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Research Note
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Evaluation of clear sky solar irradiance algorithms at high latitudes

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ABSTRACT

Several clear sky parameterizations for estimation of solar irradiance at the surface is tested against observations performed at Geophysical Institute, University of Bergen. The testing has been performed within the framework of the Ocean and Sea Ice SAF. Results show that the best results are achieved using the parameterization named Staylor, but that the McMaster model also may be used.

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CHAPTER 1

Introduction

Within the EUMETSAT Ocean and Sea Ice Satellite Application Facility framework, DNMI is developing software for estimation of the solar irradiance at the surface from AVHRR data. This report briefly address the problem of estimating the clear sky solar irradiance at the surface.

The concept solar irradiance is used about the band 0.3-4 μm. However, the data algorithms for estimation of the clear sky irradiance are tested against are pyranometer measurements representing more or less the band 0.28-3 μm. The error introduced by comparing these different bands is anticipated to be less than 1-2%, well within the accuracy of the pyranometer measurements.

First a brief introduction to equations used is given, followed by a presentation of the validation dataset. Then each of the algorithms tested are presented and followed by the results, before a brief summary.

CHAPTER 2

Background

The solar irradiance at the surface under clear-sky conditions is a function of the solar irradiance at the top of the atmosphere and the atmospheric transmittance:

$$E = S' \mu_0 T_a \qquad \text{EQ. 1}$$

where S' is the Earth-Sun distance corrected solar constant, μ_0 is the cosine of the solar zenith angle (σ) and T_a is the clear-sky transmittance.

The Earth-Sun distance corrected solar constant S' is defined as:

$$S' = S_0 v(d_n) \qquad \text{EQ. 2}$$

where S_0 is the solar constant (1358 W/m^2). The variance in solar irradiance at the Earth resulting from the elliptic orbit of the Earth around the Sun is plus/minus 3.3% of the mean. The correction term for the distance between the Earth and the Sun can be written as (Brisson et al., 1999):

$$v(d_n) = 1 + 0.0334 \cos\left(2\pi \frac{(d_n - 2)}{365.25}\right) \qquad \text{EQ. 3}$$

EQ. 3 is a short version of the full equation presented in Paltridge and Platt (1976):

$$\begin{aligned} v(d_n) = {} & 1.000110 + 0.034221 \cos\theta_0 + 0.001280 \sin\theta_0 \\ & + 0.000719 \cos 2\theta_0 + 0.000077 \sin 2\theta_0 \end{aligned} \qquad \text{EQ. 4}$$

where the angle θ_0 in radians is given by:

$$\theta_0 = \frac{2\pi d_n}{365} \quad \text{EQ. 5}$$

In this equation d_n is the day number ranging from 0 on January 1 to 364 on December 31. The definition of θ_0 in EQ. 3 differs slightly from the one in EQ. 5. EQ. 3 represents the correction term for Earth-Sun distance as given by Brisson et al. (1999). The effect of truncating is not thoroughly examined yet, but it is assumed to be less than the errors in calculation of the atmospheric transmittance. The accuracy of EQ. 4 is better than 10^{-4}.

Concerning estimation of T_a several methods exist. The Ocean and Sea Ice SAF team at CMS have reviewed several algorithms (Brisson et al., 1999). In particular they tested 3 different algorithms after a first evaluation of accessibility to methods through literature and input data. While testing the “CMS” (Brisson et al., 1994), “Frouin” (Frouin et al., 1989) and “Staylor” (Darnell et al., 1988, Darnell et al., 1992) methods they concluded to use the “Frouin” method due to satisfying results on the validation data set. The “Staylor” method also gave satisfying results (absolute bias less than 3% and standard deviation below 5% of the mean). However, they concluded the “Frouin” method to give better global results and to have a more flexible formalism.

This report is focused on comparison of the “Staylor”, “Frouin” and “McMaster” University model described by Davies and McKay (1982), as the latter has proved well at high latitudes (personal communication with Olseth, Geophysical Institute, University of Bergen, Norway). The first two were also tested by the CMS team, while the last one is not tested within the Ocean and Sea Ice SAF team before.

