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Atmospheric Boundary Layer

DYNAMICS OF THE ATMOSPHERIC BOUNDARY LAYER DURING THE 1980 TOTAL SOLAR ECLIPSE

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An atmospheric boundary layer experiment was conducted at Raichur, India to study the variations in the surface shear stress, heat flux and the meteorological processes that take place during a total solar eclipse. Interesting results were observed regarding the evolution of the planetary boundary layer. Changes in atmospheric stability from unstable to stable to unstable were observed during different phases of the eclipse. Downward propagation of negative heat flux associated with decreasing scales of convective eddies was also observed during the eclipse.

Keywords: **Atmospheric Boundary Layer; Scales of Turbulence; Solar Eclipse; Air pollution**

INTRODUCTION

During daytime conditions, temperature of the air near the earth's surface is warmer than the air above it. This causes vertical accelerations and displacement of air parcels resulting in thermally induced atmospheric turbulence. As the sun sets, temperature of the ground decreases rapidly below that of the adjoining air. Layers of air close to ground get cooler and become denser. Maintenance of turbulence implies that air is being moved continuously in the vertical plane. If the fall of density with height is large, lifting denser air against gravity at the expense of energy from mean motion is rather difficult. Turbulent motion thus becomes small. Again at the next sunrise, incoming radiation raises the temperature of the ground and that of the lowest air layers resulting in less dense air below. This causes the tendency for vertical motion to be enhanced increasing turbulence. Diurnal evolution of the atmospheric boundary layer thus depends on the variations in the incoming and outgoing radiation. An ideal experiment to study the dynamics and the evolution of the atmospheric boundary layer would be to study the variations in the boundary layer characteristics by decreasing and then increasing the solar radiation abruptly. A total solar eclipse provides the right setting for such an experiment due to near-instantaneous cut-off of the solar radiation. A patch of clouds will not satisfy the required conditions due to complex reflection and scattering of light. Constantly changing angles of the sun to the earth surface makes it difficult to interpret the results that may be obtained from an evening or an early morning experiment. A survey of the literature indicates no study of the atmospheric boundary layer during a total solar eclipse. A partial solar eclipse (80 per cent) was studied by Antonia *et al.*. (1979) in Australia.The final stages of the eclipse coincided with the normal sunset thus making it difficult to isolate the effect of the eclipse from the diurnal changes.

The atmospheric boundary layer experiment described in this paper was conducted during a total solar eclipse that occurred on 16 February 1980 over the southern part of India. Width of the shadow was about 125km. The experiment was conducted at Raichur, India (16°22′N, 77°21′E). The first contact or partial solar eclipse at Raichur began at 1425 IST (Indian Standard Time); total eclipse (second contact) occurred at 1543 IST and lasted 2 minutes and 42 seconds; the eclipse ended (fourth contact) as a partial one at 1655 IST. Normal sunset was at 1820 IST on the day of the eclipse. Thus a well-developed convective atmospheric boundary layer was present before the first contact and there was sufficient time to warm the surface of the earth after the third contact (around 1545 IST).

One of the atmospheric variables that can influence the boundary layer characteristics significantly is the synoptic condition which is a largescale feature that

