MIXED-LAYER CHARACTERISTICS AS RELATED TO THE MONSOON CLIMATE OF NEW DELHI, INDIA

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Abstract. Annual variations of mixed-layer characteristics at New Delhi, India have been studied for a weak monsoon (1987) and a strong monsoon (1988) year. In the weak monsoon year (1987), the maximum mixing depth h_{max} was found to have a value of around 3000 m during the pre-monsoon, less than 2000 m during the summer monsoon, around 2000 m during the post-monsoon, and less than 1000 m in the winter season. For the strong monsoon year (1988), h_{max} values were less than 1987 values for comparable periods throughout the year. The seasonal and yearly differences of h_{max} were explained by the surface energy balance and potential temperature gradient γ at a time close to sunrise. According to the spatial patterns of γ obtained by an objective analysis of the 850 to 700 hPa layers, mixed-layer characteristics obtained at New Delhi are representative of the north and central regions of India.

1. Introduction

Gamo (1986) studied climatic differences of mixed-layer characteristics as related to prevailing weather types at Tsukuba, Japan. In the present study, the seasonal variations of mixed-layer characteristics are investigated with respect to synoptic features at New Delhi, where the climate varies from rather cold to very hot, and the moisture varies from dry to wet.

In general, four seasons occur over the Indian subcontinent, that is, a hot (pre-monsoon) season from March to May, a monsoon season (summer southwest) from June to September, a warm dry post-monsoon season from October to November, and a winter (monsoon) season from December to February. However, there is a large year-to-year variation among these seasons. A year with abundant rainfall during the summer monsoon is termed a strong monsoon year, while a year of largely deficient rainfall is called a weak monsoon year. The year 1987 was classified as a very weak monsoon year, while 1988 was found to be a strong monsoon year.

In this paper, mixed-layer characteristics, including the maximum mixing depth h_{max}, the surface sensible heat flux H, the energy balance components within the mixed layer, and the potential temperature gradient γ of the upper stable layer which caps the mixed layer, are investigated.

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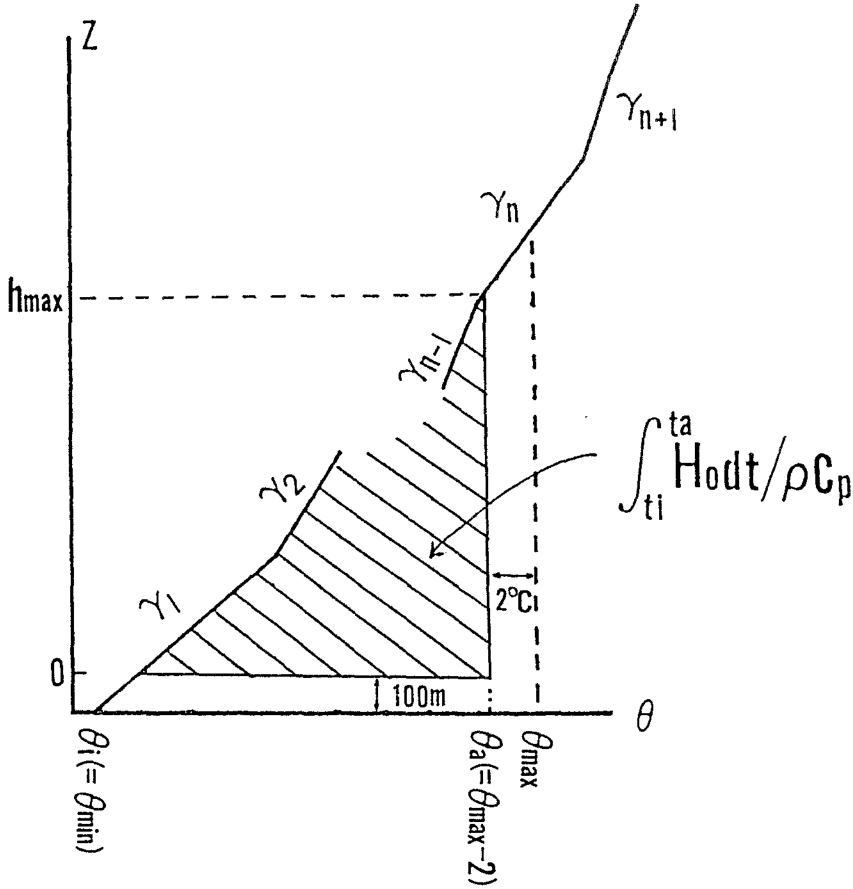

Fig. 1. The relationship among the lapse rate of potential temperature profile γ_n, the maximum mixing depth h_{max}, and the maximum potential temperature in the mixed layer θ_a. The value of γ_1 is the lapse rate of the lowest stable layer. θ_{max} and θ_{min} are the daily maximum and minimum temperatures. The surface temperature at the time of the radiosonde launch is denoted by θ_i. The hatched area shows the sensible heat flux from the surface to the mixed layer over the time interval between near sunrise (t_i) and the time when the surface temperature reaches θ_{max} (t_a). The symbol ρ denotes the mean air density in the mixed layer and C_p the specific heat of air at constant pressure.

2. Analytical Method

The maximum mixing depth h_{max} and the surface sensible heat flux H, are estimated by the method described in Gamo (1986, 1988), using vertical temperature profiles $\theta(z)$ from morning aerological data and the maximum surface temperature θ_{max}, as illustrated in Figure 1. Temperature/humidity significant level tables at New Delhi (77.20° E, 28.58° N, 216 m above sea level) were extracted from the sorted data (SD) tape compiled by the Japan Meteorological Agency. The times 0000 and 1200 GMT correspond to 0530 and 1730 Indian Standard Time (IST), respectively. Radiosonde observations are usually taken at 0500 and 1700 IST.

