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ARTICLE

Modeling Atmospheric Turbidity at Zarqa Area Using Meteorological Data

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Abstract: Clearness index (k) and atmospheric turbidity over Zarqa have been calculated using solar data obtained by a GS1 Dome Solarimeter for the period from 25th of June 2001 to 18th of May 2002. The clearness index found to be highly scattered and never exceeded 0.8. Several attempts were made in order to find a correlation between the clearness index and turbidity with measurable meteorological parameters such as air temperature, relative humidity, and atmospheric pressure. No correlations were found. However, when the clearness index was plotted against the daily temperature range (ΔT), an exponential trend that is best described by the formula $k=0.13(\Delta T)^{0.52}$ was found. This result enabled us to modify traditional formula used in obtaining atmospheric turbidity through replacing the clearness index part by $0.13(\Delta T)^{0.52}$ in order to provide a mean to calculate atmospheric turbidity based on the daily temperature range.

Key Words: Clearness Index, Atmosphere, Turbidity, Air Pollution, Air Temperature, Daily Temperature Range.

Introduction

Atmospheric turbidity (T_l), is a dimensionless measure of the opacity of a vertical column of the atmosphere (Zakey, 2004). It is of great importance to research community including atmospheric scientists and solar energy researchers. T_l is useful for understanding many physical characteristics of the structure and properties of the atmosphere (Macris, 1959). However, quantifying atmospheric turbidity is costly due to expensive instrumentation used for this purpose (Togrul and Togrul, 2002). This justifies the extensive efforts that have been spent in order to come up with empirical formula that links the atmospheric turbidity with readily measured meteorological parameters such as air temperature and water vapor content (Togrul and Togrul, 2002; Lin et al., 2005; Molineaux et al., 1995; Gueymard, 1998; Ineichen and Perez, 2002).

The clearness index (k) is defined as the attenuation of solar radiation by the atmosphere. Its value ranges from zero to one. The clearness index is affected by air pollution in both urban and rural areas. Therefore, it may serve as an indicator for air quality and air pollution by fine particles particularly for upper atmospheric layers such as the stratosphere (Zakey, 2004).

Zarqa is a growing industrial city with a population of around one million people. Zarqa hosts more than 35% of the Jordanian industrial activities including an oil refinery, a thermal power plant, steel factories, a pipe factory, a cement factory, a fertilizers factory, a wastewater treatment plant, as well as several other small industrial facilities. A total of 2400 industrial activities are registered in Zarqa Industrial Chamber. Phosphate mines and Ar-Rusaifeh landfill are other sources of air pollution in Zarqa. Motor vehicles make up additional sources of air pollution. Emissions from the oil

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refinery, the power plant, and diesel trucks contain fine particulates as sulfate and volatile organic compounds (VOCs), which are known to be good light scatterers (Seinfeld and Pandis, 2006). As a result of such concentrated anthropogenic activities, the air quality in Zarqa has been deteriorating and the clearness index is not likely to be close to 1.0 under normal conditions.

This paper aims at (1) calculating k and T_l over Zarqa using solar data and (2) developing an empirical formula that could be used in determining k and T_l from readily measured meteorological parameters.

Instrumentation

Meteorological data is obtained using a GS1 Dome Solarimeter through Delta-T Logger Devices (LtD, United Kingdom) for the period from 25th of June 2001 to 18th of May 2002. The filter of the Solarimeter is a blackened thermopile with a glass-covering dome. The dome acts as a filter letting-through solar radiation. The instrument's sensor has a flat spectral response in the range between 0.3 and 3.0 μm. The sensitivity of the solarimeter is 19.88×10^{-6} at 20^oC and 500 W/m^2 and it operates in the temperature range –40 to 80^oC.

Theoretical Computations

Solar radiation incident outside the Earth's atmosphere is called extraterrestrial radiation. On average, the extraterrestrial irradiance is 1367 W/m^2. This value varies within ±3% as the Earth orbits the sun. The cumulative extraterrestrial solar beam irradiance on a horizontal surface over twenty four hours (H_o) in joules per square meter (J/m^2), is calculated using the following formula (Togrul and Togrul, 2002):

$$H_O = \frac{86{,}400 I_{SC}}{\pi}\left[1.034\cos\left(\frac{360N}{365.25}\right)\right]\left[\cos\phi\cos\delta\cos\varpi_s + \left(\frac{\pi\varpi_s}{180}\right)\sin\phi\sin\delta\right] \quad (1)$$

where,:

I_{sc}: the extraterrestrial solar irradiance outside the Earth's atmosphere (1367 W/m^2)

N: Julian day of the year. It is a continuous count of days since December 31 of the previous year. For example, January 1 is the Julian day 1, February 1 is the Julian day 32, and December 31 is the Julian day 366 for the leap year.

