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## **LINKE TURBIDITY FACTORS FOR SEVERAL SITES IN AFRICA**

Diabaté L. (1), Remund J. (2), Wald L. (3)

(1) UFAE / GCMI, BP E4018, 410, avenue Van Vollenhoven, Bamako, Mali

(2) Meteotest, Fabrikstrasse, Bern, Switzerland

(3) Groupe Télédétection & Modélisation, Ecole des Mines de Paris, BP 207, 06904 Sophia Antipolis cedex, France. Tel.: +33 (0) 4.93.95.74.49 Fax: +33 (0) 4.93.95.75.35. E-mail : lucien.wald@ensmp.fr

### **ABSTRACT**

The Linke turbidity factor (TL) has been estimated at sixteen locations in Africa (9 stations in Egypt, 2 in Mozambique and Zimbabwe, 1 in Algeria, Tunisia and Zambia). An appropriate processing of time-series of measurements of daily sums of solar global radiation spanning several years provides mean values of TL for each month with a sufficient accuracy. Though limited to the Mediterranean area, Egypt and sub-tropical Southeastern part, this work greatly extends the knowledge on the clearness of the atmosphere in Africa, an area not much addressed in the literature. The relationship between TL and the climate is evidenced. TL is almost constant throughout the year close to the Mediterranean basin with values around 3.5. Stations located in the sub-tropical Southeastern part exhibit large variations of TL.

Keywords: turbidity, atmosphere optics, radiation

### **1. Nomenclature**

|                  |  |
|------------------|--|
| $\gamma_s$       | the solar altitude angle   |
| $\gamma_{snoon}$ | the solar altitude angle at local noon   |
| $p$              | the air pressure at the geographical site  |
| $p_0$            | the air pressure at sea level  |
| $m(\gamma_s)$    | the relative optical air mass  |
| $TL$             | the Linke turbidity factor for an air mass equal to 2                              |
| $TL_m$           | long-term monthly average of the Linke turbidity factor for an air mass equal to 2 |
| $G_{0d}$         | the extraterrestrial daily irradiation on the horizontal plane                     |
| $G_d$            | the daily irradiation (daily sum of irradiance) received by a horizontal plan.     |

|             |  |
|-------------|--|
| $KT_d$      | the clearness index for a day, that is the ratio of the daily irradiation to the extraterrestrial daily irradiation $G_{0d}$ |
| $k_h$       | the minimum sun angle corrected clearness index for each hour  |
| $k_{hmean}$ | the average value of $k_h$ for all hours of a day  |

## 2. Introduction

The Linke turbidity factor (TL, for an air mass equal to 2) is a very convenient approximation to model the atmospheric absorption and scattering of the solar radiation under clear skies. It describes the optical thickness of the atmosphere due to both the absorption by the water vapor and the absorption and scattering by the aerosol particles relative to a dry and clean atmosphere (WMO, 1981; Kasten, 1996). The larger TL, the larger the attenuation of the radiation by the clear sky atmosphere. It is a convenient parameter to summarize the turbidity of the atmosphere and is often used by engineers and consultants. It is a key input to several models assessing the downwelling irradiance under clear skies that are used by several communities in the fields of renewable energies, climatology, agro-meteorology, and atmospheric pollution. These issues are of importance in Africa and are evidenced by regional policies and international projects (e.g., Agrhymet or ACMAD).

TL can be obtained directly from observations performed during very clear sky periods, but this kind of experimental data is rarely available, thus TL is generally an estimated parameter. Also, time series of radiation data are generally too short to allow estimation on a daily basis. Fortunately, long-term monthly average values,  $TL_m$ , are sufficient for most applications. Several methods for estimating  $TL_m$  values can be found in the literature: for example from time series of daily global horizontal irradiation (Aguiar, in ESRA 2000), monthly Angström sum (Page, 1986), aerosol properties and water vapor content (Gueymard 1994) or subjective assessments of the type of atmospheric conditions prevailing in the region of interest (linear regression with latitude and with the Atmospheric Turbidity Index, Dogniaux and Lemoine, 1983).

There is only a few sites in Africa where  $TL_m$  is known. We have identified only four sites for which  $TL_m$  values are found in the literature: Northeast of Morocco (Diouri *et al.* 2000), Ile-Ife in Nigeria (Adeyefa *et al.* 1991), Cairo in Egypt (El-Hussainy, Omran 1998; Mosalam Shaltou *et al.* 1996) and El-Menia in Egypt (Mosalam Shaltou *et al.* 2001). To these, should be added the ten sites for Morocco and three for the former Spanish Sahara that can be found in the Web site [www.helioclim.net](http://www.helioclim.net) and computed from monthly Angström sums found in the ESRA (2000) (Angles *et al.* 1998, 1999). Morocco is well-covered but there is no assessment or so for the remaining of the continent.

The purpose of the study is to palliate this shortcoming and to increase the knowledge on  $TL_m$  in Africa. To reach that goal, time-series of daily sums of global radiation were collected and analyzed for sixteen sites.

## **2. Data**

In order to find out a significant mean value of the Linke factor, only stations having data measurements spanning several years were processed in this study. On the basis of this criteria, we selected stations among those proposed by the World Radiation Data Center (WRDC) at its Web site. These stations are listed in Table 1. Period is 1994-1999. We found only sixteen stations, when excluding Morocco. Nine are in Egypt. Two are in the Mediterranean area (Algeria and Tunisia). The other stations are in the Southeastern sub-tropical area (Mozambique, Zimbabwe and Zambia). The data are composed of time-series of daily sums of global radiation (daily irradiation). At the time of the data collection, it was only possible to display the data on the computer screen; the data were then manually digitized at UFAE, with possible typing errors.

The quality of the ground data measurements of the global irradiation was controlled by the means of the Web tool described by Geiger *et al.* (2002). The objective of this quality control is not to perform a precise and fine control, an objective out reach without details on the site and instruments used for measurements, but to flag the data that are obviously questionable. The aim of these procedures are to perform a likelihood control of the data and to check the plausibility of the measurements. The controlled time-series served as a basis for the present work but were also used in the framework of the project SoDa (Wald 2000; Wald *et al.* 2002), to validate the new method Heliosat-II (Lefèvre *et al.* 2002; Rigollier *et al.* 2003) and to prepare worldwide maps of the  $TL_m$  (Remund *et al.* 2003).

