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Article

Impacts of the solar eclipse of 11 August 1999 on routinely recorded meteorological and air quality data in south-west Germany

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Abstract

The total solar eclipse of 11 August 1999 over Central Europe was also visible in Baden-Wuerttemberg, a state in south-west Germany. To investigate the impact of the total solar eclipse on the lower planetary boundary layer, meteorological and air quality data extracted from routine measurements at six sites in Baden-Wuerttemberg were examined. The meteorological data were recorded at the Plittersdorf meteorological station (in the path of totality of the total solar eclipse) and at the Forestmeteorological Site Hartheim (outside the path of totality of the total solar eclipse). The air quality data were obtained from four official air quality monitoring stations located at Freudenstadt, Karlsruhe-West, Rastatt and Welzheimer Wald, all of which lie within the path of totality of the total solar eclipse. Due to cloudiness, weather conditions on 11 August 1999 were not optimal in south-west Germany. However, the transient reduction (followed by a rise) induced by the total solar eclipse on meteorological variables including global solar radiation, upward longwave radiation, net radiation, air temperature, horizontal wind speed, elevation angle of the three-dimensional wind vector as well as turbulent sensible and latent heat fluxes was quite obvious. Despite unfavourable weather conditions, half-hourly mean values of ozone routinely measured at the above-mentioned standard official air quality monitoring stations showed a varying decline up to 27% at the urban station Rastatt and 37% at the background station Welzheimer Wald. This decline was owing mainly to the fall in global radiation during the total solar eclipse. However, additional influences by advection and deposition can not be precluded.

Zusammenfassung

Die totale Sonnenfinsternis am 11. August 1999 über Mitteleuropa konnte auch im Südwesten von Deutschland im Bundesland Baden-Württemberg beobachtet werden. Ihre Auswirkung auf die untere planetare Grenzschicht wurde über Daten untersucht, die routinemäßig an der meteorologischen Station Plittersdorf in der Kernzone der Sonnenfinsternis und an der Forstmeteorologischen Messstelle Hartheim außerhalb der Kernzone der Sonnenfinsternis sowie an den vier amtlichen Luftmessstationen Freudenstadt, Karlsruhe-West, Rastatt und Welzheimer Wald innerhalb der Kernzone der Sonnenfinsternis erhoben werden. Obwohl am 11. August 1999 in Südwestdeutschland kein Strahlungswetter herrschte, ließen sich als Folge der Sonnenfinsternis die Abnahme und anschließende Zunahme von Globalstrahlung, langwelliger Ausstrahlung der Erdoberfläche, Strahlungsbilanz, Lufttemperatur, horizontaler Windgeschwindigkeit, Elevationswinkel des dreidimensionalen Windvektors sowie turbulenter Ströme fühlbarer und latenter Wärme erkennen. Trotz ungünstiger Wetterverhältnisse zeigte sich auch bei den Halbstundenmittelwerten von Ozon, die an amtlichen Luftqualitätsmessstellen in der Kernzone der Sonnenfinsternis in Baden-Württemberg routinemäßig gemessen werden, häufig eine Reduktion. Sie betrug an der Stadtstation Rastatt bis zu ca. 27% und an der Hintergrundstation Welzheimer Wald bis zu 37%. Ausschlaggebend dafür war die temporäre Abnahme der Globalstrahlung durch die Sonnenfinsternis; zusätzliche Advektions- und Depositionseinflüsse können jedoch nicht ausgeschlossen werden.

1 Introduction

On 11 August 1999, the last total solar eclipse of the 20th century occurred over Central Europe (ESPENAK and ANDERSON, 1997; ANDERSON, 1999). Although solar eclipses are astronomical events, they nevertheless provide unique opportunities for investigating various phenomena in the atmospheric environment when the incoming solar radiation suddenly dwindles and later surges. Consequently, different studies on light phenomena, changes of meteorological parameters and ozone in different layers of the atmosphere as well as reactions of animals and plants have been carried out dur-

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ing periods of partial and total solar eclipses in the past (e.g. SCHMEIDLER, 1967; BOJKOV, 1968; ANDERSON et al., 1972; QUIROZ and HENRY, 1973; ANDERSON and KEEFER, 1975; KESSLER et al., 1979; SEGAL et al., 1996; CHAKRABARTY et al., 1997; EATON et al., 1997; ANDERSON, 1999; GROSS and HENSE, 1999). To investigate the impact of solar eclipses on the atmospheric environment, different methods could be used including numerical modelling, special short-term measuring campaigns as well as analysis of solar eclipse-phenomenal data retrieved from routinely running meteorological and air pollution monitoring stations at the ground level. The third option was adopted in this study, which deals with the statistical analysis of data from two meteorological sites in a rural landscape as well as three urban and one rural official air quality monitoring sites in south-west Germany. The objective of this study is to determine the impact of a total solar eclipse, occurring only seven weeks after the summer solstice and near local noon, on meteorological and air quality variables that are routinely measured close to the base of the planetary boundary layer.

2 Sites

The two rural meteorological stations considered in this investigation are Plittersdorf meteorological station and Forestmeteorological Site Hartheim. The former is operated by the State Institute for Environmental Protection Baden-Wuerttemberg, while the latter is run by the Meteorological Institute, University of Freiburg. Plittersdorf (48°N, 8°E, 111 m a.s.l., Rhine kilometre 340) is located on the right hand bank of the Rhine river. As shown in Fig. 1, the site lies only 5 km south of the central line of the zone of totality (the core shadow in which the sun is 100% obscured). Westward, the station is situated approximately 30 m away from the river. Here, the Rhine river has a width of about 250 m and further extends to 300 m with its bank strips. The Plittersdorf station, which also lies approximately 100 m eastward to a riparian forest, was particularly set up (MAYER and AHRENS, 1997) to investigate the microclimate of flooded riparian plains within the scientific framework of REKLIP (Regio Klima Projekt). The meteorological parameters continuously measured on this site, at 2.5 m above a very moist, ecological flood meadow between the river bank and the riparian forest, include air temperature (measured with ventilated platinum resistance thermometer), air humidity (measured with LiCl humidity sensor), global radiation and shortwave reflected radiation (measured with CM 11 pyranometer from Kipp & Zonen), net radiation (measured with a net radiometer after SCHULZE) and UV radiation (measured with TUVR sensor from Eppley, i.e. sum of UV-A and UV-B). Three-dimensional wind speed at the top of a nearby 17 m tower was measured by means of a u,v,w-propeller anemometer. Disturbances of the wind field by the high riparian forest poplar stand of approximately 2 m, located approximately 100 m east of the site, were minimal but could not be completely excluded. Data recording was done on a computer located in a container close to the wind tower. Measurements at this site are usually carried out at 2 seconds interval and then averaged over 30 minutes. However, on the solar eclipse day, averaging period was reduced to 1 minute between 10:00 and 13:00 CET.

