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Article

The BAYSOFI Campaign – Measurements carried out during the total solar eclipse of August 11, 1999

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Abstract

The total solar eclipse of August 11, 1999 provided a unique opportunity to observe the input of fast day-night and night-day transitions, under high solar elevation around noon, on the earth-atmosphere-biosphere system. Within the interdisciplinary field campaign BAYSOFI, measurements of radiation, boundary layer micrometeorology and photochemistry, photosynthesis and transpiration were carried out at Freising-Weihenstephan and several locations nearby focusing on short-term effects of the eclipse. Although the overall grosswetterlage on August 11 was not favourable for viewing the eclipse, with clouds covering most of central Europe, observational conditions at Weihenstephan were fair due to a large hole in the cloud layer which appeared just half hour before totality lasting for more than one hour. Thus significant effects of the eclipse on radiation, photolysis rates, OH, the temperature, wind, turbulence structure and stratification, ozone and CO_2 fluxes, photosynthesis, transpiration and sap flow of trees could be observed which are reported and discussed in the following sequence of papers.

Zusammenfassung

Die totale Sonnenfinsternis am 11. August 1999 bot die einmalige Gelegenheit, den Einfluss schneller Tag-Nacht- und Nacht-Tag-Übergänge bei hohem mittäglichem Sonnenstand auf das System Erdoberfläche-Atmosphäre-Biosphäre zu beobachten. Im Rahmen der interdisziplinären Feldmesskampagne BAYSOFI wurden in Freising-Weihenstephan und einigen benachbarten Orten Messungen zur Strahlung, Grenzschicht-Mikrometeorologie und Photochemie, Photosynthese und Transpiration, die auf kurzzeitige Effekte der Sonnenfinsternis fokussiert waren, durchgeführt. Wenngleich die Großwetterlage am 11. August ungünstig und Zentraleuropa von einer mehr oder weniger dichten Wolkenschicht überdeckt war, herrschten in Weihenstephan recht gute Beobachtungsbedingungen dank eines großen Wolkenlochs, das sich eine halbe Stunde vor der Totalität auftat und über eine Stunde reichte. Dadurch konnten signifikante Effekte der Sonnenfinsternis auf Strahlung, Photolyseraten, OH, die Partitionierung von NO_x, Ozon- und PAN-Produktion, Temperatur, Wind, Turbulenzstruktur und Schichtung, Ozon- und CO_2-Flüsse, Photosynthese, Transpiration und Saftstrom in Bäumen beobachtet werden, die in der folgenden Sequenz von Artikeln präsentiert und diskutiert werden.

1 Introduction

The phenomenon of a solar eclipse is one of nature's most spectacular events. Its astronomical background is well understood for long and accounted for in many books, for instance those of MITCHELL (1951), LITTMAN and WILLCOX (1991) and ZIRKER (1984). A total solar eclipse causing almost complete darkness and lasting for up to a few minutes is even more spectacular but quite a rare event. If the sky is clear a wide range of optical phenomena can be observed, such as the changing colour of the sky, the moving shadow, shadow bands, the Sun's chromosphere, the corona and its prominences, the diamond ring as well as planets and

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Figure 1: Measurement locations (Lehrstuhl für Bioklimatologie und Immissionsforschung (LfBIM), nearby maize field, Kranzberger Forst and Forschungszentrum für Umwelt und Gesundheit (GSF)) for the BAYSOFI campaign. The dotted line indicates the centre of the solar eclipse.

stars that suddenly become visible against the darkening sky.

Eclipses also provide a unique opportunity to investigate the reaction of the atmosphere or the biosphere, when the incident solar radiation is suddenly turned off and then on again. While the responses are similar to those that occur as night falls, the eclipse is much more abrupt than the gradual decrease in solar energy as the evening sun approaches the horizon. Thus observations of changes in surface temperature and wind are documented related to solar eclipses: temperature falls ranging between 2 and almost 10 K depending on season and latitude (see review by ANDERSON, 1999) and decline in surface wind speed from 2.5 m/s before the eclipse to 1 m/s about 10 minutes after totality (FERNANDEZ et al., 1996).

