Characteristics of the Atmospheric Boundary Layer over a Tropical Station as Evidenced by Tethered Balloon Observations

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ABSTRACT

A tethersonde observational program was conducted for eight days during February and March 1989 at Pune (18°32′N, 73°51′E, 559 m MSL), India, during daytime for the study of mixed-layer evolution. A surface-based nocturnal inversion of intensity 8–10 K (100 m)$^{-1}$ was observed on most of the days. It takes about 2 h after sunrise for this inversion to start eroding and 4–5 h for complete erosion. Profiles of potential temperature, mixing ratio, and wind are discussed. Using Tennekes and Driedonks' convective boundary-layer model an average sensible heat flux of 129 W m^{-2} is estimated during morning hours, which is comparable to the flux value obtained by an earlier study using an eddy correlation technique at a nearby site during March and April.

1. Introduction

Evolution of daytime mixed layer has been of interest for the study of dispersal of pollutants, boundary-layer modeling, and its parameterization. Vast literature is available on the characteristics of nocturnal inversion and its erosion in plains as well as hilly terrain. Whiteman (1982) has studied the breakup of temperature inversion in the deep mountain valleys of western Colorado in different seasons. Godowitch et al. (1985) has compared characteristics of nocturnal inversion in urban and nonurban environments, as well as its breakup and transformation into mixed layer at St. Louis, Missouri. Helmis et al. (1990) has studied the destruction of morning inversion in Megalopolis Valley using tethered kytoon data. Martin et al. (1988) has studied the structure and growth of the mixing layer over the Amazonian rain forest and estimated fluxes of sensible and latent heat. Tsukamoto (1986) has studied diurnal variation in the planetary boundary layer using 213-m tower data. Coulman (1978) has used aircraft data to study dispersal of nocturnal inversion.

Using tethersonde data, this paper presents characteristics of the breakup of nocturnal inversion and evolution of convective mixed layer in a semiurban environment in early summer during February and March 1989, at a tropical station, Pune (18°32′N, 73°51′E, 559 m MSL), India. Potential temperature, mixing ratio, and wind profiles during daytime are discussed. Using the Tennekes and Driedonks (1981) model, an estimate of sensible heat flux is also made from potential temperature profiles.

2. Observations

The data were acquired using an AIR, USA, tethersonde system. All of the parameters were printed online by a printer connected to the Atmospheric Data Acquisition System (ADAS) receiver. Measurements were taken from the surface up to 900 m. For the first 200 m, the ascent rate was 30 cm s^{-1}. For the 200–400-m layer the ascent rate was 50 cm s^{-1} and in the 400–900-m layer the ascent rate was 80 cm s^{-1}. During the observational program, the first profile from the kytoon was completed before sunrise and subsequent profiles were obtained every hour until noon. The afternoon observations were taken every two hours. No observations were conducted during nighttime due to aviation restrictions.

The kytoon launchings were conducted at the Central Agricultural Meteorological Observatory on the campus of the State Agriculture College, Pune. The college is situated in the center of the city and has a two-story stone building and other surrounding low structures. The college and its agriculture field are spread over 300 acres of land. Pune is an inland city about 150 km southeast of Bombay on the western peninsula. The city and suburbs are spread over an area of 350 km^2 and have a population of 2.5 million. The city is surrounded by distant low hills (100–500 m high—Western Ghats) on the southern and western sides. Two small rivers flow into the city and have a much lower water level during February and March. The city has no major water bodies nearby. The old city has low-structure buildings. Most of the new residential units are in four-to-five-story buildings. The city is known for its comparative greenery among the major cities of India and it features large portions of vacant land. The terrain slopes toward the center of

