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OBSERVATIONS AND NUMERICAL SIMULATION OF THE EVOLUTION OF THE TROPICAL PLANETARY BOUNDARY LAYER DURING TOTAL SOLAR ECLIPSES

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Abstract—Two convective boundary layer experiments were conducted in the tropics during total solar eclipses, one at Raichur, India on 16 February 1980 and the other at Tanjung Kodok, Java, Indonesia on 11 June 1983. Period of totality was about 3 min at Raichur and 5 min at Java. With the partial phase of the eclipse extending over a combined period of about 2-h before and after totality, there was sufficient time in these experiments for the atmospheric boundary layer to react to changes in solar radiation. Results from the Indian experiment indicated significant changes in the atmospheric stability during the eclipse with slightly stable conditions present after the second contact. Java observations showed similar results but with smaller effects. Changes in stability also caused changes in turbulence structure. In this paper, we present the observations made during these two experiments, as well as the results of numerical simulations using a one-dimensional, second-order closure PBL model. In terms of location, the Raichur site with approximately homogeneous conditions was better suited for the model simulations than Tanjung Kodok, which was located about 1 km downwind from the ocean.

Key word index: Solar eclipse, planetary boundary layer, tropics.

1. INTRODUCTION

An ideal experiment to study the evolution of the Convective Boundary Layer (CBL) would be to switch off and then switch back on solar radiation abruptly. This would produce significant variations in boundary layer characteristics making it perfect to study the dynamics and evolution of the atmospheric boundary layer.

A total solar eclipse would give the right setting for this experiment providing near instantaneous cut-off of solar radiation with a sudden change in surface cooling. Due to complex reflection and light scattering, a patch of clouds covering the sun will not satisfy these conditions. Indeed, a solar eclipse in clear skies creates an unusually clean and rapid change in the chief agency driving the boundary layer, namely solar radiation. Yet, there are very few boundary layer studies during total solar eclipses found in the literature.

Antonia *et al.* (1979) conducted a PBL study on 23 October 1976, when the shadow of a partial solar eclipse fell upon parts of South Australia. This eclipse, however, reached only 80% totality. Because the period following the eclipse gradually merged into the normal sunset, the effects of the eclipse could not be easily isolated from the usual diurnal changes. Nevertheless, scientists measured the response of both velocity and temperature fluctuations in the surface layer to the decrease in surface heat flux during the solar eclipse. Their most important findings can be summarized as follows: (a) the velocity response lags behind the temperature response by about 20 min; (b) unlike the velocity spectrum which exhibits a good inertial subrange for the whole period of observation, the inertial subrange for temperature collapses shortly after the eclipse begins; and (c) the response of the surface layer turbulence to stability changes can be best described by a series of equilibrium step compensations.

The first boundary layer experiment conducted during a total solar eclipse occurred on 16 February 1980 over South India (SethuRaman, 1981). It was a relatively more comprehensive study due to the near-constant fair weather conditions that were prevalent and the distinct separation of the eclipse from normal sunset with the first contact around 1430 IST (Indian

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Standard Time). Another PBL study was conducted as part of the U.S. Solar Eclipse Expedition on 11 June 1983 in Java, Indonesia. This afforded a better opportunity to observe the boundary layer because the eclipse was centered about local noon and the duration of totality was 5.4 min. The purpose of this paper is to describe the details of these two total solar eclipse field experiments, including the mean and turbulent statistics of the boundary layer and to present the results of a numerical simulation using a one-dimensional PBL model. Dynamics of the evolving PBL over land on a time scale of the order of a few min to about 3–4 h are discussed in comparison to a time scale of about 24 h for diurnal variations.

2. DESCRIPTION OF THE TWO EXPERIMENTS

The first atmospheric boundary layer experiment was conducted during a total solar eclipse that occurred over the southern part of India on 16 February 1980 (Narasimha *et al.*, 1981; SethuRaman, 1981). The measurement site was at Raichur, India (16°12′N, 79°21′E; 400 m above mean sea level). Figure 1 shows locations of partial and totality regions of the eclipse. At Raichur the eclipse magnitude was 1.04, since it was almost exactly in the middle of the totality band, and the shadow width was approximately 125 km. The sun's inclination was about 35° during the eclipse.

Various stages of the eclipse were: first contact at 1425 h IST; second contact (total eclipse) at 1543 h 40 s and lasting 2 min and 42 s; third contact at 1546 h 22 s; and the fourth contact at 1655 h (eclipse ended). On this day the normal sunset time was 1820 h. Thus, the eclipse was well separated from sunset. A strong CBL was existent before first contact. After third contact, the surface heating and the resulting buoyant plume cycle had time to redevelop.

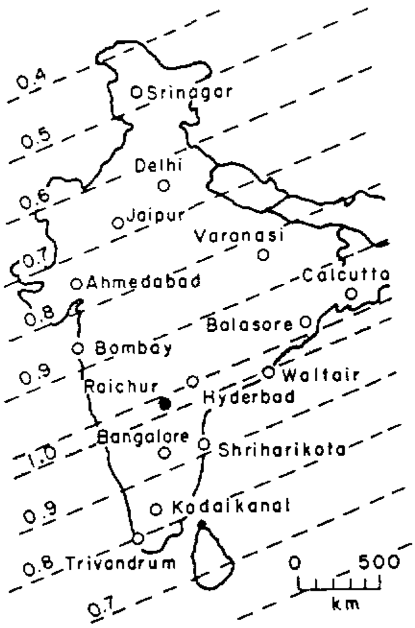

Fig. 1. Map of India showing eclipse magnitudes and the totality belt with a width of about 120 km, after Narasimha *et al.* (1981).