φ: latitude (32.2° North for Zarqa)

δ: declination angle in degrees, which is equal to

$$\delta = 23.45\pi / 180 * \sin(2\pi * (284 + N) / 365)$$

$\omega_s = \arccos(-\tan(\varphi)\tan(\delta))$ is the hour angle of sunset,

The following formula is used to compute air mass (m) at any zenith angle (θ_z), (Kasten and Young, 1989):

$$m = \frac{P}{1013.25\,[\cos\theta_z + 0.50572\,(96.07995 - \theta_z)^{-1.6364}]} \quad (2)$$

where:

P: atmospheric pressure in millibar

θ_z: Zenith angle in degrees calculated from the formula:

$$\cos\theta_z = \sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\cos(\omega)$$

The clearness index (k) is calculated using the following formula (Jallo and Barakat, 2003):

$$k = \frac{H}{H_o} \quad (3)$$

where *H* is the measured daily solar irradiance at the ground surface. The clearness index was found experimentally to depend on the daily temperature range (ΔT) such that (Togrul and Togrul, 2002):

$$k = A\,(\Delta T)^B \quad (4)$$

where A and B are constants determined from data fitting.

According to Molineaux et al.(1995), Linke turbidity is calculated from the formula:

$$T_l = \frac{1}{m(0.124 - 0.0656\ \log(m))} \ln(\frac{H_o}{H}) \tag{5}$$

The term ln(H_o/H) in equation 5 is nothing but -ln(k), therefore equation 4 will lead to the following expression:

$$\ln(\frac{H_o}{H}) = -\ln(A(\Delta T)^B) = -\ln(A) - B\ln(\Delta T) \tag{6}$$

Substituting equation 6 in equation 5 leads to the following formula:

$$T_l = -\frac{\alpha}{m(0.124 - 0.0656\log(m))}(\ln(A) + B\ln(\Delta T)) \tag{7}$$

Where α is a fitting parameter, which is crucial in improving data fitting in order to mimic actual data points.

Results and Discussion

Fig.1 shows the calculated daily clearness index. The clearness index is very scattered and ranges from zero to 0.8. The index is likely affected by the two potential air pollution sources; the oil refinery and the thermal power plant. Measurements took place at the Hashemite University campus, which is located downwind from these sources. Even if the wind direction is reversed the clearness index would not be expected to be significantly different since the wind would carry fugitive dust as it passes over the desert.

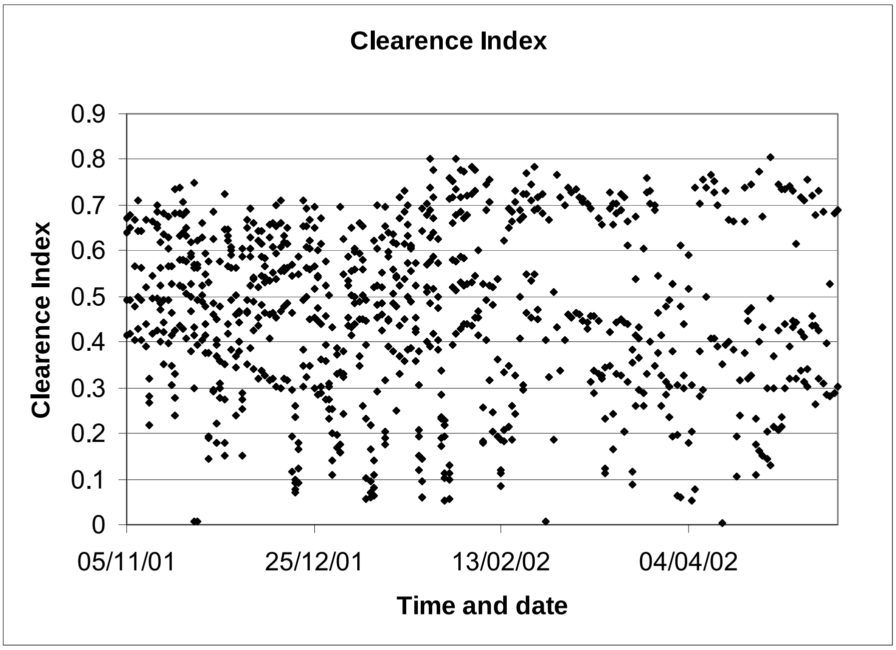

Fig. 1: Clearness index over Zarqa.