CHAPTER 3 Validation data set

The validation data used in this report were kindly provided by Jan Asle Olseth at Geophysical Institute, University of Bergen, Norway. These data are collected at the observation station for atmospheric radiation operated by the Geophysical Institute in Bergen. This station is located in the same building as the regional office of the Norwegian Meteorological Institute (DNMI). At the DNMI office, a synoptic observation programme is performed regulary (station identification number 01 317, geographical position 60.4°N, 5.3°E, 45 m a.s.l.).

The data set received covers the time period of 1965 to 1996. Each data record represents 1 hour with time given as true solar time. For each 1 hour period, the sun height, global, diffuse and direct radiation on the horizontal surface is given along with UV-radiation, longwave radiation, air pressure, surface temperature and relative humidity. All radiation measures are given in W/m^2. Air pressure is given in hPa and surface temperature in degrees Celsius.

Cloud clearance of the radiation data was performed using the synoptic meteorological observations performed at the same position as the radiation observations. The first clearing was performed using the visual cloud observations, then the symmetry of the solar irradiance throughout the day was checked to remove all observations not entirely trusted as cloudfree.

Further information of the data set can be received from Olseth, Geophysical Institute, University of Bergen.

Testing of the algorithms requires input of precipitable water and ozone. For both, climatological values are used and not dynamically updated values. Thus a slight reduction in standard deviation would be expected if actual values were used (especially of precipitable water) instead of climatological values. Furthermore, the station is situated in the middle of the city of Bergen. Bergen is surrounded by mountains, some of them as high as over 600 m. Thus the error between estimated and observed irradiance is supposed to be largest at large solar zenith angles.

CHAPTER 4

Potential algorithms

4.1 McMaster

This clear-sky algorithm has been used by Olseth and Skartveit (1993) in their formulation of global irradiance as function of routinely observed cloud data at synoptic weather stations.

The "McMaster" University model is described by Davies and McKay (1982) and Davies et al. (1988). It estimates the global irradiance under cloudless skies as the sum of the direct beam and diffuse components from aerosol and Rayleigh scatter.

$$E_{dir} = S' \cos\sigma(\tau_{o3}\tau_R - a_w)\tau_a$$

$$E_{difR} = \frac{S' \cos\sigma\tau_{o3}(1-\tau_R)}{2}$$

$$E_{difa} = S' \cos\sigma(\tau_{o3}\tau_R - a_w)(1-\tau_a)\omega_0 f$$

EQ. 6

where τ_{o3} is the ozone transmittance, τ_R is the Rayleigh transmittance, τ_a is the aerosol transmittance, a_w is the absorptivity of water vapour, ω_0 is the spectral averaged single scattering albedo for aerosol and f is the ratio of forward to total scatter by aerosols.

Multiple reflections between the surface and the atmosphere is as usual handled by the adding method.

To make the formulas above comparable with EQ. 1 it can be rewritten to:

$$E = E_{dir} + E_{difR} + E_{difa}$$

$$E = S'\cos\sigma \underbrace{\left((\tau_{o3}\tau_R\tau_a - a\tau_a) + \left(\frac{\tau_{o3}(1-\tau_R)}{2}\right) + ((\tau_{o3}\tau_R - a_w)(1-\tau_a)\omega_0 f)\right)}$$

$$T_a = (\tau_{o3}\tau_R\tau_a - a\tau_a) + \left(\frac{\tau_{o3}(1-\tau_R)}{2}\right) + ((\tau_{o3}\tau_R - a_w)(1-\tau_a)\omega_0 f)$$

EQ. 7

It is the formulation of T_a that is used in EQ. 1. There is no explicit use of the surface albedo in the "McMaster" formulation.

