Journal of Atmospheric and Solar-Terrestrial Physics 80 (2012) 28–36

Contents lists available at SciVerse ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

Impact of the total solar eclipse of 29 March 2006 on the surface energy fluxes at Ibadan, Nigeria

E.F Nymphas*, T.A. Otunla, M.O. Adeniyi, E.O. Oladiran

Department of Physics, University of Ibadan, Nigeria

ARTICLE INFO

Article history:
Received 20 August 2011
Received in revised form
6 January 2012
Accepted 29 February 2012
Available online 10 March 2012

Keywords:
Solar eclipse
Solar radiation
Energy fluxes
Global radiation
Net radiation
Soil heat flux
Nigeria

ABSTRACT

This paper document the impact of the total solar eclipse (97.4%) of 29 March 2006 on the surface energy fluxes at Ibadan, Nigeria (longitude 4.56°E, latitude 7.55°N), a tropical location. The surface energy (determined by the BREB method) was found to be grossly affected by the eclipse. The latent heat and net radiation (R_n) lagged the sensible heat by 11 min in totality. The sensible heat lagged the latent heat and R_n by 6 min before it start to increase after the totality phase of the eclipse, while global radiation (R_g) lagged R_n by 7 min. The sensible heat reversed sign, reaching a value of $-1.02\ \mathrm{Wm^{-2}}$ during the total phase of the eclipse while the latent heat dropped by 89.7%.

All the radiation fluxes (global radiation, R_g, net radiation R_n, temperature, and soil heat flux) measured during the eclipse event were significantly affected by the sudden 'cut off' of the solar irradiation. There was a 95% decrease in R_g, while R_n dropped from $354.3\ \mathrm{Wm^{-2}}$ to $-11.7\ \mathrm{Wm^{-2}}$.

1. Introduction

The total solar eclipse (TSE) of 29 March 2006, which traversed half of the earth and started from Brazil, passing over the Atlantic through North Africa, and Central Asia and ending in northern Mongolia, was visible in Nigeria. It entered Africa through the Gulf of Guinea passing through Ghana, Togo and Benin republics at a speed of $0.98\ \mathrm{k\,ms^{-1}}$ (Espenak and Anderson, 2006). The speed of the penumbra was reduced to $0.818\ \mathrm{kms^{-1}}$ by the time it entered Nigeria, taking about 16 min to cross its western part before entering Niger Republic. By this time the path of totality had expanded from 184 km when it entered Africa to 188 km (Espenak and Anderson, 2006). The Sun's altitude in Nigeria during the eclipse was 52° while the magnitude of the eclipse was 97%. Table 1 summarises the timings of the eclipse at Ibadan. The path of the TSE on 29 March 2006 is shown in Fig. 1.

Although it is an astronomical phenomenon, solar eclipses inspire meteorologists to conduct special investigations ranging from radiation measurements (e.g. Kazadzis et al., 2007; Emde and Mayer, 2007), and related studies in atmospheric chemistry (Gerasopoulos et al., 2007 and references therein). Recent focus has been on the eclipse induced changes in the spectral solar irradiatiance at the earth's surface, the effect of multiple scattering on sky brightness, and the wavelength dependence of the limb darkening effect (Kumar and Rengaiyan, 2011). Some of the studies showed that radiations in the shorter wavelength are influenced more by eclipses (Kazadzis et al., 2007; Kazantzidis et al., 2007). This effect, however decreases at large eclipses ($>85\%$) as the eclipse approaches maximum. The environmental effects of solar eclipse had been focused mainly on meteorological parameters, photochemistry, boundary layer physics, total columnar ozone, gravity waves and ionospheric parameters (Adeniyi et al., 2007, 2009; Kumar and Rengaiyan, 2011; Winkler et al., 2001). The most important environmental effects of an eclipse take place at micro-scale and involve changes on the boundary layer parameters of physical and chemical nature such as thermodynamic processes and decrease in plants' response to the level of light which subsequently causes a decrease in CO_2 flux (Fabian et al., 2001). The impact and the effects of solar eclipses on meteorological and atmospheric parameters are well documented in the literature. Unfortunately, most of the previous micrometeorological studies were made during partial solar eclipses. There are few micrometeorological measurements during TSEs (e.g. Foken et al., 2001; Fabian et al., 2001; Stoeva et al., 2005; Founda et al., 2007; Psiloglou and Kambezidis, 2007). Also there are few such special investigations during solar eclipses that have been previously carried out in tropical Africa especially in the West African sub-region. The first reported observation of TSE in the West African sub-region was made by Arthur Eddington in 1919. His observation of stars near the Sun during the total eclipse of 29 May 1919

---

* Corresponding author. Tel.: +234 802 351 6602.
E-mail address: efnda@yahoo.co.uk (E. Nymphas).

1364-6826/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jastp.2012.02.024

produced one of the first proofs of Einstein's theory of general relativity that 'massive objects warp space and time'. The scarcity of report on the micrometeorological studies during solar eclipses in this area is partly due to the rare occurrence of the event over the sub-region and/or due to the lack of facilities for such measurements. The TSE of 29 March 2006 monitored in Ibadan, Nigeria, with the equipment grant by the International Programs in the Physical Sciences (IPPS) of Uppsala University, Sweden to the Nigeria Atmospheric Research Group (NARG) provided an excellent opportunity for a micrometeorological measurement to be carried out in the sub-region. The University of Ibadan is a centre for the deployment of one set of such equipment and where such measurements were made during the total solar eclipse. One of our objectives was to determine the surface energy balance of the humid tropical area of South-Western Nigeria. The observed changes in the meteorological parameters measured during this eclipse event have been reported (Nymphas et al.; 2009). In this paper, we report the effects of the eclipse of 29 March 2006 on the surface energy balance in this humid tropical area and compare the results with similar measurements elsewhere.

There are few reports on the impact of eclipses on surface energy balance (Pruitt et al., 1965; Kessler et al., 1979; Foken et al., 2001; Ahrens et al., 2001) and most of these reports are from the temperate parts of the world with virtually none from the tropics. Generally, there are few reports on the surface energy balance in the tropics particularly sub-Saharan Africa (Wallace et al., 1992; Goutorbe et al., 1994; Verhoef et al., 1999) compared to similar studies from other parts of the world. An insight into the surface energy balance of these areas is highly desirable because of its considerable influence on global circulation, to predict the effects of climate and land use change (Verhoef et al., 1999). Also the circulation patterns over West Africa and the effects of perturbation patterns are of particular interest because of their global teleconnection role (Mauder et al., 2007). They also influence El Nino events. Section 2.1 gives a description of the weather situation on the eclipse day. Section 2.2, describes the site and the instruments deployed for the measurements during the eclipse event. Section 2.3 gives a brief description of the behaviour of the meteorological parameters while Section 3.1 gives a description of the radiative fluxes. The response of the soil temperature, and consequently, the soil heat flux is discussed in Section 3.2. The effect of TSE on the energy balance during the eclipse event is discussed in Section 3.3. A summary of the findings is given in Section 4.

Table 1
Timings of TSE of 29 March 2006 at Ibadan, Nigeria (LT is UT+1 h).

Phase of eclipse	Time (UT)	Altitude	Azimuth
Start of eclpise	08:06:52	34.7°	90.9°
Maximum	09:19:58	52.8°	94°
End of eclipse	10:40:03	72.5°	101.8°

Eclipse magnitude at maximum 97.4%.