Clearness index is plotted against measured meteorological parameters including air temperature, wind speed, relative humidity, and atmospheric pressure, (Figures 2-5). No correlations were found between clearness index and the examined parameters. Moreover, as Fig.6 shows, the variation of the clearness index is in phase with the daily temperature range. In Fig.7 the clearness index was plotted against the temperature range. A power relation was found to best fit the data. This result is supported by the finding of Jallo and Barakat (2003). The constants A and B were found to be 0.13 and 0.52, respectively.

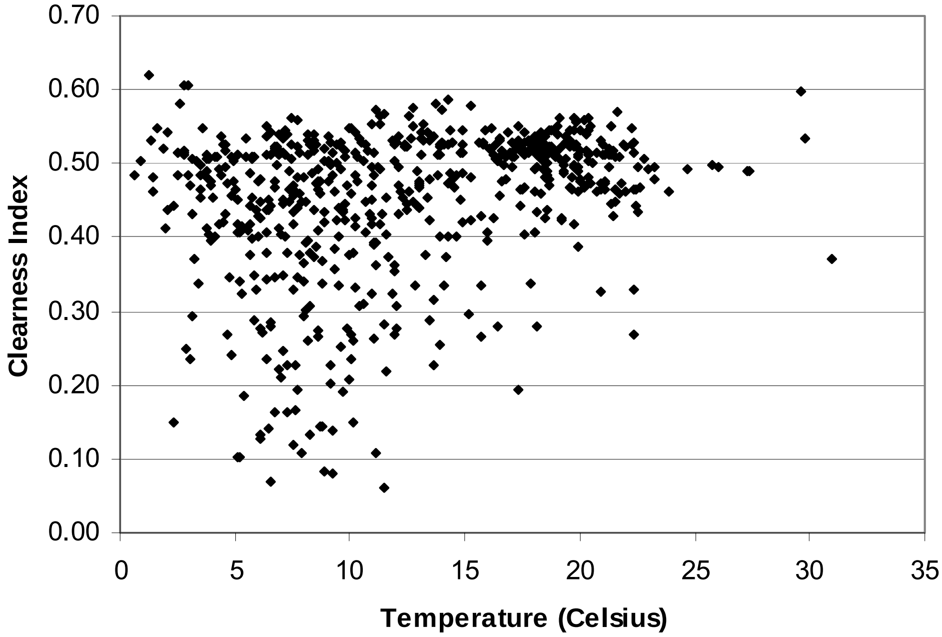

Fig. 2: Clearness index versus air temperature.

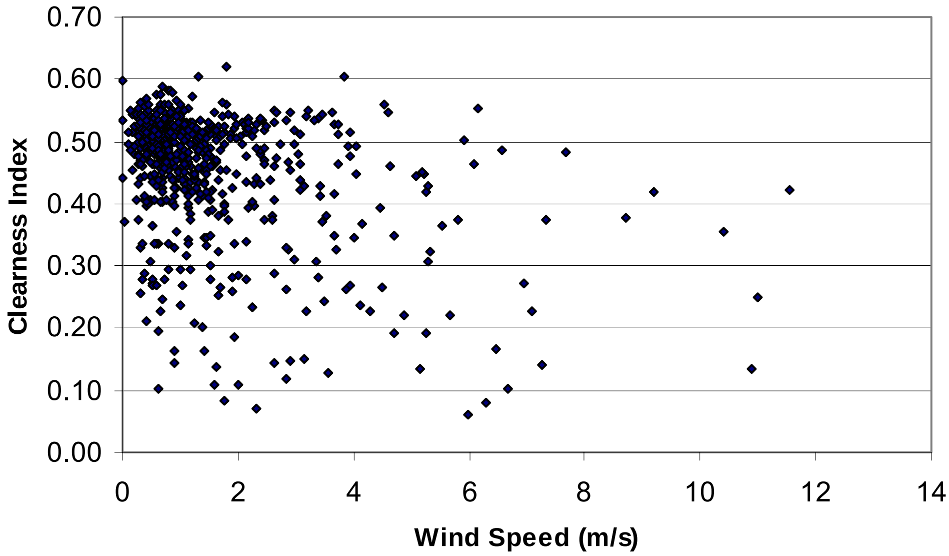

Fig. 3: Clearness index versus wind speed.

