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Estimation of Some Atmospheric Turbidity Parameters in Three Locations in Sri Lanka

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ABSTRACT

Atmospheric turbidity parameters are useful tools in air pollution monitoring and estimating atmospheric aerosol concentrations. Some atmospheric turbidity parameters, total optical depth (TOD), Linke Turbidity Factor (LTF) and Angstrom turbidity coefficient (ATC) and the maximum degree of polarization in the principal plane of the sun (MDoP) computed using ground-based solar intensity measurements are compared for three locations in Sri Lanka; Kelaniya, Kandy and Mahiyangana.TOD, LTF and ATC showed an increase with solar elevation angle in the range of 14^0 - 38^0 studied. The computed turbidity parameters were highest in Kandy and lowest in Mahiyangana indicating the highest aerosol concentration in Kandy, followed by Kelaniya and Mahiyangana. The reciprocal of MDoP showed a positive linear association with solar elevation angle implying that MDoP decreases with solar elevation angle in agreement with previous studies.

1. INTRODUCTION

Investigations on atmospheric turbidity parameters with ground based solar intensity measurements have been employed in past studies to estimate the extent of aerosol presence as well as aerosol size distribution [1- 3].The results of such investigations have been used to acquire knowledge of properties of aerosols, and to monitor the seasonal variations in atmospheric turbidity levels for meteorological purposes and for various other applications [3-6]. Studies on the polarization of skylight also show that some characteristics of the polarization pattern of skylight such as the maximum degree of polarization (MDoP), and the locations of the polarization neutral points in the principal plane are related to atmospheric turbidity [7-13]. However such studies using ground based observations have not been carried out in Sri Lanka to the best of our knowledge although some studies based on satellite data have been reported. This work is aimed at investigating the variations in the atmospheric aerosol content with solar elevation angle and location through computations of the turbidity parameters; Total Optical Depth (TOD), Linke Turbidity Factor (LTF) and Angstrom Turbidity Coefficient (ATC) based on solar intensity measurements carried out in Kelaniya, Kandy and Mahiyangana in 2018. TOD is a measure of turbidity in terms of the attenuation of light intensity in travelling through the atmosphere, LTF is a measure of the turbidity in terms of the turbidity of a clear molecular atmosphere and ATC is a measure of aerosol concentration. These parameters are also compared with the MDoP in the principal plane of the sun. A polarimeter constructed for the purpose is employed for intensity measurements. Details of the three measurement sites and the periods of data collection are given in Table 1.

Table 1: Details of the measurement sites and data collection periods

Location	**Latitude**	**Longitude**	**Altitude**	**Data Collection Period (2018)**
Kelaniya(Roof top)	6.98^0N	79.92^0E	43 m	February 2, 6, 12, 13
Kandy(Roof top)	7.28^0N	80.63^0E	586 m	May 1,2,3,5
Mahiyangana(Playground)	7.34^0N	80.99^0E	90 m	July 20, 21, 22, 23

Broad band TOD (τ) was computed by adapting the formula used for wavelength dependent TOD [6];

$$I_n = I_0 e^{-\tau \operatorname{cosec} \theta}$$

where I_0,the extra terrestrial flux was taken as that of visible light (663 W/m^{2}since the detector sensitivity is restricted to the visible region of the electromagnetic spectrum), I_n is the direct normal flux reaching the ground (in W/m^2), $\theta$is the solar elevation angle in degrees and $\tau$is the total optical depth given by,

$$\tau = \ln(\frac{I_0}{I_n}) \sin \theta$$

The following formulas were used to compute LTF(T_l) and ATC(β)[7].

$$T_l = T_{lk} \frac{\frac{1}{\delta_{Ra}(m_a)}}{\frac{1}{\delta_{Rk}(m_a)}}$$

where $T_{lk}$is the Linke turbidity factor according to Kasten (Kasten, 1980) as reported in Reference 7) and is given by;

$$T_{lk} = (0.9 + 9.4 \sin \theta).\left(\ln (I_0 (\frac{R_0}{R})^2) - \ln(I_n)\right)$$

where R and $R_0$are respectively the instantaneous and mean Sun-Earth distance and

