon solar zenith angle is relatively small and the UV index is relatively high.
3. UV index forecasts

a. EC UV index forecasts

The UV forecasts produced by Environment Canada are computed using total ozone initially forecast from model output statistics by a three-latitude-zone, two-season regression model followed by an adjustment using real-time ground-based Brewer total ozone observations (Burrows et al. 1994). Clear-sky UV index values are then calculated from total ozone and solar zenith angle using an empirical relationship derived from Brewer measurements. The CART nonlinear tree-based regression model is then applied to adjust for cloud and precipitation effects (Burrows 1997). The cloud and precipitation conditions for 50 sites across Canada that are used here are taken from the archived weather forecasts. This information along with the forecast UV index values is included in the EC UV index forecast bulletins that are used as input for this study. This forecast procedure was implemented in 1996; forecasts from 1996 onward are used in this study. In 2003, the forecast was slightly modified to take elevation and albedo (snow) into account, but this modification has no impact for most stations in summer. Comparisons are performed for two periods: 1996–2003 and 2005–09. Because of various technical issues, no forecast data are available for 28 March 2004–31 July 2005.

When the relationship between total ozone and UV index was established from Brewer measurements, the angular response correction (introduced in the late 1990s) was not applied. Without that correction, noon UV index values were underestimated by between 3% (for clear sky) and 6% (for cloudy conditions) (Fioletov et al. 2002). Since the UV forecasts were derived from a relationship that is based on uncorrected Brewer data, the forecasts were also underestimates. Since 2003, a +3% correction has been added to forecast UV index values to compensate for that error. In this study that correction has also been applied to pre-2003 UV index forecasts, since all Brewer data were processed with algorithms that include the angular response correction.

Since March of 2004, following a WHO recommendation (WHO 2002), the forecast output has been modified, and only rounded integers are output as forecast values. For consistency, all UV index forecast values and UV index measurements used in this study were rounded to their nearest integers. The 3% correction discussed in the previous paragraph was applied
prior to rounding. Rounding was determined to have little effect on the final results, since the maximum error (0.5) is less than the standard deviation of the differences between forecasts and measurements at all sites.

The EC forecasts are issued for 12 and 24 h ahead. Only 12-h forecasts are examined in this study. Following a WHO recommendation (WHO 2002), five UV index exposure categories have been established for UV reporting: low (UV index that is less than or equal to 2), moderate (3–5), high (6–7), very high (8–10), and extreme (11 or above). The archived EC UV index forecast bulletins also contain information about cloud conditions and precipitation that will be used here to evaluate the forecast performance under different weather conditions.

b. NOAA UV index forecasts

The NOAA NWS, in collaboration with the U.S. Environmental Protection Agency, started UV index forecasting in 1996 (Long et al. 1996). In the current forecast scheme, introduced in 2005, the UV index is computed on the basis of a radiative transfer model and total ozone amounts forecast by the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) at a resolution of $0.5^\circ \times 0.5^\circ$, which assimilates satellite ozone measurements. Clear-sky erythemal dose rates are determined using the Tropospheric Ultraviolet and Visible (TUV) radiative transfer model (Madronich 1993) for the 280–400-nm spectral range. The clear-sky UV index forecasts are adjusted for clouds. The cloud transmission is determined by taking the ratio of the downwelling radiation at the surface for the 290–320-nm range in the presence of model clouds and without model clouds included. This transmission value is then applied to the above resultant dose rates to determine the final dose rate.

The forecasts are further adjusted for the effects of elevation, surface albedo, and tropospheric aerosol loading (Long 2003). In the following analysis, 12-h forecasts for May–August of 2006 and 2007 are used. The model outputs forecast UV values on a global grid from which values over the Canadian Brewer sites were extracted. The forecasts were downloaded from the Internet on a daily basis (ftp://ftpprl.ncep.noaa.gov/pub/data/nccf/com/hourly/prod).

