Solar and Wind Energy Resource Assessment (SWERA)

DLR - activities within SWERA

Final report prepared by DLR

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Notice

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Part I – activity report

Overview

This final report gives an overview about the activities of the DLR – “Deutsches Zentrum für Luft- und Raumfahrt” within the UNEP/GEF project SWERA – „Solar and Wind Energy Resource Assessment“. The activities have been accomplished during the period from July 2001 until September 2004 by two DLR-Institutes, namely „Institut für Physik der Atmosphäre“ and the „Institut für Technische Thermodynamik“.

For the SWERA-project the DLR provides data on the global horizontal and direct normal irradiance (GHI and DNI) with a spatial resolution of 10 x 10 km². Within SWERA. this 10 km irradiance data are also called “high-resolution data”. These irradiance data, which are monthly and annual sums of the hourly irradiance for the participating countries and hourly time series for selected sites within each country, are based on satellite data. For each country, a high resolution solar resource assessment report is provided. Within these country reports, the results of DLR activities are described. Furthermore, the used method, the used atmospheric input data and comparison with ground measurements (if provided by the countries) are described. All data and documentation for each country are published on the SWERA homepage (http://swera.unep.net) and are sent to the national country partners. All country reports are also attached to this final report.

For following countries and for following time periods the irradiance data were determined. These countries are within the field of view of the used Meteosat satellites.

- NE-Brazil (2003 for inter-comparison purposes only)

For each country, monthly and annual maps are provided as digital data in ESRI-Shape-format. Furthermore, for several selected sites which are chosen by the country partners, time series of hourly values of the GHI and DNI are provided for 3 years in ASCII-format.

The following chapters describe the DLR activities as defined in the Terms of References (ToR).
Activity 1: Satellite Image Archive

(ToR: An archive of images from the Meteosat-5 and Meteosat-7 satellites will be established covering the total area of all countries in Africa, Asia and North East Brazil, that participate in the project. The archive will contain half-hourly images for 3 years that will be quality controlled and corrected, if necessary. Both the infrared and visible channel of the satellites will be recorded. The archive will be the basis for the detection of clouds that are of first order importance for the intensity of solar radiation on the ground (Activities 2 and 3). The archive will also serve as reference for the results of satellite data retrieved by the participants from India, China and Brazil (Activity 4). This activity will be concluded during the first 12 months of the project.)

Due to the used irradiance model, data of the geostationary satellite Meteosat (Meteorological Satellite) had to be archived and prepared for the processing. The operational Meteosat satellites gather half-hourly information of the system earth/atmosphere for more than 2/3 of the earth’s surface. The field of view of both satellites is shown in figure 1. Information on the cloud coverage can be extracted from these data.

![Figure 1: Field of view of METEOSAT-7 (left) and METEOSAT-5 (right), © EUMETSAT 2004.](image)

The DLR-archive activities for the data of Meteosat-7 (covering Africa, West-Asia and North-East Brazil) were completed in the year 2003. Three years (2000, 2001 and 2002) of half-hourly data are now available at the local DLR archive. For the comparison region (NE-Brazil) data for the time period Jan. 2003 until Oct. 2003 were also archived.

The archive activities for Meteosat-5 (covering Asia and West-China) were performed during the complete duration of the SWERA project. Three years (2000, 2002 and 2003) of half-hourly data are now available at the local DLR archive. Data of the year 2003 instead of 2001 were archived due to delivery problems from the Meteosat-archive at EUMETSAT. All data were quality checked and repaired (if necessary) by DLR. Figure 2 shows the monthly amount of archived data for the two satellites.
Figure 2: Monthly amount of Meteosat data (Meteosat-7 left, Meteosat-5 right) stored at the local DLR archive for the SWERA project.

These half-hourly data were prepared for the cloud detection processing. After this preparation, the local archive at the DLR consists of three years of half-hourly satellite data of the visible and infrared channel for the regions as shown in figure 3.

