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Investigation of Radiative Characteristics of the Kenyan Atmosphere due to Aerosols Using Sun Spectrophotometry Measurements and the COART Model

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ABSTRACT

Variations in the radiative characteristics of aerosols can be used to quantify their effects on climate. This study evaluated the temporal-spatial variability of aerosol radiative characteristics at λ = 440 nm, λ = 675 nm, λ = 870 nm and λ = 1020 nm over the Nairobi-1°S, 36°E, Mbita-0°S, 34°E and Malindi-2°S, 40°E sites of Kenya. Aerosol optical properties from AERONET were used as inputs in the Coupled Ocean Atmosphere Radiative Transfer (COART) code to model aerosol radiative effects. The results over Nairobi showed an increase in reflectance of 2.6%, 6.7%, 7.2% and 2.4% for 2006–2007 at the specified wavelengths, respectively. Drops of 2.7%, 12.2%, 50.6% and 25.6% were noted in the same wavelengths for the 2007–2008 period. The reflectance over Mbita (0.2284) was higher than that over Nairobi (0.1396) at λ = 675 nm for 2007, due to biomass burning at site. Maritime conditions and aerosols coupled with long range transport of monsoon winds explain the higher reflectance observed over Malindi when compared to Nairobi, except for λ = 440 nm in 2008. This is as a result of aerosols from vehicular and industrial emissions that dominate the λ = 440 nm over Nairobi. The variability of downward and upward spectral irradiance measured at the surface and 12 km levels depended on the wavelength of measurement, but was temporally invariant. Upward irradiance decreased with increasing Solar Zenith Angles (SZAs) due to strong Fresnel reflection at large angles. The equality in the upwelling irradiances at the two atmospheric levels at all sites for λ = 870 nm and λ = 1020 nm was due to the near IR absorption by aerosols. The radiant flux lost in the spectral range 440–1020 nm remained relatively constant over the study sites, and thus the influence of aerosols on radiative characteristics was independent of both site and period of study.

Keywords: Radiative characteristics; Reflectance; Aerosols; Kenyan atmosphere.

INTRODUCTION

Radiative forcing by natural and anthropogenic aerosols presently presents one of the most uncertain aspects of climate models due to its dependence on various atmospheric processes e.g., coagulation, cloud cycling and aerosol long distance transport (Hansen *et al.*, 1997; Penner *et al.*, 2002). The physical and chemical properties of atmospheric aerosols depend on their origin; for instance, aerosols in an urban environment have a higher concentration of sulfur and heavy metals as compared to those from rural environments (Latha and Badarinath, 2005). On the other hand, maritime aerosols consist of mainly sea-salt and sulfate particles that are produced through wave breaking and oxidation of dimethyl sulfide respectively.

Atmospheric aerosol particles can scatter or absorb the incoming solar radiation, hence, altering the radiative characteristics on the Earth's surface (Seinfeld *et al.*, 2004; Satheesh and Moorthy, 2005). Therefore, continuous monitoring of aerosol optical properties via different aerosol networks e.g., AErosol RObotic NETwork (AERONET) can contribute to the general understanding of aerosol effects over the respective study sites (Holben *et al.*, 1998, 2001). Utilizing aerosol optical properties (for example aerosol optical depth, single scattering albedo, asymmetry factor) with the help of a suitable computational model, spectral and integrated solar irradiances together with the reflectance of atmospheric aerosols can be determined. This forms the benchmark for quantifying aerosol radiative effects on regional climate. Scattering and absorption of solar radiation by aerosols (and gases) causes a net decrease in global irradiance reaching the Earth surface, thus altering its radiative budget. Variability in both downward and upward spectral and integrated solar irradiance due to aerosols significantly affects the regional climate; hence, there is a need to quantify their variations be it temporal or spatial to effectively asses aerosol effects on the regional climate.