4. Forecast performance assessment

Figure 2 is an illustration of measured and forecast UV index values. Toronto data for a 12-week period in 2007 are shown. On average, both forecasts overestimate UV index by about 1 unit. Although the forecasts are able to capture most of the UV variability, both forecasts have discrepancies with the measurements. This point can be further illustrated by the correlation coefficients: for the example shown in Fig. 2, the correlation coefficient between Brewer measurements and forecasts from EC and NOAA are 0.52 and 0.75, respectively. The correlation coefficient between the two forecasts is 0.46. Some statistics of the difference between measured and forecast values are discussed below.
a. Comparison of EC UV forecasts with Brewer measurements

The mean difference between forecast and measured noon UV index values (or the forecast bias) and the standard deviation of the difference are presented in Table 1 for two intervals, 1996–2003 and 2005–09, along with the means and standard deviations of the measured and forecast UV index values themselves for the summer months of May–August. The values are given in nondimensional UV index units and in percent of Brewer local noon mean UV index values. For sites with multiple Brewer instruments, values are given for each instrument.

With the exception of Resolute, Nunavut, all sites in this study are located within a 10°-wide belt between 44° and 54°N. With the exception of Goose Bay, Labrador, these sites experience clear-sky conditions from 37% to 47% of the time. Goose Bay has the lowest percentage of clear-sky days (33%) as well as the highest percentage of rainy days (35%). The mean summer UV index values at these midlatitude sites during the period of study were between approximately 5 and 6, except for Goose Bay where the more frequent occurrence of clouds reduced the mean value to 4.

Table 1 indicates that forecasts overestimate UV index values on average by 8%–20% at most sites with two exceptions: Saturna, British Columbia, and Resolute. The UV forecasts for Resolute during 1996–2003 did not account for snow albedo, which enhances UV by as much as 40% (Fioletov et al. 2003, 2004). After this correction is added to the forecast in 2003, the bias largely disappears and the forecast values are slightly higher than measurements.

With this exception, the differences between forecast and measured values are close to those seen between satellite estimates of erythemal UV and Brewer measurements (see Fioletov et al. 2002), as is illustrated in Table 2. Both satellite estimates and EC forecasts are noticeably higher than measurements at all sites except Saturna, where the differences are close to zero. Like EC UV index forecasts, satellite estimates of UV are based on clear-sky UV calculated from total ozone and solar zenith angle and adjusted for cloud conditions. Therefore, the factors responsible for the mean difference between satellite estimates and ground-based measurements may play a role in the observed differences between forecast and measured values. The sources of the difference between satellite and ground-based UV measurements have been widely discussed in
the literature (e.g., Krotkov et al. 1998; Wenny et al. 1998, 2001; McKenzie et al. 2001; Tanskanen et al. 2007; Esteve et al. 2009; Anton et al. 2010), with absorbing aerosol such as black carbon in the boundary layer being one of the main factors (Barnard et al. 2003; Bilbao et al. 2008; Cachorro et al. 2010). For the Canadian sites, it is likely that the difference in absorbing aerosol loading between individual sites is responsible for the observed mean forecast biases (Fioletov et al. 2002). The atmosphere is presumably cleaner at such a remote west coast site as Saturna, reducing the bias between measurements and forecasts.

The agreement of the EC UV forecast data with the ground-based Brewer measurements can also be expressed as the percentage of forecast values within 1 index unit of Brewer UV measurements. A difference of up to 1 unit can be caused by rounding since the UV index is reported as an integer. Table 3 shows these results at 10 Canadian Brewer sites. The dynamic range of UV index values at high latitudes is relatively small in comparison with that at lower latitudes, so it is not surprising that the probability of a UV forecast falling within 1 index unit of the observed value at high altitude is higher than that at low latitudes: it is the highest (94%) at Resolute and is between 60% and 70% for all other sites.

Figure 2 shows that on 9 and 10 July, the EC model forecast moderate UV index values (4), while the measured values were in the high (7) and very high (8) categories. As well, on 1 June both EC and NOAA forecasts predicted high values (6 and 7, respectively), but the measured UV index was low (2). This type of error should also be addressed, in addition to the traditional difference statistics.

An accurate forecast of high (6–7) or very high UV index values is particularly important: according to Health Canada recommendations (http://www.hc-sc.gc.ca/hl-vs/sun-sol/protect-protegez/index-uv-indice-eng.php), protection from UV is required for such UV levels. It is also important to avoid unnecessary false alarms. Two statistics, probability of detection (PD) and false-alarm rate (FAR), were used to evaluate the accuracy of high and extreme case forecasts. The PD is the probability of actual high and very high UV index value occurrences (or “events”) being correctly forecast. For convenience, we express it in percent, with 100% being a correct forecast of all high and very high cases. FAR is the probability of all high and very high events forecast for which subsequently observed values were low or moderate (i.e., below 6), with 0% being a forecast with no false alarms. The more often that a high or very high event was forecast but did not occur, the higher is the rate.