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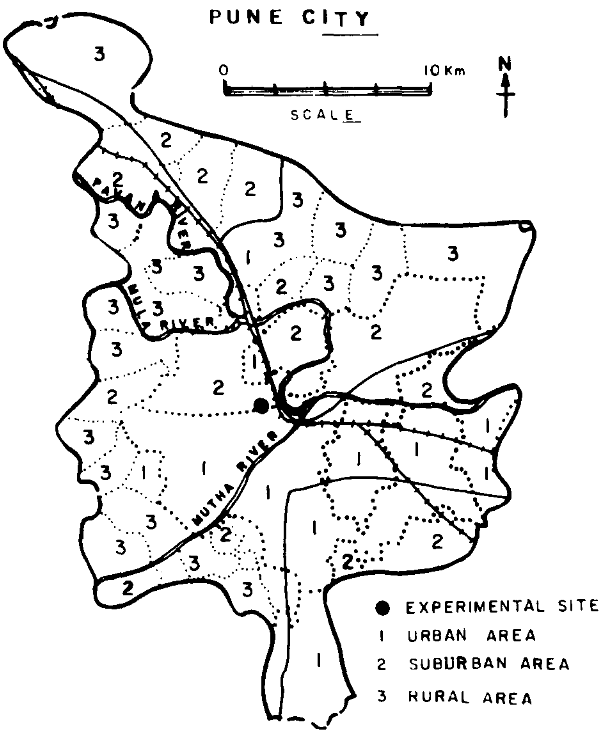

FIG. 1. Map of the experimental site and the surrounding areas.

the city. Southwest of the observational site, the nearest hill, at a distance of 1 km, is 100 m high and is spread laterally farther to a distance of 3 km; other hills are 5–6 km away. Figure 1 shows the urban, suburban, and rural areas around the experimental site.

The experiment was carried out during the period 22 February 1989 to 2 March 1989. There were no major weather disturbances during the observational period. Observations started in the morning with clear sky conditions on all the days. On certain days cirrus clouds appeared later in the day. The sky conditions for all the days are given in Table 1, along with the duration of cloud cover. Additionally, the inversion intensities (vertical temperature gradients) observed before sunrise and two hours after sunrise are classified into two layers: (i) surface to 100 m, and (ii) surface to the maximum height reached by the kytoon.

On the days of observation the maximum and minimum temperatures were around 34° and 12°C respectively. Sunrise and sunset varied between 0659 and 0654 and 1837 and 1839, respectively. All times indicated in diagrams are Indian standard time (IST).

3. Data analysis

For the analysis, only the data collected during ascents are utilized. Normally each launching was completed in 25–30 min. All profiles are displayed with mean time of ascent. As it is not possible to deal with all cases, only two days' data for 23 February 1989 (clear sky all through the day) and 27 February 1989 (3/8 cirrus clouds after 1530 IST) are considered for discussion.

Figure 2 shows potential temperature profiles for various ascents on 23 February 1989. A surface-based inversion in the morning began to erode around 0900 IST. The boundary layer becomes thoroughly mixed near 1100 IST—as shown by the uniform potential temperature up to 900 m. Time sections of potential temperature for various heights (surface, 20, 50, 100,

TABLE 1. Characteristics of inversion intensity.

		Inversion intensity in morning (first sounding)		Inversion intensity after 2 h of sunrise	
Date	Sky conditions with timing of cloudiness	Surface–100 m (K)	Surface–maximum height of kytoon (K)	Surface–100 m (K)	Surface–maximum height of kytoon (K)
22 February 1989	Clear sky throughout the day	+8.8	+12.6 (0–500)	+1.1	+6.1 (0–800)
23 February 1989	Clear sky throughout the day	+9.9	+12.0 (0–300)	+0.7	+5.4 (0–600)
24 February 1989	7/8 Ci 0750–0945 IST 5/8 Ci 1020–1255 IST clear sky afterward	+10.2	No data	+3.2	+9.2 (0–600)
25 February 1989	1/8 Ci 0730–1350 IST	+10.2	+15.9	+2.4	+8.2 (0–600)
26 February 1989	6/8 Ci 0740–1115 IST	+9.4	+11.1 (0–150)	+2.5	+9.3 (0–600)
27 February 1989	3/8 Ci 1530–1710 IST	+6.3	+12.2 (0–400)	+4.7	+8.0 (0–300)
28 February 1989	5/8 Ci 1530–1710 IST	+8.2	+11.7 (0–200)	+0.6	+7.6 (0–500)
1 March 1989	2/8 Ci 0820–1030 IST	+6.7 (20–100)	+7.5 (20–150)	+2.8	+5.2 (0–200)