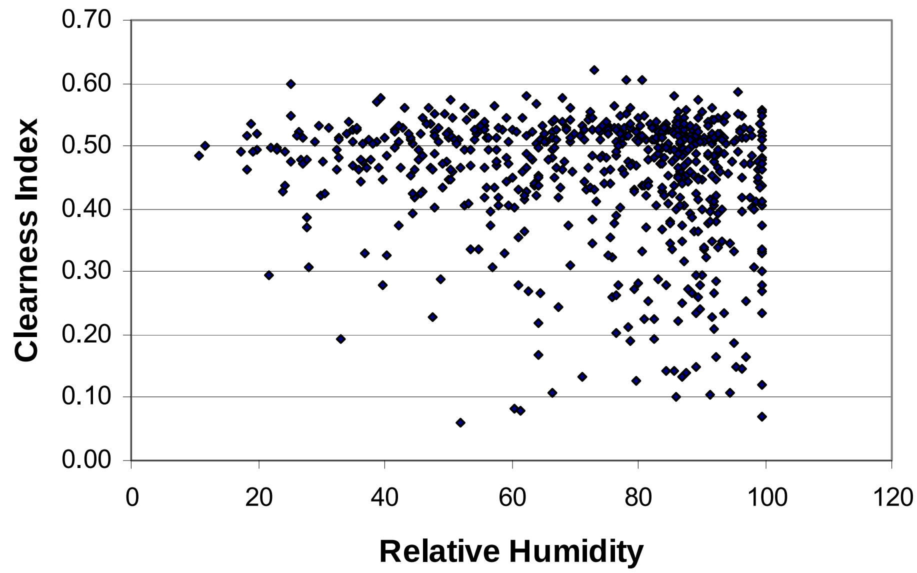

Fig. 4: Clearness index versus relative humidity.

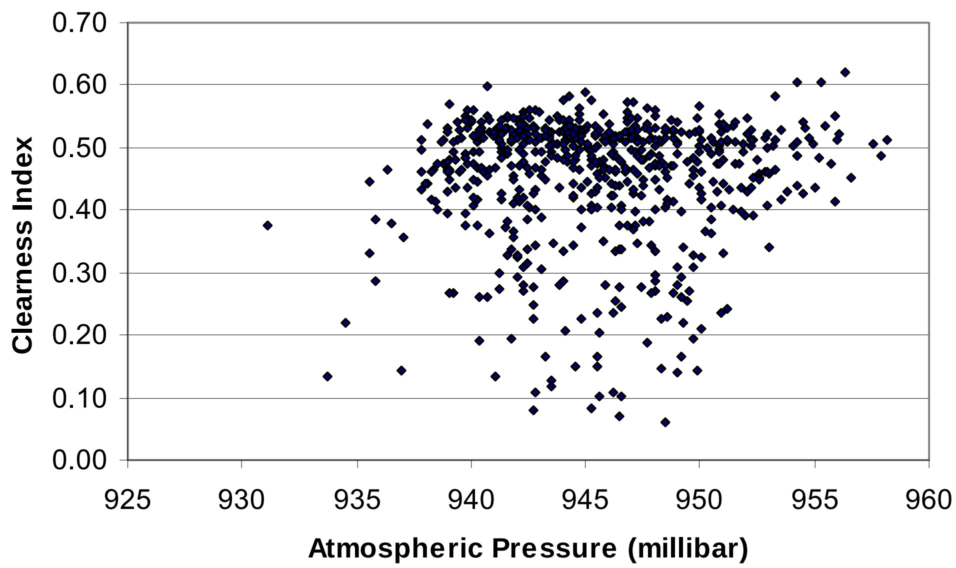

Fig. 5: Clearness index versus atmospheric pressure.

