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Impact of low level clouds on convective boundary layer equilibrium structure

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A study has been carried out using the concepts of saturation point and conserved variable plots utilising the aerological observations collected at an inland station, Pune (18°32′N, 73°51′E, 559 m a.s.l.) during the summer monsoon seasons of 1980 and 1981 to investigate the impact of low level clouds on equilibrium structures in the atmospheric boundary layer (ABL). The days have been categorized according to the distribution of clouds vis-a-vis equilibrium structure of ABL. The study suggested a close association between amount of clouds in the lower atmosphere and the thermodynamical characteristics of ABL. The results of the study are discussed.

1 Introduction

Boundary layer cloudiness influences the earth atmosphere radiation budget and hence plays an important role as far as the thermodynamics of the convective boundary layer (CBL) is concerned. The parametrization of the zonally-averaged annual longwave flux at the top of the atmosphere, in terms of surface temperature and cloud cover, showed that the amount of cloud cover exerts a considerable feedback effect on the net radiation[1]. Although the clouds reflect less incoming shortwave radiation, they cover a large area and thus play an important role in the boundary layer equilibrium by transporting water vapour upwards and enhancing the surface evaporation[2,3]. The studies[2,3] documented the internal structure of the different cloud regimes and also showed that the transition between broken cumulus and stratocumulus is associated with a distinct change in thermodynamical structure. Also, the use of conserved variable diagrams (θ_{SL} vs q_{SL}) was demonstrated[3].

During 1982, concept of saturation point (SP) to represent the moist thermodynamics was introduced[4] and its usefulness in understanding the cloud processes in terms of conserved thermodynamic variables was illustrated. Also, a new insight into atmospheric mixing instabilities and thermodynamic equilibrium was given by simplifying the representation of cloud-clear air mixing processes.

For the first time, it was proposed that mixing line slopes would give a useful categorization of different cloud regimes and their stabilities[4]. This was confirmed from the observations made at the coast of southern California[3]. In the present studies an attempt has been made to examine this by using the aerological observations carried out during two consecutive summer monsoon seasons of 1980 and 1981 at a tropical location in India. Further, the purpose of this paper is to show the usefulness of plots of conserved variables, i.e. (q_{SL} vs θ_{SL}) in determining the transitions in stability of the mixing line associated with different cloudiness in the CBL.

2 Location of observations

Special aerological observations were carried out at Pune (18°32′N, 73°51′E, 559 m a.s.l.) during the summer monsoons of 1980 and 1981, in connection with the warm cloud seeding experiments conducted by the Indian Institute of Tropical Meteorology, Pune, over the Deccan Plateau region. Each year the observations were made daily during convective conditions between 1130 and 1200 hrs IST from the last week of June to the first week of September. There are, in all, 162 radiosonde ascents during the above two-year period, which have been used in this study. These observations were taken from the surface up to 500 hPa at an interval of 50 hPa. The meteorological conditions responsible for rainfall over Pune and topography of the region are described elsewhere[5].

3 Method of analysis

The transition in thermodynamic structure associated with transition in cloudiness from a clear sky through tiny cumulus and broken stratocumulus to a solid stratocumulus deck is explored using θ_{SL} vs q_{SL} plots[3]. The remarkable feature of the observational area considered in the above study[3] is the transition from a clear sky in the west through tiny cumulus and broken stratocumulus to solid stratocumulus in the east. The observational data were collected through NCAR Electra aircraft. Four categories considered in the above paper[3], classified on the basis of cloud regimes, were: clear, cumulus, broken and stratocumulus. In order to study the thermodynamic structure associated with different cloud regimes over the Indian inland station, the observations were classified into four different categories for both the years, viz. 1980 and 1981, separately. These categories were made on the basis of the type of low level clouds reported in *Indian Daily Weather Reports* published by India Meteorological Department. The four categories Cu, Cb, Sc and St represent cumulus, cumulonimbus, stratocumulus and stratus clouds, respectively (hereafter referred to as categories I to IV). There were 15, 20, 31 and 16 soundings, respectively, in the four categories, i.e. I to IV, during the year 1980 and 17, 20, 40 and 3 soundings, respectively, during the summer monsoon of 1981. The average values of temperature (T, °C) and dew point temperature (T_d, °C) from surface up to 500 hPa at an interval of 50 hPa in the respective categories were used to compute the thermodynamic parameters such as potential temperature (θ_{SL},°C), mixing ratio (q_{SL}, gm kg^{-1}) and pressure (p_{SL}, hPa) at the level of saturation. Also, some other thermodynamical parameters such as virtual potential temperature (θ_v,°C), saturation pressure deficit (P^*, hPa) and wet virtual potential temperature (θ_{ev},°C) were computed. The computational procedure for the above parameters is described as follows.

