Comparison of mesospheric mean vertical winds between MST radar and empirical model over a tropical station

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Monthly and seasonal variations of mesospheric vertical winds observed by MST radar located at Gadanki (13.5°N, 79.2°E) are compared with the mesosphere/lower thermosphere (MLT) prevailing empirical wind model. Though there is a difference in the wind magnitude between MST radar observations and the model, the trends match well particularly between 70 and 75 km. The model output has been further used to estimate the diurnal and semi-diurnal amplitudes and phases of tidal components at mesospheric altitudes to assess the contribution of these to the mean mesospheric vertical winds derived from the radar, as the latter does not provide wind information for complete 24 h. From this exercise it has been found that the radar provides reasonably reliable information on mesospheric vertical winds between 70 and 80 km. The observed mesospheric vertical wind is generally upward in all the seasons and is consistent with the general circulation multi-cell features at mesospheric altitudes.

Keywords: Lower thermosphere, mesosphere, mesospheric vertical winds, MST radar, wind model.

MEASUREMENTS of vertical velocities by radars in the lower and middle atmosphere have proven valuable in defining the character and variability of the motion spectrum due to gravity wave, tidal motions and inferring the general circulation features. In general, they play a key role in the transport of minor gaseous constituents (for example, hydroxyl, atomic oxygen and ozone) in the upper atmosphere. However, its measurement in the mesosphere is difficult because of the general inaccessibility of the region to many techniques (such as balloons and aircraft), and of its relatively smaller magnitudes. Many techniques are available for measuring horizontal winds, but the only method capable of measuring the vertical winds in the lower mesosphere (60–85 km) is the very high frequency (VHF) coherent radar technique.

The VHF radar mechanism enables determination of horizontal and vertical winds in the lower atmosphere 2–22 km and in the mesosphere ~ 60–85 km, with high temporal and altitude resolution. Radar measurements of vertical velocities have already been shown to have an important potential role for research applications, both in diagnostic studies and for verification, but the difficulty has been in testing the technique. There are no other techniques for measuring vertical winds over temporal and spatial scales comparable to those sampled by the radars. In the lower atmosphere, Larsen *et al.*[1] used the velocity-azimuth display (VAD) technique for measuring vertical wind. This is in good agreement with the direct measurement by the radar, but at mesospheric heights such techniques are not available so far.

A few models like CIRA-86 (the COSPAR International Reference Atmosphere)[2], HWM93 (Horizontal Wind Model)[3], GEWM (Global Empirical Wind Model)[4] and HMW-07 (Horizontal Wind Model, 2007)[5] also have given glimpses of the mesospheric circulation. But all these models have been developed using either earlier observations, including some satellite (High Resolution Doppler Imager (HRDI), Wind Imaging Interferometer (WINDII)) and radar measurements (empirical models like HWM93, HMW-07 and GEWM), or winds retrieved from temperature observations using geostrophic approximation (CIRA-86). However, these are useful to retrieve mean horizontal winds and do not provide vertical wind information.

A method to deduce vertical wind from the mean horizontal winds was originally proposed by Ebel[6], and later used by Miyahara *et al.*[7] and Portnyagin *et al.*[8]. Utilizing most of the available radar data, they constructed an empirical model for the meridional mean winds in the mesosphere–lower thermosphere (MLT) region. Using the continuity equation, they further deduced the associated mean vertical winds. Using this empirical model, Miyahara *et al.*[7] and Portnyagin *et al.*[8] have shown that the knowledge of vertical and meridional mean winds allows one to estimate the mean momentum balance, adiabatic cooling and heating, and provides new information on their latitudinal distribution and role in this region. Although the approach used by them gives important information, the use of their empirical model suffers from an important drawback. Indeed, most of the observations are made at the northern hemisphere mid-latitudes; only a few data are available near the equator (Mogadisho (2°N, 45°E), Christamas Island (2°N, 158°W))[4], and only a few stations are represented in the southern hemisphere. Thus, how realistically is the atmosphere represented by such a model is an open question. To overcome these drawbacks, Fauliot *et al.*[9] deduced the mean vertical wind in MLT (80–120 km) region using the WINDII observations, made on-board Upper Atmosphere Research Satellite (UARS), which provide a regular sampling of the MLT-region winds. Again the drawback of this method is that, it will not give wind information in the lower mesosphere (~ 65–80 km). Recently, Portnyagin *et al.*[10] deve-