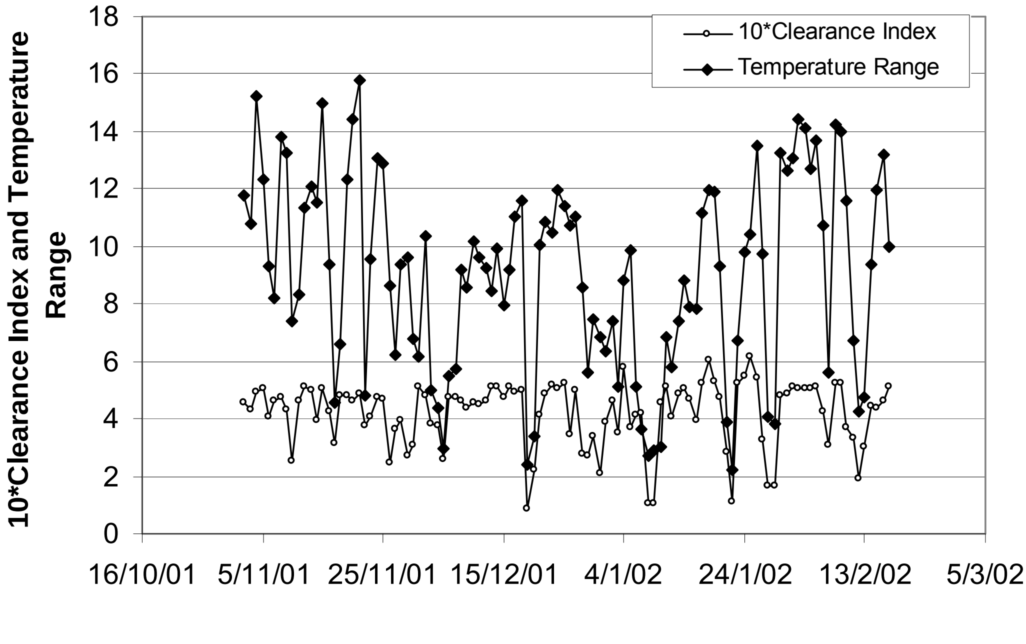

Fig. 6: Daily temperature range and clearness index over Zarqa during winter. The clearness index is multiplied by 10 in order to help visualizing its trend and how it matches the daily temperature variation.

Based on the values of the constants A and B obtained from Fig.7, the revised formula of Linke Turbidity (equations 7) can be rewritten as a function of the temperature range as follows:

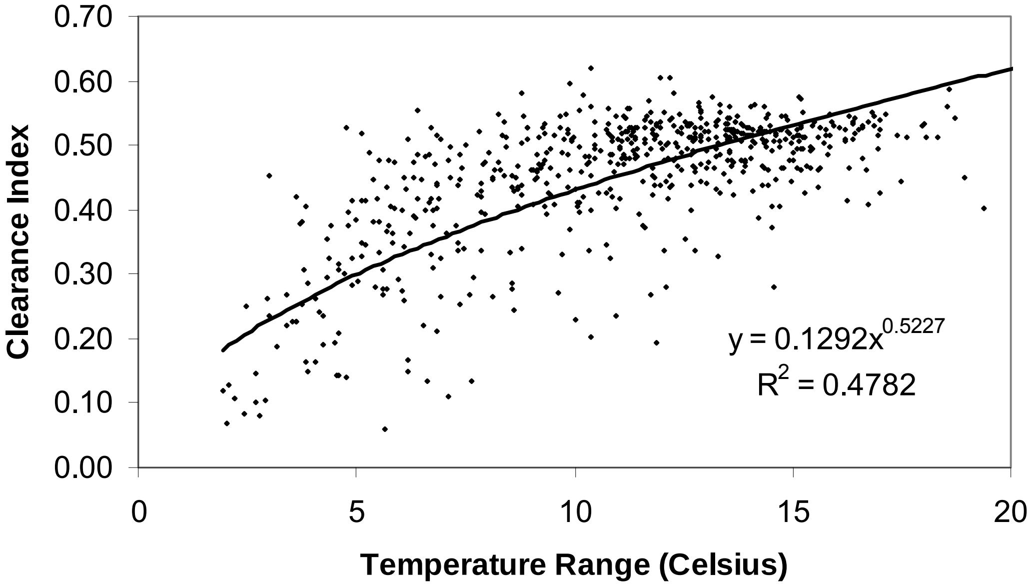

Fig. 7: The relation between the clearness index and daily temperature range.

$$T_l = -\frac{\alpha}{m(0.124 - 0.0656\log(m))}(\ln(0.1292) + 0.5227\ln(\Delta T)) \quad \ldots\ldots (8)$$

Fig.8 presents the calculated T_l using equation 5. The figure shows that T_l is less than 10 for most of the days with few exceptions. We have also used equation 8 to calculate Linke Turbidity based on the temperature range and compared the results with the values obtained based on equation 5 using solar data (Fig.9).