The PD and FAR for high or very high UV levels for EC UV forecast data are listed in Table 3. With the exception of Goose Bay, PD values are between 85% and 95%, indicating a fairly high detection rate, and FAR varies from 20% to 40%. Thus, for the most important conditions when UV values are in the high

Table 2. Aggregate data from Table 1, for EC forecasts for May–August 1996–2009. For comparison purposes, the differences between satellite retrievals and Brewer measurements estimated by Fioletov et al. (2002) are shown in the last column.

<table>
<thead>
<tr>
<th>Station</th>
<th>N</th>
<th>Forecast–Brewer difference</th>
<th>SD</th>
<th>Forecast–Brewer difference (%)</th>
<th>Satellite–Brewer difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Edmonton</td>
<td>1360</td>
<td>0.4</td>
<td>1.7</td>
<td>7.9</td>
<td>7.9</td>
</tr>
<tr>
<td>Goose Bay</td>
<td>1206</td>
<td>0.4</td>
<td>1.5</td>
<td>9.1</td>
<td>12.7</td>
</tr>
<tr>
<td>Saskatoon</td>
<td>774</td>
<td>0.7</td>
<td>1.7</td>
<td>14.2</td>
<td>10.5</td>
</tr>
<tr>
<td>Regina</td>
<td>1410</td>
<td>0.4</td>
<td>1.7</td>
<td>8.0</td>
<td>7.9</td>
</tr>
<tr>
<td>Winnipeg</td>
<td>926</td>
<td>0.5</td>
<td>1.7</td>
<td>10.3</td>
<td>9.5</td>
</tr>
<tr>
<td>Saturna</td>
<td>1461</td>
<td>0.1</td>
<td>1.6</td>
<td>0.8</td>
<td>-0.6</td>
</tr>
<tr>
<td>Montreal</td>
<td>932</td>
<td>0.8</td>
<td>1.8</td>
<td>13.7</td>
<td>5.7</td>
</tr>
<tr>
<td>Halifax</td>
<td>882</td>
<td>0.9</td>
<td>1.8</td>
<td>16.2</td>
<td>9.0</td>
</tr>
<tr>
<td>Toronto</td>
<td>2019</td>
<td>1.1</td>
<td>1.9</td>
<td>18.9</td>
<td>12.8</td>
</tr>
</tbody>
</table>

Table 3. Percentage of the UV forecasts (from 1996 to 2009) that are within 1 index unit of the Brewer reference, the probability of detection, and the false-alarm rate for high or very high UV predictions.

<table>
<thead>
<tr>
<th>Station</th>
<th>Brewer no.</th>
<th>Within 1 unit (%)</th>
<th>PD (%)</th>
<th>FAR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolute</td>
<td>13</td>
<td>94.1</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>31</td>
<td>90.9</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Edmonton</td>
<td>55</td>
<td>69.8</td>
<td>84.4</td>
<td>37.1</td>
</tr>
<tr>
<td>Goose Bay</td>
<td>18</td>
<td>70.3</td>
<td>75.8</td>
<td>52.7</td>
</tr>
<tr>
<td></td>
<td>39</td>
<td>70.7</td>
<td>68.8</td>
<td>52.2</td>
</tr>
<tr>
<td>Saskatoon</td>
<td>11</td>
<td>67.6</td>
<td>86.7</td>
<td>41.4</td>
</tr>
<tr>
<td>Regina</td>
<td>71</td>
<td>73.1</td>
<td>86.7</td>
<td>28.2</td>
</tr>
<tr>
<td></td>
<td>111</td>
<td>70.5</td>
<td>89.5</td>
<td>25.4</td>
</tr>
<tr>
<td>Winnipeg</td>
<td>83</td>
<td>70.0</td>
<td>91.3</td>
<td>31.0</td>
</tr>
<tr>
<td>Saturna</td>
<td>12</td>
<td>75.4</td>
<td>85.7</td>
<td>20.0</td>
</tr>
<tr>
<td>Montreal</td>
<td>79</td>
<td>65.2</td>
<td>89.8</td>
<td>30.2</td>
</tr>
<tr>
<td>Halifax</td>
<td>84</td>
<td>66.6</td>
<td>91.9</td>
<td>28.6</td>
</tr>
<tr>
<td>Toronto</td>
<td>14</td>
<td>60.9</td>
<td>93.9</td>
<td>28.9</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>56.6</td>
<td>89.3</td>
<td>32.5</td>
</tr>
</tbody>
</table>
or very high exposure categories, the probability of a correct forecast is high, although the FAR could be improved.