The potential temperature profile at 0500 IST was assumed to be the initial potential temperature profile at the onset of the growth of the daytime mixed layer, since sunrise varies from 0500 IST (in June and July) to 0645 IST (in January). Therefore, the surface value of the initial temperature profile θ_i closely coincides with the daily minimum temperature θ_{min}. The daily maximum temperature at the Safdarjung weather observing station, New Delhi (77.12° E, 28.35° N, 216 m above sea level) was used as θ_{max}.

An unstable layer usually exists near the surface. Therefore, the assumption that θ_{max} equals θ_a (vertically constant maximum potential temperature within the mixed layer) causes an overestimation of h_{max} and the integrated surface sensible heat flux $\int H\,dt$, as was shown in Gamo (1986). In the present study, θ_a is assumed to equal $\theta_{max} - T_{diff}$, where T_{diff} is dependent on the site, season, meteorological conditions, and method of measurement. In the present study, 2.0 °C is used as T_{diff}, as in Gamo (1986). The time lag of the radiosonde thermometer is assumed to be 100 m, also used in Gamo (1986).

The pressure-height co-ordinate in the aerological data was replaced by height z(m) using the barometric altimetry (Laplace) method, considering latitude and profiles of temperature and mixing ratio. The virtual potential temperature θ_v [K] was estimated as follows; $\theta_v = T_v(p_{surf}/p)^{0.286}$, $T_v = T(1 + 0.608/1000q)$.

Here, T_v [K] is the virtual temperature, p the pressure, p_{surf} the surface pressure and q [g/kg] the mixing ratio. The initial virtual potential temperature gradient γ is calculated from the θ_v profiles. However, for estimating h_{max}, the potential temperature θ [K], obtained from $\theta = T(p_{surf}/p)^{0.286}$ is used, since there are no humidity data for the time when θ_{max} is obtained. The difference between γ obtained using $\theta(z)$ and $\theta_v(z)$ is very small. Each day during the two years (April, 1987 to March, 1989) was analyzed.

3. Monsoon Characteristics for 1987 and 1988

Figure 2 illustrates the dates of the advance (onset) of the summer monsoon, and rainfall data for the two years (left; 1987, right; 1988; after *Mausam* (1988, 1989)). The shaded portions in the left-hand figure (1987) show rainfall deficits from the average monsoon season (from June to September) of more than 50%. In the right-hand figure, excesses of more than 50% are shown for 1988. Examination of the left-hand figure reveals that 1987 was a very weak monsoon year, particularly in northern India. Rainfall deficiency was 63% (normal rainfall is 535 mm) at New Delhi and surrounding areas. The arrival of the monsoon was very late and not clearly defined at New Delhi in 1987. On the other hand, 1988 was a strong monsoon year throughout the Indian subcontinent. Rainfall excesses in the regions around New Delhi were + 88%, which classifies 1988 as a very strong monsoon. The monsoon onset at New Delhi in 1988 was on the 23rd of June, indicating that the monsoon advanced at a normal rate.

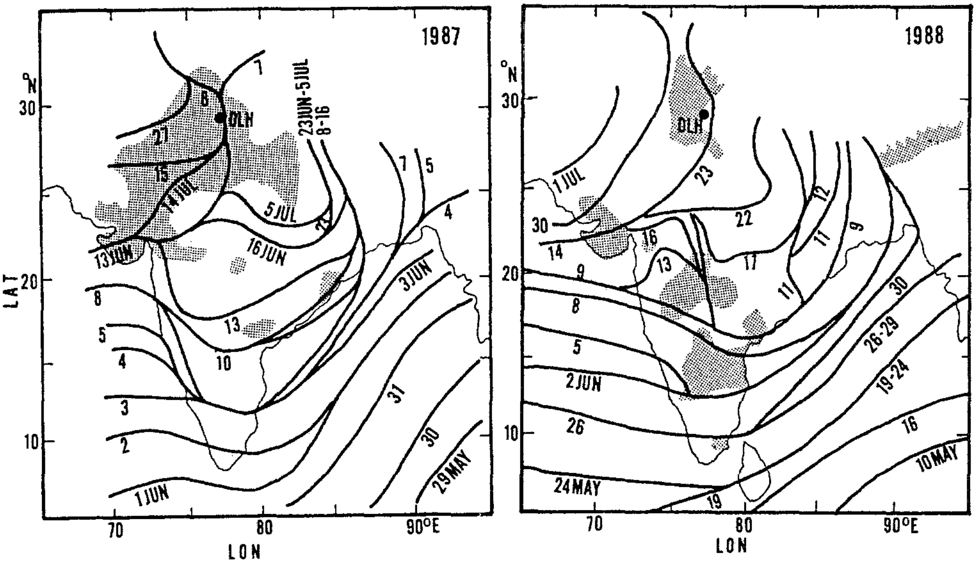

Fig. 2. Maps showing the dates of the advance of the summer southwest monsoon during 1987 (left) and 1988 (right). The shaded areas show rainfall deficiency regions for 1987, and rainfall excess regions for 1988. The figure is taken from *Mausam* (1988,1989).

4. Vertical Profiles of Virtual Potential Temperature

The seasonal change in virtual potential temperature θ_v profiles provides a rough image of the annual variation of the mixed-layer structure. Figure 3 displays daily θ_v profiles at 0500 and 1700 IST for four months, representing the four seasons during the weak monsoon year of 1987. Monthly mean θ_v profiles and their standard deviations are also shown. Figure 4 shows monthly means and standard deviations of θ_v profiles at 0500 IST for the four months during the strong monsoon year of 1988. The profiles of θ_v displayed in Figures 3 and 4 reveal large year-to-year variations. However, the degree of scatter in θ_v is very small during each individual month.

