Application of Dobson and Smith's solar radiation model to German Bight data

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SUMMARY

The model for global radiation at the sea surface proposed by Dobson and Smith was tested for the Inner German Bight, North Sea with an 18-year time series of 3-hourly measurements of cloudiness and daily global radiation. The model, with unchanged parameters that were originally derived for oceanic stations, is suitable for use in coastal seas and seems best suited for simulating global radiation for long time-scales. Modelled monthly means of global radiation deviate from the measured monthly means by less than 5% except for June and July (11%), two months with large solar insolation. For short time-scales, root-mean-square errors from 14% (for 10 days) to 24% (for 1 day) occur. The application of the bulk model will be particularly useful to researchers working in the marine coastal areas of northern Europe.

1. INTRODUCTION

Dobson and Smith (1988) tested seven models, based on empirical or simple physical formulae, that calculate solar radiation from solar elevation, hourly cloudiness and also in some models cloud type. Therefore, the question arose: which model would be most suitable for calculating global radiation and would be portable to most areas of the world ocean? One would prefer a model that is simple, capable of resolving the annual cycle, and which relies only on meteorological standard measurements.

None of the models proved to be very good at reproducing individual observations. None estimated the long-term mean insolation better than the formula by Reed (1977) that relies only on noon solar elevation and daily mean cloud amount. But the hourly models did reproduce seasonal, monthly and daily variations better. The introduction of the cloud type changes the results only marginally.

One of the seven models tested by Dobson and Smith (1988) proved to be the best and simplest: the ‘octa model’, which was proposed by Dobson and Smith (1985). It is based only on reported total cloud amount in oktas (9 categories, from 0 to 8 eighths). This model performs well (in the root-mean-square (r.m.s.) sense) for calculating the hourly, daily, monthly and seasonal radiation means.

We have tested this model with another long time-series of global radiation data, which originates from the German Bight (North Sea) and which is apparently the only available off-shore long time-series for radiation in the North Sea (personal communication by Dr. Hein-Dieter Behr, Deutscher Wetterdienst, D-2000 Hamburg 60). This data set enables a further test of the validity and portability of the model. The testing of the model with this data set is well-suited to answer the question: is the cloud-type-independent model formulation sufficient for this area?

The motivation for our study was the potential use of the radiation model for calculating a 25-year time-series of global radiation for forcing physical and biological upper-layer models (Radach and Moll 1990).

2. THE DATA

The global radiation data were obtained from the roof of the Biologische Anstalt Helgoland (54°10.8'N, 7°53.6'E) at a height of 15 m on Helgoland, an island in the inner German Bight in the south-east of the North Sea. The station is located about 55 km off the coast in an area of about 30 m water depth. The data were provided by Dr. Erik Hagmeier (by personal communication, Biologische Anstalt Helgoland, D-2192 Helgoland, FRG) as daily integrals for the period 21 June 1965 to 31 December 1982. The solar radiation observations at Helgoland were not continued after that date.

Global radiation was measured with a bi-metal actinograph (Robitsch–Fuess) until 1977 and then during the following years with a solarimeter (Kipp & Zonen CMS). The daily totals of solar radiation by the actinograph will be accurate to no more than 5 to 10 per cent (Sellers 1965). Both instruments were pyranometers; they were cleaned irregularly, but at least monthly.

Standard meteorological observations from the light-vessel (LV) ELBE 1, about 30 km south-east of Helgoland, are available from 1962 to 1986 as 3-hourly values. The LV ELBE 1, which

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<table>
<thead>
<tr>
<th>Cloud amount (oktas)</th>
<th>OWS ‘P’ (Dobson and Smith 1985)</th>
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<th>Sable Island (Dobson and Smith 1989)</th>
<th>Swift Current (Dobson and Smith 1989)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$A$</td>
<td>$B$</td>
<td>$A$</td>
<td>$B$</td>
</tr>
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<td>0.391</td>
<td>0.400</td>
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<tr>
<td>sky obscured</td>
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<td>—</td>
<td>0.134</td>
<td>0.295</td>
</tr>
</tbody>
</table>

For explanation of $A$ and $B$ see text.
was originally situated at 54°N, 8°10.7' E, but from 1 December 1972 at 54°N, 8°7' E, is the only station close to Helgoland where continuous measurements of standard meteorological observations are available for such a long time period. LV ELBE 1 was replaced in April 1988 by an automatic lightship and the observations discontinued.

