SODAR STUDIES OF THE MIXING HEIGHT IN THE ARABIAN GULF COAST REGION

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الخلاصة :

أُجريت هذه الدراسة على إحدى المناطق الساحلية من المنطقة الشرقية بالمملكة العربية السعودية لمدة عام كامل ١٩٩٥ م وذلك بهدف قياس ارتفاع الخلط بواسطة نظام (سودار) وكذلك قياس المتغيرات المناخية السطحية. يُعتبر نظام السودار كأداة فعالة للقياسات الجوية ولتوفير سجل مستمر حول البناء الحراري للجو وذلك في المنطقة السفلى من الغلاف الجوى (التروبوسفير). تقوم هذه الورقة بإلقاء الضوء على الحالات المناخية السائدة والتي صُودفت خلال فترة البحث (١ يناير – ٣١ ديسمبر). وقد وجد أن ارتفاع الخلط كان منخفضاً نوعاً ما خلال أشهر الصيف بسبب الحرارة المرتفعة على السطح، وكان ارتفاع الخلط عالياً خلال الأشهر التي تتغير فيها الفصول. وستتم مقارنة المقاس وارتفاع الخلط المُقدَّر في هذه الورقة، وقد استنتج من ذلك أن ارتفاع الخلط المُقدَّر كان أعلى وأكبر من المُقاس. وتُعرض هذه الورقة أيضاً الباروميترات الأرصادية (المتوسط اليومي للضغط السطحي والحرارة فقط) بالنسبة للارتفاع المختلط والتي تم قياسها في محطة الظهران للأرصاد .

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ABSTRACT

This study was conducted, at a coastal location in Northeastern Saudi Arabia for one complete year (1995), to measure the mixing height using a Doppler acoustic sounder called Sonic Detection And Ranging (sodar) System. Sodar is an exceptionally effective tool for making atmospheric measurements and provides continuous record of the atmospheric thermal structure of the lower troposphere. The mixing height, also called the planetary boundary layer height (PBLH), within this region was found to be quite low during the summer months in association with the Arabian heat (thermal) low and high during the inter-seasonal months. Comparisons between measured and estimated mixing heights were also made in this paper. It is concluded that estimated mixing heights are found to be higher than the measured ones. This paper also presents the meteorological parameters (daily mean surface pressure and temperature values only) with respect to the mixing height, which were measured at the Dhahran meteorological station.

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1. INTRODUCTION

The planetary boundary layer (PBL) is the layer of the lower atmosphere wherein significant heat, mass, and momentum transfers take place. The atmospheric Planetary Boundary Layer Height (PBLH) varies with existing meteorological conditions. It is low under weak turbulent conditions and high under strong unstable conditions of the atmosphere. PBLH is defined as 1 km in thickness from the Earth's surface and containing about 10% of the mass of the atmosphere [1]. The boundary layer height, also called mixing height, is primarily determined by the solar heating of the Earth's surface during daytime, horizontal advection of mixing heights, subsidence in the free atmosphere, and radiative cooling during nighttime.

Even though height of the boundary layer can be estimated using either the boundary layer models or thermodynamic diagrams, the acoustic remote sensing (sodar) provides fairly accurate PBL height measurements [2–3]. Acoustic sounders have three distinct advantages over radiosondes. The sodar measurement is relatively inexpensive. The sounder can be run continuously and can be spatially distributed throughout a basin to measure the spatial and temporal variation in inversion height.

Sodar detection is based on the back-scattering of sound waves by small-scale temperature or velocity variations in the atmosphere [4]. Sound waves are projected upward using transmitters situated at a ground station. A small portion of these projected sound waves is scattered back towards the ground. A sodar system capturing backscattered signals is capable of monitoring temperature variations only and is referred to as monostatic sodar, since the transmitters and receivers are situated at the same physical location. Monostatic sodar has also been used for atmospheric stability classification [5]. Many of the commercially available monostatic sodar systems (including the particular one used in this study) use the same antenna as both transmitter and receiver.