2. Data collection and analysis

2.1. Weather conditions

In the morning of the eclipse day, the cloud cover was very large (six octas, 6/8). The sky was covered with low, unstable, non-dissipating cumulus and stratocumulus clouds which gradually decreased as the eclipse event was approaching. This is in support of the anecdotal evidence that the sky clears just before totality (Aplin and Harrison, 2001). There were no thunderstorms during or after the eclipse but rains of 0.19 mm occurred over the station a day preceding the eclipse (15:40–16:00 LT). There was a general decline in cloudiness during the eclipse (a decline of more than 35% in cumulus cloudiness has been reported by (Anderson, 1999). The extent of decline in cloudiness depends on the cloud type, size and

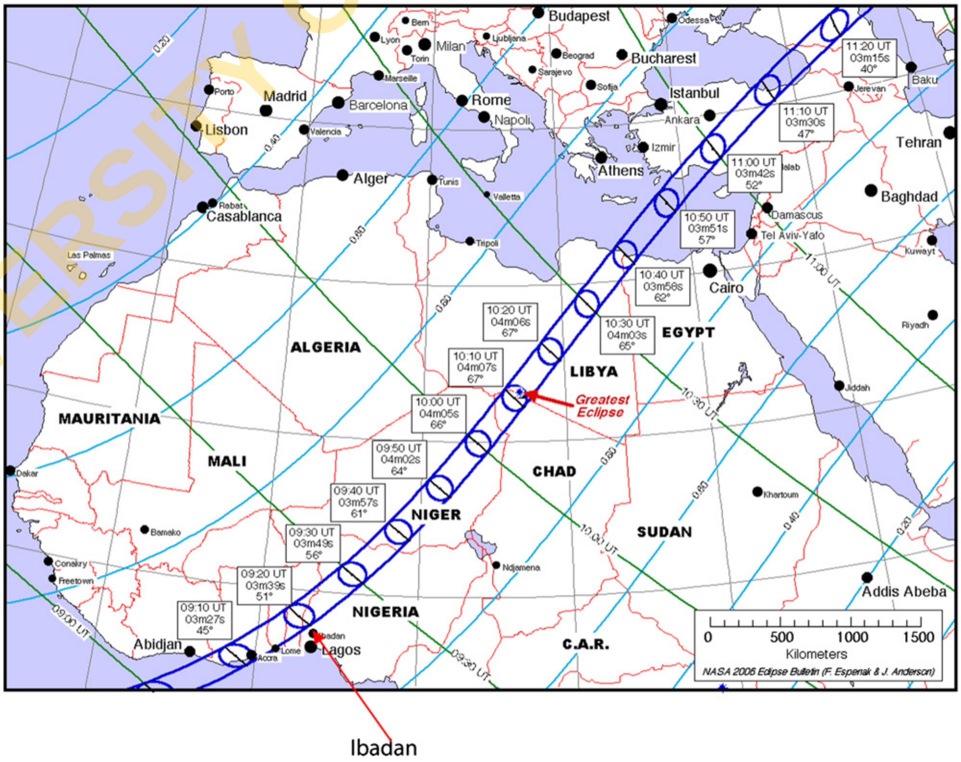

Fig. 1. The path of the total solar eclipse of 29 March 2006 through Africa. Also shown is the location of Ibadan. (*Source:* http://Sunearth.gsfc.nasa.gov/eclipse/SEmono/TSE2006/TSE2006.html).

location. Small convective clouds weaken or disappear during the early stages of an eclipse. At times non-precipitating clouds are forced to dissipate about half an hour before totality. There are reported cases of dramatic rapid decline in cumulus and towering cumulus in the tropical environment (Anderson, 1999). However, not all cloudiness is reduced by eclipse. Low-level stratus and stratocumulus often increase in thickness while mid- and high-level clouds continue without significant changes (Anderson, 1999). The cloudiness over the West African sub-region during the TSE of 29 March 2006 is shown in Fig. 2. The surface pressure at our observatory on the eclipse day continued to increase till after the event after which the pressure began to decline (Nymphas et al., 2009). Fig. 3 shows the pressure pattern and the position of the InterTropical Convergence Zone (ITCZ) over the sub-region during the TSE of 29 March 2006.

2.2. Measurement site, instrumentation and observations

The Ibadan station is about 145 km away from the Gulf of Guinea, within the University of Ibadan. The location of the meteorological mast is 7.44°N, 3.89°E and 206 m a.s.l. The vegetation is characterised as fallow bush-land of 0.5 m canopy height. This canopy height was further reduced to bare surface and maintained as such throughout the measurement period. The fetch is more than 150 m and the nearest building more than 100 m from the mast. All the radiation sensors were mounted above the ground surface on horizontal booms protruding about 2 m from the mast to minimise the possibility of shadowing by the mast. The details of the instruments deployed during this special observation is given in Nymphas et al. (2009). The data acquisition system and reduction was realised using CR10X data logger from Campbell Scientific and computer programmes for analysing the data, developed at Obafemi Awolowo University (OAU) and University of Bayreuth, Germany (Jegede et al., 2004; Mauder et al., 2007). The data was sampled at 20 Hz and later averaged at 1 and 10 min.

The few cumulus clouds that emerged did not obstruct visual observation of the eclipse. Also, there was no harmattan (which usually characterises this period of the year in West Africa) few days before or during the eclipse period. The observed changes in the meteorological parameters during the TSE of 29 March 2006 in this region has been reported earlier (Nymphas et al., 2009). Here, we only report on the perturbations of the surface energy

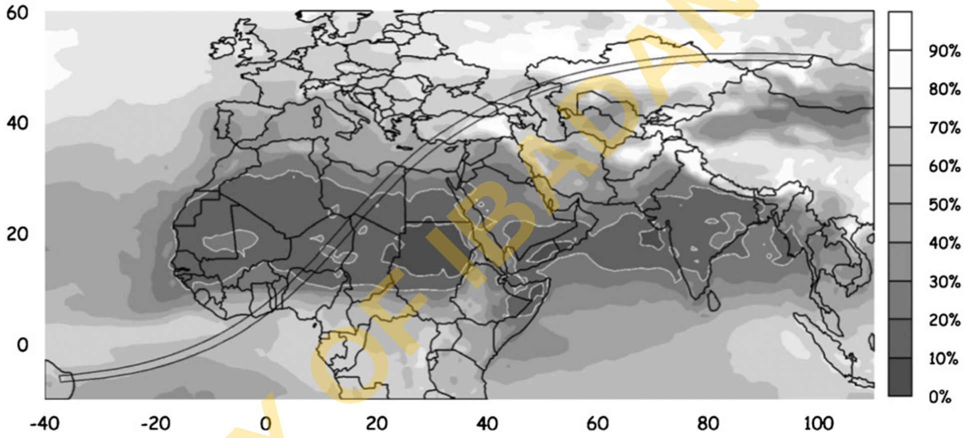

Fig. 2. Map of mean cloudiness during the TSE of 29 March 2006 (Espenak and Anderson, 2006).
Source: http://Sunearth.gsfc.nasa.gov/eclipse/TSE2006/TSE2006.html.

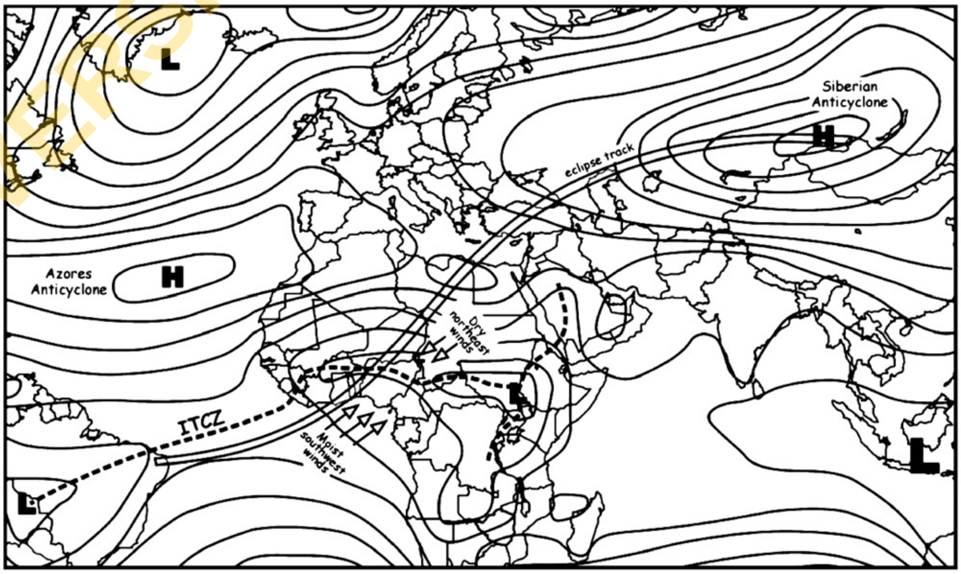

Fig. 3. Map of mean surface pressure during the TSE of 29 March 2006 showing the controlling weather systems, the average location of the ITCZ and eclipse track. (Espenak and Anderson (2006)).
Source: http://Sunearth.gsfc.nasa.gov/eclipse/TSE2006/TSE2006.html.

balance in this tropical region of West Africa during the TSE of 29 March 2006. The importance of such perturbations, especially of the weather patterns over this sub-region, has been emphasised earlier. The results are then compared with those of other eclipses (partial or total) from other parts of the globe.

