A Study of Thermal Plumes

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Thermal convection has been observed to be a daytime atmospheric phenomenon. The thermal plumes have been recorded with an echosonde over Punjabi University, Patiala. These plumes have been observed up to an altitude of one kilometre of the planetary boundary layer. Detailed studies of the growth and dissipation, occurrence, height, diameter and velocity of the plumes and their effect on microwave communication have been made. They have periods ranging from 1 to 20 min and the diameter varies from 0.12 to 2.40 km, while the vertical velocities vary from a fraction of a metre to 2 metres per second. It is recommended that the pollutants should be released into the atmosphere only under the plume conditions so as to minimize the environmental pollution.

1. Introduction

Air heated at the earth's surface during sunshine develops thermal instabilities resulting in convection. The first few metres constitute the region of forced convection and above this for several hundred metres the region is one of free convection. All this forms what we call the planetary boundary layer (PBL). However the PBL which is influenced by the earth's surface, extends to an altitude of around 2-3 km. It varies from place to place and with seasons. It is dominated by general turbulent mixing or penetrative convection. The size of the irregularities or the convection cells is comparable to the characteristic size of flow in a direction normal to the mean flow field. It has large scale vertical motions well correlated with temperature. With the solar radiation budget on a clear sunny day the vertical motion dominates the shears or horizontal dissipation and the energy through thermal plumes is transported upwards to stable layers at higher altitudes. In the stable layers the energy is dissipated largely against Archimedean forces, producing temperature fluctuations which in turn achieve equilibrium by molecular diffusion. But if the energy in the region of free convection is transported along the surface, there may be nothing left to be carried upwards and dissipated in the stable layer.

The primary advantage of the study of plumes is to get an idea how high the convective cells move. The release of latent heat of condensation is the major source for the building of clouds. However, the low level inversion can suppress convection and inhibit the formation of clouds and rainfall as observed over Rajasthan desert during the months of summer monsoon.

The plumes have been observed by many workers using echosonde and lidar over warm tropical oceans, over a warm current in the north pacific, over the Antarctic sheet and even aboard the research vessel planet in the North sea.

At Punjabi University, Patiala (30.358°N; 76.443°E), an echosonde has been designed and developed, and is in operation since July 1980. The present paper deals with the preliminary study of thermal plumes observed during the initial probing of the atmosphere using the echosonde operating at 2.4 kHz and probing up to an altitude of 1.02 km.

2. Observations

The data included in the present paper refer to the period 12 Aug. 1980-11 Sep. 1980 during which 654 hours of data have been recorded in 24 hr of the day and night.

For the same period the observations are also available from the radiosonde flights giving thermal parameters of lower atmosphere twice a day, i.e. 05.15 hrs and 16.45 hrs. These flights largely cover the same volume of the atmosphere as both the echosonde and the radiosonde are located on the roof of the same building.

Ground surface is not horizontally uniform even within a short distance, because of the presence of irregular land, soil conditions and man-made structures. As a result, the temperature differences up to 0.5°C develop over short distances during sunshine.
The warmer areas on the ground surface transfer their heat content to the air in contact, which in turn becomes warmer and starts to rise as a buoyant parcel of air, known as a thermal. When the thermals are a few metres above the ground, their heat supply is cut off. As they ascend they are subjected to a gradually decreasing atmospheric pressure and therefore experience a quasadiabatic expansion. The temperature gradient is given by

\[ \frac{dT}{dz} = \frac{(A g / C_p)}{(T / T)} \]  

where \( A \) is the reciprocal of mechanical equivalent of heat, \( C_p \) is the specific heat of air at constant pressure, \( g \) is the acceleration due to gravity and \( T \) is the average temperature. The gradient, \( dT/dz \) has a value of about 9.8°C/km and is known as dry adiabatic lapse rate. But air contains water vapour, and as it rises, condensation occurs depending upon the temperature and pressure at that altitude. The dry adiabatic lapse rate no longer applies.

