Total Solar Eclipses and Atmospheric Boundary Layer Response

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Abstract. The effect of three total solar eclipses on meteorological parameters is discussed in the paper. Measurements were conducted at the village of Ravnets,General Toshevo municipality, Bulgaria, 1999,in Manavgat, near Antalya, Turkey, 2006 and in TianHuangPing, China, 2009.

The observed decrease of the sky illumination (incoming solar radiation) during the eclipses was proportional to the percentage of solar coverage. The after eclipse sky illumination level is due to the effect of the natural change of the solar elevation angle. For the 1999 TSE it did not regain its pre eclipse value, it has exactly the same value for the 2006 TSE, and, It is three times larger than the pre eclipse value for the 2009 TSE. This fact can be easily explained by the Local Time of the maximum of the eclipses: LT 13:12, LT 12:58, and LT 09:34, respectively.

Measurements showed significant changes in the surface air temperature. The minimum of the air temperature during the 2009 TSE (Tmin=4.5°C) was measured 6 min after the end of the total phase. This minimal temperature drop and larger time lag can be explained with the huge artificial lake near the place of observation, which minimizes the temperature response due to its larger heat capacity.

During the 1999 TSE, minimal temperature (Tmin=6.4°C) is measured 7 min 30 s after the total phase, and for the 2006 TSE (Tmin=5°C) - 5 min. It is in accordance with the fact that the temperature minima at residential/commercial stations occurred in general, before the minima at stations in agricultural terrains. In 2006 we were at the yard of the hotel, and in 1999 in the countryside.

The wind velocity drops during the total phase as a result of the cooling and stabilization of the atmospheric boundary layer. The wind direction during the total phase changes and the wind begins to blow in the same direction as the direction of motion of the lunar shadow on the earth.

Cirrus and cirrostratus clouds were observed during the 2006 total solar eclipse. Cloud structures in the form of narrow concentric arcs, equally detached from one another were observed for 20 minutes, after the beginning of the maximum phase of the 1999 TSE.

Keywords:

Introduction

It is well known that the short-wavelength solar radiation in the troposphere is absorbed by the ground or water surface and distributes towards the higher layers through long-wavelength radiation and convective transference. During a significant reduction or cutting of the solar radiation around dusk (full cloudiness, solar eclipse etc.), cooling of the troposphere is most intensive in the nearest to the Earth's surface layers (Herman and Goldberg, 1981).

Meteorological observations during a total solar eclipse (TSE) give the possibility of examining changes in the physical state of the Surface Boundary Layer in conditions of reduced solar radiation. Solar eclipses are of a great interest because they resemble short time controlled experiments.

Climate of the Surface Boundary Layer during a total solar eclipse is determined by the heat and water balance in the air volume displaced in the cone of the Moon's shadow. Wind velocity and direction and turbulent exchange connected with them are of great importance.

The pattern and amplitude of the temperature drop is different for each location and can vary from less than one to several degrees depending on many factors. The percentage of sun coverage, the latitude, the season and time of the day, the synoptic conditions, the height of measurements, the climatic and other local features (e.g. topography, vegetation, soil conductivity) account for the different patterns of the temperature fluctuations during a solar eclipse. The time lag between the occurrence of the temperature minimum and the totality (or aximum partiality) is a result of the thermal inertia of the air and the ground, in a similar way that the diurnal temperature maximum on a clear day does not coincide with the zenith of the sun but occurs some hours later (Fernandez et al., 1993).

Recent observations, indicate a deceleration of the mean wind flow during a solar eclipse and this is attributed to the combined effect of the decrease of the thermal gradient, the stabilization of surface layer following the drop of temperature and the suppression of turbulent processes, in a similar way that wind speed decreases after sunset.

Despite the large number of investigations concerning eclipses, the event of a solar eclipse is always unique since it happens at different seasons, different time of the day, different locations and under different synoptic conditions. Founda et al. (2007) investigate in details the effect of the total solar eclipse of 29 March 2006 on meteorological variables across Greece.

Studying the effects of the eclipse on surface boundary layer meteorological parameters, field experiments were conducted at Ravnets, General Toshevo municipality, Bulgaria, 1999, Manavgat, near Antalya, Turkey, 2006, and TianHuangPing, China, 2009 (Stoev et al., 2005, 2008; Stoeva et al., 2009).