The present study has evaluated the radiative characteristics of the Kenyan atmosphere due to aerosols utilizing AERONET sun radiometry measurements and the COART

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Model. Following AERONET network large spread of sites over the world, the network is capable of improving atmospheric monitoring capacity as impacted on by atmospheric aerosols from both natural and anthropogenic sources. COART models the absorption and scattering process in the atmosphere and ocean explicitly by considering them as one coupled system and treats the ocean strata just as additional atmospheric layers with different optical properties; similar to the atmosphere, the ocean can also be subdivided into an arbitrary number of layers required to resolve the vertical variations of water properties (Zhonghai *et al.*, 1994, 2006).

The atmosphere is found to be heated by aerosols as much as 25 W/m^2 with highest values over areas characterized by strong absorbing mineral particles and high surface albedo (e.g., Sahara) (Hatzianastassiou *et al.*, 2004). The downward solar radiation at the surface is drastically reduced due to the presence of aerosols by up to 30 W/m^2; the largest decrease is found over regions with high aerosol optical depths (τ). An increase in relative humidity increases the outgoing solar radiation over oceans through increased aerosol scattering from about 1 W/m^2 to 2 W/m^2 (Hatzianastassiou *et al.*, 2004). Other studies e.g., (Sokolik *et al.*, 1998) show that there is a reduction in uncertainties associated with the estimation of direct radiative forcing when regionally and temporally varying dust mineralogical composition are incorporated in general circulation models.

Studies between December 2010–May 2011 over Pune in India show significant day to day variability and covaries with AOD as a result of the anticorrelation between aerosol direct radiative forcing (ADRF)/AOD, and also the differences in the daily maximum minus minimum relative humidity and temperature. Specifically, at Nowrosjee Wadia College, ADRF ranges between –37.7 W/m^2 (highest) and –5.9 W/m^2 (lowest). For 500 nm, ADRF takes values in the range –17.3 ± 7.1 W/m^2 to 54.2 ± 5.5 W/m^2 at Pune University, whereas the corresponding values at IGO are –15.1 ± 2.1 W/m^2 and –36.6 ± 6.4 W/m^2 (Pawar *et al.*, 2012). A study over Pune in India using a multiplatform measurements show that maximum AOD values and minimum preciptable water were observed during a drought year (2009) when compared to normal monsoon years (2008 and 2010) (Vijayakumar *et al.*, 2012).

Radiative transfer modeling through the Dust and Biomass-burning Experiment (DABEX) by Johnson *et al.* (2009) over West Africa suggested a 130–160 W/m^2 instantaneous reduction of downwelling solar radiation by aerosol columns (15–18% of the total flux). Studies over Hyderabad, India reveal that tropospheric aerosol loading has significant impact on the solar irradiance reaching urban environments (Badarinath *et al.*, 2007). A dimming of about 7 W/m^2 per decade at land surface stations worldwide was observed between 1961 and 1990 (Gilgen *et al.*, 1998; Power and Mills, 2005). A study by Alpert *et al.* (2005) also indicates that stations from which the analysis took place were predominantly urban, hence, it was expected that dimming could be less or even missing in rural areas.

IPCC, (2007) report estimates the total global average (TOA) forcing by aerosol from pre-industrial conditions is –1.3 (–2.2 to –0.5) W/m^2. Studies on the evaluation of radiative effects of desert dust on UVB irradiance levels by means of radiative forcing and forcing efficiency over Sahara-Sahel and Gibo deserts show that the net effect of radiative forcing estimates for the two regions in the UVB spectral range are comparable (Garcia *et al.*, 2009).

Aerosol transport and atmospheric dynamics over Kenya is both local and long-range with most of the former associated with the coarse fraction aerosols from the nearby natural and anthropogenic sources (Gatebe *et al.*, 2001). On the other hand, studies by Gatari *et al.* (2009) over Nairobi, Kenya, reveals that particles from a typical urban environment have a mixture of soil dust, industrial activities and vehicular emissions. The elemental concentrations of suspended particulate matter were noted to be in the order of 10^{-4} to 10^{-6} μg/m^3 over Nairobi (Gatebe *et al.*, 1996). Nairobi's urbanization trends accelerates the concentration of atmospheric pollutants due to the increase in the number of vehicles, extent of industrial activity and burning of wood charcoal and refuse (Van Vliet and Kinney, 2007).