These Doppler sodar systems detect both the intensity and frequency shifts of the sound waves. The integrated intensity data are indicative of the thermal structure of the atmosphere and can be displayed on a facsimile recorder or monitor. The detection of frequency shift, or Doppler effect, on the other hand, allows for the measurement of a variety of wind parameters as a function of altitude.

Knowledge of boundary layer height is essential for boundary layer parameterization in weather forecasting [6–9] and in air pollution studies [2, 3, 10]. When atmospheric pollutants are emitted into the atmosphere, they travel and mix within the planetary boundary layer. When the mixing height is high, the ground level atmospheric pollutant concentrations are expected to be low and vice versa. Therefore, an accurate and precise value of mixing height is very crucial for environmental impact studies, prediction of the results of nuclear accidents, or toxic chemical spills *etc.*

The main objective of this paper is to present and study the sodar derived mixing heights for a period of one complete year (1995) near the Arabian Gulf coast region. The monitoring station is about 60 km away from the Dhahran meteorological station. Also one of the prime interests of this study has been to examine the behavior of the planetary boundary layer height variation with respect to season and prevailing meteorological conditions over the region of interest.

2. FIELD EXPERIMENT

The study area is located on the shoreline of the Arabian Gulf in Northeastern Saudi Arabia, near the city of Dhahran (26.3°N; 50.1°E). The area is considered to be a semi-desert region, due to extremely low precipitation rate (less than 80 mm/year), high temperatures, and frequent windstorms [11, 12]. The region is under the influence of an anticyclonic flow in January and cyclonic flow in July [13]. Occasional heavy sand storms during late spring and summer cause drift in sand dunes which tend to affect the vegetation along the West Coast of the Arabian Gulf.

A Remtech phased array (PA2) Doppler sodar system was used to measure half-hourly mixing heights, wind speed and direction, vertical motions, and stability of the lower troposphere. The system basically consists of one sole outdoor antenna and an electronic cabinet placed in a temperature-controlled room. The system uses a single, multicellular antenna whose beam is steered electronically. This particular antenna composed of 196 small antenna elements that is capable of measuring up to 1500 m. Transmitting power of this sodar system is 30 W and its operating frequency is 2100 Hz. The system allows for full-control of the antenna beams so those horizontal and vertical components of wind velocities are measured. Measurements have been made over twenty slices of the lower atmosphere between the altitudes of 50 and 810 meters above the ground. The thickness of each slice was 40 m.

3. DATA ANALYSIS TECHNIQUE

The mixing height values averaged over 30 minutes interval were recorded and stored. From this data set, half-hourly, hourly, and daily averaged mixing height values were computed using standard statistical procedures. The mean, maximum, and minimum hourly values were calculated and graphically displayed. The missing values of mixing height due to a power failure or weak return signal were interpolated using a cubic spline subroutine.

4. RESULTS AND DISCUSSIONS

It is known that the meteorological processes across the Saudi Arabian Peninsula, particularly Northeastern Saudi Arabia, are dominated by the extent of two major pressure systems: the Siberian High (subtropical high) in winter and the Basra Asian Low (subtropical low), which is embedded in the inter tropical convergence zone (ITCZ) [12].

The experimental results show that the daily surface pressure value, which is very close to the sea surface pressure, varied from 1040 mb to 1000 mb during the monitoring period. Figure 1 shows the daily surface pressure values and patterns for the year 1990 and 1991 taken at the Dhahran meteorological station, which was near to the monitoring station. The daily sodar mixing height values are presented in Figure 2 for the complete year (1995). It can be seen from this figure that the daily mixing height was high during the inter-seasonal months (March, April, October, and November) and low during the summer months (June, July, and August). This is because during the inter seasonal months the atmosphere tends to be convective and the convective boundary layer as seen by sodar extends up to 900 meters. The highest daily maximum mixing height was observed to be 1087 m in October. In Figure 3, it is clear that during first half of November the diurnal variation is high. On the other hand, the reverse is true during the period from November 13–21.

