Tracking Urban Planetary Boundary Layer of Hong Kong by Aerosol Monitoring

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Abstract

Boundary layer has a diurnal variation of temperature near the ground with thickness variation ranging from hundreds of meters to a few kilometers. The dynamics of this layer can reveal the trapped pollutants related to atmosphere, climate, and human activities in urban areas of a city. In this paper, we present the first time a comprehensive result of tracking urban planetary boundary layer of Hong Kong (22.3N, 114.7E). The daily and seasonal variations of the mixing depth in the planetary layer over urban areas in Kowloon have been investigated using a ground-base Lidar station situated in the City University of Hong Kong to monitor relative aerosol concentration. The relationships between the aerosol profile, which is used to estimate the depth of the mixing layer, and the virtual potential temperature as well as relative humidity are examined. The Lidar observations and the radiosonde data obtained from the local meteorological station are in close agreement.

1. INTRODUCTION

In a populated city, aerosols are mainly formed by suspended particulates in the air. In particular, dust particles of less than 10 μm in diameter are easily inhaled and unhealthy to people with asthmatics and heart problems. Therefore, aerosol characteristics in the lower troposphere of a city become one of the significant atmospheric parameters in environmental monitoring. The atmospheric echo intensity in the lower troposphere is mainly the aerosol's back-scattered intensity which can in turn approximately represent the aerosol distributions. Hong Kong is a city full of environmental and geographical complexity. The essential geography of the city consists of an island (Hong Kong Island) ten miles wide, standing off the southern edge of a ragged peninsula (Kowloon) to form a long sheltered harbor in the strait with several developing satellite towns in the New Territories connecting the mainland China. Urban areas are characterised by a unique setting : situated on hillsides and facing the sea; mixture of many skyscrapers and clusters of residential quarters with the world's most populated areas where traffic is slow among many narrow streets. Because the International Kai Tak Airport is located in the Kowloon peninsula, the busy air traffic also frequently perturbs and pollutes the lower troposphere of Hong Kong.

Understanding the patterns of mixed layer depth variation in the planetary boundary layer (PBL), where most of the air pollution occurs, will improve our ability to forecast pollution events. Marsik et al. (1995) investigated the diurnal cycle of the mixing depth by several remote sensing techniques and suggested that different collecting systems should be used in order to give a more precise measurement. They also pointed out that it was difficult to determine the mixing depth in the late afternoon period when strong convective clouds developed. The diurnal variation of mixing depth is only a short-term characteristic of the mixed layer. In order to study the long-term patterns of its variation, the seasonal behavior of these patterns should also be examined. While such studies have been made in many places (Padilla et al. 1993, Glaser et al. 1993, Cooper and Enchinger 1994, etc.) these areas are mostly at the higher latitudes. Hong Kong is situated at the subtropical region so that a study of its monthly variation of the mixing depth may help to learn the seasonal behavior of the urban PBL in the lower latitudes. In this paper, we present the first time a comprehensive result of tracking urban PBL of Hong Kong (22.3N, 114.7E). The daily and seasonal variations of the mixing depth in the planetary layer over urban areas in Kowloon have been investigated using a ground-base Lidar station situated in the City University of Hong Kong to monitor relative aerosol concentration. In addition, since cold fronts occur quite often in the winter season in Hong Kong, the variations of the mixing depth in such meteorological events are also studied and will be presented separately.

2. THE LIDAR AEROSOL MONITORING SPECIFICS

In Hong Kong, the first Nd:YAG based lidar was established in 1996 at the City University of Hong Kong and commenced its aerosol monitoring in the middle of 1996. The Lidar system developed (Leung et al., 1994) by the Lidar group of the City University of Hong Kong, located on top of the tallest university building housed in an observational dome. Because of its relatively strategic location (58 m above sea level and near some of the busiest traffic clusters), the Lidar can scan the lower atmosphere of Kowloon urban areas horizontally as well as vertically. Measurements were mainly performed during the daytime. The Lidar transmitter is a Nd:YAG laser which is doubled to 532 nm with pulses of 10 ns at a repetition rate of 10 Hz. The scan-rate is 2-degree per sec. Data acquisition rate is 25 MHz, i.e., one data point per 6-meter. The analog signals collected by a high-gain photomultiplier are digitized using an 8-bit A/D converter and stored in a Pentium-Pro PC computer ready for data processing. A schematic diagram of the Lidar system is shown in Fig.1.