2.3. *Meteorological parameters*

As reported earlier (Nymphas et al., 2009) and from the experience in other places of the world (Eaton et al., 1997; Segal et al., 1996; Ahrens et al., 2001; Fabian et al., 2001; Foken et al., 2001; Aplin and Harrison, 2001; Prakash et al., 2002; Founda et al., 2007), all the meteorological parameters measured during the eclipse event of 29 March 2006 at Ibadan were significantly affected. The degree and magnitude of the effect depend on the parameter measured. The meteorological changes result from the abrupt change in the incoming solar radiation, causing cooling in the surface layers of the atmosphere and damping of atmospheric turbulence from the surface upwards (Kirshnan et al., 2004). The change in the radiative heating or cooling of the atmosphere is first felt in the atmospheric surface layer (ASL) where turbulence dominate in the transport of mass, energy and momentum. Accordingly, temperature is one of the parameters that is mostly influenced by the eclipse. In Ibadan, the amplitude of the temperature change ranged between 0.8 °C and 1.6 °C depending on the height of measurement. The temperature dropped by 1.6, 1.0 and 0.8 °C at 1, 6, and 12 m height respectively (Nymphas et al., 2009). This observation is similar to those of Tzanis et al. (2007) and Economou et al. (2008) who reported temperature drops in the range of 0.7 °C and 2.2 °C. The altitude dependence of air temperature as observed from other stations around the globe showed a fall varying from 9.7 °C at 0.13 m above the ground to 0.4 °C at 20 m above the ground (Anderson, 1999). When solar radiation begins to decrease, surface or air temperature decreases too. The pattern and the precise amount of decline of the meteorological parameters are unique at each location, depending on the time of the day, the climate, the site, its surrounding vegetation, the exposure to the sky, and the wind (Ahrens et al., 2001). The temperature fall is usually greatest at the ground level due to the energetic processes responsible for cooling and warming the air, resulting in the establishment of surface-based inversion and decoupling with air (Anderson, 1999). In most cases, temperature decreases with the start of the eclipse. The combination of light ‘switch off’ and increase in humidity, together with decrease in temperature during eclipses have high impact on forests and trees (Steppe et al., 2002).

There is a large variation in the decline in air temperature during eclipses depending, as stated earlier, on many factors. For example, Segal et al. (1996) observed that regardless of the closeness of the locations of the stations in their measurements during the annular eclipse of 10 August 1994, sheltered temperature was affected. The magnitude of the drop in the midlatitudes depend upon the time of the eclipse occurrence and nonlinearly upon the degree of the eclipse obscuration. They attributed this to the nature of the terrain and variations in land use. The dependence of the changes in temperature on the percentage obscuration was recently challenged by Founda et al. (2007) who reported that the changes are mostly due to the surrounding environment and local conditions rather than the obscuration percentage. Our observation at Ibadan is in line with the former argument that the changes in temperature are due to the percentage obscuration.

A wind gust, believed to be ‘eclipse wind’ was observed before the first contact (start of the eclipse). The amplitude of the wind speed reached 2.02, 2.40, 2.67 and 3.07 ms^{-1} before droping to 0.50, 0.76, 0.92 and 1.14 ms^{-1} respectively at the four levels of the mast (1, 3, 6 and 12 m) during totality (Nymphas et al., 2009). Some workers have observed a continuous decrease in wind speed without a significant change in direction (Kolev et al., 2005, Founda et al., 2007) while others reported a shift in wind direction without any change in wind speed (Kumar and Rengaiyan, 2011). The later workers attributted their results to the change in the pressure gradient force during the eclipse. The decrease in wind gustiness around totality has been attributed to the depression of turbulence mechanism due to the cooling of the air (Founda et al., 2007) in agreement with the observations of Kirshnan et al. (2004) and Anfossi et al. (2004) who observed less turbulent wind during solar eclipses. At Ibadan, there was a considerable increase in wind speed without any significant change in wind direction before first contact after which it started to decrease, reaching minimum value at the maximum phase of the eclipse (Nymphas et al., 2009). This decrease in wind speed during a solar eclipse is due to the stabilisation of the atmosphere (Fernendez et al., 1996). Unlike the measurements in some parts of Greece (Founda et al., 2007), the wind speed at Ibadan started recovering almost immediately after totality (Nymphas et al., 2009). There was a time difference of 32 min between the minimum of global radiation and the minimum of wind speed (Fig. 4). This result is comparable with that of Foken et al. (2001) but contrary to the observations in New Mexico during the partial solar eclipse of 1994 (Eaton et al., 1997). This observed large time lag can only be phenomenological. Two possible expalnations are: it could be due to the decoupling of the lower part of the atmospheric surface layer at local scale because of the start of stable stratification. Second, it could be due to change in pressure gradient in a mesoscale due to a reduced surface heating. Unfortunately, we were not able to carry out measurements in the whole atmospheric surface boundary layer at Ibadan. This would have given further explanation. It must be pointed out that the eclipse wind has been a subject of debate among many workers for several years now though it has emerged throughout multiple eclipses (Gerasopoulos et al., 2007). In many cases, it has been related to the subjective perception of a pronounced wind chill effect (Anderson, 1999).

Pressure imbalances usually result from the rapid cooling caused by the penumbra travelling at supersonic speeds (Aplin and Harrison, 2001). Unlike the observations of Founda et al. (2007) and Economou et al. (2008) who observed a pressure decrease of 1.8 hPa and 0.7 hPa respectively in Greece during the eclipse of 29 March 2006, and many others, the pressure in Ibadan remained constant throughout the period of the eclipse event. It started to increase only some few minutes to the end of the clipse, reaching a maximum value of 1317.01 hPa in 63 min after totality, after which it continued to decrease.

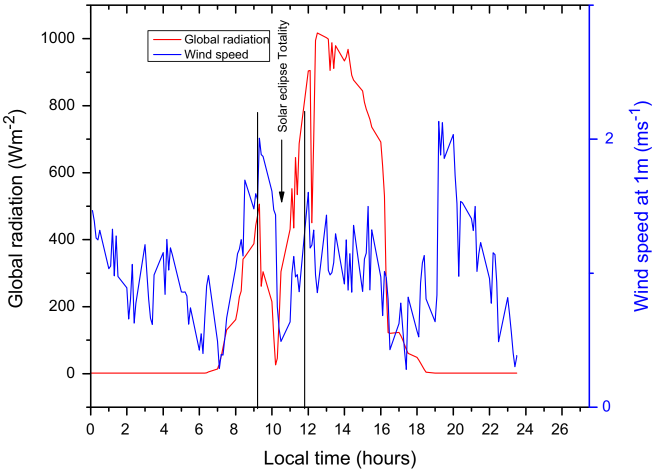

Fig. 4. Wind speed at 1 m and global radiation showing the time lag when each parameter reached minimum during maximum phase of the eclipse.