$$\frac{1}{\delta_{Ra}}(m_a) = 6.6296 + 1.7513 m_a - 0.1202 {m_a}^2 + 0.0065 {m_a}^3 - 0.00013 {m_a}^4$$

$$\frac{1}{\delta_{Rk}}(m_a) = 9.4 + 0.9\, m_a$$

The following equations were used to calculate $\frac{R_0}{R}$: $\frac{R_0}{R} = \sqrt{1+\epsilon}$ where,

$$\epsilon = 0.03344 \cos(j - 0.049)$$

$$j = d \frac{2\pi}{365.2422}$$

j : day angle in radian

d is the day number ranging from 1 to 365 and air mass m_a is given by,

$$m_a = m_r \frac{p}{101325}$$

where m_r is the air mass under standard conditions given by,

$$m_r = [\sin \theta + 0.15(3.885 + \theta)^{-1.253}]^{-1},$$

the local pressure p (in Pascals) is given by

$$p = 101325 \exp(-0.0001184\, z)$$

where z is the altitude of the location above sea level in meters.

$$\beta = \frac{T_l - [\frac{\theta + 85}{39.5 \exp(-\omega_p) + 47.4} + 0.1]}{16 + 0.22 \omega_p}$$

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where ω_p is the precipitation amount in centimeters given by,

$$\omega_p = 0.493\ \frac{\emptyset}{T}\exp\left(26.23 - \frac{5416}{T}\right)$$

T is the temperature in Kelvin and ϕ is the relative humidity as a fraction of one.

2. METHODOLOGY

A fully automated polarimeter was constructed to take measurements for computing the polarization pattern of skylight in the principal plane of the sun (scattering plane) which is a graphical representation of the variation of the degree of polarization with the solar elevation angle θ. The actual measurements were the voltages across a light detecting resistor (LDR)corresponding to the intensities (I_{max} and I_{min}) of solar radiation polarized in two mutually perpendicular directions in a plane normal to the principal plane[15] which were later converted to intensities (in Lux and Watts-m^{-2}) through a calibration curve obtained using a BH1750FVI light sensor as the Lux meter, an intense LED lamp as the light source and two linear polarizers for controlling the light intensity. The maximum intensity obtained using the above set up was restricted by the source intensity. Voltages corresponding to higher intensities were converted to Lux by extrapolating the calibration curve. The polarimeter is somewhat similar in its functioning to a partially automated polarimeter constructed earlier [16] other than for some additional features which include a sun tracker and a temperature and humidity sensor and will not be described in detail here. All data were collected between 0700h-0850h in the mornings with solar elevation angles in the range 14^0 - 38^0.

The degree of polarization in the direction θ ($DoP(\theta)$) was computed as,

$$DoP(\theta) = (I_{max}(\theta) - I_{min}(\theta))/(I_{max}(\theta) + I_{min}(\theta))$$

Graphs of $DoP(\theta)$ vs θ were plotted for values of θ for each of the three locations Kelaniya, Kandy and Mahiyangana, from which the maximum degree of polarization, *MDoP* could be read around $\theta = 90^0$.

It was possible to compute LTF and ATC related to atmospheric turbidity from the above measurements using the total intensity $I(0)$ directly under the sun and the formulas given in Section 1where,

$$I(0) = I_{max}(0) + I_{min}(0).$$

3. RESULTS AND DISCUSSION

Statistical analysis of the variation of MDoP with θ gave the following functional relations between MDoP and θ for the three sites and are graphically illustrated in Figure 1.

Kelaniya: $\mathrm{MDoP} = 1/(0.052\theta + 5.78)$
Kandy: $\mathrm{MDoP} = 1/(0.052\theta + 4.95)$
Mahiyangana: $\mathrm{MDoP} = 1/(0.052\theta + 6.65)$

It is evident from the graphs that MDoP decreases with increasing solar elevation as has been reported by many researchers [11-13]. The highest MDoP was observed in Kandy while the lowest was seen in Mahiyangana.

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All three turbidity parameters (TOD, LTF and ATC) were computed using the formulas given in section 1 for white light and each parameter showed an increase with the solar elevation (Θ). The variation of total optical depth τ with Θ is shown in Figure 2. LTF and ATC showed similar graphs which are not shown due to space constraints.