The back-scattered signals can be displayed in the form of aerosol intensity after making range and pulse-energy corrections, as well as noise-reduction processing. The calculation of the aerosol extinction coefficients was based on Klett's method (1980) of solving the Lidar equation. Assume that the ratio of the aerosol extinction coefficient and the back-scatter coefficient is independent of the spatial parameter, then Klett's solution for the aerosol extinction coefficients is :

$$\sigma(R) = \exp(S - S_m) / [(1/\sigma_m) + 2 \int_{R}^{R_m} \exp(S - S_m) dR'] \tag{1}$$

where $\sigma(R)$ is the extinction coefficient and $S \equiv S(R) = \ln[R^2 P(R)]$ with $P(R)$ to be the normalized Laser echo signal and $R^2 P(R)$, the intensity; $S_m \equiv S(R_m)$ and $\sigma_m \equiv \sigma(R_m)$ with R_m as the monitoring range of interest. For illustration, typical signal processing profiles are depicted in Fig.2.

To perform the tracking of the PBL in urban area of Hong Kong, we use the following strategy in Lidar monitoring of aerosol dynamics. Cooper and Enchinger (1994) have used vertical scan to observe the structure of the PBL and estimate the mixed layer depth over Mexico City. For this work, we have used both vertical and azimuthal scanning arrangements. The vertical scan appears as a wedge-shaped angle with the scan direction being perpendicular to the ground and the lidar is at the apex of the triangle while the Earth's surface is the base. A routine scanning arrangement was made from late September 1996 to January 1998 with some exceptions due to weather or instrumentation problems. To study the daily variation of the PBL, data were taken in approximately 3 hours interval (i.e., 0800, 1100, 1400, 1700, and 2000 Local Time) twice a week. Non-routine measurements were also made based on special meteorological forecast announced by the local meteorological station. For example, in Hong Kong a cold frontal passage is a common occurrence during the winter season. Northerly winds associated with such passages often carry large amount of pollutants from mainland China. The winds are also very strong and convective clouds usually occur with heavier precipitation. All of these can cause noticeable change in aerosol dynamics near the surface area of the city. We have attempted to monitor PBL as many cold frontal passages as allowable. Such measurements were made from one day before to one day after the passage at a 3-hours interval during the daytime. An illustration of these measurements will be presented in the following workshop.

3. TRACKING URBAN PBL OF HONG KONG BY AEROSOL MONITORING

a. *Diurnal variation of mixing layer depth*

It has been shown that the atmospheric PBL region can have a stratified structure which may respond to surface forcing with a time scale of about one hour or less (Stull, 1988). Forcing mechanisms may include contributions from frictional fog, evaporation, transportation, heat transfer, pollutant emission and other unknown atmospheric dynamics. An example of this stratified structure is shown in Fig. 3a, which displays a contour plot of the lidar backscattering coefficients profile at 1950LT on 11 January 1997. This is the averaging result of 12 vertical scans from 27° to 51° azimuth. Marked stratification can be found within the altitude range of 400-1800m, at the regions of 640-700m and 1100-1700m. Such clear stratified structure gives a good description of the atmospheric PBL over Hong Kong. This structure is in good agreement with the result obtained from the radiosonde data (Fig. 3b). Under the basic assumption that the top of the mixed layer is located at the position where the first sharp increase in virtual potential temperature is found, the mixed layer depth can be identified at 620m altitude, which is the height where a horizontal boundary is found in Fig. 3a. This comparison demonstrates that the idea of applying lidar to track the PBL via aerosol monitoring is practical. In this work, we used the Lidar signal to estimate the mixed layer depth where the region having a sudden decrease in backscattering intensity which is consistent with Kaimal's work (1982).