## **3. Method used to estimate $TL_m$**

Cucumo *et al.* (2000) propose a method for calculating  $TL_m$  from a time series of daily irradiation. This method is based on i) the computation of the direct and diffuse components by the means of the Collares-Pereira and Rabl correlation, ii) the modeling of each component as an analytical function of  $TL_m$  and iii) the inversion of these models. The method was applied to several sites in Italy. For these sites, the authors used the maximum daily irradiation values read per month in the ESRA (1984). These maxima are those found in the time-series of daily irradiation spanning the period 1966-1975.

Walkenhorst *et al.* (2002) processed time-series of hourly means of beam irradiance. The Linke turbidity factor was calculated for the four hours around noon for each day by inverting the ESRA formula for the clear sky

beam irradiance (ESRA 2000; Rigollier *et al.* 2002). From the resulting calculated set of TL for each month, the smallest three are averaged and this mean serves as an approximation for  $TL_m$ .

The approach used here is based on that proposed by Aguiar in 1995, reported in the ESRA (2000). It is easier to implement and operated than that of Cucumo *et al.* It does not require the analytical inversion of the clear-sky model. Given a time-series of daily sums spanning several years, the maximum daily irradiation is retained for each year of the period and each month at each site. Here, five years are available and thus five maxima are extracted for each month. In order to avoid cloudy days, these daily irradiations must satisfy the following criteria based on the daily clearness index,  $KT_d$ :

$$KT_d = G_d / G_{0d} \quad (1)$$

where  $G_d$  is the daily irradiation and  $G_{0d}$  the extraterrestrial daily irradiation. Define  $\gamma_{noon}$  as the solar altitude angle at local noon. Let define also  $k_h$  for each hour as the minimum sun angle corrected clearness index (Pedros *et al.* 1999):

$$k_h = 0.7 / [1.031 \exp(-1.4/(0.9+9.4/(m p / p_0))) + 0.1] \quad (2)$$

where  $m$  is the air mass, defined in the clear sky model (Geiger *et al.* 2002; Remund *et al.* 2003):

$$m(\gamma_s) = 1 / [ \sin \gamma_s + 0.50572 (\gamma_s + 6.07995)^{-1.6364} ] \quad (3)$$

Let define  $k_{hmean}$  as the average value of  $k_h$  for all hours of the day. The conditions to be filled by the daily clearness index  $KT_d$  are (Remund *et al.* 2003):

If  $\gamma_{noon} > 30^\circ$ ,  $KT_d$  should be greater than  $0.8 k_{hmean}$ , otherwise reject data

If  $30^\circ \geq \gamma_{noon} > 15^\circ$ ,  $KT_d$  should be greater than  $0.6 k_{hmean}$ , otherwise reject data

If  $15^\circ \geq \gamma_{noon} > 4^\circ$ ,  $KT_d$  should be greater than  $0.4 k_{hmean}$ , otherwise reject data

If  $4^\circ \geq \gamma_{noon}$ , reject data

To further filter cloudy days, only are kept the three greatest values for each month. They are averaged and this forms the clear sky daily irradiation characterizing the site under concern. No processing was done if the number of years was less than 5. In these cases it was believed that no reliable estimate of  $TL_m$  can be obtained.

For each site and each month,  $TL_m$  is varied from 2 to 8 by step of 0.1 until the output of the clear sky model corresponds to this clear sky daily irradiation. In that way, twelve values of  $TL_m$  are obtained for a given site, one per month.

The clear sky model used is that of the ESRA (2000), detailed and validated by Rigollier *et al.* (2000), including the corrections described in Remund and Page (2002) and Page (submitted for publication), already used and reported by Geiger *et al.* (2002) and Remund *et al.* (in press). In the original model, the formula for the Rayleigh

optical thickness behaves incorrectly with terrain altitude. This was not evidenced in the paper of Rigollier *et al.* because the sites used for validation have altitudes less than 500 m. Also the TL value in the diffuse transmittance should be corrected by a multiplying factor  $p/p_0$ , where  $p_0$  is the air pressure at sea level and  $p$  that at the site. The model was developed by the means of data acquired in Europe. The tests made by Rigollier *et al.* spanned several latitudes and climates in Europe and included the station of Sede Boquer in Israel. There is no indice that indicates that the model behaves incorrectly for other climates, especially in Africa.

The whole approach was tested by using several groups of sites for which  $TL_m$  was estimated in an independent way. In the first of the four tests,  $TL_m$  was estimated by the means of the measurements of the water vapor pressure and aerosol optical depth at 440 and 1020 nm performed in the AERONET network (Holben *et al.* 2001) following the work of Gueymard (1994) (Remund *et al.* 2003). Two other stations (Patras and Toledo) were added for which  $TL_m$  is considered known (Table 2). Nine surrounding stations are available with long-term time-series of daily irradiation and located within  $1^\circ$  of arc angle of one of the seven stations of reference with a difference in altitudes less than 200 m. The periods of measurements are not the same for these nine stations and differ from those of the seven stations. For these nine stations,  $TL_m$  was assessed as explained above. Those estimates were compared to the known values (Table 2). The bias is  $-0.1$  and the root mean square difference (RMSD) is 0.9 (Table 5). One may note in Table 2 the large fluctuations that can be observed between estimates at three different sites and known values for the station Ispra. The bias is very different and this tells us how cautious we should be in using such references.

In the three other tests, sites are used for which time-series of daily beam irradiation are available. From these time-series,  $TL_m$  is computed in an analytical way by inverting the equations for the beam component in the clear sky model (Remund *et al.* 2003). The minimum value is retained as  $TL_m$ . In the second test, six stations are used (five in Europe, one in Alaska, Table 3). Thirteen surrounding stations (same conditions as above) were found for which  $TL_m$  is derived by the explained approach from time-series of global irradiation. The periods of measurements are not the same. The bias is 0.1 and the RMSD is 0.8 (Table 5).