The elements of EQ. 7 are described in EQ. 8.

$$\tau_{o3} = 1 - \frac{0.1082X_1}{(1+13.86X_1)^{0.805}} - \frac{0.00658X_1}{1+(10.36X_1)^3} - \frac{0.002118X_1}{1+0.0042X_1+0.00000323X_1^2} \qquad \textbf{EQ. 8}$$

$$X_1 = m_r U_{o3}$$

$$a_w = \frac{0.29X_2}{(1+14.15X_2)^{0.635} + 0.5925X_2}$$

$$X_2 = m_r W$$

$$m_r = \frac{35}{(1+1224(\cos\sigma)^2)^{0.5}}$$

$$\tau_R = \frac{x}{1+x}$$

$$x = 8.688237m^y$$

$$y = 0.0279286(\ln m)0.806955 \qquad m = \frac{p}{p_s}m_r$$

$$f = 0.93 - 0.21\ln m \qquad \omega_0 = 0.75$$

U_{o3} is the atmospheric amount of ozone, and W is the amount of water vapour, both expressed in mm. σ is the solar zenith angle, p_s is the normal air pressure at sea level (1013 hPa) and p is the actual air pressure, both expressed in hPa. The formulation of τ_{o3} and a_w follows the work of Lacis and Hansen (1974), and is also described in Paltridge and Platt (1976).

4.2 Frouin

The Frouin method is described in Frouin et al., 1989 and Brisson et al. (1999). T_a is calculated using optical depths due to water vapour, ozone, aerosols and Rayleigh scattering. In addition correction of multiple scattering between the surface and the atmosphere is performed as a function of surface albedo and horizontal visibility.

$$T_a = \frac{\tau_w \tau_{o3} \tau_R}{\left(1 - \alpha_s\left(a_2 + \frac{b_2}{V}\right)\right)} \qquad \textbf{EQ. 9}$$

where

$$\tau_w = e^{-0.102\left(\frac{W}{\cos\sigma}\right)^{0.29}} \quad \text{EQ. 10}$$

$$\tau_{o3} = e^{-0.041\left(\frac{U_{o3}}{\cos\sigma}\right)^{0.57}}$$

$$\tau_R = e^{-\frac{\left(a_1 + \frac{b_1}{V}\right)}{\cos\sigma}}$$

where a_1, a_2, b_1, b_2 are coefficients depending on aerosol type (TABLE I). Furthermore, α_s is the surface albedo, W is the vertical water vapour content (g/cm^2), σ is the solar zenith angle, U_{o3} is the amount of ozone (atm cm) and V is the visibility in km.

TABLE I **Frouin coefficients depending on aerosol type.**

	a_1	a_2	b_1	b_2
maritime	0.059	0.089	0.359	0.503
continental	0.066	0.088	0.704	0.456

4.3 Staylor

The "Staylor" algorithm is described in Darnell et al. (1988), Darnell et al. (1992) and Brisson et al. (1999). The implementation tested here is similar to the one tested in Brisson et al. (1999). The atmospheric transmittance is calculated using absorption in water vapour, ozone, oxygen, carbon dioxide, scattering by aerosols in addition to Rayleigh scattering. Atmospheric backscatter is parameterized by surface pressure and albedo.

$$T_a = e^{-\tau}(1 + 0.065 p_s \alpha_s) \quad \text{EQ. 11}$$

with:

$$\tau = \tau_0\left(\frac{1}{\mu_0}\right)^N \qquad N = 1.1 - 2\tau_0 \quad \text{EQ. 12}$$

$$\tau_0 = \tau_{o3} + \tau_w + \tau_{o2} + \tau_{co2} + \tau_R + \tau_a$$

$$\tau_{o3} = 0.038 U_{o3}^{0.44}$$

$$\tau_w = 0.104 W^{0.3}$$

$$\tau_{o2} = 0.0075 p_s^{0.87}$$

$$\tau_{co2} = 0.0076 p_s^{0.29}$$

$$\tau_R = 0.038 p_s$$

$$\tau_a = 0.007 + 0.009 W$$

In the equations above, τ represents optical depth due to different absorbers, μ_0 is the cosine of the solar zenith angle, and p_s is the nominal surface air pressure (atmospheres), W is the precipitable water vapour (in cm) and U_{o3} is the ozone burden in cm. According to Darnell et al. (1988), the formulas for optical depth according to water vapour, ozone and Rayleigh scattering are derived from the formulas presented by Lacis and Hansen (1974). Similarly, the formulas for optical depth due to oxygen and carbon dioxide are derived from the formulas presented by Yamamoto (1962).