Conditions at Raichur were excellent for boundary layer studies given light winds and sunny skies. The effects of imposing a cut-off of solar radiation could be felt near-instantaneously at the surface where free convection dominated the evolving daytime PBL. The surface synoptic weather map for 16 February 1980 indicated weak pressure gradients over South India. The experiment was conducted jointly by Brookhaven National Laboratory, New York, and the Indian Institute of Science, Bangalore. The experimental objective was to study boundary layer dynamics through observations of surface heat flux, winds and temperature and the turbulence structure. The instrument mast was set up in a flat, open field ($Z_0 \approx 0.05$ m). To separate out any site-dependent boundary layer characteristics, measurements were made for 2 days prior to and one day after the eclipse day. The observational equipment used during the experiment consisted of the following:

(a) a 12 m micrometeorological tower supporting five instrument booms, at heights of 1.3, 2.25, 4.25, 6.8 and 10.25 m above ground. Mean winds were measured at all five levels, and fluctuating velocity–longitudinal, lateral and vertical components were measured by fast sensors at four levels, and temperature fluctuations and mean temperatures were measured at four levels and at two levels (2 m and 12 m), respectively. In addition, two radiation sensors were located on the 1.3 m boom, one to measure solar radiation flux perpendicular to the ground and the other to measure radiation through a surface normal to the sun tilt (35°) at totality. These data were acquired using a pulse-code-modulated, transmission–reception system and collected via a mini-computer controlled digital cassette tape recorder;

(b) mini-radiosondes attached to slowly rising balloons collected pressure and temperature information and telemetered these data to a microprocessor controlled ground station. These provided the mean PBL temperature profiles up to nearly 3 km;

(c) and vertical velocity and temperature fluctuations were measured by a propeller-type anemometer (R. M. Young, Inc.) and a resistance element thermometer (A.I.R., Inc), respectively, at 6.8 m. Analog data were stored on a magnetic recorder and later digitized at 8 s^{-1}. The eddy correlation technique was used to compute surface fluxes.

The second boundary layer experiment was conducted during a total solar eclipse over the island of Java, Indonesia on 11 June 1983. The measurement

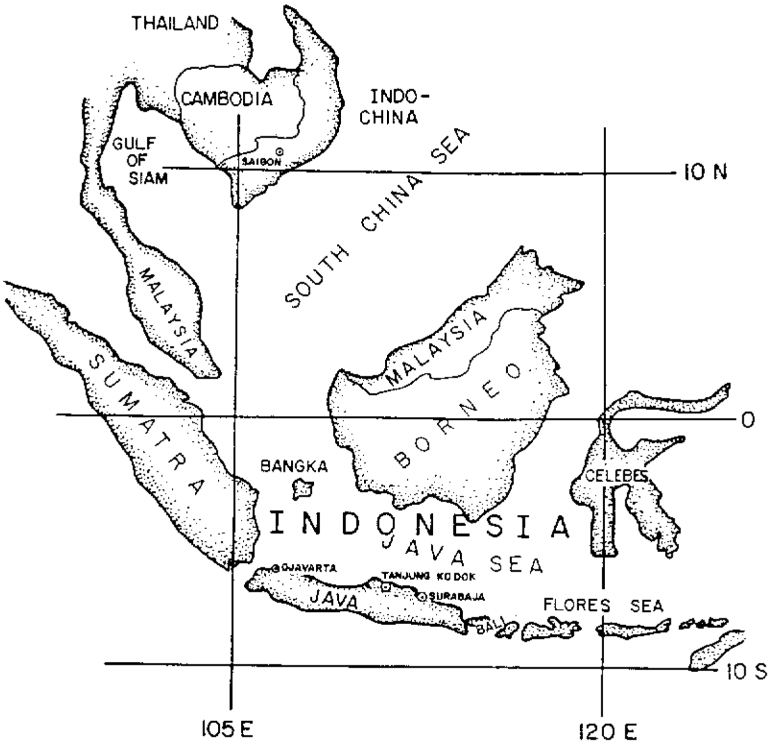

Fig. 2. Map of Indonesia showing the location of the experiment site at Tanjung Kodok, Java.

site was located at Tanjung Kodok (see Fig. 2) near Surabaya, Indonesia (5°S), approximately at sea level. The experiment was conducted by North Carolina State University (NCSU) as part of the U.S. Solar Eclipse Expedition.

The eclipse times were: first contact at 1000 h LST (local standard time); second contact at 1133 h LST; third at 1138 h LST; with the eclipse ending at 1300 h. The timing was almost perfect because of the symmetrical occurrence about local noon. Weather was good on the day of the eclipse except for a fast developing thunderstorm near fourth contact. There was precipitation in the area immediately after the end of the eclipse associated with large scale instability.