A wide range of observations is documented for the upper atmosphere, too. CHIMONAS (1971) predicted the formation of stratospheric gravity waves, but searches for the pressure wave associated with these predictions did not provide consistent results (see review by DAVIES, 1982). Ozone measurements generally show a slow decline in column-ozone during the darkening phase followed by a sharp peak at or just after totality, with a slow recovery to pre-eclipse values thereafter (BOJKOV 1968, CHAKRABARTY et al. 1997), although other patterns have been reported as well. Eclipse-related changes are also documented for the ionosphere, such as sudden drops of the ion and electron densities HORVATH and THEON 1972). A recent paper by JAKOBI and KÜRSCHNER (2000) reports a strong decrease of D-region (60–90 km) ionization during the August 11, 1999 solar eclipse, enabling wind measurements at mesopause level which normally can be achieved during night only.

2 The BAYSOFI-Campaign

The total solar eclipse of August 11, 1999 provided the potential for new findings, since the lunar shadow passed over highly instrumented parts of Europe (for details see ESPENAK and ANDERSON, 1997). At our institute site at Freising-Weihenstephan (Lat. 48°24’5”N, Long. 11°43’10”E), about 30 km NE of Munich in southern Germany, it occurred at 10:37.20 UT (12:37 CEST), with totality lasting about 2.3’ minutes, at a solar zenith angle of 34°. It thus provided an interesting opportunity for investigating the impact of the eclipse during high solar elevation conditions.

Within BAYSOFI (Bayerische Sonnenfinsternis), an interdisciplinary field campaign focused on the effects of the total solar eclipse on radiation and air chemistry, micrometeorology as well as physiology, coordinated measurements were carried out at the institute site (LfBIM), in a nearby maize field, at a forest site about 5 km towards NW (Kranzberger Forst) and at the GSF laboratory site at Neuherberg, some 20 km towards SW. These locations are shown in Fig 1.

Additional measurements of photosynthesis and sap flow were carried out at two forest sites close to Oberammergau (80 km SW) and Landau/Isar (80 km NE), respectively. Simultaneously, measurements of meteorological and chemical parameters were conducted at a 50 m mast in Garching and at the Meteorological Observatory Hohenpeißenberg (MOHp), a site of the WMO Global Atmospheric Watch program, about 70 km SW of Weihenstephan. Although the eclipse at this place reached 99% of totality only, these additional measurements proved to be very important.

At the time of the eclipse, the centre of an upper level trough was located over Central Europe (Fig. 2).

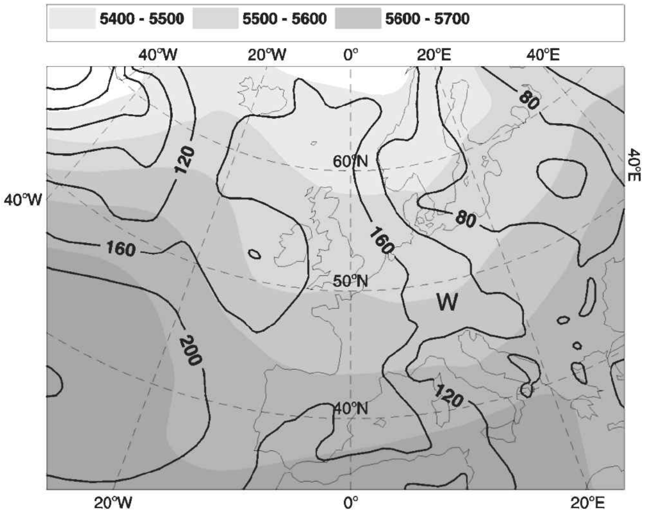

Figure 2: Geopotential at the 500 hPa (shaded every 100 gpdm with light colours denoting low values) and at the 1000 hPa (isolines every 40 gpdm) surfaces over Europe on 11 August, 1999 at 12 UTC. The plot is based on analysis data from the European Center for Medium-Range Weather Forecasts (ECMWF). The location of the measurement site at Weihenstephan is marked with ”W“.

At 1000 hPa, a high pressure ridge extended from the Atlantic towards Western Europe and the British Isles. A cold front occlusion was located over Southern Germany, nearly parallel to the totality path of the eclipse, which produced dense clouds penetrating southeastwards along the backside of the upper-level trough. Occasional rain showers and thunderstorms also occurred in the region, due to the instability caused by the upper-level cold air advection (Fig. 3).

Nevertheless, observational conditions were fair. From 10:00 UTC until 11:10 UTC a window in the otherwise dense cloud cover allowed viewing the eclipse at Weihenstephan during its most interesting phase. At Hohenpeißenberg, a few short rain showers occurred which, however, did not severely disturb the measurements (see FABIAN et al., 2001; WINKLER et al., 2001).