Potential temperature (θ) and potential temperature at saturation level (θ_{SL}) is given by

$$\theta = \theta_{SL} = T\left(\frac{1000}{p}\right)^{0.286} \quad \dots (1)$$

and mixing ratio (q) is given by

$$q = q_{SL} = 622 \times \frac{e}{p-e} \quad \dots (2)$$

$$e = 6.11 \times 10^{\left[\frac{7.5\ T_d}{T_d + 237.3}\right]}$$

where, e is the pressure due to water vapour and p is the pressure of the air parcel; T and T_d are in °C.

Virtual potential temperature (θ_v) is given by

$$\theta_v = \theta\ (1 + 0.61q) \quad \dots (3)$$

The level where an unsaturated air parcel becomes saturated with the available moisture when lifted dry adiabatically is termed as saturation level (SL). Thermodynamical parameters at this level, viz. pressure (p_{SL}), temperature (T_{SL}), potential temperature (θ_{SL}), saturation pressure deficit (P^*) are computed using the following formulae.

$$T = T + 273.16$$

$$T_d = T_d + 273.16$$

$$T_c = T_d - 0.62 \times (T - T_d)$$

$$G = \frac{15.77\ T_c}{2501 - 2.37\ T_d}$$

$$H = \frac{T - T_d}{9.76 - G}$$

$$T_{SL} = T - 9.76 \times H$$

$$p_{SL} = 1000 \times \left(\frac{T_{SL}}{\theta}\right)^{3.4965}$$

$$P^* = p_{SL} - p \quad \dots (4)$$

Here, T_c, G and H are intermediate terms. The procedure for computation of wet virtual adiabat (θ_{ev}) is described elsewhere[3].

4 Results and discussion

Thermodynamic characteristics representative of the CBL over the Deccan Plateau region for the four categories have been investigated using mixing parameter β, vertical profiles of P^*, and conserved variable diagrams (q_{SL} vs θ_{SL}). A detailed account of each one of them is given in the following subsections.

4.1 Saturation pressure deficit (P^*)

Figure 1[(a) and (b)] shows mean vertical plots of P^* (i.e. p_{SL} - p) against pressure (p) for the categories I-IV during the summer monsoons of 1980 and 1981, respectively. This P^* is a very useful parameter and a good indicator of amount of saturation present in the layer. Negative values of P^* are associated with lack of saturation, i.e. subsaturation and positive values of P^* indicate cloudiness, i.e. supersaturation. From these values of P^* it is evident that the cloud layer deepened from category I to IV during both the years.