Gatebe *et al.* (2002) and Remer *et al.* (2001) on the other hand, suggested that VIS/SWIR surface reflectance relationships are angle dependent. The two noted that at different possible angle parameters (solar zenith angle, sensor zenith angle, glint angle or scattering angle), the scattering angle had the largest influence on the VIS/SWIR surface reflectance relationship. Additionally, spectral variations in surface reflectivity database for northern Africa and the Arabian Peninsula using the Sea-viewing Wide Field of view Sensor (SeaWiFS) in February 2000 are noted (Christina *et al.*, 2004). These were; western Mauritania, Niger desert, Bodele depression (in Chad) and the Libyan desert whose spectral variations in surface reflectivity ranged between 0.1–0.5, 0.1–0.55, 0.2–0.45 and 0.15–0.55 respectively and when compared to the AERONET values over the sites, an agreement of within 30% was achieved.

It was noted that previous studies on aerosols over Kenya emphasize the aspects of atmospheric pollution and air quality over urban sites mostly Nairobi. Limited and non continuous acquisition of aerosol data averaged either daily or weekly was used. Hence there is need to quantify otherwise the radiative characteristics of atmospheric aerosols and to evaluate their spatial and temporal variability in Kenya. This study is part of a comprehensive regional effort which contributes towards a global climate modeling hierarchy as influenced by atmospheric aerosols. Evaluation and quantification of aerosol radiative characteristics either temporally or spatially can only be inferred from long-term measurements through passive remote sensing techniques that are now available for example AERONET network, whose measurements were used in this work.

METHODS

Aerosol optical properties i.e., aerosol optical depth, single scattering albedo, asymmetry parameter and the refractive indices were retrieved from Cimel sun spectrophotometers from the AERONET network as detailed by Holben *et al.* (1998). The annual averages of these optical properties

were then used as inputs to the COART model to determine radiative characteristics i.e., spectral irradiance, integrated fluxes, and reflectance (ratio of upward to downward irradiance) according to the procedures described by Zhonghai and Stamnes (1994) and Zhonghai *et al.* (2006). In these procedures, atmospheric profile utilized in this model was tropical (since all the sites under consideration lye in the tropics) with a boundary layer aerosol model of MODRAN urban, rural and maritime for Nairobi-1°S, 36°E, Mbita-0°S, 34°E and Malindi-2°S, 40°E respectively.

Spectral irradiances i.e., upward and downward (at λ = 440 nm, λ = 675 nm, λ = 870 nm and λ = 1020 nm); integrated fluxes (λ from 440 nm to 1020 nm spectral range) for Solar Zenith Angles (SZAs) from 0° to 80° taken in steps of 10 degrees were determined at 0 km and 12 km levels. On the other hand, the ratio of upward to downward irradiance (reflectance) at the Earths surface in the specified spectral range was obtained as detailed in Tables 1 and 3. The 12 km atmospheric altitude was considered since it is the standard height at which aircraft emissions into the atmosphere are prevalent. Also, the troposphere has its average altitude value at this point in which aerosol concentration is highest as assumed by many radiative transfer models (IPCC, 2001).

Irradiance, $E(\lambda)$ is the radiative energy flux per unit time in a given wavelength interval through a horizontal surface of unit area. The irradiance is obtained by integrating the radiance that is weighted with the cosine of the viewing zenith angle, $\mu = \cos\theta$, over all viewing directions in a hemisphere of 2π steradians. Since we mainly used spectrally integrated irradiances we define:

$$E = \int_{440\ nm}^{1020\ nm} E(\lambda) d\lambda \quad (1)$$

with the unit [W/m^2]. The downward solar irradiance at the surface is often called the global irradiance (E_{glo}). The E_{glo} can be separate into the downward irradiance at the surface in a direct part (unscattered radiation) and a diffuse part (scattered radiation), denoted by E_{dir} and E_{dif} respectively. So, we have at the surface:

$$E_{glo} = E_{dir} + E_{dif} \quad (2)$$

On the other hand, aerosol number densities in Table 2 were obtained by dividing annual averages of both aerosol optical depths with its extinction cross-section in any given wavelength as detailed in Bolle (1977).