The objective of this experiment was to study boundary layer dynamics through the wind, temperature, and moisture data. Whereas Raichur was primarily a dry site, the Java measurement area was within about 0.5 km of water with air arriving from a cross-water fetch, which could affect observations at upper levels of the PBL. The instruments used during the experiment consisted of the following:

(a) a 6 m micrometeorological tower supporting a single instrument boom with instrumentation at 6 m. Mean wind speed was measured by a cup anemometer, velocity fluctuations by a fast response Gill propeller anemometer, vertical angle by a bidirectional vane, and mean temperature by a thermistor. In addition, a fast response temperature sensor was used for measuring temperature fluctuations;

(b) a miniradiosonde, balloon data collection system was used for the PBL soundings. This provided mean temperature and moisture profiles;

(c) surface humidity was measured using sling psychrometers;

(d) and the soil film temperature during different phases of the eclipse was determined using a thermistor.

The analog data were digitized and recorded on a data logger at the rate of $10\ \mathrm{s}^{-1}$.

3. OBSERVATIONS OF MEAN AND TURBULENT STATISTICS

The short-wave radiation pattern for Raichur, India on the eclipse day (Fig. 3) reveals an eclipse-induced minimum at second contact, which in turn caused a complete turnaround in the PBL energy flux, surface temperature, static stability, and wind regimes. Fifteen min average values of the sensible surface heat flux, $H=\rho c_p \overline{w\theta}$, 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. 4. The dotted line shows the variation observed at the site on 17 February, a non-eclipse day.

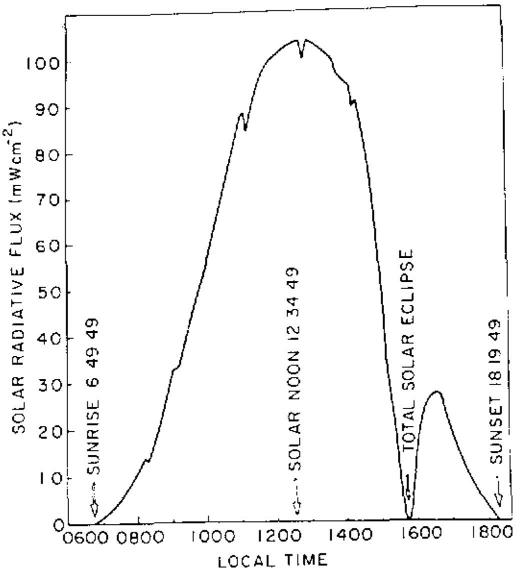

Fig. 3. Incoming short wave pattern for the eclipse day, 16 February 1980 at Raichur, India.

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-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 in general just before sunset with reduced radiation due to a low angle of the sun.

Temperature variations at a height of 1.3 m for the eclipse day (16 February) and a non-eclipse day (17 February) are presented in Fig. 5. For a non-eclipse day (17 February), the general diurnal temperature variation indicates a peak of 34°C. This peak occurred at around 1530 h followed by a 1°C h^{-1} temperature decrease. During the day of the eclipse the temperature increased at the normal rate until first contact, but during the period of solar eclipse, the output energy flux density by net long-wave radiation loss soon exceeds the tapering short wave radiation, resulting in an almost immediate surface temperature drop of about 2°C h^{-1}. Therefore, the lowest layers of the atmosphere respond thermally to the eclipse on a time scale of the order of minutes. The eclipse induced minimum temperature (30.5°C at this height) occurred approximately at the time of totality (1545 h). By fourth contact (1655 h) the mean temperature had increased to the usual daily value.

Interestingly, after the eclipse was over, the temperature started decreasing steeply (2.5°C h^{-1}) relative to a non-eclipse day (1.4°C h^{-1}). By 2000 h, 3 h after fourth contact, the temperature was 3°C lower than normal which suggests an additional time scale of the order of a few hours. A similar variation of the mean temperature occurred at the 2.25 m height.

Variation of the standard deviation of temperature fluctuations (σ_T) at 2.25 m (not shown) for 16 and 17 February indicate that σ_T decreases rapidly after first contact, and remains low thereafter till 2000 h at least. The standard deviation of the velocity fluctuations σ_u (shown in Fig. 6) lags behind σ_T, but has dropped significantly by the time of totality. This lag of about 30 min between the response of velocity and tempera-

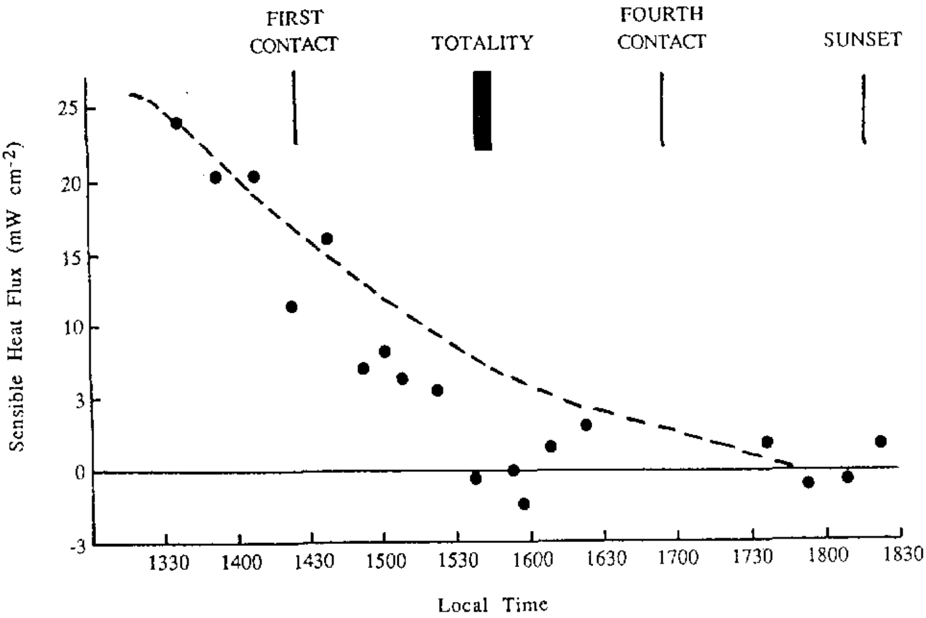

Fig. 4. Time variation of averaged surface sensible heat flux at Raichur, India for eclipse day (dots) and non-eclipse day (line).