The atmospheric lapse rate conditions over Patiala for a number of days at fixed hours of morning and evening are plotted in Fig. 1. Under the category marked A, atmospheric plumes have been observed; the atmosphere under such circumstances is known as unstable; while under the category marked B, the lapse rate is opposite to the one given by Eq. (1) up to a certain altitude. The atmosphere under such circumstances is known as stable and temperature inversions are observed. However, it is important to note that the evening (1645 hrs) flight on 1 Sep. 1980 shows an inversion which is a rare phenomenon. Fig. 1 also indicates variability in the lapse rate conditions both during the morning and the evening hours. The lapse rate during the evening hours as observed on a particular day depends upon the prevailing weather conditions. A cloud coverage over an area reduces the surface heating and hence the well defined convection. Typical records of the plume observations are shown in Fig. 2(a-c).

3. Plume Characteristics

Plumes appear in the form of dark vertical structures during daytime with their width decreasing with height on an echogram. Of course, there are a family of convective cells rising to different heights, some touching several hundred metres [Fig. 2(a-c)].

It is seen from the Fig. 2(a-b) that within the boundary of a plume there are localized regions of darker intensity representing much greater temperature gradient structures.

Shor: plumes with high temperature gradient or \( C_l \) are also commonly observed. Such types of plumes are seen with a family of plumes in which smaller plumes probably merge into larger plumes.

On several occasions the upwind edge, occurring later in time has been observed to be more sharply defined than the earlier downwind edge. Echo returns are stronger from upwind edge indicating greater temperature fluctuations from such a location.

Under wind shear conditions plumes are not straight in their appearance as shown in Fig. 2(b). It shows several plumes in which the plume axis is rather not vertical, with different inclinations at different height ranges. The measure of plume tilt from the vertical, which gives an indication of deviation of convective air parcels from their normal upward flow due to wind
shear cannot be measured quantitatively by using a monostatic sounder, as it scans only the mean horizontal flow past the vertically directed transceiver. However, the measurements of such tilts show that the angles go as high as 20° from the vertical.

4. Onset and Dissipation of Plumes

The ground-based temperature inversion does not get dissipated immediately after sunrise; rather the entire volume of positive lapse rate moves upwards. Fig. 3 shows a rising inversion in the morning and under the inversion, plumes are being formed. The thickness of the inversion goes on decreasing with time and finally it dissipates at certain altitude depending on its nighttime temperature gradient and daytime heating conditions. Fig. 4 shows the average behaviour of all the rising inversions observed on the echograms. The layer rises slowly in the initial phase after sunrise but the rise becomes faster as the time advances. The rate is about 6 times more during 1030-1130 hrs compared to the rate observed during period of 0630-0730 hrs.

For comparison the average incoming direct and diffused radiations over Patiala are shown in Fig. 5. The direct radiation almost increases linearly, while the layer height increases non-linearly. In the initial phases after sunrise most of the heat is utilized in heating the ground which in turn warms up the atmosphere. The warming up rate of the atmosphere then increases rapidly pushing the layer upwards at a faster rate. The rate of heating of the ground on a particular day could be altogether different from the average behaviour (Figs. 5 and 6). The incoming solar radiation for 17 Aug. 1980 shows several depressions due to the cloud coverage over Patiala (Fig. 6). A cloud patch does not cause much difference in the air temperature but if it persists for sometime, it has a definite effect on the
Fig. 7—Dissipation of the thermal plumes and the formation of nighttime structure recorded on 20 Aug. 1980

Fig. 8—Height and time of the dissipation of the morning inversion and the thermal plumes

The dissipation of plumes, as shown in Fig. 7, is seen normally in the evening hours when the atmosphere moves towards a more or less homogeneity. The time and height of the dissipation of rising inversion and the time of dissipation of plumes are plotted in Fig. 8. It is seen that there is a considerable scatter in both dissipation timings even over a period of a month, but most of the inversions dissipate between 0900 and 1100 hours IST and the plumes around 1730 hours IST over Patiala.

