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Study of thermal structure differences from coordinated lidar observations over Mt. Abu (24.5° N, 72.7° E) and Gadanki (13.5° N, 79.2° E)

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Abstract

Rayleigh lidars at Gadanki (13.5° N, 79.2° E), a tropical site, and at Mt. Abu (24.5° N, 72.7° E), a subtropical site, in India were operated simultaneously during the months of March, April, and May 2004. Significant differences are found in the temperatures over both the locations. Higher temperature, ~10–20 K, in the altitude region of 40–65 km is found during March 2004 over Mt. Abu. The mean stratopause temperature during March 2004 is found ~284 K at an altitude of 48 km over Mt. Abu, which is 18 K higher than the observed stratopause temperature of ~266 K over Gadanki. During April and May 2004, the temperatures over Mt. Abu are higher in the entire altitude range of 30–70 km than over Gadanki. Lidar-observed temperatures, over both the locations, are compared with the temperatures observed by SABER (Sounding of the Atmosphere using Broadband Emission Radiometry; onboard TIMED (Thermosphere Ionosphere Mesosphere Energetics and Dynamics)) and HALOE (Halogen Occultation Experiment; onboard UARS (Upper Atmosphere Research Satellite)). It is found that the lidar-observed temperatures are in qualitative agreement with the temperature observed by satellites, though quantitatively there are significant differences. Wave types of fluctuations have been noted in the upper stratosphere and in the lower mesosphere over both the locations.

Background

The middle atmosphere is an important region of the Earth's atmosphere and plays very important role in deciphering atmospheric dynamics. Baldwin et al. (2003) emphatically stated the importance of the stratosphere in deciding terrestrial weather and most importantly the role of the stratosphere in weather forecasting. Temperature is an important physical entity to understand the chemical and dynamical features of this region (Singh et al. 1996). A Rayleigh lidar provides vertically well-resolved density and temperature profiles in the middle atmosphere above the altitude of 30 km. Several studies have been made in the past for studying atmospheric temperature using a Rayleigh lidar, at mid- and high-latitude stations (e.g., Hauchecorne and Chanin 1980; Shibata et al. 1986; Jenkins et al. 1987; Whiteway and Carswell 1994). In the last decade, there have been a number of studies of the temperature structure at low latitudes (e.g., Parameswaran

et al. 2000; Sivakumar et al. 2003; Chen et al. 2004; Chandra et al. 2005; Sharma et al. 2006; Batista et al. 2008; Kishore Kumar et al. 2008; Dou et al. 2009; Batista et al. 2009; Sivakumar et al. 2011; Sharma et al. 2012, and references therein).

Batista et al. (2009) studied middle atmospheric temperatures in the southern hemisphere at Sao Jose dos Campos, Brazil (23° S, 46° W) using 14 years of lidar data. They found smaller seasonal thermal amplitude and significant differences from the MSISE-90 model, with temperature lower than the model below the stratopause and higher above the stratopause. Sivakumar et al. (2011) presented a middle atmospheric thermal structure over a southern hemispheric French station, Reunion Island (20.8° S, 55.5° E) using a Rayleigh lidar. Observed temperature profiles were compared with observations from different satellites and they noted reasonably good agreement.

There are several studies on different types of atmospheric waves, using radars, lidars, radiosondes, and optical observations in the middle atmosphere and lower thermosphere over low and equatorial latitudes (e.g., Hirota 1978;

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Hauchecorne and Chanin 1983; Vincent et al. 1998; Yoshida et al. 1999; Kovalam et al. 1999; Gurubaran et al. 2001; Rajeev et al. 2003; Batista et al. 2004; Lima et al. 2004; Sasi et al. 2005; Takahashi et al. 2007; Lima et al. 2008; Guharay et al. 2011; Rao Venkateswara et al. 2012; Guharay et al. 2013, and reference therein). Recently, Araujo et al. (2014) and Guharay et al. (2014) have presented a comprehensive study on seasonality and variability in the planetary waves and long-period atmospheric oscillations observed over equatorial and low-latitude stations. In their study, they have used long-term meteor wind radar measurements over Sao Joao do Cariri (7.4° S, 36.5° W) and Cachoeira Paulista (22.7° S, 45.0° W) in the southern hemisphere.