Table 1 shows the occurrence of the mixing height (in percentage) with respect to 11 layers, of 100 m each, for the 12-month monitoring period. It is clear from this table that the occurrence of mixing height below 200 meters were 93.8%, 88.1%, and 82.4% in the months of August, July, and September, respectively. On the contrary, the occurrence of mixing height above 500 meters were 10.1%, 7.4%, and 5.9% in the months of November, April and March, respectively.

In the absence of convective activity at night during the summer months (August), the mixing height values are in the range of hundred meters (Figure 4). Mainly large-scale subsidence and the Arabian thermal heat low are presumed to play

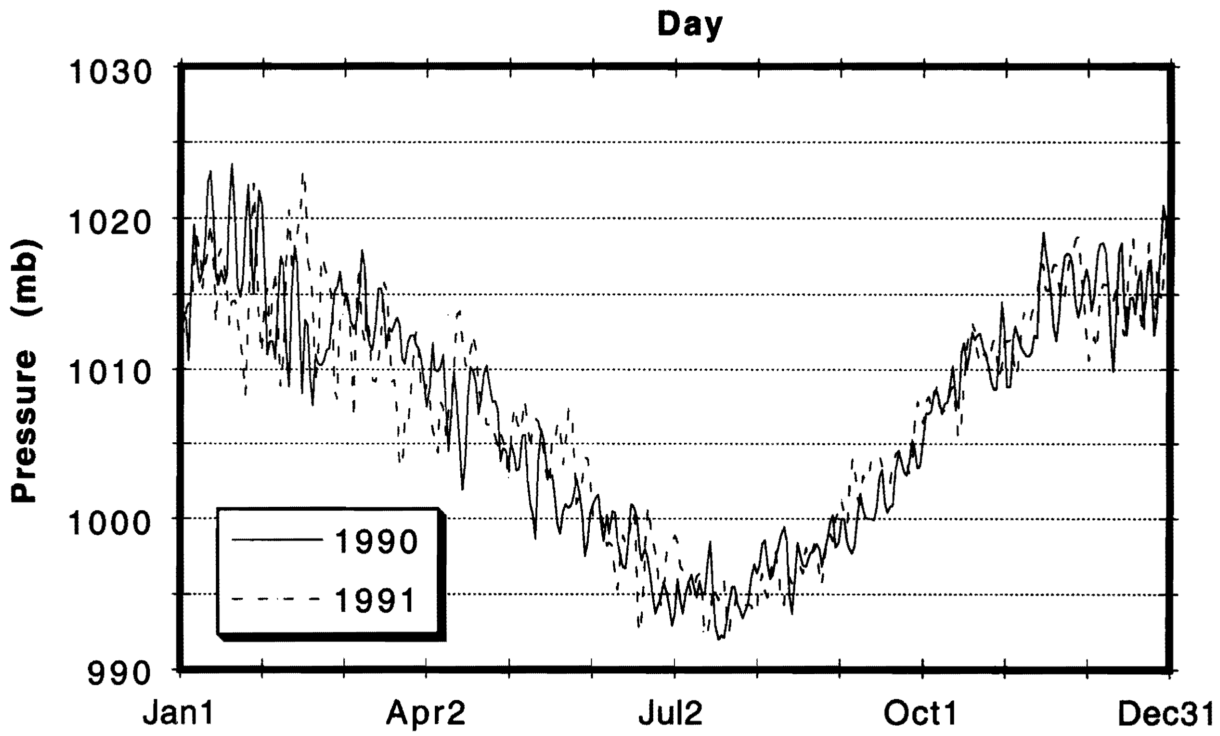

Figure 1. Surface pressure values (mb) for the year 1990 and 1991 measured at the Dhahran international–national meteorological station.

an important role in suppressing the boundary layer growth. The atmospheric pressure was low due to high temperatures during summer (Figure 5). Daily mean temperature reaches more than 38°C during this period. It is known that immediate effect of local heating is to tilt the isobaric surfaces in the atmosphere over the heat source. This produces the upper level high and outflow of air aloft. This in turn reduces the surface pressure and consequently induces an inflow of air into the surface low.