Figure 3: Archived regions (grey rectangles) stored at the local DLR-archive from METEOSAT-7 (left) and METEOSAT-5 (right), © EUMETSAT 2004.
Activity 2: Atmospheric Data Archive

(ToR: A second archive will hold the physical atmospheric data sets that define the solar radiation
intensity on the ground as function of location and time. The archive will cover the following
atmospheric data sets in order of their significance for ground radiation intensity (in brackets: spatial
resolution, time resolution, representative period of data):
- Cloud Index (in satellite resolution of approx. 5 km x 5 km at the Nadir 0°E and 63°E above
  equator, hourly means, 3 years)
- Aerosol Optical Thickness (0.8°x1°, monthly means, climatology)
- Precipitable Water (2.5°x2.5°, daily means, 3 years)
- Total Ozone (5° zonal, monthly means, 3 years)
- Transmission of Raleigh Atmosphere and Mixed Gases (O2, CO2, uniform and steady state
  standard atmosphere)

Using the archive satellite data, the hourly cloud information with a resolution of
10 km x 10 km at the nadir (Sub satellite point -SSP) was produced. This cloud information
was stored in a Cloud-Index. The Cloud-Index (CI) was produced within the Meteosat-7
field of view for the regions/countries:
- NE-Brazil (for the time period Jan. 2003 to Oct. 2003 for the cross check comparison)
- Ethiopia (for the period Jan. 2000 to Dec. 2002)

The Cloud-Index CI was produced within the Meteosat-5 field of view for the
regions/countries:

Additional data of aerosol optical thickness (monthly climatological values), water vapor,
precipitable water (daily values) and ozone (monthly values) were stored at the local DLR
archive and were prepared for use. Following atmospheric data were stored and used:

To take into account the atmospheric absorption of ozone, monthly mean values derived by
the Total Ozone Mapping Spectrometer (TOMS onboard NASA’s Earth Probe satellite) with
an spatial resolution of 1.25° x 1° is used.

The absorption of water vapor was calculated by using mean daily values of precipitable
water, that are based on 6-hour values of the National Centers for Environmental Prediction
(NCEP) -Reanalysis of the National Oceanic and Atmospheric Administration - Climate
Diagnostic Center (CDC-NOAA). The spatial resolution is 2.5° x 2.5°.

A compromise between global availability and an appropriate spatial and temporal resolution
of aerosol was found in the climatological values of aerosol optical thickness (AOT) derived
by a transport model from the Global Aerosol Climatology Project (NASA-GACP). This
project was started 1998 within the NASA Radiation Sciences Program and the Global
Energy and Water Cycle Experiment (GEWEX). This database was interpolated to a grid of
0.8°x1° and consists of climatological monthly values of the Aerosol Optical Thickness
(AOT).
To take into account the Rayleigh-Atmosphere, data of the US-Standard atmosphere are taken. Further information on the atmospheric input data can be found at each attached country report.

Activity 3: Solar Radiation Data Processing

(ToR: The data sets from the archive established within Activity 2 will be combined to high resolution maps and to site specific hourly time series of Global and Direct Radiation using the methodologies of DLR for Direct Radiation and of SUNY for Global Radiation. The data will cover the land areas of Ethiopia, Kenya, Ghana, Bangladesh, India, Nepal, Sri Lanka, China and the North East of Brazil. High resolution maps of monthly and yearly sums of solar radiation will be provided individually for each country as standard GIS data sets and as printed maps, showing the spatial distribution of the solar energy resource including microclimatic effects. For 10 selected sites in each country specified by latitude and longitude, annual hourly time series of Global and Direct Radiation will be provided as data files that may serve as basis for detailed performance and economic assessment studies.

Activity 3.1 Global and Direct Radiation Data Processing

ToR: This activity includes the preparation of maps, GIS data sets and hourly time series of Global Horizontal Irradiation (GHI) and Direct Normal Irradiation (DNI) for each country. The preparation of GHI and DNI data sets in all participating countries in Asia, Africa and America requires the collaboration of DLR and SUNY to combine their methodologies on an in-kind basis, which will take place in parallel to the Activities 1 and 2 during the first 6 months of the project. The production of the final country data sets and maps within Activity 3 will commence after the 12th month of the project and end after the third year. Samples of data sets and preliminary results may be produced earlier within the first year of the project in order to show the principles and resolution of the data, but may not have the final quality and performance.)