April 1987, shown in Figure 3, is representative of the hot dry pre-monsoon season, whose characteristics are as follows:

1. The stable layer formed at the surface by radiative cooling develops to heights of 200 to 300 m by 0500 IST.
2. A slightly stable, near neutral layer is formed above the surface stable layer up to heights of 3–5 km.
3. Above the middle layer, a strong stable layer exists, at least up to heights of 8 km.

Characteristics of θ_v for April 1988 exhibit the same tendencies as those of April 1987, with the exception that the stable surface layer during 1988 is somewhat

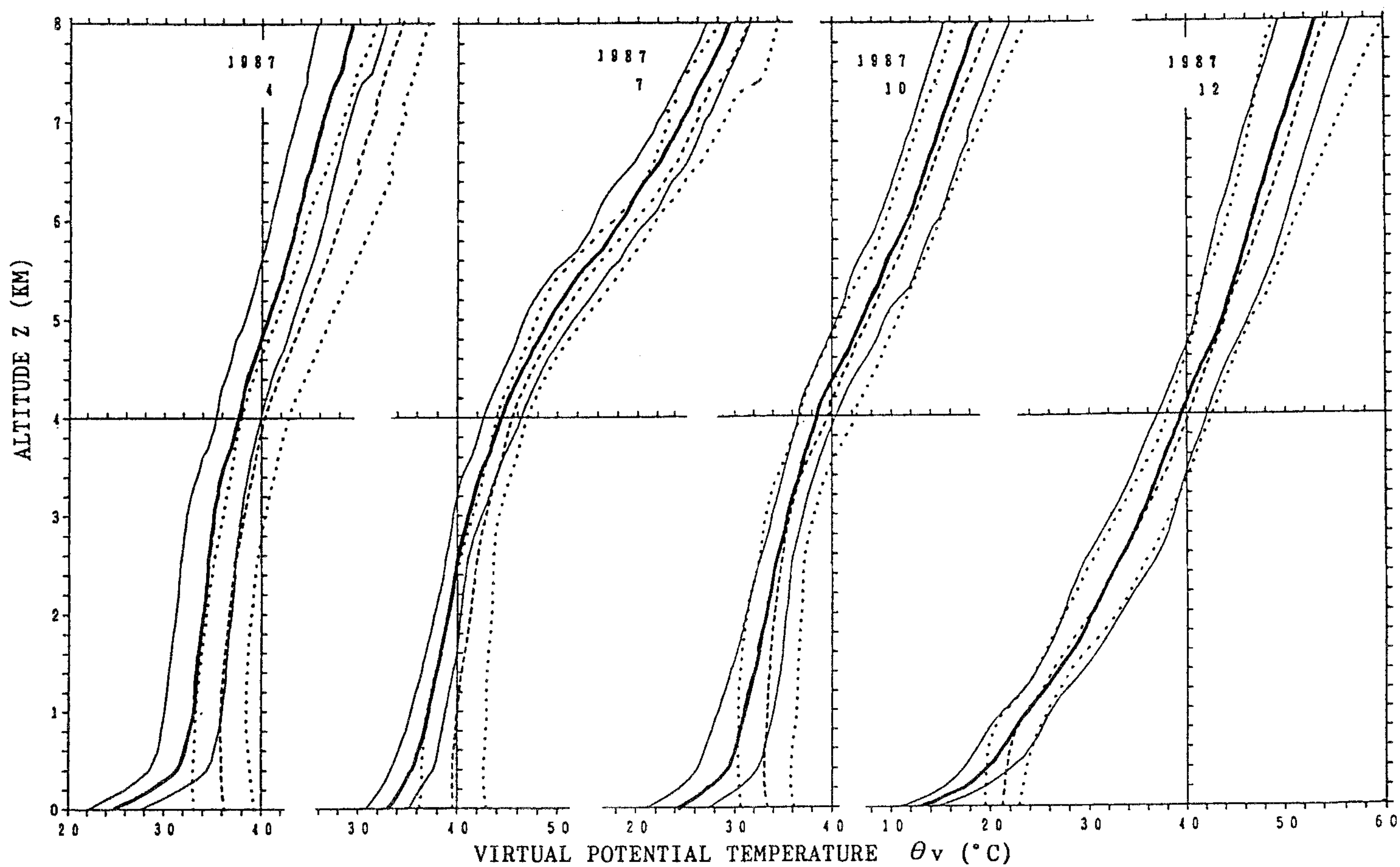

Fig. 3. Monthly means of virtual potential temperature profiles for April, July, October, and December 1987. The thick solid and broken line represent mean profiles at 0500 and 1700 IST, respectively. The thin solid and dotted lines denote mean value ± standard deviation at 0500 and 1700 IST, respectively.