In the third test, twenty-two stations are used for which time-series of daily global and beam irradiation are available but for different periods (Table 4). The bias is  $-0.3$  and the RMSD is 0.6. The fourth test is performed with a sub-set of these stations for which the time-series are available simultaneously for the period 1981-1990 (ESRA 2000). The six stations under concern are Uccle, Hamburg, Braunschweig, Dresden, Trier, Würzburg and Weihestephan. The bias is  $-0.5$  and the RMSD is 0.6 (Table 5).

From these tests, one obtains hints of the uncertainties attached to the assessments of  $TL_m$  based on time-series of global irradiation. It can be concluded that the uncertainty is  $\pm 0.6-0.9$ . This is fairly large but in any case less than the day-to-day variations of TL.

#### **4. Results and discussions**

The series of  $TL_m$  obtained are reported in Table 6 for the sixteen stations. Six groups of stations were identified according to the values of  $TL_m$  and their variations during the year. These groups have links to climate zones:

- sub-tropical humid climate in the South of Africa, at sea level (Fig. 1),
- sub-tropical humid climate in the South of Africa, high elevation plateaus (Fig. 2),
- Sahara climate at high elevation (Fig. 3),
- industrialized areas in semi-arid climate (Fig. 4),
- desert Nile climate (Fig. 5),
- Mediterranean climate (Fig. 6).

The intra-group variations are large and once the uncertainty in the assessment of  $TL_m$  taken into account, the number of groups may differ. The first four groups will remain as they exhibit very different features but the two last groups: desert Nile climate and Mediterranean climate, may be aggregated.

There are five stations located in the South of Africa, in a sub-tropical humid climate. Two of them, Maputo and Tete (both in Mozambique) are located either at the ocean shoreline (Maputo) or along the Zambeze River at low elevation (Fig. 1). The  $TL_m$  values for both sites follow the same trend; they fluctuate around 3.5 ranging between 3 and 4 throughout the year. The lowest values are found in March-May and the highest in September-November. In Figure 1, one may note two outliers, one for Tete in September, the other for Maputo in October. The causes are unknown. They may result from bad quality or inappropriate data sets.

The  $TL_m$  values differ for the three other stations that have higher elevation. The stations in Zambia and Zimbabwe are on high plateaus, with elevations close to or higher than 1300 m (Fig. 2).  $TL_m$  offers a large range of values (2.5 to 7) and exhibits the same dynamics: the values decrease from January (around 6) to May (approx. 3.5), are more or less constant till July and then increase with a maximum attained in October-December. These three periods may be related to the local climate that is hot and humid in January (austral summer), dry and cool during the austral winter (low  $TL_m$ ), then hot but still dry with increasing aerosol loading due to wind carrying dust (Trewartha 1954).

The Tamanrasset station is single in the Sahara climate group (Fig. 3). This station has a high elevation (1377 m). This property may prevent this station to be used as a representative for the Sahara desert.  $TL_m$  reaches its lowest in February (2.6), then increases fairly regularly up to 4.7 in October, which is its maximum.

The industrialized areas in semi-arid climate group (Fig. 4) comprises the stations Tahrir, Bahtim and Cairo, located in Egypt. These stations are characterized by a semi-arid climate that differs from that of the Mediterranean shoreline and they are close to or within the large cities of Cairo and Alexandria. Cairo is one of the largest cities in Africa (approximately 13 million of inhabitants); Alexandria comprises approximately 3 million inhabitants. Both cities are the seat of industries and the traffic of vehicles is large. The  $TL_m$  values are large compared to those of the Mediterranean group and range between 4 and 6. The group is heterogeneous. The station Cairo HQ exhibits the extreme values of this group, with low values in winter and high values in spring and summer, in agreement with the previous work of El-Hussainy, Omran (1998) on Cairo and to a lesser extent with that of Mosalam Shaltout *et al.* (1996) for the city of Helwan, in the suburb of Cairo, who processed only one year of data. These agreements sustain the validity of our method.

The stations of Asyut, El Arish and Aswan compose the desert Nile climate group (Fig. 5). They are located along the Nile River in the desert. The values are quasi-constant from January to June, around 3.5, with a minimum in February-March. Then, the values increase up to 4.5 in August and decrease till February. Mosalam Shaltout *et al.* (2001) analysed hourly irradiation data for the year 1997 for the city of Menia, approximately 200 km North of Asyut. They reported a similar behavior with minima in winter and maxima in summer, the latter being due to dust and partly to the local industry.

The Mediterranean climate group (Fig. 6) comprises the stations located close to the Mediterranean Sea: one in Tunisia (Sidi Bou Said) and three in Egypt (Sidi Barrani, Rafah and Mersa Matruh).  $TL_m$  is almost constant all along the year and fluctuates around 4 with low values in winter (3.5) and largest values (4.5) in August-September. One may notice the case of Mersa Matruh. This station has the same latitude than Sidi Barrani and is located approximately 200 km to the East. It exhibits extreme values for most of the months compared to the others and the fluctuations are more pronounced. This may be explained either by the quality of the data or by local orographic effects but we cannot go further with our set of data.



In the graph are reported three time-series of  $TL_m$  obtained for the stations of Al Hoceima, Tetouan and Nador, located on the Mediterranean coast of Morocco. These values are derived by the means of the Page formula (1986) applied to the monthly Angström sum found in the ESRA (2000). One sees that these values are in fairly agreement with the four others. However, one may note that this group is very heterogenous. The behaviour for all stations is not the same. The stations for Morocco have a very similar behaviour but differ from the others. This may be explained either by the way  $TL_m$  has been derived for these stations or by the hypothesis that there is not an unique optical climate for the African Mediterranean area. More studies are needed for this area.

## **5. Conclusion**

This work provides estimates of long-term monthly average values of the Linke turbidity factor  $TL_m$  for sixteen stations in Africa. Agreement with previous works made on coincident stations or areas in Egypt show that the approach is valuable for Africa. These results strongly increase the sparse knowledge available in Africa on this parameter. The analysis of the values of  $TL_m$ , the range and the behavior throughout the year, demonstrates that  $TL_m$  is related to the climate, a unsurprising result.

The values obtained by this study have been used by the project SoDa for the creation of world-wide maps of the Linke turbidity factor for each month (Remund *et al.* 2003; Lefèvre *et al.* 2003). The method for assessing  $TL_m$  can be re-used on other time-series of daily sums of global radiation spanning several years. Tests made with other sites in the world demonstrate an uncertainty in the assessment of 0.6-0.9.