For the calculation of the Global Horizontal Irradiation (GHI), the clear-sky model developed by the SWERA-partner SUNY (State University of Albany, New York) was implemented in the DLR-algorithm. Together with the Direct Normal Irradiation (DNI) algorithm of DLR, for each country the hourly global and direct solar radiation was calculated for the defined years. The hourly values were integrated to monthly and annual values of the average daily total sum in Wh/m²/day. All values were stored in a digital database in the ESRI-Shapefile-Format which can be used with ArcView or ArcInfo. For several selected sites which were defined by the country partners hourly time series for three years were provided and stored in digital ASCII-files. All results (digital maps, time series and documentation) can be downloaded from the SWERA homepage. The annual values of GHI and DNI are shown in the country report. To give an impression of the available data, figure 4 and 5 shows the average daily total sum of DNI in Wh/m²/day for the year 2000 for all processed countries. The colors of the values shown in these two figures differs from the classified ones as shown in the DLR country reports and at the SWERA-homepage.
Figure 4: Annual average total daily sum of DNI in Wh/m²/day for the year 2000 for the countries within the field of view of Meteosat-7, namely Ghana, Kenya and Ethiopia.

Figure 5: Annual average total daily sum of DNI in Wh/m²/day for the year 2000 for the countries within the field of view of Meteosat-5, namely China (South-West), Nepal, Bangladesh and Sri-Lanka.
Activity 3.2 Quality Assessment

(ToR: This activity includes comparison of the global and direct data sets and maps with existent ground measurements and other data sources, as far as available. Consistency checks of all data sets will be performed and the data will be flagged according to the results.)

Brazil (cross-check)
For cross-check purposes, data of the measurement stations Caicó and Florianopolis in Brazil were used. Therefore, the subset of Meteosat-7 covering the area around Caicó and Florianopolis in Brazil was extracted from the Meteosat-7 full-disk. For the comparison, data of Caicó and Florianopolis for the period 1.1. 2003 until 31.10.2003 are used. The data of Balbina was not included in the inter-comparison, because no DNI-measurements were available for this site and the quality of available measurement is of limited quality.

The derived relative Mean Bias Deviation rMBD and Root Mean Square Deviation rRMSD for the comparison with hourly DNI and GHI-values are given in table 1, for daily sums in table 2. Figure 6 and 7 show scatter plots of hourly and daily DNI and GHI values for both stations. Only daylight values are taken into account.

All comparison results were presented at the Eurosun2004 conference in Freiburg with the publication by H. G. Beyer et al.: Assessing satellite derived irradiance information for South America within the UNEP resource assessment project SWERA.

<table>
<thead>
<tr>
<th></th>
<th>DNI (hourly)</th>
<th>GHI (hourly)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>rMBD [%]</td>
<td>rRMSD [%]</td>
</tr>
<tr>
<td>Caicó</td>
<td>-5.98</td>
<td>48.70</td>
</tr>
<tr>
<td>Florianopolis</td>
<td>-0.01</td>
<td>78.44</td>
</tr>
</tbody>
</table>

Table 1: Relative MBD and RMSD of the comparison with hourly values for the complete period in 2003.

<table>
<thead>
<tr>
<th></th>
<th>DNI (daily)</th>
<th>GHI (daily)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>rMBD [%]</td>
<td>rRMSD [%]</td>
</tr>
<tr>
<td>Caicó</td>
<td>-5.78</td>
<td>26.70</td>
</tr>
<tr>
<td>Florianopolis</td>
<td>-0.98</td>
<td>49.42</td>
</tr>
</tbody>
</table>

Table 2: Relative MBD and RMSD of the comparison with daily sums for the complete period in 2003.
Figure 6: Comparison of hourly (left), daily (right) DNI (top) and GHI (bottom) measured and satellite-derived values for Caicó, Jan 2003 – Oct 2003.

