

QBO or the ENSO. The second mode is close to the 60-year cycle noted in earlier work. The present analysis suggests the existence of an 80-year quasi-cycle as well; those with average periods of 12 and 22 years invite an obvious association with sunspot cycles.

It is significant that the 120-year rainfall time series data analysed here shows clear evidence of 7 prominent modes in the monsoon rainfall. None of these is strictly periodic, but the allowance for scale modulation in wavelet analysis permits us to identify quasi-cycles (with jittery periods) more clearly than with any spectral method.

A more detailed analysis, showing the evolution of each quasi-cycle over time, and the identification of different regimes in the rainfall time series in different regions of India, will be published elsewhere<sup>20</sup>.

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## Evolution of an atmospheric boundary layer at a tropical semi-arid station, Anand during boreal summer month of May – A case study

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The evolution of an Atmospheric Boundary Layer (ABL) over a semi-arid land station, Anand, (22°35'N, 72°55'E, 45.1 masl) in India, during the summer month of May, is examined using surface meteorological and radiosonde temperature and humidity data collected during LASPEX-97 for a 5-day period from 13–17 May 1997. These 5 days remained undisturbed, and clear sky weather conditions prevailed. However, the data obtained on these days are helpful in understanding the diurnal variation of the ABL over a land station. There are 5 observations per day at an interval of 3 h beginning with 0530 IST. The 0530 IST ascents are chosen to find out the initial ABL heights which exhibit the nocturnal cooling conditions. It is observed from the analysis of  $\theta_v$ ,  $\theta_e$ ,  $\theta_{es}$ ,  $q$ , and  $P$  profiles that the nocturnal boundary layer is stable with an inversion close to the ground. The top of an inversion layer is characterized by a  $\theta_e$  minimum and a  $\theta_{es}$  maximum. After dawn, the ABL grows to a height of 827 m at 0830 IST. Aloft, a residual layer up to ~3200 m is observed. The daytime strong insolation causes formation of an unstable boundary layer close to the ground at 1130 IST with an elevated stable layer between 550 and 930 m. It is only by 1430 IST that the stable layer gets completely wiped out and a convective mixed layer develops up to a height of 3280 m. Lack of moisture inhibits formation of clouds. Hence the ABL at a semi-arid station like Anand is stable in the morning with residual layer aloft and develops into a dry convective boundary layer in the afternoon and evening. Growth of the convective boundary layer (CBL) is observed to be very rapid as it reaches a height up to 3280 m by the afternoon.

THE Atmospheric Boundary Layer (ABL) is that region of the atmosphere where the influence of the ground can be felt through turbulent exchanges of momentum, heat and moisture fluxes. The ABL forms due to interactions between the atmosphere and the underlying surface over a time period of a few hours to about one day. The depth and stability characteristics of the ABL vary temporally on the diurnal, meso, synoptic and seasonal scale and spatially due to changing characteristics of the underlying surface and also due to intensity of the weather patterns. A number of observational studies<sup>1,2</sup> and numerical mod-

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elling experiments<sup>3,4</sup> have shown the importance of ABL processes in the development and maintenance of tropical systems. Although the ABL comprises only a small fraction of the atmosphere, the processes occurring within the ABL are of profound importance to weather forecasting and climate studies, air pollution, micrometeorology, agriculture meteorology and physical oceanography.

A number of field experiments have been conducted on the land in mid-latitudes (Wangara 1967, Kansas 1968, Oklahoma 1983, KONGEX 1995) or over the tropical Pacific and Atlantic Oceans (Atlantic Tropical Experiment, ATEX 1969; Global Atlantic Tropical Experiment, GATE 1974). Over the Indian Ocean, the International Indian Ocean Expedition (IIOE, 1963–1965), ISMEX-73, MONSOON-77, MONEX-79, and Monsoon-88 focused on the study of the Arabian Sea and the Bay of Bengal marine ABL. To study the structure of monsoon ABL over the land and its interaction with the monsoon trough a Monsoon Trough Boundary Layer Experiment (MONTBLEX) was conducted in 1990 (refs 5 and 6). The MONTBLEX has provided useful insight into thermal and wind structures in the monsoon trough boundary layer<sup>7,8</sup>. However, the structure and evolution of ABL over land during pre-monsoon is not fully understood for want of

systematic surface flux and ABL data during the pre-monsoon period. In order to understand the evolutionary processes that take place in the ABL over a time frame of one year, a Land Surface Processes Experiment (LASPEX) was conducted from January 1997 to March 1999 in the Sabarmati river basin in Gujarat, India. This was a part of the project of the Department of Science and Technology (DST), Government of India. This experiment has provided very useful data comprising surface, subsoil, micrometeorological, tower and radiosonde observations, from which we have used only radiosonde and tower observations in the present study for the pre-monsoon month of May 1997. In this study, we have attempted to understand the evolution of the thermal and moisture structures of the ABL during daytime with the marching of the sun in the horizon from dawn to sunset for a period of 5 days from 13 to 17 May 1997. This study also gives an insight into the problem of understanding the effect of solar heating on the ABL development and is useful for comparison of ABL in subsequent monsoon months.