A typical PBL pattern of the diurnal variation in Hong Kong tracked by Lidar aerosol signals is shown in Fig. 4. The tracking was performed on 16 December 1997 starting at 800LT with a shallow mixed layer developing near the ground as the sunlight began to warm-up the local surface. The mixed layer depth was estimated to be 500m and then increased quickly to 800m at 1400LT. In the early afternoon, the depth continued to increase and reach its maximum of about 1100m at around 1700LT. At that time, a capping layer stayed on the top of the mixed layer, and the aerosols were also much more concentrated in that region. The mixed layer depth remained almost constant over the afternoon. With the beginning of the sunset, the mixed layer depth decayed quickly to 700m by 2000LT.

b. Seasonal variation of mixing layer depth

In contrast to the diurnal variation of mixed layer depth, the seasonal variation may be driven by a long-term weather pattern that warrants a comparison to be made only between monthly data instead. The following analysis is based on the measurements from the late autumn of 1966 (early October) to the mid-winter of 1977 (end of January). The monthly averaged diurnal variation of the mixed layer depth shows that the average mixed layer depth decreases from the late autumn to mid-winter (Fig. 5) Such a pattern mainly results from the thermal energy exchange between the air in the mixed layer and the earth surface. In late autumn, the temperature at the earth surface is higher than that in winter, and the sum of the thermal energy emitted from the earth surface to the lower mixed layer is also much larger. The entrainment zone (EZ) may therefore appear at a higher altitude. Another reason affecting the mixed layer depth is the different azimuths of the sun in autumn and winter. An analysis of the rate of change of the mixed layer depth for the three months indicates that the mixed layer depth varies similarly. In general, in the late morning, the mixed layer depth increases at the fastest rate of 17-25 m per hour, and then continues increasing at the slower rate of 5-13 m per hour. The rate of change of the mixed layer depth reaches its maximum in the mid-afternoon and begins to decrease. At sunset time, it decreases at nearly the same rate of 37 m per hour. Such a periodic property describes the nature of the development of inversions. Table 1 summarizes the mixed layer depth for the late afternoon for a period of 3 months. The seasonal variation of the maximum mixed layer depth shows a declining trend of the mixed layer depth with time (Fig. 6).

Table 1. Summary of the late afternoon mixed layer depth tracked by Lidar aerosol monitoring.

Date	*Season*	*Mixed layer depth (m)*
12 Oct 1996	Autumn	1400
19 Oct 1996	Autumn	1300
26 Oct 1996	Autumn	1000
30 Nov 1996	Early winter	1300
05 Dec 1996	winter	700
14 Dec 1996	winter	1200
17 Dec 1996	winter	1000
19 Dec 1996	winter	1200
30 Dec 1996	winter	500
31 Dec 1996	winter	800
07 Jan 1997	winter	900
09 Jan 1997	winter	600 and 1000
11 Jan 1997	winter	700 and 1200

c. Comparison between the radiosonde data and lidar tracking urban PBL

To understand the urban PBL structure, radiosonde data are often used to identify the mixed layer depth. In our work, comparisons between the virtual potential temperature, relative humidity, wind speed and lidar backscattering data are also made. From the radiosonde data, the inversion region can be defined as the location where a sharp increase in virtual potential temperature or decrease in relative humidity first occurs.

In general, it is difficult to identify the fine structure of the lidar extinction coefficient profile due to its low signal to noise ratio in daytime tracking. Late-afternoon Lidar data is easier for such comparison. However, a qualitative correlation of the mixed layer depth can be realized. An illustrated comparison is shown in Fig. 7.

