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Boundary Layer Characteristics over the Central Area of the Kathmandu Valley as Revealed by Sodar Observation

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ABSTRACT

The characteristic behavior of prevailing boundary layer over the central area of the Kathmandu valley was continuously monitored by deploying a monostatic flat array sodar during the period of 03 to 16 March 2013. Diurnal variation of wind and mixing layer height were chosen to describe the boundary layer activities over the area by considering the day of 12 March 2013 as the representative day for the period of observation. The study shows that central area of the valley remains calm or windless under stable stratification throughout the night and early morning frequently capped by northeasterly or easterly wind aloft. Strong surface level thermal inversion prevails during the period up to the height of 80m above the surface. This inversion tends to lift up as the morning progresses and reaches to the height of 875 m or so close to the noontime. Intrusion of regional winds as westerly/northwesterly and the southerly/southwesterly from the western and southwestern low-mountain passes and the river gorge in the afternoon tends to reduce the noontime mixing layer height to about 700 m. The diurnal variation of wind and mixing layer height suggest that Kathmandu valley possesses a poor air pollution dispersion power and hence the valley is predisposed to high air pollution potential.

Keywords: Sodar, boundary layer, mixing layer, complex terrain, Kathmandu valley.

INTRODUCTION

The boundary layer (BL) of the atmosphere is that part of troposphere that is directly influenced by the presence of the earth's surface, and responds to surface forcings with a time scale of about an hour or so (Stull 1989). The lowest part of the BL that exhibits extensive vertical mixing of air masses is called as mixing layer. The depth of the mixing layer also called the mixing layer height (MLH) is an important parameter in characterizing the lower atmosphere and to assess various atmospheric processes including air pollution dispersion. Availability of detail knowledge on wind and mixing layer profiles largely determines the understanding of atmospheric transport processes and their implications for prevailing weather, climate and the environment. Different ground based and upper air remote sensing instruments are used to measure the vertical profiles of wind and mixing heights of the atmosphere over an area of interest.

Among the ground based remote sensor, Sonic Detection and Ranging (sodar) is considered to be one of the important sensors for measuring vertical profile of wind and MLH. Different studies (Neff 1986, 1988, 1990, Neff & King 1987, 1988, Coulter & Martin 1983, Coulter *et al.* 1989, Neff *et al.* 1980) have demonstrated the importance and usefulness of sodar in the study of boundary layer processes over complex terrains. Various other parameters can be diagnosed from the basic sodar data sets.

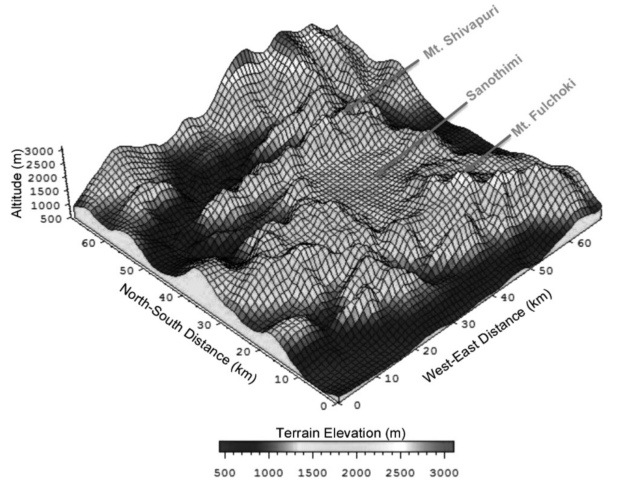

Fig. 1. The three-dimensional topographic view of Kathmandu valley.

Very few, but important studies were carried out in the early 2010 over the Kathmandu valley (Regmi *et al.* 2003, Panday 2006) aiming to characterize the boundary layer processes over the valley supplementing the numerical predictions. Nearly a decade has passed since those studies were made. Over period, the valley has seen dramatic changes in the pattern of land use, population, and emission activities. Thus, the present study was conceived to understand the boundary layer activities over the valley as revealed by a sophisticated monostatic flat array sodar.

Sanothimi, located at the center of the Kathmandu valley (Fig. 1) represents an ideal site to monitor the boundary layer activities over the areas as well as to assess the overall scenario of the boundary layer activities over the valley. This is the area where the prominent wind systems of the valley, namely, the southwesterly that intrudes into the valley from the southern low-mountain passes and the Bagmati River Gorge and the northwesterly that intrudes into the valley from the western low-mountain passes merge into a westerly wind. The westerly channels into the eastern neighboring valley Banepa via the eastern low-mountain passes (Regmi *et al.* 2003). In consideration with these knowledge achieved from past studies, boundary layer activities over Sanothimi area were continuously monitored during 03 to 16 March 2013 from the premises of the office of University Grants Commission (UGC), Nepal (Fig. 2a).