Figure 7: Comparison of hourly (left), daily (right) DNI (top) and GHI (bottom) measured and satellite-derived values for Florianópolis, Jan 2003 – Oct 2003.
Bangladesh

Ground measurements of the GHI are available for one site in Bangladesh, namely Dhaka (Latitude 23° 44', Longitude 90° 24', Elevation 17 m). The GHI was measured by an Eppley Pyranometers, the diffuse radiation was also measured by an Eppley Pyranometers with an additional manually tracked shadow ring. The DNI value was calculated as (GHI – DIF) / cosθ₂ where θ₂ is the hourly zenith angle. Clock time is corrected for solar time to obtain solar time hour angles, which has been used to get cosθ₂. The ground measurements were provided by the Renewable Energy Research Centre (RERC) of the University of Dhaka. RERC provided monthly values for the year 2002, hourly values for the year 2003.

The inter-comparison of hourly values leads to a relative MBD of 0.3% and a relative RMSD of 35.4% for GHI. A comparison with values of DNI was not performed due to the lack of qualified direct normal measurements.

The inter-comparison of monthly values of GHI leads to a relative MBD of 0.2% in 2002 and 2003 and a relative RMSD of 10.3% in 2002 and 6.6% in 2003. More information can be found in the Bangladesh country report.

China

There were no ground measurements provided by China in time.

Ghana

Ground measurements of GHI were available for several sites in Ghana, but none for DNI. The GHI was derived from sunshine duration measurements (MSD). For the site Kumasi, GHI values were also measured by a pyranometer (KNUST) with a higher accuracy than the sunshine duration measurements. All ground data were taken from the "Solar Data Analysis Report" for Ghana (KNUST, 2003) provided within the SWERA-project.

For this comparison, monthly average daily sums were compared for 19 sites. Kumasi is the only site with both, MSD and KNUST, measurements. The overall rMBD is –11.6%, the rRMSD is 16.3. For the more accurate GHI measurements of Kumasi using the KNUST pyranometer values, a rMBD of -0.4% and a rRMSD of 13.6% is derived. More information can be found in the attached Ghana country report.

Ethiopia

There were no ground measurements provided by Ethiopia in time.

Kenya

There were no ground measurements provided by Kenya in time.

Nepal:

There were no ground measurements provided by Nepal in time.

Sri Lanka

Ground measurements of the GHI were available for one site in Sri Lanka (Colombo, Latitude: 6 54' 30", Longitude: 79 51' 30", Elevation: 10 m). The data was provided by the Renewable Energy Department of the NERD Centre of Sri Lanka. The GHI was measured by a high precision Pyranometer OSK 15306. The measured values were integrated to hourly values for this comparison. Hourly values were available for the period 1998 to 2003. For the comparison values of the year 2000, 2002 and 2003 were taken. All ground data were provided from NERDC within the SWERA-project.

The relative MBD for the hourly values for the year 2000, 2002 and 2003 is 1.0%, the relative RMSD is 37.1%. The relative MBD for all monthly values is 2.4%, the relative RMSD is 9.3%. More information can be found in the Sri Lanka country report.
Activity 3.3  Documentation

(ToR: A documentation of the theoretical principles, methodology, data processing, results and quality assessment will be elaborated individually for each country. The documentation will contain:

- **Theoretical background** of the generation of global and direct radiation data using satellite images and other remote sensing data sources.
- **Description of equipment, software and data processing** including satellite image retrieval, atmospheric data archive, methodology to yield GHI and DNI data sets and maps.
- **Resulting maps and GIS data sets** of monthly and yearly sums of Global Radiation and of Direct Radiation covering the land areas of Ethiopia, Kenya, Ghana, Bangladesh, Nepal, Sri Lanka, China and the North East of Brazil, with an expected accuracy of better than 10 % with respect to the annual sum of solar radiation, a spatial resolution of approximately 5x5 km per pixel (China approx. 15 km per pixel ). The maps will be based on 3 years of time series data with a time resolution of 1 hour.
  - Resulting hourly time series of Direct and Global Radiation for selected sites in each country. This data will be useful for detailed performance modelling and economic assessment. The sites will be selected during the project on the basis of the solar radiation maps.
  - **Description of quality assessment** including the applied methodology, reference data and the results of quality assessment for each country.)

To provide a complete documentation for each participating country, each DLR-country report includes a description of the used data and method. Within these reports, example maps of annual average daily total sum were given for GHI and DNI. If the country provided ground measurements in time, the comparison with these measurements is also included.