Figure 2 also indicates peak values of 800 m or so in April, through July and September to November. There is a tendency for the mixing heights to be lower during January, February, and March when the Siberian High is under control. There is not much of seasonal variation evident in this figure and it is much less than the inter-diurnal (day to day) variation. This inter-diurnal variation is observed to be high in the months of July and September to November. Since sensible heat warming

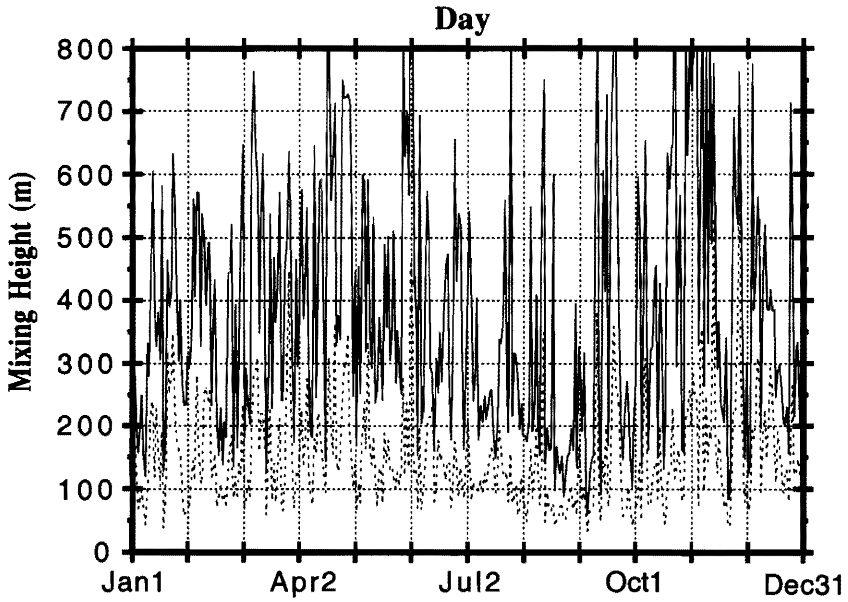

Figure 2. Sodar derived daily mean (dashed line) and daily maximum (solid line) mixing height (m).

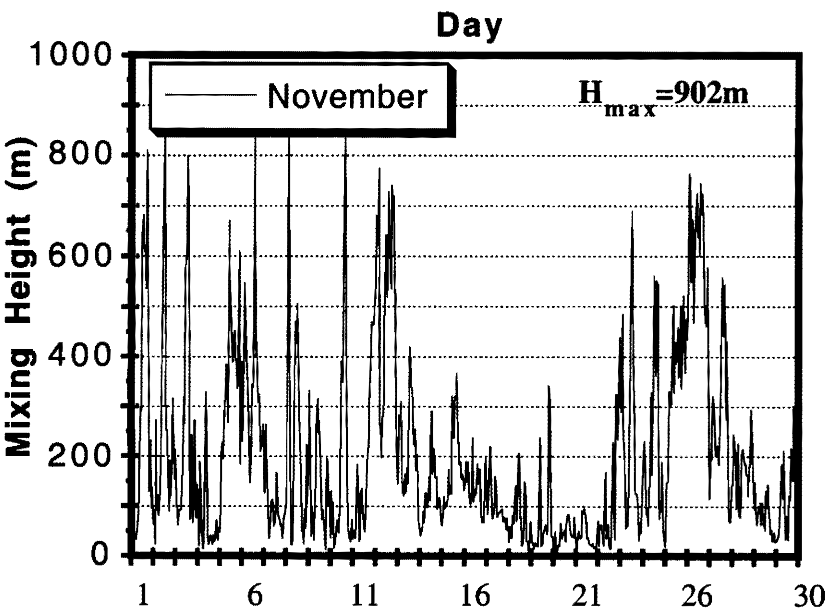

Figure 3. Sodar derived daily mean mixing height (m) in the month of November.