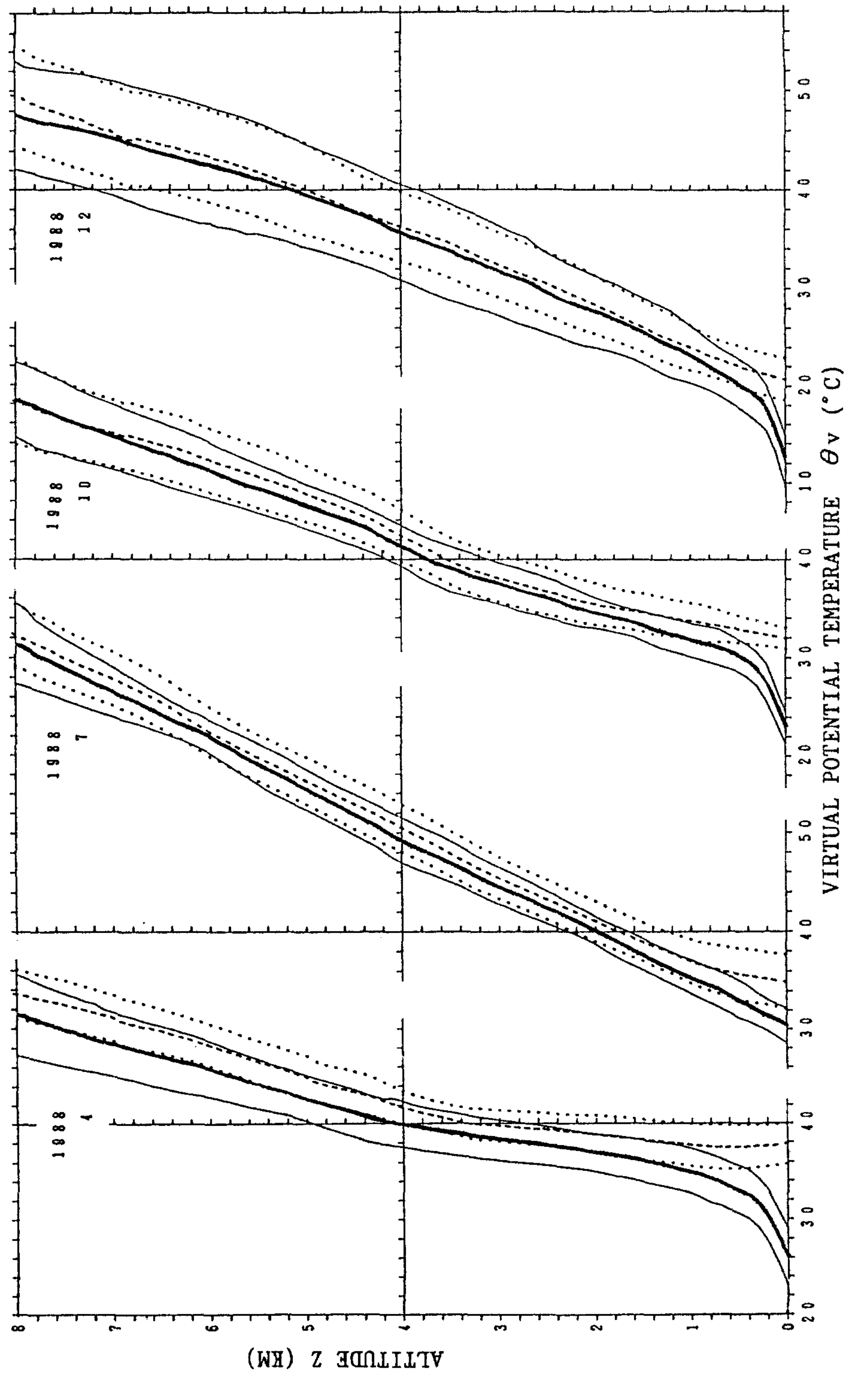

Fig. 4. Same as in Fig. 3, but for 1988.

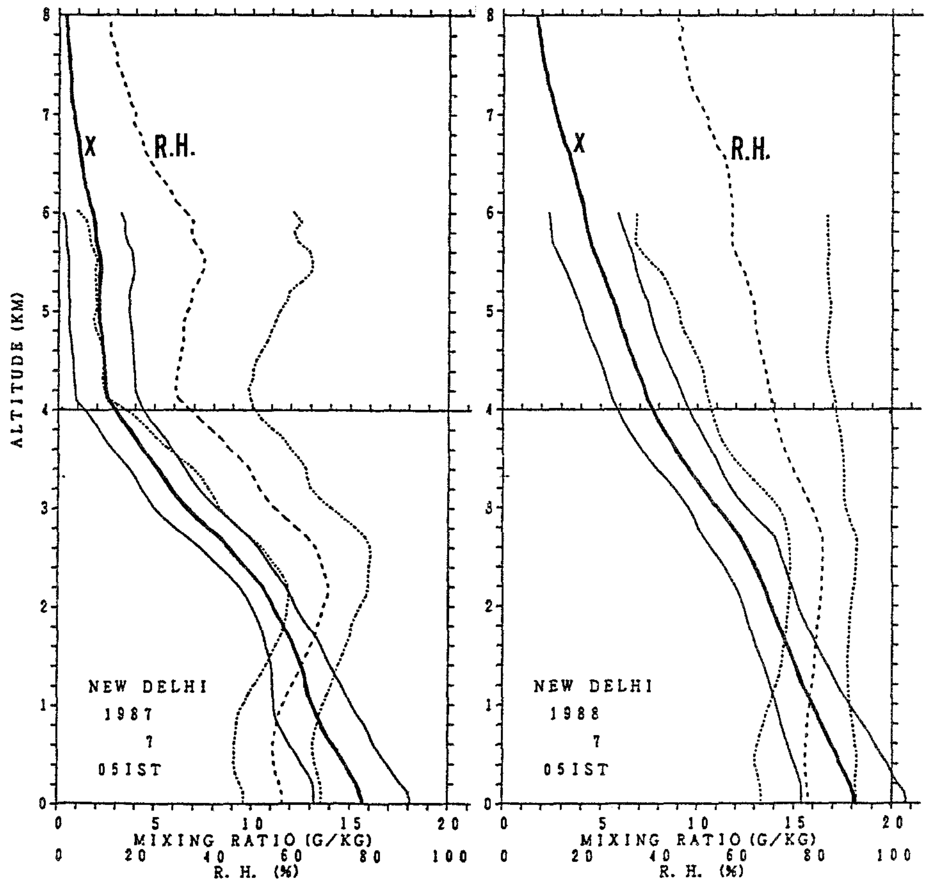

Fig. 5 Monthly mean profiles of mixing ratio x (thick solid line) and relative humidity R.H. (thick broken line) for July 1987 (left) and 1988 (right). The thin solid and dotted lines denote mean value $\pm$ standard deviation up to a height of 6 km.

stronger than that in 1987. The value of θ_v in the upper stable layer at 1700 IST is 2–3 °C higher than that at 0500 IST for both years. This tendency appears only in April.