3. THE MODEL

Local incident global radiation as the sum of direct solar and diffuse radiation depends on the incidence angle of direct radiation, duration of solar radiation, cloudiness, and on the reflection from the sea surface. The dependence on these parameters is described by Kondratyev (1969). Aerosol and water vapour effects are not considered in the model. The short-wavelength downward radiative energy flux (W m⁻²) at the sea surface per unit surface element and unit time is given by the formula (Lumb 1964; Sellers 1965):

\[ I = Q_o * S * (A + B * S) \]

where the mean solar flux \( Q_o \) is taken to be 1368 W m⁻² after Fröhlich and London (1986) and \( S \) is the sine of the solar elevation. \( A \) and \( B \) are the coefficients for linear fit to measured incident solar radiation, stratified by cloud amount.

We have adopted a computer routine to calculate the solar elevation as a function of time, position, and annual variation in earth–sun distance (Sellers 1965). Accounting for the significant time variation of the solar constant we chose the best value for the time period of the observations (1965–82), although Lee et al. (1988) gave a value of 1365 W m⁻² for the last decade.

Cloudiness modulates reflection and absorption of radiation in the atmosphere. This dependence is parametrized by Dobson and Smith (1985, 1988, 1989) by two parameters, \( A \) and \( B \), which depend on the cloud coverage. They gave these parameters for conditions in the Pacific at 50°N, 150°W (Ocean Weather Station (OWS) 'P'), in the west Atlantic at 44°N, 60°W (Sable Island off Nova Scotia), and for one continental station, Swift Current, Saskatchewan (Table 1).

The solar radiation was computed directly from the time-series of reported cloud amount. Rejecting days with incomplete data, a large proportion of months contain gaps. These gaps in cloud observations were filled by linear interpolation between the adjacent two observations. (This was possible because only 2.9% of the 3-hourly data were missing).

Albedo at the sea surface has been extensively discussed by Payne (1972), who gave monthly mean values for the albedo for the North Atlantic depending on latitude in 10-degree latitudinal intervals (Table 2). Climatological albedo values may not provide adequate detail for low sun elevation, but averaged over a summer day the light from the sun and sky is fairly evenly distributed over elevation angles (Payne 1972). This is reflected in the nearly uniform albedo value of about 0.06 for the summer months. Payne gave an accuracy of 10% for low-latitude albedos and up to 25% for higher latitudes.

<table>
<thead>
<tr>
<th>TABLE 2. MEAN MONTHLY ALBEDO FOR THE ATLANTIC AFTER PAYNE (1972)</th>
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<tbody>
<tr>
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<tr>
<td>60.0°N</td>
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<tr>
<td>54.0°N</td>
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<td>50.0°N</td>
</tr>
</tbody>
</table>

The data for 54.0°N are interpolated.

4. RESULTS

(a) TEST BY REGRESSION

We compared, by linear regression analysis, the radiative fluxes simulated with the model of Dobson and Smith (1985, 1988, 1989) with the observed daily integrals of radiative fluxes at Helgoland.

Figure 1 and Table 3 show that the simulated annual cycle lies well within the band of the monthly means plus/minus the standard deviations. The agreement is quite satisfactory, especially during the months September to May. Only during the summer months of June and July do the
modelled monthly means of global radiation deviate markedly, by about 11% (Table 3), from the measured monthly means. From the point of view of radiant flux considerations, the uncertainty from changes in the albedo could be a possible reason for differences between the summer months and the rest of the year. But this is unlikely, because the largest changes in surface albedo occur in winter.