Sites and Conditions of Observation

Microclimatological measurements, during the total solar eclipse (TSE) on August 11, 1999 were conducted in the village of Ravnets, General Toshevo municipality, Bulgaria (φ=43°41.7′ N, λ =28°11.5′ E). The site is near the central line of the totality band. The beginning of the eclipse (first contact) was at 09:45 UT, the beginning of the full phase (second contact) - at 11:10 UT, the end of the full phase (third contact) – at 11:12 UT and the end of the eclipse (fourth contact) was at 12:32 UT. The local conditions were excellent for conducting measurements as the day was sunny, hot and dry and the sky was cloudless. The wind was light and the synoptic conditions were steady, with absence of noticeable advection.

We observed the TSE on March 29, 2006 and conducted our experiments from Manavgat, near Antalya, together with our colleagues from Kandilli Observatory, Istambul, because it is one of the sunniest places in Turkey – the percent of possible sunshine is 60%. Full phase of the eclipse begins at 10h 55min 57s 10:56 UT and its full duration is 3 min 46 s (Espenak and Anderson, 2004).

The observations of the July 22, 2009 total solar eclipse were conducted near the town of TianHuangPing, China, close to the central line of the eclipse. Co-ordinates of the site – near the upper reservoir of the Pumped Storage Power Station - are as follows: φ = 30°28′14.2″ N, λ = 119°35′29.0″ E, Alt. = 909m.

The Tianhuangping Power Station is the biggest of its type in Asia. It is located in Anji County in Zhejiang, about 175km from Shanghai and lies in a green bamboo forest regarded as one of the main bamboo production bases in China.

Table 1. Information on the sites of observation of the three total solar eclipses.

Location	Latitude	Longitude	Alt, m	Total Phase UTC
Ravnets Bulgaria 11.08. 1999	43°41.7′N	28°11.5′E	200	11:12
Manavgat, Turkey, March 29, 2006	35°45′27.59″ N	31°27′14.11″E	2	10:58
TianHuangPing, China, July 22, 2009	30°28′14.2″N	119°35′29.0″E	900	03:34

These three total solar eclipses are observed at middle latitudes, at altitude of 200m, at the sea level, and 900m. All of them are during the summer. The 1999 TSE is just before the maximum of the 23rd Solar cycle, the 2006 TSE is in minimum - on the falling branch of the 23rd solar activity cycle. The 2009 TSE is also in minimum but on the rising branch of the 24th solar cycle, at a very low solar activity

Observations and measurements

Variations of the sky zenith illumination during the eclipses were measured with the help of luxmeters LUX-PU-150.

During the 1999 total solar eclipse mercury thermometers with accuracy of 0.1°C, barometers with accuracy of 1 hPa, Asman's aspiratory psychrometers with accuracy of 1% and cup anemometer with accuracy of 0.1m/s were used. The air temperature was measured at four altitudes : 0.1m, 0.5m, 1m and 2m above the Earth's surface. The soil temperature was measured up to 10 cm in depth. The air humidity and pressure were measured at a height of 1.5 m and the wind velocity - at a height of 2 m.

Data from the automatic meteorological stations of the Bulgarian Ministry of Environment and Waters in the towns of Stara Zagora, Kazanluk, Samuil and Emine cape have been used for comparison. All the standards needed for conducting meteorological measurements have been taken into account.

During the 2006 and 2009 total solar eclipses, temperature were measured with high resolution at three levels - 10 cm, 50cm and 200cm, and in the 10 m air layer, respectively. In addition, in 2009, temperature in the 10 cm soil layer was also measured. Temperature was measured with high speed electric thermometers with an automatic registration.

Analyses and results

Illumination

The sky illumination during the 1999 eclipse reaches its first significant decreasing around UTC 10:02, 17 minutes after the first contact and reached a minimum at UTC 11:12 (maximum of the eclipse) (Stoev et al., 2002a).

In general, the observed decrease of the sky illumination (incoming solar radiation) during the eclipse was proportional to the percentage of solar coverage.