With respect to the monsoon season, the differences between 1987 and 1988 are very clear. During July 1987, a weak stable layer exists from 200–300 m to 3–4 km at 0500 IST. On the other hand, the July 1988 stability is fairly constant, at least up to 8 km. This difference mainly results from the difference in water vapor content. Figure 5 shows daily vertical profiles of mixing ratio x and relative humidity R.H. for July 1987 (left) and July 1988 (right). The July 1987 mixing ratio begins to decrease around 2 km, being very small in the layers above 4 km. On the other hand, the mixing ratio exhibits a constant decrease up to heights of

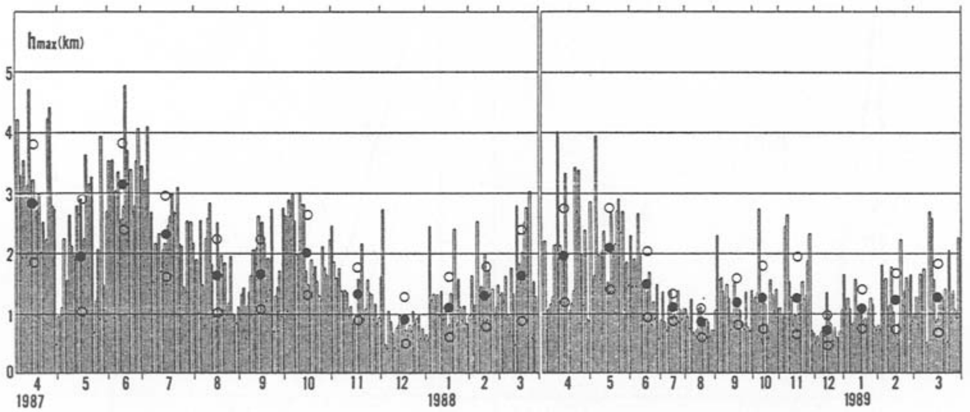

Fig. 6 The temporal variation of values of h_{max} for mixed-layer developing days at New Delhi, from April 1987 to March 1989. The solid circles represents the monthly mean of h_{max}, and the open circles denote standard deviations.

8 km during 1988. Low-level moisture is supplied by the active monsoon, as was shown in Srinivasan and Sadasivan (1975).

October is representative of the post-monsoon season, with a nearly neutral layer existing up to about 3 and 2 km in 1987, 1988, respectively. Stratification of the slightly stable layer is stronger and with shallower depths than in the pre-monsoon season for both years.

In the winter season of 1987 (December), a very stable surface layer developed up to heights of about 3 km. December of 1988 exhibits stratification similar to that of 1987, but the scatter is larger, due to the influence of synoptic-scale disturbances. Profiles at 1700 IST show that the mixed layer did not develop to heights higher than 1 km.

5. Annual Variations of h_{max}

Figure 6 shows the variation of the daily maximum mixing depths h_{max} over the two years from April 1987 to March 1989. A mixed layer is said to develop, based on the following two conditions: (1) h_{max} must be greater than 300 m; and (2), the temporally integrated sensible heat flux ΣH from sunrise to the time of maximum temperature θ_{max} (around 1400 or 1500 IST) must be greater than 1.5 MJ/m^2. The number of days when h_{max} and H are greater than zero are 329 and 290 for 1987 and 1988, respectively. The respective number of mixed-layer days for each year is 269 and 188. Figure 7 shows the temporal variation of the daily θ_{max} and θ_{min} for mixed-layer days. The value of θ_{max} varies from 45 °C during the pre-monsoon season to 29 °C in winter, while θ_{min} varies from 35 °C to 5 °C.

Figure 8 shows the annual variation of the monthly averaged h_{max} for days with

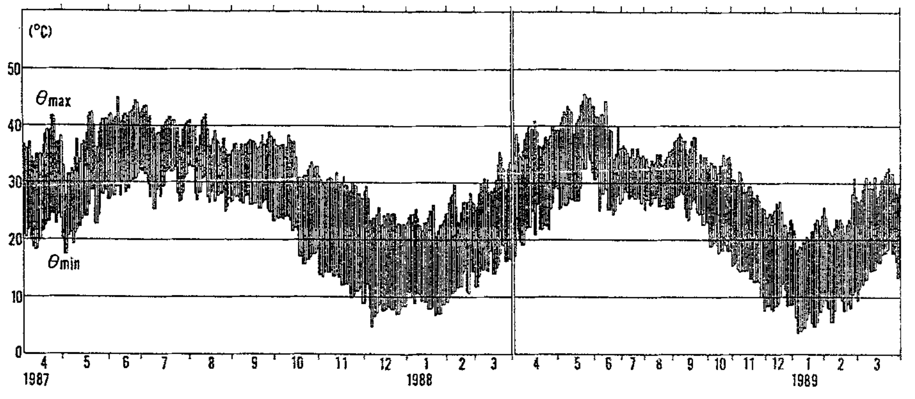

Fig. 7. The temporal variation of the range of θ_{max} and θ_{min} at New Delhi for mixed-layer developing days, from April 1987 to March 1989.

