Linke’s Turbidity Factor Applied to Worldwide Global Horizontal Irradiance Measurements

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Abstract

The data collection phase of the Danish Galathea III Expedition was conducted from August 2006 until April 2007 [1]. During this period the research vessel *Vædderen* undertook a round the world voyage of nearly 100.000 kilometers while acting as a platform for scientific research in a range of disciplines. The researchers and instruments aboard the ship collected data from many locations around the world from 66.9^0 N to 67.5^0 S latitude. Among the experiments aboard the ship was an optics table sponsored by SolData Instruments and containing among other instrumentation three pyranometers for continuous measurement of global solar irradiance on a horizontal surface [2]. Knowledge of global solar irradiance is important for studies of the atmosphere and solar radiation and consequently for modeling the evolution of the Earth’s climate. We employ the Linke turbidity factor in our analysis, for this parameter is often referred to in the literature of atmospheric physics [3].

Keywords: Galathea Expedition, Linke turbidity factor, solar irradiance

1. Introduction

The purpose of this paper is to present an analysis of the global irradiance measurements. In particular we will focus on the computation of Linke’s turbidity factor T_L at a wide range of locations and the implications of these results for a general description of solar resources around the world. The factor T_L is closely related to the transmittance of the atmosphere on clear days [4]. As a general rule the atmosphere is clearer at higher latitudes, and the large amount of data available from the expedition has permitted the development of an algorithm to describe this relationship. Among the useful results obtained is a correlation between the Linke turbidity factor and the latitude. Secondary parameters such as the surface air water vapor content are also examined.

The turbidity factor was obtained from the horizontal radiation data using an incident direct plus diffuse radiation model, observed values of the solar irradiance and a numerical algorithm to determine T_L. Based on these results it is possible to provide a highly realistic prediction of the global irradiance on a clear day in a maritime environment. The model developed also supplies information about the distribution of diffuse and direct irradiance, information which is important for the design of solar energy systems. Furthermore T_L has implications for atmospheric visibility.

2. The Galathea Expedition

2.1. Research platform

The Danish King Christian VIII sent the first Galathea Expedition to the Far East in 1845-1847. The second Galathea Expedition took place 100 years later from 1950-1952, devoted primarily to ethnographic research. The present paper describes data collected on the Galathea III Expedition which was undertaken from August 2006 through April 2007. Figure 1 shows the Royal Danish Navy (RDN) vessel Vædderen which was converted to a research platform for the expedition.

Figur 1: *The RDN vessel Vædderen served as the research vessel. On the right the SolData Instruments optics table can be seen with the Palmer Peninsula in the background.*

2.2 Data collection

Data was integrated over 10-minute intervals and recorded with a Cambridge Scientific CR10X data logger along with date, time and position information. Data was uploaded via a satellite link to the internet weekly. Thanks to excellent support from the Danish Department of Fisheries a complete data set is available for every single day of the 8 month expedition. This high level of data integrity is partly because the data logger was battery powered with a continuous trickle charge and could be independent of external power during for up to several days if necessary. The complete data set has been placed on the internet, and it is available in Excel format at the home page www.soldata.dk. Click on the link "Galathea data...".

2.3 Parameters measured

The SolData optics table was equipped to measure: global irradiance (3 instruments), ultraviolet B (UVB), illuminance (lux), barometric pressure (hPa), background radiation (counts/10 min), sky luminance (cd/m^2) and PAR (einstein/m^2). These measurements have been described in other work [5]. The focus of this paper is on further analysis of the global solar irradiance data. Other research groups on board the research vessel contributed to another database, and this database is also accessible (5-minute values) including relative humidity, a parameter which will also receive attention in this paper.

2.4 Global solar irradiance

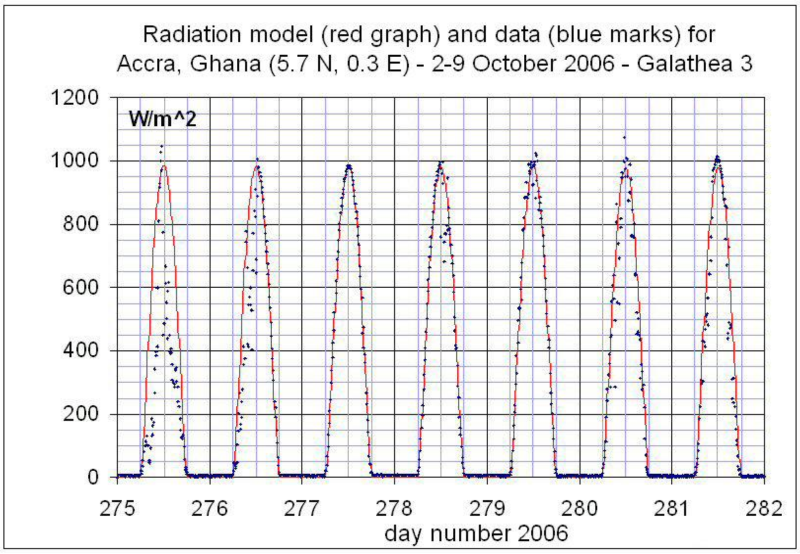


Figure 2: *Global solar irradiance from Accra, Ghana, October 2006.*

Figure 2 shows typical global irradiance data – in this case when the expedition was near the Ghanan city of Accra off the western coast of Africa. We have focused on days which were “clear”, i.e. cloud cover was so insignificant that a clear day global irradiance model could be fitted to the global irradiance data for a given day. A significant number of days during the eight month voyage of Galathea III were so clear, that this procedure was possible.