CHAPTER 5 Evaluation

5.1 McMaster

The "McMaster" algorithm tested on data from Bergen gave a bias of 3.23 W/m^2, and a standard deviation of 12.8 W/m^2. Thus the "McMaster" algorithm slightly overestimates the clear sky solar irradiance for the test data set.

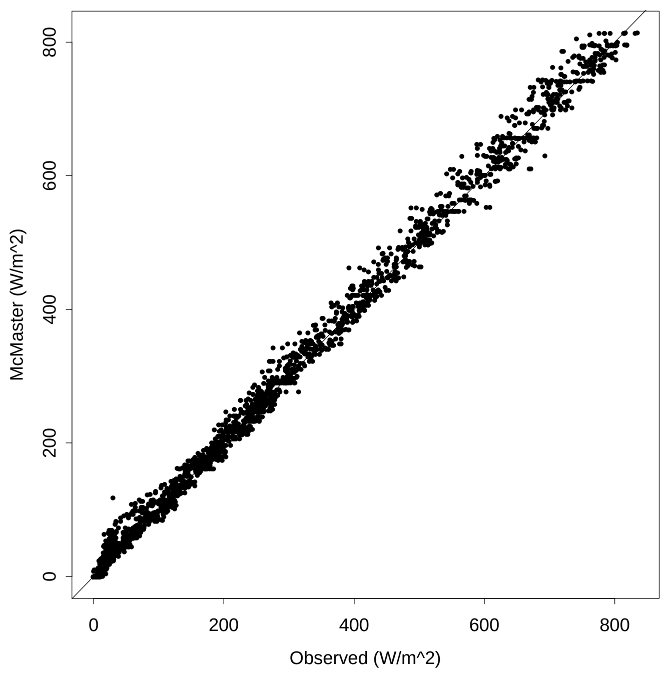

FIGURE 1 *Scatter plot presenting solar irradiance estimated using the "McMaster" algorithm versus observed clear sky irradiance for Bergen.*

To examine the performance of the estimates, 3 different plots featuring estimated versus observed solar irradiance (FIGURE 1), the difference between estimated and observed versus observed (FIGURE 2) and solar zenith angle (FIGURE 3).

The "McMaster" algorithm performs rather well. A general increase in the error as a function of the observed irradiance is observed, but there is no obvious trend as function of the solar zenith angle.

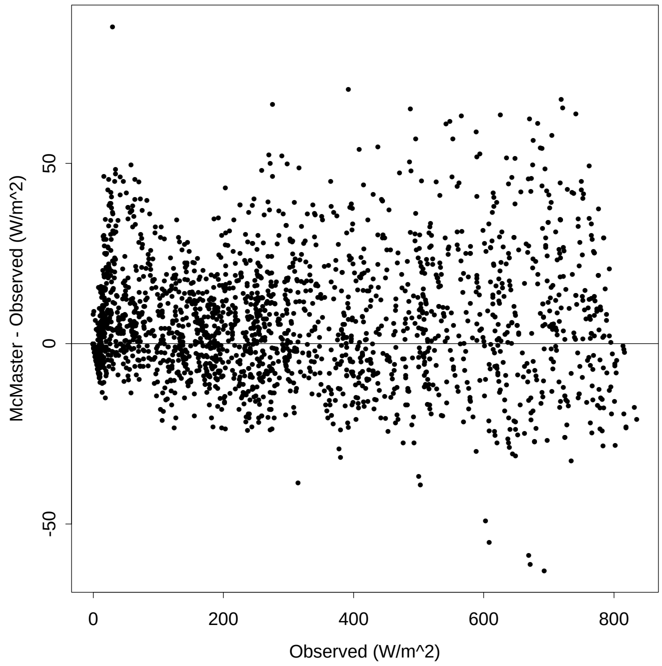

FIGURE 2 *Difference between observed and estimated solar irradiance using "McMaster" versus observed irradiance.*