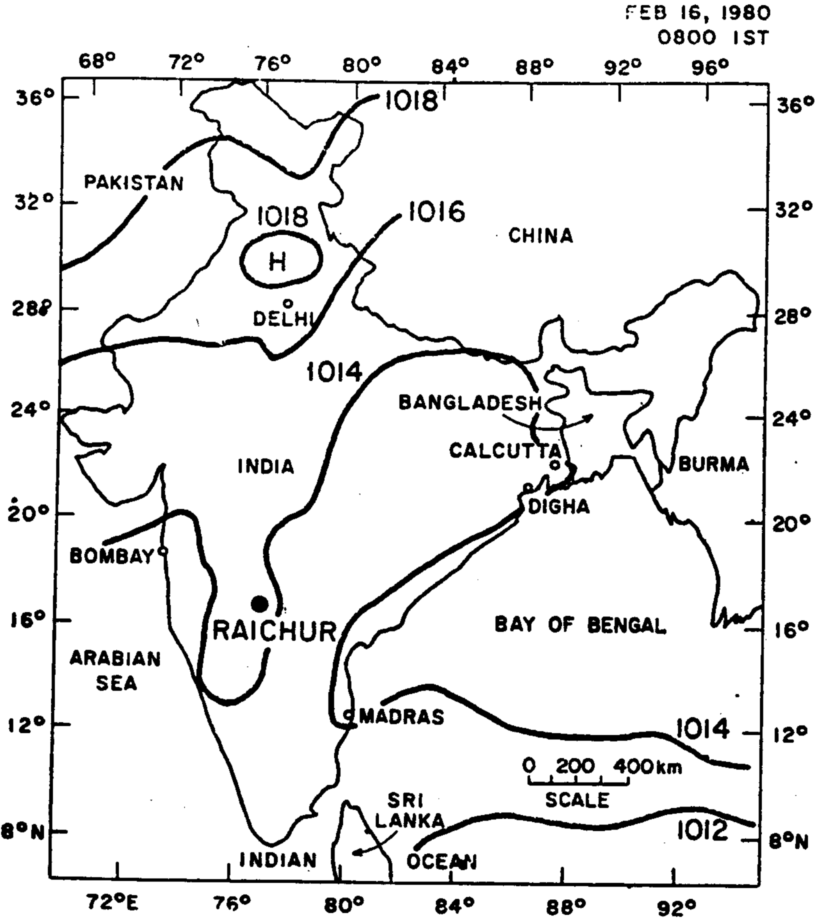

FIG. 1. Surface weather chart at 0800 IST on 16 February 1980 indicating weak pressure gradients. This is typical of the synoptic conditions that existed over the southern part of India during the week of the eclipse.

modifies the day-to-day flows. The conditions experienced at Raichur were ideal for a boundary layer experiment of this type due to near-constant fair weather conditions that prevailed. This was expected over most of the interior southern part of India due to the month of February being in a non-monsoon period of the year. Synoptic surface weather map for 16 February 1980 shown in Fig. 1 indicates weak pressure gradients over southern India. Surface maps for 15, 17, and 18 February also indicated the same feature. Thus significant free convection was present,. providing an opportunity to study the evolution of the boundary layer during the eclipse.

MEASUREMENTS

The boundary layer experiment described in this paper was conducted in collaboration with the Indian Institute of Science (I. I. Sc.), Bangalore. Our objective was to study the dynamics of the boundary layer through the observations of the variations in the surface fluxes of momentum and heat and the thermal structure. The measurement system had the following components: (*a*) a 12m micro-meteorological tower (Fig. 2) with instruments to measure longitudinal, lateral, and vertical velocity and temperature fluctuations at four levels, mean winds at five levels and mean temperatures at two levels; (*b*) a mini-radiosonde system to measure mean temperature profiles to a height of 2 to 3km—it used slowly rising balloons with battery-operated instrument packages that measured and telemetered pressure and temperature information to a microprocessor-controlled ground station; (*c*) pilot balloon sounding system to measure wind speed and direction in the planetary boundary layer; and (*d*) a pyranometer to measure direct solar radiation.

The surface layer fluxes discussed in this paper were measured at a height of 6.8m above the surface. The measurements at this height consisted of longitudinal velocity fluctuations with a small three-cup anemometer (developed by the I. I. Sc.), vertical velocity fluctuations by a propeller-type anemometer (of R. M. Young Inc.) and the temperature fluctuations with a resistance element thermometer (of A. I. R. Inc.). The distance constants of the cup anemometer, propeller anemometer, and the temperature sensor are estimated to be about 0.5m, 0.8m and 0.1m, respectively. The analog data were recorded with a magnetic recorder, digitized at the rate of eight per second and analyzed with a digital computer. The fluxes were computed with the eddy-correlation technique by correlating the longitudinal and vertical velocity fluctuations for momentum and the vertical velocity and the temperature fluctuations for sensible heat. The observations were made for two days prior to and one day after the day of the eclipse to determine the characteristics of the atmospheric boundary layer that may be site-dependent.