3. Results

3.1. Radiative fluxes

The radiative fluxes at Ibadan were significantly affected during the eclipse event. There was an immediate response of solar radiation at Ibadan just after first contact with a dramatic reduction in all the meteorological parameters measured during the eclipse event (Nymphas et al., 2009). Marked effects on meteorological parameters within the atmospheric surface layer have been reported from sites across the globe during partial or total solar eclipses. The observed effects across the globe include the modulation of surface fluxes, significant reductions in turbulence, surface pressure perturbations associated with total solar eclipse, amongst others (Anderson et al., 1972; Kunhikrishnan and Krishnanmurphy, 1982). The global radiation (R_g) and net radiation (R_n) reached peak values of 512.9 $\mathrm{Wm^{-2}}$ and 354.3 $\mathrm{Wm^{-2}}$ before dropping to 25.4 $\mathrm{Wm^{-2}}$ and -11.7 $\mathrm{Wm^{-2}}$, respectively, during the eclipse maximum. Similarly, the soil heat flux dropped from 74.7 $\mathrm{Wm^{-2}}$ by 9.30 LT to -36.4 $\mathrm{Wm^{-2}}$ by 10.30 LT when totality occurred contrary to the observations of Ahrens et al. (2001). This 95% reduction in R_g during the TSE of 29 March 2006 in Ibadan, Nigeria, is comparable to the results of Founda et al. (2007) who recorded a reduction of between 89% and 100% in R_g for the same eclipse in Greece. According to Founda et al. (2007), R_g decreased progressively as the Sun was being obscured from 894 $\mathrm{Wm^{-2}}$ (during the start of eclipse) to almost zero during the total phase of the eclipse in Greece. R_g started to increase again after the third contact.

In contrast to the observations of Eaton et al. (1997) during the partial eclipse of 10 May 1994 in Germany, and that of Ahrens et al. (2001) during the TSE of 11 August 1999, a negative R_n was observed during the eclipse event at Ibadan. A minimum R_n of -11.7 $\mathrm{Wm^{-2}}$ was observed during totality. A similar observation was also made by Foken et al. (2001) and Fabian et al. (2001) who reported negative values for R_n during the TSE of 11 August 1999 in Germany.

3.2. Soil temperature and soil heat flux

The thermal regime in soils are known to be disturbed by solar eclipses (Leeds-Harrison et al., 2000; Foken et al., 2001; Dolas et al., 2002; Kirshnan et al., 2004; Founda et al., 2007; Nymphas et al., 2009). The degree of the disturbance decreased with the depth at which the soil temperature was measured and the nature of the soil (bare or vegetated) among other factors. The variation in soil temperature is usualy assumed sinusoidal in a cloudless sky, providing sinusoidal temperature waves with decreasing amplitude and increasing phase shift with depth (Leeds-Harrison et al., 2000). This variation is, however, affected by several factors such as intermitent reductions in solar radiation at the soil surface, passage of clouds, and complications caused by soil and water content variations, which produce temperature variations that depart from the sinusoidal form. These factors are further accentuated by solar eclipses.

During the TSE of 29 March 2006, soil temperature was measured at Ibadan, with PT-100Q thermistor thermocouple at 5, 10, and 30 cm depths in a bare loam sandy soil. The temperatures were recorded at 20 Hz and averaged at 10 min by a CR10X Campbell Scientific datalogger. The observed temperatures at these three levels and the soil heat flux are shown in Fig. 5. The solid curves represent the soil temperature variations on the eclipse day while the dot and dash-dot curves show the mean values at 5 and 10 cm for the non-eclipse days prior to the event but excluding the day preceding the eclipse. As shown in Fig. 5, soil temperature at 5 cm and 10 cm depths continued its normal diurnal rise after the first contact reaching 30.56 °C by 9:48 LT and 30.10 °C by 10.31 LT, respectively. The temperature at 5 cm depth then remained virtually constant for about 14 min, increasing only by 0.07 °C before reaching a minimum value of 30.01 °C at totality. Again it remained virtually constant for about 11 min after which it started to increase and resumed its normal diurnal cycle.

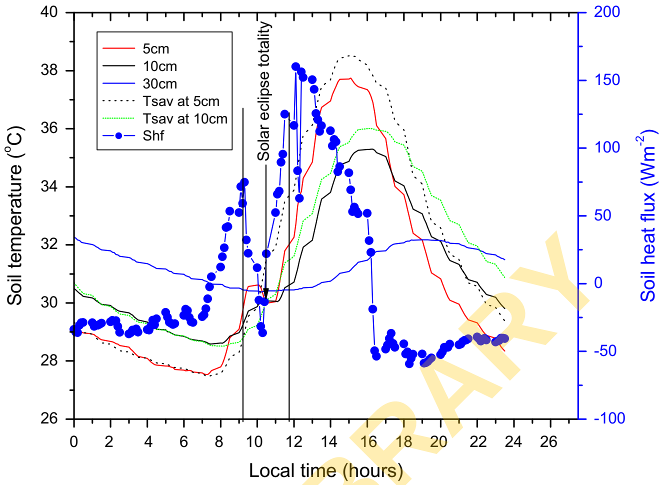

Fig. 5. Soil heat flux and soil temperature at 5, 10, and 30 cm during the eclipse event and mean values of soil temperatures at 5 cm and 10 cm on non-eclipse days. Also shown is the soil heat flux. The vertical lines show the begining and end of the eclipse event.

On the other hand, the temperature at 10 cm depth decreased from 30.12 °C when totality began to 30.04 °C at the end of toality after which it continued its normal diurnal trend. There was no significant effect at the 30 cm depth. These observations are in agreement with those during previous eclipses (Anderson, 1999; Leeds-Harrison et al., 2000; Ahrens et al., 2001; Foken et al., 2001; Fabian et al., 2001; Dolas et al., 2002; Kirshnan et al., 2004; Founda et al., 2007). These workers reported a decline in temperature at the subsurface soil. However the degree of the decline depended on whether the soil is bare or covered with vegetation and the type of vegetation, among other factors.

In order to determine the effect of the type of vegetation cover on soil temperature during an eclipse, Foken et al. (2001) measured soil temperatures at 2, 5, 10, 20 and 50 cm depths for soils covered with grass and maize during the TSE of 11 August 1999. They observed a decrease in temperature of 0.2 °C at 2 cm while at 5 cm, only the increase according to the daily cycle was interrupted by the eclipse with a time shift from the totality of about 35 and 40 min, respectively. There was no detectable influence of the solar eclipse on the temperature measurement at 10 and 20 cm. They also observed that the results for 2 cm depth under maize were similar to that at 5 cm depth under grass and no noticeable effect of the solar eclipse on the soil temperature were measured at depths deeper than 2 cm under maize. Our results showed that the usual rise in temperature at this time of the day (morning) at 5 cm was halted for about 16 min before the maximum phase of the eclipse as a result of the reduction in solar radiation input, and fell for about 41 min to reach a minimum value at eclipse maximum. It was then delayed for about 19 min before resuming its normal increase some 28 min before fourth contact (end of eclipse). Leeds-Harrison et al. (2000) reported that the normal rise in temperature in bare soil at 0.10 cm was halted for about 30 min before maximum eclipse, falling for about 1 h before resuming its normal increase 30 min before fourth contact. Anderson (1999) reported a decline in subsurface soil temperature in response to an eclipse. According to Anderson, the subsurface temperature laggs the surface temperature minimum by

24 min at a depth of 2 cm. The results at Ibadan showed that the subsurface soil temperature at 5 and 10 cm declined in response to the eclipse, lagging the surface air temperature minimum by 13 and 35 min respectively. Kirshnan et al. (2004) observed that soil temperature at depths of 20 and 40 cm were least affected by the solar eclipse of 11 August 1999 in India. At 5 cm depth, however, the subsurface soil temperature decreased significantly, but the decline became faster as the eclipse progressed and followed the air temperature at 3 m level. Dolas et al. (2002) reported that the subsurface soil temperature at 5 cm depth follows closely the changes at the surface during the day time. Unlike the observations at 20 cm and below reported above, Founda et al. (2007) observed that the diurnal course of soil temperature at 10 and 20 cm slowed down for the period between mid-eclipse and the last contact, after which it resumed its normal march.