## **6. Acknowledgements**

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| <b>Station Name</b>     | <b>Latitude (°)</b> | <b>Longitude (°)</b> | <b>Elevation (m)</b> | <b>Period of Measurement</b> | <b>WMO-Nr</b> |
|-------------------------|---------------------|----------------------|----------------------|------------------------------|---------------|
| Tamanrasset (Algeria)   | 22.78               | 5.52                 | 1377                 | 1995-1999                    | 60680         |
| Sidi Barrani (Egypt)    | 31.63               | 25.85                | 26                   | 1994-1998                    | 62301         |
| Mersa Matruh (Egypt)    | 31.33               | 27.22                | 38                   | 1995-1998                    | 62306         |
| Rafah (Egypt)           | 31.22               | 34.22                | 73                   | 1994-1998                    | 62335         |
| El Arish (Egypt)        | 31.12               | 33.75                | 32                   | 1994-1998                    | 62337         |
| Tahrir (Egypt)          | 30.65               | 30.70                | 19                   | 1994-1998                    | 62345         |
| Bahtim (Egypt)          | 30.15               | 31.25                | 17                   | 1994-1998                    | 62369         |
| Cairo HQ (Egypt)        | 30.08               | 31.28                | 36                   | 1994-1998                    | 62371         |
| Asyut (Egypt)           | 27.20               | 31.50                | 52                   | 1994-1998                    | 62392         |
| Aswan (Egypt)           | 23.97               | 32.78                | 192                  | 1994-1998                    | 62414         |
| Tete (Mozambique)       | -16.18              | 33.58                | 123                  | 1994-1998                    | 67261         |
| Maputo (Mozambique)     | -25.97              | 32.60                | 70                   | 1994-1998                    | 67341         |
| Lusaka (Zambia)         | -15.42              | 28.32                | 1280                 | 1994-1998                    | 67666         |
| Harare (Zimbabwe)       | -17.83              | 31.02                | 1471                 | 1994-1998                    | 67774         |
| Bulawayo (Zimbabwe)     | -20.15              | 28.62                | 1343                 | 1994-1998                    | 67964         |
| Sidi Bou Said (Tunisia) | 36.87               | 10.23                | 127                  | 1994-1998                    | No index      |

**Table 1.** Description of the stations and data used to calculate the Linke turbidity factor. They are ranked by WMO identifying number

| <b>Station.<br/>Estimated</b> | <b>Lat (°)</b> | <b>Lon (°)</b> | <b>Elev.<br/>[m]</b> | <b>Period</b> | <b>Station.<br/>Measured</b> | <b>Lat (°)</b> | <b>Lon (°)</b> | <b>Elev.<br/>[m]</b> | <b>Period</b> | <b>Bias</b> | <b>RMSD</b> |
|-------------------------------|----------------|----------------|----------------------|---------------|------------------------------|----------------|----------------|----------------------|---------------|-------------|-------------|
| Magadino                      | 46.16          | 8.94           | 200                  | 1995-99       | Ispra*                       | 45.80          | 8.62           | 235                  | 1997-98       | -1.05       | 1.24        |
| Locarno-Monti                 | 46.17          | 8.78           | 366                  | 1981-90       | Ispra*                       | 45.80          | 8.62           | 235                  | 1997-98       | -0.60       | 0.66        |
| Lugano                        | 46.00          | 8.97           | 273                  | 1987-96       | Ispra*                       | 45.80          | 8.62           | 235                  | 1997-98       | 0.12        | 0.69        |
| Trappes                       | 48.77          | 2.02           | 168                  | 1981-90       | Palaiseau*                   | 48.70          | 2.20           | 156                  | 1999-2000     | 0.94        | 1.09        |
| Carpentras                    | 44.08          | 5.05           | 99                   | 1971-80       | Avignon*                     | 43.92          | 4.87           | 32                   | 1999-2001     | 0.32        | 1.09        |
| Artaa                         | 39.17          | 21.00          | 10                   | 1981-90       | Patras                       | 38.38          | 21.78          | 64                   | 1973-76       | -0.08       | 0.33        |
| Fairbanks                     | 64.82          | -147.87        | 138                  | 1961-90       | Bonanza*                     | 64.73          | -148.30        | 150                  | 1995-2000     | 0.69        | 0.81        |
| Toledo                        | 41.6           | -83.8          | 211                  | 1961-90       | Toledo                       | 41.6           | -83.8          | 211                  | 1971-85       | -0.13       | 0.36        |
| Honolulu                      | 21.33          | -157.92        | 5                    | 1961-90       | Lanai*                       | 20.82          | -156.98        | 80                   | 1995-99       | 1.15        | 1.24        |

\*AERONET (= measured Water vapor pressure, aot440,1020)

**Table 2. Comparison between measured values of TL and estimates (first test). RMSD means root mean square difference.**