DISCUSSION OF RESULTS

Dynamics of the Surface Layer

Variation of the thermal stability of the atmospheric boundary layer during the eclipse due to changes in the solar radiation is of major interest. Changes in the stability in turn affect the turbulence characteristics of the boundary layer. Mean potential temperatures measured at 2m and 12m successively by the same sensor

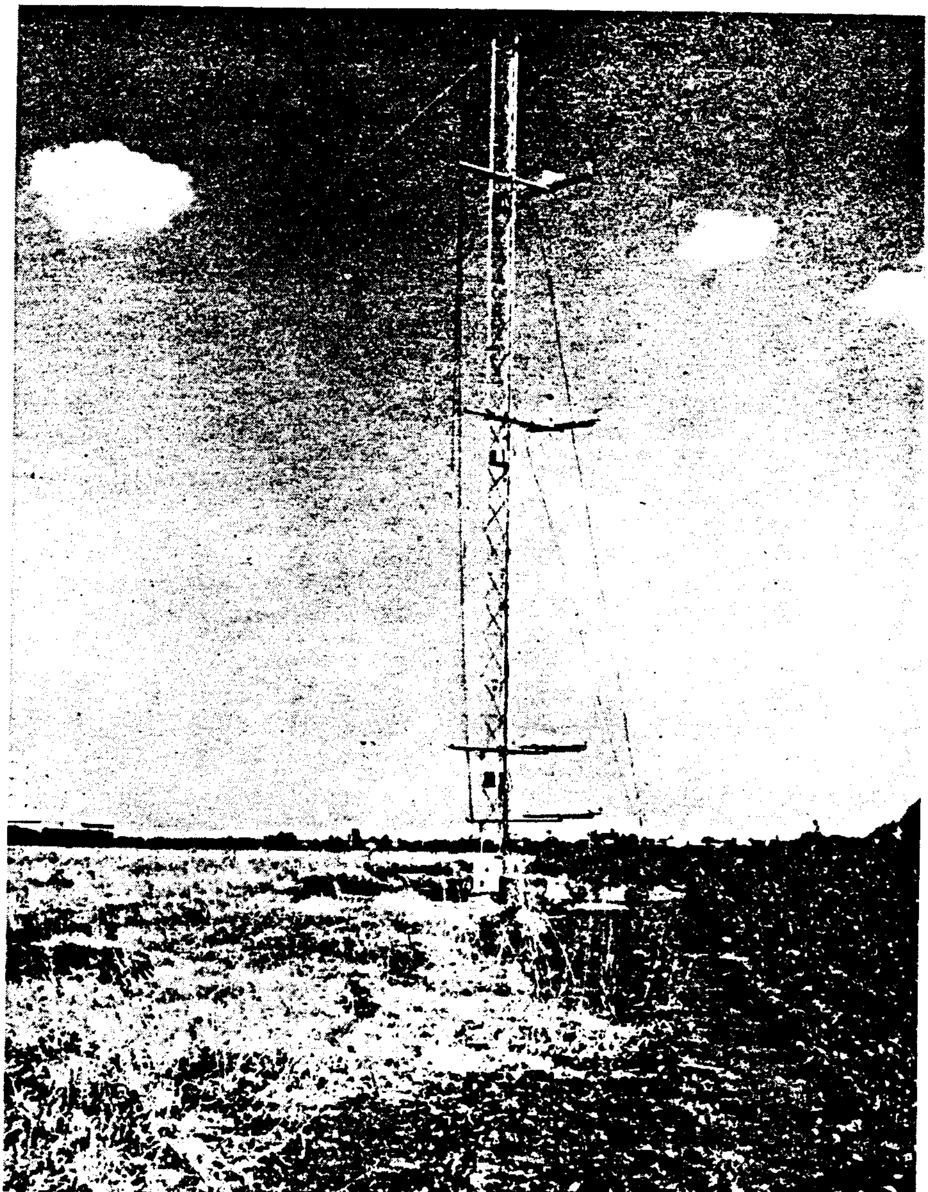

FIG. 2. Micrometeorological tower (12m high) used to measure the surface layer turbulence, fluxes of momentum and heat and the gradients of mean temperature.

during different phases of the eclipse are given in Table I. Results indicate the onset of stable conditions in the surface layer approximately at the time of totality and the return of the convective conditions a few minutes after the third contact.

Sensible heat flux H is given by

$$H = \rho\, C_p\, w'\, T' \qquad \ldots(1)$$

TABLE I

Temperature lapse rates in the surface layer

Time (IST)	Potential Temperature (C) 2m	Potential Temperature (C) 12m	Phase of the eclipse
1055	29.4	28.4	
1430	32.7	32.1	First contact
1503	33.7	32.8	
1551	31.5	31.6	3 minutes after 3rd contact
1606	32.0	31.9	
1635	33.5	33.4	10 minutes before 4th contact
1900	28.9	30.8	