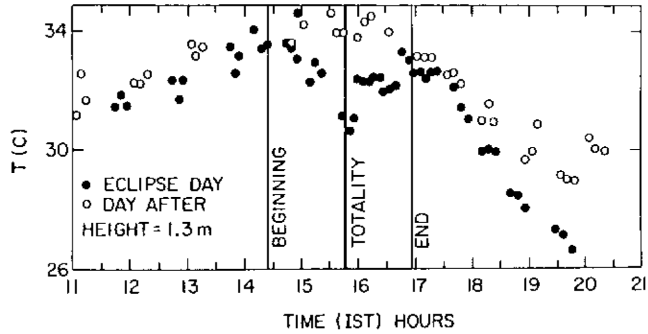

Fig. 5. Time history of mean temperature (T) at 1.3 m, after Narasimha *et al.* (1981).

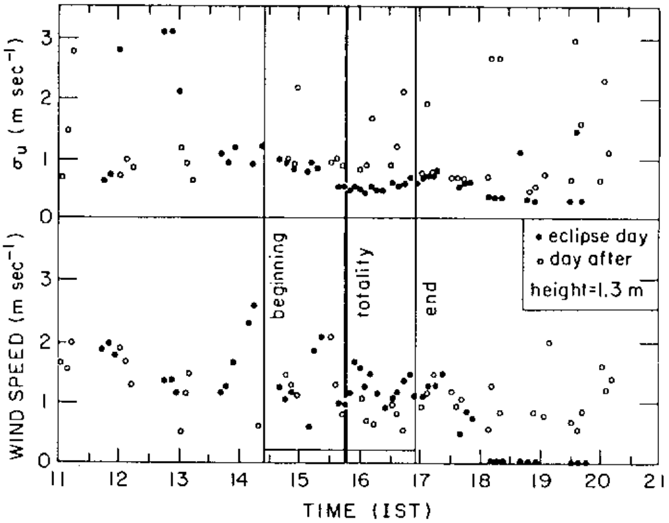

Fig. 6. Time history of U and σ_u at 1.3 m, after Narasimha *et al.* (1981).

ture fluctuations has been observed earlier during a partial eclipse (Antonia *et al.*, 1979). Measurements at other levels on the 12 m tower indicated similar features.

The changes in the surface layer during the eclipse can be understood in terms of the variations in the atmospheric boundary layer thermal stability due to changes in solar radiation. The morning and early afternoon boundary layers were quite unstable and convective until immediately after totality, thereafter unstable conditions returned rather quickly in response to gradually increasing solar radiation and the boundary layer became convective again. Figure 7 shows the variation of the Monin–Obukhov similarity parameter, z/L, for different phases of the eclipse. Essentially z/L behaved in the same way as the surface heat flux. Values of L varied from about -22 m to $+100$ m. Variations in turbulence and surface heat flux in the surface layer are consistent with the changes in the atmospheric stabilities. Values of u_* and σ_w at 6.8 m decreased by a factor of about four just before totality and increased again after the third contact. The surface layer solar radiation response time seems to be of the order of a few (< 10) min.

Mean temperature profiles to a 3 km height measured with the miniradiosondes are shown in Fig. 8. On 15, 16 and 17 February the inversion-capped height of the convective mixed layer was approximately 2800 m. However, on the day of the eclipse (16th), a second inversion appeared at about 2100 m for two ascents, one (1520–1550 h) near totality and the other (1615–1645 h) toward the end of the eclipse. The first period approximately coincided with the time when stable conditions existed in the surface layer. According to Kaimal *et al.* (1976) and Caughey and Kaimal (1977) the transition to negative heat flux occurs first in the upper regions of the boundary layer, propagating downward to the surface. This is likely to be in some way related to the variations in scales of convective eddies due to changes in solar radiation received by the earth's surface (SethuRaman, 1981). The temperature profile after fourth contact does not show the second inversion, indicating buildup of the convective boundary layer once again.