On 11 August 1999 the soil surface at the Plittersdorf site was still very humid after an intermittent flooding which lasted for some weeks. The surface was hence densely covered with fresh wild grass of about 50 cm height. The obscuring of the sun by the moon commenced at 10:12 CET at the Plittersdorf site and ended at 12:55 CET, with the total solar eclipse been observed between 11:32 and 11:34 CET.

The measurements taken at the Plittersdorf site on 11 August 1999 afforded comparison with those obtained at the Forestmeteorological Site Hartheim (MAYER et al., 2000) which is operated by the Meteorological Institute, University of Freiburg. The Hartheim site (47°56'N, 7°36' E, 201 m a.s.l.) is located at about 120 km south of Plittersdorf. It is situated in the middle of an extended Scots pine forest (*Pinus sylvestris*) at a distance of approximately 1 km to the river Rhine. Mean stand height *h* at the forest is presently about 14 m. Results accruing from long-term radiation measurements at the Hartheim site constitute the basis for a comparative analysis of the radiation data taken on 11 August 1999. The maximum obscuration of the solar disc over the Forestmeteorological Site Hartheim on 11 August 1999 amounted to 98.8%. The distance to the southern edge of the zone of totality was about 64 km (Fig. 1). Similar to the Plit-

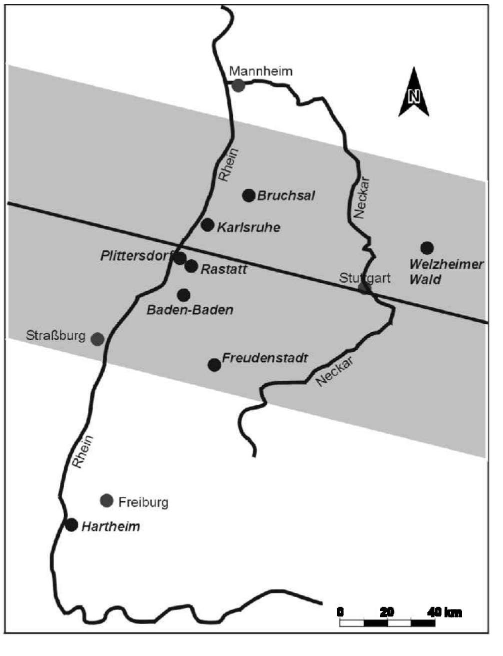

Figure 1: Mid-eclipse and zone of totality of the solar eclipse of 11 August 1999 in south-west Germany.

tersdorf site, the averaging period of measured meteorological variables was adjusted to 1 minute during the solar eclipse period.

In order to investigate possible effects of the total solar eclipse on air pollution, ozone (O_3) and nitrogen dioxide (NO_2) data were analysed. The data were recorded at the stations Freudenstadt, Karlsruhe-West, Rastatt and Welzheimer Wald, all of which are located within the zone of totality (Fig. 1) and belong to the official air quality monitoring network in Baden-Wuerttemberg, a state in south-west Germany. In addition, wind speed data (obtained at 10 m above ground level) for three of these stations were analysed to determine possible wind field changes due to the solar eclipse. Unfortunately, unlike the 1 minute data averaging procedure adopted at the Plittersdorf and Hartheim sites during the solar eclipse period, the routine 30 minutes averaging interval for O_3, NO_2 and wind speed data at the aforementioned sites were not altered during the time of the solar eclipse.

3 Weather conditions on 11 August 1999 in south-west Germany

On the day of the solar eclipse, the sky over south-west Germany was overcast. The weather was dull and cloudy giving rise to local showers. Germany was situated under a weak upper trough between a high pressure centre over England and a low pressure centre over the Adriatic Sea. A weakly developed cold front passed the investigation area from north to south during the night before, driven by winds from west to north-west. The weather in the rear was heavily influenced by accompanying moist maritime air which resulted in convective clouds. These gave rise to showers, particularly on hilly and mountainous terrain. Wind speed in the Upper Rhine valley in the morning of 11 August 1999 was only weak, with highest half-hourly mean values (measured at 10 m above ground level) amounting to 3 m/s due to a generally weather situation with low gradients. Weather observations in the area of investigation on the morning of 11 August 1999 recorded a spatially and temporally variable cloudiness. A more specific weather characterisation is provided from observations made at the Karlsruhe synoptic station (belonging to the German Weather Service) at 11:00 CET viz.: 4/8 cumulus congestus, 2/8 stratocumulus, some altocumulus (cirrus were observed before the exact time of observation), ceiling about 800 m, no precipitation (0.1 mm from 0 to 6 UTC) and visibility of about 20 km.

4 Results

4.1 Radiative fluxes

On 11 August 1999 the influence of varying cloudiness was particularly dominant on the shortwave downward

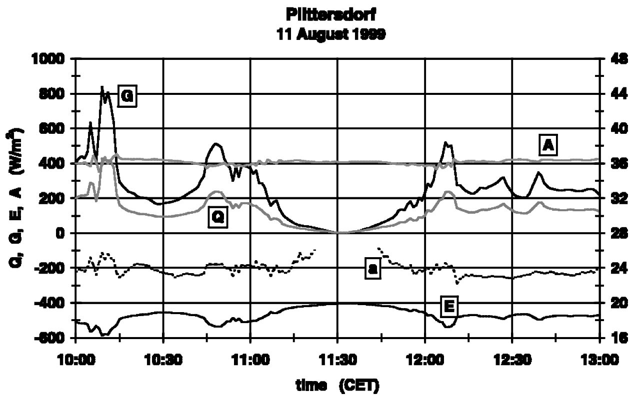

Figure 2: Global radiation *G*, shortwave albedo *a*, upward longwave radiation *E*, downward longwave radiation *A* and net radiation *Q* during the solar eclipse of 11 August 1999 at the Plittersdorf site.