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loped an empirical model for deducing monthly mean vertical wind between the 70 and 110 km region using ground-based and satellite-based instruments (WINDII, HRDI) and constructed global height distribution of vertical wind variation for different seasons. In the present study, this model output is compared with the directly measured vertical winds by MST radar over the Gadanki region.

The Indian MST radar is a monostatic coherent pulsed Doppler radar operating at 53 MHz with a peak power aperture product of 3×10^{10} W m^2 and is located at a tropical station, Gadanki. Details of signal processing are given in Rao *et al.*[11]. The data collected during January 1998–December 2009 are used to evaluate the mean vertical winds. Though the observations are available for all the six/five beams, we have used only zenith-Y observations as we are mainly dealing with vertical winds in the present study. Although data used for this study have been collected with range resolutions of 1.2 and 2.4 km, the data have been suitably averaged to obtain a uniform range resolution of 2.4 km. A detailed description of the mesospheric data and signal delectability has been given in Kumar *et al.*[12].

Vertical wind velocity profiles of individual days are carefully examined for interference, if any, and the same removed using a special algorithm. After removing the interference and also outliers in the velocity data, percentage of occurrence (PO) of echoes in each range bin is estimated using the relation PO = 100 × (number of samples with SNR > –12 dB)/(total number of samples), and a minimum PO threshold criterion has been applied to the data. After trying out several threshold criteria to the data, it is found that reliable estimates of vertical wind can be obtained using a threshold of 20% for PO. Thus, the echoes in range bins with PO less than 20% are omitted. After applying this algorithm, the mean vertical wind for each day of observation is estimated.

The prevailing climatic 2D MLT (70–100 km) wind model was constructed on the basis of wind measurements from the 47 ground-based (GB) medium frequency (MF) and meteor radar (MR) stations located at different latitudes over the globe during the period 1991–2003. Additionally, the space-based (SB) WINDII data during 1992–1993 and HRDI (1992–1999) were also used in the model. The basic model construction and evaluation of the errors while correlating the GB and SB instruments can be obtained from Portnyagin *et al.*[10]. The zonal mean prevailing vertical wind is calculated using continuity equation and the following relation:

$$\frac{1}{a\cos\theta}\frac{\partial}{\partial\theta}(v\cos\theta)+\frac{\partial w}{\partial z}-\frac{w}{H}=0, \tag{1}$$

where v and w are the wind velocities in meridional and vertical directions respectively; a the radius of the Earth; H the scale height (= 7 km); $z = -H \ln(p/p_0)$ the log-pressure height; p the pressure; p_0 the constant conditional pressure and θ the latitude. The calculation was performed from the top downward. The condition $w = 0$ is set as the upper boundary of the model (100 km).

In order to perceive the model results exactly over Gadanki, the mean monthly averaged profiles between 12.5°N and 15°N lat. are again averaged and then seasonal mean was obtained.

Before going into further details, we would like to stress upon the limitations in the vertical wind measurements using the MST radar. For the configuration of the MST radar experiment used in the present study with the number of fast Fourier transform (FFT) points being 128, inter-pulse period of 1000 μs and number of coherent integrations of 64, the vertical velocity resolution comes out as 0.35 m/s. Taking this into account, we considered in the present study, vertical velocities greater than 0.35 m/s. Since the vertical winds are relatively much smaller than the prevailing horizontal winds, a number of possible observational errors due to factors like beam-pointing accuracy, tilted atmospheric structures and rate of change of electron density[13] could affect the measurements. The beam pointing accuracy of the MST radar at Gadanki is 0.1° and the mean horizontal wind between 65 and 85 km over this location is approximately 40 m/s (refs 14, 15). These result in an error of 0.07 m/s in the vertical wind, which is very small compared to the observed vertical winds. Balsley and Riddle[13] argued that, 'when the tropospheric mean vertical winds are not biased even though horizontal wind magnitude is comparable to the mesospheric horizontal wind', which is similar to our case. So we may also conclude that 'significant errors in mesospheric vertical wind do not arise from beam-pointing errors (~ 0.1°) of the vertical antenna beam'.