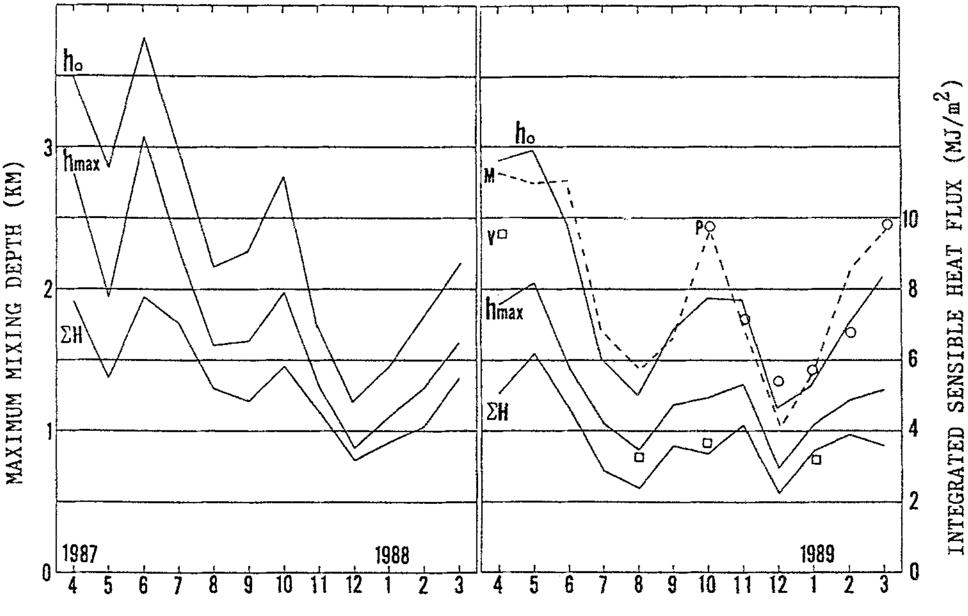

Fig. 8. Monthly mean values of the maximum mixing depth h_{max} and integrated sensible heat flux ΣH. Values of h_{max} are for mixed-layer days when $\theta_a = \theta_{max} - 2$ °C; h_o are for mixed-layer days when $\theta_a = \theta_{max}$. The letter *M* denotes results from Manju Kumari (1985), *P* is from Padmanabhamurty and Mandal (1979), and *V* is from Vittalmurty *et al.* (1980). ΣH is the integrated surface sensible heat flux from near sunrise to the time when the surface temperature reaches θ_{max}.

mixed layers. For the weak monsoon year of 1987, h_{max} is somewhat less than 3000 m during the pre-monsoon season, slightly above 1500 m in the monsoon period, near 2000 m during the post-monsoon season, and less than 1000 m in the winter season. For the strong monsoon year of 1988, the values are about 500 m less than in 1987 for the pre-, post and monsoon seasons, but only slightly less in the winter season.

Figure 8 also displays another type of maximum mixing depth h_o, obtained when θ_a is assumed equal to θ_{max}. The annual variations of h_o over the 1988 year coincide with the results from Manju Kumari (1985) which was obtained by the method of Holzworth (1967) over a five year period from 1968 to 1972. The rainfall departures from normal were within ±25% at New Delhi and the surrounding region for these five years, which were average monsoon years. Manju Kumari (1985) excluded days when the maximum mixing depth was greater than 3000 m, which were not considered to be mixed layers in the general sense. In this paper, cases where h_{max} are greater than 3000 m are included, since free convection develops up to a height of about 4 km at 1700 IST, as was shown in Figure 3.

Figure 8 also shows the averaged maximum mixing depth during 1970–1977 (all years except 1974 were considered average or strong monsoon years around the New Delhi area) obtained by Padmanabhamurty and Mandal (1979). Vittalmurty *et al.* (1980) obtained rather low values of maximum mixing depths for the five year period from 1959 to 1963, shown by the open squares which consisted of three average and two strong monsoon (rainfall excess of more than 25%) years. The above results were also obtained by use of the Holzworth method.

Vittalmurty *et al.* (1980) and Manju Kumari (1985) estimated the maximum mixing depth from monthly averaged potential temperature profiles and maximum surface temperatures, assuming that the variation in the climatological averages is small. This is understandable, since values of θ_v are nearly the same within the same month, as was shown in Figures 3 and 4.

Figure 8 also shows the annual variation in the surface sensible heat flux ΣH integrated from near sunrise to the occurrence time of θ_{max} (for mixed-layer developing days). Values of ΣH from the pre-monsoon to post-monsoon season for 1987 are much larger than those during the year 1988.

Figure 9 displays the annual variations of the energy balance components. Net radiation ΣR represents integrated values over the period of 0700 to 1500 IST at New Delhi. The data are 15-year averages (from 1957 to 1978) taken from the Handbook of Solar Radiation Data for India (1980). Since ΣR data were obtained for all days, including days when the mixed layer did not develop, ΣH in this figure is also averaged over all days. the value of ΣLE is the integrated surface latent heat flux obtained as the difference $\Sigma R - \Sigma H$. Here, the heat transfer G into the soil is assumed to be negligibly small (see Gamo, 1988). Manju Kumari and Sharma (1987) obtained energy balance components from empirical formulae for four months. Their values of G were about 10% of the surface sensible heat flux. Here, it is of interest to compare the Bowen ratios B_o they obtained with