2.5 Simplified global irradiance model

We have shown in earlier work how a simplified model can be used to achieve a good fit to the global irradiance data [2]. The following expression shows that the global irradiance on a horizontal surface I_G as the sum of two terms: the first term expresses the *direct solar beam irradiance*, and the second term expressed the *diffuse irradiance* due to Rayleigh and Mie scattering from molecules and aerosols in the sky and from clouds.

$$I_G = I_0 \, F_J \, a^L \sin V + I_F \tag{1}$$

I_0 = 1367 W/m^2 is the solar constant. F_J takes account of the yearly variation of the solar irradiance due to the elliptical orbit of the earth around the sun. A practical equation for F_J is available in reference [6]. The factor a^L accounts for the attenuation of direct beam irradiance due to absorption and scattering, where L is the Rayleigh air mass. Finally, the factor $\sin V$ takes the geometry of the situation into account for a solar elevation angle V. The solar elevation angle can be computed with knowledge of the latitude, the solar declination angle and the local time. The equation required is widely available in the literature of solar energy design [6].

The air mass L through which the direct rays of the sun must pass depends of course on the angle V between the horizontal and a line from the observer to the center of the sun. For angles $V > 25^0$ a simple drawing will show that the air mass $L = 1/\sin V$, for in this case it is reasonable to assume that the earth is a flat surface with a thin layer of atmosphere. However, for angles less than 25^0 with the sun low on the horizon it is essential to take the curvature of the earth and temperature gradients into account. Fritz Kasten and Andrew Young have developed a good, practical formula which is well suited for use with small solar elevation angles [8]:

$$L = \frac{1.002432 \sin^2 V + 0.148386 \sin V + 0.0096467}{\sin^3 V + 0.149864 \sin^2 V + 0.0102963 \sin V + 0.000303978} \tag{2}$$

This equation approaches the simple expression $1/\sin V$ asymptotically for angles greater than 25^0. (The reader may wish to try using the angle $V = 90^0$ in the Kasten-Young equation. Note that $L = 1$ with the sun directly overhead.)

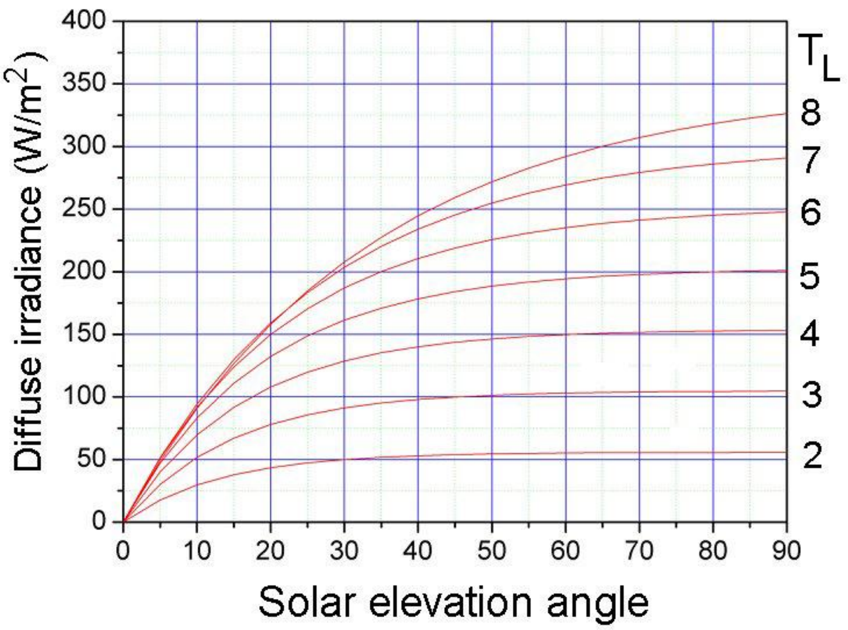
2.6 Enhanced global irradiance model

One would expect the diffuse contribution I_F to the global irradiance to increase with increasing atmospheric turbidity (increasing values of a) and that these two quantities are related to one another and to the solar elevation angle. This connection has been examined in earlier work, and the graphical result is shown in Figure 3 [7]. The Linke turbidity factor T_L enters the analysis in the term for the direct irradiance and is equal to unity for a pure Rayleigh atmosphere (no aerosols – only molecular scattering). The term a^L is in this formulation replaced by:

$$a^L = \exp\left[-0.8662 \cdot T_L \cdot L \cdot D_R(L)\right] \tag{3}$$

where $D_R(L)$ is the Rayleigh optical depth as a function of the air mass L. A very useful empirical equation for $1/D_R$ has been developed by Louche, Peri and Iqbal and modified by Fritz Kasten [8]:

$$\frac{1}{D_R(L)} = 6.6296 + 1.7513 \cdot L - 0.1202 \cdot L^2 + 0.0065 \cdot L^3 - 0.00013 \cdot L^4 \tag{4}$$