| <b>Station.<br/>Global</b> | <b>Lat (°)</b> | <b>Lon (°)</b> | <b>Elev.<br/>(m)</b> | <b>Period</b> | <b>Station.<br/>Beam</b> | <b>Lat (°)</b> | <b>Lon (°)</b> | <b>Elev.<br/>(m)</b> | <b>Period</b> | <b>Bias</b> | <b>RMSD</b> |
|----------------------------|----------------|----------------|----------------------|---------------|--------------------------|----------------|----------------|----------------------|---------------|-------------|-------------|
| Broom's Barn               | 52.27          | 0.57           | 75                   | 1981-90       | Garston                  | 51.71          | -0.37          | 80                   | 1992          | -0.54       | 1.05        |
| London                     | 51.52          | -.12           | 77                   | 1981-90       | Garston                  | 51.71          | -0.37          | 80                   | 1992          | -0.25       | 0.75        |
| Payerne                    | 46.82          | 6.95           | 490                  | 1987-96       | Payerne                  | 46.82          | 6.95           | 491                  | 1998          | 0.93        | 0.99        |
| Luzern                     | 47.48          | 8.53           | 436                  | 1981-90       | Reckenholz               | 47.43          | 8.52           | 443                  | 1990-91       | 0.61        | 0.86        |
| Zuerich-<br>Kloten         | 47.03          | 8.30           | 456                  | 1987-96       | Reckenholz               | 47.43          | 8.52           | 443                  | 1990-91       | 0.06        | 0.32        |
| Haerkingen                 | 47.31          | 7.82           | 420                  | 1995-99       | Payerne                  | 46.82          | 6.95           | 491                  | 1998          | -0.04       | 0.26        |
| Geneva                     | 46.25          | 6.12           | 420                  | 1981-90       | Payerne                  | 46.82          | 6.95           | 491                  | 1998          | 0.82        | 0.86        |
| Sion                       | 46.22          | 7.33           | 482                  | 1987-96       | Payerne                  | 46.82          | 6.95           | 491                  | 1998          | 0.06        | 0.52        |
| Schleswig                  | 54.53          | 9.55           | 59                   | 1981-90       | Hamburg                  | 53.65          | 10.12          | 49                   | 1981-90       | -1.17       | 1.21        |
| Freiburg                   | 48.00          | 7.82           | 308                  | 1981-90       | Reckenholz               | 47.43          | 8.52           | 443                  | 1990-91       | 0.67        | 4.36        |
| Wien H.<br>Warte           | 48.12          | 16.57          | 203                  | 1981-90       | Bratislava               | 48.17          | 17.08          | 195                  | 1994          | 0.30        | 0.60        |
| Bratislava                 | 48.17          | 17.12          | 292                  | 1981-90       | Bratislava               | 48.17          | 17.08          | 195                  | 1994          | -0.88       | 0.99        |
| Barrow                     | 71.3           | -156.78        | 4                    | 1961-90       | Barrow                   | 71.32          | -156.61        | 8                    | 1992          | -0.73       | 1.14        |

*Table 3. Comparison between two sets of values of TL estimated from global and beam radiation (second test).*

*RMSD means root mean square difference.*

| Name              | Latitude<br>(°) | Longitude<br>(°) | Elevation<br>(m) | Period -beam    | Period - global | WMO-Nr |
|-------------------|-----------------|------------------|------------------|-----------------|-----------------|--------|
| Uccle             | 50.80           | 4.35             | 100              | 1981-90         | 1981-90         | 6447   |
| Hamburg           | 53.65           | 10.12            | 49               | 1981-90         | 1981-90         | 10141  |
| Braunschweig      | 52.30           | 10.45            | 83               | 1981-90         | 1981-90         | 10348  |
| Dresden-Wahnsdorf | 51.12           | 13.68            | 246              | 1981-90         | 1981-90         | 10486  |
| Trier             | 49.75           | 6.67             | 278              | 1981-90         | 1981-90         | 10609  |
| Wuerzburg         | 49.77           | 9.97             | 275              | 1981-90         | 1981-90         | 10655  |
| Weihenstephan     | 48.40           | 11.70            | 472              | 1981-90         | 1981-90         | 10863  |
| Payerne           | 46.82           | 6.95             | 491              | 1998            | 1987-96         | 6610   |
| Barrow            | 71.32           | -156.61          | 8                | 1992            | 1961-90         | 70026  |
| Miami             | 25.80           | -80.27           | 2                | 1978-85         | 1961-90         | 72202  |
| Brownsville       | 25.90           | -97.43           | 6                | 1978-84, 88     | 1961-90         | 72250  |
| El Paso           | 31.80           | -106.40          | 1194             | 1988-90         | 1961-90         | 72270  |
| Los Angeles       | 33.93           | -118.40          | 32               | 1978-80         | 1961-90         | 72295  |
| Raleigh           | 35.87           | -78.78           | 134              | 1988-90         | 1961-90         | 72306  |
| Fresno            | 36.77           | -119.72          | 100              | 1978-80         | 1961-90         | 72389  |
| Dodge City        | 37.77           | -99.97           | 787              | 1978-80, 88-90  | 1961-90         | 72451  |
| Salt Lake City    | 40.77           | -111.97          | 1288             | 1988-90         | 1961-90         | 72572  |
| Eugene            | 44.12           | -123.22          | 109              | 1988-90         | 1961-90         | 72693  |
| Caribou           | 46.87           | -68.02           | 190              | 1978-85, 88, 90 | 1961-90         | 72712  |
| Great Falls       | 47.48           | -111.37          | 1116             | 1988-90         | 1961-90         | 72775  |
| Seattle           | 47.45           | -122.30          | 122              | 1978-80, 88-90  | 1961-90         | 72793  |
| San Juan          | 18.43           | -66.00           | 19               | 1979-80         | 1961-90         | 78526  |

Table 4. List of the stations used in the third test

| <b>Test Properties</b>  | <b>Bias</b> | <b>RMSD</b> |
|---|-------------|-------------|
| Nine stations. Seven "reference" stations. Measured values of TL and estimates. Different periods and stations        | -0.1        | 0.9         |
| Thirteen stations. Six "reference" stations. TL assessed by beam and global radiation. Different periods and stations | 0.1         | 0.8         |
| Twenty-two stations. TL assessed by beam and global radiation. Different periods. Same stations                       | -0.3        | 0.6         |
| Eight stations. TL assessed by beam and global radiation. Same periods and stations                                   | -0.5        | 0.6         |