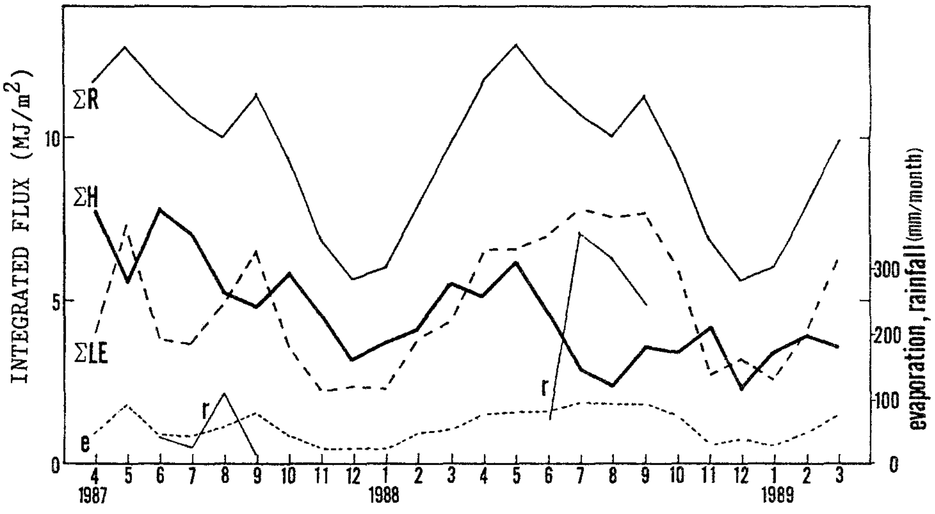

Fig. 9. Monthly variations of energy balance components integrated from near sunrise to the time when the surface temperature reaches θ_{max}. The thick solid line represents ΣH, the surface sensible heat flux, the thin solid line ΣR, the net radiation, and the dashed line ΣLE, the surface latent heat flux. The letter e denotes surface evaporation (mm/month), which corresponds to ΣLE. The letter r represents the rainfall (mm/month) in New Delhi and surrounding areas.

the present values. The values of $B_o(\Sigma H/\Sigma LE)$ were 1.5, 1.3, 1.1, and 1.2 for February, March, September, October, respectively. Figure 9 reveals that values of B_o are nearly 1.0 for September and October 1987, February, March, and October 1988, and February 1989. The previous results compare relatively well with the results of the present study except for September 1988 and March 1989. The difference between ΣH and ΣLE for these two years is very large, particularly during June, July and August. Values of ΣH are greater than ΣLE in 1987, and ΣH is less than ΣLE in 1988 over these periods.

Figure 9 also shows the surface evaporation expressed by mm/month, which corresponds to ΣLE, and the rainfall (mm/month) at New Delhi and surrounding areas (*Mausam*, 1988, 1989). During the monsoon season in 1987, the rainfall was nearly the same as the surface evaporation. From June to September 1988, the rainfall was about three times larger than surface evaporation.

6. Mixed-Layer and Synoptic-Scale Phenomena

The lapse rate γ is an important parameter in the determination of the height of the mixed layer. In this connection, because $\gamma(z)$ is influenced by synoptic features, such as air-mass, moisture, etc., γ is dependent on the season. Figure 10 shows the seasonal change of $\gamma(z)$ over both years. The figure reveals that the atmosphere is slightly stable up to heights of 4 km during the pre-monsoon season (April and

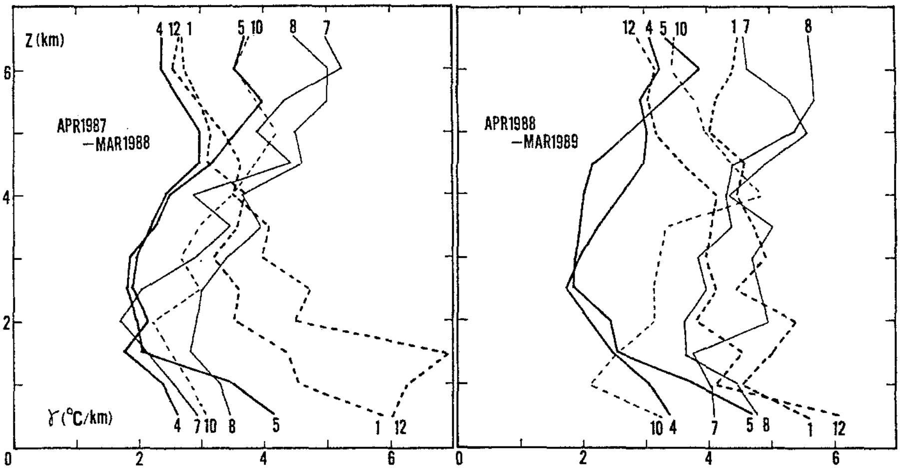

Fig. 10. Lapse rates $\gamma(z)$ averaged for mixed-layer developing days for pre-monsoon (April and May), monsoon (July and August), post-monsoon (October), and winter (December and January) months during the weak monsoon year (left), and the strong monsoon year (right). The numerals indicate the month of the year.

May) in both years, resulting from strong dry convection caused by strong insolation. The stability of the layer near the surface during 1988 is greater than in 1987, resulting in an h_{max} about 500 m lower than in 1987. Above the weakly stratified layer, the stratification sharply increases, which means that h_{max} reaches about 4 km over New Delhi.

Generally, the summer monsoon reaches 6.5 km over Bombay and 5 km over the New Delhi area. The lapse rate for July and August decreases sharply at a height of 4–5 km in both years. However, γ is large in the layer below the top of the monsoon, so the mixed layer does not develop to any great extent. The 1988 value of γ in the layer below 3 km is 1.5 times larger than in 1987.

As shown by $\gamma(z)$ in October, a weak stable layer appears in the post-monsoon season, but it is shallower than in the pre-monsoon season.

During the winter, the northeast monsoon covers northern India. This results in atmospheric subsidence and a thick strong stable surface layer, which developed up to 3 km in December 1987 and January 1988. Above the deep stable surface layer, stability is rather small, probably due to the presence of the westerly jet. For the winter of 1988, a rather weak stable surface layer exists, probably due to the appearance of numerous western disturbances, caused by the southern branch of the jet stream flowing over the northern part of India. During the winter, the strongly stable surface layer obstructs the development of a mixed layer. Light winds associated with anticyclonic conditions and the shallowness of the mixed layer cause high air pollution potential.