In 1997, a LASPEX was conducted in Sabarmati river basin in Gujarat<sup>9</sup>. The location map of the experimental site is shown in Figure 1. The station Anand is centrally located among 5 stations, viz. Khandha, Arnej, Derol, Sanad and Anand. Geographically, the site lies in a semi-arid region having a gentle slope from north to south and is surrounded by agricultural fields. Sabarmati and Mahi are two major rivers which flow across the area. The soil texture is of clay type in the south (Khandha, Arnej) and sandy type in the north (Derol and Sanad). In 1997, radiosonde observations were taken by India Meteorological Department at Anand at 5 synoptic hours, from 00 to 12 UTC at an interval of 3 h during an intensive observational period from 13 to 17 of every month. The radiosonde observations consist of pressure, temperature, humidity, wind speed and direction at a vertical resolution of 200 m (20 hPa). During the period from 13 to 17 May 1997, dry weather with clear skies prevailed over the region. No synoptic weather system affected the Gujarat region. A trough up to 0.9 km asl was seen from west Rajasthan to north Assam across north Madhya Pradesh and Bihar. Maximum temperature over Gujarat for the week ending on 21 May 1997 was 37°C, 2°C above normal.

The primary reason for selecting the month of May is due to the fact that it is the hottest month of the year in

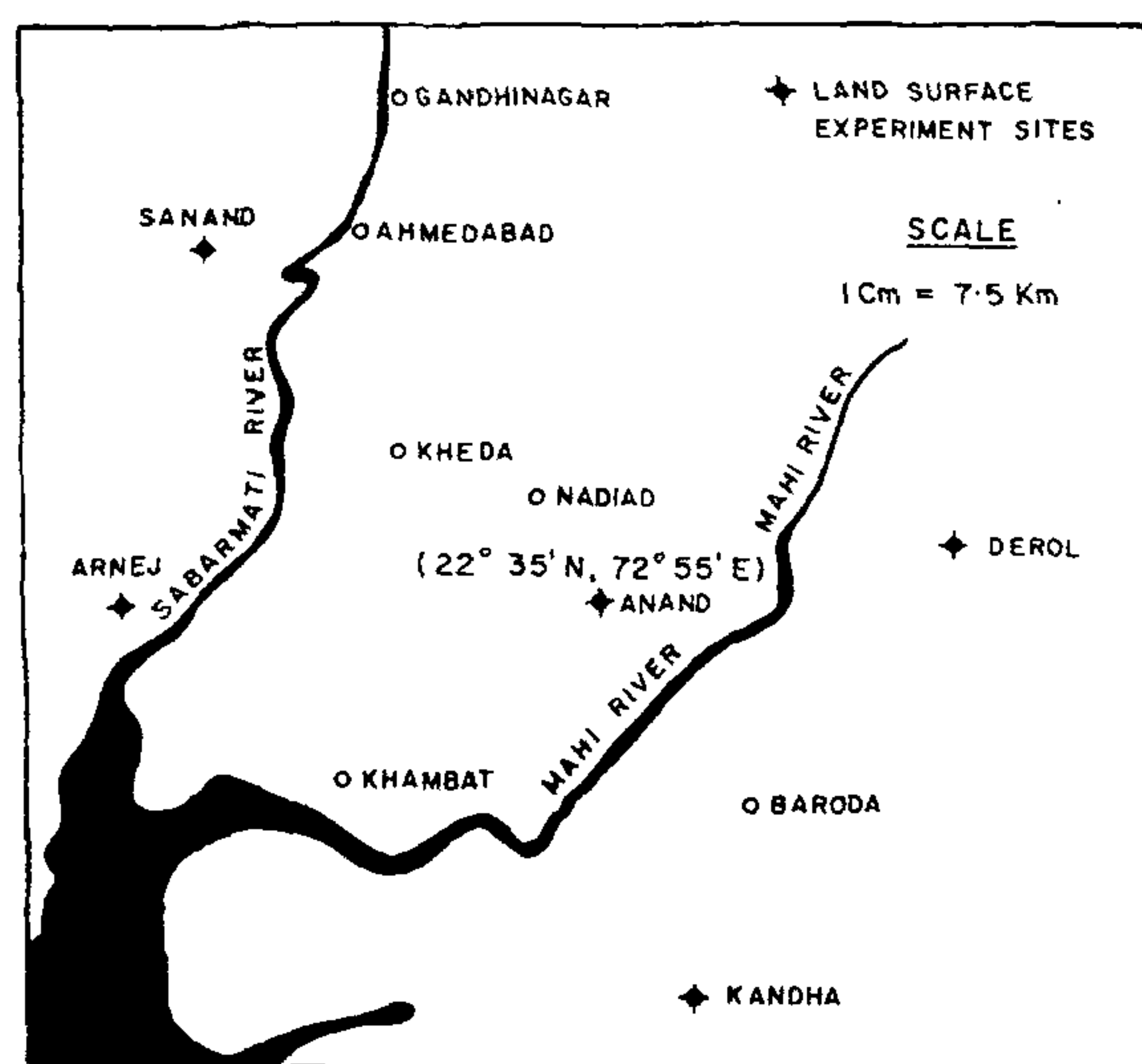


Figure 1. Location of experimental sites in the Sabarmati river basin.