*Table 5. Summary of the tests. RMSD means root mean square difference.*



| Station Name            | Jan. | Feb. | Mar. | Apr. | May | Jun. | Jul. | Aug. | Sep. | Oct. | Nov. | Dec. |
|-------------------------|------|------|------|------|-----|------|------|------|------|------|------|------|
| Tamanrasset (Algeria)   | 2.7  | 2.6  | 3.2  | 3.3  | 3.2 | 3.9  | 4.0  | 4.4  | 4.5  | 4.7  | 3.5  | 3.7  |
| Sidi Barrani (Egypt)    | 3.4  | -    | 4.0  | -    | 4.1 | -    | 4.2  | -    | -    | 4.5  | -    | 4.1  |
| Mersa Matruh (Egypt)    | 2.6  | 4.3  | -    | -    | 4.4 | 4.3  | -    | 4.9  | 4.5  | 3.0  | -    | -    |
| Rafah (Egypt)           | 4.2  | 3.8  | -    | 3.9  | 4.2 | 3.9  | 4.2  | 4.6  | 4.4  | -    | -    | 4.0  |
| El Arish (Egypt)        | 4.5  | 3.8  | 2.9  | 4.0  | 3.9 | 3.7  | 3.4  | 4.2  | 4.1  | 4.6  | 4.3  | 4.3  |
| Tahrir (Egypt)          | -    | 4.5  | 4.5  | -    | 4.0 | 4.2  | -    | 4.7  | 4.7  | 5.0  | 5.2  | 4.3  |
| Bahtim (Egypt)          | -    | 4.6  | 4.5  | 4.9  | 5.2 | 4.3  | 4.6  | 4.9  | 5.3  | 5.2  | 5.4  | -    |
| Cairo HQ (Egypt)        | -    | 3.9  | 4.7  | 4.8  | 5.3 | -    | 5.4  | 5.9  | 5.6  | 5.3  | 5.6  | -    |
| Asyut (Egypt)           | 3.8  | 3.4  | 3.2  | 3.7  | 3.7 | 3.6  | 4.0  | 4.6  | 4.2  | 4.6  | 4.4  | 4.3  |
| Aswan (Egypt)           | 3.5  | 3.3  | 3.9  | 3.9  | -   | 4.0  | 4.3  | 4.4  | 4.3  | -    | 3.7  | 3.6  |
| Tete (Mozambique)       | 3.8  | 3.3  | 2.9  | 2.8  | 2.8 | 3.0  | 3.3  | 3.7  | 5.3  | 4.1  | 4.3  | 3.0  |
| Maputo (Mozambique)     | 3.7  | 3.8  | 3.3  | 3.5  | 3.0 | 3.1  | 3.1  | 3.0  | 4.0  | 2.9  | 3.5  | 3.2  |
| Lusaka (Zambia)         | 6.3  | -    | 6.3  | 5.0  | 2.5 | 3.1  | 2.7  | 3.6  | 4.9  | 7.0  | 5.8  | 4.4  |
| Harare (Zimbabwe)       | 6.3  | 5.7  | -    | -    | -   | -    | 4.4  | 3.9  | -    | 4.5  | 6.1  | 6.6  |
| Bulawayo (Zimbabwe)     | 5.0  | 4.9  | 4.7  | 4.8  | 3.8 | 3.7  | 3.7  | 3.9  | 4.6  | 5.5  | 5.4  | 5.5  |
| Sidi Bou Said (Tunisia) | 3.8  | 3.7  | 3.5  | 4.3  | 4.2 | 4.1  | 4.5  | 3.6  | 4.4  | 3.6  | 3.6  | 3.1  |