The ground heat flux, which is the rate of heat transfer from the ground surface into the deeper soil levels (Ahrens et al., 2001), is influenced by the surface temperature, soil moisture and vegetation. It was measured at Ibadan by HFP01 heat flux sensor manufactured by Hukseflux (Delft, The Netherlands) for Campbell Scientific. It is a self calibrating (calibrating every two hours) and corrects errors due to differences in thermal conductivity between the sensor and surrounding medium, temperature variations, and slight sensor instabilities. Since temperature is highly influenced by solar eclipses, it is expected that soil heat flux will be proportionally affected. The soil heat flux at Ibadan dropped from 74.62 Wm^{-2} to -35.82 Wm^{-2} shortly before totality. It then began to rise thereafter following the normal diurnal course (Fig. 6). The soil moisture, which started to decrease immediately after the first contact, however, could not recover throughout the day (Nymphas et al., 2009). Foken et al. (2001) reported a reduction of 10 Wm^{-2} in soil heat flux at 2 cm below grass. However, Ahrens et al. (2001) could not detect any significant influence of the solar eclipse on 11 August 1999 for the soil heat flux.

3.3. *Surface energy balance*

The Earth's surface provides major energy transfer for the atmospheric processes. It is usually heated up by the downwelling shortwave irradiation from the Sun with only a part being reflected back. The energy is then transported into the soil due to ground heat flux and is stored by plants, buildings, etc (Foken, 2008). According to the law of conservation of energy, the energy balance at the Earth's surface, Q_s, is given as

$$-Q_s^* = Q_H + Q_E + Q_G + \Delta Q_s \tag{1}$$

where Q_H is the sensible heat flux which is responsible for heating the atmosphere from the surface upwards. On a typical day (devoid of strong convection) the sensible heat can heat or warm the atmosphere up to 100 m; Q_E is the latent heat flux which is the rate of moisture energy transfer per unit area from the ground surface to the atmosphere, Q_G is the ground heat flux and ΔQ_S is the energy stored by plants and ground.

The surface energy flux has been defined as the sum of the radiative, sensible and latent energy fluxes (Gross and Hense, 1999; Ahrens, et al., 2001). The radiative fluxes consists of global radiation (R_g) and net radiation (R_n). On the ground surface and from the law of energy conservation, R_n on the surface is given as the sum of the first three terms on the rhs of eq. 1 (Arya, 2001), assuming the energy stored by the plants is negligible,

$$R_n = Q_H + Q_L + Q_G \tag{2}$$

where Q_H and Q_L are the sensible and latent heat fluxes to and from the air, and Q_G is the ground heat flux. Eq. (2) describes how R_n at the surface must be balanced by a combination of the sensible and latent heat fluxes in the air and the heat flux to the surface medium. The actual magnitudes of these various components are, however, affected by several factors such as the type of surface and its characteristics (soil moisture, texture, vegetation, etc), month or season, time of the day, geographical location, weather, etc. On a typical day, $R_n > 0$ which means the surface has received radiative energy.

As stated earlier, there was a dramatic decrease in the radiative fluxes during the total solar eclipse of 29 March 2006 at Ibadan. Therefore, impacts of the TSE on the other terms of the surface energy balance equation are expected like in other eclipses (Neumann and Den Hartog, 1994; Ahrens et al., 2001). Reports on the measurement of surface energy balance during solar eclipses (partial or total) in the tropics especially the West African sub-region are very scarce. The impact of the TSE of 29 March 2006 on sensible heat and latent heat fluxes, soil heat flux, global radiation, net radiation fluxes and air temperature at 1 m above the ground at Ibadan is presented in Fig. 6. The variability seen around 9:46 LT, 11:16 LT and 13:37 LT is due to clouds covering the Sun. It will be observed that the sensible and latent heat fluxes reached peak values of 52.2 Wm^{-2} and 226.3 Wm^{-2} respectively by 9:27 LT before they were interupted by the start of the eclipse event. The sensible heat then dropped to -1.02 Wm^{-2}

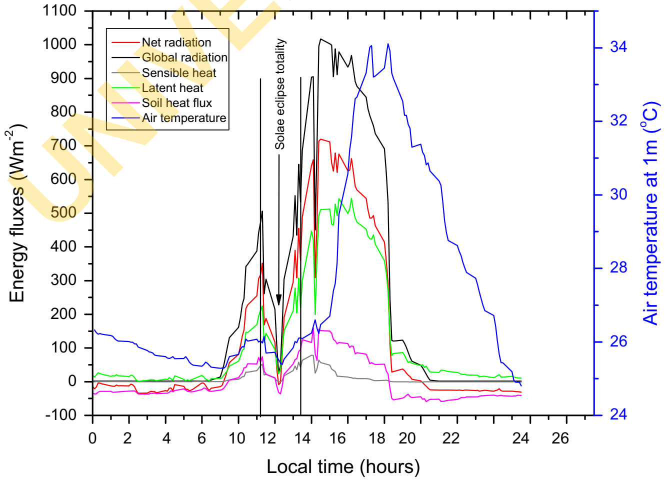

Fig. 6. Time series of the energy fluxes during the eclipse. The vertical lines show the begining and end of the eclipse event.

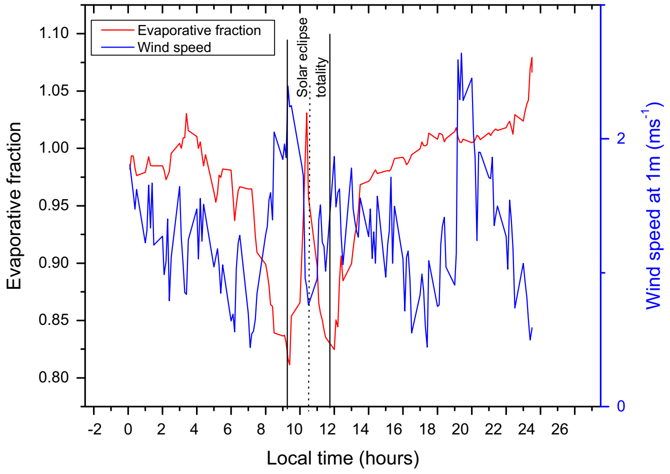

Fig. 7. The evaporative fraction during the eclipse event of 29 March 2006. The begining and end of the eclipse event is shown by the vertical lines while the doted line shows the time of solar eclipse maximum.

by 10:30 LT while the latent heat dropped by 89.7% to 23.2 Wm^{-2} at 10:20 LT. Similar effects of solar eclipse on sensible heat and raditaion fluxes have been reported by Antonia et al. (1979) and Eaton et al. (1997). According to these authors, the effect of the solar eclipse on sensible heat flux and radiation flux near the surface was so ubrupt that the atmospheric surface layer turbulence followed a continuum of equilibrium state in response to the stability changes brought about by the changes in surface heat flux. Segal et al. (1996) demonstrated that this reduction in sensible heat flux during an eclipse event delays the breakup of the surface inversion thereby giving rise to peak values in simulated sheltered temperatures.

Solar eclipses are also known to have cooling effect due to the sudden ‘cut off’ of solar insolation. The combination of light ‘switch off’ and increased humidity, together with the decrease in temperature during eclipses have an impact on forest trees (Steppe et al., 2002). In the biosphere, particularly in crops, various species respond differently to the induced changes in solar radiation. Economou et al. (2008) reported that solar eclipses greatly influence species of field crops and zoo plankton, cautioning that future climates influencing the amount of radiation that reaches the Earth’s surface may disturb the stability of ecosystems with direct impacts on crop productivity.

Table 2
Correlation of different fluxes with net radiation (R_n) in the period 8:00 to 13:00 LT (41 data points) for the eclipse day.