Photochemistry in the boundary layer and the effect of the reduced solar radiation during the eclipse was one of the issues of interest: Simultaneous measurements of radiation, photolysis frequencies, O_3, CO, PAN, NO_x and meteorological parameters carried out at Weihenstephan show the interactions between radiation and photochemistry under fast ”day-night“ and ”night-day“ transitions at high solar elevation. The instruments used during BAYSOFI and their characteristics are listed in Table 1.

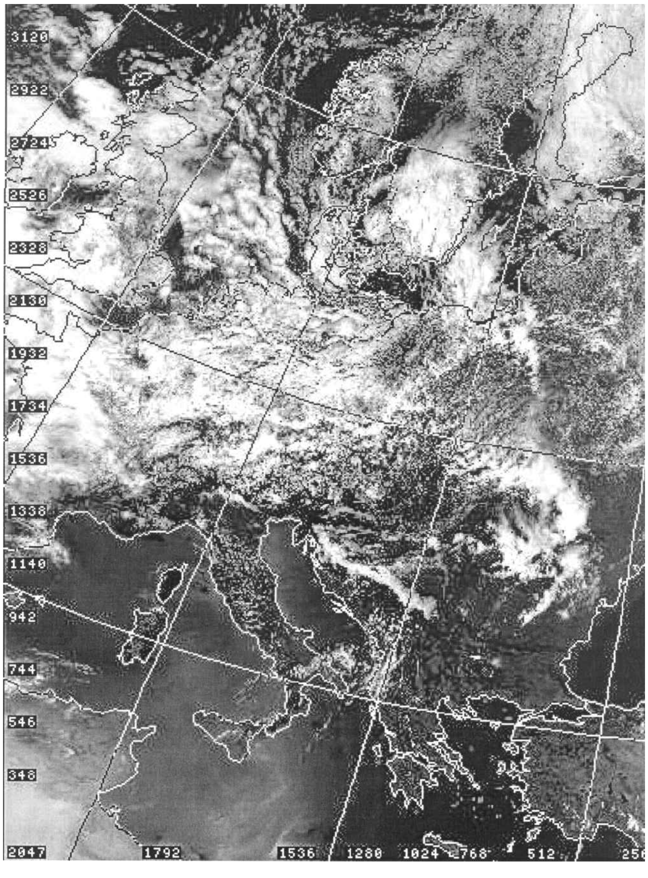

Figure 3: AVHRR image aboard a NOAA polar orbiting satellite in the visible channel on 11 August, 1999 at 13:36 UTC. Image courtesy of the Dundee Satellite Receiving Station, Dundee University, Scotland.

Concurrently with the rapid darkening of the atmosphere, most photochemical reactions are also dramatically reduced, mainly because of the rapid decline of the hydroxyl radical (OH) concentration. OH, the major oxidant in the atmosphere, was measured during the eclipse at Hohenpeißenberg in conjunction with a broad range of other gaseous as well as meteorological and aerosol parameters. The contribution of the major OH source, i.e., ozone photolysis, to the observed OH levels can be estimated. Furthermore, the effects of declining OH levels on the concentrations and atmospheric lifetimes of other important compounds can be estimated. As an example, the temporal changes of gaseous sulfuric acid concentrations which were also measured during the eclipse can be compared with model calculations of the H_2SO_4 balance. The photochemical cycle controlling the interconversion between the highly reactive NO and NO_2 also adjusts very rapidly to the radiation environment. To study the interchange of NO and NO_2 during the solar eclipse the parameters of the so-called photostationary state ratio

$$[NO_2]/[NO] = k[O_3]/j_{NO_2}$$

were measured simultaneously with a high time resolution (≤ 1 s). Here, k is the temperature dependent reaction rate coefficient of the reaction of NO with ozone and j_{NO_2} is the rate coefficient of the photodissociation of NO_2. In order to monitor the expected decrease of the NO volume mixing ratio to zero over a wide range of concentrations, a high-sensitivity chemiluminescence instrument with a very low detection limit of only 3 pptv was used (see Table 1). Thereby, the partitioning between NO and NO_2 as a function of j_{NO_2} could be measured over the entire period of the solar eclipse. Additionally simple box model simulations were used to show the effect of reduced solar radiation on the photochemical production of O_3 and PAN. (FABIAN et al., 2001; KOEPKE et al., 2001).