Activity 4:  Methodology Transfer to India, China and Brazil

(ToR: Scientists from China and India will participate for three months (month 19-21) in the satellite image retrieval and data processing at DLR in order to learn how the DLR methodology works. Together with the documentation provided for their country by DLR, they will be enabled to transfer the DLR/SUNY methodology to their satellite and produce similar and consistent results for countries in East Asia that are not in the range of the METEOSAT-satellites. In a later phase, DLR personnel will backstop and supervise the implementation activities in China and India and help with the methodology transfer. With the participants from India, China and Brazil, radiation data sets will be exchanged and evaluated in order to countercheck results derived from the INSAT, GOES and from the METEOSAT satellites and to get consistency of solar radiation data and methodologies all around the globe.)

This activity was canceled, because of the unclear and delayed access to INSAT-data. Instead more emphasis is laid on demonstration of the results to country partners. E.g. SWERA was presented at the Renewables 2004 Conference in Bonn and the SolarPACES Symposium in Oaxaca Mexico (see separate report).

For the seven countries, Bangladesh, Ethiopia, Ghana, Kenya, Nepal, Sri-Lanka and West-China for which DLR applied a high resolution solar assessment within SWERA separate country reports are produced.
References:


(http://www.ngdc.noaa.gov/seg/topo/globe.shtml)


Method description

Satellite Data

The high resolution solar radiation assessment is based on data of the geostationary satellite Meteosat. Due to the location of the participating SWERA countries, data of Meteosat 7 (M-7) for the years 2000, 2001 and 2002 (for Ghana, Kenya and Ethiopia) and data of Meteosat 5 (M-5) for the years 2000, 2002 and 2003 (for Bangladesh, West-China, Nepal and Sri Lanka) are used. M-5 has its position at 0° latitude and 63° East longitude, M-7 is located at an orbit at 0° latitude and 0° longitude. Figure 8 gives the field of view of both satellites which scans the specific area every 30 minutes with a spatial resolution of 5x5 km².

![Figure 8: The solar irradiance data is derived from Meteosat a 0° (red circle) and at 63° East (orange circle). The brightened area marks the quantitatively analyzable region. (Meyer et al., 2004).](image)

Data of the visible (VIS) channel, which gives the reflection of the system earth/atmosphere (including clouds) and data of the infrared (IR) channel, which represents the temperature of the surface and atmosphere, are used for gathering information about the clouds. Both are used in a different way to assess the global horizontal (GHI) and the direct normal radiation (DNI) at ground. Additionally, data of the most important atmospheric components that attenuate the radiation, namely ozone, water vapor and aerosols, are used to take into account the clear-sky conditions of the atmosphere. In the following, the method for deriving DNI based on the DLR method and the method for deriving GHI, based on a combined method of DLR and SUNY, is described.
Method for Direct Normal Radiation (DNI)

The calculation of DNI bases on the clear-sky model of Bird and Hulstrom (1981) as described in Iqbal (1983) which was modified by Schillings et al. (2004) for taking into account cloudy conditions with

\[
DNI = 0.9751 \cdot I_0 \cdot \tau_R \cdot \tau_{Gas} \cdot \tau_{Ozone} \cdot \tau_{WV} \cdot \tau_{Ac} \cdot \tau_{vis} \cdot \tau_{ir} \tag{1}
\]

Each atmospheric transmittance coefficient \( \tau_i \) is calculated separately using atmospheric input data. All equations for calculating the clear-sky transmittances are described in Iqbal (1983).

Transmittance for Rayleigh scattering

\[
\tau_R = \exp\left[-0.0903m_a^{0.84}(1.0 + am_p - am_p^{1.01})\right] \tag{2}
\]

Transmittance for equally distributed gas (mainly O\textsubscript{2} and CO\textsubscript{2})

\[
\tau_{Gas} = \exp\left(-0.0127am_p^{0.26}\right) \tag{3}
\]

Transmittance for ozone

\[
\tau_{Ozone} = 1 - \alpha_{Ozone} \tag{4}
\]

\[
\alpha_{Ozone} = 0.1611\chi^{(1.0 + 139.48\chi)^{-0.3035}} - 0.002715\chi^{(1.0 + 0.044\chi + 0.0003\chi^2)^{-1}} \tag{5}
\]

\( \chi = u \cdot am \), with the vertical ozone layer thickness \( u \) in cm[NTP] and the airmass \( am \).