We correlated the observed and simulated daily radiation for all cloudiness values together as well as for each okta of cloudiness separately. The mean cloudiness for this area lies between 5 and 6 oktas. Figure 2 shows the regressions for two cases, namely for all values of cloudiness and for 6 oktas, and for the two methods of integrating daily radiation described in section 4(b). The regressions are highly significant in all cases for the trapezoidal integration (Table 4). Our standard error of estimation is in good agreement with the results of a comparison of satellite information with empirical formulae techniques (Frouin et al. (1988)). The conclusion was that simple global radiation models often over-estimate insolation because they are based on visual cloud-cover estimates.

Figure 1. Mean annual cycle of global radiation at Helgoland: the monthly means (——) of the measurements are given with their monthly standard deviations (vertical bars), together with the simulated monthly means of global radiation with different cloud parameters: (-----, Dobson and Smith 1988), (---, Dobson and Smith 1985) and (----, Dobson and Smith 1989 (Sable Island)). The mean monthly cloudiness at LV Elbe 1 is also shown.

| TABLE 3. COMPARISON OF MEASURED AND SIMULATED MONTHLY MEANS AND STANDARD DEVIATIONS OF GLOBAL RADIATION (W m⁻²) IN THE GERMAN BIGHT |
|-----------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Month  | Measured | Standard | Number of daily | Simulated | Standard | % Simulated | Standard | % |
|        | deviation | deviation | measurements  | trapezoidal | deviation | triangular | deviation | |
| Jan.   | 18.0      | 11.3      | 523            | 17.0        | 7.9       | 5.6       | 19.5        | 7.8           | -8.3 |
| Feb.   | 43.0      | 25.2      | 480            | 42.2        | 18.2      | 1.9       | 45.8        | 17.6          | -6.5 |
| Mar.   | 88.0      | 42.3      | 525            | 86.7        | 33.1      | 1.5       | 97.7        | 29.6          | -11.0 |
| Apr.   | 153.8     | 60.2      | 510            | 151.0       | 47.8      | 1.5       | 168.5       | 40.4          | -9.6 |
| May    | 204.9     | 71.5      | 526            | 212.3       | 59.0      | -3.6      | 234.9       | 43.3          | -14.6 |
| June   | 218.0     | 70.2      | 518            | 241.7       | 56.1      | -10.9     | 267.1       | 41.8          | -22.5 |
| July   | 200.4     | 62.8      | 556            | 221.7       | 52.5      | -10.6     | 244.1       | 39.9          | -21.8 |
| Aug.   | 170.0     | 53.3      | 557            | 182.7       | 44.6      | -7.5      | 191.5       | 33.1          | -12.6 |
| Sept.  | 106.7     | 41.6      | 538            | 112.8       | 35.6      | -5.7      | 117.8       | 29.0          | -10.4 |
| Oct.   | 52.4      | 27.3      | 557            | 54.8        | 22.2      | -4.6      | 57.7        | 21.5          | -10.1 |
| Nov.   | 24.0      | 14.2      | 537            | 22.2        | 10.4      | 7.5       | 24.6        | 10.0          | -2.5 |
| Dec.   | 13.5      | 8.6       | 556            | 11.1        | 4.9       | 17.8      | 12.9        | 4.9           | 4.4 |

Simulations with coefficients from Table 1 (Dobson and Smith 1985). Percentages are the differences between measured and simulated monthly means for the trapezoidal and triangular integration scheme, respectively.
Figure 2. Linear correlations of observed against simulated radiation for (a) all values of cloudiness and (b) 6 oktas. Left panels for the trapezoidal integration scheme, right panels for the triangular integration scheme.