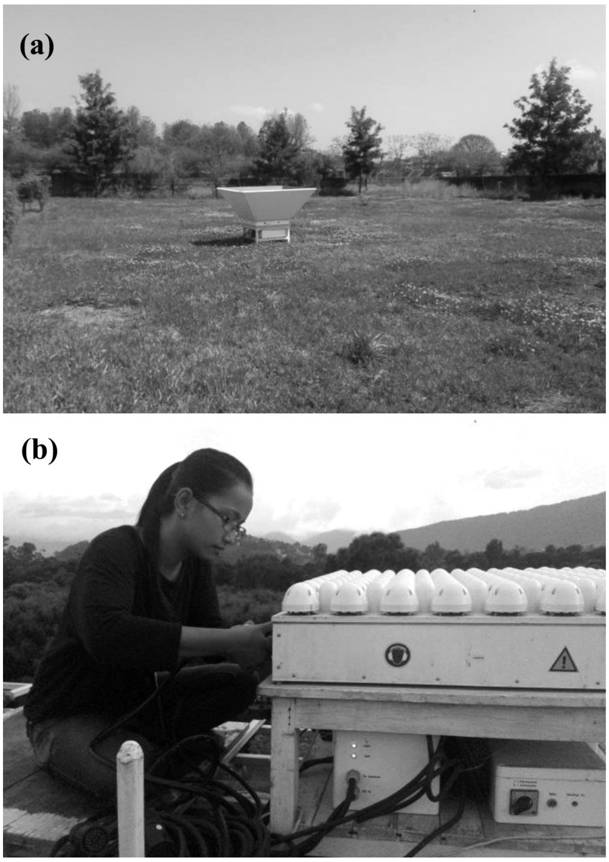

Fig. 2. Sodar antenna setup in the premise of the office of University Grants Commission, Nepal in Sanothimi (a) and the MFAS64 sodar antenna (b).

In this paper, we will discuss the diurnal variation of boundary layer activities, particularly, the wind fields and mixing height by selecting the day of 12 March 2013 as a representative day for the early spring season.

INSTRUMENTATION & METHODOLOGY

A monostatic flat array doppler sodar (MFAS64 Scintec Co. Germany make), available at National Atmospheric Resource and Environmental Research Laboratory (NARERL), Central Department of Physics, Tribhuvan University was installed and operated from the premises of UGC located at Sanothimi, Bhaktapur.

The sodar was configured at 15-min averaging time interval of wind components and directions. It was installed at the large open space of the UGC (Fig. 2a). The sodar was continuously operated by setting its probing up to the height of 600 m AGL with the vertical resolution of 10m for two weeks during 03 to 16 March 2013, which is long enough to gather representative data.

Since turbulence-produced refractive index fluctuations depend almost instantaneously on wind shear and stratification (Neff 1990), sodar can provide instantaneous information on vertical structure of wind and turbulence. Analyzing the backscattered intensity profile one can assess and estimate the mixing layer height at a particular time and hence the diurnal characteristics if continuous measurement is made. Since the sodar used in this study is monostatic, it measures the backscattered signal, i.e., 180^o scattered. The equation of scattering cross section for backscattering is given as

$$\sigma = 0.0039k^{\frac{1}{3}}\left(\frac{{C_T}^2}{{T_0}^2}\right) \ldots\ldots\ldots\ldots\ldots (1)$$

Where k is the acoustic wave number

$$k = \frac{2\pi}{\lambda} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

C_T^2 is the constant temperature structure function, λ is the acoustic wavelength and T_o is the local temperature. From equation 1 it can be inferred that backscattering depends only on temperature fluctuation. For this reason, sodar data reflect, albeit indirectly, the temperature structure of wind flows (Neff 1990).

RESULTS

Understanding the boundary layer activities and their implications over an area of interest largely comes through the understanding of the wind structure and the mixing layer height. Thus, in the following sub-sections, we will discuss diurnal characteristics of wind field and mixing layer height over the central part of the Kathmandu valley as revealed by the facsimiles derived from the observed sodar data.