Table 1. Surface mean meteorological parameters at Anand during 13–17 May 1997

Time (IST)	0530	0830	1130	1430	1730
Mean sea level pressure (hPa)	1003.2	1004.5	1004.3	1002.8	1001.0
Ground temperature (°C)	23.8	37.2	52.5	55.6	43.5
Air temperature (°C)	22.5	28.7	36.2	38.8	38.2
Relative humidity (%)	84	49	31	18	21
Mixing ratio (g/kg)	13.9	12.5	10.1	7.7	8.5
Sensible heat flux (W/m <sup>2</sup> )	-45	53	268	227	38

Gujarat and is also ideal for understanding the dry convective processes that associate with the evolution of the boundary layer under dry and hot weather conditions. The boundary layer heights during the period of observation are assessed by computing various thermodynamic parameters ( $\theta_v$ ,  $\theta_e$ ,  $\theta_{es}$ ,  $q$ ,  $p^*$  and  $\mathcal{P}$ ), as discussed later in the article. Standard formulae are used to compute these variables<sup>10</sup>.

On the days of clear skies most of the solar energy is transmitted to the ground with typical absorption of the order of 90% and little solar radiation is absorbed in the free atmosphere. It is the ground that warms and cools in response to this incoming solar radiation which in turn forces the change in the boundary layer height through transport processes. Desert and semi-arid regions in the

tropics are characterized by a high range of diurnal variation of temperature and other meteorological parameters. Mean sea level pressure (MSLP), mean ground temperature, air temperature (at 1.2 m), relative humidity (RH), mixing ratio ( $q$ ) and sensible heat flux ( $Q_H$ ) at 5 synoptic hours, viz. 0530, 0830, 1130, 1430 and 1730 IST are shown in Table 1. The mean ground temperature for the period 13–17 May at Anand varies from 23.8°C at 0530 IST to 55.6°C at 1430 IST giving a diurnal range of 32°C. The MSLP varies from 1001.0 to 1004.5 hPa, the RH varies from 18 to 84%, the air temperature varies from 22.5 to 38.8°C and  $Q_H$  varies from  $-45$  to  $268 \text{ Wm}^{-2}$ .

The radiosonde observations were used to compute thermodynamic parameters such as virtual potential temperature  $\theta_v$ , equivalent potential temperature  $\theta_e$ , saturated