RESULTS AND DISCUSSIONS

Spectral Irradiance (E(λ))

The ratio of upward/downward irradiance (reflectance) for the net spectral irradiance at 12 km and 0 km altitude were determined as shown in Table 1. This was done at λ = 440 nm, λ = 675 nm, λ = 870 nm and λ = 1020 nm and at zero SZA over the study sites. An increase in reflectance signifies an increase in radiant energy lost in the atmosphere at a given wavelength per unit surface area and vice versa.

It is notable from Table 1 that the reflectance over each site of study decreased with increasing wavelength of measurement in the time interval considered. It is also noted that an increase in aerosol number density (Table 2) for the 2006–2007 period for Nairobi is accompanied by a

Table 1. Net upward and downward irradiances (at zero SZA) at the specified discrete wavelengths over study sites.

Site	Year	λ (nm)	Net-downward irradiance (W/m^2/nm)	Net-upward irradiance (W/m^2/nm)	Reflectance
Nairobi	2006	440	291.6 ± 3.2	138.8 ± 1.2	0.4760
		675	119.8 ± 3.2	15.6 ± 1.2	0.1302
		870	56.6 ± 1.8	5.9 ± 0.8	0.1042
		1020	53.4 ± 1.8	4.3 ± 0.5	0.0805
	2007	440	224.5 ± 3.2	109.6 ± 1.2	0.4882
		675	74.5 ± 3.2	10.4 ± 1.2	0.1396
		870	53.6 ± 1.8	9.6 ± 0.8	0.1791
		1020	47.9 ± 1.8	4.8 ± 0.5	0.1002
	2008	440	265.1 ± 3.2	125.4 ± 1.2	0.4730
		675	107.4 ± 3.2	13.1 ± 1.2	0.1220
		870	50.1 ± 1.8	4.4 ± 0.8	0.0878
		1020	52.6 ± 1.8	3.8 ± 0.5	0.0722
Mbita	2007	440	274.7 ± 3.2	125.6 ± 1.2	0.4572
		675	106.4 ± 3.2	24.3 ± 1.2	0.2284
		870	53.5 ± 1.8	2.8 ± 0.8	0.0520
		1020	47.5 ± 1.8	2.2 ± 0.5	0.0463
Malindi	2008	440	306.8 ± 3.2	120.6 ± 1.2	0.3931
		675	129.6 ± 3.2	22.4 ± 1.2	0.1728
		870	68.8 ± 1.8	7.4 ± 0.8	0.1076
		1020	60.4 ± 1.8	5.8 ± 0.5	0.0960

NB: There was no AERONET data for 2006 and 2008 (Mbita); and 2006 and 2007 (Malindi).

Table 2. Average aerosol number density distribution over the study sites.

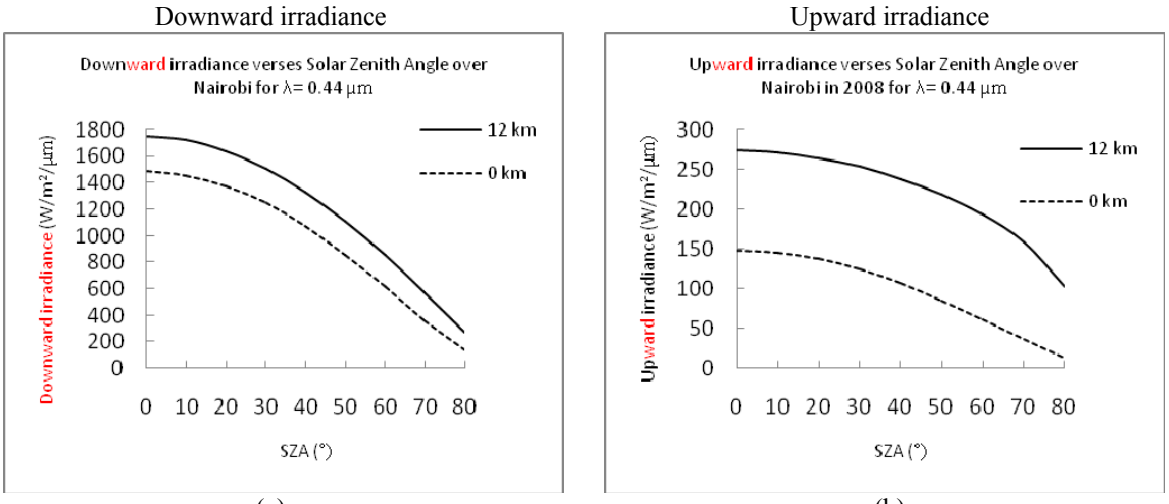
Site	Year	(N) × 10^7/cm^3			
		λ = 440 nm	λ = 675 nm	λ = 870 nm	λ = 1020nm
Nairobi	2006	8.35	1.97	1.02	1.10
	2007	11.55	3.63	2.02	1.35
	2008	9.87	3.35	1.85	1.35
Mbita	2007	11.23	3.97	1.52	0.98
Malindi	2008	13.8	4.47	2.53	1.71