The aim of the micrometeorological programme was not merely focused on classical meteorological measurements (radiation, temperature) as during the last important partial (> 80%) solar eclipse on June 30, 1954 in Germany (HINZPETER and WÖRNER, 1955), but rather on phenomena which can only be observed during a total eclipse. Therefore, the eclipse was used as a ’laboratory‘ experiment carried out in nature. The main difference between a cloud covered sun and an eclipse is a negative net radiation (night time conditions) during the eclipse. The change of the irradiation conditions from day to night occurs during a much shorter time period and considerably faster during an eclipse than at nightfall. This offers the possibility to study time response functions dependant on the forcing by the sun's radiation. Such functions are of special interest for the energy transition to turbulent and plant physiological processes. This was the inspiration for including a micrometeorological and plant ecological programme into the BAYSOFI experiment and the cluster of resulting publications. The mi-

Table 1: Instruments used during BAYSOFI.

Air Chemistry	*Type of instrument*	*Detection limit*	*Accuracy*	*Temporal resolution*	*Site*	*Reference*
O_3	ML 8810	1 ppb	± 2%	1 min	WHS	
PAN	Scintrex LPA-4	30 ppt	± 5%	5 min	WHS	
NO_2	Scintrex LMA-3	5 ppt	± 5%	1 min	WHS	Kelly et al. (1990)
NO	CLD 780 TR	3 ppt	± 10%	1 s	WHS	
NO_x	CLD 780 TR + PLC 762	5 ppt	± 15%	5 s	WHS	Schlager et al. (1997)
CO	AL5001	2 ppb	± 15%	3 s	WHS	Gerbig et al. (1996)
OH, H_2SO_4	CIMS	0.015 ppt	± 52%	5 min	MOHp	Berresheim et al. (2000)
Radiation	*Type of instrument*	*Detection limit*	*Accuracy*	*Temporal resolution*	*Site*	*Reference*
global radiation	Kipp & Zonen pyranometer	0.3–3 μm		1 min	WHS	
UV radiation	Eppley UV radiometer	295–385 nm		1 min	WHS	
$j_{\mathrm{O(^1D)}}$	filter radiometer	290–325 nm	± 15%	10 s	WHS	Junkermann et al. (1989)
$j_{\mathrm{O(^1D)}}$	filter radiometer	290–325 nm	± 15%	1 min	MOHp	Müller (1994)
$j_{\mathrm{NO_2}}$	filter radiometer	290–420 nm	± 10%	10 s	WHS	Reuder (1999)
diffuse sky irradiance (D)	pyranometer CM11 Kipp & Zonen	integral 0.3–3μm		1 min	WHS	
spectral UV irradiance	double monochromator BENTHAM DM300	spectral 310 nm		10 s	NH	
Meteorology	*Type of instrument*			*Temporal resolution*	*Site*	
dry temperature	Th. Friedrichs Frankenberger Psychrometer			1 min	WHS	
Wind velocity	Th. Friedrichs wind velocity sensor			1 min	WHS	
Wind direction	Th. Friedrichs wind direction sensor			1 min	WHS	

crometeorological measuring programme with measurements of sensible and latent heat, carbon dioxide and ozone fluxes using the eddy covariance method was one of the first carried out during a total solar eclipse condition. A similar experiment was made in the USA during a partial (94%) eclipse, on May 10, 1994 (Eaton et al., 1997), yet with partial success only, because net radiation did not turn negative.

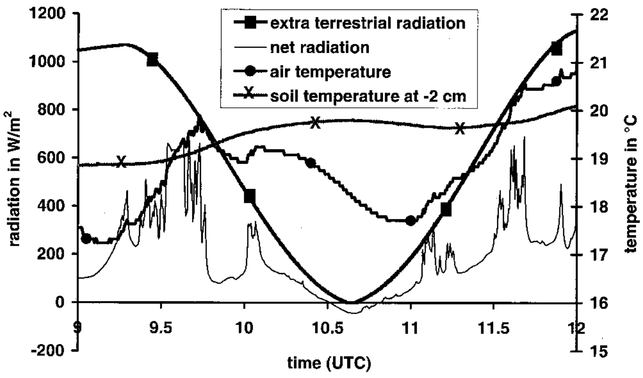

Figure 4: Time shift between the net radiation, air temperature and soil temperature.