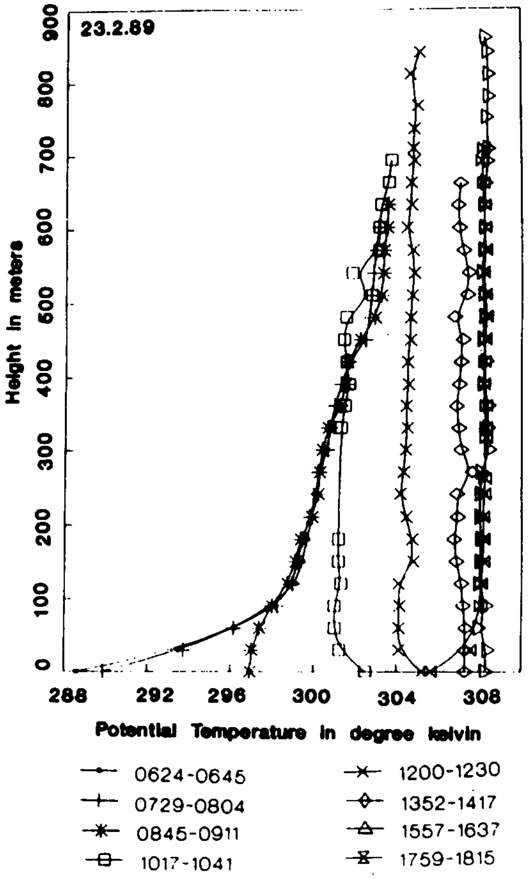

FIG. 2. Potential temperature profiles at different times on 23 February 1989.

150, . . . , 700, and 800 m) are given in Fig. 3. The thick solid line indicates the surface potential temperature for various soundings during the day. There was a strong morning inversion of 10 K (100 m)$^{-1}$ near the surface on 23 February 1989. The criterion for any level to be considered mixed at a particular time is that its potential temperature should be less than the surface potential temperature at that time. It is inferred from the figure that the atmospheric boundary layer became mixed up to 100 m by 0900 IST, which is about two hours after sunrise.

Figure 4 shows the time variation of potential temperature at different heights for 27 February 1989. There was a morning inversion of 6 K (100 m)$^{-1}$ at the surface. This inversion further strengthened to 8 K (100 m)$^{-1}$ during the second kytoon sounding at 0720 IST (mean time). The fall in temperature in the second sounding is seen up to a 300-m height except at the 150-m level. This feature of temperature decrease after sunrise is observed on all observation days except on 22 February 1989 and 23 February 1989. On certain days this feature is also observed at greater heights during the third sounding (around 0900). The decrease of temperature after sunrise is believed to be associated with wind direction (refer to Fig. 7), which lies mainly in the 0°–120° sector of the observation site. This suburban sector, extending out to 10 km, has comparatively less urban density due to well-separated small structures and thus has a lower environmental temperature. In a sharp contrast, the southwest sector is very thickly populated and has four-to-five-story concrete buildings. There are no independent observations on the urban heat island over Pune but it can be inferred from the above that an urban heat island persists up to 300 m in the southwest sector during the early morning hours. The location of the heat island may be at a distance of 2–3 km from the observation site in the south to southwest sector, which features the maximum density of buildings and population. This urban heat island induces cool airflow from the 0°–120° sector, which explains the decrease in temperature up to 300 m at the upwind experimental site. Thus, the fall in temperature up to about 300 m is believed to be due to advection rather than attributed to the radiational cooling. At 100 and 150 m, there is no fall in temperature because the wind direction does not lie