where ρ is the density of air, Cp is the specific heat of air at constant pressure, and $\overline{W'T'}$ is the cross-covariance between the vertical velocity and temperature fluctuations. A positive H indicates upward heat flux found in a convective boundary layer and a negative H represents downward heat flux usually present during clear nights over land surface with stable atmospheric conditions. Fifteen minute average values of H estimated from the measurements of the fluctuations of vertical velocity and temperature during different phases of the eclipse on 16 February are shown in Fig. 3. The dotted line shows the variation observed at the site on 17 February, a non-eclipse day. Observations of heat flux indicate a sharp decrease immediately after the first contact, a gradual decrease for the next hour, a sharp decrease just before totality with a change in sign and a gradual increase to the normal non-

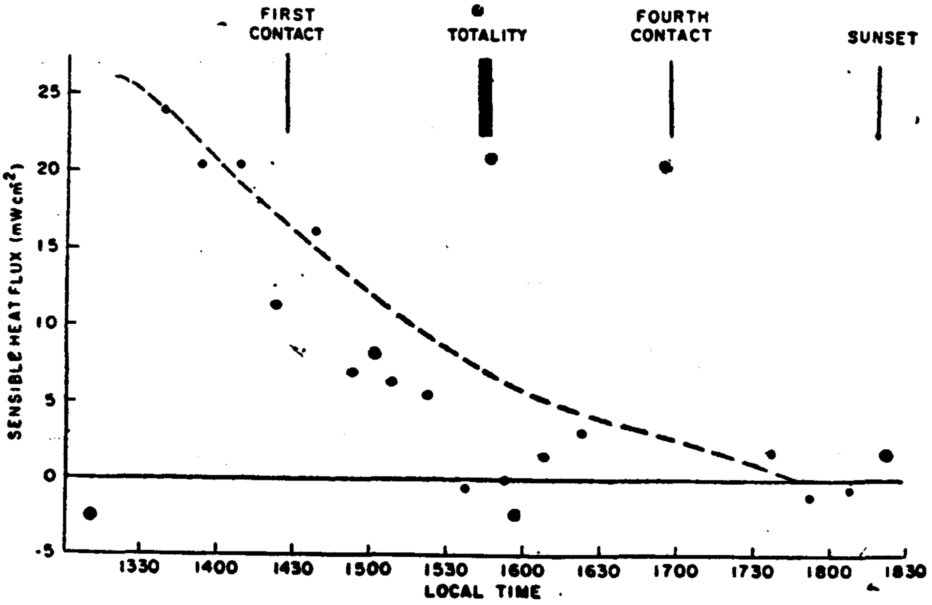

FIG. 3. Variation of the sensible heat flux during different phases of the eclipse. Dotted line indicates the variation at the site a day after.

eclipse day values after the third contact. It is interesting to note that the negative sensible heat flux occurs even before the second contact. This is somewhat similar to the conditions that exist just before sunset with reduced radiation due to a low angle to the sun.