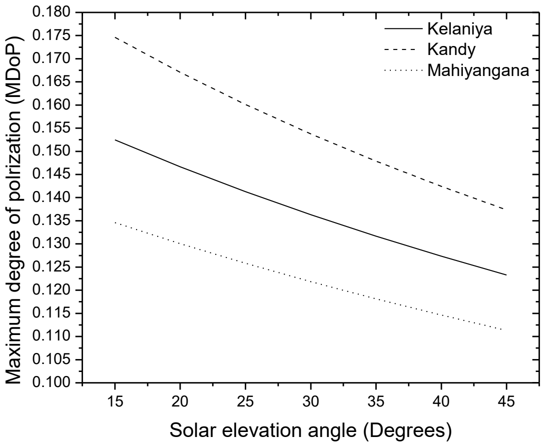

Figure 1: Maximum degree of polarization as a function of the solar elevation angle in Kelaniya, Kandy and Mahiyangana

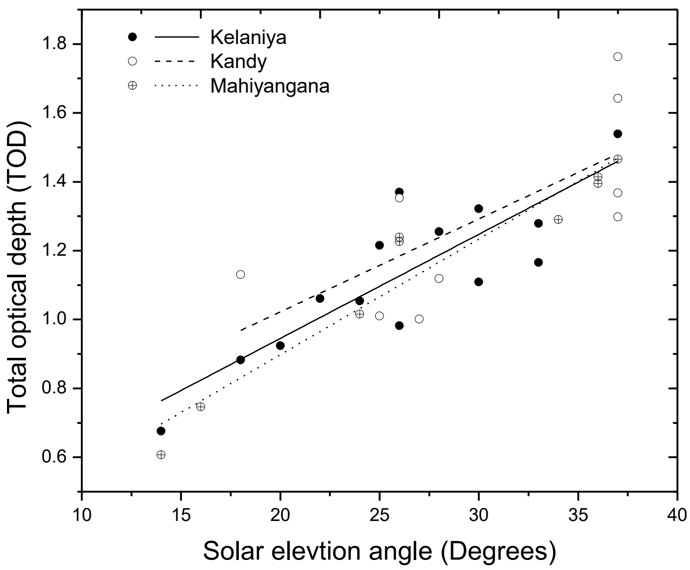

Figure 2: Total Optical Depth as a function of the solar elevation angle in Kelaniya, Kandy and Mahiyangana

A linear functional relation between each of the turbidity parameters and solar elevation was obtained for each location and that for TOD (τ) is shown in Table 2 with the corresponding R^2 values. Such variations with the solar elevation even when the atmospheric conditions remain unchanged have been reported and conventionally, the values computed at 30^0 are used [14]. The parameters computed for θ = 30^0using the relations obtained are shown in Table 2 along with the corresponding standard deviations within parenthesis.

Table 2: Equations of best-fit straight lines for TOD(τ), their R^2 values, the turbidity parameters TOD (T_l), and ATC (β) for solar elevation angle $30^0$and the respective standard deviations (within

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Although according to Figure 2, the highest turbidity is seen in Kandy while the lowest is seen in Mahiyangana at the different periods of data collection, the statistical analysis

Location	**Equation of Best-fit Line for TOD**	**R^2 Valu**	**TOD** (τ)	**LTF** (T_l)	**ATC** (β)
Kelaniya	$\tau(\theta) = 0.031\theta + .331$	.71	1.26(0.22)	12(1.64)	0.57(0.09)
Kandy	$\tau(\theta) = 0.027\theta + .482$	.43	1.29(0.27)	12.5(2.11)	0.59(0.12)
Mahiyangana	$\tau(\theta) = 0.032\theta + .250$	.91	1.21(0.24)	11.9(1.60)	0.58(0.09)

Although according to Figure 2, the highest turbidity is seen in Kandy while the lowest did not reveal any significant dependence of turbidity level on the location. According to the report *Solar Resources in Sri Lanka and the Maldives* published in 2003 based on satellite data which is shown in Figure 3, aerosol optical depth shows seasonal variations [15]. If the seasonal aerosol averages are removed, the order of turbidity levels stated above may show a statistical significance. TOD computed here is the sum of aerosol optical depth (AOD), Rayleigh optical depth and the cloud optical depth. Since AOD is highest in July when Mahiyangana data was collected, removing seasonal averages from the data would further reduce the low TOD computed in Mahiyangana while the minimally affected TOD values would be those in Kandy where data was collected in May with the lowest seasonal AOD. Kelaniya data collected in February will show only as light reduction in the TOD values. Therefore it could be concluded that local aerosol concentration in descending order is found in Kandy, Kelaniya and Mahiyangana in the said periods.
The lowest R^2 value associated with the TOD values as well as the highest standard deviations in all three turbidity parameters in Kandy could be the result of the larger variability in the clouds in Kandy compared to the other two sites.