A. WIND STRUCTURE

Fig. 3 shows the facsimile plots of the diurnal variation of wind speed and wind direction on the day of 12 March 2013. Careful examinations of these facsimiles in reference to the wind speed color bar, it can be inferred that during the night hours, the immediate atmosphere over the Sanothimi area remains calm or windless (Fig. 3a). During the period of 0000 to 0400 Local Standard Time (LST), the wind speed varies from 0.5 to 2.0ms^{-1} from bottom to the top of the probing height. The top of the probing height was set at 600m AGL for this particular measurement. However, patches of wind speed of about 2.0ms^{-1} often appear at about 200m AGL during the same period. It is interesting to note that both the speed (Fig. 3a) and direction (Fig. 3b) over the area do not show persistency but are rather random in their behavior. Nevertheless, northeasterly appears to dominate up to the height of 400m AGL and more westerly wind aloft. Moreover, during the night hours, a weak easterly wind may also prevail occasionally over the area. The wind pattern thus inferred from sodar observation over the Sanothimi area during the night hours appears to be consistent with the numerical predictions made for the central area of the valley (Regmi *et al.* 2003, Kitada & Regmi 2003). The authors argued that intermittent downslope winds over the surrounding mountain slopes generate a weak but complex flows pattern over the central part of the valley that often may undergo anticlockwise circulations and easterly shooting keeping the near surface air mass stagnated.

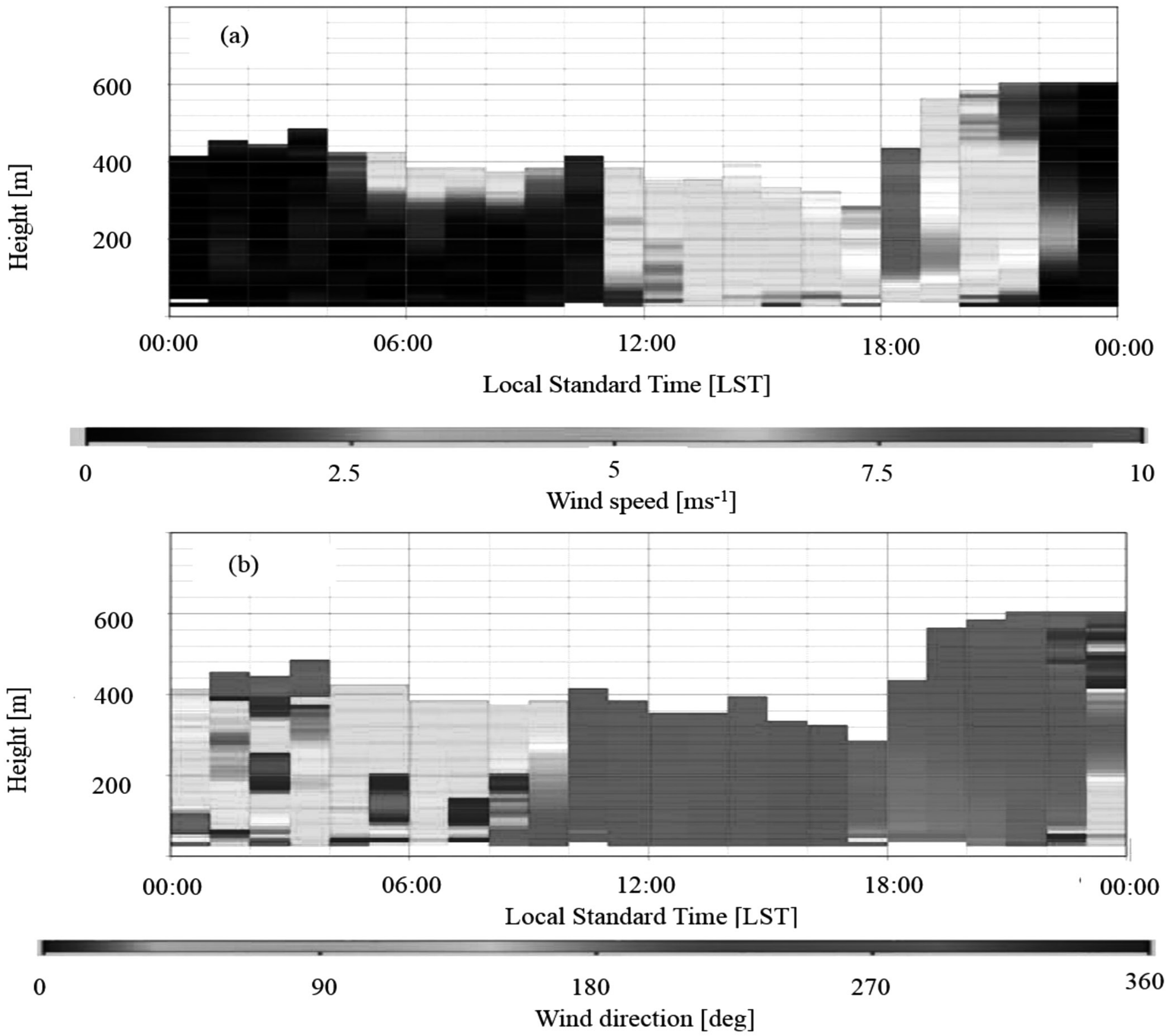

Fig. 3. Facsimile plots of hourly averaged wind speed (a) and wind direction (b).