Our micrometeorological programme focused on measurements of all parameters determining both the radiation balance equation and the energy balance equation. Therefore, the sensible and latent heat fluxes were directly measured by means of the eddy covariance technique (FOKEN et al., 2001). For comparison with the physiological measurements the carbon dioxide flux was also measured. The programme was completed by profile measurements of wind, temperature and humidity along with soil temperatures. For the combination with plant physiological measurements, a maize field was selected because of the high transpiration rate (even non-irrigated) in mid August.

Fig. 4 shows the time shift between the net radiation, air temperature and soil temperature. The decrease of the air temperature by about 2 K is in a good agreement with data of a large number of solar eclipses observed earlier (ANDERSON, 1999). It is considerably smaller, however, than the temperature drop of up to 7 K predicted for the upper Rhine valley for the August 11, 1999 eclipse based on cloudless conditions (VOGEL et al., 2001). At a depth of 2 cm in a grass-covered soil the decrease was only 0.5 K. Moreover, a strong decrease of the wind velocity, with low values persisting up to 30 minutes after totality, was measured. Due to this effect all fluxes were forced by net radiation and turbulence (FOKEN et al., 2001).

In contrast to the crop plantation, photosynthesis and transpiration of leaves in tall forest trees were examined for effects of the solar eclipse. Of special interest were the responses of canopy transpiration and water flux through the whole tree, as the latter was uncertain to be affected by the short, transitional impact of the totality on the stomatal regulation. One point of interest was the question: does the tall dimension of forest trees with its water storage 'filter out' effects of canopy response on the water transport through the trunk? Measurements were conducted on mature individuals of spruce, beech and oak at low and high-altitudinal sites near Freising, Oberammergau and Landau/Isar (HÄBERLE et al., 2001).

The differences in short term responses for these processes elucidates our insight into ecophysiological processes and can be used for scaling purposes. Therefore, the physiological programme was aimed at identifying the different time scales of physiological and meteorological responses to the rapidly changing irradiation (Photosynthetic active Photon Flux Density, I_{PPFD}) and environmental conditions during the total solar eclipse around noon. It was focused on the water – and CO_2 – exchange in the selected Zea maize on the leaf level. The assimilatory flux AL measured for five selected leaves follows the variation observed for the photosynthetically active radiation (Fig. 5), with a time delay of about 35 ± 15 s due to the physiological behaviour of the stomatal conductance. It is interesting to note that assimilatory fluxes turned negative during totality indicating that photosynthesis switched to respiration during this short period of darkness.

In the following separate contributions, experiments and the main results obtained during the eclipse on August 11, 1999, are described and discussed. We concede that no breathtaking new discoveries were made during the event. The total solar eclipse as a "laboratory experiment" carried out by nature, however, provided the unique opportunity to test our understanding of radiation, photochemical, micrometeorological and physiological processes. Neither measurements carried out during dusk or dawn nor those performed during temporal cloud cover provide these ideal conditions of a total solar eclipse around noon, with rapid darkening, complete darkness and rapid brightening thereafter, at high solar elevation. Our results show, with few exceptions due to lacking complete information, that the observed variations can be explained. Moreover, observations related to the limb darkening effect, photolysis rates and fast radical photochemistry, the fast transitions of the thermal stratification of the boundary layer, radiative budget, photosynthesis and transpiration triggered by the eclipse are important and interesting case studies. A total solar eclipse, being a very rare event of short duration only, certainly has no lasting impact on the atmosphere-biosphere system. But just because it happens once in a long while only, observations carried out during such a rare event certainly deserve publication.

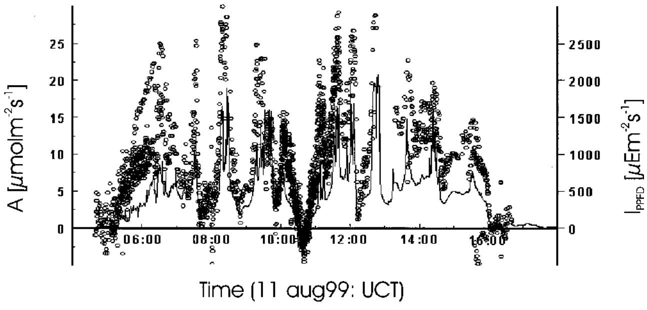

Figure 5: Observed I_{PPFD} (line) and A_L (circles) between dawn and dusk during the total solar eclipse on August 11, 1999.

Acknowledgments

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