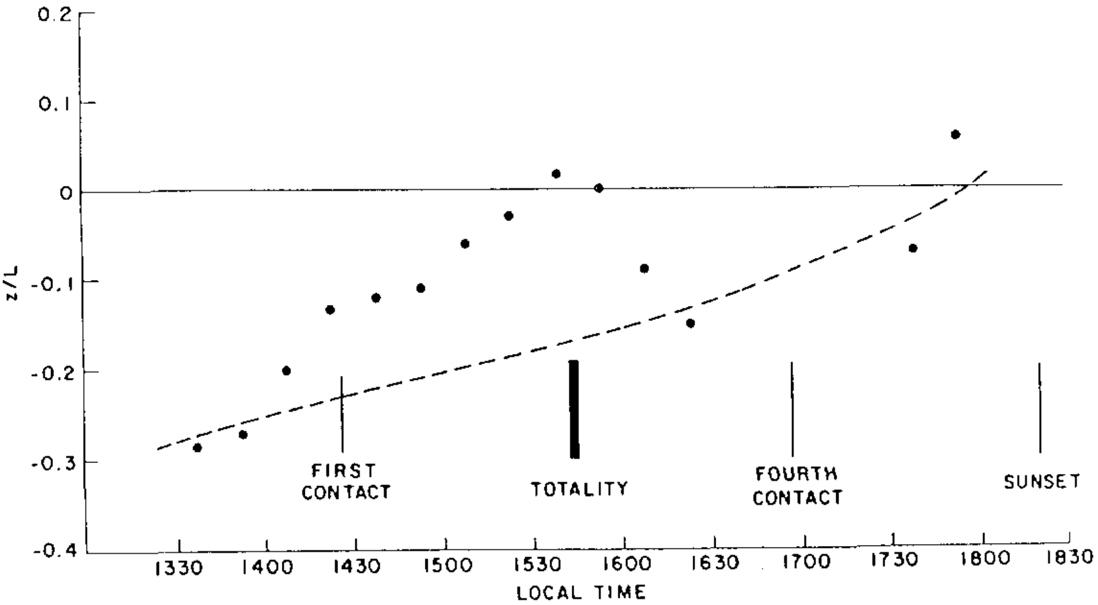

Fig. 7. Variation of stability parameter (z/L) at Raichur, India. Dots denote the eclipse day and the dashed line is for a non-eclipse day.

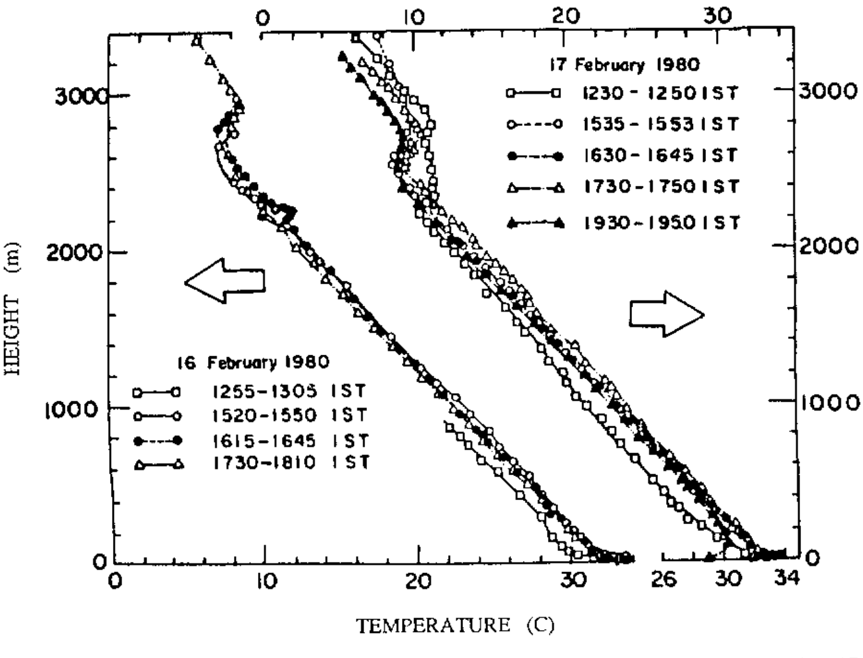

Fig. 8. Comparison of temperature profiles on eclipse day (16 February) vs non-eclipse day (17 February).

A qualitative meteorological observation of importance was that a few, puffy, fair weather cumulus which developed in the morning dissipated around 1530 h and reformed just a few minutes before totality. This may be related (in a manner not yet clear) to the temperature structure variations discussed above, thus suggesting significant changes in boundary layer processes when solar radiation is reduced to zero during a period of the order of 1 h or less.

Horizontal temperature variations in the earth–atmosphere system give rise to horizontal pressure differences, which result in motion (winds). From Fig. 1, one can observe that there are large areas over which the net insolation would have been lower on the eclipse day. Thus, many of the observed changes in the wind field, especially after totality, may be due to local or mesoscale circulations induced by the eclipse's travelling cold spot. However, at this time there is no

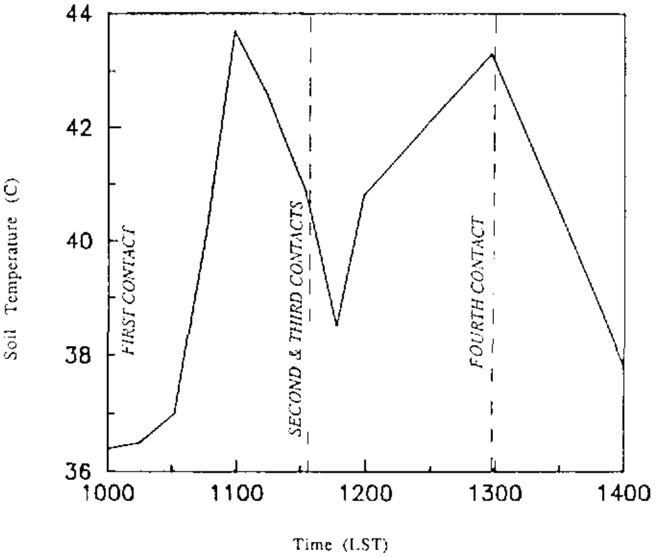

Fig. 9. Time variation of soil film temperature at Java site on 11 June 1983.

satisfactory theoretical model to account for the phenomenon reported here.