5. Plume Height
As the day advances the height of the plumes increases; however the plumes may not reach the height at which the inversion dissipates. The main reason could be that the temperature gradient of the inversion could be much higher than the normal temperature gradient developing under convective conditions.

The diurnal variation of the average plume height is shown in Fig. 9. The average maximum height is about 410 m and occurs around 1500 hrs. The plume height goes down to as low as 125 m. In fact the evening cooling of the earth’s surface and hence plumes are also affected.

The transition from convection to inversion activity itself is very interesting as it follows the three modes, viz. (i) generally the plumes disappear completely leaving a clear demarcation between the daytime and the onset of nighttime structures; (ii) on some days the daytime structure does not dissipate completely but rather turns out slowly from convective to less convective and to a mixed structure, which takes the shape of a typical nighttime structure. It is further observed that on these days the temperature drop is faster than that on the normal days (Fig. 7); and (iii) on rare occasions the convection can be transformed to a nighttime structure any time of the day [Fig. 2(c)] and it may continue till the following day. These occasions arise due to cold fronts, rain and storms which cause a large decrease in temperature on the ground suppressing the plumes completely and the lowered surface temperature is not able to reactivates the plume activity [Fig. 2(c)].

6. Horizontal Extent
The horizontal extent of plumes in terms of plume periods can be directly measured from the echograms. These periods range from 1 to 20 min. The plumes with shorter periods attain lower heights while those with larger periods attain higher heights (Fig. 10). Only the data pertaining to clear plumes are included. It shows that in general there is an increase in plume height with plume period up to 6 min but thereafter the scattering is quite high indicating that the larger plumes attain different height.

The plume period on an average is an indication of the diameter of the plume and gives an idea of the horizontal extent or diameter of the thermal plume base on the ground as well as at other altitudes. The horizontal extent, of the plumes is given by $S = tv$, where $S$ is the diameter (what we call horizontal
extent), $t$ is the plume period and $v$ is the surface wind velocity.

The area of the plumes, $A$, on the ground is given by

$$A = \pi (tv)^2 / 4$$

Hence the plumes have horizontal extent as short as 120 m and as large as 2.4 km corresponding to an area of 0.01 km² to 4.53 km on the ground.

7. Plume Velocity

The time taken by the convection to reach any height yields an average upward velocity of plumes $w$ given by

$$w = 2H / t$$

where $H$ is the plume height and $t$ is the plume period. Such velocities can be derived directly from Fig. 10 in which plume height has been plotted versus plume period. The velocity varies from a fraction of a metre/sec to about 2 m/sec.

The velocity of plumes as calculated on a clear sunny day is shown in Fig. 11. The envelope in Fig. 11 indicates that up to a certain altitude say around 200 m the plumes build up, rise faster and slow down thereafter. The curve where it touches the vertical scale probably gives an indication of the height up to which the mixed layer extends for practical purposes.

8. Temperature Structure Parameter ($C_T$)

Little determined $C_T^2$ and from the echopower Neff gave a complete discussion of $C_T^2$ and its relation to the physics of the PBL. The power scattered from a unit volume per steradian, for unit incident flux is given by

$$\sigma = 7.2 \times 10^{-3} \lambda^{-1/3} C_T^2 / T^2$$

where $\lambda$ is the wavelength of the probing acoustic energy, $T$ is the ambient temperature and $C_T^2$ is known as the temperature structure parameter given by

$$C_T^2 = (T_1 - T_2)^2 / r^{2/3}$$

$r$ being the distance separating the points where the temperatures $T_1$ and $T_2$ are measured. Since $\lambda$ is fixed for an echosonde the echoreturns can be utilized to calculate $C_T$ if $T$ is known. Under unstable conditions $C_T$ is related to temperature gradient by

$$C_T = aS^{-2/3} (K_h/K_m)^{1/2} h^{2/3} z^{-1/3} T^*$$

where

- $a$ Constant estimated to be 0.47
- $S$ Dimensionless wind shear term
- $K_h$ Coefficient of heat conduction
- $K_m$ Coefficient of viscosity
- $h$ van Karman's constant = 0.4
- $z$ Vertical height
- $T^*$ Gradient of mean temperature given by $\partial T / \partial (\log z)$