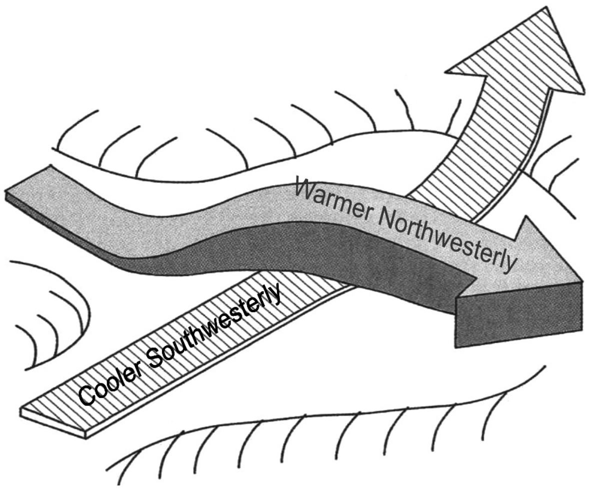

Fig. 4. Conceptual picture of afternoon time prominent wind systems over the Kathmandu valley. The cooler southwesterly is capped by the relatively warm northwesterly wind over the central and eastern part of the valley (Regmi *et al.* 2003).

The wind pattern undergoes dramatic changes as the early morning progresses (Fig. 3a & 3b). The most important pattern seen in the sodar measurement is the intrusion of relatively strong easterly wind from above 180 m AGL beginning from as early as 0400 LST that may continue up to 1000 LST. The easterly wind might have been induced by the large-scale downslope wind that flows from Himalaya down to the Ganga Plain via eastern low mountain passes. Prevalence of the easterly wind only at higher levels strongly suggests that stably stratified nocturnal layer of cold air pool might have been formed. The stably stratified cold air pool effectively inhibits easterly wind to penetrate at surface levels but can easily overshoot from aloft the stratified layer.

The easterly wind gradually increases and may reach up to 6 ms^{-1} around 0610 LST but keeps the lowest 200 m air mass calm and stratified. More or less the same situation may continue until late morning.

Beyond 1030 LST the easterly ceases and the southwesterly appears to prevail over the area but only below 120 m AGL. This southwesterly is quickly replaced by westerly at about 1100 LST with overall increase in the speed of wind from ground to the probing height. In the afternoon (Fig. 5c) the wind speed up to the height of 180 m AGL appears to be below 4ms^{-1} but reaches up to 8.5 ms^{-1} at about 360m AGL. In between 1500-1900 LST the southwesterly strengthens significantly (Fig.3) and becomes more southerly in later hours. This southerly appears to be the dominating wind system over the valley in the later hours. The vertical distribution of the wind speed and the direction suggest the double layering structure of wind over the central area of the valley.

Similar observations (Regmi *et al.* 2003) with sodar from Maitighar, Kathmandu, which lies in the western central area of the valley, had also captured the double layering flow system over the valley. Concurrent numerical