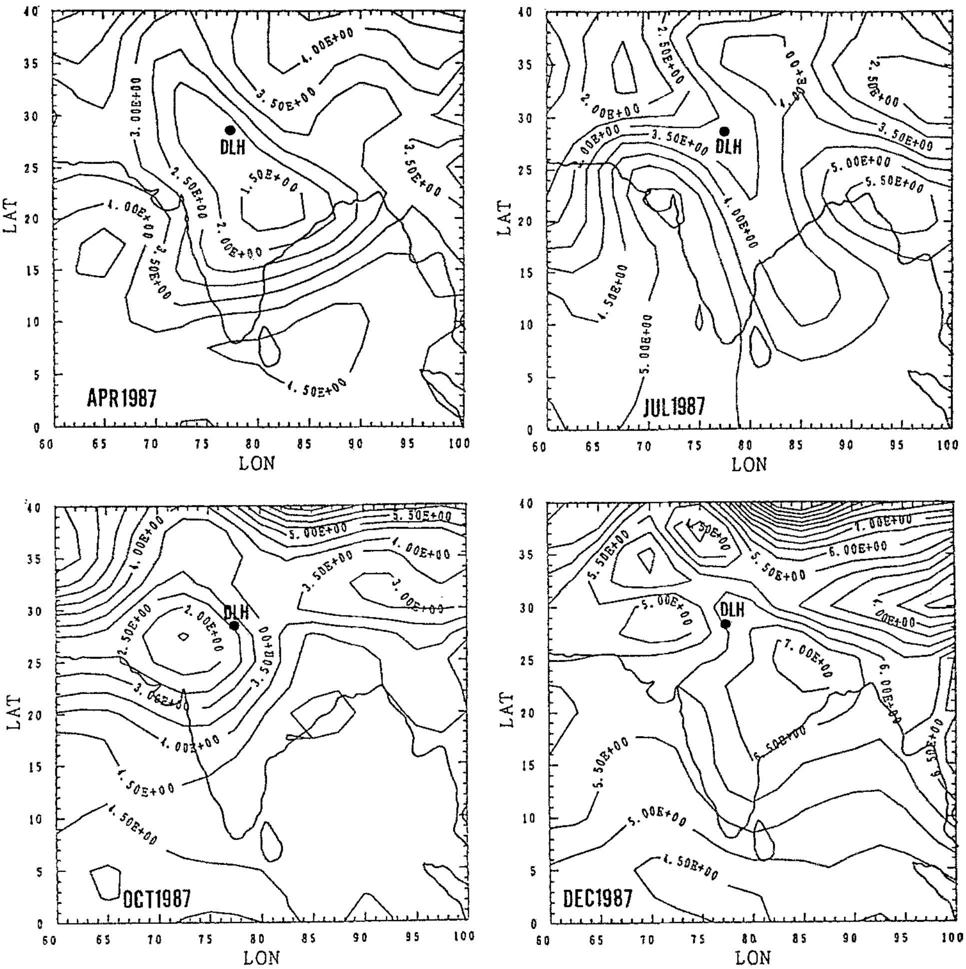

Fig. 11. Monthly averaged horizontal distribution of γ over the height interval between 700 and 850 hPa, for four representative months, obtained from objective analysis data compiled by the Japan Meteorological Agency. Contour values are in °C per km.

7. The Spatial Pattern of γ

Figure 11 displays the monthly averaged horizontal variation of γ between the 850 and the 700 hPa levels, that is, between 1.5 and 3.0 km above the surface, for four representative months during 1987. These graphs were obtained from an objective analysis on a 2.5 deg latitude-longitude grid compiled by the Japan Meteorological Agency. The value of γ over New Delhi obtained from the objective analysis is nearly the same as that in Figure 10, except for July, when it becomes larger, probably because γ in Figure 11 is a monthly averaged value including rainy days when γ is large, while γ in Figure 10 is also only for days when a mixed layer develops.

In April there is a large area of small γ, from the northwest to central India. This pattern is quite similar to the surface synoptic pressure pattern on the weather map which is caused by the heat low.

In July, γ is 2–3°/km in the region from the northwest to the southeast part of India. This is characteristic of the very weak monsoon year 1987. For the strong monsoon year, the value of γ is about 5 °C/km throughout the Indian sub-continent, resulting from the high humidity of the summer monsoon.

In October an area where γ is small appears again in the northern part of the Indian sub-continent. A region of low values of γ also exists in western India, over the Thar Desert. The values of γ over New Delhi are larger than in April. Mukerji *et al.* (1972) constructed a map of the horizontal distribution of the stability parameter (their definition of this parameter is a little different from the present one), which exhibits the same tendencies as those of the present distributions of γ in April and October.

In December, γ becomes largest over the Indian subcontinent, particularly in the northeastern part of Peninsular India, due to radiative cooling.

8. Conclusions

In the pre-monsoon season, usually from late March to the beginning of June at New Delhi, the mixed layer develops to great heights, sometimes over 4000 m, due to the large sensible heat flux from the surface and the deep weakly stratified layer, which appears only above desert areas (Kato, 1987; Gamo, 1992). During the summer monsoon, usually from the middle of June to the beginning of October, h_{max} is relatively low, around 1500–2000 m, resulting from a large γ due to high water vapor content. In the post-monsoon season from the beginning of October to the beginning of November, h_{max} reaches values up to 2000 m or more, because the potential temperature gradient capping the mixed layer γ is small. However, h_{max} is not as great as in the pre-monsoon season, because of a smaller sensible heat flux from the surface. In winter, from the middle of November to the middle of February, h_{max} is less than 1000 m, due to small values of H and a very large γ owing to the strong stable surface layer due to radiative cooling. There is a significant difference in mixing heights between strong and weak monsoon years.

Acknowledgements

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