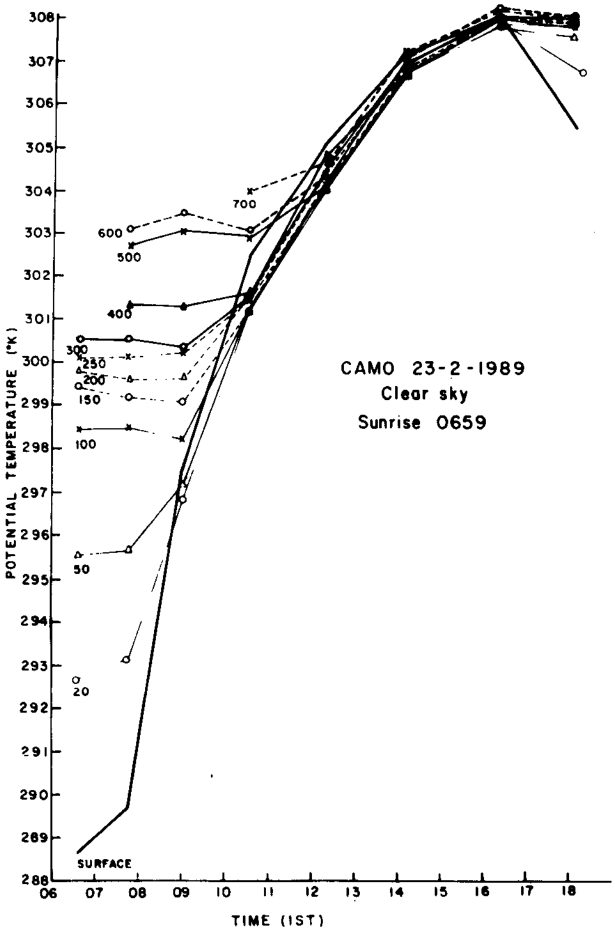

FIG. 3. Time section of potential temperature for different heights on 23 February 1989.

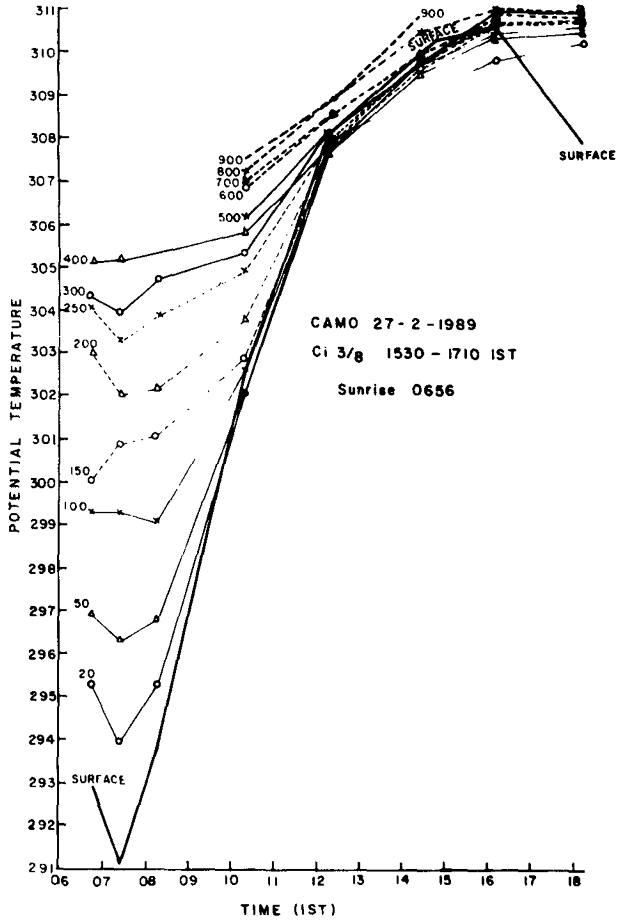

FIG. 4. Time section of potential temperature for different heights on 27 February 1989.