4. CONCLUSIONS

Although the report of the Lidar measurements and data analysis of urban PBL of Hong Kong for this study is preliminary, this is the first time a comprehensive result of tracking urban PBL of Hong Kong (22.3N, 114.7E) for a long-term observation. Hong Kong is situated at the subtropical region so that a study of this kind may help to learn the seasonal behavior of the urban PBL in the lower latitudes. The diurnal variation of the mixed layer depth has been verified to be consistent with the changes in virtual potential temperature and relative humidity provided by the radiosonde measurements. Analyses of the seasonal variation of the mixed layer depth basically depends on the energy exchange between the earth surface and the mixed layer. The rate of change of the mixed layer depth changes faster in the warmer days than in cooler ones. The mixed layer depth is much more stable in the mid-afternoon than in the morning or night unless rapid change of weather episodes occur such as a cold frontal passage. As a result, such a property indicates the capping inversion is more stable at the top of the mixed layer in the mid-afternoon and such inversions become less active in winter. In addition, from autumn to winter, a decreasing trend of the mixed layer depth was found. To improve our understanding of the urban PBL of Hong Kong, further work needs to be pursued. For example, we plan to obtain more Lidar data during the coming spring and summer which may provide further information of the mixed layer in the subtropical region.

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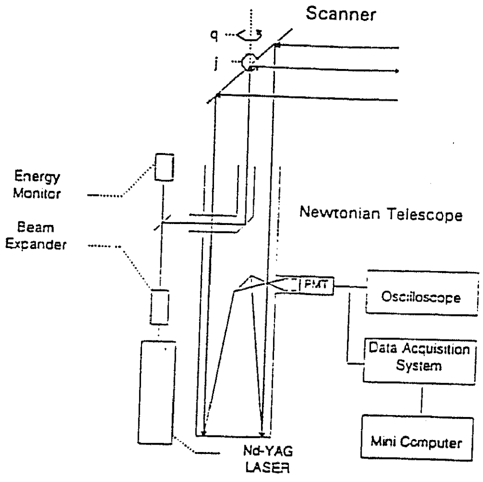
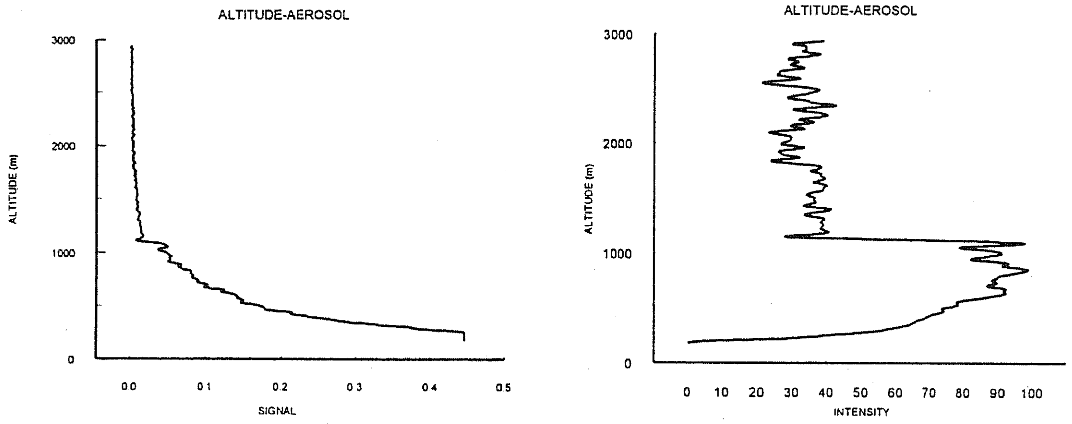
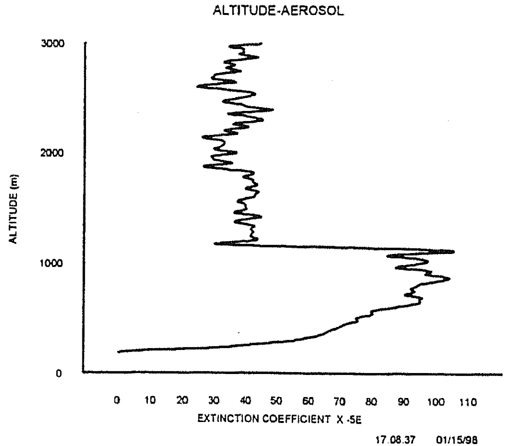


Fig. 1. Schematic diagram of the Lidar system at the City University of Hong Kong.