percentage increase in the reflectance by 2.6%, 6.7%, 7.2% and 2.4% (Table 1) for λ = 440 nm, λ = 675 nm, λ = 870 nm and λ = 1020 nm wavelengths respectively. On the other hand, a decrease in aerosol number density from 2007–2008 which was due to wet removal process of atmospheric aerosols as deduced from rainfall data was accompanied by a corresponding decrease in reflectance by 2.7%, 12.2%, 50.6% and 25.6% for λ = 440 nm, λ = 675 nm, λ = 870 nm and λ = 1020 nm respectively. Comparison of Tables 1 and 2 for each wavelength shows that reflectance and aerosol number densities are directly related in that an increase in aerosol number densities leads to increase in the radiant energy lost per unit surface area and vice versa. There is a significant increase in reflectance at λ = 675 nm and λ = 870 nm over Nairobi for the 2006–2007 period. This suggests that aerosols in these wavelengths dominate over Nairobi, which may be as a result of mixture of soil dust, vehicular and industrial emissions (Gatari *et al.*, 2009).

Comparison of reflectance was made as follows: Nairobi-Mbita and Nairobi-Malindi in 2007 and 2008 respectively in order to probe its spatial variability. Comparison between Malindi and Mbita wasn't possible since there was no data for any common year. Reflectance at every wavelength (except for λ = 675 nm in 2007) over Nairobi remained relatively higher than that of Mbita. This difference may be due to the effect of fresh smoke aerosol particles from biomass burning over Mbita (i.e., higher reflectance of 0.2288) as compared to Nairobi (reflectance of 0.1390) (see Table 1) in 2007. On the other hand, reflectance for Malindi remained relatively higher when compared to that of Nairobi at all wavelengths except for λ = 440 nm. This is as a result of both sea spray and sea salt aerosols and prevailing maritime conditions coupled with their long distance transport as aided by the effect of Monsoon winds. These aerosols scatter more incoming solar radiation, leading to higher reflectance.

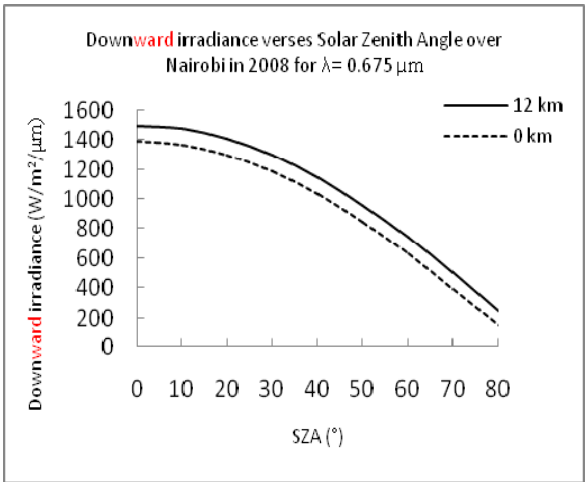
Figs. 1(a)–1(h) show the spectral irradiance versus SZAs graphs over Nairobi in 2006 that are representative of Nairobi (2007, 2008), Mbita (2007) and Malindi (2008) since they were same. Hence, the graphs remained invariant in shape for the period of study at each site when compared to that of Nairobi in 2006. Variation in spectral irradiance with SZAs is therefore wavelength dependent but temporally and spatially invariant. The temporal invariance may be attributed to the fact that changes in radiative characteristics vary in time scale i.e., from minutes to a full solar cycle (Mendoza, 2005).