Parameter	Correlation coefficient
Global radiation, R_g	0.998
Sensible heat, Q_H	0.850
Latent heat, Q_E	0.982
Soil heat flux, Q_G	0.927

The high obscuration of the eclipse at Ibadan, (97.4%), gave rise to a very high evaporative cooling and a reversal in sign of the sensible heat, net radiation, soil heat flux, and a reduction in surface air tempearture during totality (Fig. 6). The cooling effect of the elipse is expressed as the evaporative fraction (EF) given as (Lohou et al., 2010),

$$EF = \frac{LE}{H+LE} \tag{3}$$

where H=sensible heat, LE=latent heat.

The cooling effect of the eclipse on 29 March 2006 as expressed by eq. (3) is shown in Fig. 7. This is not surprising since the eclipse took place in mid-morning hours of the day. Morning eclipses are known to interrupt the breakup of the surface inversion more quickly, decoupling the atmospheric surface layers from regions above and causing a larger temperature drop at screen level than would be experienced later in the diurnal cycle (Anderson, 1999). Similarly, the soil heat flux decreased from 74.62 Wm^{-2} by 9:34 LT to -35.82 Wm^{-2} during the total phase of the eclipse. There was a 95% decrease in global radiation between 9:27 LT (first contact) and 10.24 LT while the net radiation decreased from 357.13 Wm^{-2} by 9:27 LT to -11.70 Wm^{-2} by 10:17 LT. It can also be observed from Fig. 5 that the latent heat flux responds faster to the eclipse effect than the sensible heat. The latent heat reached minimum at about the same time with the net radiation 11 min before the sensible heat flux. At the total phase of the eclipse event, the effect of the eclipse on the latent heat, global radiation, sensible heat and soil heat flux are all similar to the effect on net radiation. These pronounced effects of the TSE of 29 March 2006 on the surface energy balance terms are in agreement with the results of Gross and Hense (1999) over central Europe. These authors reported peak values in surface energy flux ranging between 250 Wm^{-2} and 300 Wm^{-2} with an overshoot in amplitude ranging from

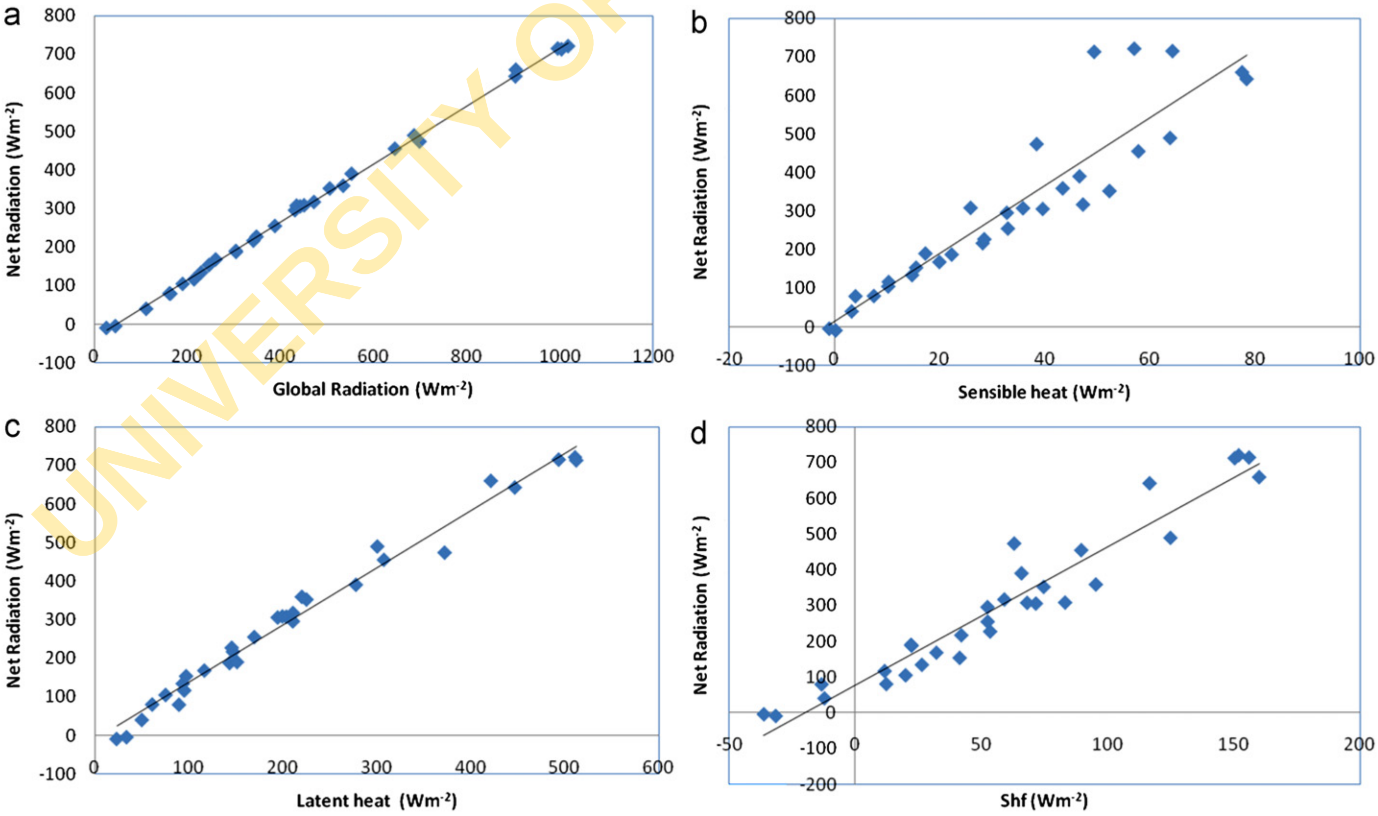

Fig. 8. (a) Correlation between net and global radiations for 41 data points (08:00–13:00 LT); (b) as in (a), but between net radiation and sensible heat fluxe; (c) as in (a), but between net radiation and latent heat flux; (d) as in (a), but between net radion and soil heat flux.

50 Wm^{-2} to 100 Wm^{-2} one hour after totality. Our results indicate that surface energy balance terms continued their normal diurnal rise after the eclipse event, reaching peak values in the early hours of the afternoon suggesting that the results of Gross and Hense (1999) may apply only to TSEs rather than partial eclipses as Kessler et al. (1979) could not observe any significant impact of the partial eclipse of 1976 on the energy balance terms.

After the total phase of the eclipse, the sensible heat, the latent heat, the soil heat flux, the global radiation and net radiation all continued to rise along the normal diurnal course. Q_H, *and* Q_E reached peaks of 77.6 Wm^{-2} by 12:10 LT, 446.8 Wm^{-2} at 12:00 LT before dropping to 25.9 Wm^{-2} 10 min later and 199.6 Wm^{-2} also 20 min after, respectively. R_n reached 659.1 Wm^{-2} at 12:10 LT before dropping to 308.7 Wm^{-2} by 12:20 LT. R_g also reached 910.2 Wm^{-2} by 12:10 LT before dropping to 454.5 Wm^{-2} 7 min later after which it raised to its diurnal maximum. Similarly, the soil heat flux dropped from 156.7 Wm^{-2} by 12:10 LT to 71.9 Wm^{-2} by 12:30 LT after which it continued its diurnal trend. The effect of the intermittent appearance of the cloud could also be clearly seen. The correlation coefficients between the different fluxes during the eclipse is shown in Table 2 while Fig. 8(a-d) show the correlations between them. It is observed that all the parameters (except sensible heat) are highly correlated with net radiation.

According to Foken et al. (2001), the variation of the sensible and latent heat fluxes was similar to the net radiation one with transition to stable conditions from 8:44 to 13:00 LT (Fig. 9). These results are also similar to those obtained during partial eclipses (Eaton et al., 1997). However, unlike the results of Foken et al. (2001), the latent heat flux follows exactly the same course with that of net radiation through out the day. There was no observed time lag between the time when each parameter started its decrease after the first contact and when they started their increase after totality. However, the sensible heat lagged the latent heat and R_n by 6 min before it started to rise after totality while global radiation lagged net radiation by 7 min. Since the eclipse occured in the morning when there was an increase in turbulence, all the heat fluxes follow their normal diurnal increases after the eclipse event, decreasing in the early afternoon, and reaching minimum at sunset.