If the echoes are not from horizontal stratifications (from tilted structures) within the radar-illuminated volume, then the contamination from horizontal winds could affect the vertical winds. Similar argument may be applicable to the vertically propagating gravity waves with tilted phase fronts. However, the anisotropy at mesospheric altitudes in this location is reported to be very small[12]. Individual cases with large vertical winds are also checked and found that these high magnitudes of vertical winds are not the manifestation of horizontal winds. Since most of the observations considered utilize observations around noon time, rate of change of electron density for a given season would be the same and hence contamination of the data through this process can also be considered as insignificant. Thus, based on the above discussion, it is reasonable to conclude that the vertical velocity data obtained from the radar observations can be considered as reliable, as also discussed by Balsley and Riddle[13].

It is well known that the mesospheric echoes from VHF radar are greatly influenced by the presence of

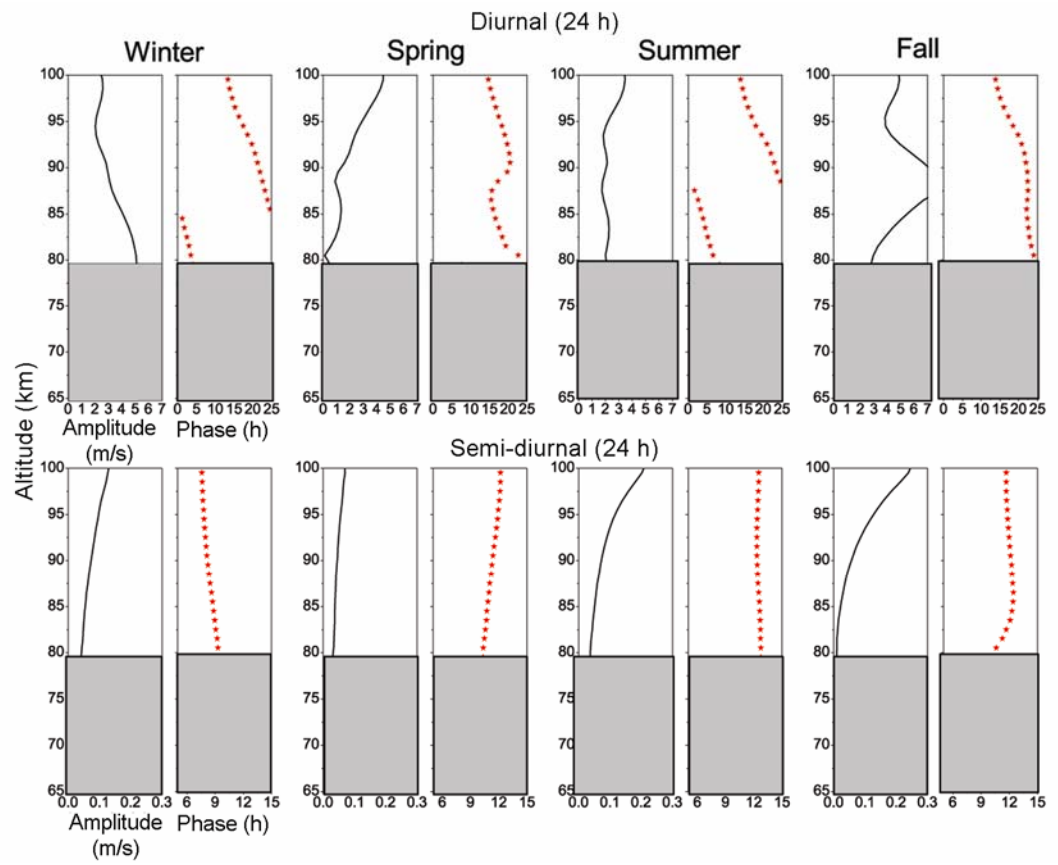

Figure 1. Profiles showing the diurnal (top panel) and semi-diurnal tidal (bottom panel) amplitudes and phases derived from mesosphere/lower thermosphere (MLT) prevailing wind model outputs for Gadanki latitude (12.5° and 15° lat. averaged) observed during different seasons.

electron density fluctuations, which are prominent during the daytime, and hence MST radar observations are confined to daytime only, which involves the difficulty of estimating diurnal and semi-diurnal components. We have used a simple averaging of daytime wind velocity, which is widely used as the mean wind estimation for the MST radar. However, note that by using this simple averaging, the observed wind may be biased by any existing diurnal variations. Since tidal variability will be large at mesospheric altitudes, now the question arises as to whether VHF radar-observed daytime vertical wind will represent the background wind. To estimate the bias induced by tidal components in the averaging processes, we have estimated the diurnal and semi-diurnal components using the empirical model dataset. It is well known that tidal (diurnal and semi-diurnal) amplitudes will reach a peak in the mesosphere and it will be interesting to know the diurnal and semi-diurnal amplitudes in the vertical wind at mesospheric altitudes. This bias might be smaller at the lower heights (below 70 km), since the tidal amplitudes are usually smaller at lower heights[16] compared to those of higher altitudes. Hence, before going to further analysis we studied diurnal and semi-diurnal tidal components using the model data.