To better understand the nature of correct UV forecasts and false alarms of UV forecasts, an investigation was made of the effects of different meteorological conditions, divided into three main categories: sunny, cloudy, and rain. The meteorological conditions were taken from the forecast bulletins; that is, they were also forecast parameters. Three types of occurrence were considered:

1) correct high or very high forecasts were made,
2) high or very high values were observed but not forecast, or
3) high or very high values were forecast but only low or moderate values observed.

Forecast statistics (the mean and standard deviation of forecast biases, percentage of forecasts within 1 unit of Brewer reference data, and PD and FAR for high/very high UV cases) under the three main forecast weather conditions (clear, cloud, and rain) at 10 Canadian Brewer sites are summarized in Table 4. The forecasts are most accurate under clear-sky conditions, with the lowest values of the forecast bias mean and standard deviation, highest percentage values of forecasts within 1 unit of the Brewer reference, and highest PD and lowest FAR for high/very high UV. The PD values are above 92% at all sites, with an average of 97%, and the average FAR value is about 25%. For Toronto, all measured high and very high UV events were accurately predicted. For cloudy conditions, PD values are between 82% and 96% (again with the exception of Goose Bay), although the average FAR of about 40% is higher than for clear-sky conditions. Forecasts for expected rainy conditions are very unreliable; they are negatively biased (the UV index is underestimated) and have very low PD values (29%), with the average FAR being 61%.

If one further divides the cloudy category into light cloud and heavy cloud, Fig. 3 shows the fraction of the four weather categories associated with cases 1–3. Not surprising is that detection of high and very high UV is most accurate under clear-sky and light-cloud conditions. High and very high values were most often observed but not forecast when clouds or especially rainy conditions were forecast. From 60% to 90% of observed but not forecast high and very high UV index values were for days for which rain or heavy cloud was predicted. For Toronto that number was almost 100%, meaning that nearly all cases of underprediction of high UV were for days with predicted heavy clouds/rain. Almost one-half of all cases of high or very high UV being forecast but not observed are related to light-cloud conditions. That means the model predicts clouds but underestimates the UV reduction by these clouds.

The standard deviation of the difference between forecast and measured values (or the forecast bias) indicates how the distribution of forecast biases is spread. The standard deviations of forecast biases are smallest (ranging from 1.0 to 1.5) under clear conditions, increase (ranging from 1.4 to 1.9) under cloud conditions, and further increase (ranging from 1.6 to 2.2) under rain. All of these results point to poor performance of the EC UV index forecasts under heavy-cloud and rainy conditions.

The mean and standard deviation of forecast errors only evaluate the overall forecast performance. The distribution of forecast errors reveals additional information.
Figure 4 shows the experimental density estimate of the forecast bias at 10 Canadian Brewer stations under different weather conditions (clear, light cloud, heavy cloud, and rain).

Note that there is a positive bias to forecasts at a majority of sites and the distributions of forecast bias have long right tails (are positively skewed) for clear and light-cloud conditions. Under rain conditions, the distributions of forecast bias are generally negatively skewed but are flatter and more symmetric than those for clear and cloud conditions. In general, the forecast is more likely to underestimate UV values for rain conditions. The flatter shape of the bias distributions under cloud and rain conditions indicates that the forecast bias is more divergent than for clear conditions.

b. Comparison of EC and NOAA UV index forecasts

The EC and NOAA UV index forecasts for the summer months (May–August) of 2006 and 2007 were compared with Brewer measurements to evaluate the relative performance of the two forecasting algorithms. The comparisons were made on a dataset composed of days for which both forecasts as well as Brewer measurements were available. The total number of such days was between 160 and 190 (out of a potential 246), depending on the site.