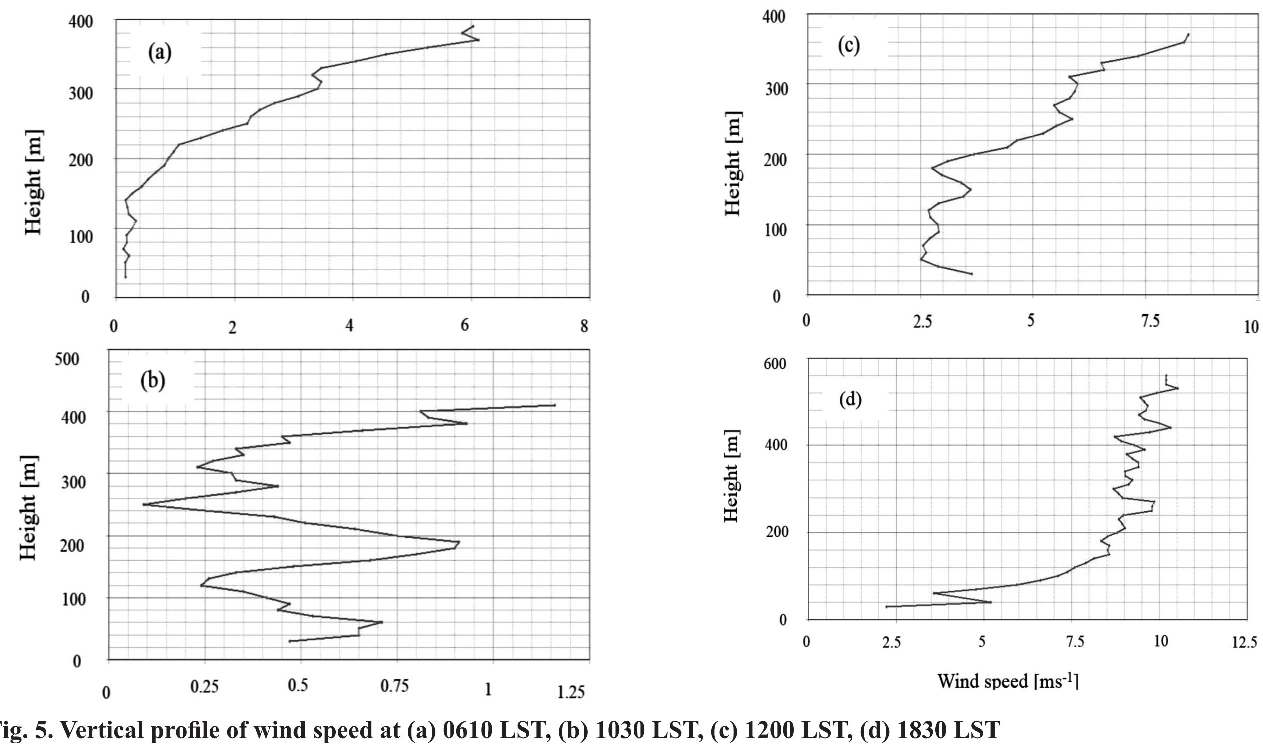

Fig. 5. Vertical profile of wind speed at (a) 0610 LST, (b) 1030 LST, (c) 1200 LST, (d) 1830 LST

simulation of the flow field over the valley (Regmi *et al.* 2003) further clarified the mechanism of development of double layering wind structure. According to Regmi *et al.* (2003), Kathmandu valley possesses two major wind systems, namely, the southwesterly and northwesterly. The southwesterly makes its way to eastern Banepa valley assuming the banana shape whereas the northwesterly makes a hydraulic jump in the western part of the valley and lifts up and then flows over the southwesterly. The southwesterly is very shallow extending only up to 250m AGL. The conceptual diagram (Fig. 4) illustrates the late afternoon time double structure of wind over the valley. Thus, the present measurement further verifies the late afternoon time flow structure predicted and measured by Regmi *et al.* (2003).

The vertical profile of wind speed at 1830 LST (Fig. 5d) indicates that the lowest 200m layer of the atmosphere suffers from strong wind speed shear. Thus, the lower atmosphere of the valley can be expected to be highly turbulent since the speed of the wind quickly increases to about 10.5 ms^{-1} at the height of about 450m AGL. The dramatic increase in the speed of the wind may be understood as plain to mountain wind breaking into a basin when surface energy budget reverses in the late afternoon (Whiteman 2000).

However, beyond 1900LST and until 2200LST the strength of the wind over the valley gradually decreases (Fig. 3a) with southerly/southwesterly in the lower most part topped by the westerly wind. The flow structure also indicates the significant directional wind shear during the period apart from wind speed shear discussed above. Beyond this time, the prominent afternoon time winds tend to cease and the valley gradually regains calmness as described above for early morning time in consistent again with numerical predictions made by Regmi *et al.* (2003).

B. MIXING LAYER HEIGHT

Within the Atmospheric Boundary Layer (ABL) the mixing layer height (MLH) is defined as the height up to which vertical dispersion of pollutants is caused by turbulent mixing associated with thermal structure of the boundary layer (Seibert *et al.* 2000, Schäfer *et al.* 2006). An extensive description of the methods to assess the mixing layer height from sodar data can be found in Beyrich (1997), Asimakopoulos *et al.* (2004) and Emeis *et al.* (2008). Among the different methods to estimate the mixing layer height, present study adopted the two methods, namely, the Acoustic Received Echo (ARE) and the Vertical Wind Variation (VWV). The ARE and VWV methods are applied, respectively, for the estimation of nighttime and daytime MLH.