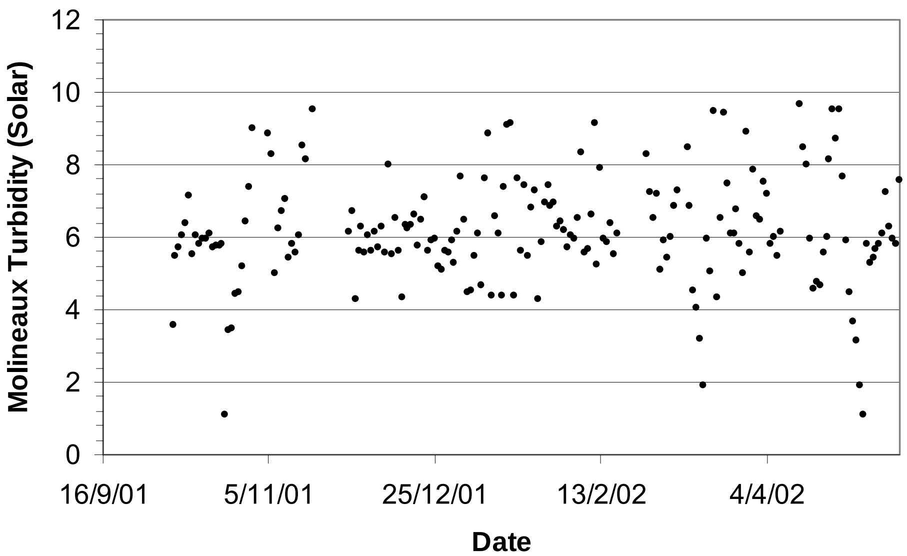

Fig. 8: Linke turbidity over Zarqa calculated based on the formula modified by Molineaux et al., (1995).

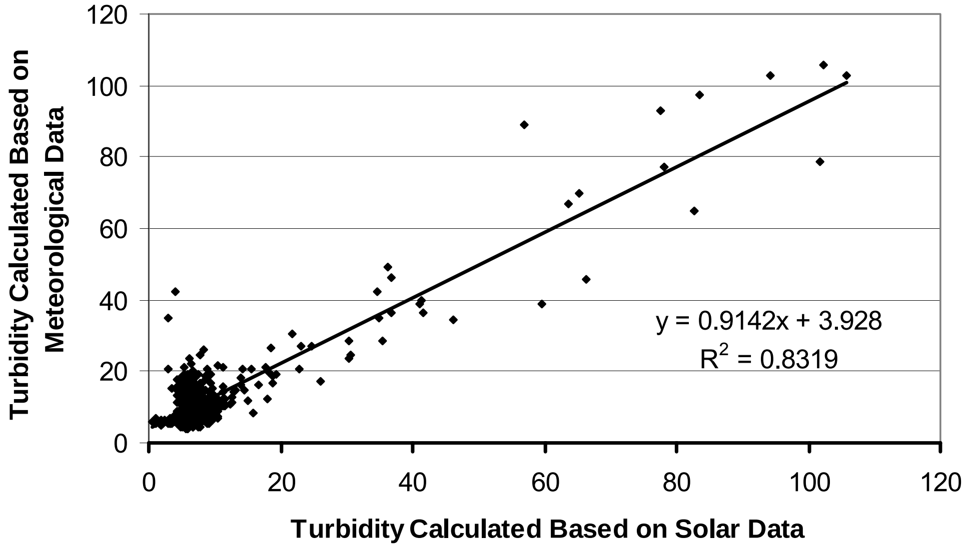

Fig. 9: Correlation between turbidity as calculated using meteorological data and turbidity as calculated using solar data. α that gave the best fit is 6.

As can be learned from Fig.9, Linke turbidity calculated using daily temperature range (solid line) matches its values obtained by applying traditional formula (dotted line).It is evident that the two techniques yield similar values. The root mean square value (R^2 = 0.83) indicates a strong correlation between modelled and actual values of the turbidity.

Summary and Conclusions

Clearness index and atmospheric turbidity are of great importance to a broad range of atmospheric and solar energy experts. However, quantifying them is not an easy task due to costly instrumentation needed for obtaining solar data. In this research, several attempts were made in order to come up with correlations that may relate the clearness index and atmospheric turbidity with meteorological parameters routinely measured in traditional weather stations such as air temperature, atmospheric pressure, wind speed, and relative humidity. No significant correlations were observed. In addition, the clearness index was plotted against the daily temperature range and it was evident that there is an exponential relation of the form $k=0.13(\Delta T)^{0.52}$ between the two parameters. The power law dependence of the clearness index on the daily temperature range enabled us to modify the traditional formula used in obtaining atmospheric turbidity. The new modified formula for the atmospheric turbidity is based on the daily temperature range which is routinely measured throughout the world at low cost.

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