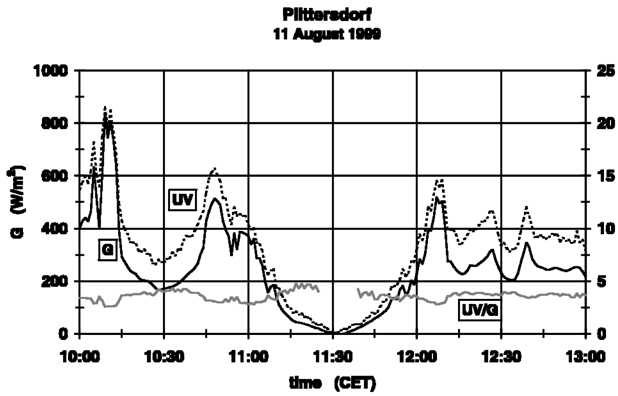

Figure 3: Global radiation *G*, UV radiation *UV* and ratio *UV*/*G* during the solar eclipse of 11 August 1999 at the Plittersdorf site.

radiation until 11:00 CET at the Plittersdorf site (Fig. 2). Global radiation *G* reached about 500 W/m^2 within a short period with cloud gaps at about 10:45 CET. Following this, a continuous decrease of *G* was observed. *G* fell to zero at 11:30 CET. From 11:35 CET, *G* rose again and reached values close to 500 W/m^2 shortly after 12:00 CET. This is comparable to measurements observed at about 10:45 CET. Thereafter, cloudiness which gradually intensified caused a stronger decrease in the downward shortwave radiation. The duration for which the values of global radiation equals to zero (approximately 5 minutes) was twice as long as the astronomical duration of the eclipse being 2:30 minutes. This can be attributed to the threshold of accuracy of the pyranometer which was determined to be 2 W/m^2. Surface albedo a on the day of the solar eclipse was about 24% which is a typical value for the vegetative surface cover at the Plittersdorf site.

Compared to *G*, the response of the upward longwave radiation *E* (Fig. 2) to the solar eclipse was not so pronounced. Nevertheless, a corresponding change in *E* as a function of the variability of *G* was observed from 11:00 to 12:00 CET. The downward longwave radiation *A* is the only radiative flux which did not show any measurable response to the momentary total solar eclipse. The course of the net radiation *Q* (Fig. 2), which is the

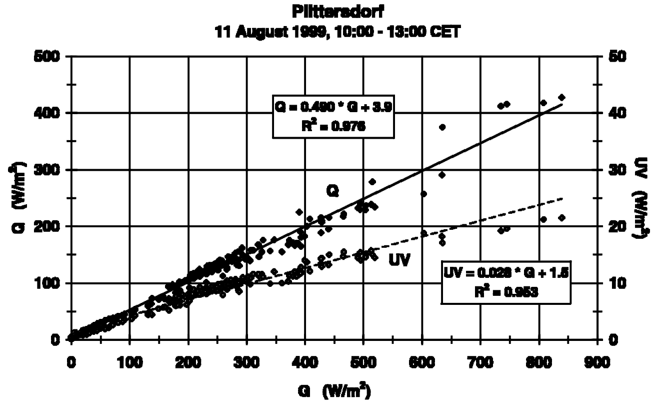

Figure 4: Relationships between global radiation G and net radiation Q as well as UV radiation UV during the solar eclipse of 11 August 1999 at the Plittersdorf site.

sum of single radiative fluxes, runs parallel to the course of G. During the period of the solar eclipse, however, Q did not entirely drop down to zero, but was negligibly above zero. Comparing the measurements of UV radiation to those of G (Fig. 3), a quite similar course in both spectral ranges of downward shortwave radiation was observed. The UV radiation showed a decrease starting at the same time as G, but since the UV level was generally higher, its decrease appears delayed. The ratio UV/G was quite constant, indicating a nearly synchronous behaviour of the last two curves. Like Q, UV radiation did not entirely fall to zero during the period of the solar eclipse, too (Fig. 4). But it is noteworthy that Q and UV radiation values obtained during the total eclipse period were also within the range of measuring accuracy. The non-zero UV values recorded during the period of the solar eclipse may be attributed indirectly to a visually observed blue beam ranging from the top of a northerly exposed and vertically far extended cumulus cloud at the Plitterdorf site. Radiation in the shortwave range of the spectrum exhibits stronger scattering than that in the longwave range. Thus, scattered light from outside of the core shadow may be the source factor of the remaining UV radiation. On average, UV radiation amounted to 3.6 per cent of G from 10:00 to 13:00 CET with slightly higher values at about solar eclipse time.

Global radiation G at the Forestmeteorological Site Hartheim showed a temporal pattern (Fig. 5) which is quite similar to G in Plittersdorf. For instance at the Hartheim site, G was also observed to fall to zero despite the fact that the maximum obscuration of the solar disc over this site amounted to 98.8%. Although global solar radiation at Hartheim was measured by means of a CM 21 type pyranometer, which has a slightly better accuracy than the CM 11 pyranometer utilised at Plittersdorf, the zero values of G at Hartheim may, however, be an indication that the measuring capacity of the used pyranometer is not sensitive enough to detect the effect of a 1.2% uncovered portion of the solar disc. Due to cloudy sky conditions on 11 August 1999, it was impossible to detect a major difference of G between Plittersdorf and Hartheim owing to the different location of both sites with respect to the zone of totality. The loss of solar radiation during the period of the solar eclipse on 11 August 1999, which was owing to the combined effect of the eclipse and cloudiness, can be deduced from long-term solar radiation values for that day. On the basis of overall mean of hourly values of G for all sky conditions from 11:00 to 12:00 CET during the period 1990 to 1998, this solar radiation loss amounts to approximately 620 W/m^2 (Fig. 5).