Diurnal and semi-diurnal amplitudes and phases observed during different seasons over Gadanki region estimated using the model data are shown in Figure 1. Note that the region of current interest is between 65 and 85 km, but the model provides tidal information from 70 to 100 km and only for migrating tides. Large tidal amplitudes are evident in all the seasons above 80 km. During spring equinox, the amplitude increase from 90 km, reaching a peak around 100 km, whereas in fall equinox amplitudes reach a peak around 90 km, with values as high as 7 m/s. Relatively small amplitudes are noticed in summer. During winter season the amplitudes seem to be high even at 80 km resembling that they are still high below 80 km. Semi-diurnal amplitudes are relatively very small during all the seasons with no significant change in the phases. It is evident from Figure 1 that except in winter the tidal amplitudes are very small between 70 and 85 km; hence the bias in the vertical wind obtained while averaging within the daytime instead of the complete diurnal cycle will be very small, that we cannot completely rule out the role of the tidal contribution. Moreover, the mesospheric echoes are intermittent in time. These echoes are confined to a few kilometres primarily in the 70–80 km height region, as discussed in detail by

Kumar *et al.*[12], and intermittent above and below 70–80 km. Hence the mesospheric winds are more reliable between 70 and 80 km than either at lower or higher altitudes. Thus, MST radar-observed vertical wind between 70 and 80 km height regions is the true wind, and is not influenced by any significant diurnal and semi-diurnal components. Note that practically this region cannot be properly sensed with any GB technique with good temporal resolution, except by MST radars. Thus in the absence of any information, VHF radar provides valuable data on the vertical wind at the mesospheric heights. However, caution is advised as we have dealt with only migrating tides and at low latitudes, the non-migrating tides can be the prevailing tidal components.

After carefully checking each day's individual profile of the MST radar, by applying the special algorithm, all the profiles in a month for all the 12 years were averaged in order to obtain mean monthly profile; again all the monthly mean profiles in that season were averaged. In order to elucidate the variabilities in the vertical wind derived both from MST radar and model output, the seasonally mean profiles of vertical winds observed during different seasons at mesospheric altitudes were averaged and are illustrated in Figure 2. In general, the magnitude of the vertical wind obtained from the model was five times lower than the direct measurement with the VHF radar technique, though the trend matches well particularly between 70 and 75 km. The difference in the trends was much higher above 80 km in all the seasons possibly due to large bias in the radar-observed vertical winds due to increase in the tidal effects at higher altitudes.