(a) Average Vertical Lidar Signal Profile

(b) Range Corrected Lidar Signal Profile



(c) Extinction Coefficient Profile

Fig. 2. Different profiles derived from Lidar backscattering signals.

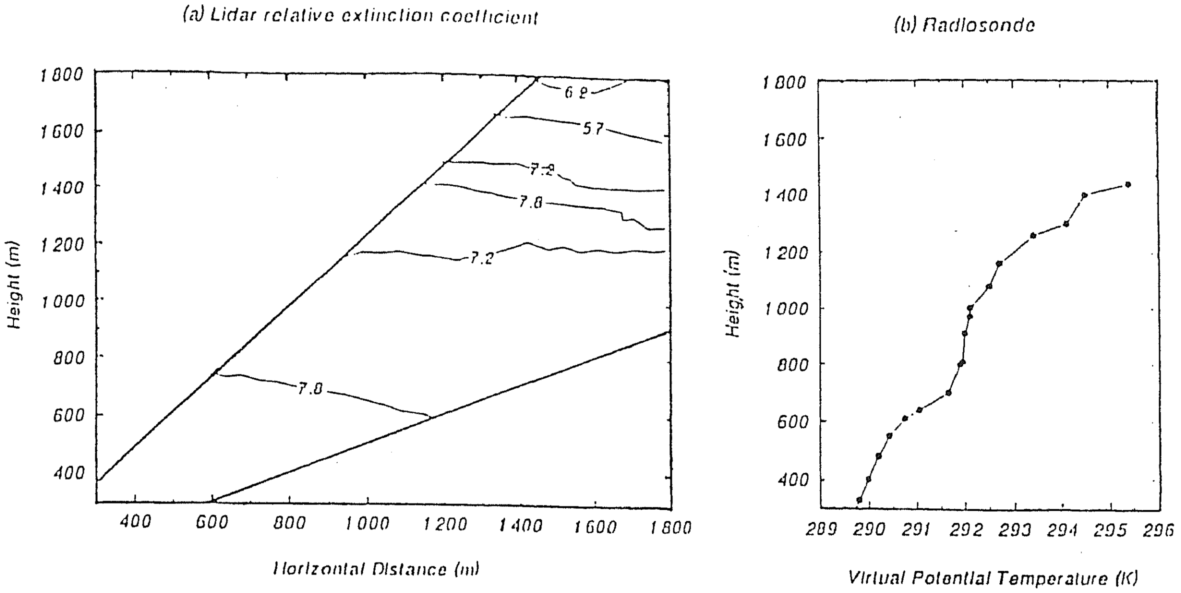
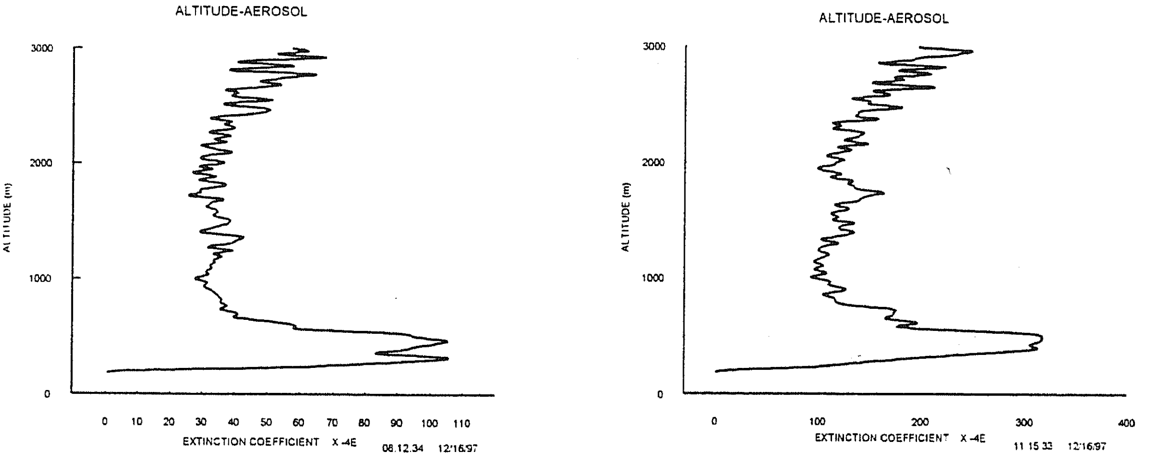
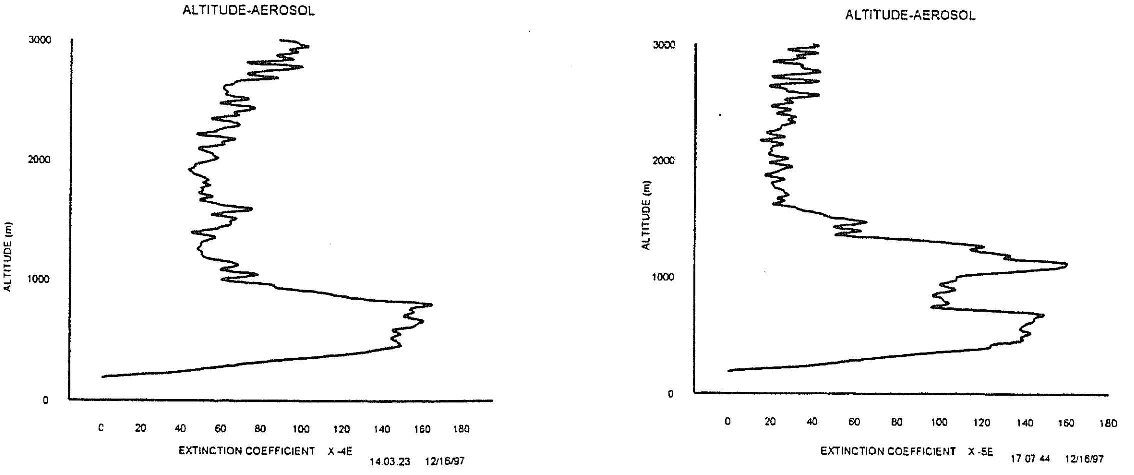