On 29 April 1976 a previous solar eclipse had been observed in Central Europe. It was only a partial eclipse with maximum sun obscuration of 43.6% occurring at 11:20 CET on a completely clear sunny day. The Forestmeteorological Site Hartheim was already in operation at this time and the influence of the solar eclipse on energy fluxes measured at this site has been reported (KESSLER et al., 1979). To analyse the temporal behaviour of radiative fluxes during both solar eclipses and to make for comparison, Fig. 6 presents the ratios of 15 minute mean values of selected radiative fluxes from the 1999 and the 1976 events as well as the diurnal variation of downward shortwave radiation G during the solar eclipse of 11 August 1999. The 1976 mean values was shifted 15 minutes forward to obtain a temporal congruence of both solar eclipse events. Although the time of both solar eclipse differed only by about 10 minutes, Fig. 6 reveals a more pronounced impact of the 1999 solar eclipse on the courses of both global radiation G and net radiation Q, as the ratios of corresponding G and Q for both years were below 1. These results are basically due to the effect of cloudy sky conditions as well as the totality of the solar eclipse of 11 August 1999 vis-à-vis the partial solar eclipse and clear sky weather condition recorded of 29 April 1976. The ratio of 15 minute mean values of upward longwave radiation E for both events is almost constant indicating a more uniform behaviour than that for G and Q during both solar eclipses. Its mean value of 1.1 results from the higher mean radiation temperature of the Hartheim forest on 11 August 1999. The ratio of the downward longwave radiation A

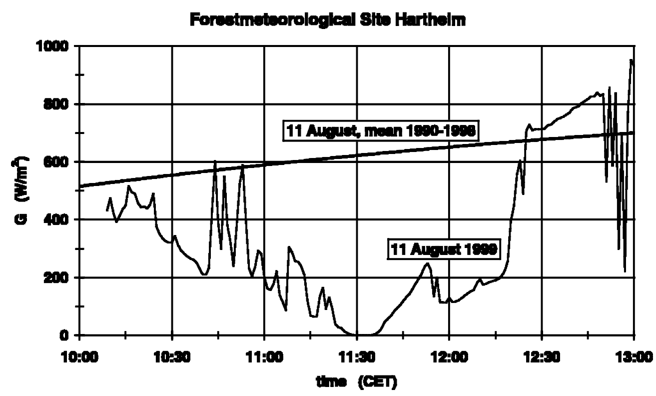

Figure 5: Global radiation G during the solar eclipse of 11 August 1999 compared with that of nine years average (1990–1998) for 11 August at the Forestmeteorological Site Hartheim.

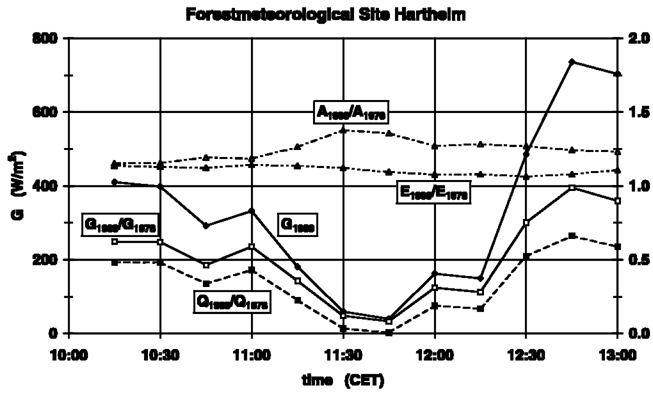

Figure 6: Global radiation G during the solar eclipse of 11 August 1999 as well as ratios of G, upward longwave radiation E, downward longwave radiation A and net radiation Q measured during the solar eclipses of 11 August 1999 and 29 April 1976 at the Forestmeteorological Site Hartheim.

is also above 1 due to a warmer and moister planetary boundary layer on 11 August 1999. Compared to E, the variability of the A ratio is slightly higher, which may be caused by the cloudy weather on 11 August 1999.

4.2 Air temperature

The loss of radiative energy due to solar eclipse leads to a decreasing air temperature T_a in the planetary boundary layer. ANDERSON (1999) has compiled measured changes of T_a at different heights above ground resulting from past eclipse events. He reported that the cooling begins to be noticeable when the sun is about half-covered, with T_a reaching its minimum between 5 and 20 minutes after mid-eclipse when the sun's limb has began to reappear on the west side of the moon. However, the pattern and precise amount of the decline in T_a are unique to each location, depending on various factors such as the time of day, local climate, site, surrounding vegetation, exposure to the sky and wind. Due to the energetic processes which are responsible for cooling and warming the air, the fall in T_a is greatest at ground level (SEGAL et al., 1996; GRIES, 1999). Altitude dependence of T_a showed a fall varying from 9.7°C at 0.13 m above ground to 0.4°C at 20 m above ground (ANDERSON, 1999).

GROSS and HENSE (1999) as well as PIRIOU and LAMBOLEY (1999) investigated the impact of the solar eclipse of 11 August 1999 on T_a by means of weather forecast models. Between 11:00 and 12:00 CET GROSS and HENSE (1999) simulated, on average, a drop in T_a of 3.5°C at screen level with peak values larger than 5°C. PIRIOU and LAMBOLEY (1999) considered both clear sky and overcast conditions for a meteorological station in Saint-Avold (Moselle). For T_a at screen level they simulated a decline of 3.2°C on a sunny day and a decline of 1.4°C in the presence of cloudiness.