In the ARE method (Asimakopoulos *et al.* 2004), strong backscattered intensity is considered to be associated with temperature inversion. Examining the vertical profile or time series facsimile of backscattered intensity, one can find the layer of air adjacent to the stronger intensity and hence the MLH averaged at a particular interval or its evolution with respect to time. Fig. 6 shows the hourly averaged vertical profile of backscattered intensity at 0100 LST. In the profile, we can see the first intensity maxima at about 80m AGL. This implies building up of strong thermal inversion at this height and hence the atmosphere below this height is strongly stratified. The high intensity record at 80m in between 0000 to 0600 LST (Fig. 7a) indicates that the nocturnal inversion at about 80m AGL continues to prevail close to the sunrise and may also extend for about an hour or so even after sunrise. In such situations concentration of particular chemical species in the region is expected to be almost constant in absence of any active source or sink or dispersion mechanism.

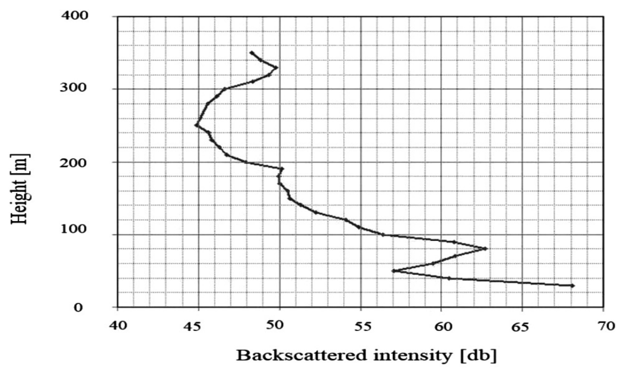

Fig. 6. Vertical profile of backscattered intensity at 0100 LST.

The high backscattered intensity apparent at about 300m AGL around 0700 LST indicates that as morning progresses the inversion layer shifts upward from the ground. The existence of inversion at about 300m AGL appears to be associated with the prevailing easterly wind at that level. Thus, the easterly wind must be warmer than the air mass of the valley underneath the easterly wind.

The stable layer persists until it is destroyed by the convective turbulence initiated by the increasingly heated surface with the increasing solar insolation. In addition to the convective turbulence, the subsidence over the central area of the valley to compensate the air mass loss due to the upslope winds over the surrounding mountain slopes might also have played an important role in eroding the nocturnal stable layer.

With the increasing solar insolation and hence the convective turbulence, mixing activities accelerates and further deepens up into the sky of Kathmandu valley. The depth of the mixing layer height reaches to its maximum close to the noontime (Fig. 7a). The vertically upward lift of high backscattering intensity level (Fig. 7a) signifies the above assertions regarding the evolution of MLH. However, it should be noted that lifting of high backscattered intensity level might not appear as distinct as it appears during morning times (Fig. 7a). In such situations, we may utilize the method of VWV for the estimation of MLH. According to this method (Asimakopoulos *et al.* 2004, Emeis *et al.* 2008), the MLH is 2.5 times the height of maximum value of vertical wind speed variance (Z_m).