<table>
<thead>
<tr>
<th>Cloud amount (oktas)</th>
<th>Number of observations (N)</th>
<th>Regression (r)</th>
<th>Random r for p = 0.010 and N</th>
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</thead>
<tbody>
<tr>
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<tr>
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<tr>
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<td>7</td>
<td>1121</td>
<td>0.921</td>
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<tr>
<td>8</td>
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<td>0.877</td>
<td>0.071</td>
</tr>
<tr>
<td>all data</td>
<td>6383</td>
<td>0.958</td>
<td>0.032</td>
</tr>
</tbody>
</table>

The regressions are significant, using the F-variance-ratio test, for all cloud amounts.
If the cloud-type climate at the stations in the German Bight were marine in winter and terrestrial in summer the discrepancy would be explained, but a simulation with Sable Island coefficients in summer and Swift Current coefficients in winter (Table 1) gave the worst agreement for monthly mean values.

Thus, the most likely cause for the differences in measured and simulated global radiation is to be found in the different cloud transmissivity at Helgoland and LV Elbe 1. The explanation for the over-estimation in summer seems to be the large gradients of mean cloudiness in coastal zones, and the irregular cleaning intervals.

(b) Integration scheme

A comparison of measured incoming solar radiation at Helgoland with predicted radiation at LV ELBE 1 is only possible for the daily integrals of radiation. For the calculation of the daily integrals we applied two numerical schemes. We used the trapezoidal integration formula based on 3-hourly cloudiness values, taking account of sun set and sun rise. For comparison, we calculated the daily integrals of radiation by a simpler method, namely the triangular formula as used by Reed (1977), using the hour of sunrise and sunset and the radiation value at noon.

The results obtained by the triangular integration scheme deviate too much from the measurements (Fig. 2, right panels). The triangular method is systematically biased because the noon solar radiation is multiplied by daily mean cloud amount. It is not recommended. The integrated radiation is better approximated by the trapezoidal scheme with 3-hourly values. Davies and McKay (1988) showed that only little error is introduced in solar radiation estimates by 3-hourly cloud observations instead of hourly values.

(c) Time-scales

We restricted the consideration of the goodness of the fit to the statistics of the daily, 10-daily, monthly, seasonal (3-monthly), annual and long-term means. The statistics are given by the r.m.s. errors for differences of measured radiation (at Helgoland) and simulated radiation (at LV ELBE 1), averaged over the above mentioned time intervals.

The model seems best suited for simulating global radiation for long time-scales. For short time-scales, r.m.s. errors from 11% (for 3 months) up to 24% (for 1 day) occur (Table 5). The r.m.s. error for the long-term mean at LV ELBE 1 is smaller when compared with model statistics for Sable Island after Dobson and Smith (1988), but all r.m.s. errors for shorter time-scales are higher. The differences increase up to 24% in the r.m.s. sense for daily estimates of solar radiation.

| TABLE 5. ERRORS (W m⁻²) IN MODELLING GLOBAL RADIATION AT LV ELBE 1 |
|--------------------|--------|--------|--------|--------|--------|--------|--------|
| Location           | 1-day  | 10-day | 30-day | 91-day | Annual | Long-term |
|                    | r.m.s. | error  | r.m.s. | error  | r.m.s. | mean error |
| LV ELBE 1          | 26     | 15     | 13     | 12     | 8      | 4        |
|                    | 24%    | 14%    | 12%    | 11%    | 7%     | 4%       |
| Sable I.           | 29     | —      | 7      | —      | 8      | —10      |
|                    | 20%    | —      | 5%     | 5%     | 5%     | 7%       |

Coefficients from OWS ‘P’ are compared with model statistics for Sable Island, after Dobson and Smith (1988).

It is probably wrong to think of the short-term differences as ‘errors’, because the radiation and cloud measurements are geographically separated and there might be gradients in cloud cover in this coastal zone. It should be emphasized, finally, that the radiation measurements appear to be too small, depending on irregular cleaning intervals.

ACKNOWLEDGEMENTS

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NOTES AND CORRESPONDENCE

Hamburg) for providing the standard meteorological observations for LV ELBE 1. Mrs. O. Kleinow provided expert computational support. Thanks are also due to Dr. H. Baumert, Dr. H. Behr, Prof. H. Graßl and Mr. A. Köhler for their valuable comments on the manuscript. We appreciate the detailed and thoughtful comments of the two anonymous reviewers.

REFERENCES