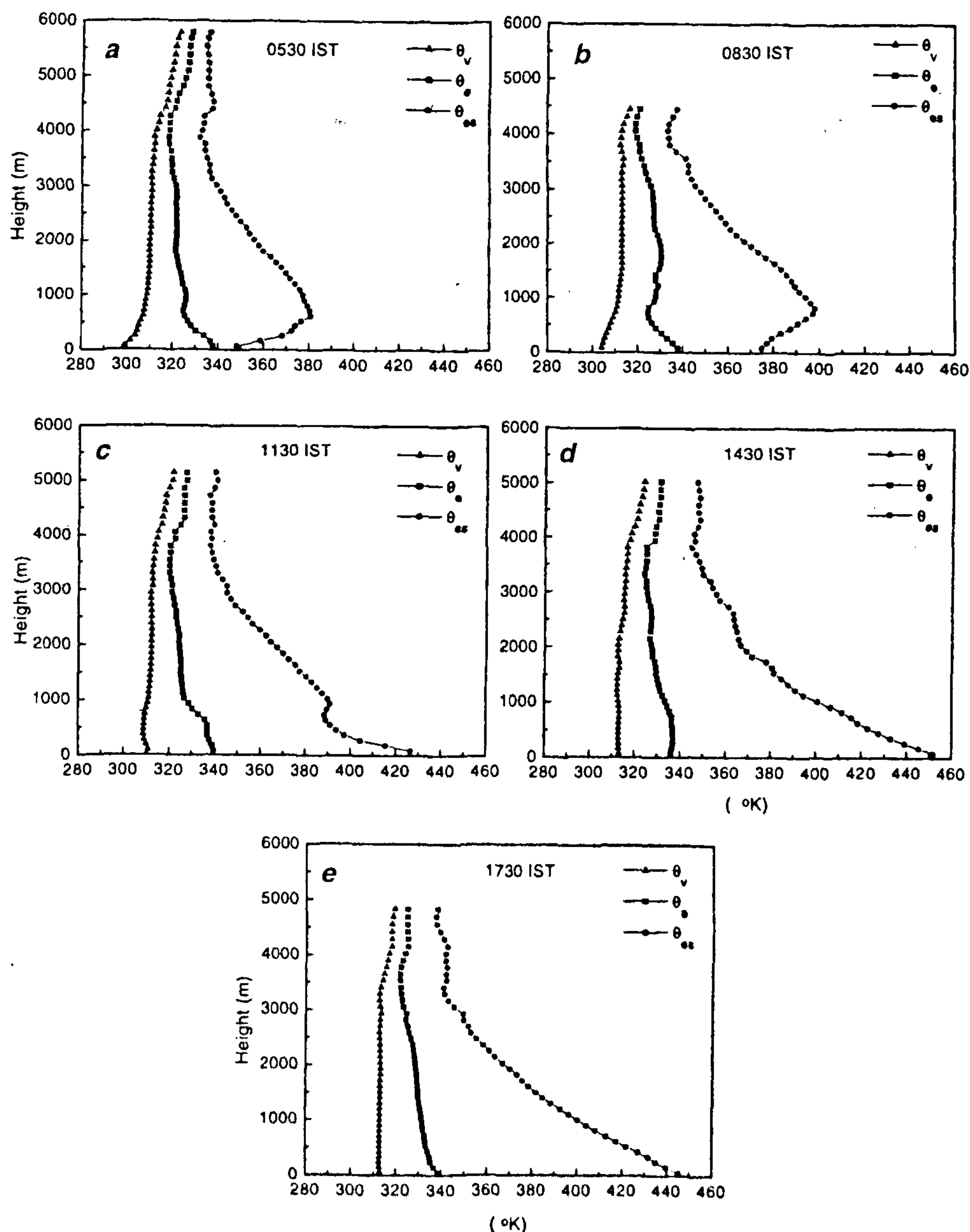


Figure 2. Daytime mean variation of  $\theta_v$ ,  $\theta_e$  and  $\theta_{es}$  at Anand during 13–17 May 1997.

equivalent potential temperature  $\theta_{es}$ , saturation point pressure  $p^*$  and saturation pressure departure  $P = p^* - p$ . The constant  $\theta_v$  line gives the extent of mixed layer heights whereas  $\theta_{es}$  is useful to identify the base of the stable layer. In some earlier studies of the CBL over the Pacific Oceanic region, it was found that the minimum and maximum values of  $\theta_{es}$  coincided with the base and top of the inversion, respectively<sup>11</sup>. Low level stability can be assessed with  $\theta_e$  and  $\theta_{es}$  profiles<sup>12</sup>.  $p^*$  and  $P$  are useful parameters to determine the cloud base and cloud top.  $P$  gives the level of sub-saturation. The mean profiles of thermodynamic parameters  $\theta_v$ ,  $\theta_e$  and  $\theta_{es}$  at 5 synoptic hours for the period 13–17 May 1997 are shown in Figure 2,

and  $q$  and  $P$  profiles are shown in Figure 3. Features giving details of the type and height of the ABL, the height of Lifting Condensation Level (LCL),  $\theta_e$  minimum,  $\theta_{es}$  maximum and  $P$  minimum are summarized in Table 2. The LCL is assumed as the lowest level from where clouds tend to form by an adiabatic ascent of an air parcel from the ground surface. It is seen that the height of mean LCL varies from 627 m to 3280 m between 0530 and 1730 IST, the height of  $\theta_e$  minimum varies from 711 to 3525 m, the height of  $\theta_{es}$  maximum varies from 506 to 3700 m and that of  $P$  minimum varies from 711 to 3650 m during the course of the day from 0530 IST to 1730 IST.