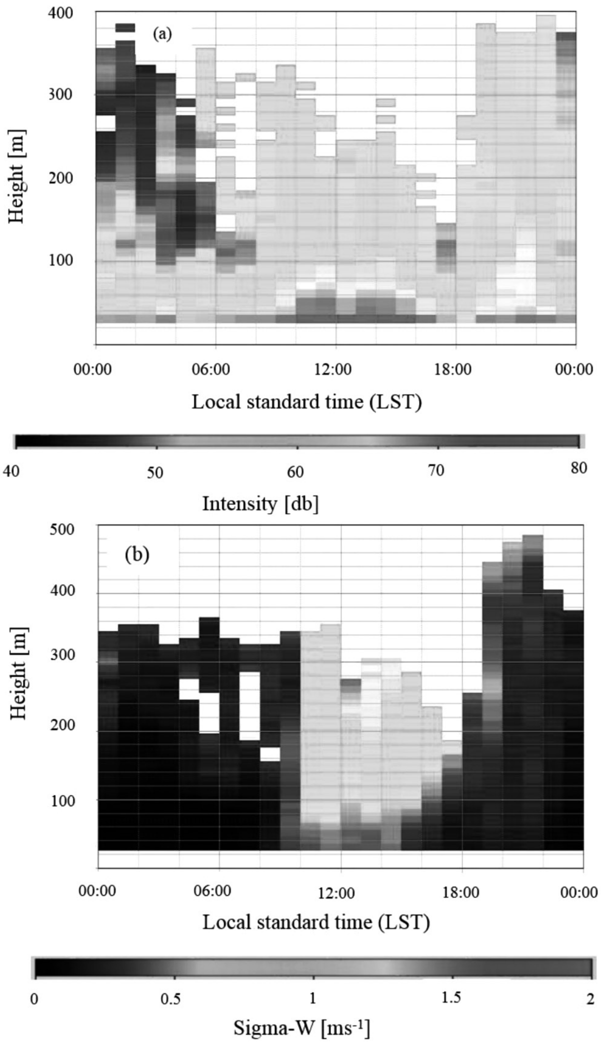

Fig. 7. Facsimile plots of hourly averaged profile of backscattered intensity (a) and the vertical wind variance, sigma-w (b).

In reference to the Fig. 8a, the Z_m appears to be at 145m at 0900 LST and multiplying this value with 2.5 yields the MLH of about 360m. If we examine the facsimile plot of sigma-w until the noontime, it appears that the MLH continuously increases (Fig. 7 & 10). At 1200 LST, Z_m is 350m and hence the MLH would be around 875m. It is important to note that the value of Z_m does not appear to exceed more than 310m during the period of 1200 LST to 1800 LST (Fig. 7b) and hence the mixing layer height should remain less than 800m during the afternoon time. The mixing layer height assessed through this method appears quite consistent with numerical prediction made by Regmi *et al.* (2003) where the authors categorically indicated that mixing layer height remains in between 700 to 900m above the valley floor during the afternoon time. The consistency between the numerical prediction and sodar observation should ensure that the mixing layer height over the Kathmandu valley during the late winter or early springtime is very low as it remains below 900 m AGL.

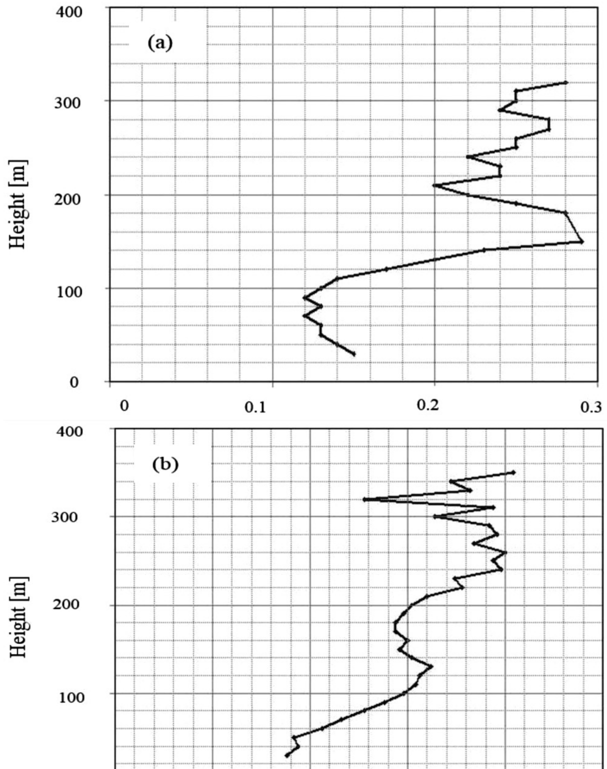

Fig. 8. Vertical profile of sigma w at (a) 0900LST and (b) 1200LST.

As the sun sets, the generation of convective turbulence decreases to the point where turbulence cannot be maintained against dissipation (Nieuwstadt & Brost, 1986). With the decrease in the convective turbulence, increase in the radiative heat loss from the ground and pooling of cool downslope wind into the valley, MLH continuously decreases and nocturnal stable layer gradually increase in its thickness.