in the 0°–120° sector. On 23 February 1989, though the winds were from the same sector, there was no fall in temperature. This may be due to weakening of the urban heat island because of comparatively strong winds prevailing at all levels. This feature of a drop in temperature up to 300-m height after sunrise was also reported by Godowitch et al. (1985), while analyzing data for nocturnal inversion erosion at an urban site.

From Table 1, it is observed that in the early morning hours (before sunrise) up to 100 m, the inversion intensity varies between 6 and 10 K $(100\ \mathrm{m})^{-1}$ whereas the inversion intensity two hours after sunrise changes rapidly and is around 0.6–5 K $(100\ \mathrm{m})^{-1}$. The fourth and sixth columns of the table give the inversion intensities between the surface and the maximum height reached by the kytoon. Comparing the time section profiles of the potential temperature on 23 and 27 February, it is observed that the inversion intensity was greater on 23 February in the first sounding. However, on 27 February, the inversion intensity strengthened comparatively in the second and third soundings because of cold-air advection, thus causing the inversion to erode late in the day.

Figure 5 shows the time–height cross section of the mixing ratio q on 23 and 27 February 1989. The thick line represents the boundary-layer height or the base height of nocturnal inversion as inferred from Figs. 3 and 4. A marked contrast is seen between the two days. On 23 February 1989, as on all the normal days, the mixing ratio at any height increases continuously up to 1600 IST. However, on 27 February 1989 the mixing ratio at all heights is fairly constant up to 0900 IST and then increased up to 1300 IST, after which there was a decrease until the evening. The moisture decrease may be due to the downward entrainment of dry air from the higher levels. In general, on the other days there was an increase in the mixing ratio when the wind direction changed to southerly or westerly or when there was a sharp increase in the wind speed. This may be due to the more green hilly terrain in these two directions or orographically induced convergence.

Another feature observed on almost all the days in the mixing ratio profile is that in the early morning soundings before 0800 IST, the surface mixing ratio