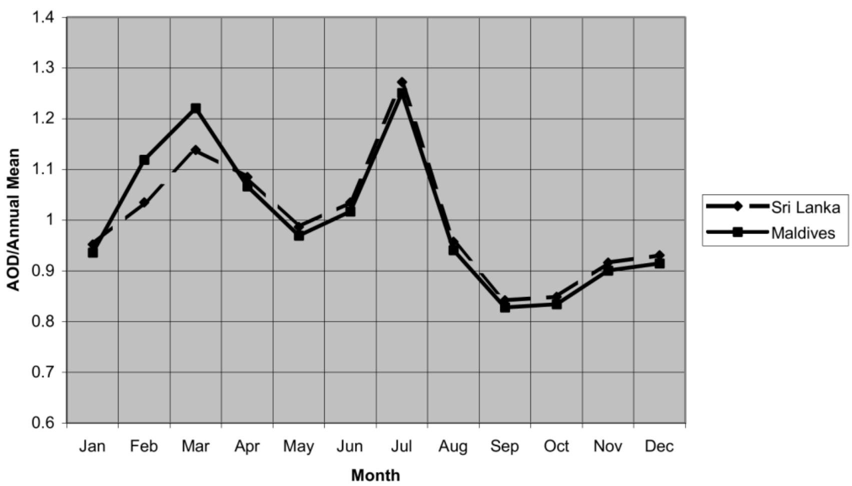

Figure 3: Seasonal patterns of Aerosol Optical Depth (AOD) for Sri Lanka and the Maldives. Ordinate value is the ratio of monthly AOD to the chosen annual AOD value [15]

A comparison of the MDoP with turbidity parameters was not possible among the three sites due to the vastly different surface albedo effects at the three sites. The lower

values of MDoP computed in Mahiyangana could be due to surface reflection effects from the ground and surrounding mountains which is minimal in Kelaniya site and less in Kandy since the measurement sites were on roof tops in these two locations. Also since the air column above the Kandy site is shorter than those of the other two sites due to its high altitude, which can result in a higher MDoP value in Kandy. None the less MDoP can be considered for comparing the turbidity levels on different days at the same location and the same solar elevation.
The main source of errors in the computed turbidity parameters is the supposedly random variations associated with cloud optical depth. Throughout the data taking periods, cloudy skies prevailed and clear days were scarce. The other possible source of error is the uncertainties in the intensities above 1000 Lux which were computed by extrapolating the calibration curve beyond the 0-1000 Lux range restricted by the maximum source intensity. The measured intensities over 1000 Lux could be underestimated resulting in an overestimation in the turbidity parameters for higher solar elevations when the intensities were high. This error can be eliminated by replacing the LDR sensor used in the polarimeter by a BH1750FVIlight sensor which gives the intensity in Lux directly.

4. CONCLUSION

In conclusion, this research has presented a cost-effective optical method of estimating the atmospheric turbidity parameters; Linke turbidity factor and Angstrom turbidity coefficient using ground based observations which can be further developed and employed for air pollution monitoring in Sri Lanka. The investigation revealed that the local aerosol concentration is highest in Kandy and lowest in Mahiyangana while the aerosol concentration in Kelaniya takes an intermediate value. Also the study shows that broad band measurements can be used for the purpose in place of the more complex spectral measurements.
The investigation can be extended to monitor the variations in the turbidity levels throughout the year in a particular location as well as to compare turbidity levels at different locations at the same time. It would be possible to obtain results with higher accuracy through further investigations along with measurements on air pollution using other methods to validate the results.