NOAA forecasts were analyzed in the same manner as EC forecasts, with the mean difference, standard deviation of the difference, percentage of forecasts within 1 unit from the measured value, PD, and FAR calculated. These results are presented in Table 5. The NOAA UV forecast biases are nearly the same (within 0.2 units) as the EC forecast biases, except at Resolute, where NOAA forecasts are about 0.7 units higher than both EC forecasts and Brewer measurements. The standard deviations of the differences are lower for the NOAA forecast than for the EC forecast at all sites, indicating a higher precision for the NOAA predictions. In addition, the forecast is more frequently within 1 unit of the measured value at all sites: overall, 73% of the time versus 67% for EC forecasts. The average PD value for five sites in Table 5 is 88% for EC forecasts and 92% for NOAA forecasts, and the average FAR for NOAA forecasts is lower than for EC forecasts (32% and 35%, respectively).

To evaluate the performance of the two forecast systems under different weather conditions, the description of cloud and precipitation properties that accompanies the EC UV index forecasts was used to divide the forecasts by weather type: cloud-free sky (type 1); light clouds, including a few clouds, partly cloudy, cloudy periods, increasing cloudiness, and variable cloud (type 2);...
FIG. 4. Histograms of the distribution of the differences between forecast and measured UV index values at nine Canadian Brewer stations, under four forecast weather conditions.
TABLE 5. The mean and the standard deviation of the difference between UV forecasts and Brewer measurements, the percentage of the UV forecasts that are within 1 index unit of the Brewer reference, and the PD and FAR (for high or very high UV prediction) for EC and NOAA UV index 12-h forecasts at six Brewer stations. May–August data for 2006 and 2007 were used.

<table>
<thead>
<tr>
<th>Forecast source</th>
<th>Mean ± SD</th>
<th>Within 1 unit (%)</th>
<th>PD (%)</th>
<th>FAR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolute</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EC</td>
<td>−0.1 ± 1.0</td>
<td>86.5</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>NOAA</td>
<td>0.7 ± 0.8</td>
<td>87.6</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Edmonton</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EC</td>
<td>0.6 ± 1.6</td>
<td>71.7</td>
<td>89.3</td>
<td>32.9</td>
</tr>
<tr>
<td>NOAA</td>
<td>0.5 ± 1.5</td>
<td>74.9</td>
<td>85.4</td>
<td>25.4</td>
</tr>
<tr>
<td>Goose Bay</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EC</td>
<td>0.5 ± 1.7</td>
<td>62.4</td>
<td>83.3</td>
<td>63.8</td>
</tr>
<tr>
<td>NOAA</td>
<td>0.7 ± 1.2</td>
<td>73.5</td>
<td>93.3</td>
<td>57.6</td>
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heavy clouds, including cloudy, morning cloud, afternoon cloud, mainly cloudy, and overcast (type 3); and rain (type 4).

Figure 5 shows scatterplots of EC forecasts (blue circles) and NOAA forecasts (red pluses) and their linear regression fits at all observations sites, in relation to the Brewer measurements. There is not much difference in the performance of the two forecast systems for clear-sky and light-cloud conditions, although EC forecasts tend to overestimate UV when the measured UV index is low under those conditions. For heavy clouds and particularly under rainy conditions, EC forecasts tend to underestimate the UV index. The significant underestimation of EC forecasts for rainy conditions also indicates that the cloud adjustment of the EC UV forecast model might be too aggressive for high cloud optical depth. Note that the weather conditions referred to are part of the UV forecast and are not the actual weather conditions at the time of UV measurements. If the forecast correctly predicts a rainy day, it is still possible that UV can be high during a break in the cloud cover. It appears that the EC model may have difficulties handling this type of situation. Further analysis shows that the EC forecast values are almost constant for rainy conditions, mostly 2 or 3 for showers, and either 1 or 2 for rain, whereas the measured UV index varies, reaching values as high as 8. The NOAA forecast, which is based on physical principles (estimates of downwelling UV band radiation), performs noticeably better.