At the Plittersdorf site T_a was measured at approximately 2 m above mean terrain and vegetative surface level. As indicated by GROSS and HENSE (1999), a smaller decrease of T_a than for short grassland was expected at Plittersdorf during the solar eclipse of 11 August 1999. This is due to the moist ground and the heat storage in the dense vegetation cover of the nearby riparian forest. The results of the T_a measurements at the Plittersdorf site (Fig. 7) showed that T_a reached its minimum about 5 minutes after mid-eclipse. The maximum fall of T_a amounted to 2.1°C with respect to air temperature at 12:09 CET and 1.7°C with respect to air temperature at 11:00 CET. As mentioned above, the range of T_a drop is the result of local factors at the Plittersdorf site coupled with energy balance governing cloudiness.

As a way of further comparison, a decline of T_a at screen level up to 2.7°C due to the solar eclipse of 11 August 1999 were observed at three meteorological sites in France with various cloudiness (CROCHARD and RENAUT, 1999), viz. Saint-Quentin (Dept. Aisne) 0.8°C, Beauvais (Dept. Oise) 2.1°C and Abbeville (Dept. Somme) 2.7°C.

4.3 Air humidity

As total solar eclipse has a significant impact on the surface energy balance, a response of air humidity would have also been expected, more-so since the available energy is temporally reduced. However, literature texts do not express any information on the behaviour of air humidity during solar eclipse events. The weather conditions on 11 August 1999 were not ideal in south-west Germany to investigate impacts of solar eclipse on air humidity. That should be the major reason why no typical pattern of vapour pressure VP (Fig. 7) was observed at the Plittersdorf site during the solar eclipse. The fluctuation (increase and decrease) of the relative humidity RH around 11:30 CET was caused by the behaviour of T_a and is, therefore, not occasioned by the water vapour content in the lower planetary boundary layer.

4.4 Wind speed

A controversial discussion about changes in wind speed during the course of solar eclipses exists in literature.

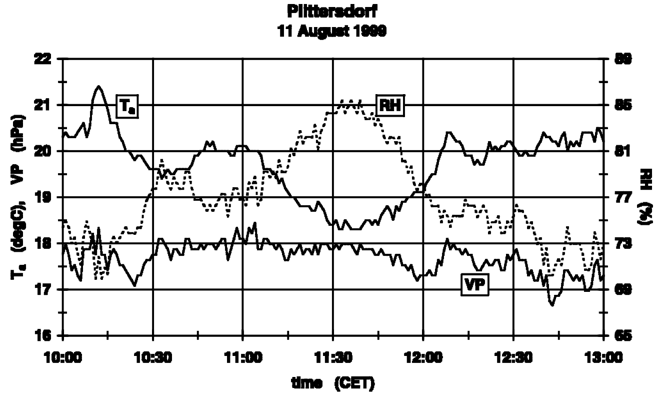

Figure 7: Air temperature T_a, vapour pressure VP and relative humidity RH at screen level during the solar eclipse of 11 August 1999 at the Plittersdorf site.

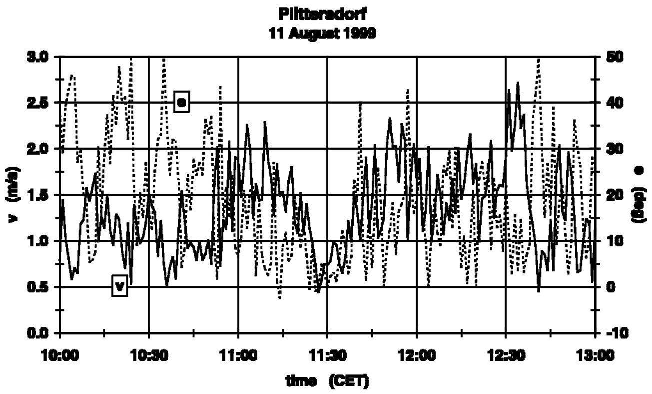

Figure 8: Horizontal wind speed *v* and elevation angle *e* of the three-dimensional wind vector at 17 m above ground level during the solar eclipse of 11 August 1999 at the Plittersdorf site.

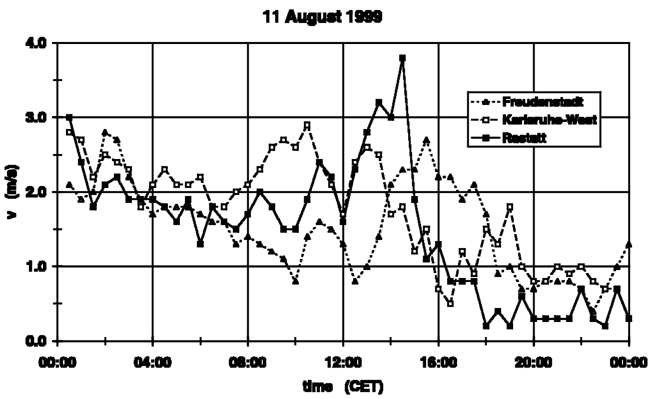

Figure 9: Half-hourly mean values of horizontal wind speed *v* at 10 m above ground level on 11 August 1999 at the official air quality stations Freudenstadt, Karlsruhe-West and Rastatt in Baden-Wuerttemberg.

ANDERSON (1999) provides an overview on the different possible effects and its interpretation. Logically, the gradual cooling of the boundary layer and the reduction in turbulent transports as the atmosphere stabilises should reduce the wind speed during a solar eclipse. However, not all results from measurements performed during solar eclipses show a clear reduction in the wind speed. This is because there are different factors (e.g. type of the terrain) which affect wind speed.

At the Plittersdorf site a drop in the horizontal wind speed v measured at about 17 m above the ground was observed during the solar eclipse of 11 August 1999 (Fig. 8). v was observed to fall from 2.3 m/s at 11:09 CET to 0.4 m/s at 11:27 CET. At the time of total solar eclipse v was slightly below 1 m/s, reaching values of about 2 m/s after 11:50 CET. The decrease and increase of v occurred within a time interval of about one hour.

An impact of the declining global radiation and an ensuing stabilisation of the atmosphere due to the solar eclipse can be better appreciated from the vertical elevation angle e of the three-dimensional wind vector. In spite of short-term fluctuations, e values close to zero occurred at the Plittersdorf site during the eclipse time (Fig. 8) indicating no upward vertical motion. Half an hour before and after the total solar eclipse, 1 minute mean values of *e* were about 30 deg.