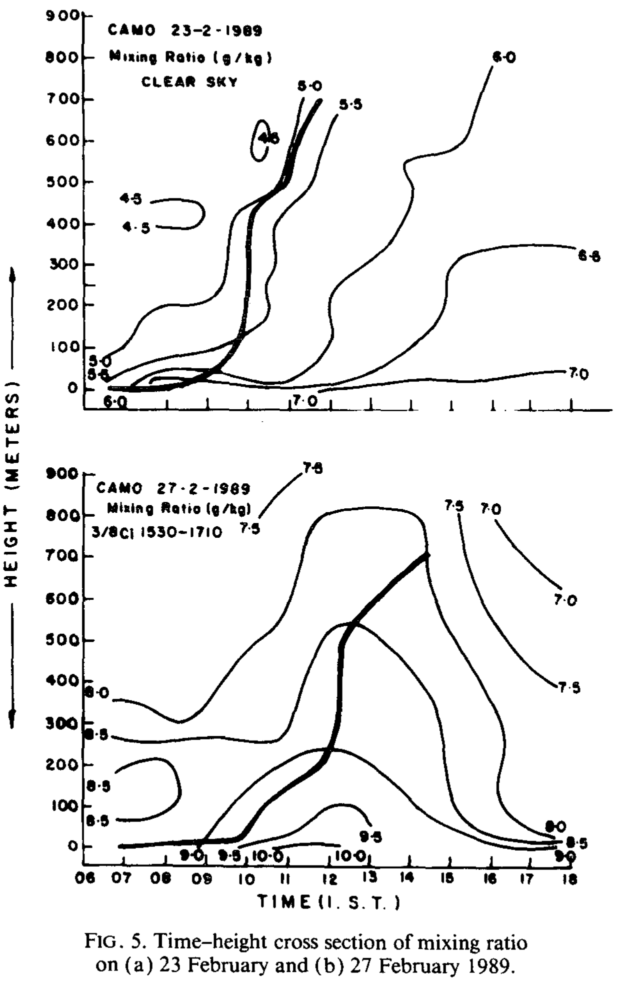

FIG. 5. Time–height cross section of mixing ratio on (a) 23 February and (b) 27 February 1989.

was less than that at the 20-m level. This may result from dew formation close to the surface that depletes the water vapor in the atmosphere (Oke 1987).

Figure 6 shows the diurnal variation of potential temperature θ and mixing ratio q at 10, 100, and 500 m on 23 February 1989. It is seen that variation in the potential temperature is minimum at the 500-m level and there is a progressive increase in its variation at lower levels. Also, when potential temperature at these three levels is compared, it is seen that $d\theta/dz$ is positive throughout the 10–500-m layer before 1000 IST, after which it becomes fully convective around 1200 IST. Again, between 1415 and 1600 IST $d\theta/dz$ becomes positive in the 10–100-m layer and extends to 500 m between 1615 and 1800 IST. The mixing ratio at 10 m progressively increases up to 1400 IST, after which time it starts decreasing. There is a maximum increase in the mixing ratio between 1215 and 1400 IST due to maximum convection at this level during this time. At the 100-m level there is no increase in mixing ratio until 0900 IST, at which time it starts increasing progressively throughout the day. It is during 0900–1030 IST that the atmosphere becomes convective at this level. At the 500-m level, the mixing ratio is almost constant up to 1030 and between 1030 and 1215 IST there is a maximum increase in the mixing ratio. During this period the atmosphere became mixed. After 1215 IST, the change in mixing ratio is minimal at this level. From the above observations, it is clear that whenever there is change in thermal stability from stable to unstable, a sudden increase occurs in the mixing ratio, whereas the change is slow when the stability changes from unstable to stable. If the mixing ratio between any of the above layers is compared during the day, it is found that throughout the day dq/dz is negative. Therefore, during the day, although $d\theta/dz$ changes sign from positive during morning hours to negative during the day, and again to positive in the evening hours, dq/dz remains negative throughout the day. Similar results have been reported by Tsukamoto (1986) in terms of sensible heat flux and water vapor flux while analyzing 213-m tower data at Tsukuba, Japan. Tsukamoto's observations are based on fluctuations around the mean value of potential temperature and specific humidity.