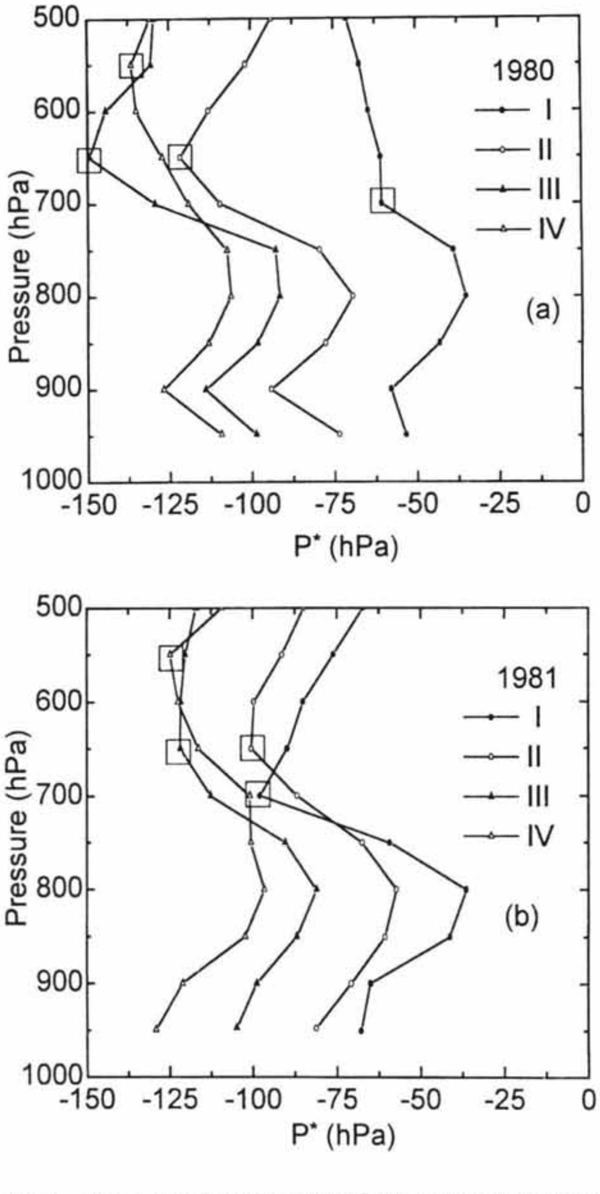

Fig. 1—Mean vertical profiles of P^* for the categories I-IV during the year (a) 1980 and (b) 1981 over Pune region [The profiles are shifted by −25 hPa from categories II-IV. The CBL top is marked by a square in all the profiles.]

From the comparison of P^* for the years 1980 and 1981 it is observed that the CBL is more saturated during 1980 as compared to 1981 at all levels in all categories except in the category I. The lifting condensation level (LCL) shifts to lower levels during both the years (listed in Table 1) from category I to IV. However, LCL is observed at higher levels during the year 1981 as compared to those during 1980. This indicates lack of moisture in the surface layer during 1981 as compared to 1980. The different sublayers, viz. subcloud layer, cloud layer and capping stable layer in the CBL are characterized by different slopes of P^*. For example, the CBL top is associated with the minimum value of P^*, whereas cloud layer is characterized by nearly constant values of P^*. During 1980 the strength of the stable layer, which is above the cloud layer, increases from category I to III and it is found to be minimum in the category IV. The top of the CBL during categories I to IV is found to be at 700, 650, 650 and 550 hPa (Table 1), respectively, during both the years. However, P^* minima is not clearly seen in category I during 1980. Similar CBL structure was observed over the Pune region in case of four categories, viz. isolated, scattered, fairly widespread and widespread, which were classified according to aerial rainfall of the region[5].

4.2 Parameter β

The parameter β, which characterizes the vertical thermodynamic structure of the CBL, is defined as $\beta = \frac{\partial p_{\mathrm{SL}}}{\partial p}$. This represents the gradient of P^*. The value of $\beta = 0$, represents a well-mixed layer, $\beta < 1$ is a layer not as well-mixed in which T and T_{d} (or θ and q) converge towards the mixing line and $\beta = 1$ is a partially mixed structure in which the T and T_{d} profiles are approximately parallel to the mixing line. The value of $\beta > 1$ represents the divergence of T and T_{d} from the mixing line which is the characteristic of the transition at the top of a convectively mixed layer to the free atmosphere[2]. The parameter β is computed for the categories I-IV for the years 1980 and 1981. The category-wise distribution of β and extent of each layer, i.e. subcloud, cloud and stable layers are presented in Table 1. In Table 1, top of the CBL, LCL height and slope of the mixing line (linear fit) in each category during both the years are also given. It is observed that β is greater than 1 in the subcloud layer in all the categories during 1980, whereas during 1981 it lies between 0.78 and 0.94. Thus, subcloud layers during the year 1981 are better mixed as compared to those during the year 1980. These values in the subcloud layer are higher compared to the value of 0.3 as suggested by the investigation carried out over the Equatorial Pacific region[6]. But they are of approximately the same order ($\beta = 0.76$) as obtained over the Pune region[7]. In the present case, the higher values of β observed in subcloud layer may be the characteristic of monsoon boundary layers. These values suggest that the subcloud layers are not well-mixed since well-mixed layers are characterized by β=0. In cloud layers, β lies between 0.7 and 0.94, and it is found to