The Bowen ratio during the eclipse event, determined by the Bowen Ratio Energy Balance method, is shown in Fig. 10. The effect of the total solar eclipse can be clearly seen from the figure. It reached the minimum value of −0.03 at the maximum phase of the eclipse.

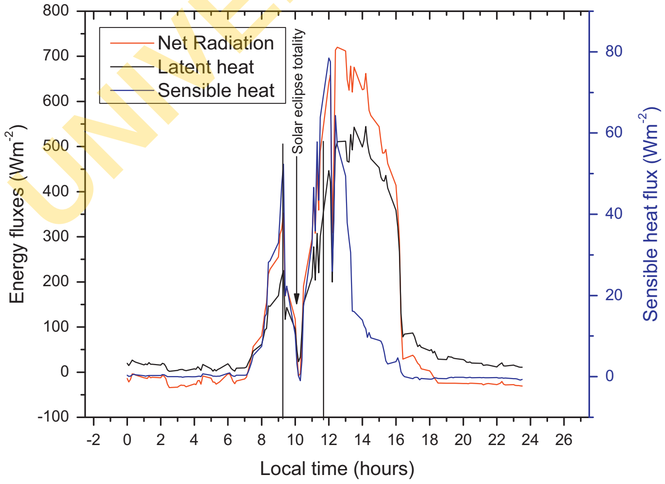

Fig. 9. Variation of the sensible and latent heat fluxes during the eclipse event. The vertical lines represents the begining and end of the eclipse.

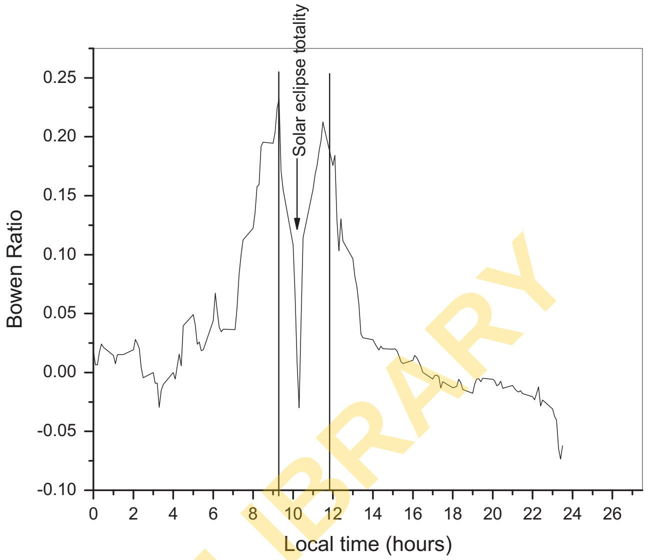

Fig. 10. Bowen Ratio of the energy fluxes on the eclipse day. Vertical lines indicate the begining and end of the eclipse event.

4. Conclusion

The impact of the TSE on 29 March 2006 on the surface energy and radiation flux components measured at Ibadan, Nigeria showed that the sensible heat, latent heat and all radiation fluxes were considerably affected by the eclipse event, begining from the first contact of the eclipse. The sensible heat reversed sign during the maximum phase of the eclipse while the latent heat decreased by 89.7%. The global radiation decreased by 95% while the net radiation and the soil heat flux also all reversed sign during the total phase of the eclipse. It was also observed that the latent heat lagged the sensible heat and net radiation by 11 min at totality. Similarly, the sensible heat and global radition lagged net radiation by 6 and 7 min respectively during the eclipse maximum.

Acknowledgement

The authors would like to thank the IPPS Sweden for the equipment donation to NARG. We also want to thank the African Regional Centre for Space and Technology Education in English (ARCSTEE), the National Aerospace Development Agency (NARSDA) of the Federal Ministry of Science and Technology, Nigeria for their support at various stages of NIMEX activities; and the University of Ibadan for the Senate Research Grant awarded to Dr E. F. Nymphas.

References

Adeniyi, J.O., Radicella, S.M., Adimula, I.A., Willoughby, A.A., Oladipo, O.A., Olawepo, O., 2007. Signature of the 29 March 2006 eclipse on the ionosphere over an equatorial station. Journal of Geophysical Research 112, A06314. doi:10.1029/2006JA012197.

Adeniyi, J.O., Oladipo, O.A., Radicella, S.M., Adimula, I.A., Olawepo, A.O., 2009. Analysis on 29 March 2006 eclipse effect on the ionosphere over Ilorin, Nigeria. Journal of Geophysical Research 114, A11303. doi:10.1029/2009JA014416.

Ahrens, D., Moses, G.I., Jaeger, L., Andreas, M., Mayer, H., 2001. Impacts of the solar eclipse of 11 August 1999 on routinely recorded meteorological and air quality data in south-west Germany. Meteorologische Zeitschrift 10 (3), 215–223.

Anderson, J., 1999. Meteorological changes during a solar eclipse. Weather 54, 207–215.

Anderson, R.C., Keefer, D.R., Myers, O.E., 1972. Atmospheric pressure and temperature changes during the 7 March 1970 solar eclipse. Journal of Atmospheric Science 29, 583–587.

Anfossi, D., Schayes, G., Goulart, A., 2004. Atmospheric turbulence decay during the solar total eclipse of 11 August, 1999. Boundary Layer Meteorol 111, 301–311.

Antonia, R.A., Chambers, A.J., Phong-Anani, D., Rajagopalan, S., Sreenivasan, K.R., 1979. Response of atmospheric surface layer turbulence to a partial solar eclipse. Journal of Geophysical Research 84 (C4), 1689–1692.

Aplin, K.L., Harrison, R.G., 2001. Meteorological effects of the eclipse of 11th August 1999 in cloudy and clear conditions. Proceedings of the Royal Society of London A, 353–371.

Arya, S.P., 2001. Intorduction to micrometeorology. Academic Press, Sen Diego.

Dolas, P., Ramchandra, R., Sengupta, K., Patil, S.M., Jadhav, P.N., 2002. Atmospheric surface – layer processes during the total solar eclipse of 11 August 1999. Boundary – layer Meteorology 104, 445–461.

Eaton, F.D., Hines, J.R., Hatch, W.H., Cionco, R.M., Byers, J., Gravey, D., 1997. Solar eclipse effects observed in the planetary boundary layer over a desert. Boundary-Layer Meteorology 83, 331–346.

Economou, G., Christou, E.D., Giannakourou, A., Geasopoulos, E., Georgopoulo, D., Kotoulas, V., Lyra, D., Tsakalis, N., Tziortzou, M., Vahamidis, P., Papathanassiou, E., Karamanos, A., 2008. Eclipse effects on field crops and marine zooplankton: the 29 March, 2006 total solar eclipse. Atmospheric Chemistry and Physics Discussions 8, 1291–1320.

Emde, C., Mayer, B., 2007. Simulation of solar radiation during a total eclipse: a challenge for radiative transfer. Atmospheric Chemistry and Physics 7, 2259–2270.

Espenak, F., Anderson, J., 2006. NASA Technical Publication “Total solar eclipse of 2006 March 29” (NASA/TP-2004-212762).

Fabian, P., Benhard, R., Andreas, S., Werner, H., Martins, W., Hans, S., Koepke, P., Reuder, J., Wolfram, B., 2001. Boundary layer photochemistry during a total solar eclipse. Meteorologische Zeitschrift 10 (3), 187–192.

Fernendez, W., Hidalgo, H., Coronel, G., Morales, E., 1996. Changes in meteorological variables in Coronel Oviedo, Paraguay, during the total solar eclipse of 3 November, 1994. Earth, Moon, and Planets 74, 49–59.

Foken, T., 2008. Micrometeorology. Springer-Verlag, Berlin Heidelberg, pp. 1–23.