There is an observable reduction in the difference between downwelling irradiances with increasing wavelengths between 0 km and 12 km. This reduction shows that absorption and scattering of solar radiation by aerosols between the two altitudes dominates at λ = 0.44 μm compared to λ = 1.02 μm. The decrease is more marked at larger SZA since most of the incoming solar radiation is diffuse in nature due to scattering effects. The low sun case (SZA 0°–SZA 20°) is characterized by high downwelling irradiances

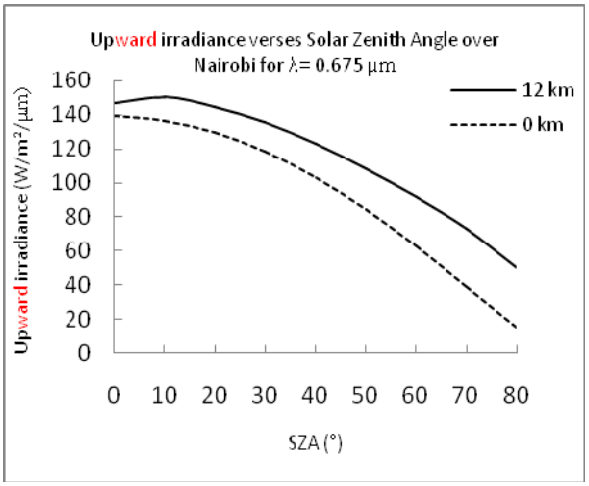


(a) (b)

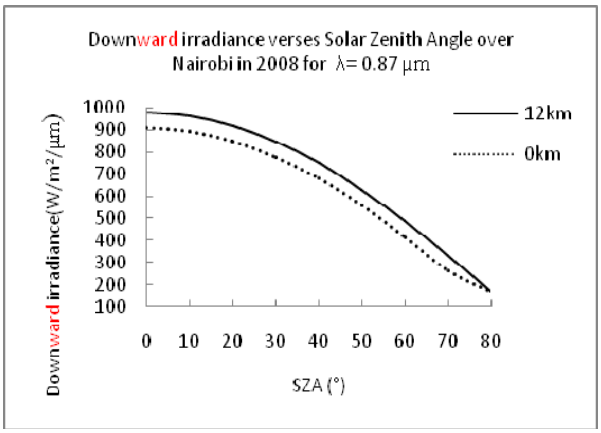
Fig. 1. COART-modeled spectral irradiances (downward and upward) as a function of SZAs for specified discrete wavelengths over Nairobi in 2008.



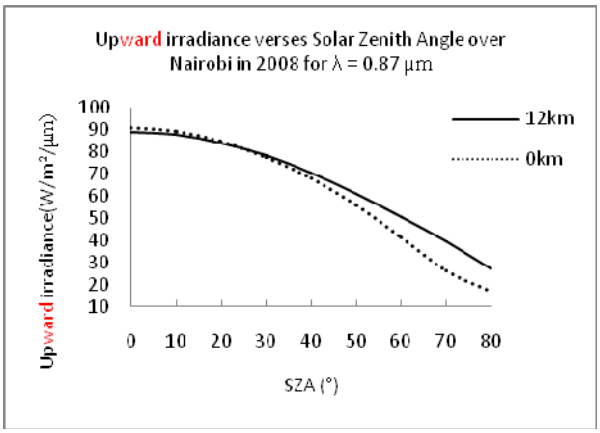
(c)



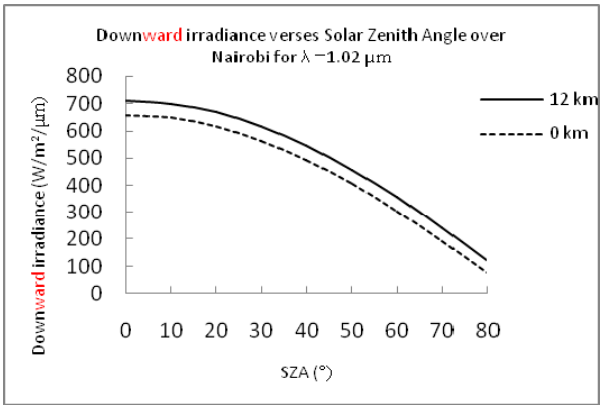
(d)