occurs throughout the year, other factors controlling the mixing height are considered to be subsidence and advection. Also it is seen that the average high peak was reached for most number of times in November and the low peak was reached in August. Due to the heavy rainfall event, the lower mixing height was seen in the middle of December.

Figure 6 illustrates the sodar derived half-hourly mean vertical velocities (cm/s) at the four different times during the monitoring period. It is clear from this figure that on 2 August and 4 September (when the mixing heights were quite low), the vertical motion was downward with velocities in the range 0 to −40 cm/s, whereas the vertical velocity was upward in the range 10 to 110 cm/s on 26 April (when the mixing height was high due to the convective activities). November and April are the inter-seasonal months in this region when a lot of convective activities are observed. The vertical velocities

Table 1. Occurrence (%) of Planetary Boundary Layer Height (PBLH) During Different Months in 1995 Over the Region of Interest.

N	PBLH-RANGE(m)	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	0 <PBLH < 100	42.6	47.3	45.0	38.3	45.4	44.5	44.8	69.6	62.1	57.7	39.7	33.5
2	100 <PBLH < 200	26.5	28.4	23.1	27.6	30.0	31.0	43.3	24.2	20.3	22.6	24.3	38.2
3	200 <PBLH < 300	16.7	13.4	14.9	14.3	14.8	14.8	8.7	2.3	6.3	7.7	12.6	16.1
4	300 <PBLH < 400	10.2	7.3	6.6	7.4	3.6	3.0	2.0	1.3	4.4	4.3	7.8	8.9
5	400 <PBLH < 500	2.8	2.5	4.4	5.0	3.4	2.6	0.5	1.1	2.2	3.1	5.4	2.2
6	500 <PBLH < 600	0.9	1.0	3.8	4.2	2.2	1.3	0.4	0.4	2.2	2.6	4.0	0.5
7	600 <PBLH < 700	0.3	0.0	1.7	1.4	0.4	0.9	0.1	0.4	1.5	1.2	3.3	0.4
8	700 <PBLH < 800	0.0	0.0	0.4	1.7	0.1	0.9	0.0	0.7	0.7	0.5	2.1	0.3
9	800 <PBLH < 900	0.0	0.0	0.0	0.1	0.1	0.4	0.0	0.0	0.1	0.3	0.6	0.0
10	900 <PBLH <1000	0.0	0.0	0.0	0.0	0.0	0.4	0.1	0.0	0.1	0.0	0.1	0.0
11	1000 <PBLH <1100	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0