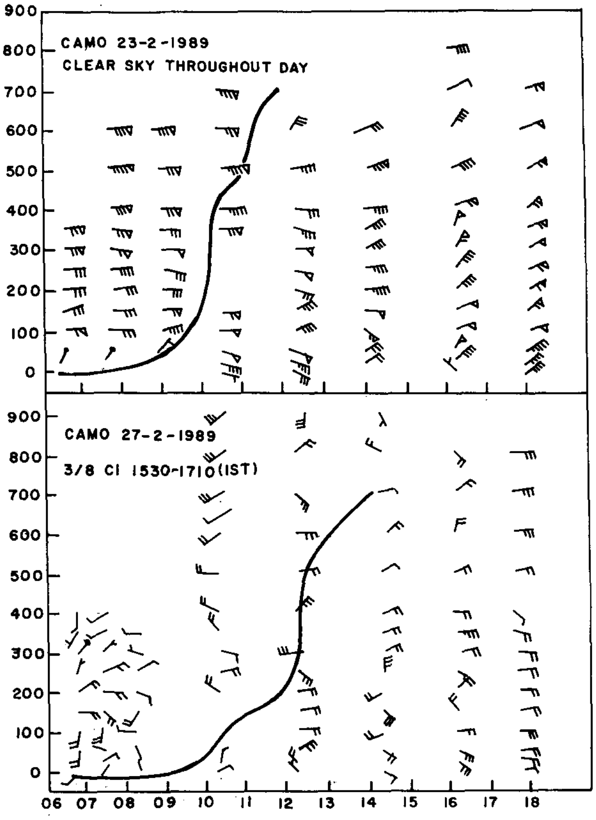

FIG. 7. Wind profiles on (a) 23 February and (b) 27 February 1989. One flag is 5 m s^{-1} and one barb is 1 m s^{-1}.

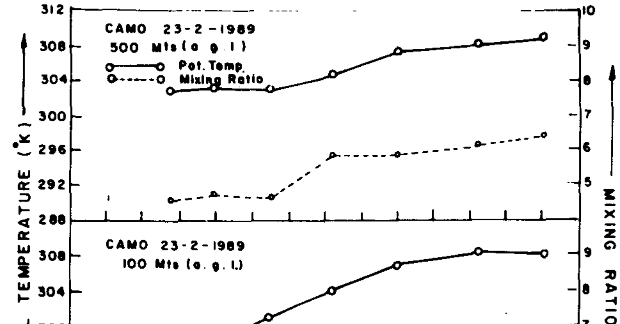

FIG. 6. Diurnal variation of potential temperature and mixing ratio at different heights on 23 February 1989.

Figure 7 shows wind profiles on 23 February 1989 and 27 February 1989. In general, winds were low and variable in the morning at lower levels (<100 m) on all the days. From 22 February 1989 to 26 February 1989 winds were mostly from the 30°–150° sector and comparatively higher (5 m s^{-1}) between 200 and 300 m and still higher above these levels. This situation remained constant throughout the day. From 27 February 1989 to 1 March 1989 winds were low and of variable direction throughout the day.

4. Computation of surface heat flux $(\overline{\theta'w'})_s$ during the formation of mixed layer

The estimation of sensible heat flux over an urban terrain is complicated because of different roughness features and thermal gradients caused by varying land use and structures of different heat capacities. This causes significant advective heat flux over an urban environment in the morning hours. By taking observations with an instrumented helicopter at different along-wind locations over rural, suburban, and urban areas at St. Louis, Missouri, Godowitch et al. (1987) concluded that the contribution of advective heat flux in the morning hours was positive at upwind locations of the urban heat island and negative downwind of the urban heat island. The positive values shifted toward the urban heat island with time but remained on the upwind direction only. The estimation of the advective flux requires temperature and wind observations at different locations over urban areas in the along-wind direction.

The present observational program was at a single location, therefore the estimation of advective flux is not possible. As the observational site is on the upwind direction of the heat island, it can be inferred that the contribution of the advective heat flux there is positive. Further, the nocturnal inversions were ground based on all the days of the observations and there was sufficient fetch on the upwind side of the observation site. Hence, the location is like a rural terrain. While discussing the mixing height "doming" over an urban area, Briggs (1988) opines that enhancement of the mixing height over an urban area is a function of the ratio of urban–rural heat fluxes. Due to the ground-based inversions at the observation site, the difference between the urban–rural fluxes may be minimum over the site. Hence, Tennekes and Driedonks' (1981) convective boundary-layer model has been used for the estimation of average sensible heat flux. This model estimates average heat flux between the morning hours and the time when the surface-based inversion is eroded. According to this model, the surface flux is related to the boundary-layer height (h) and the jump ($\Delta\theta$) in the potential temperature immediately above the inversion layer. The relations are as follows:

$$\frac{d}{dt}(h\Delta\theta) = \gamma h \frac{dh}{dt} - (\overline{\theta'w'})_s, \qquad (1)$$

where $(\overline{w'\theta'})_s$ is the surface flux, and γ is the lapse rate immediately above inversion. If γ is taken to be independent of the height of boundary layer, (1) can be integrated to yield:

$$h(\Delta\theta) - (h\Delta\theta)_0 = \gamma \frac{(h^2 - h_0^2)}{2} - \int_0^t (\overline{\theta'w'})_s dt'. \qquad (2)$$