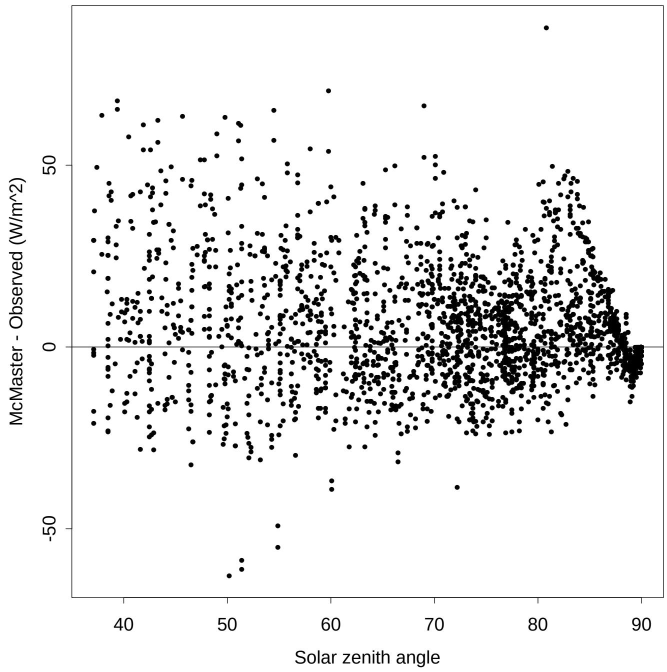

FIGURE 3 *Difference between observed and estimated solar irradiance using "McMaster" versus solar zenith angle.*

5.2 Frouin

Two different version of the “Frouin” algorithm were tested. One version using continental aerosols and one version using maritime aerosols. The station in Bergen is situated in a coastal area with many fiords surrounding the site. Only the results from the maritime aerosol load is presented here.

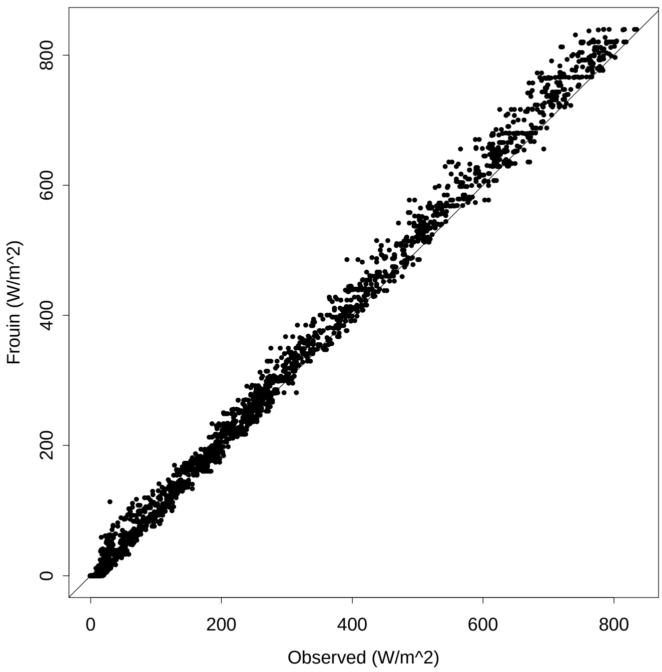

FIGURE 4 *Scatter plot presenting solar irradiance estimated using the “Frouin” algorithm for maritime conditions versus observed clear sky irradiance for Bergen.*

Analysis of FIGURE 4 - FIGURE 6 reveals a bias of 7.26 W/m^2, and a standard deviation of 16.9 W/m^2. Furthermore, a distinct linear trend is found in the error as function of solar zenith angle using the “Frouin” parameterization.