Fig. 3. (a) 2-D contour map of Lidar aerosol extinction coefficients of the mixed layer; and (b) Vertical variation of virtual potential temperature with height from radiosonde data at 2000LT on 11 January 1997.



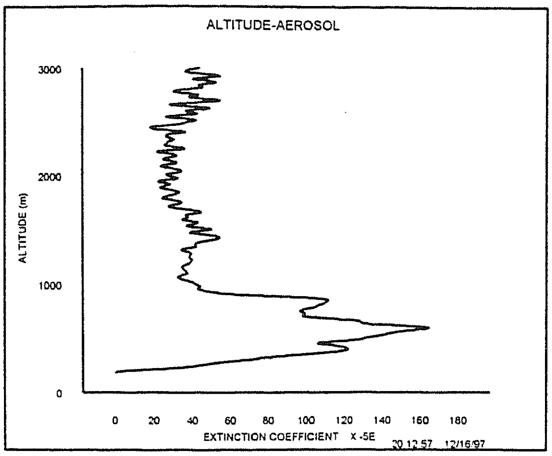
(a) Variation of Signal Peaks with Altitude at 8:00

(b) Variation of Signal Peaks with Altitude at 11:00



(c) Variation of Signal Peaks with Altitude at 14:00

(d) Variation of Signal Peaks with Altitude at 17:00



(e) Variation of Signal Peaks with Altitude at 20:00

Fig. 4. Daily variation (a) to (e) of aerosol extinction profiles measured by Lidar on 16 December 1997.