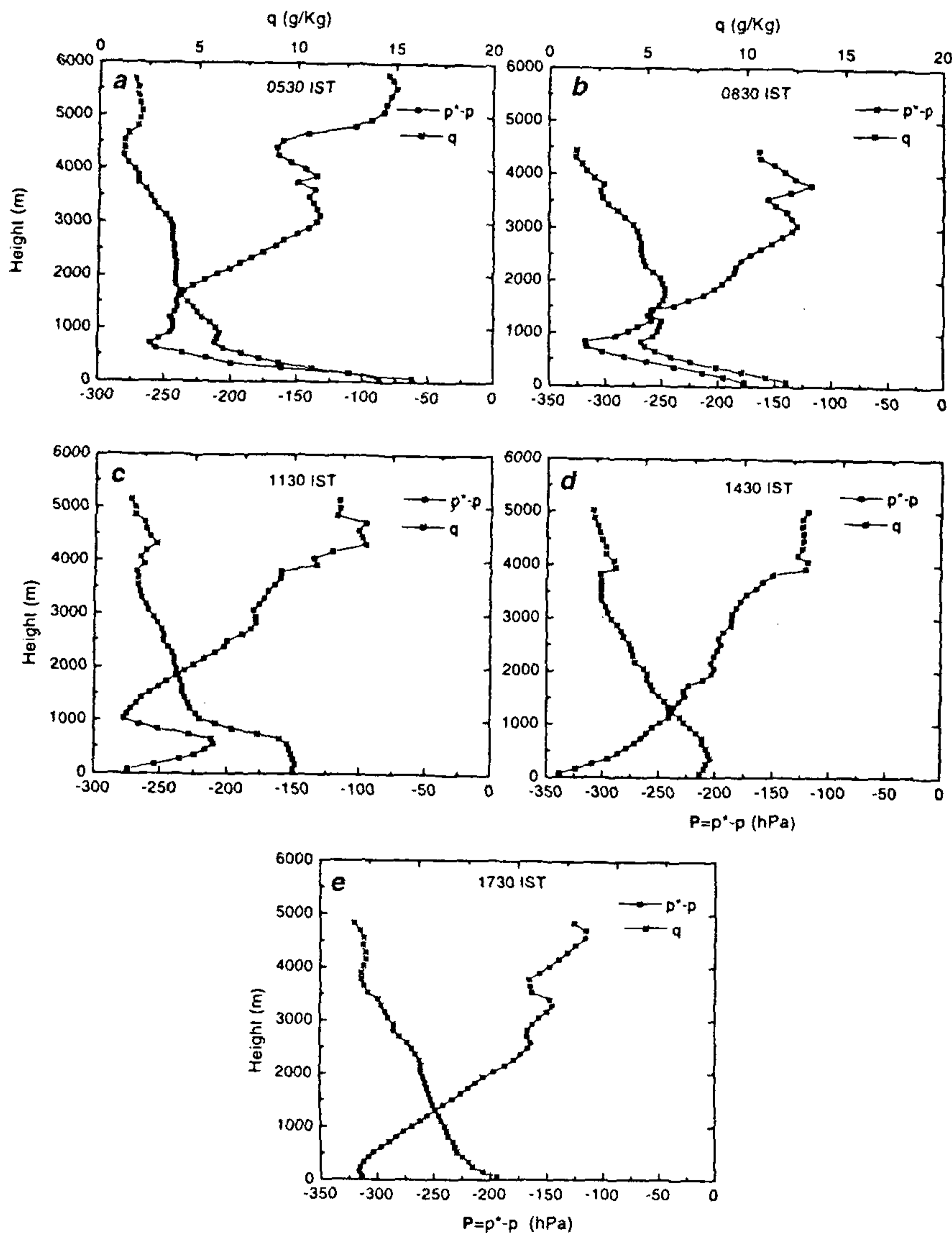


Figure 3. Daytime mean variation of  $P$  and  $q$  at Anand during 13–17 May 1997.

During a boreal summer night, the atmospheric layer close to the ground surface is transformed into a stable boundary layer by its contact with the cold ground surface. Radiational cooling from the ground surface plays an important role in the formation of a nocturnal stable boundary layer. The depth and intensity of the stable layer depends upon the amount of radiational cooling from the ground. The mean sunrise time at Anand between 13 and 17 May 1997 was 0557 IST. Thus the 0530 IST (00 UTC) profile in Figure 2 *a* is representative of the night time conditions. It is characterized by a well-defined inversion up to 940 hPa (506 m). The top of this inversion is marked by  $\theta_{es}$  maximum and  $\theta_e$  minimum<sup>11</sup>. The sharp decrease in  $q$  (18 g/kg/km) is seen in Figure 3 *a*. It is capped by a stable layer between 940 and 890 hPa in which increase in  $\theta_v$  (< 2.5 K/km) and a gradual decrease in  $q$  (1.5 g/kg/km) are observed. With these two layers together, ABL from the surface to 890 hPa (1080 m) is found to be statistically stable. A residual layer of thickness (~ 2100 m) is seen extending from 890 to 690 hPa (3250 m). It is the remanent part of previous day's mixed layer which starts eroding near the surface just before the sunset as the thermals cease to form<sup>13</sup>. It leads to the formation of stable layer close to the ground, topped by the residual mixed layer. During the night due to radiational cooling, the nocturnal stable layer gradually increases in thickness by modifying the bottom of the residual layer. The top of the neutral residual layer is marked by a stable layer, displaying gradual increase of  $\theta_v$ .