In order to be able to use the results obtained from this experiment to other sites and other heights in the surface layer, Monon-Obukhov length L, a similarity parameter and an index of stability was computed. This length is defined as

$$L = \frac{-u_*^3}{kgH/\rho C_p\theta} \qquad \ldots 2$$

where u_* is the friction velocity, k is Von Karman constant ($\sim$ 0.4), and θ is the mean absolute potential temperature. On any given occasion L is constant, and all height-dependent quantities such as gradients, and transfer coefficients are expected to be, when suitably normalized, universal functions of z/L, where z is the height of measurement. In unstable conditions, L is negative, in stable conditions positive. With strong thermal effects as is usually found with large heat flux and weak wind, L is small. For near-neutral conditions, L becomes very large. Variation of z/L during different phases of the eclipse is shown in Fig. 4. Values of L varied from about –22m to +100m. Dotted line indicates the normal variation of z/L on a non-eclipse day. The similarity parameter varied in essentially the same way as the heat flux. Change in sign corresponding to stable condition occurred a few minutes before totality.

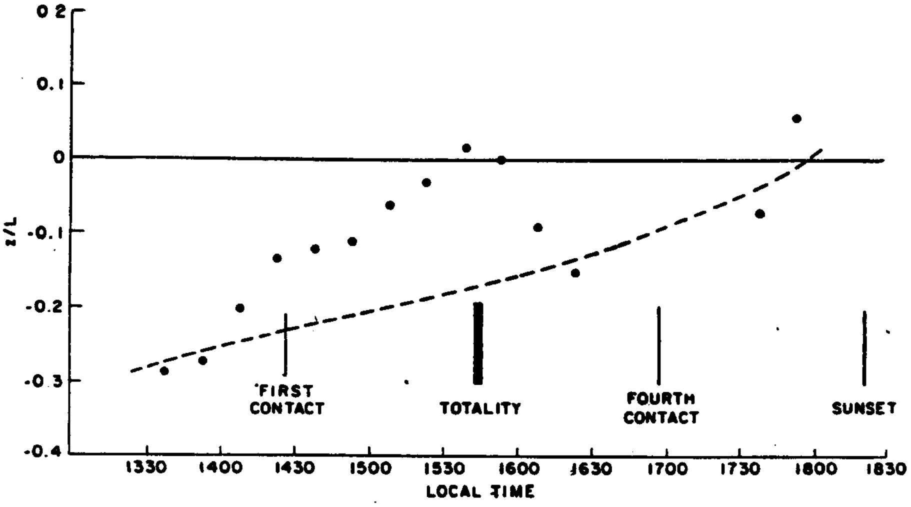

FIG. 4. Variation of the Monin-Obukhov similarity parameter, z/L, for different phases of the eclipse. Dotted line indicates the variation at the site a day after.

Variations of the friction velocity, u_* and the standard deviation of the vertical velocity fluctuations, σ_w on 16 February are given in Table II. The measurements were made at a height of 6.8m. The values of u_* and σ_w decreased by a factor of about four just before totality and increased again after the third contact. The response of the surface layer to solar radiation seems to be of the order of a few (< 10) minutes.