Figur 3: *The observed diffuse irradiance on a horizontal surface depends upon the value of the Linke turbidity factor* T_L *and the solar elevation angle.*

The data of Figure 3 has been used to find an expression for the diffuse irradiance on a horizontal surface I_F as a function of the elevation angle V and the turbidity factor T_L:

$$I_F = (49.04 \cdot T_L - 42.32) \cdot (1 - \exp[0.1 \cdot T_L - 0.0908 \cdot V]) \quad (5)$$

2.7 Equation for finding T_L from observations

In view of the foregoing remarks it is now possible to write an algorithm for the determination of the Linke turbidity factor from observations of the global solar irradiance on a horizontal surface and with knowledge of the solar elevation angle. The elevation angle is readily computed when the latitude, longitude and time of day are known.

$$I_G = I_0 \cdot F_J \cdot \sin V \cdot e^{(-0.8662 \cdot T_L \cdot L \cdot D_R)} + (49.04 \cdot T_L - 42.32) \cdot (1 - e^{(0.1\, T_L - 0.0908\, V)}) \quad (6)$$

I_G is the global irradiance measured, and V can be found from the time and position data. Knowledge of V yields the air mass L which in turn permits the optical depth D_R to be determined. The only unknown parameter in the equation is the Linke turbidity factor T_L which can then be calculated. This program has been carried out for clear days at a wide range of locations during the voyage from the Arctic to the Antarctic.

2.8 Results

For all of the good, clear days during the eight month expedition the Linke turbidity factor was computed using the algorithm described above. For these same days the mid day temperature and relative humidity were obtained by examination of the Galathea III database. From the temperature and humidity data it is straightforward to compute the amount of water present in a cubic meter of surface air. These calculations were performed with the data shown in Figure 4 as the result. The regression shows that a moisture content close to zero should yield a Linke turbidity factor near unity as expected. The value 1,19 may reflect the fact that some aerosols will typically be present in the maritime environments from which data is available in addition to water vapor.

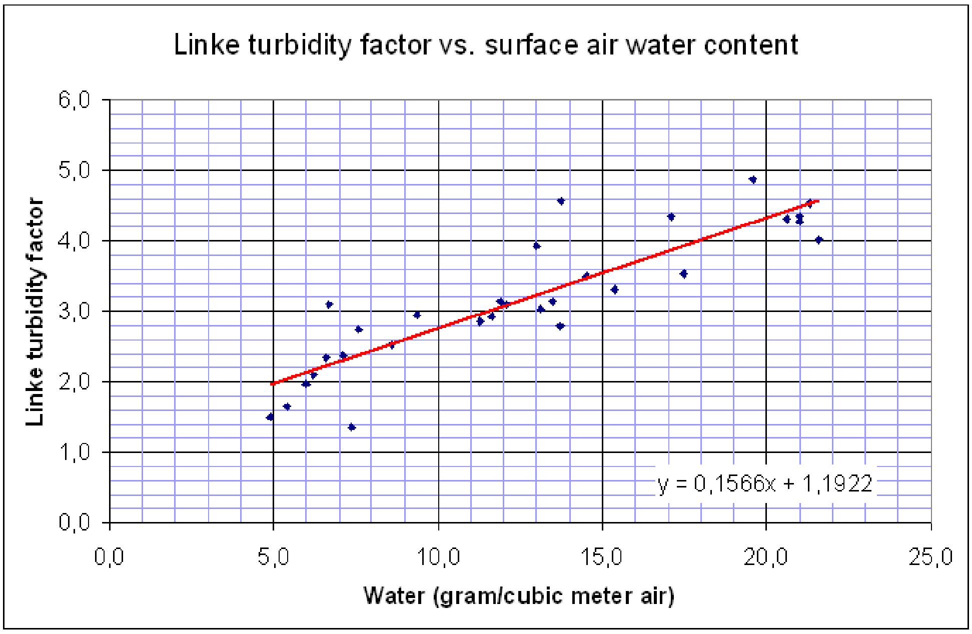


Figure 4: *The Linke turbidity factor as a function of the moisture present in the air.*

This analysis permits the estimation of the Linke turbidity factor in maritime environments based upon knowledge of the temperature and relative humidity. Compute the water content of a cubic meter of surface air, and apply the equation shown in Figure 4 to find T_L. With T_L in hand a good prediction of the global irradiance on the horizontal on a clear day, including the distribution of direct and diffuse irradiance, can be made using Equation 6. As local temperature and relative humidity are standard meteorological parameters, no special equipment or data is needed to do the calculations. Visibility conditions are also derivable from knowledge of the turbidity factor as discussed elsewhere [7]. This method does not take account of other aerosol which may be present, but it can be applied in typical maritime conditions with a modest amount of dry atmospheric aerosol particles.

References:

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