For example, the wind speed at a height of 1.3 m (Fig. 6), showing appreciable variation during the eclipse, is, if anything, rather higher between the 3rd and 4th contacts than on a normal day (Narasimha *et al.*, 1981). On the other hand, beginning around 1800 h (an hour after 4th contact) the wind speed drops rapidly by an order of magnitude. Measurements at the site on a non-eclipse day after about 1900 h, showed a wind direction shift, from southeasterly to easterly, and a wind velocity increase to 5–6 m s^{-1}. Large values of σ_u also indicated a transition between the two wind regimes. These winds are believed to be associated with katabatic flow from low hills about 3 km east of the site. Yet, on the day of the eclipse, these strong nocturnal winds were missing. This is probably due to eclipse-induced cooling of relevant layers and subsequent suppression of the necessary thermal differences that drive the winds.

The surface temperature time history at Tanjung Kodok is shown in Fig. 9. The temperature continues to increase well past first contact (1000 h LST), eventually rising to 44°C before suddenly falling to 38°C a few minutes past totality (1133–1138 h). Shortly after this the temperature begins to recover its normal daily form. The rapid cooling after 4th contact is due to a local thunderstorm that occured around 1330 h.

Potential temperature profiles in the boundary layer (Fig. 10) further illustrate the effects of the eclipse. The early morning profile clearly shows evidence of strong surface heating. A superadiabatic lapse rate still prevails in the surface layer well past first contact. However, by the time of second contact (1133 h), a surface-based inversion has developed. Five minutes after 3rd contact, the stable layer has deepened although is no longer very strong. Before the eclipse ends (1245 h) the superadiabatic lapse rate has returned to the surface layer.

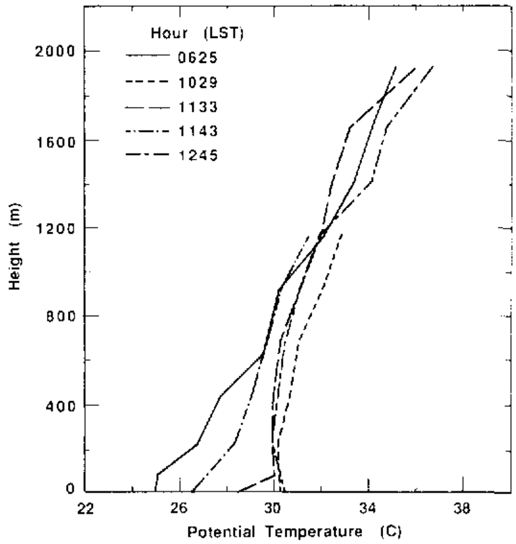

Fig. 10. Potential temperature profiles at Java, Indonesia on 11 June 1983.

Spectra of vertical velocity fluctuations at 0915 h (before first contact), 1115 h (between first and second contacts), 1142 h (12 min inclusive of the totalicity), and at 1240 h (between third and fourth contact) are shown in Fig. 11. They clearly show the expected changes in energies of eddies as the eclipse-induced boundary layer evolved.

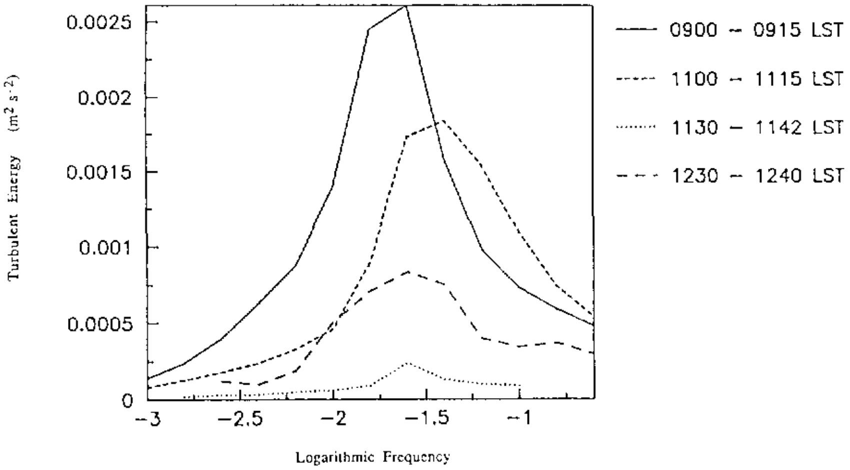

Fig. 11. Spectral energy during eclipse period at Java on 11 June 1983—*w* component.

4. NUMERICAL SIMULATIONS

The observations, discussed above, show that the PBL responded quickly to the changes in thermal forcing at the surface resulting from the total solar eclipse. There was a marked difference in the structure of the boundary layer as the solar radiation diminished between the first and second contacts, and again when it increased between the third and fourth contacts. It would be interesting to study how a simple numerical model simulated the structure of the PBL as the surface heat flux was varied through the period of a total solar eclipse.