The same features that were observed in FIGURE 4 - FIGURE 6 were found in the continental aerosol load. However, using continental aerosols gave a negative bias of -2.51 W/m^2 indicating that the “Frouin” parameterization underestimates the solar irradiance during clear sky conditions. The standard deviation were 13.6 W/m^2. Thus it seems that the “Frouin” parameterization has a strong dependence on the solar zenith angle and thus it is not well suited for use at high latitudes.

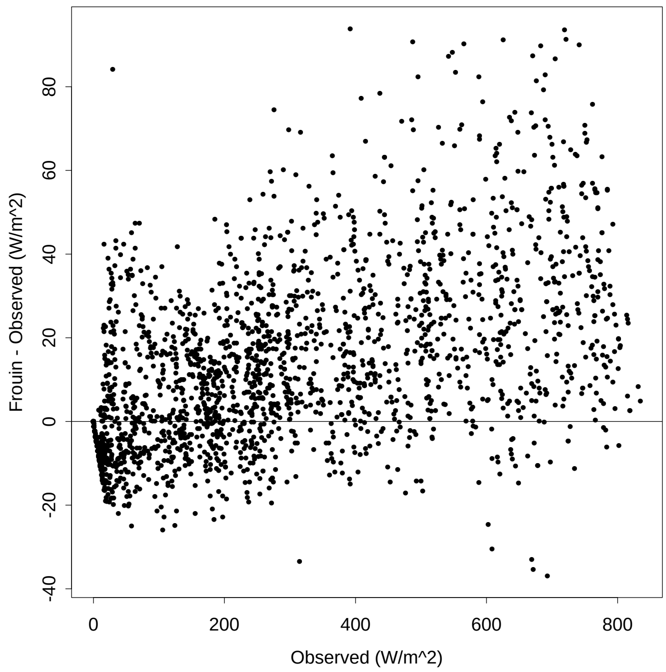

FIGURE 5 *Difference between observed and estimated solar irradiance using "Frouin" for maritime conditions versus observed irradiance.*

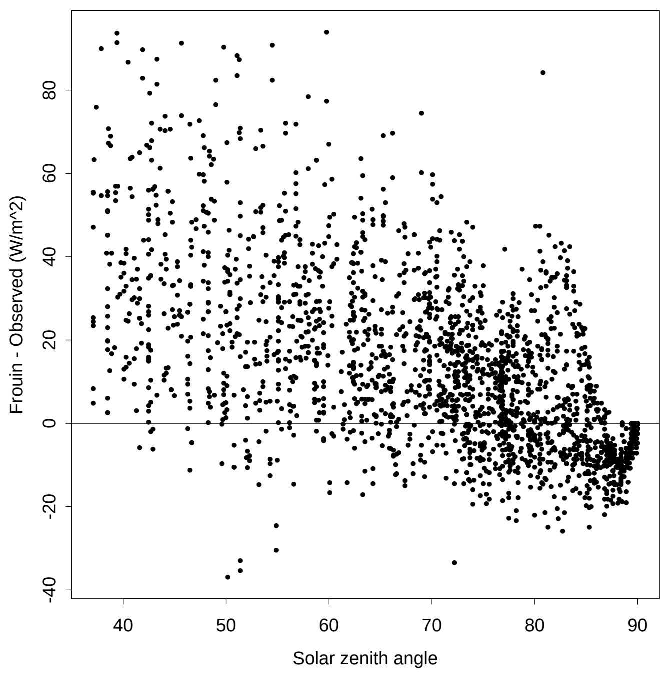

FIGURE 6 *Difference between observed and estimated solar irradiance using "Frouin" for maritime conditions versus solar zenith angle.*

5.3 Staylor

The “Staylor” parameterization gave a bias of 0.89 W/m^2 and a standard deviation of 12.7 W/m^2. There is no obvious trend in the error.