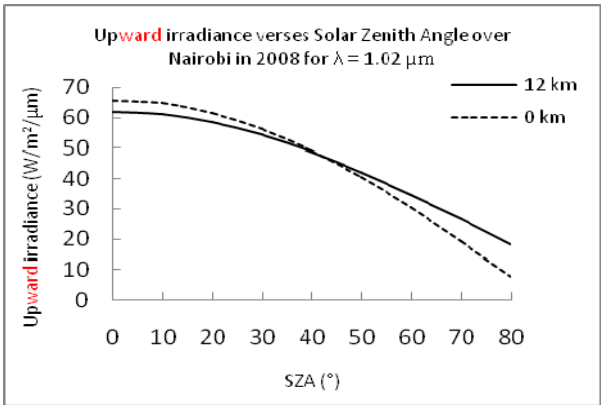
(e)



(f)



(g)



(h)

Fig. 1. *(continued).*

since most of the incoming solar radiation is direct and strikes the surface at a glancing angle unlike in the high sun case (SZA 50°–SZA 80°) where most of the downwelling irradiance is diffuse, hence the low spectral irradiance values (Zhonghai *et al.,* 2006).

Figs. 1(b), 1(d), 1(f) and 1(h) show that upward irradiances in the atmosphere over the study sites decrease with increasing SZAs for all wavelengths. The decrease is attributed to strong Fresnel reflection on the Earth's surface experienced by the incoming solar radiation. Figs. 1(f) and 1(h) correspond to λ = 870 nm and λ = 1020 nm respectively. The two wavelengths present a special case where the radiant energy reflected into the atmosphere from the surface is slightly higher than that at 12 km i.e., (SZA 0°-SZA 20° and vice versa for SZA 40°-SZA 80° at λ = 870 nm and SZA 0°-SZA 40° and vice versa for SZA 60°-SZA 80° at λ = 1020 nm). The point of intersection between the upwelling irradiances is at SZA 30° and SZA 50° respectively. This equality in the upwelling irradiances at 0 km and 12 km levels at all sites for λ = 870 nm and λ = 1020 nm is a

consequence of the near IR absorption by atmospheric aerosols. This causes the upward irradiance at the surface to be more as compared to that at 12 km for higher optical air mass factor values and vice versa for lower optical air mass factor values which translates to cooling effect on the Earth's surface.

Integrated Fluxes

The spectral range through which the Integrated Fluxes (IF) were obtained are λ = 440–1020 nm with a spectral resolution of 10 nm. Variations in net down and up integrated fluxes at zero SZA are shown in Table 3 together with the upward/downward ratio over the study sites.

Variations in integrated fluxes correspond to those of aerosol number densities over Nairobi at the two atmospheric levels. An increase in aerosol number densities (Table 2) in the spectral range under consideration for 2006–2007 time interval translates to an increase in the upward/downward integrated flux ratio by ≈ 3.1%. Thus, an increase in aerosol number densities allows for more attenuation of incoming solar radiation through absorption and scattering. On the other hand, a decrease in aerosol number density from 2007–2008 translates to a decrease in the ratio by about 6.8% since attenuation of incoming solar radiation is enhanced between the two altitudes. It was also noted that the up to down ratio in Table 3 remains virtually constant over the study sites.

The trend in the graphs for both downward and upward integrated fluxes versus SZAs over the other study sites i.e., Mbita and Malindi was the same to that of Nairobi in 2008 and are as shown in Figs. 2(a)and 2(b) respectively.