A closer inspection of the seasonally averaged vertical wind both from the direct measurement and from the model study shows that, in all the seasons the vertical wind points upward, which is clearly pragmatic in both the datasets and always the maximum vertical wind from the model data was noticed at around 78 km, whereas the MST radar observed maximum vertical wind varied from season to season. The increase in the vertical wind with respect to altitude above 80 km was noticed in all the seasons in the MST radar observations, whereas it was not so in the model dataset. This may be partly attributed to not addressing the tidal effects in case of MST radar observations, where the effects are larger above 80 km. The magnitude of upward wind is moderately high in summer and equinoxes, and lower in winter.

During spring equinox, the MST radar-observed maximum upward wind magnitude was very high (> 0.1 m/s) and appeared between 70 and 75 km and again above 80 km, reaching as high as 0.2 m/s. Whereas the model showed maximum upward wind between 75 and 78 km with highest magnitude of > 0.03 m/s. During summer and fall equinox, the radar-observed vertical wind was more or less constant up to 80 km with magnitude 0.08 and 0.09 m/s respectively, and started increasing thereafter. Whereas the model estimated maximum upward wind around 78 km with magnitude 0.01 and 0.012 m/s respectively.

Figure 3 shows the composite monthly mean behaviour of mesospheric vertical wind obtained from both the MST radar (top panel) and the model (bottom panel). Note that vertical wind magnitude scales are different. A closer inspection of Figure 3 reveals that, although the mean vertical wind shows upward motion most of the time, there are clear patches where large upward winds are noticed particularly during the winter months (NDJF) and the summer month of June. During winter months, the maximum upward winds extended up to 85 km, whereas they were restricted to 80 km during June. There was a slight shift in the maximum vertical winds in the case of the model output, particularly during July, whereas it was observed in June in case of MST radar. Empirical model results suggest that maximum upward motions in the mesospheric vertical winds are observed during equinoxes (March–April and October) and in July.

We have compared and presented monthly and seasonal variations of mesospheric vertical wind with the data obtained by MST radar for more than one solar period (12 years) and the empirical MLT prevailing wind model output. Further, the diurnal and semi-diurnal tidal

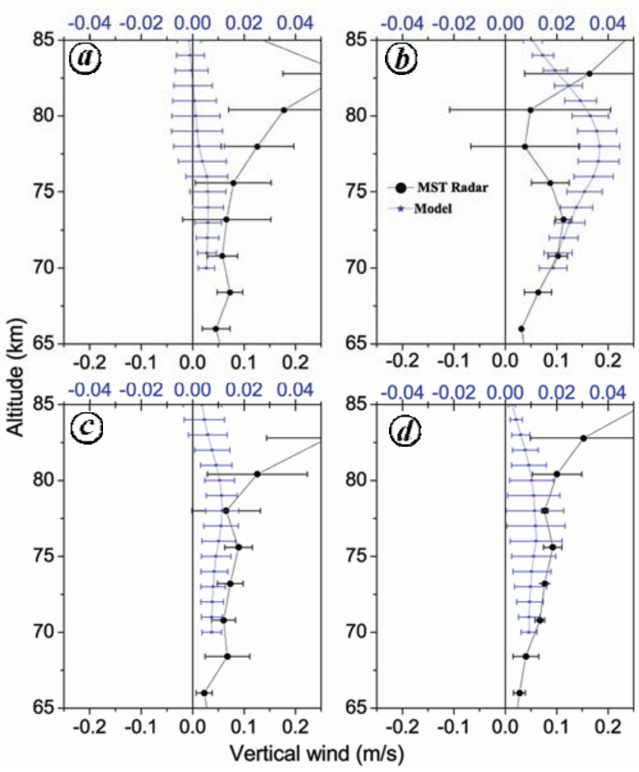

Figure 2. Seasonal mean profiles of mesospheric vertical wind obtained both from the Indian MST radar (black line) and the empirical model output (blue line) observed during (***a***) winter (NDJF), (***b***) spring equinox (MA), (***c***) summer (MJJA) and (***d***) fall equinox (SO). Horizontal bars indicate the standard devaition obtained while averging over several years (1998–2009).