Table 1—Thermodynamic and SP parameters at different levels

Parameters	1980				1981			
	I	II	III	IV	I	II	III	IV
Subcloud layer								
β	1.09	1.43	1.32	1.36	0.94	0.78	0.87	0.84
Extent (hPa)	948-900	948-900	948-900	948-900	950-900	947-900	947-900	949-900
Cloud layer								
β	0.77	0.75	0.86	0.87	0.71	0.87	0.94	0.86
Extent (hPa)	900-800	900-800	900-750	900-750	900-800	900-800	900-750	900-750
Stable layer								
β	1.25	1.35	1.57	1.15	1.61	1.29	1.31	1.12
Extent (hPa)	800-700	800-650	750-650	750-550	800-700	800-650	750-650	750-550
CBL top (hPa)	700	650	650	550	700	650	650	550
LCL height (hPa)	895.4	900.0	900.0	914.1	882.5	891.4	892.4	895.3
Slope of ML	−0.76	−0.84	−0.99	−1.55	−0.70	−0.92	−0.99	−1.40

be highest in the stable layers overlying the cloud layer in all categories. However, in case of category IV, values of β are observed to be minimum in the stable layers as compared to other categories during both the years.

4.3 q_{SL} vs θ_{SL} diagrams

Thermodynamic profiles on a conserved variable diagram of q_{SL} against θ_{SL} are shown in Fig. 2 [(a) and (b)] for the four categories I - IV during the years 1980 and 1981, respectively. Constant wet virtual adiabat (θ_{ev}) line (thick solid line) is also shown. In all the profiles, below cloud base, the mixing line is nearly parallel to the q_{SL} axis in all the categories during both the years and indicates drastic drop in mixing ratio. This may be due to the drying of the subcloud layer. From cloud base up to the CBL top (marked by square) nearly linear mixing line with characteristic slopes can be seen in all the conserved variable plots. The mixing line is very unstable with respect to wet virtual adiabat (θ_{ev} = 340 K) in case of categories I and II during 1981 [Fig. 2(b)]. Whereas mixing line is slightly unstable with respect to constant θ_{ev} line in case of category III and is nearly parallel to the θ_{ev} line in case of category IV [Fig. 2(b)]. Thus, mixing line showed gradual increase in stability from category I to category IV [Fig. 2(b)] during 1981. This means that the mixing line in the CBL shifts towards the wet virtual adiabat to attain equilibrium from category I to IV. Mixing lines on conserved variable plots showed similar trend during 1980 [Fig. 2(a)] as is observed during 1981. However, during the year 1980 more moisture was present at all levels as compared to the year 1981. This may be due to the fact that better monsoon activity was observed during 1980 as compared to 1981.

The (q_{SL} vs θ_{SL}) profiles through the CBL are slightly curved. Therefore, a linear regression line fit was used from surface to the top of the CBL. The CBL top is marked by a square in all the categories. The slope of the mixing line during 1980 is found to be −0.76, −0.84, −0.99 and −1.55 in categories I to IV, respectively. These slopes are −0.7, −0.92, −0.99 and −1.4 during 1981 (listed in Table 1). Thus, from these values it is observed that mixing line slopes increase from category I to category IV which indicates that mixing line structure tries to attain equilibrium from category I to category IV during both the years.

5 Summary

The investigations carried out using the aerological observations during the summer monsoon season over the Deccan Plateau region by applying concepts of saturation point and conserved variables explored the variation in thermodynamical characteristics of CBL in the four categories of clouds (I-IV). The investigations showed the following:

(i) The P^* profiles indicated increase in cloud layer depths (from 900-800 to 900-750 hPa), decrease in strength of the stable layers overlying the cloud