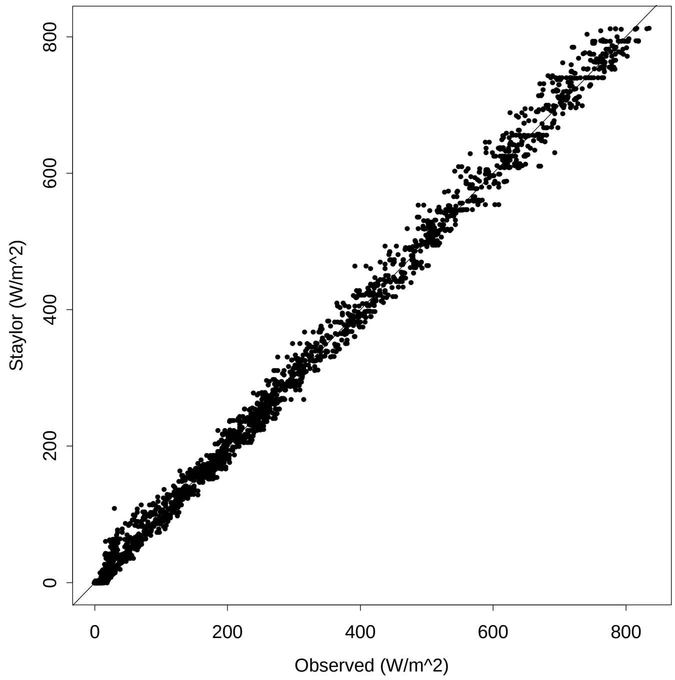

FIGURE 7 *Scatter plot presenting solar irradiance estimated using the “Staylor” algorithm versus observed clear sky irradiance for Bergen.*

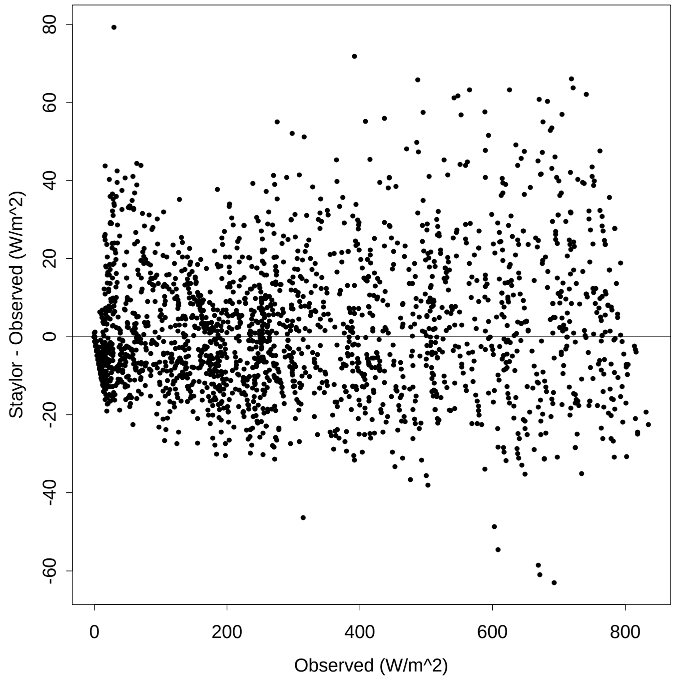

FIGURE 8 *Difference between observed and estimated solar irradiance using the "Staylor" parameterization versus observed irradiance.*