Most of the studies are emphasizing more on the climatological thermal structure over a given location. Currently, there are two operational Rayleigh lidars at low latitudes in India, one at Gurushikhar, Mt. Abu (24.5° N, 72.7° E, mean sea level height 1.7 km), and the other at Gadanki (13.5° N, 79.2° E, mean sea level height 0.4 km). Both the lidars are in regular operation since 1998. For a comparative study, lidars were operated in a co-coordinated fashion during March, April, and May 2004 for several nights at both the locations. In this paper, we briefly present lidar-observed short-term variability in the thermal structures, emphasizing the observed differences in the thermal structure over two sites in the Indian region.

Methods

Lidar probing of the Earth's atmosphere was initiated at the Physical Research Laboratory (PRL) during the early 1990s, and initially lidar was operated over Ahmedabad, a subtropical location, for the study of stratospheric temperature and aerosols (Jayaraman et al. 1995, 1996). Similar aerosol studies were carried out using ground-based lidar in the tropical atmosphere (Devara and Raj 1993; Raj and Devara 1993).

A Rayleigh lidar was set up at Gurushikhar, Mt. Abu, during the year 1997 to study neutral atmospheric density and temperature in the height range of 30–80 km and operated, for few nights around new moon, every month except the monsoon season. Details of the Rayleigh lidar experimental setup at Mt. Abu and specifications are described in earlier papers (Chandra et al. 2005; Sharma et al. 2006; Sharma et al. 2012). Another Rayleigh lidar system was commissioned, around the same time, at Gadanki (National Atmospheric Research Laboratory, NARL) (Parameswaran et al. 2000; Bhavanikumar et al. 2000; Sivakumar et al. 2003; Kishore Kumar et al. 2008, and references therein) and operated extensively. Major specifications of both the lidar systems are given in Table 1. Temperature profile is derived from relative density profile using the hydrostatic equation and ideal gas law by taking an upper-level pressure value from the CIRA-86 model following the method described by Hauchecorne

and Chanin (1980). Photon counts were integrated for 6000 laser shots at Mt. Abu and for 3600 laser shots at Gadanki. Effective vertical resolution is 480 m at Mt. Abu and 300 m at Gadanki. Pressure value from the CIRA-86 model is fitted at 80 km to derive the temperature profile. Error in derived temperature is inversely related to the photon counts and varies between less than 0.5 K at 40 km to 15 K at 70 km for a 60-min integration time and from less than 0.5 K at 40 km to 10 K at 70 km for a 120-min integration time for both the observing stations. In this study, we have used the data collected during March, April, and May 2004 at both the observing sites. It should be noted that as long as weather and atmospheric seeing condition permitted, we have collected data simultaneously. Strictly with the above criterion, we have about 25 nights of good-quality data. For each night, more than 2–3 h of observations have been used in deriving temperatures at both the locations. Data collected in earlier years over the two locations, during March–April–May, have also been used for comparison.

Furthermore, temperature profiles observed by SABER (Sounding of the Atmosphere using Broadband Emission Radiometry), onboard TIMED (Thermosphere Ionosphere Mesosphere Energetics and Dynamics), were used in the present study. SABER was launched, onboard the TIMED satellite, into a 74.1° inclination, 625-km orbit with a period of 1.7 h in December 2001. It is a ten-channel broadband limb-scanning infrared radiometer covering the spectral range from 1.27 to 17 μm (Russell et al. 1999, Yee et al. 1999). Among many other parameters, SABER provides vertical profiles of kinetic temperature, pressure, and water vapor. Its vertical instantaneous field of view is approximately 2.0 km at a 60-km altitude, the vertical scanning step is ~ 0.4 km, and the atmosphere is scanned from the surface up to the height of ~ 400 km. The latitudinal coverage has a 60-day yaw cycle that allows observing latitudes from about 82° S to 82° N. SABER temperatures are retrieved from the limb radiance in the 15- μm CO₂ band that is formed by radiative transitions from the vibrationally rotationally excited levels of CO₂ molecules. Remsberg et al. (2008) have given comprehensive analysis of the current SABER V1.07 temperature. The SABER Version 1.07 kinetic temperature is validated by Remsberg et al. (2008) who provided the following systematic error due to CO₂ abundance uncertainty: 1.3 K at 80 km, 3.6 K at 90 km, and 1.4 K at 100 km.