The graph for the 2006 TSE (it is together with the temperature, Fig.4) shows that the first significant decreasing occurred around UTC 10:25, that is to say 47 minutes after the first contact and reached a minimum at maximum eclipse (UTC 10:58). After that, rapid recovery of the illumination levels could be seen.

Decreasing of the sky illumination was generally gradual in the early stages of the 2009 TSE following the first contact, but was rapid around totality. The first significant decreasing occurred around LT 09:00, 40 minutes after the first contact and reached a minimum at LT 09:34 (maximum of the eclipse). Recovery of illumination levels was then rapid.

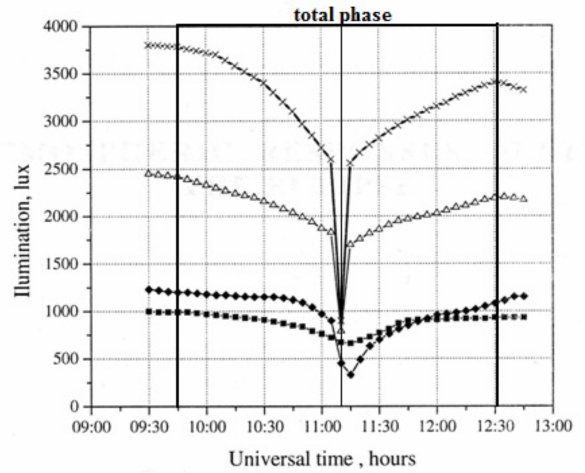


Fig. 1. Variations of the sky illumination during the 1999 TSE in four areas:

■ - the horizon illumination, ◆ - the zenith illumination, △ - around the sun illumination and X - the solar disk illumination during the eclipse.

Illumination, Lux

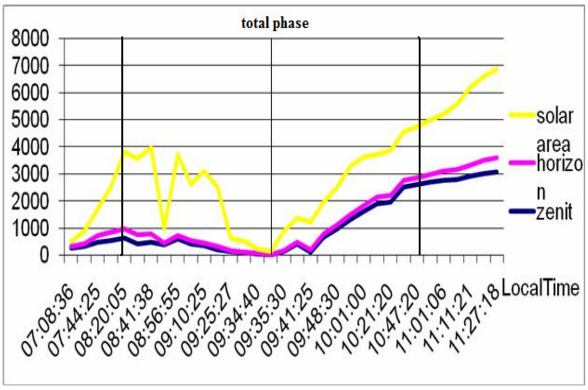


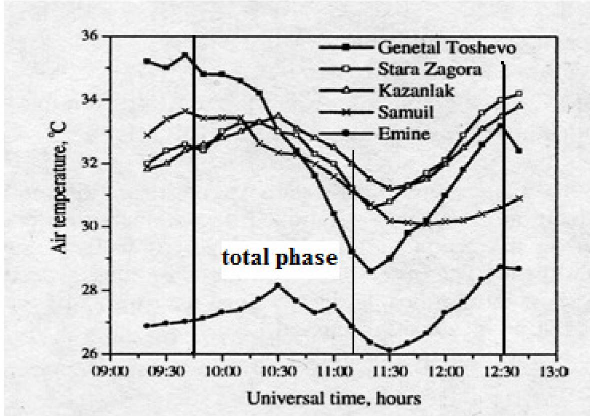
Fig. 2. Dynamics of the sky illumination during the July 22, 2009 total solar eclipse

The illumination started to increase again after the 3rd contact (end of the total phase) and reached value three times larger its pre-eclipse value by the end of the eclipse (4th contact). We see smaller or larger minima in the course of the illumination of the solar area due to the clouds.

The after eclipse sky illumination level is due to the effect of the natural change of the solar elevation angle. We see that it did not regain its pre eclipse value for the 1999 TSE, it has exactly the same value for the 2006 TSE, and it is three times larger than the pre eclipse value for the 2009 TSE. This fact can be easily explained by the Local Time of the maximum of the eclipses: LT 13:12, LT 12:58, and LT 09:34respectively.