Transmittance for water vapor

\[
\tau_{WV} = 1 - \alpha_{WV} \tag{6}
\]

\[
\alpha_{WV} = 2.4959\gamma^{[1.0 + 79.034\gamma^{0.6828} + 6.385\gamma]}^{-1} \tag{7}
\]

\( \gamma = w \cdot am \), with the pressure-corrected relative optical path length of precipitable water \( w \) in cm[NTP].

Transmittance for aerosols

\[
\tau_{Ac} = \exp\left[-k_a^{0.873}(1.0 + k_a - k_a^{0.7088})am_p^{0.9108}\right] \tag{8}
\]

\[
k_a = 0.2758k_{a,0.38\mu m} + 0.35k_{a,0.5\mu m} \tag{9}
\]

with the aerosol optical thickness \( k_{a,\lambda} \) at the wavelength 0.38 \( \mu m \) und 0.5 \( \mu m \).

Transmittance for clouds

using the visible Cloud-Index CI\_vis

\[
\tau_{vis} = e^{(-CI_{vis} \cdot 0.1)} \tag{10}
\]

and using the infrared Cloud-Index CI\_ir

\[
\tau_{ir} = e^{(-CI_{ir} \cdot 0.07)} \tag{11}
\]
For the clear-sky atmospheric transmittance, the airmass is needed which is calculated by

\[
am = \frac{1}{\cos \Theta_Z + 0.15(93.885 - \Theta_Z)}^{-1.253}
\]  

(12)

The pressure correction is made by

\[
am_p = am \cdot \frac{p}{1013.25}
\]  

(13)

with

\[
\frac{p}{p_0} = \exp(-0.0001184z)
\]  

(14)

The clear-sky radiation is calculated each 20 minutes (10, 30, 50 minutes of each hour) for the maps and each 5 minutes (5, 10, 15, ..., 55, 60 minutes each hour) for the time series. The influence of the clouds is taken into account hourly, therefore all maps (monthly and annual average daily sums) and time series are based on an hourly calculation of the radiation. The DLR-model output for DNI is sampled at a 10km spatial resolution.
Method for Global Horizontal Radiation (GHI)

The calculation of GHI bases on the method of Perez et al (2002) and Ineichen and Perez (2002). GHI is calculated with (Perez et al., 2002)

\[ GHI = ktm \cdot Ghc \cdot (0.0001 \cdot ktm \cdot Ghc + 0.9) \]  

(15)

with \( ktm \)

\[ ktm = 2.36 \cdot CI^5 - 6.2 \cdot CI^4 + 6.22 \cdot CI^3 - 2.63 \cdot CI^2 - 0.58 \cdot CI + 1 \]  

(16)

GHI is calculated using the cloud information based on infrared (IR) and visible (VIS) Meteosat data which lead to a single Cloud-Index CI with

\[ CI = \max( CI_{\text{vis}}, CI_{\text{ir}} ) \]  

(17)

For the determination of the clear-sky global irradiance \( G_{hc} \) the new formulation as described in Perez et al (2002) is used with

\[ Ghc = cg1 \cdot I_0 \cdot \cos \Theta_z \cdot \exp(-cg2 \cdot am \cdot (fh1 + fh2 \cdot (TL - 1))) \cdot \exp(0.01 \cdot am^{1.8}) \]  

(18)

with

\[ cg1 = (0.0000509 \cdot \text{alt} + 0.868) \]
\[ cg2 = (0.0000392 \cdot \text{alt} + 0.0387) \]
\[ I_0 = \text{Solar constant (eccentricity corrected)} \]
\[ \Theta_z = \text{solar zenith angle} \]
\[ fh1 = \exp(-\text{alt} / 8000) \]
\[ fh2 = \exp(-\text{alt} / 1250) \]
\[ am = \text{elevation corrected air mass} \]
\[ \text{alt} = \text{altitude in meters} \]
\[ TL = \text{Linke turbidity} \]