Fig. 9 presents additionally wind speed values *v* measured at 10 m above ground on 11 August 1999 at the official air quality monitoring stations Rastatt, Karlsruhe-West and Freudenstadt, which were located within the path of totality of the solar eclipse in south-west Germany. Unfortunately, the data were only available as half-hourly mean values. Wind speed were simultaneously reduced at Rastatt and Karlsruhe-West during the period from 11.30 to 12:00 CET and at Freudenstadt (which is further away from the central line of the solar eclipse) from 12:00 to 12:30 CET. This reduction of wind speed, which reached the order of magnitude of about 1 m/s, may be interpreted as an impact of the solar eclipse. Like air temperature and air humidity, the investigation of the influence of the solar eclipse on the wind conditions in the lower planetary boundary layer was also disturbed by the non-ideal weather conditions in south-west Germany during the solar eclipse period.

An intensifying of orographically induced wind systems by the formation of cool downslope flows was observed when the impacts of the solar eclipse on 11 August 1999 were simulated with a mesoscale circulation model (VOGEL et al., 2001). This meteorological situation is usually observed on clear sky nights. This modelled result was confirmed by wind measurements at the official air quality monitoring station Baden-Baden (Fig. 1) which is located within a long carved valley at the western edge of the Black Forest. There, a change of wind direction from west to the east combined with low wind speeds was observed during the time interval from 11:30 to 12:00 CET. Afterwards, wind direction shifted back to the west with increasing wind speed.

4.5 Surface energy balance

As reported above, downward radiative fluxes were mostly affected by the solar eclipse of 11 August 1999. Therefore, impacts on the other terms of the surface energy balance equation should be expected (NEUMANN

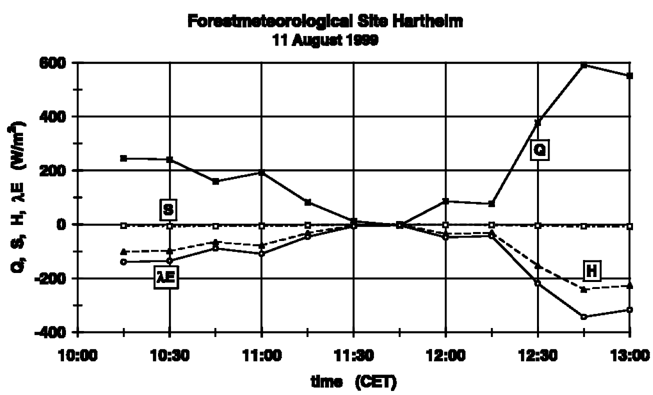

Figure 10: 15 minute mean values of net radiation *Q*, soil heat flux *S*, turbulent heat flux of sensible heat *H* and turbulent flux of latent heat λE for the Scots pine stand at the Forestmeteorological Site Hartheim during the solar eclipse of 11 August 1999.

and DEN HARTOG, 1994). GROSS and HENSE (1999) examined the surface energy flux defined as the sum of radiative, sensible and latent energy fluxes. Under extreme summer conditions in Central Europe, they determined a strong decline in surface energy flux with an average value of 120 W/m^2 and peak values ranging from 250 W/m^2 to 300 W/m^2. After the eclipse, they obtained an overshoot of the surface energy flux with an amplitude of 50 W/m^2 to 100 W/m^2. This occurred approximately one hour after the time of totality. The simulated values of surface energy flux, which is equal to the soil heat flux, seem to be relatively high, even though extreme summer situation and an averaged land use were considered.

To compare modelled values of surface energy flux with actual measurement under the weather conditions of 11 August 1999, Fig. 10 presents 15 minute mean values of the components of the surface energy balance calculated for the Hartheim Scots pine stand using BREB (**B**owen **R**atio **E**nergy **B**alance) method. As net radiation Q declined to nearly zero, the turbulent fluxes of sensible heat H and latent heat λE followed its course. An impact on the soil heat flux S was hardly detected, as its magnitude was too small compared to the other energy fluxes. The impact of the partial solar eclipse of 1976 on the energy balance terms were similar, but not quite pronounced (KESSLER et al., 1979). This implies that the results of GROSS and HENSE (1999) proposed for Central Europe can not be adapted to individual sites without additional investigations.

4.6 Nitrogen dioxide and ozone

Due to their radiation-dependent process of formation, nitrogen dioxide (NO_2) and ozone (O_3) are significant components of near surface air quality in summer. Special measurements of total ozone has been performed during past solar eclipses (BOJKOV, 1968; CHAKRABARTY et al., 1997). However, results from these past investigations seem to be sometimes contradictory due to various influencing factors (e.g. cloudiness).

In order to investigate the impact of the solar eclipse of 11 August 1999 on the air quality within its path of totality, half-hourly mean values of near-surface NO_2 and O_3 measured at the urban stations Freudenstadt (Fig. 11), Karlsruhe-West (Fig. 12) and Rastatt (Fig. 13) as well as the background station Welzheimer Wald (Fig. 14) are compared with that of ten years average (1989–1998) measured at these sites for 11 August. With respect to the air quality conditions, the station Freudenstadt located at an altitude of 750 m a.s.l. in the Black Forest is merely comparable to the background station Welzheimer Wald. Since locally enhanced nitrogen oxide emissions always result in reduced ozone concentrations at the same location, it therefore follows that stations with high traffic density in their neighbourhood always show a well pronounced daily variation of O_3 with a comparatively low daily mean value (MAYER, 1999).