A one-dimensional, time-dependent, second-order closure PBL model (Wyngaard and Cote, 1974; Wyngaard *et al.*, 1974) was used to simulate the CBL during the 1980 solar eclipse. Starting with approximate neutral profiles corresponding to morning transition, the equilibrium neutral profiles were generated first. Then the CBL was simulated using a specified surface heat flux variation based on observations.

The PBL model consists of exact equations for the mean horizontal wind components (U, V) and potential temperature (Θ), and a full set of turbulence equations (for momentum and heat fluxes, and viscous dissipation rate) which are closed approximately. The turbulence time scale used in these closure approximations is determined by the model itself, as the ratio of the turbulent kinetic energy to the viscous dissipation rate, and not specified externally. The lower boundary conditions are based on relations derived from surface-layer similarity theory and measurements from field experiments (Businger *et al.*, 1971; Panofsky *et al.*, 1977). At the upper boundary, which lies within the elevated inversion, all turbulence quantities and vertical gradients of mean variables are set to zero. A description of this PBL model, including the model equations and boundary conditions for different thermal stratifications, can be found in Rao and Snodgrass (1978).

The closed equation of 14 coupled partial differential equations, subject to the specified boundary and initial conditions, was numerically integrated in time on a digital computer using a Dufort–Frankel explicit finite difference scheme. To obtain a fine computational mesh near the ground, a logarithmic transformation of the vertical coordinate was used to a height of 210 m after which a linear transformation was used up to the upper boundary at 3100 m.

The PBL simulation was driven by the specified surface heat flux variation shown in Fig. 12, where fourth-order polynomials were used to match the observations almost exactly for the two days that were modeled. Table 1 shows surface layer comparisons between observations and model predictions. The model predicts u_* and σ_w better than σ_u.

Computed variances σ_u^2, σ_v^2 and σ_w^2 for the non-eclipse day (17 February) at 10 m are illustrated in Fig. 13a. All components showed a steady decline after their peak at local solar noon (1300 h). On the eclipse day (Fig. 13b), the interruption by the solar eclipse was obvious within the surface layer at 1600 h. Variances decreased by a factor of 5 near totality. Maximum variances calculated in the boundary layer during the

Table 1. Comparison of observed (O) surface layer parameters with model (M) predictions for the 16 February 1980 solar eclipse at Raichur, India

IST (h)	u_* (cm s^{-1})		σ_u (cm s^{-1})		σ_w (cm s^{-1})		Eclipse phase
	M	O	M	O	M	O	
1400	42	35	102	43	92	70	
							Contact 1
1500	39	34	82	58	74	64	
							Contact 2 Contact 3
1600	29	20	53	17	41	20	
							Contact 4
1800	27	28	47	32	35	28	

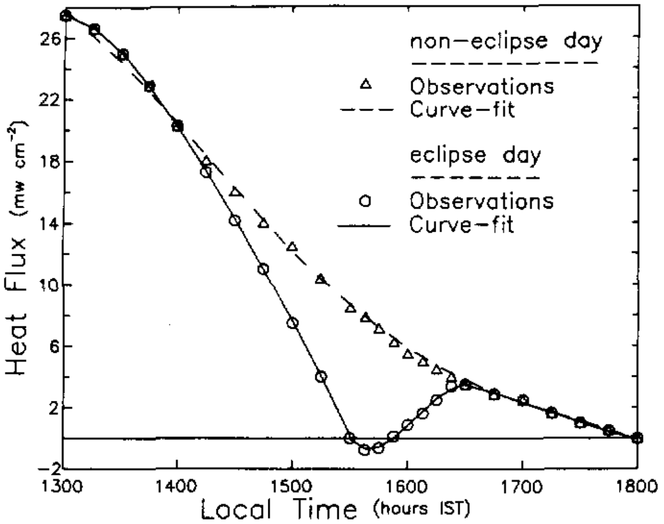

Fig. 12. Surface heat flux at Raichur, India (observed vs polynomial fitted).

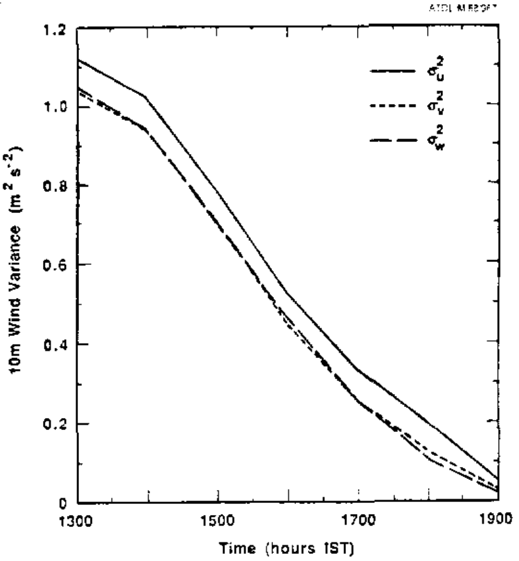

Fig. 13a. Time history of model wind components variance at Raichur, India (non-eclipse day).