Due to missing values of the Linke turbidity \( TL \) for the parameterization of the clear-sky atmosphere, data of the atmospheric components ozone, water vapor and aerosols are used. These atmospheric data are also used for the DNI. To derive \( TL \) from atmospheric data we use the following formulation as described by Ineichen and Perez (2002) with

\[ TL = (((11.1 \cdot \ln(b \cdot \frac{I_0}{B_{ncl}})) / am) + 1 \]  

(19)

with \( b = 0.664 + (0.163 / fh1) \)  

(20)

and the clear-sky direct normal irradiance \( B_{ncl} \)

\[ B_{ncl} = I_0 \cdot \tau_{ra} \cdot \tau_{ae} \cdot \tau_{o3} \cdot \tau_{ga} \cdot \tau_{wv} \]  

(21)

The calculation of transmittance coefficients \( \tau_i \) and the used atmospheric input data are described in the method for the DNI.

The clear-sky radiation is calculated each 20 minutes (10,30,50 minutes of each hour) for the maps and each 5 minutes (5,10,15,…,55,60 minutes each hour) for the time series. The influence of the clouds is taken into account hourly, therefore all maps (monthly and annual average daily sums) and time series are based on an hourly calculation of the radiation. The DLR/SUNY-model output for GHI is sampled at a 10km spatial resolution.
Input Data

Elevation

Figure 9: Elevation from GLOBE.

Ozone
The monthly ozone data are taken from TOMS published by the NASA/GSFC TOMS Ozone Processing Team [http://toms.gsfc.nasa.gov/], (McPeters et al., 1998).

Figure 10: Ozon monthly average for February 2003 in [DU] from TOMS

Water vapor
The daily water vapor data are taken from the NOAA-CIRES Climate Diagnostics Center in Boulder Colorado, USA (NCEP/NCAR) [http://www.cdc.noaa.gov/] (Kalnay et al., 1996).

Figure 11: Water vapor daily mean for 7. February 2003 in cm[NTP] from NCEP/ NCAR-Reanalysis
Aerosol
The monthly climatological aerosol optical thickness data are taken from NASA-GACP, [http://gacp.giss.nasa.gov/index.html], (Mishchenko et al, 2002).

![Figure 12: Aerosol optical thickness for February from NASA-GACP.](image)

Clouds
The hourly cloud information are based on half-hourly Meteosat-5 IR and VIS data (© EUMETSAT, 2004). The determination of the cloud indices is described in detail in Mannstein et al. (1999) and Schillings et al. (2004). The basic approach for deriving VIS cloud information is described with

\[ CI_{\text{vis}} = \frac{\rho - \rho_{\text{min}}}{\rho_{\text{max}} - \rho_{\text{min}}} \]  

where \( \rho \) is the actual reflectivity measured by the satellite, \( \rho_{\text{min}} \) corresponds to the surface albedo and \( \rho_{\text{max}} \) is the maximum reflectivity measured for overcast cloudy conditions. The similar approach is used for IR-data, with the actual, minimum and maximum brightness temperatures \( T \) measured by the satellite:

\[ CI_{\text{ir}} = \frac{T_{\text{min}} - T}{T_{\text{min}} - T_{\text{max}}} \]
Hourly time series

For each country, hourly time series for selected sites are provided. Some countries did not yet specify their sites, therefore only for five countries, following sites are processed. The ASCII-files can be downloaded from the SWERA-homepage.

**Bangladesh:** (10 sites)

<table>
<thead>
<tr>
<th>Stations/Sites</th>
<th>Lat (degree)</th>
<th>Long (degree)</th>
<th>Elevation (m)</th>
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<td>Cox's Bazar</td>
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**China:** Information on selected sites still missing

**Ethiopia:** (17 sites)

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**Ghana**: (22 sites)

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**Kenya**: (32 sites)

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**Nepal:** Information on selected sites still missing

**Sri Lanka: (3 sites)**

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<th>Long(degree)</th>
<th>Elevation (m)</th>
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<td>Colombo</td>
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<tr>
<td>Jaffna</td>
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<tr>
<td>Kalmunai</td>
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<td>81.80</td>
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</table>
Radiation maps

The shown maps differ in the displayed color and legend scale from the maps provided on the SWERA-server at http://swera.unep.net or the country reports. The chosen scales give a good impression of the spatial variability of the radiation regime during the year for each country. The maps represent the 3-years means of monthly and annual average total daily sums in Wh/m².