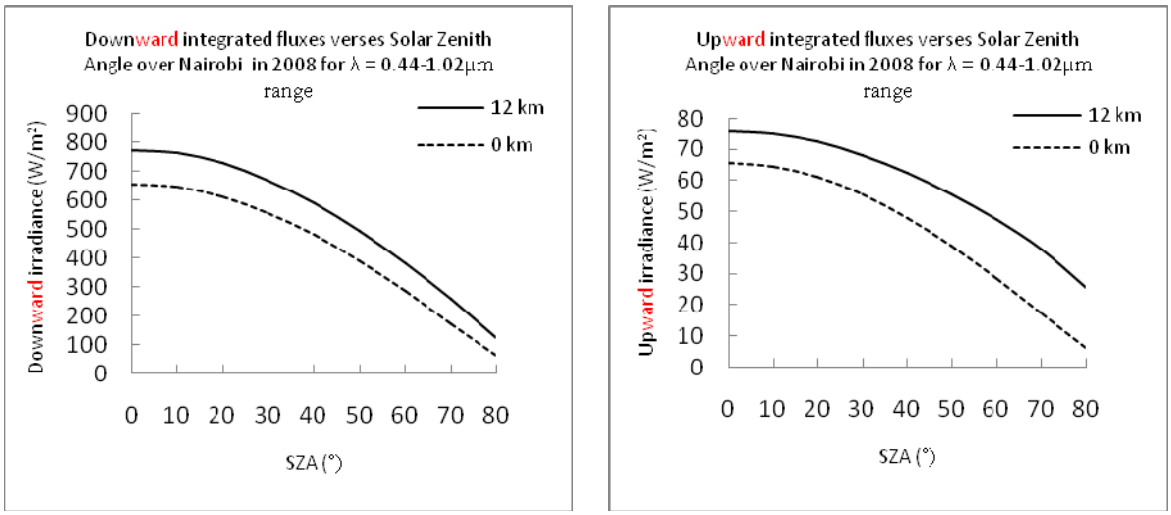
Fig. (2a) shows a reduction in the difference for the downward irradiance with increasing SZAs. This may be attributed to the fact that at low SZAs most of the incoming solar radiation is direct. Both downward and upward integrated irradiance decreased with increasing optical air mass factor (increasing SZAs) as indicated in Figs. 2(a) and 2(b). The net downward and upward integrated irradiance over Nairobi in the 2006–2008 period was noted to vary with aerosol number densities over the site.

CONCLUSIONS

This study evaluates the radiative characteristics of selected sites in the Kenya's atmosphere due to aerosols via sun spectrophotometry measurements and the COART model. It was observed that the radiant energy lost in the atmosphere due to aerosols reduced with increasing wavelength and the previous being proportional to aerosol number density. Spatio-temporal investigations of the selected radiative characteristics were found to be invariant except for selected wavelengths. Influence of mixture of soil dust, vehicular and industrial emissions over Nairobi explains higher reflectance values compared to those of Mbita at all wavelengths except for λ = 675 nm; at this wavelength, fresh smoke aerosol particles from biomass burning activities

Table 3. Variation in net integrated fluxes at the two atmospheric levels over the study sites.

Site	Year	Net downward (± 2.3W/m^2)	Net upward (± 0.5W/m^2)	Reflectance
Nairobi	2006	121.9	12.9	0.1058
	2007	103.2	11.3	0.1143
	2008	118.4	12.1	0.1022
Mbita	2007	114.4	11.9	0.1040
Malindi	2008	130.8	14.2	0.1086



(a) (b)

Fig. 2. COART modeled downward and upward integrated fluxes at 12 km and 0 km altitude for varying SZAs respectively over Nairobi in 2008.

over Mbita explain the disparity. For Malindi, reflectance was relatively higher when compared to that of Nairobi at all wavelengths except for λ = 440 nm as a result of both sea spray and sea salt aerosols and prevailing maritime conditions coupled with the Monsoon winds effects. The radiant flux lost in the λ = 0.44–1.02 μm spectral range was observed to remain constant for the period of study. The low sun case is characterized by high downwelling irradiances and vice versa for the high sun case where most of the downwelling irradiance is diffuse in nature hence the low spectral irradiance values. Equality in the upwelling irradiances at 0 km and 12 km levels at all sites for λ = 870 nm and λ = 1020 nm is a consequence of the near IR absorption by atmospheric aerosols.

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