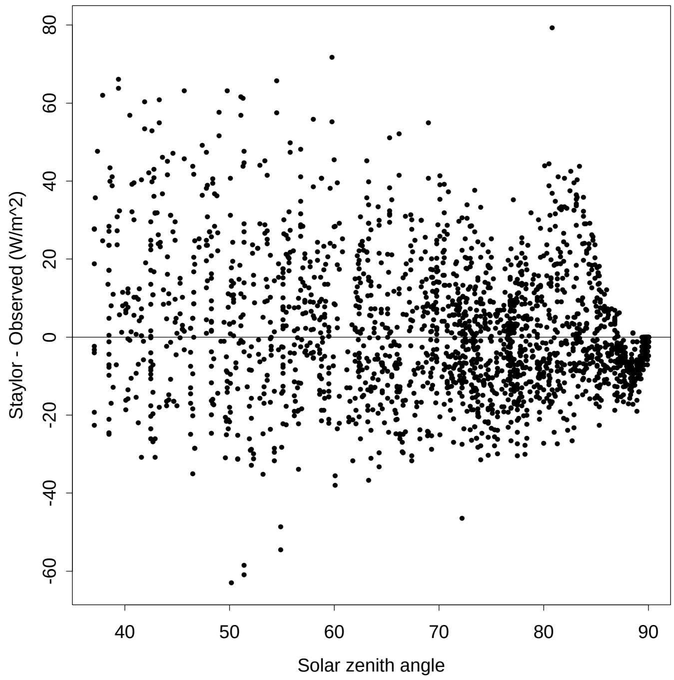

FIGURE 9 *Difference between observed and estimated solar irradiance using the "Staylor" parameterization versus the solar zenith angle.*

CHAPTER 6

Discussion and Conclusion

The parameterization named “Staylor” gives best results on the Bergen data set. Both bias and standard deviation are smallest for this parameterization. Contrary to the “Frouin” parameterization, “Staylor” and “McMaster” have no obvious trend in the error. However, the “McMaster” parameterization has larger bias than the “Staylor” parameterization. The standard deviation of these two parameterizations are similar. The performance of the “McMaster” algorithm may improve if it is tuned. Furthermore, the “McMaster” algorithm is divided in a direct and a diffuse part. According to Jan Asle Olseth, Geophysical Institute, University of Bergen, the accuracy of these elements of the total radiation are not convincing, but the overall performance of the algorithm on the combined estimate is quite good.

References

Brisson, A., P. LeBorgne, and A. Marsouin, 1999: Development of algorithms for Surface Solar Irradiance retrieval at O&SI SAF Low and Mid Latitudes, *Internal report* at Météo France/SCEM/CMS, February 1999.

Darnell, W.L., F. Staylor, S.K. Gupta, and F.M. Denn, 1988: Estimation of surface insolation using sun-synchronous satellite data, *J. Climate*, Vol. pp. 820-835, 1988.

Darnell, W.L., W.F. Staylor, S.K. Gupta, N.A. Ritchey, and A.C. Wilbur, 1992: Seasonal variation of surface radiation budget derived from international satellite cloud climatology project C1 data, *J. Geophys. Res.,* Vol. 97, pp. 15 741 - 15760, 1992.

Davies, J. A., and D. C. McKay, 1982: Estimating solar irradiance and components, *Solar Energy*, Vol. 29, No. 1, pp. 55-64, 1982.

Davies, J.A., D.C. McKay, G. Luciani, and M. Abdel-Wahab, 1988: Validation of models for estimating solar radiation on horizontal surfaces, *International Energy Agency*, Solar heating and cooling programme, Task IX, Solar radiation and Pyranometry Studies, Volume 1: Report, June 1988.

Lacis, A.A., and J.E. Hansen, 1974: A parameterization for the absorption of solar radiation in the earth's atmosphere, *J. Atmos. Sci.*, Vol. 31, pp. 118-133, 1974.

Olseth, J.A., and A. Skartveit, 1993: Characteristics of hourly global irradiance modelled from cloud data, *Solar Energy*, Vol. 51, No. 3, pp. 197-204, 1993.

Paltridge, G.W, and C.M.R. Platt, 19776: Radiative processes in meteorology and climatology, Elsevier Scientific Publishing Company, ISBN 0-444-41444-4, 318pp, 1976.

Yamamoto, G., 1962: Direct absorption of solar radiation by atmospheric water vapour, carbon dioxide and molecular oxygen, *J. Atmos. Sci.*, Vol. 19, pp. 182-188.