Air temperature

The change of the Surface Boundary Layer temperature at 2 m above the ground level during the 1999 TSE is shown on Fig. 5. The minimum temperature, t°min = 28.6°C, was measured 7min 30sec after the total phase (Stoev et al., 2002b). A dramatic reduction of the air temperature was also observed at other sites - meteorological stations, within the Bulgaria domain, which is proportional to the percentage of the sun obscuration – Stara Zagora, Kazanluk, Samuil and Emine.



Local Time, hh:mm

Fig. 3. Dynamics of the sky illumination during the July 22, 2009 total solar eclipse

The fall of the temperature during the March 29, 2006 eclipse was clearly expressed (Stoev et al., 2008). Temperatures started to fall from 21°C shortly after the first contact and reached a minimum of 16°C five minutes after the end of totality or maximum eclipse (UT=10:58). The difference in temperature changes at different heights before, during and after the total phase was in the interval 16°C – 16.5°C. The recovery of temperature was then quite rapid with pre-eclipse values reached at 11:45.

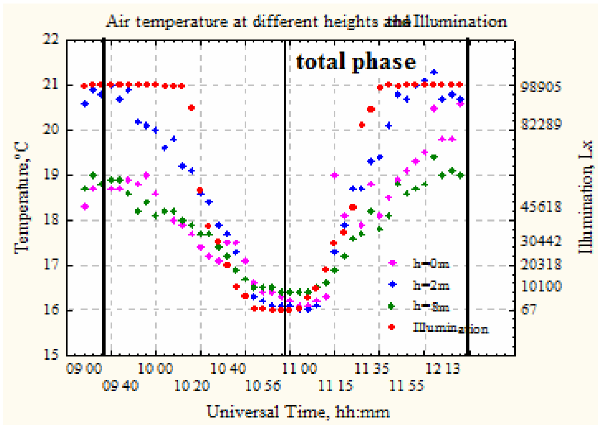


Fig. 4. Dynamics of the temperature and illumination during the total Solar eclipse on March 29, 2006.

The difference in temperature changes at TianHuangPing, China at different heights before, during and after the total phase was about 10°C. At 2m above the ground level temperature dropped with 4.5°C. Minimum of the air temperature during the TSE was measured 6 min (LT 09:40) after the end of the total phase (LT 09:34) (Stoeva et al., 2009).

The response of the soil temperature was another interesting feature of the eclipse effect. The temporal variation of the soil temperature at 10 cm depth in TianHuangPing is shown. It remains one and the same for 65 minutes – 4 minutes before the mid eclipse and

61 min after the total phase, after which it continues to enhance

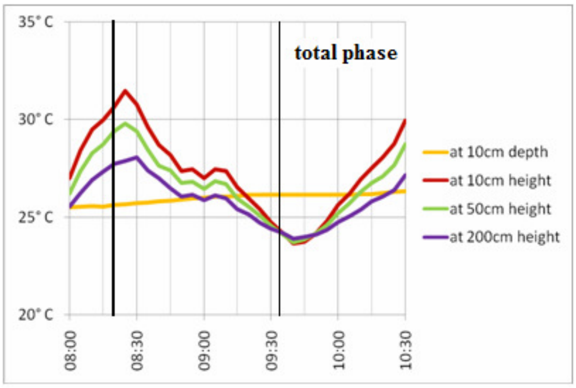


Fig. 5. Dynamics of the temperature during the July 22, 2009 TSE, China

Table 2. Surface air temperature drop at various sites and the time lags from mid-eclipse

Site of the eclipse - measurement height above ground level	Temperature drop (°C)	Time lag from Total Phase (min)
TianHuangPing (2.0 m) China 2009	4.5	6m 00s
Manavgat (2.0 m) Turkey 2006	5.0	5m 00s
Ravnets (2.0 m) Bulgaria 1999	6.4	7m 30s

Table 2 includes the temperature drop and the time lag of the temperature response with respect to the mideclipse for all the sites.

Strictly speaking, a comparison between microclimatic parameters during different eclipses cannot be done because of the substantial difference between the local relief, altitude, the albedo of the specific land type, geographic position and moment of the total phase. Variations in thermal response are more closely related to the albedo of the particular land type than to other factors. When typical albedo differences are not significant between two lands characteristics other than albedo (turbulence and wind direction) are most likely controlling the timing of the temperature minima. Temperature starts to drop several minutes after the first contact. The actual time lag is related to the thermal inertia of the surface layer (Aplin and Harrison, 2002) although it is also subject to the prevailing conditions (e.g. cloudiness, wind etc) effect.