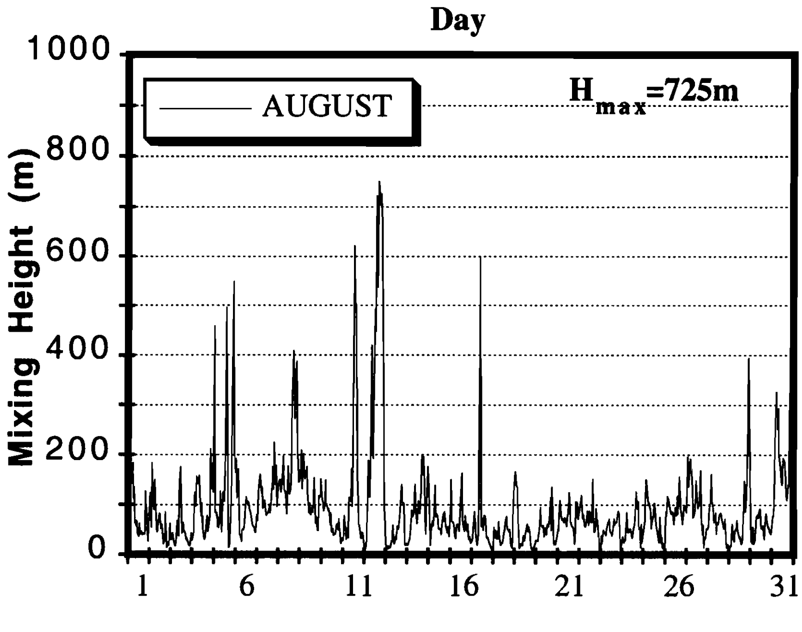

Figure 4. Sodar derived daily mean mixing height (m) in the month of August.

were downward on 12 March until 20:00 LST. Until this time, the low inversion layer was well maintained by subsidence and the total rainfall amount was 7.0 mm between 20:00 and 23:00 LST.

Nighttime mixing height values were much lower than those in daytime. Figures 7 and 8 illustrate the nighttime (03:00 LST) and the daytime (15:00 LST) sodar derived hourly mean mixing height values. As expected, due to radiative cooling during the nighttime, low mixing height values were recorded. On the other hand, due to daytime solar insolation, higher mixing height values were observed. The hourly mixing height patterns were almost the same for both daytime (15:00 LST) and nighttime (03:00 LST), except that daytime values were generally 100 to 300 m higher.

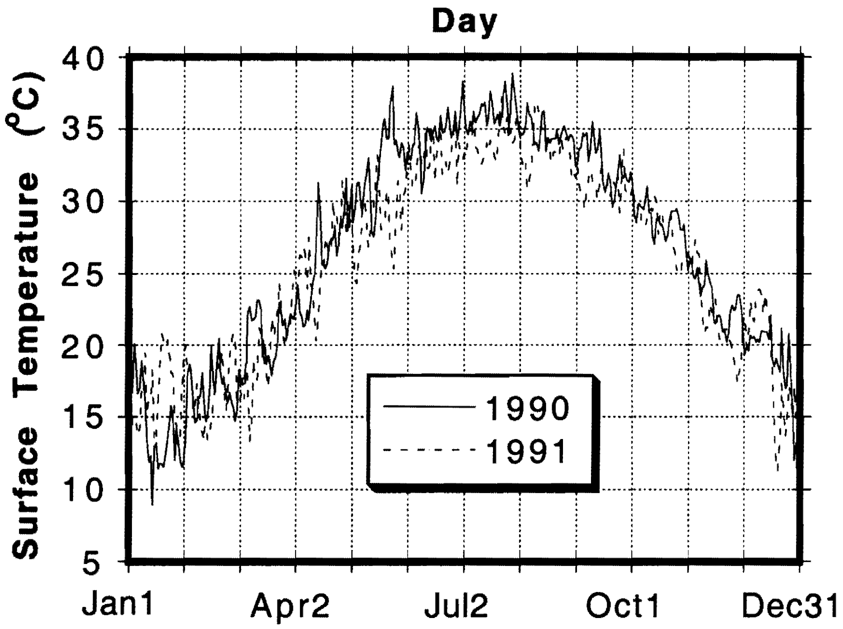

Figure 5. Daily mean surface temperature (°C) for the year 1990 and 1991 measured at the Dhahran international–national meteorological station.