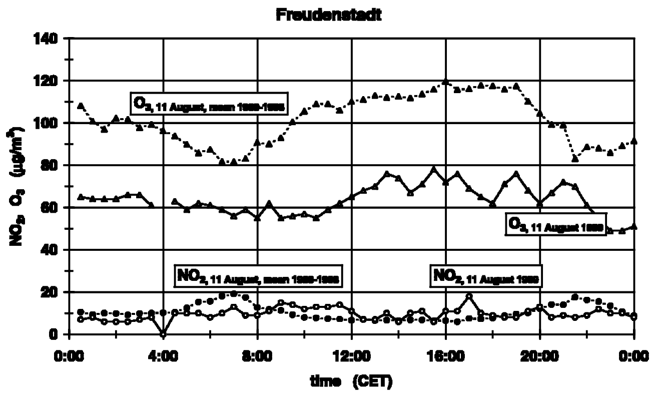

Figure 11: Half-hourly mean values of nitrogen dioxide (NO_2) and ozone (O_3) on 11 August 1999 compared with that of ten years average (1989–1998) measured at the official air quality station Freudenstadt for 11 August.

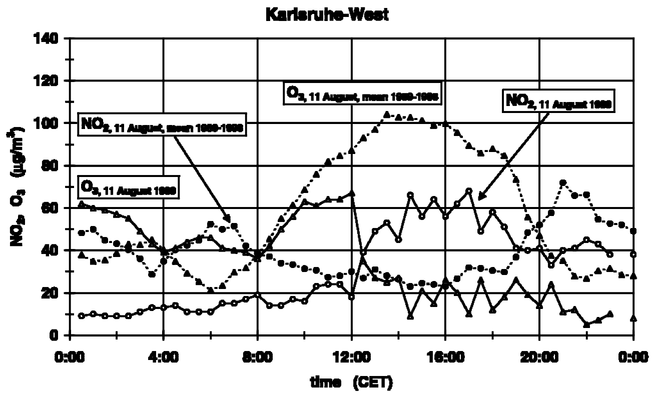

Figure 12: Half-hourly mean values of nitrogen dioxide (NO_2) and ozone (O_3) on 11 August 1999 compared with that of ten years average (1989–1998) measured at the official air quality station Karlsruhe-West for 11 August.

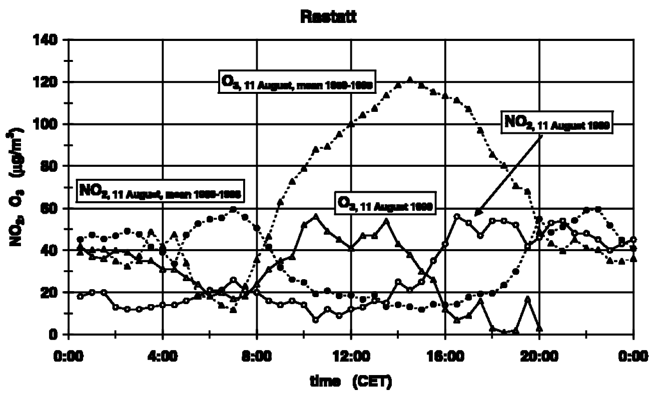

Figure 13: Half-hourly mean values of nitrogen dioxide (NO_2) and ozone (O_3) on 11 August 1999 compared with that of ten years average (1989–1998) measured at the official air quality station Rastatt for 11 August.

Near surface O_3 concentrations are determined by three main factors: photochemical production and titration, deposition, and advection. For a rural area in California, NEUMANN and DEN HARTOG (1994) observed that O_3 production came to a halt during a partial eclipse

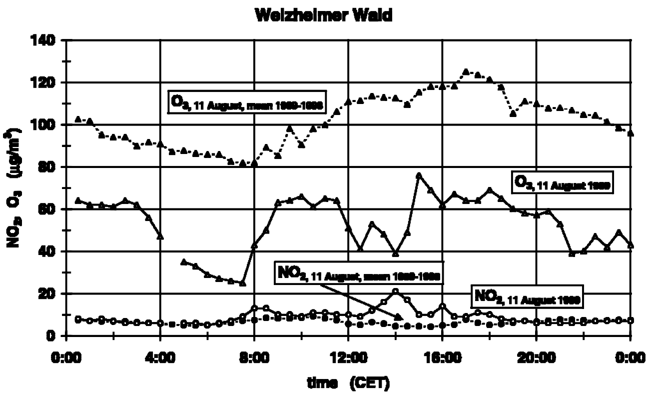

Figure 14: Half-hourly mean values of nitrogen dioxide (NO_2) and ozone (O_3) on 11 August 1999 compared with that of ten years average (1989–1998) measured at the official air quality station Welzheimer Wald for 11 August.

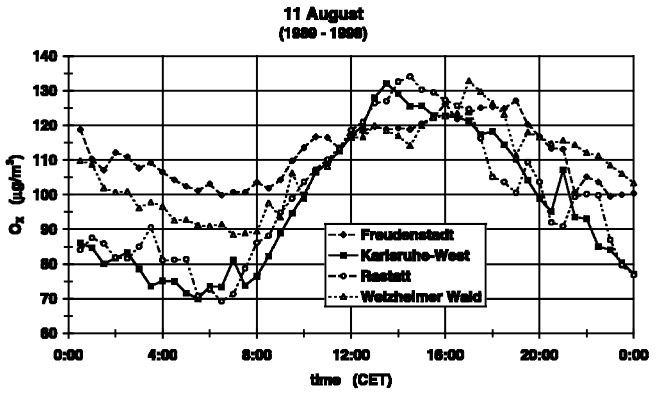

Figure 16: Half-hourly mean values of O_X (i.e. O_3 + NO_2) on 11 August at the official air quality stations Freudenstadt, Karlsruhe-West, Rastatt, and Welzheimer Wald averaged over the period 1989 to 1998.

of 60%. Due to the non-ideal weather conditions during the solar eclipse of 11 August 1999 in Baden-Wuerttemberg, O_3 concentrations were much lower than expected. This view is on the basis of 10 year mean values for 11 August. The highly elevated station Freudenstadt (Fig. 11), which is located close to the southern border of the zone of totality, almost showed no solar eclipse effect. The concentration pattern of O_3 on 11 August 1999 closely followed the mean ten year daily course, although at a lower level. Typical of air quality background stations, the NO_2 concentrations at Freudenstadt were comparatively low. Only a secondary effect of the solar eclipse on NO_2 was observed at Karlsruhe-West (Fig. 12), which is surrounded by streets of supraregional importance and characterised by high vehicle traffic. A very pronounced increase in the NO_2 concentrations from 20 to 65 μg/m^3 occurred approximately one hour after the end of the totality due to the traffic onset of solar eclipse tourists. In line with personal observations, vehicle traffic was not so high in the hours before the eclipse (Fig. 15 for NO). As a result, local air-chemical reactions initiated a strong decrease of the O_3 concentrations. A pronounced decrease in ozone concentrations of approximately 27% coupled