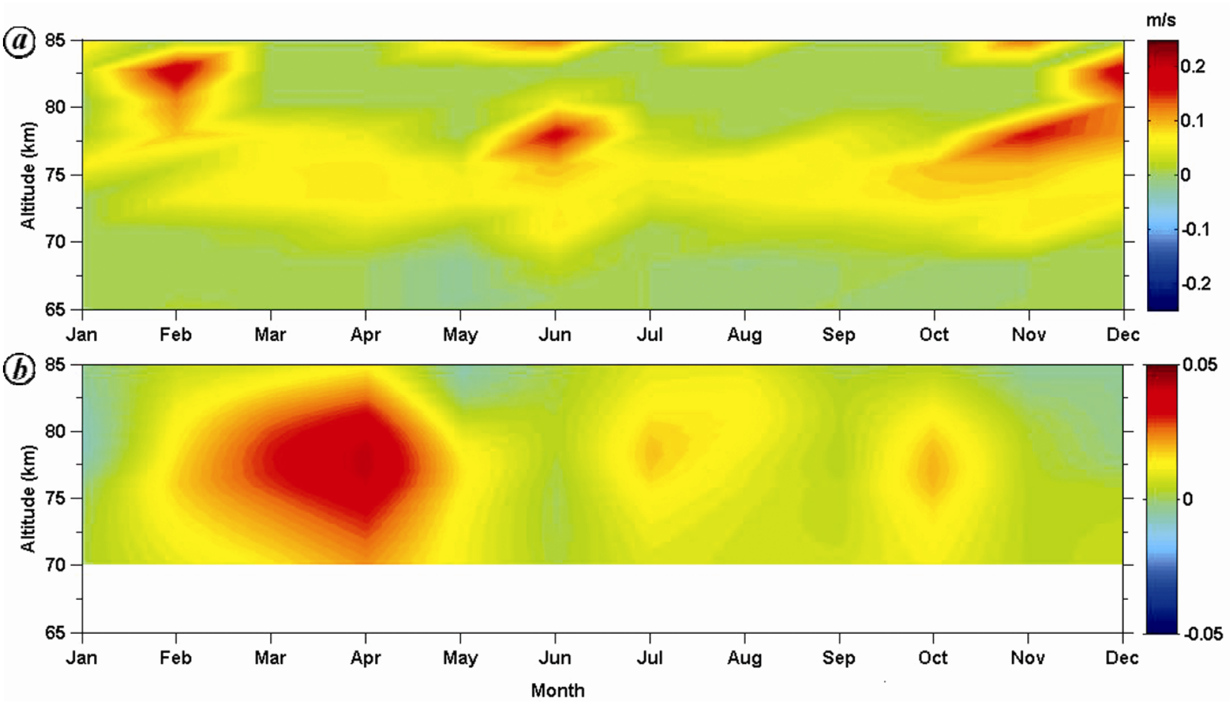

Figure 3. Composite monthly mean variation of mesospheric vertical wind observed by (***a***) Indian MST radar (1998–2009) and (***b***) MLT prevailing wind model data outputs.

effects on these vertical winds have been discussed with model-estimated tidal components. The main results are summarized below:

(1) Large amplitudes in the vertical winds due to diurnal tides were observed using the model data at 80 km and above (except in winter where it is slightly at lower altitudes), suggesting that non-availability of complete diurnal data in case of MST radar will not significantly affect the vertical wind between 70 and 80 km. In the absence of any information, MST radar has the unique capability in providing background mean vertical winds.