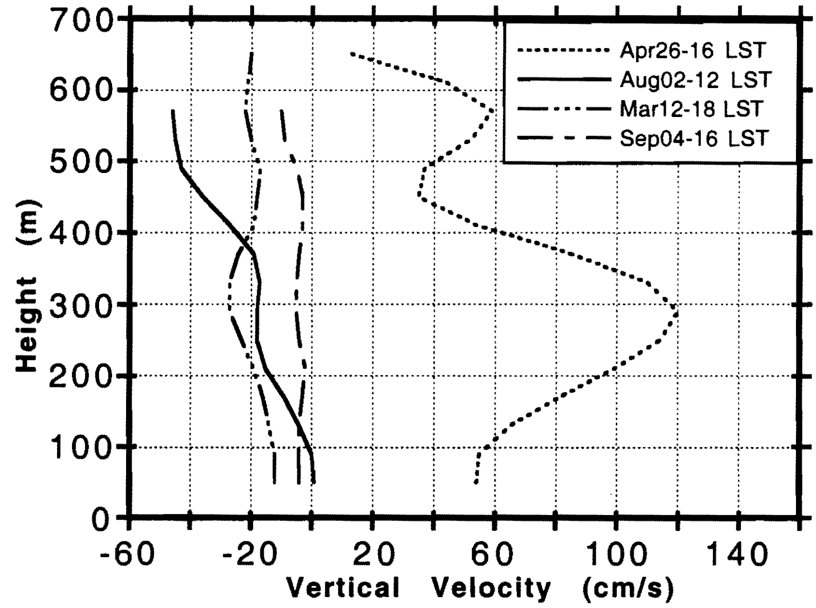

Figure 6. Sodar derived half-hourly mean vertical velocities (cm/s) at four different times of the year. Note the strong updraft due to the convective instability in April, and moderate subsidence due to the Arabian Heat Low in August.

In a separate study [14], the heights of the planetary boundary layer were estimated for the Dhahran meteorological station at 00:00 Universal Time Zone (UTZ) (*i.e.*, 03:00 LST) and 12:00 UTZ (*i.e.*, 15:00 LST) using the potential temperature profiles obtained from radiosondes measurements for a period of six years between 1986 and 1991. Tables 2 and 3 present the comparisons between the sodar derived monthly-mean mixing heights in the year 1995 and the estimated monthly-mean mixing heights averaged over six years (from 1986 to 1991) at 03:00 UTZ and 15:00 UTZ, respectively. The estimated mixing heights were almost 200 m and 400 m higher than that of measured ones at 03:00 and 15:00 LST, respectively. It can be also seen from Table 3 that both measured and estimated mixing heights were lower in summer months as compared to winter.

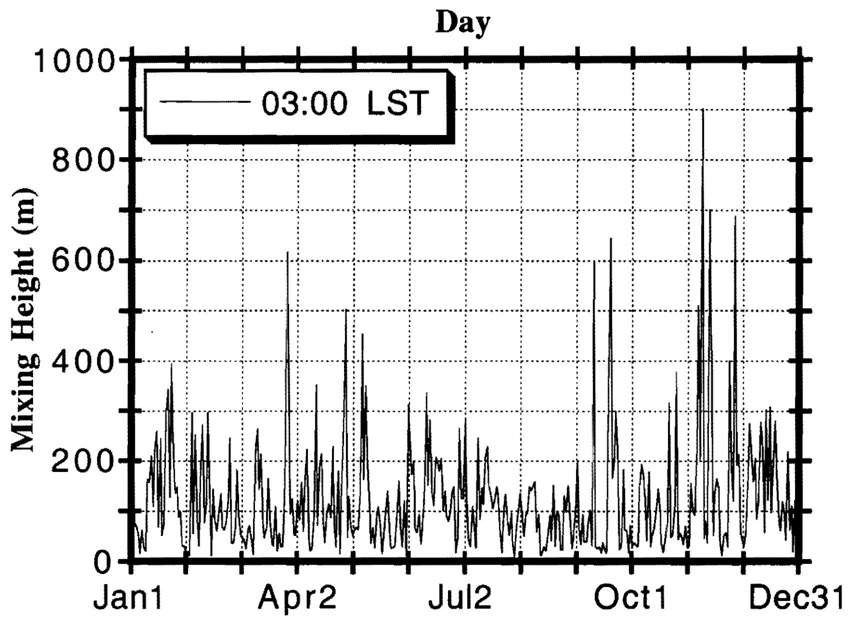

Figure 7. Sodar derived hourly averaged mixing heights (m) at 03:00 LST (00:00 UTZ) for the year 1995.