**Table 6.** Linke turbidity factor (TL) values for the 16 stations

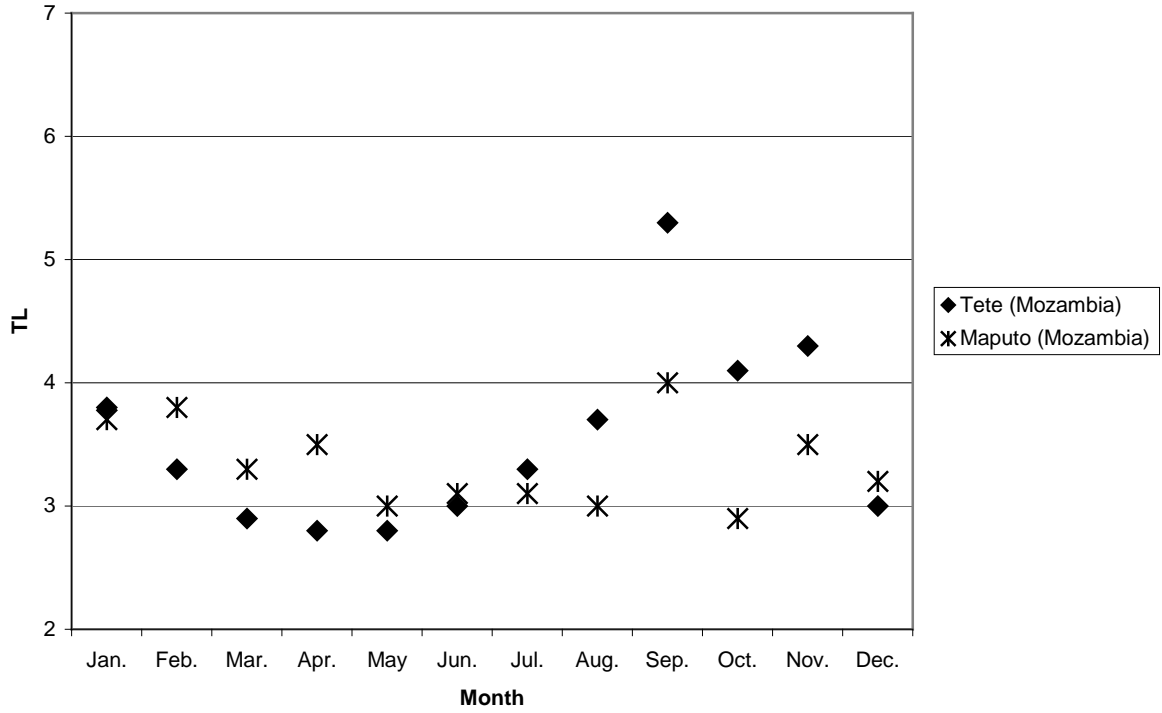


Figure 1: TL<sub>m</sub> for stations in Mozambia

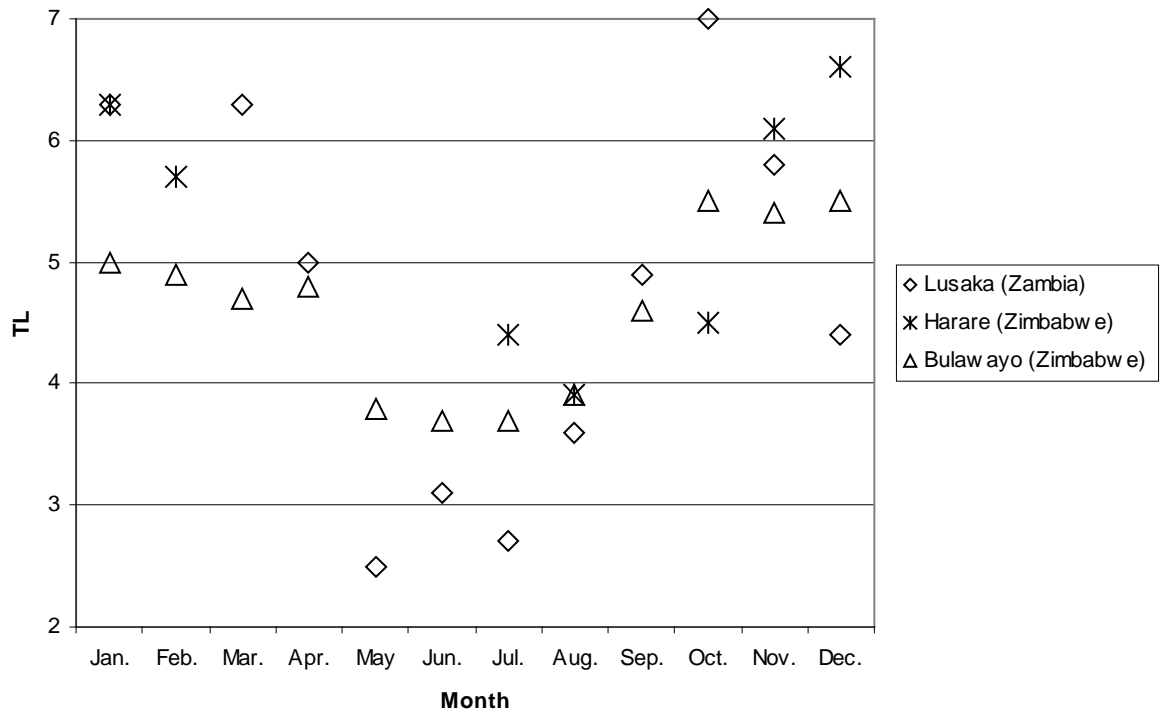


Figure 2: TL<sub>m</sub> for stations in Zimbabwe and Zambia

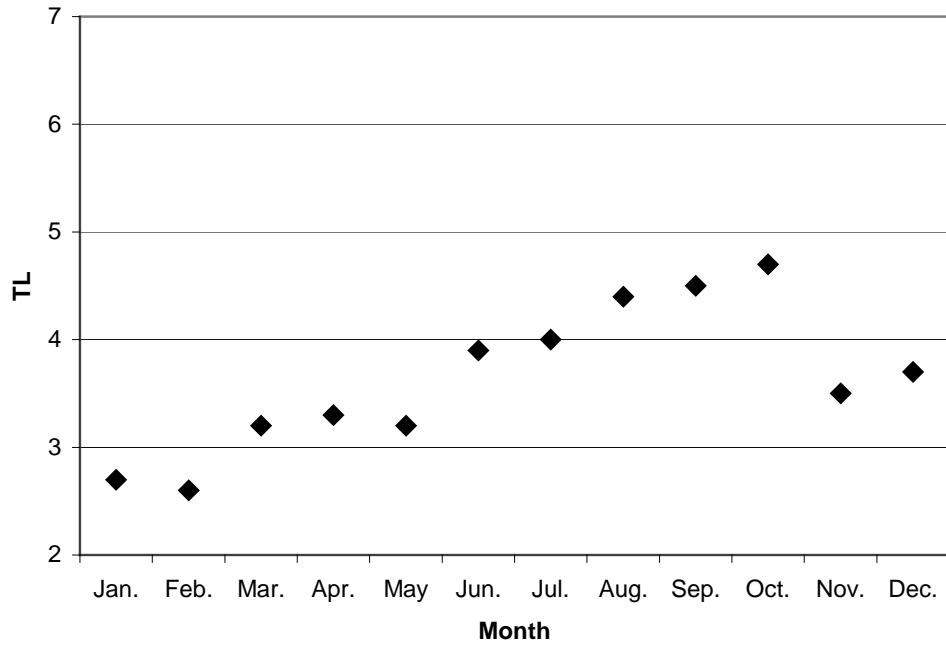


Figure 3: TL<sub>m</sub> for Tamanrasset (Algeria) - Sahara zone

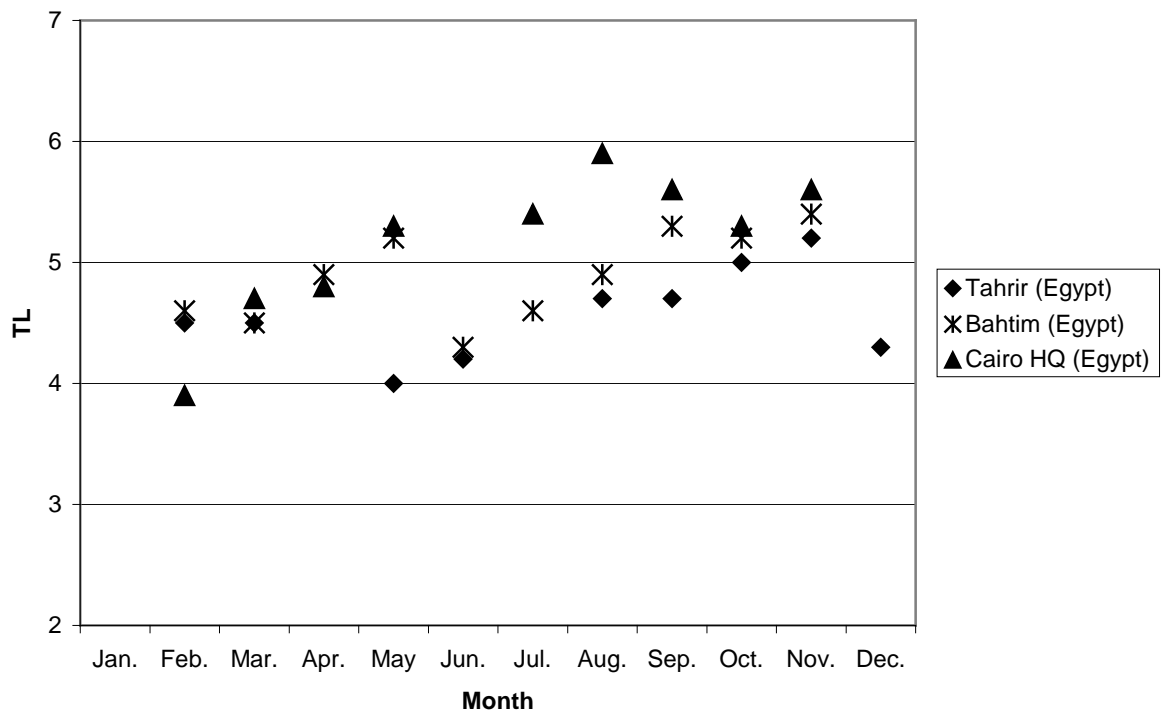