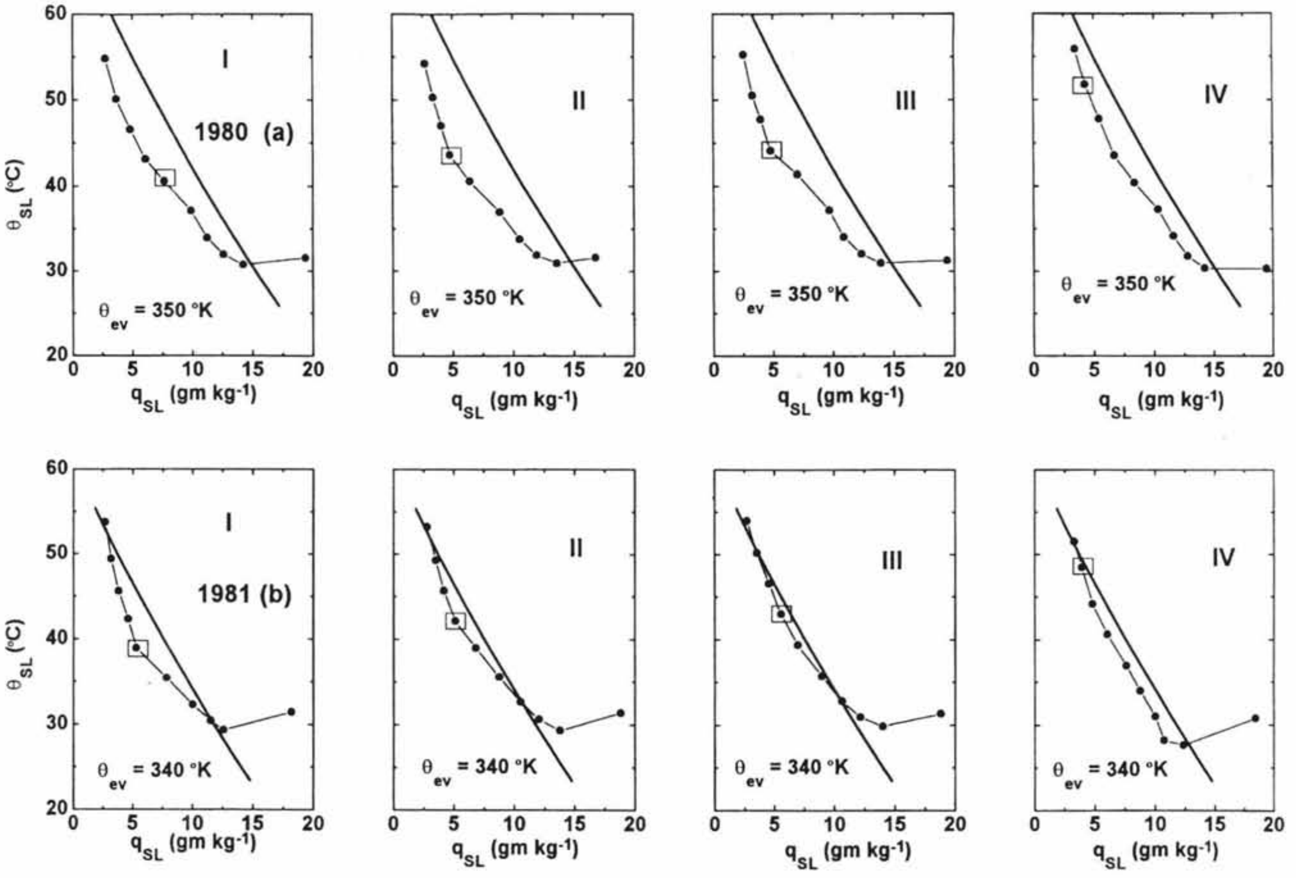

Fig. 2—Conserved variable plots (q_{SL} vs θ_{SL}) for the categories I - IV during the year (a) 1980 and (b) 1981 [The thick solid line represents the constant wet virtual adiabat (θ_{ev}). The top of the CBL is marked by a square in all the plots.]

layer and increase in the extent of the CBL from category I to IV (from 700 to 550 hPa), i.e. from cumulus clouds to stratus clouds.

(ii) The high values of gradient of P^* (>0.78) suggested that the subcloud layers were not well-mixed in all the categories. The values of β were found to be minimum in the cloud layers and maximum in the stable layers overlying the cloud layers.

(iii) Conserved variable diagrams for the four categories showed increase in mixing line slopes from category I to IV (−0.76 to −1.55 during 1980 and −0.70 to −1.40 during 1981) indicating increase in boundary layer equilibrium structure. This indicates that, with the increase of cloudiness in the lower atmosphere, the CBL structure shifts towards the wet virtual adiabat. This study clearly confirms that mixing line slope would give a useful categorization of different cloud regimes and their stability. In other words, this study clearly shows the impact of low level clouds on the equilibrium structure of the boundary layer. However, the results obtained from aerological observations may be representative of conditions during two consecutive summer monsoon seasons. These investigations may be further confirmed with different database collected for the region under different cloud regimes.

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