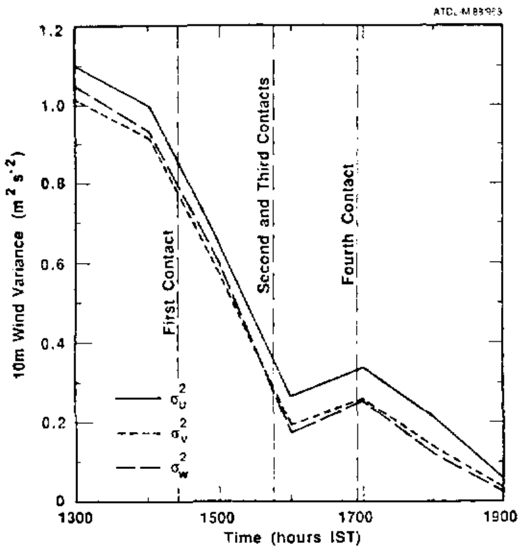

Fig. 13b. Time history of model wind components variance at Raichur, India (eclipse day).

non-eclipse day and during the day of the eclipse (not shown) indicated that σ_w^2 did not rebound back to normal day values as well as σ_u^2 or σ_v^2. This suggests that vertical buoyant energy was especially damped by diminution of solar radiation. Figure 14 shows the calculated vertical profiles of all three variances near totality; they were smaller at practically every level up to 3000 m on the eclipse day.

A comparison of the model-predicted vs observed potential temperature profiles for the non-eclipse day is shown in Fig. 15. The most important feature was that the lapse rates agreed quite well: the model generated an adiabatic profile in the mixed layer which also coincided with observations. The differences in magnitudes could be adjusted by specifying a different, initial average PBL temperature in the model. However, the model could not account for the development of the second (lower) inversion which was observed on the eclipse day (see Fig. 8), as this phenomenon was poorly understood. Observations of winds aloft would have been useful in improving the simulations since the model provided for specifying the geostrophic wind variation in the input. The pilot-balloon wind data, collected by another organization participating in the Raichur experiment, were irretrievably lost; the only data available were from the surface

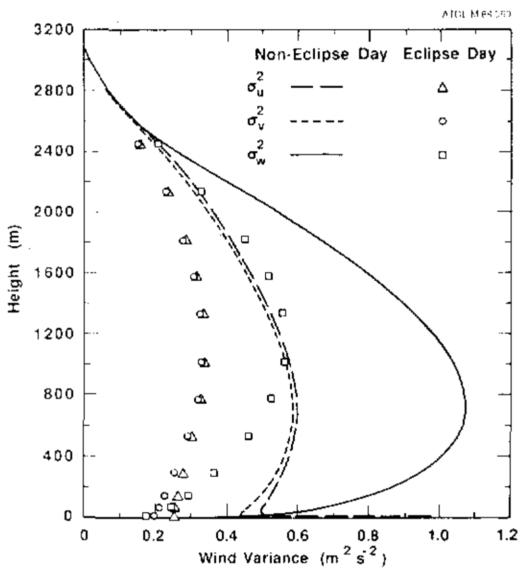

Fig. 14. Comparison profiles of model values of wind variance ($m^2 s^{-2}$) near second contact on eclipse day vs non-eclipse day at Raichur, India.

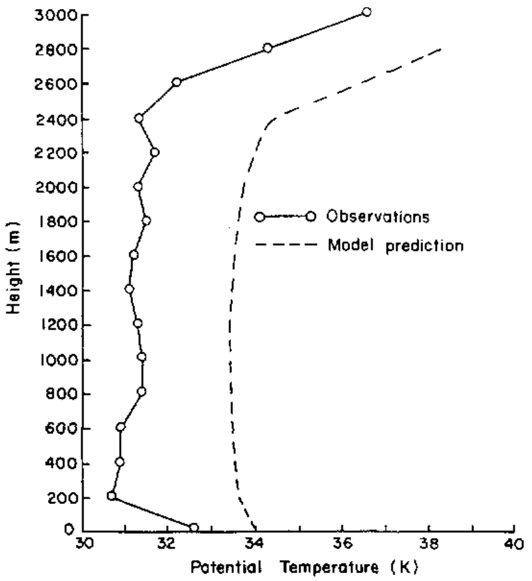

Fig. 15. Model predicted vs observed potential temperature profiles for the non-eclipse day at Raichur, India.

layer, and these showed the model predictions of mean winds to be high.

As mentioned before, because of the proximity of a large body of water, Java Sea (Fig. 2) for the 11 June 1983 eclipse, simulations by the one-dimensional model may not be appropriate and hence was not attempted.

5. CONCLUSIONS

The planetary boundary layer responded to eclipse-induced changes in surface heat flux by rapidly decreasing mean air temperature in the surface layer resulting in the formation of a shallow surface-based inversion. The response time of the surface layer to changes in solar radiation appears to be less than 10 min. Changes in temperature variance, σ_T^2 preceded velocity variances, σ_u^2, σ_v^2 and σ_w^2 by about one-half hour. Turbulence parameters σ_u^2, σ_v^2 and σ_w^2 decreased by a factor of 4–5 near eclipse totality.

Overall, the one-dimensional PBL model is very helpful in providing insight into the evolving PBL. It simulates the atmospheric stability changes and the turbulence structure in response to varying surface heat flux. It fills in many gaps left in the data allowing one's basic intuition to be scientifically verified.

However, the development of a secondary lower inversion near totality during the collapse of the daytime boundary layer was not handled well by the model due to the lack of the necessary external forcing. The downward directed heat flux probably first develops in the upper layers and rapidly progresses toward the surface as the solar radiation diminishes. This phenomenon needs further study to facilitate its incorporation into PBL models.

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