As Fig. 3 demonstrates, most cases in which high or very high values are observed are not forecast by the EC model occurred when heavy clouds or rain were predicted. This result could be caused by incorrect prediction of heavy clouds or rain or by incorrect UV index estimations under such conditions. Although the former possibility cannot be ruled out, the two global weather forecast models show similar skill in general (http://www.emc.ncep.noaa.gov/mmb/ylin/pcpverif/scores/), suggesting that the problem is largely related to the treatment of the predicted cloudy/rainy conditions in the EC UV forecast. Note, however, that in the summer of 2006 the Canadian model appears to have performed less well at forecasting rain than did the NOAA GFS.

For all weather types, the NOAA forecasts demonstrate a higher degree of correlation with the measurements than do the EC forecasts, and the difference is particularly large for rainy conditions. This reflects the lower bias and smaller scatter of the NOAA forecast errors. This is further illustrated by Fig. 6, in which histograms of forecast error from the EC and NOAA UV prediction models are plotted. For cloud-free sky and under light clouds, the distributions are similar, although both show positive skewness. Under heavy-cloud or rainy conditions, EC forecasts show notable negative skewness (i.e., they tend to underestimate UV) while NOAA forecasts show notable positive skewness. Figure 6 also shows that large negative errors (less than −1), are infrequent for NOAA forecasts but account for about 30% of all EC forecasts for heavy-cloud or rainy conditions. For all four weather categories, the error distributions for NOAA forecasts are more peaked than are those for EC forecasts, reflecting the higher precision of NOAA forecasts.

5. Summary and discussion

The EC and NOAA daily UV index 12-h forecasts have been compared with mean noon (1100–1300 local solar time) Brewer UV index measurements at Canadian sites for the summer months (May–August), for different cloud and precipitation conditions. Under clear-sky conditions, both forecasts performed well, with a mean difference of less than 0.2 units (much less than the standard error). The NOAA model demonstrated higher correlation with measurements than did the EC model (0.79 vs 0.76) and lower scattering (standard deviation was 1.2 vs 1.3). Since clear-sky UV is mostly determined by solar elevation and total ozone, this result indicates that both
UV index forecast models can successfully estimate total ozone, although the EC model could be improved.

Both EC and NOAA forecasts successfully predict high and very high UV index levels with average probability of detection of about 88% for EC forecasts and about 92% for NOAA forecasts. The PD is even higher for clear-sky conditions: close to 100%. The false-alarm rate (i.e., the percentage of high and very high event forecasts that are observed as moderate or low) is 35% and 32% for EC and NOAA, respectively. Reduction of the FAR should be a focus of future work to improve UV index forecasts.

On average, both EC and NOAA forecasts tend to overestimate measured values. The mean bias ranges from near 0 at Saturna to almost 20% for Toronto. The forecast versus measurement biases for individual sites are very similar to the biases between satellite and ground-based noon UV measurements. This bias is also close to 0 at Saturna and is as high as 13% at Toronto. This situation suggests that local conditions, especially absorbing aerosol loading, are mainly responsible for the observed discrepancies. The NOAA forecast uses climatological aerosol values, but they are based on satellite measurements in the visible part of the spectrum that may not represent aerosol effects on UV properly.

The EC forecasts tend to underestimate UV index when heavy clouds and/or rain are in the forecast. This is
unexpected given that the forecast is based on a statistical model and should not have a systematic bias. The explanation is likely related to the input data that are used to establish the regression model that is used for the forecast. The model was derived from individual Brewer measurements matched with the weather conditions (Burrows 1997). Therefore, it should produce unbiased estimates for measurements taken, for example, under rainy conditions. “Rain” in the forecast does not necessarily mean that all measurements on that day are taken under rainy conditions, however: measurements taken under light clouds or breaks in the cloud cover would yield higher-than-predicted UV values, producing a positive bias in the comparison.

The more sophisticated NOAA forecast model performs better than the EC model for all criteria used in this study. Although the mean differences between forecast and measured values are similar, the scattering of the differences is higher for the EC model than for the NOAA model. The EC model performance is particularly poor when heavy clouds and/or rain are predicted, with both bias and scattering of the forecast values for the EC model being larger than those for the NOAA model.

A physically based model for ozone forecasts, coupled with a radiative transfer model that includes forecast clouds, is currently under development at EC. The results of this study suggest that it should offer significant improvement in UV index forecasts.

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REFERENCES