Foken, T., Bodo, W., Klemn, O., Gerchan, J., Martin, W., Tamas, W., 2001. Micrometeorological measurements during the total solar eclipse of August 11, 1999. Meteorologische Zeitschrift 10 (3), 171–178.

Founda, D., Melas, D., Lykoudis, S., Lisaridis, I., Gerasopoulos, E., Kouvarakis, G., Petrakis, M., Zerefos, C., 2007. The effect of the total solar eclipse of 29 March 2006 on meteorological variables in Greece. Atmospheric Chemistry and Physics Discussions 7, 10631–10667.

Gerasopoulos, E., Zerefos, C.S., Tsagouri, I., Founda, D., Amiridis, V., Bais, A.F., Belehaki, A., Christou, N., Economou, G., Kanakidon, M., Karamanos, A., Petrakis, M., Zanis, P., 2007. The total solar eclipse of March 2006: Overview. Atmospheric Chemistry and Physics 8, 5205–5220.

Goutorbe, J.P., Lebel, T., Tinga, A., Bessemoullin, P., Brouwer, J., Dolman, A.J., Engman, E.T., Gash, J.H.C., Hoeppfner, M., Kabat, P., Kerr, Y., Monteny, B., Prince, S., Said, F., Sellers, P., Wallace, J.S., 1994. HAPEX-Sahel: a large scale study of land-atmosphere interactions in the semi-arid tropics. Annales Geophysicae 12, 53–64.

Gross, P., Hense, A., 1999. Effects of a total solar eclipse on the mesoscale atmospheric circulation over Europe—a model experiment. Meteorology and Atmospheric Physics 71, 229–242.

Jegede, O.O., Mauder, M., Okogbue, E.C., Foken, T., Balogun, E.E., Adedokun, J.A., Oladiran, E.O., Omotosho, J.A., Balogun, A.A., Oladosu, O.R., Sunmonu, L.A., Ayoola, M.A., Aregbesola, T.O., Ogolo, E.O., Nymphas, E.F., Adeniyi, M.O., Olatona, G.I., Ladipo, K.O., Ohamobi, S.I., Gbobaniyi, E.O., Akinlade, G.O., 2004. The Nigeria micrometeorological experiment (NIMEX-1). An overview. Ife Journal of Science 6 (2), 191–202.

Kazadzis, S., Bais, A., Blumthaler, M., Webb, A., Kouremeti, N., Kift, R., Schallhart, B., Kazantzidis, A., 2007. Effects of the total solar eclipse of 29 March 2006 on surface radiation. Atmospheric Chemistry and Physics 7, 5775–5783.

Kazantzidis, A., Bais, A.F., Emde, C., Kazadzis, S., Zerefos, C.S., 2007. Attenuation of global ultraviolet and visible irradiance over Greece during the total solar eclipse of 29 march 2006. Atmospheric Chemistry and Physics 7, 5959–5969.

Kessler, A., Jaeger, L., Schott, R., 1979. Die Auswikungen der Sonnenfinsternis vom 29 April 1976 auf die Energieflüsse an der Erdoberfläche. Meteorol. Rdsch 32, 109–115.

Kirshnan, P., Kunhikirshnan, P.K., Muraleeddharan Nair, S., Ravindran, S., Ramachandran, R., Subrahamanyam, D.B., Ramana, M.V., 2004. Observations of atmospheric surface layer parameters over a semi arid region during the solar eclipse of August 11th, 1999. Proceedings of the Indian Academy of Sciences 113 (3), 353–363.

Kolev, N., Tatarov, B., Grigorieva, V., Donev, E., Simenonov, P., Umlensky, V., Kaprielov, B., Kolev, I., 2005. Aerosol Lidar and in situ ozone observations of the planetary boundary layer over Bulgaria during the solar eclipse of 11 August 1999. International Journal of Remote Sensing 26, 3567–3584.

Kunhikrishnan, P.K., Krishnanmurphy, B.V., 1982. Atmospheric pressure perturbations during total solar eclipse on 16 February 1980. Proceedings of the Indian National Science Academy 48A, 238–253. Supplement no. 33.

Kumar, S.S., Rengaiyan, R., 2011. Influence of solar eclipse on sea water. Natural Science 3 (1), 69–74.

Leeds-Harrison, P., Youngs, E.G., Blackburn, D.W.K., 2000. Soil temperatures during the total solar eclipse on 11 August 1999. European Journal of Soil Science 51, 183–184.

Lohou, F., Said, Frederique, Durand, Marie Lothon.Pierre, Serca, Dominique, 2010. Impact of boundary-layer processes on near-surface turbulence within the West African Monsoon. Boundary-Layer Meteorology 136, 1–23.

Mauder, M., Jegede, O.O., Okogbue, E.C., Wimmer, F., Foken, T., 2007. Surface energy balance measurement at a tropical site in West Africa during the transition from dry to wet season. Journal of Theoretical and Applied Climatology 89, 171–183.

Neumann, H.H. and G. Den Hartog (1994). Changes in the eddy fluxes of heat, latent heat, carbon dioxide and ozone over a vineyard during a partial solar eclipse. In: Proceedings of the 21st Conference on Agricultural and Forest Meteorology, San Diego, American Meteorological Society, Boston, MA, USA, pp. 60–63.

Nymphas, E.F., Adeniyi, M.O., Ayoola, M.A., Oladiran, E.O., 2009. Micrometeorological measurement in Nigeria during the total solar eclipse of 29 March 2006. Journal of Atmospheric and Solar–Terrestrial Phyics 71, 1245–1253.

Prakash, M.Dolas, Ramchandran, Radhika, Sengupta, K., Patil, S.M., Jadhav, P.N., 2002. Atmospheric surface-layer processes during the total solar eclipse of 11 August 1999. Boundary-layer Meteorology 104, 445–461.

Psiloglou, B.E., Kambezidis, H.D., 2007. Performance of the meteorological radiation model during the solar eclipse of 29 March 2006. Atmospheric Chemistry and Physics 7 (23), 6047–6059.

Pruitt, W.O., Lourence, F., Grawford, T.V., 1965. Radiation and energy balance changes during the eclipse of 20 July 1963. J. Appl. Meteorol. 4, 272–278.

Segal, M., Turner, R.W., Prusa, J., Bitzer, R.J., Finley, S.V., 1996. Solar eclipse effect on shelter air temperature. Bulletin of the American Meteorological Society 77 (1), 89–99.

Steppe, K., Lemeur, R., Samson, R., 2002. Sap flow dynamics of a beech tree during the solar eclipse of 11 August 1999. Agricultural and Forest Meteorology 112 (3-4), 139–149.

Stoeva, A., Stoeva, P., Valev, D., Kishkinova, N., Tasheva, T., 2005. Dynamics of the microlimatic parameters of the ground atmospheric layer during the solar eclipse of August 11, 1999. Geophysican Research Abstracts 7, 10209.

Tzanis, C., Varotsos, C., Viras, L., 2007. Impacts of solar eclipse of 29 March 2006 on the surface ozone and nitrogen dioxide concentration at Athens, Greece. Atmospheric Chemistry and Physics Discussions 7, 14331–14349.

Verhoef, A., Allen, S.J., LLyod, C.R., 1999. Seasonal variation of surface energy balance over two Sahellian surfaces. International Journal of Climatology 19, 1267–1277.

Winkler, P., Kaminski, U., Köhler, U., Reidl, J., Schroers, H., Anwender, D., 2001. Development of meteorological parameters and total ozone during the total solar eclipse of Agust 11, 1999. Meteorologische Zeitschrift 10 (3), 193–199.

Wallace, J.S., Allen, S.J., Culf, A.D., Dolman, A.J., Gash, J.H.C., Holwill, C.J., Llyold, C.R., Stewart, J.B., Wright, I.R., 1992. SEBEX: The Sahelian Energy Balance Experiment. Final Report on ODA project T06050C1, ODA-Report 92/9.