TABLE II

Variation of u_* and σ_w at 6.8m above the surface

Time (IST)	$\bar{u}$ (cm sec^{-1})	σ_u	u (cm sec^{-1})	σ_w (cm sec^{-1})	Phase of the eclipse
1330–1345	107	47	35	65	
1345–1400	129	43	35	70	
1400–1415	118	52	39	74	
1415–1430	115	51	41	71	First contact 1425 IST
1430–1445	105	49	43	57	
1445–1500	83	58	34	64	
1500–1515	76	61	41	43	
1515–1530	98	49	35	51	
1530–1545	122	9	10	14	Second contact 1543 IST
1545–1600	137	17	20	20	Third contact 1546 IST
1600–1615	130	19	22	28	
1615–1630	126	25	23	29	Fourth contact 1655 IST
1730–1745	85	28	25	34	
1745–1800	83	32	28	28	

Dynamics of the Boundary Layer

Mean temperature profiles from the surface to a height of about 4km were measured at about 30-minute intervals in the afternoon on the day of the eclipse

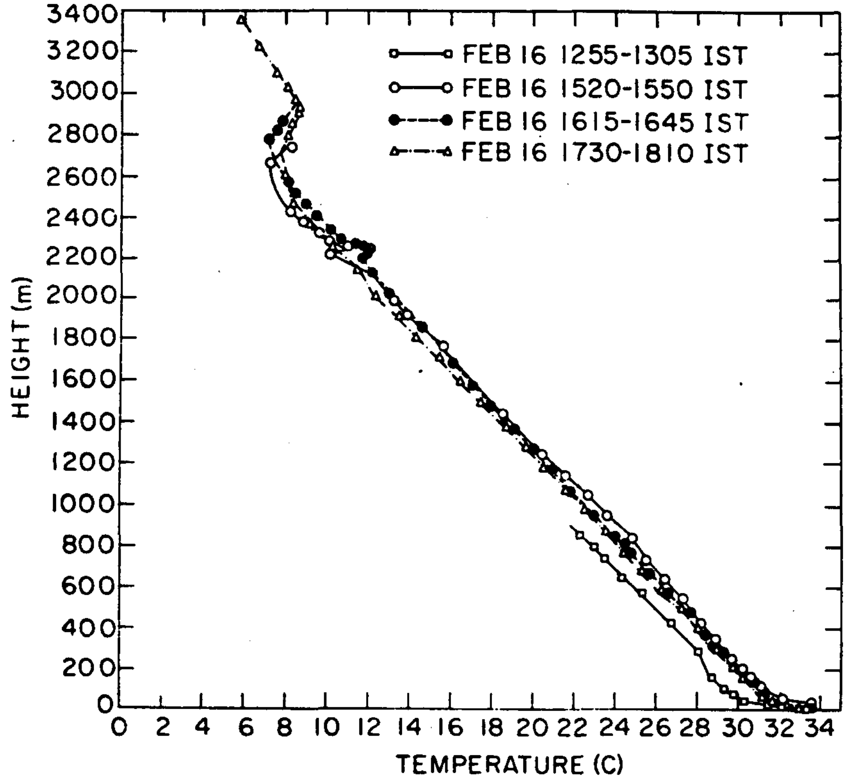

FIG. 5. Typical mean temperature profiles on a non-eclipse day. Note the super-adiabatic lapse rate near the surface and an elevated inversion at about 2500m.

(16 February), a day before and the day after (17 February). From the rate of rise of the balloon and from the response time of the temperature sensor, depth of resolution of the temperature measurements was estimated to be 10m. Mean temperature profiles measured on 17 February, a day after the eclipse, are shown in Fig. 5. A well developed convective boundary layer or mixed layer appears to be present to a height of about 2500m capped with an inversion. Although the height of this mixed layer might vary from day to day within a few hundred meters, it is reasonable to expect that the basic structure would remain the same. The thermal structure during typical daytime conditions normally consists of a superadiabatic lapse rate near the surface (~tens of meters), dry adiabatic lapse rate for the remaining portion of the convective boundary layer (~hundreds of meters) and a stable layer on the top.