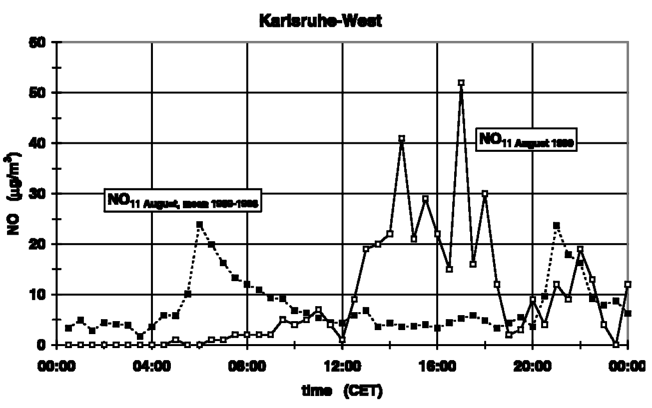

Figure 15: Half-hourly mean values of nitrogen oxide (NO) on 11 August 1999 compared with that of ten years average (1989–1998) measured at the official air quality station Karlsruhe-West.

with a simultaneous NO_2 increase was observed in Rastatt (Fig. 13) between 10:30 and 12:00 CET. This effect was likely caused by the solar eclipse. But additional influences by both advection and deposition of O_3 can not be precluded. For example, less insolation leads also to less vertical mixing of the planetary boundary layer resulting in a larger influence of O_3 deposition and, therefore, to a lower O_3 concentration.

At the station Welzheimer Wald (Fig. 14), a decline in O_3 was observed starting from 11:00 CET, without any significant change in NO_2 concentration. The occurrence of this ozone decline, which is a contrast to the average daily O_3 pattern, can indeed be attributed to the reduced global radiation combined with decreasing photochemical formation of O_3 during the solar eclipse period. Relative to the O_3 concentration at 11:00 CET, the O_3 reduction was approximately 37%. The enhanced traffic after the end of the totality could be observed even at the background station Welzheimer Wald where an increase of NO_2 from 10 μg/m^3 at 12:00 CET to 21 μg/m^3 at 14:00 CET and a reduced O_3 concentration at 14:00 CET were observed.

Overall, the obtained results showed only small impacts of the solar eclipse on O_3 and NO_2 measured at official air quality stations within the zone of totality in Baden-Wuerttemberg. These impacts reached the order of magnitude of daily variations caused by thick and changing cloudiness. Nevertheless, a slight minimum of O_3 concentrations was observed at many stations of the official air quality monitoring network in Baden-Wuerttemberg between 11:30 and 12:30 CET. The local site of each air quality station veiled the effects of the spatial reduction of the downward shortwave radiation in various ways. In addition, the variability of the weather on 11 August 1999 somewhat compounds the interpretation of the measured half-hourly O_3 and NO_2 values on the day of the solar eclipse.

An overview of the role of photochemistry during the solar eclipse reported here can be obtained by examining O_X, which is the sum of O_3 and NO_2. When compared to long-term half-hourly mean values of O_X on 11 Au-

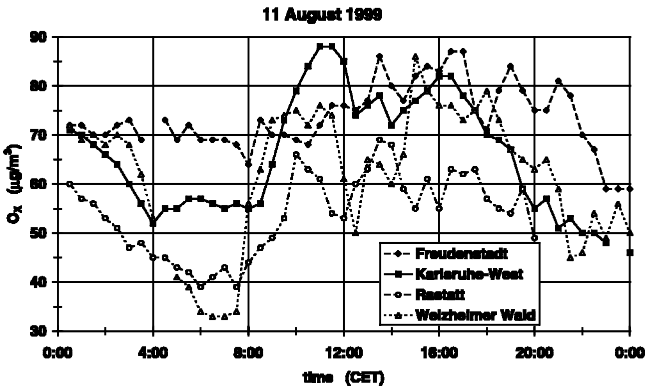

Figure 17: Half-hourly mean values of O_X (i.e. O_3 + NO_2) on 11 August 1999 at the official air quality stations Freudenstadt, Karlsruhe-West, Rastatt and Welzheimer Wald.

gust for the period 1989 to 1998 (Fig. 16), the stations showed a drop of O_X (Fig. 17) around the time of the solar eclipse, which, however, was not pronounced at the station Freudenstadt. Afterwards O_X was approximately constant at the urban stations Freudenstadt, Karlsruhe-West, and Rastatt for at least four hours indicating a NO titration.

5 Conclusion

In general, responses of divers processes to solar eclipses can be examined from sub-surface soil layers to the mesosphere. This study was, however, confined to the investigation of the responses of meteorological and air quality parameters to the solar eclipse of 11 August 1999. Data on the parameters used for this study were extracted from routine measurements taken at different stations in south-west Germany. These stations lie within and outside the path of totality of the total eclipse. The weather in south-west Germany during the solar eclipse was not particularly optimal, as clouds did not allow for a clear sky condition and the much desired ideal radiation. Although 1 minute averaging interval should be a well suited time span to observe the impacts of a transient solar eclipse on the atmospheric environment, this goal, however, was not realised at some of the investigating stations (particularly the air quality monitoring stations) due to their designated role as long-term monitoring stations. Nevertheless, the examination of the available routinely measured meteorological and air quality data for the lower planetary boundary layer showed marked responses to the solar eclipse. The impact of the solar eclipse of 11 August 1999 on meteorological and air quality parameters as well as radiative and energy fluxes would have been more significant given a clear sky weather condition and more so if additional vertical soundings and process studies were performed. A thorough analysis of the atmospheric effects of solar eclipse can be achieved by compiling various investigations bordering on this event.

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