For Bangladesh, Nepal, Sri Lanka and West-China the years 2000, 2002 and 2003 are averaged, for Ghana, Ethiopia and Kenya the years 2000, 2001 and 2002 are averaged.

Notice: The scale bar can differ between each country and between DNI and GHI, so the maps are not comparable! Please use the original data provided in the ESRI-Shapefiles published at the SWERA homepage for comparison purposes!
Bangladesh

DNI

Figure 13a: Bangladesh: Annual average daily total sum of DNI in Wh/m²/day (3-years average).
Figure 13b: Bangladesh: Monthly average daily total sum of DNI in Wh/m²/day (3-years average), color palette as for annual values.
Figure 13c: Bangladesh: Annual average daily total sum of GHI in Wh/m²/day (3-years average).
Figure 13d: Bangladesh: Monthly average daily total sum of GHI in Wh/m²/day (3-years average), color palette as for annual values.
Ethiopia

**Figure 14a:** Ethiopia: Annual average daily total sum of DNI in Wh/m^2/day (3-years average).
Figure 14b: Ethiopia: Monthly average daily total sum of DNI in Wh/m²/day (3-years average), color palette as for annual values.
Figure 14c: Ethiopia: Annual average daily total sum of GHI in Wh/m²/day (3-years average).
Figure 14d: Ethiopia: Monthly average daily total sum of GHI in Wh/m²/day (3-years average), color palette as for annual values.
Ghana:

DNI

*Figure 15a*: Ghana: Annual average daily total sum of DNI in Wh/m²/day (3-years average).
Figure 15b: Ghana: Monthly average daily total sum of DNI in Wh/m²/day (3-years average), color palette as for annual values.
Figure 15c: Ghana: Annual average daily total sum of GHI in Wh/m²/day (3-years average).
Figure 15d: Ghana: Monthly average daily total sum of GHI in Wh/m²/day (3-years average), color palette as for annual values.
Kenya:

DNI

Figure 16a: Kenya: Annual average daily total sum of DNI in Wh/m²/day (3-years average).
Figure 16b: Kenya: Monthly average daily total sum of DNI in Wh/m²/day (3-years average), color palette as for annual values.
Figure 16c: Kenya: Annual average daily total sum of GHI in Wh/m²/day (3-years average).
Figure 16d: Kenya: Monthly average daily total sum of GHI in Wh/m²/day (3-years average), color palette as for annual values.
Nepal

DNI

Figure 17a: Nepal: Annual average daily total sum of DNI in Wh/m²/day (3-years average).
Figure 17b: Nepal: Monthly average daily total sum of DNI in Wh/m²/day (3-years average), color palette as for annual values.
Nepal

GHI

Figure 17c: Nepal: Annual average daily total sum of GHI in Wh/m²/day (3-years average)
Figure 17d: Nepal: Monthly average daily total sum of GHI in Wh/m²/day (3-years average), color palette as for annual values.
Sri Lanka:

DNI

Figure 18a: Sri Lanka: Annual average daily total sum of DNI in Wh/m²/day (3-years average).
Figure 18b: Sri Lanka: Monthly average daily total sum of DNI in Wh/m²/day (3-years average), color palette as for annual values.
Figure 18c: Sri Lanka: Annual average daily total sum of GHI in Wh/m²/day (3-years average).
Figure 18d: Sri Lanka: Monthly average daily total sum of GHI in Wh/m²/day (3-years average), color palette as for annual values.
Figure 19a: West-China: Annual average daily total sum of DNI in Wh/m²/day (3-years average).
Figure 19b: West-China: Monthly average daily total sum of DNI in Wh/m²/day (3-years average), color palette as for annual values.
Figure 19c: West-China: Annual average daily total sum of GHI in Wh/m²/day (3-years average).
Figure 19d: West-China: Monthly average daily total sum of GHI in Wh/m²/day (3-years average), color palette as for annual values.