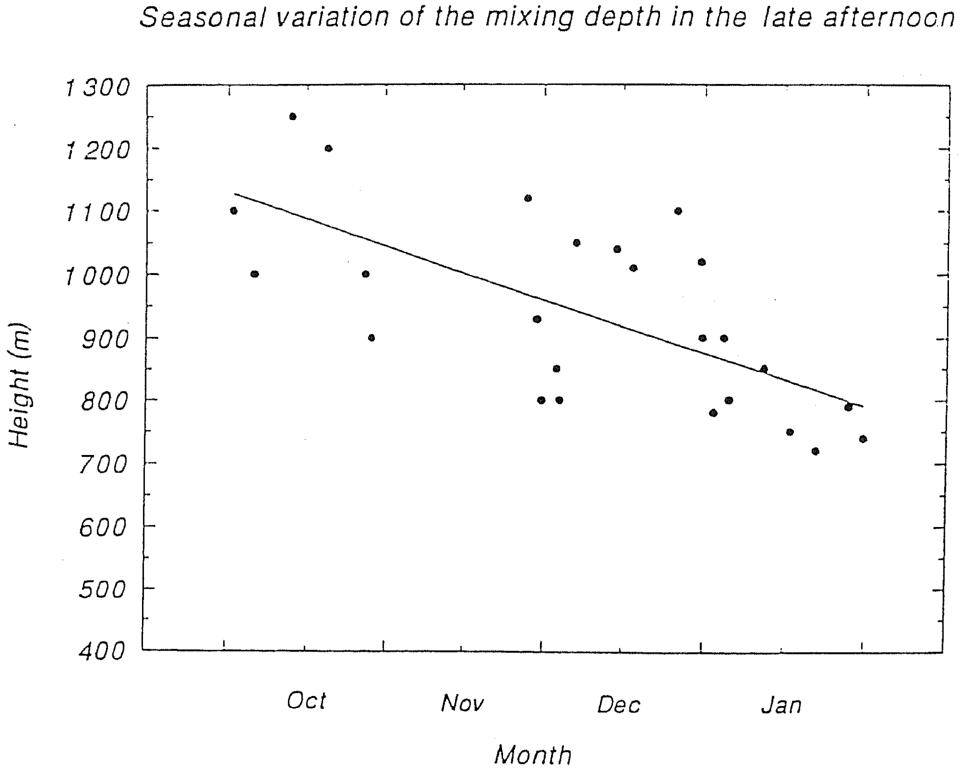


Fig. 5. Seasonal trend of the mixed layer depth in the late afternoon from October 1996 to January 1997.

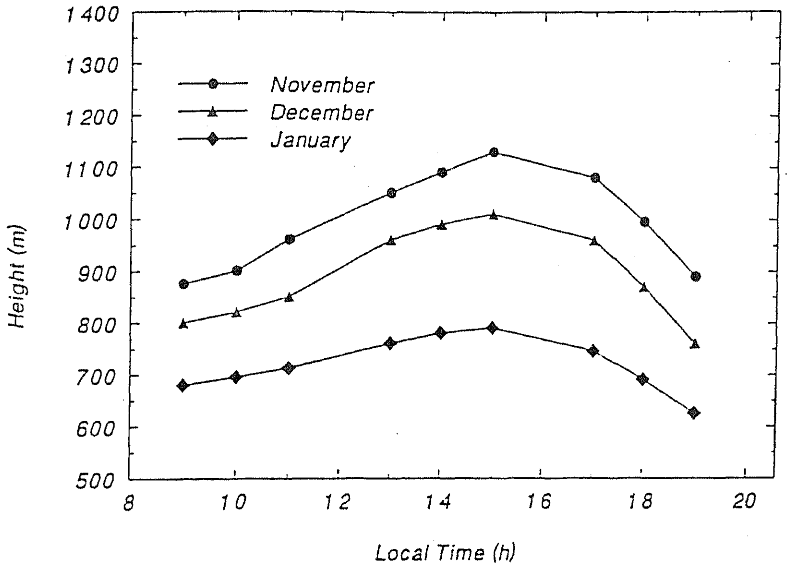


Fig. 6. **Monthly average of the mixed layer depth from November 1996 to January 1997.**