(2) Contribution of semi-diurnal tides to the background mean vertical wind at mesospheric altitudes was found to be very small.

(3) Model datasets heavily underestimate the mean vertical wind by an order of magnitude when compared to directly measured MST radar-observed vertical winds, though the trends remains more or less similar (particularly between 70 and 75 km). This may be partly due to not considering the tidal effects in the MST radar observations and also partly due to stationary non-zonal structures.

(4) The mesospheric vertical winds showed upward motion most of the time. Maximum upward winds were noticed during winter months and in June. However, model datasets showed maximum upward winds during equinoxes and in July.

To the best of our knowledge there have been no studies earlier comparing mesospheric mean vertical winds between directly measured and the model outputs. The present observations are consistent with the general circulation features shown in the zonal mean meridional wind and vertical winds by Portnyagin *et al.*[10], for low-latitude locations with northward[15] and upward wind (present study) prevailing throughout the year representing part of the meridional circulation. Since good agreement in the trend was found between direct measurement of the MST radar and the model output, hence the multi-cell structured circulation cells can be ascertained as shown by Portnyagin *et al.*[10]. It may be noted here that Balsley and Riddle[13], while presenting vertical wind observations at a high-latitude station (Poker Flat) from VHF radar, also suggested the possibility of a multi-cell meridional circulation. It would be of great importance to see the implication of the observed low-latitude mesospheric upward winds prevailing throughout the year on the low-latitude mesopause.

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ACKNOWLEDGEMENTS. We are grateful to Prof. B. V. Krishna Murthy (formerly at ISRO) for fruitful discussions on the topic. We acknowledge the Advanced Centre for Atmospheric Science funded by the Department of Space (DOS) under RESPOND to S. V. University, Tirupati, and University Grants Commission for providing fellowship to S.E. and also the necessary facilities to carry out this work.

Received 14 September 2011; revised accepted 29 March 2012

Spatial variation of soil organic carbon stock in a typical agricultural farm of hot arid ecosystem of India

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Soil organic carbon (SOC) is the largest among three major carbon pools of global ecosystems. During the past few years, global warming and forcible land-use changes have resulted in a huge loss of this major carbon pool and as a consequence, concentration of atmospheric CO_2 has increased. To mitigate the potential risks arising from atmospheric abundance of CO_2, adoption of carbon sequestration strategies at different landscape scales is a major option. For this purpose, proper estimates of SOC stock per unit area are essential. In this study, we have estimated the SOC stock of a typical agricultural farm from hot arid ecosystem of India and also its spatial variation within the farm. The surface map of the SOC stock revealed that introduction of cultivation practices in fragile lands of the desert region has resulted in huge depletion of soil carbon. For example, the SOC stock of 10-years cultivated plots was found to be almost half of the SOC stock of recently cultivated plots of the farm. The results also showed that previous reports on large-scale estimates of SOC stock for hot arid region of India do not match with the current estimate from a farm scale of the same region. Consideration of spatial variation of SOC during calculation of SOC stock has helped us prepare a surface map of SOC stock of the farm, which may further be used as an essential requirement for implementation of site-specific carbon sequestration strategies and proper carbon credit programmes in the agricultural farms of India.

Keywords: Agricultural farm, hot arid ecosystem, soil organic carbon, spatial variation.

SOIL organic carbon (SOC) stock is the largest contributor to total global carbon stocks, contributing 1550 Pg (1 Pg = 10^{15} g) of carbon to 1 m depth, which is about three times that of biotic and twice that of the atmospheric pools[1]. Presently, in the context of global warming scenarios and forcible land-use changes under increased population pressure, soil carbon is continuously being lost to the atmosphere[2,3]. Intensive cultivation in dryland regions has resulted in decline of its meagre SOC pool (~ less than 1 g kg^{-1} in most areas) at a faster rate and even more under climate change-related desertification processes[4]. It was also reported that a great share (~ 80%)

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