Mean temperature profiles to heights of about 3km measured with miniradiosondes during the day of the eclipse are shown in Fig. 6. Inversioncapped height of the convective mixed layer was observed to be about 2800m on 15, 16 and 17 February. On the day of the eclipse (16 February) temperature profiles showed a second inversion at about 2100m for two ascents, one immediately prior to totality and the other towards the end of the eclipse. Referring to Table I, the first period (1520–1550 IST) is approximately the same as the one during which stable atmospheric conditions existed in the surface layer. The inversion aloft (at about 2100m) persisted

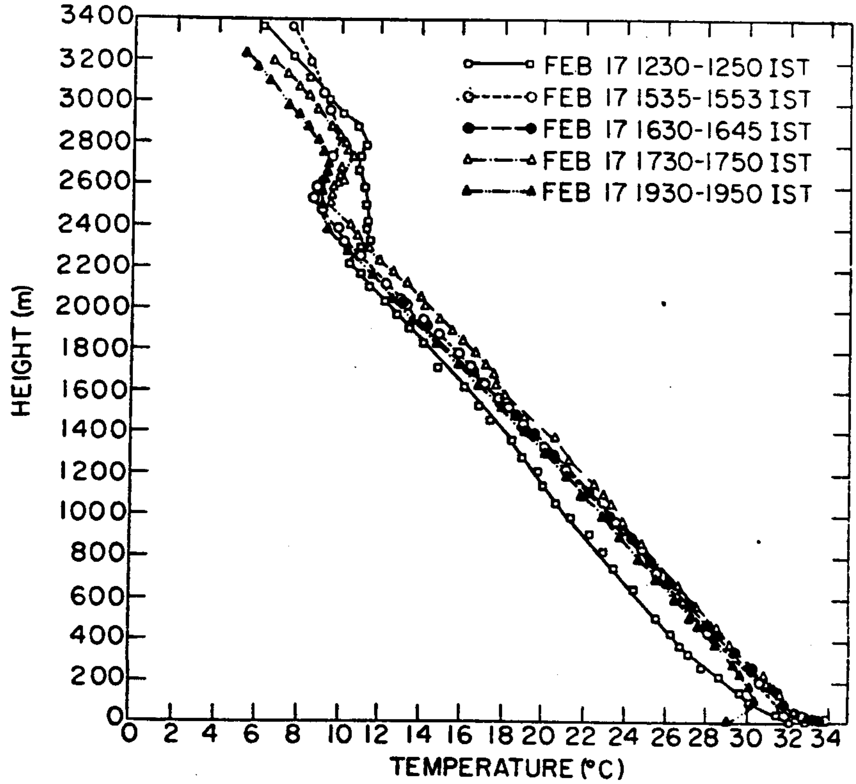

FIG. 6. Mean temperature profiles on 16 February during different phases of the eclipse. Note the onset of a second inversion at 2200m (negative heat flux) and its disappearance after the fourth contact.

longer than the one near the surface. Caughey and Kaimal (1977) found that around sunset the transition to negative heat flux occurs first in the upper regions of the boundary layer propagating downward to the surface. Temperature profile taken after the fourth contact does not show the second inversion indicating build-up of the convective boundary layer once again. The second inversion appeared at about $0.75h$ where h is the mixing height (~2800m). The downward propagation of negative heat flux is believed to be related to the reduction in the size of the convective eddies as the solar radiation is diminished.

CONCLUSIONS

The boundary layer experiment conducted during the 1980 total solar eclipse revealed the changes in the atmospheric stability occurring during different phases of the eclipse. Boundary layer became stable just before totality. Convective processes were observed immediately after totality which suggests that the response of the boundary layer is of the order of a few (~1–10) minutes. The negative heat flux seems to propagate downwards when the solar radiation was diminished. This is probably related to the variations in the scales of the convective eddies due to changes in the solar radiation received by the earth surface. This feature is closely related to the evolution of the atmospheric boundary layer. Solar eclipse provides a unique opportunity to study the dynamics of this process and understand the physical processes involved in the diurnal evolution of the earth's planetary boundary layer.

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