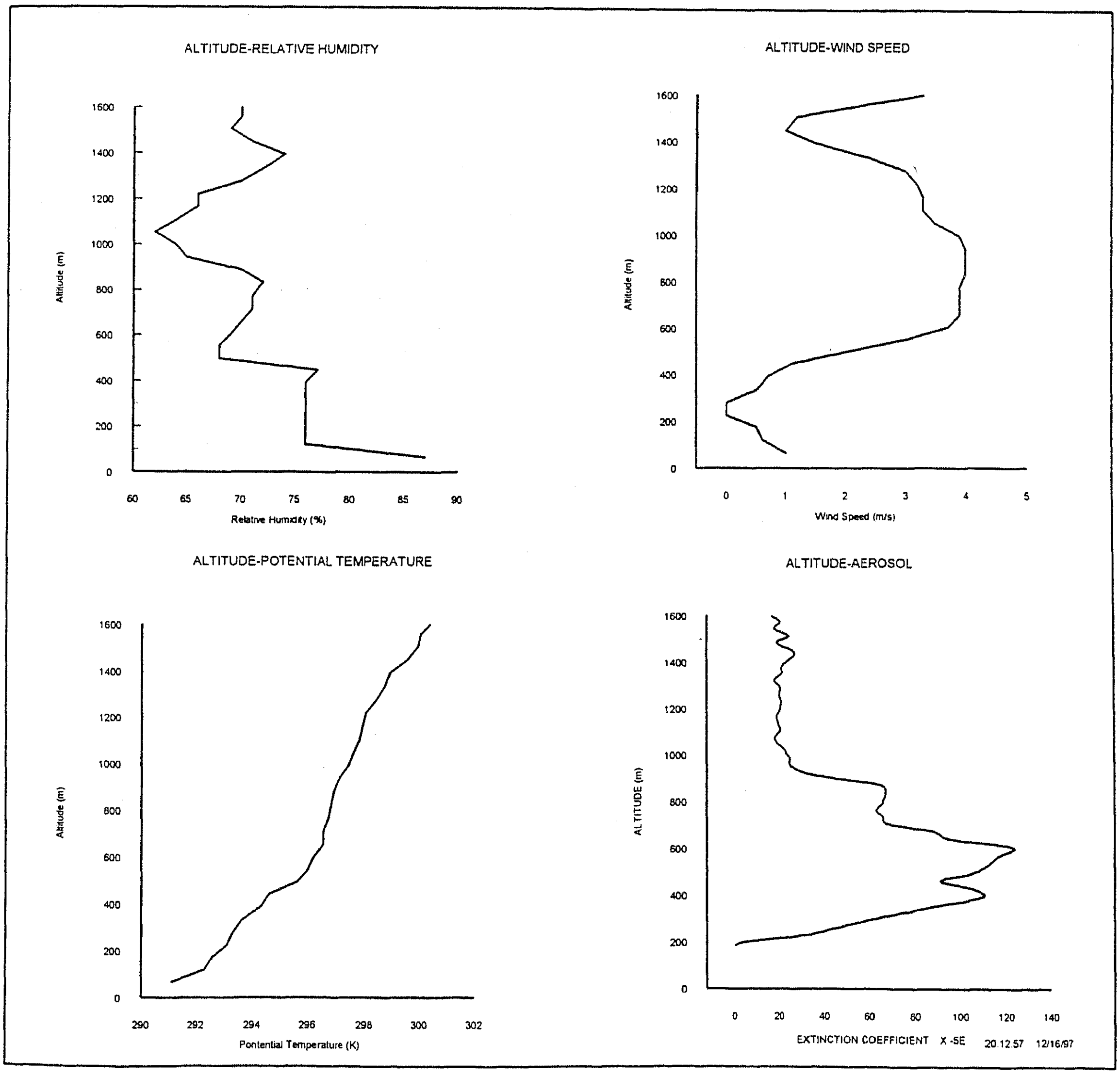


Fig. 7. Comparison of variation of radiosonde data with Lidar monitored aerosol extinction coefficient profile measured at 20:00LT on 16 December 1997.