By 0830 IST, the ground warmed up by 13–15°C and sensible heat flux increased from  $-45 \text{ W/m}^2$  at 0530 IST to  $53 \text{ W/m}^2$  at 0830 IST. This increase in ground temperature and sensible heat flux is not able to wipe out strong inversion as seen from Figure 2 *b*. It causes a decrease in lapse rate of the inversion layer from 18°C/km at 0530 IST to 9°C/km at 0830 IST. At the same time the top of the inversion layer increases from 500 to 827 m. The top of the inversion is also supported by  $\theta_{es}$  maximum and  $\theta_e$  minimum. The inversion layer is capped by the stable transition layer up to 1527 m. The thickness of the residual layer is reduced to 1880 m when compared to 2100 m at 0530 IST (Figure 2 *b* and Figure 3 *b*).

Further, due to continued solar heating between 0830 and 1130 IST, the ground temperature rises by another

15°C. This results in a significant increase in the sensible heat flux from  $53 \text{ W/m}^2$  at 0830 IST to  $268 \text{ W/m}^2$  at 1130 IST giving rise to intense thermals. These thermals wipe out the inversion layer close to the ground and an unstable layer develops up to 546 m as seen by a decrease of  $\theta_v$  in Figure 2 *c*. It displays the characteristics of a mixed layer having nearly constant  $\theta_v$  and  $q$  profiles. The unstable layer is topped by a stable layer up to 930 m having a positive gradient of  $\theta_v$  (Figure 2 *c*) and a sharp decrease in  $q$  (Figure 3 *c*).  $\theta_{es}$  maximum and  $\mathcal{P}$  minimum coincide with the top of the stable layer. The residual layer persists up to 3270 m topped by a stable layer.

Maximum ground temperature of about 56°C is recorded around 1430 IST which thereafter decreases slowly. The sensible heat flux and thermals attain their peak value between 1130 and 1430 IST primarily by the energy drawn from the underlying surface. Figure 2 *d* shows the growth of unstable layer at 1430 IST resulting in the complete erosion of the stable transition layer. In this process it gets linked up with the residual layer and the entire layer from the surface to 3200 m becomes a CBL with  $\theta_v$  lapse rate < 1 K/km (Figure 2 *d*). It exhibits a minor gradient in the  $q$  profile (Figure 3 *d*) and thus does not present a well-mixed layer in a classical sense (having constant  $\theta_v$  and  $q$  profiles)<sup>13</sup>.

Towards the late afternoon and early evening, the incoming solar radiation tends to reduce to its minimum value. Following this reduction in the solar heating, the air temperature also tends to decrease simultaneously due to the decrease in ground surface temperature. Hence, there is a reduction in the sensible heat flux. At Anand, the ground surface temperature dropped by about 12°C from 1430 IST to 1730 IST.  $Q_H$  decreased from  $227 \text{ W/m}^2$  at 1430 IST to  $38 \text{ W/m}^2$  at 1730 IST. Consequently, the ground-based convection weakens and ceases the growth of the CBL height. The  $\theta_v$  profile in Figure 2 *e* shows a well-mixed layer up to a height of 3200 m and this height is nearly the same as the observed CBL height at 1430 IST. A stable capping layer is seen above the mixed layer. The top of the stable capping layer shows minor flat minimum of  $\theta_e$  and maximum of  $\theta_{es}$  and  $\mathcal{P}$  minimum (Figure 3 *e*). It is worth noting that well-marked capping inversion and associated distinct  $\theta_e$  minimum and  $\theta_{es}$  maximum are observed in marine CBL<sup>11</sup>, where sharp decrease in moisture and increase in temperature are seen just above the cloud

Table 2. ABL features at Anand during 13–17 May 1997

Time (IST)	0530	0830	1130	1430	1730
Layer type	Inversion/stable	Inversion/stable	Unstable (mixed)	Mixed	Mixed
Thickness (m)	506/1029	827/1527	546	3206	3280
LCL height (m)	627	1562	2868	3640	3280
Height of $\theta_e$ minimum (m)	711	730	3187	3600	3525
Height of $\theta_{es}$ maximum (m)	506	827	937	–	3700
Height of $\mathcal{P}$ minimum (m)	711	827	1028	–	3650