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REFERENCES

[1] Cuomo V, EspositoF, Pavese G,SerioC, *Determining Ångström's Turbidity Coefficients: An Analysis with a Wide-Range Grating Spectrometer*, Aerosol Science and Technology, 18:1 (1993) 59-69.
[2] Kaskaoutis D.G, Kambezidis H.D,*Investigation into the wavelength dependence of the aerosol optical depth in the Athens area*, Quarterly Journal of the Royal Meteorological Society: A journal of the atmospheric sciences, applied meteorology and physical oceanography, 132 (2006) 2217-2234.
[3] Ramachandran S, Kedia S,*Aerosol optical properties over South Asia from ground-based observations and remote sensing*, Climate, 1 (2013) 84-119.

[4] Dubovik O, Holben B, Eck T.F, Smirnov A, Kaufman Y.J, King M.D, Tanré D, Slutsker I,*Variability of absorption and optical properties of key aerosol types observed in worldwide locations*, Journal of the atmospheric sciences, 59 (2002) 590-608.

[5] Boesche E, Stammes P, Ruhtz T, Preusker R, Fischer J,*Effect of aerosol microphysical properties on polarization of skylight: sensitivity study and measurements*, Applied optics, 45 (2006) 8790-8805.

[6] Toledano C, Cachorro V.E, Berjon A, De Frutos A.M, Sorribas M, De la Morena B.A, Goloub P.*Aerosol optical depth and Ångström exponent climatology at El Arenosillo AERONET site (Huelva, Spain),* Quarterly Journal of the Royal Meteorological Society: A journal of the atmospheric sciences, applied meteorology and physical oceanography, 133 (2007) 795-807.

[7] Marif Y, Bechki D, Bouguettaia H, Zerrouki M, Belhadj M.M,*Determination of Linke turbidity factor from solar radiation measurement in Adrar city*, International Renewable and Sustainable Energy Conference (IRSEC), IEEE, (2016) 183-186.

[8] Sekera Z,*Light scattering in the atmosphere and the polarization of sky light*, JOSA, 47 (1957) 484-490.

[9] Liu Y, Voss K,*Polarized radiance distribution measurement of skylight. II. Experiment and data*, Applied Optics, 36 (1997) 8753-8764.

[10] Holzworth G.C, Rao C.N, *Studies of skylight polarization*, JOSA, 55 (1965) 403-408.

[11] Dahlberg A.R, Pust N.J, Shaw J.A,*Effects of surface reflectance on skylight polarization measurements at the Mauna Loa Observatory*, Optics Express, 19 (2011) 16008-16021.

[12] Pust N.J, Shaw J.A, *Comparison of skylight polarization measurements and MODTRAN-P calculations*, Journal of Applied Remote Sensing, 5 (2011) 053529-1-16.

[13] Stamov D.G, *Light polarization as an independent measure of atmospheric purity and transmittance*, Atmospheric Optics, Springer, Boston, MA (1970) 80-85

[14] Martin K.*Development of Broadband Aerosol Optical Depth Models,* University of Tartu Press (2016) 11-17.Available from: cyber.ee › research › theses › martin_kannel_phd.[Acesseed on 14th October 2019].

[15] Renné D, George R, Marion B, Heimiller D, Gueymard C. *Solar resource assessment for Sri Lanka and Maldives*, National Renewable Energy Lab.(NREL), Golden, CO (United States), (2003) 1-18. Available from: www.https://www.osti.gov/biblio/15004299-solar-resource-assessment-sri-lanka-maldives[Accessed on 10th July 2019].

[16] Li Z, Goloub P, Dubovik O, Blarel L, Zhang W, Podvin T,Sinyuk A, Sorokin M, Chen H, Holben B, Tanré D,*Improvements for ground-based remote sensing of atmospheric aerosol properties by additional polarimetric measurements*, Journal of Quantitative Spectroscopy and Radiative Transfer, 110 (2009) 1954-1961.

[17] Smith G.S,*The polarization of skylight: An example from nature*, American Journal of Physics. 75 (2007) 25-35.

[18] Abayaratne C.P, Wickramarathna A.V.U.A, Rodrigo D.D, Mannathunga K.S, *A low-cost partially automated polarimeter for investigating skylight polarization*, J.Natn.Sci.Foundation Sri Lanka. 44(1) (2016) 95-103.