It is worth to note that the subjective feeling of cooling during the eclipses was much stronger. This is related to the delay of the human nervous system to react to sudden temperature changes resulting to a destabilization of the thermal energy balance of the body for some time (Fernandez et al., 1993), but also to a pronounced wind chill effect due to the sudden increase of the wind speed.

During the 1999 TSE, minimal temperature (Tmin=6.4°C) is measured 7 min 30 s after the total phase, and for the 2006 TSE (Tmin=5°C) - 5 min. It is in accordance with the fact that the temperature minima at residential/commercial stations occurred in general, before the minima at stations in agricultural terrains. In 2006 we were at the yard of the hotel, and in 1999 in the countryside.

The minimum of the air temperature during the 2009 TSE (Tmin=4.5°C) was measured 6 min after the end of the total phase. It is the minimal value observed. It was also expected that temperature will faster reach its minimum because of the smaller difference between the day and night temperature at high altitudes (TianHuangPing is at 900 m asl). This minimal temperature drop and larger time lag can be explained with the observational place, which was near the upper reservoir of the Pumped Storage Power Station at Tianhuangping, China. It is a huge artificial lake on the top of the mountain, which minimizes the temperature response due to its larger heat capacity.

Winds and clouds

The wind velocity drops during the total phase and after that increases again. The wind direction during the total phase changes and the wind begins to blow in the same direction as the direction of motion of the lunar shadow on the earth (Fig. 6).

Clouds appear as a result of the disturbed meteorological conditions. The supersonic motion of the Moon's shadow causes an impact wave in the atmosphere and decrease of the temperature what is the reason of relative humidity increase and creation of conditions for condensation and cloud formation.

The direction, in which the cloud structures are observed coincides with the direction of the Moon's shadow movement.

Cloud structures during the 2009 TSE was not observed because of the quiet and cloudy weather on July, 22.

Cirrus and cirrostratus clouds were observed during the 2006 total solar eclipse.

Cloud structures in the form of narrow concentric arcs, equally detached from one another were observed after the beginning of the maximum phase of the 1999 TSE. They were observed low above the horizon for 20 minutes and after that quickly dispersed.

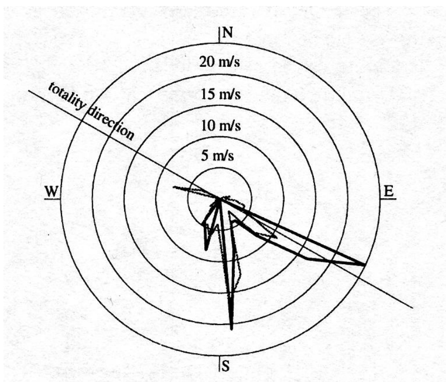


Fig. 6. Polar diagram of the wind velocity, estimated for the whole day of August 11, 1999 and during the time interval between the first and the fourth contact

Concluding remarks

Meteorological observations during the total solar eclipses in 2009, 2006 and 1999 showed a strong eclipse-induced response on all measured variables.

A dramatic decrease of the sky illumination (incoming solar radiation), proportional to the percentage of the sun obscuration was observed during all the eclipses. The after eclipse sky illumination level is due to the effect of the natural change of the solar elevation angle.

The magnitude of surface air temperature decrease and time lag were determined by a combination of several factors such as the surrounding environment and local cloudiness. A less pronounced temperature drop is mainly due to the influence of water surface – lake or sea, which confined the effect of the eclipse. Surface air temperature drop ranged from 4.5°C (TianHungPing) to 6.4°C (Ravnets) and the time lag – from 5 min (sea coast) to 7min 30 sec (countryside).

A decrease in surface wind speed was observed at all sites as eclipse progressed towards maximum phase. Cirrus and cirrostratus clouds were observed during the 2006 total solar eclipse and cloud structures in the form of narrow concentric arcs, were observed for 20 minutes, after the beginning of the maximum phase of the 1999 eclipse.

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