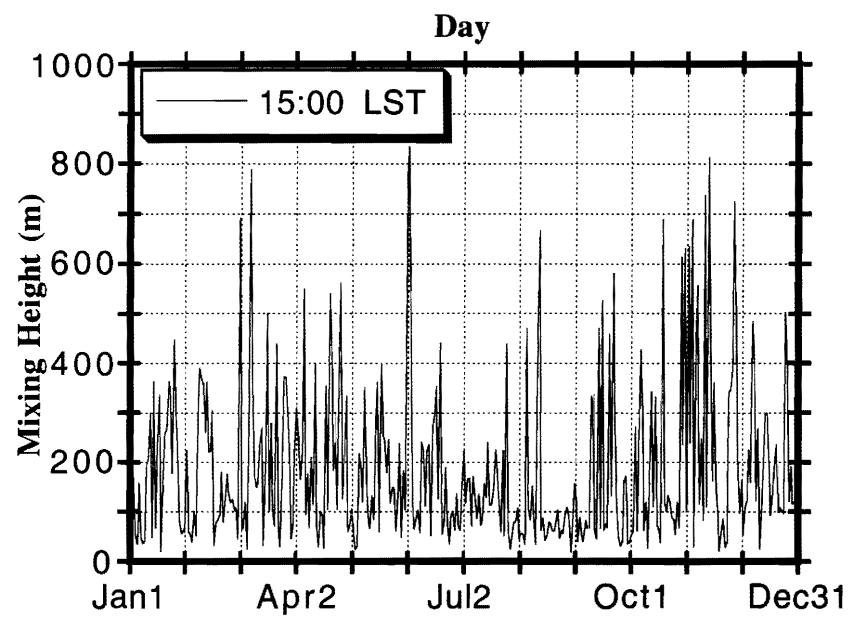

Figure 8. Sodar derived hourly averaged mixing heights (m) at 15:00 LST (12:00 UTZ) for the year 1995.

Table 2. Comparison of Measured (from Sodar) and Estimated (from Radiosonde) Monthly Mean Mixing Height (PBLH) Values at 03:00 LST. In this Table, the Estimated Values are the Average of 6 Years from 1986 to 1991.

Source	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Measured PBLH (m)	137	116	113	130	99	147	110	82	127	92	200	144
Estimated PBLH (m)	283	307	302	342	360	411	393	379	362	345	301	284
Difference (m)	146	191	189	212	261	264	283	297	235	253	101	140

Table 3. Same as Table 2 Except at 15:00 LST.

Source	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Measured PBLH (m)	187	170	218	226	159	199	136	119	157	192	295	186
Estimated PBLH (m)	913	754	797	544	517	492	450	476	497	529	735	740
Difference (m)	726	584	579	318	358	293	314	357	340	337	440	554

5. CONCLUSIONS

In this study, Doppler sodar derived mixing height data were collected, processed, and studied. The mixing height values were high during the winter months and low in the summer months. This is probably because the atmosphere during winter tends to be convective and unstable. The highest daily maximum mixing height was observed to be 1087 m in October. Furthermore, the mixing height values were high during the daytime and low during the nighttime in accordance with the solar heating and nocturnal cooling. The inversion layer acts like a lid to suppress any vertical activities so that mixing height diminishes during the nighttime. Thus, it can be concluded that the ground level air pollutant concentrations is expected to be high when the mixing height is low, particularly during the night and summer times in the Arabian Gulf coast region under the same pollutant emission rate throughout the year.

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