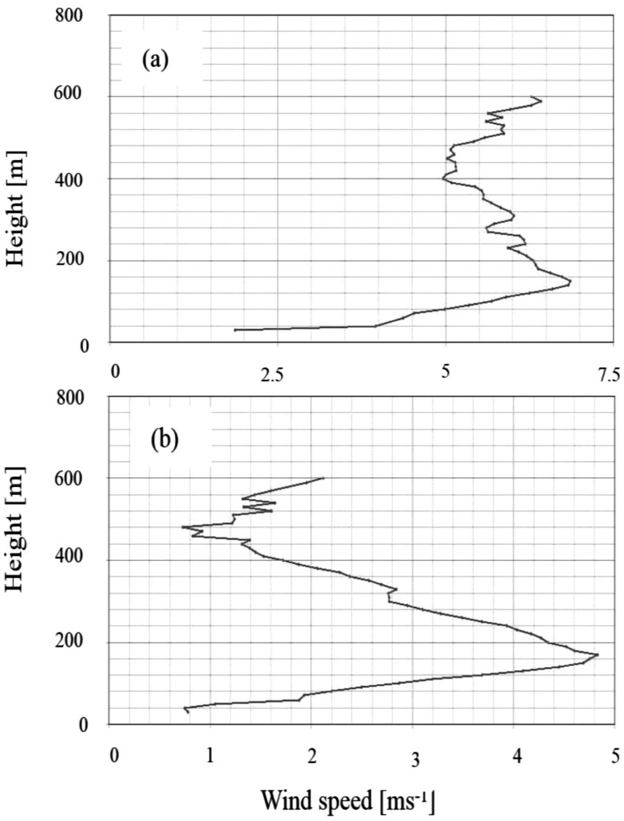

Fig. 9. Vertical profile of wind speed at (a) 2000 LST and (b) 2200 LST.

Interesting enough (Fig. 7a), the backscatter intensity at 250m AGL at 1900 LST is higher than in the lower layers of the atmosphere. It again indicates higher temperature at elevated layer compared to the lower layers.

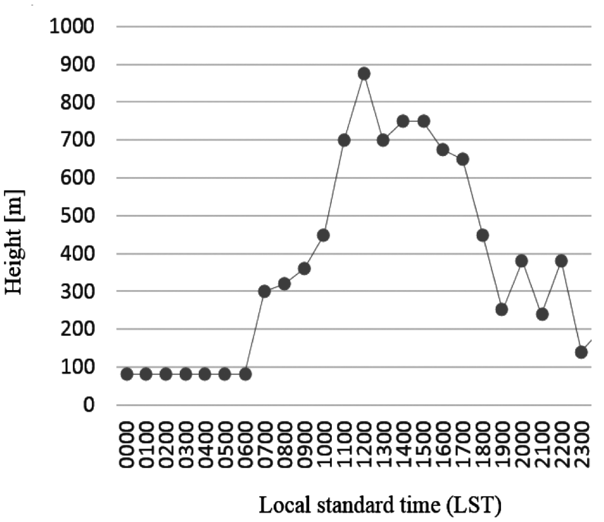

Fig. 10. Diurnal variation of mixing layer height over the central area of the Kathmandu valley on 12 March 2013.

The situation reflects the case of thermal inversion. This may imply the accumulation of cold air mass at the bottom of the valley. A gradual decrease in MLH is also observed until 2100 LST. However, beyond this time and until the midnight (Fig. 7a) significant turbulent activities appear over the central area of the valley. This can be understood as the effect of wind shear that can be inferred from the vertical profile of wind speed during the time (Fig. 9).

The mixing layer height and its diurnal variation (Fig. 10) at the center of the Kathmandu valley strongly suggest that the valley possesses very limited air pollution dispersion power.

CONCLUSION

The late winter/early springtime diurnal characteristics of boundary layer processes over the central area of the Kathmandu valley have been assessed with the data derived from monostatic sodar (MFAS64 Scintec Co., Germany) observations. The sodar was continuously operated from 03 to 16 March 2013. Among the several parameters derived from sodar observation or can be diagnosed from basic parameters, the diurnal characteristics of wind speed, wind direction and the mixing layer height were chosen to assess the boundary layer characteristics over the central area of the valley. The observed characteristics were examined against the earlier numerical predictions. Very good consistencies in between the present observation and numerical prediction made in early 2010 have been found.

Present study shows that central area of the Kathmandu valley remains calm or windless under stably stratified near surface atmosphere. Very strong surface inversion builds up over the central area of the valley at about 80m AGL during the night and early morning hours. The mixing layer height increases with the progressing morning and attends its maximum of about 875m AGL close to the noontime. The prominent afternoon time wind systems of the valley, namely, northwesterly and southwesterly wind that intrude up into the valley close to the noontime, appear to limit the growth of the MLH beyond 900m AGL.

The daytime boundary layer of the valley close to the surface appears to be quite turbulent due to the convective heating. High wind speed is observed around the sunset time that gradually decreases and vanishes by late evening. The near surface boundary layer may remain highly turbulent during the late evening time until midnight initiated by wind shear. Examining the several day data of the observation period, very strong diurnal periodicity can be expected over the valley in the pattern of wind speed, wind direction and of mixing layer depth with little day-to-day variation.

Based on the present observation and earlier numerical predictions, it can be said that Kathmandu valley possesses very poor air pollution capacity or holds very weak dispersion power.

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