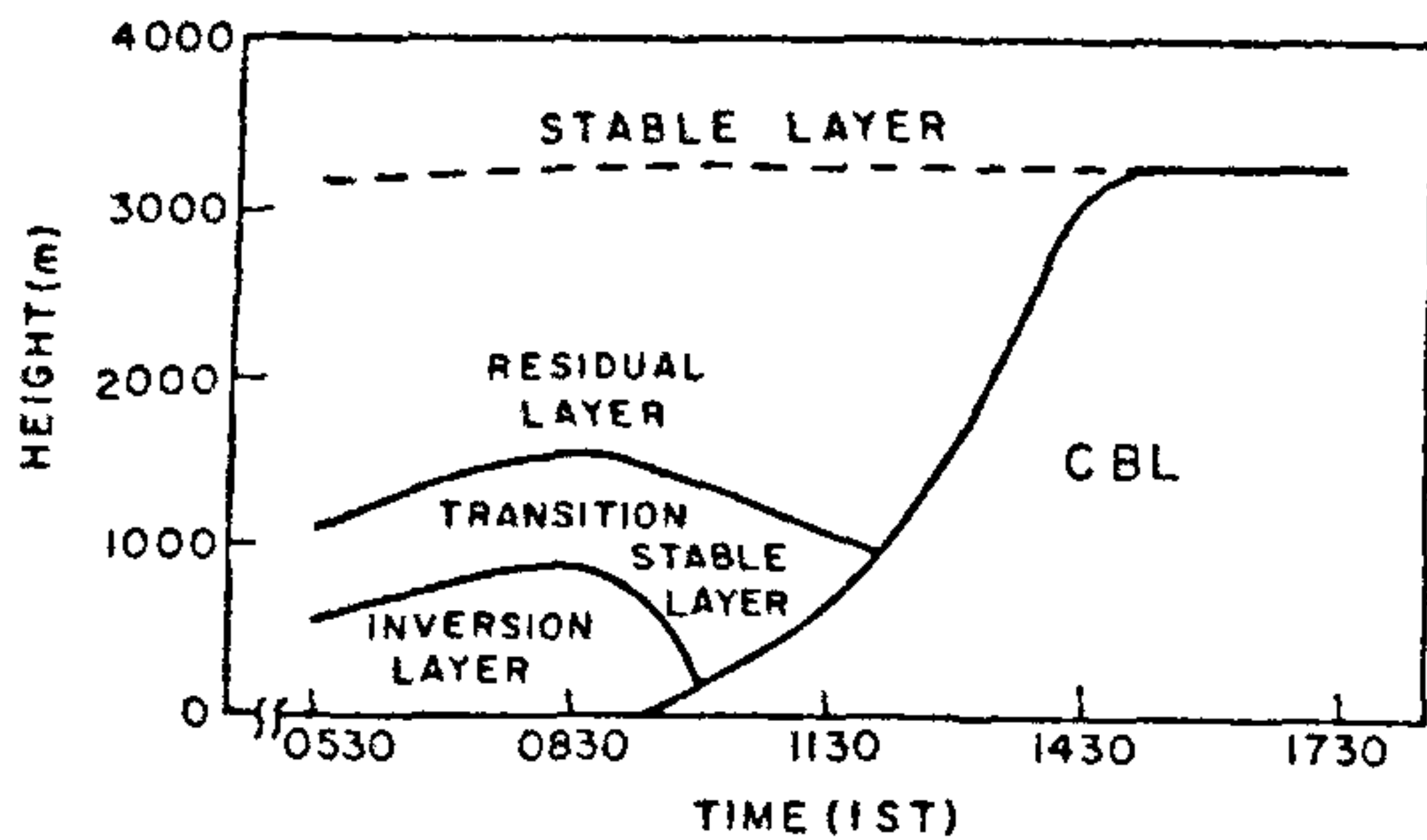


Figure 4. Schematic diagram of daytime variation of ABL at Anand, during summer (13–17 May 1997).