Tatarskii measured $C_T$ from meteorological data near the ground under both stable and unstable conditions and plotted them as a function of $k^{2/3} z^{-1/3} T^*$. The values of $C_T$ as calculated from the echosonde observations from both plumes and inversions at a fixed height of 150 m are plotted in Fig. 12. The behaviour of the observed data is similar to the observations made by Tatarskii, i.e. the echo intensity on the echograms can be used as an index of the variations in thermal structure parameter $C_T$.

The field strength of line-of-sight microwave communication during the plume activity in the atmosphere is compared. The observations of the
The plumes observed in an urban environment with echosonde are seen to have the same dimensions and vertical velocities as those over uniform land surfaces or water\textsuperscript{12}.

The absence of echoes from the levels above the plume heights is due to the limitation of the technique as we know that convection and vertical transport of heat must be going on even at higher levels. Frisch and Ochs\textsuperscript{26} have shown from in situ measurements that the model of $C_f$ decreasing with height to the $4/3$ power extends to at least 80\% of the convective layer. Bourne and Keenan\textsuperscript{27} have detected plumes up to nearly 2 km by using an acoustic sounder transmitting 1 kW of power.

Beran\textsuperscript{28} demonstrated the use of Doppler echosonde to derive the vertical velocity of echo return from thermal plumes. The velocity up to 2 m/sec has been reported by Hall \textit{et al.}\textsuperscript{13} and Beran \textit{et al.}\textsuperscript{29}.

The study of onset time and dissipation time of plumes in each season yields an information about the duration of convection conditions. Similarly the dissipation of the morning inversions and the heights they attain before dissipation is important in an industrial area to know the fumigation timings\textsuperscript{30 - 31}.

The plumes provide a natural force to dilute the air pollution near the ground, implying that the effluents should be released into the atmosphere only under the plume conditions. The results of the effect of plumes on communication is in agreement with the earlier observations\textsuperscript{32 - 33}.

10. Limitation of the Technique

The echosonde having the advantage of depicting actual temporal variations of the thermal structure of the atmosphere quickly has its limitations too. Above several hundred metres the temperature fluctuations are so small that they may not be detected by the echosonde system on account of absorption of the transmitted signals and the scattered acoustic energy at larger ranges. Thus the disappearance of plumes on the facsimile records is not necessarily because the mixed layer extends no higher. At larger ranges signals become so week that it is difficult to make the echoes indiscernible. Also the height of an individual plume as seen from the echosonde may not be its true height as it is quite possible that the plume may not have passed over the antenna along its diameter. However, this does not result in any error in the measurement of velocity of the plumes.

Moreover the temporal variations as observed by a single monostatic system do not depict accurately the shape and orientation of the phenomena under observations. This limitation however, can be overcome by using a three axis Doppler sounding system.
11. Conclusions

(i) Atmosphere depicts great day-to-day variability in the vertical temperature distribution.

(ii) Plumes are seen on the facsimile records developing soon after the sunrise but such plumes remain below the rising inversion. The dissipation of this inversion is seen mostly during 0900-1100 hrs indicating the atmosphere to be in a fully convective state. Plumes dissipate around 1730 hrs during August-September period over Patiala.

(iii) Tilted plumes are also seen indicating wind shears in the atmosphere.

(iv) Plumes have periods of the order of a few minutes. The horizontal extent varies from a few tens of metres to around 2.4 km.

(v) The study of plumes using a single monostatic echo sounder has some limitations and for further study a three axis transreceiver should be employed.

(vi) Plumes provide a natural force to dilute the airpollution near the ground and the effulents should be released into the atmosphere under the plume conditions.

References

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