If $\Delta\theta = 0$ at all the times, we have

$$\gamma \frac{(h^2 - h_0^2)}{2} = \int_0^t (\overline{\theta'w'})_s dt'. \qquad (3)$$

If $h_0 = 0$,

$$\frac{h^2}{2} = \frac{1}{\gamma} \int_0^t (\overline{\theta'w'})_s dt'. \qquad (4)$$

Equation (4) gives the total amount of heat entering between the first sounding at sunrise and the sounding taken around mixed-layer formation time between $t = 0$ and t' (refer to Fig. 2). Solving this equation with the center difference method and assuming $(w'\theta')_i = 0$ (flux at the inversion base is taken to be zero), we arrive at:

$$(\overline{\theta'w'})_{S_{t=t'}} = \gamma h \frac{[h(t+\Delta t) - h(t-\Delta t)]}{2\Delta t}. \qquad (5)$$

To process (5) for calculating the heat flux, a minimum of three potential temperature profiles at three different times are required—the first one during early morning hours, second later in the morning, and third during mixed-layer formation. The second morning profile is considered the middle point of the difference method. If there are four soundings before the formation of mixed layer we get two flux values. The fluxes determined above correspond to the second and third flights at the end of which the mixed-layer phenomena is observed. On most of the days, the inversion reached up to a range of 100–150 m by this time. Table 2 gives the values of the surface fluxes computed after multiplying $(\overline{w'\theta'})_s$ by a factor ρC_p. In the case of two flux values, their average is taken. On most of the days the surface flux value is around 105 W m^{-2} with the average value being 129 W m^{-2}. These flux values are comparable to those reported by Sivaramakrishnan et al. (1988) using eddy correlation technique over complex terrain near the present experimental site during March and April 1985–86.

5. Summary

The erosion of nocturnal boundary-layer inversion and the growth of the convective mixed layer was studied with the help of temperature profiles. It is observed that though the experimental site is in the center of the city, the suburban upwind fetch may result in the surface-based nocturnal inversion of varying intensity,

TABLE 2. Computed values of the surface heat flux.

Date	Time (IST)	Flux (W m^{-2})
22 February 1989	0714–0945	107
23 February 1989	0622–1041	104
24 February 1989	0623–0951	108
25 February 1989	0629–1020	107
26 February 1989	0632–1033	154
27 February 1989	0620–1043	94
28 February 1989	0717–1030	151
1 March 1989	0650–1032	210
2 March 1989	insufficient data	—
		129 W m^{-2} average value

which is a rural characteristic. The inversion starts eroding about 2 h after sunrise on most of the days and complete erosion takes place in 4–5 h. A drop in temperature from the surface to 300 m, usually observed after sunrise, is attributed to the advection of cold air from the surrounding suburban areas because of the heat-island effect. A comparison of potential temperature and mixing ratio at 10, 100, and 500 m shows that while the thermal stability changes from positive in the early morning to negative during daytime and again to positive in the evening, the gradient of mixing ratio remains negative throughout the day. There is a sharp increase in the mixing ratio value at different levels when thermal stability breaks down in the morning. In the evening when thermal stability near the surface is reestablished, there is a very slow decrease in the mixing ratio. In the early morning soundings there is an increase in mixing ratio from the surface to about 20-m height that may be due to depletion of water vapor near the surface because of dew formation.

Using Tennekes and Driedonks' convective boundary-layer model for early morning soundings, an average sensible heat flux of 129 W m^{-2} is estimated. This heat flux value is comparable to an earlier estimate by eddy correlation technique during March and April at a nearby site.

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