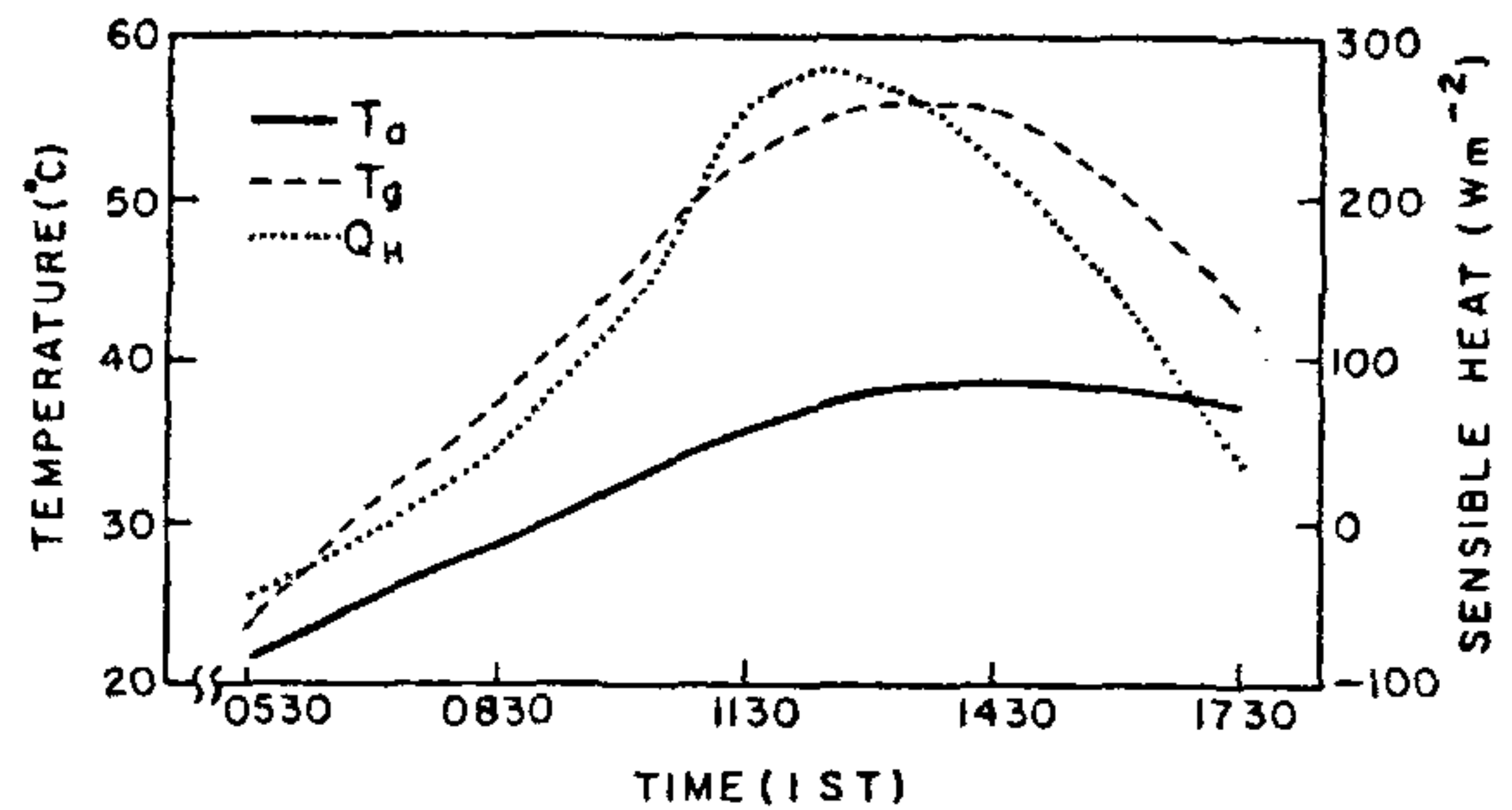


Figure 5. Diurnal variation of air temperature at 1.2 m ( $T_a$ ), mean ground temperature ( $T_g$ ), and sensible heat flux ( $Q_H$ ) at Anand during 13–17 May 1997.

top. In a dry convective CBL, transition from mixed layer to free atmosphere is not very sharp. In fact, in the late evening profile (Figure 3 e), the mixing ratio remains constant above the mixed layer. This is one of the reasons for the absence of distinct  $\theta_e$  minimum and  $\theta_{es}$  maximum in CBL profiles of our study. Primarily because of lack of moisture, LCL heights are observed to be very high, inhibiting the formation of clouds. At 1430 and 1730 IST, the LCL heights are in close agreement with the top of the CBL and thus represent dry convective conditions in the afternoon.

It is seen from the above discussion that the dry atmospheric boundary layer shows marked diurnal variation in stability characteristics and height in response to surface heating and cooling. It is observed that the boundary layer at 0530 IST consists of a surface inversion and stable transition layer topped by a residual layer and on the other hand, in the afternoon by 1430 IST it becomes entirely CBL. Thus during the course of the day four types of layers are observed in the ABL at Anand, viz. inversion layer, transition layer, residual layer, and CBL. A schematic representation of the evolution of the different layers in the ABL is depicted in Figure 4. The corresponding daytime variations of mean ground temperature, air temperature and sensible heat flux are shown in Figure 5. Though basic features like stable nocturnal boundary layer, residual layer and convective mixed layer are similar to those observed in mid-latitudes<sup>13,14</sup>, the thickness of various layers is significantly different. The stable nocturnal boundary layer extends up to 1500 m at 0830 IST and the CBL grows rapidly up to 3200 m at 1430 IST. Growth of the CBL is in phase with the rise of ground temperature and sensible heat flux confirming that during an undisturbed dry period the evolution of CBL is mainly controlled by surface forcings.

The evolution of the ABL over a tropical semi-arid station, Anand during boreal summer has been studied using LASPEX-97 data for 5 days, 13–17 May 1997. The following chief features were noticed during the study of this undisturbed period.

The evolution of ABL is governed mainly by surface insolation. The stable layer grows up to a height of 500 m. It is capped by a thick (1500 m) residual layer up to 3000 m. Surface insolation causes formation of an unstable layer close to the ground by 1130 IST, with elevated stable layer between 550 and 930 m. By 1430 IST the stable layer is completely wiped out and a convective mixed layer develops up to a height of 3200 m. Unlike sharp gradients of  $\theta_v$  and  $q$  above the mixed layer observed in mid-latitudes, the tropical atmosphere over Anand, a semi-arid region, shows a gradual changeover to the free atmosphere from the mixed layer.

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