Figure 4: TL<sub>m</sub> for stations in industrial areas in semi-desert zone

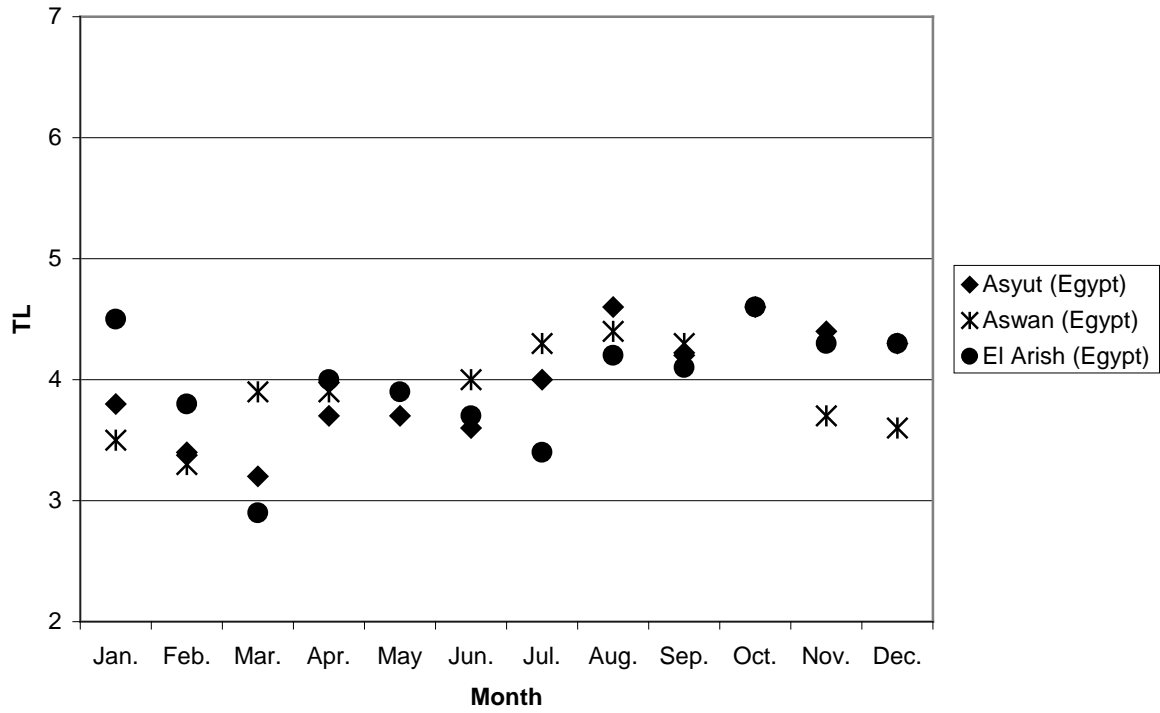


Figure 5: TL<sub>m</sub> in desert zone

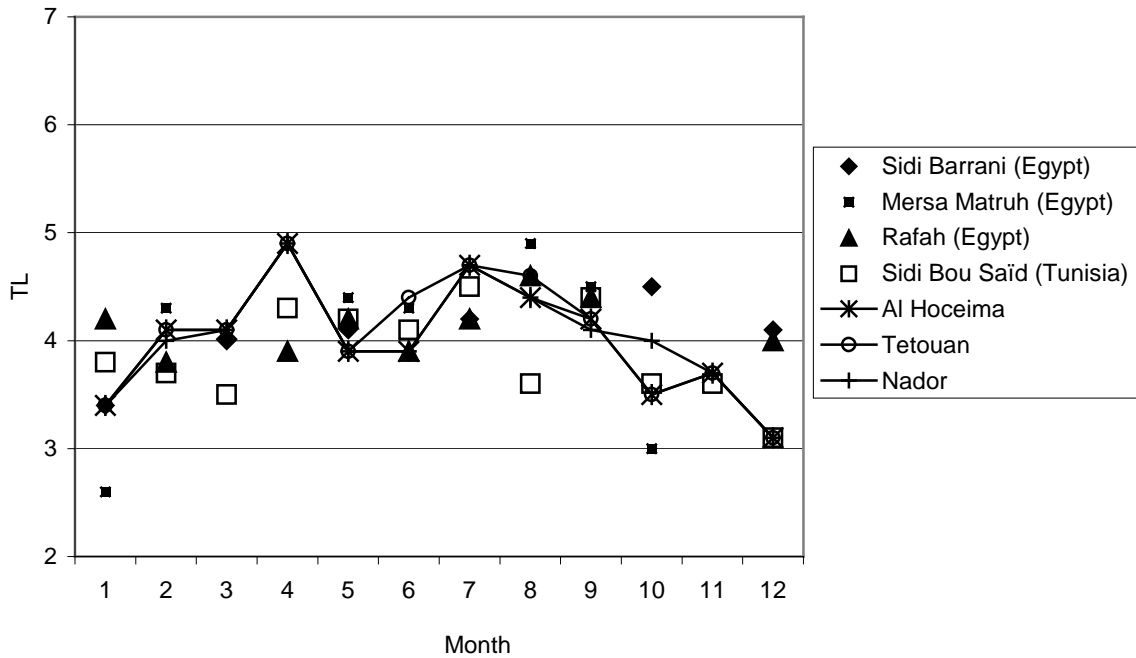


Figure 6: TL<sub>m</sub> for stations in Mediterranean zone. Superimposed are TL<sub>m</sub> values derived from the ESRA (2000) for 3 sites in Morocco (Al Hoceima, Tetouan, Nador).