Observations from another satellite experiment, HALOE (Halogen Occultation Experiment) onboard UARS (Upper Atmosphere Research Satellite), were also used along with ground-based lidar observations. The HALOE was launched onboard a UARS spacecraft in September 1991. The experiment uses solar occultation to measure vertical profiles of temperature, a number of

Table 1 Major specifications of lidar systems at PRL and NARL

Specifications	Lidar-PRL	Lidar-NARL
Transmitter		
Laser source	Nd:YAG	Nd:YAG
Model	581C-10 (Quantal, France)	PL8020 (Continuum, USA)
Operating wavelength (nm)	1064, 532, and 355	532
Average energy per pulse (mJ)	1000, 440, and 180	550
Pulse width (ns)	7	7
Pulse repetition frequency (Hz)	10	20
Beam width (mm)	10 (expanded to 60)	9 (expanded to 90)
Beam divergence (mRad)	0.3	0.45
Receiver		
Telescope type	Cassegrain	Newtonian
Diameter (mm)	900	750
Field of view (mRad)	6	1
Interference filter (nm)	1	1.07
Maximum transmission	48 %	48 %
Photomultiplier tube		
Model	Thorn EMI, UK, A9813	Hamamatsu, Japan, R3234-01
Data acquisition		
Software	SR430 (Stanford Research Systems), USA: Programmable	Four-channel PC-based data acquisition system operating with EG & G ORTEC MCS software
Bin width (μ s)	640×10^{-3}	2
Scan length	1024	1024
Integration time (s)	600 (for 6000 shots)	250 (for 5000 shots)

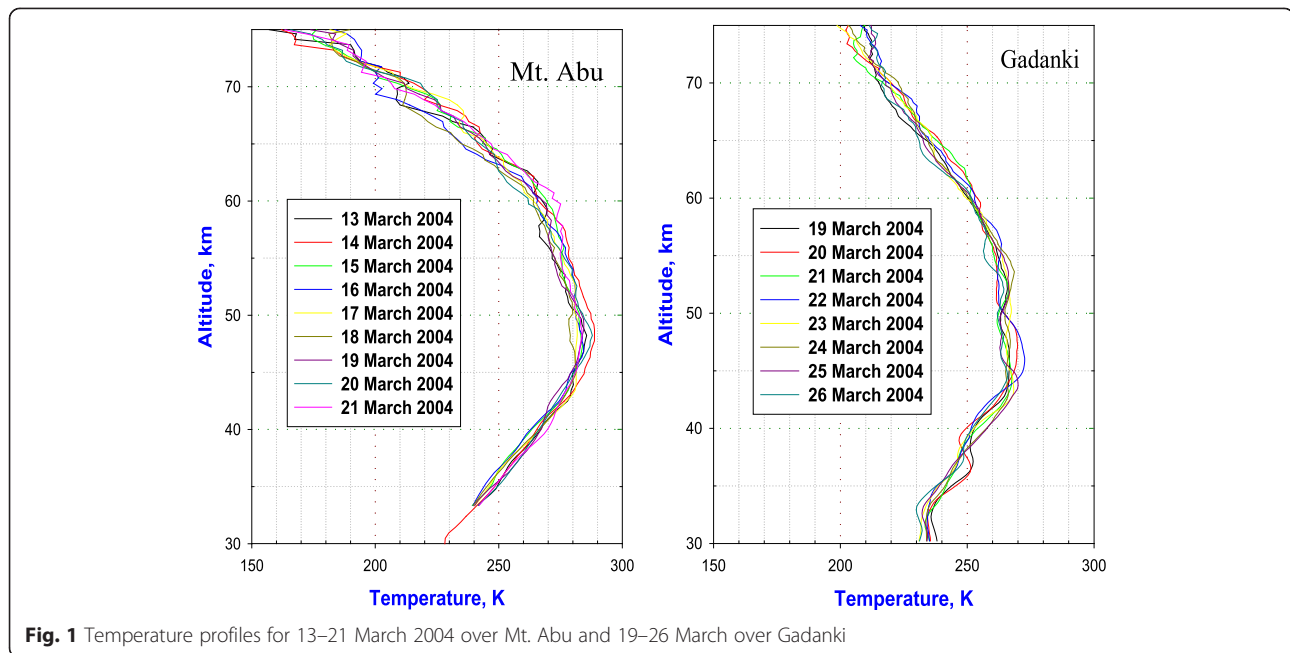
minor constituents, and aerosol concentration with a height resolution of 3.7 km for an instantaneous field of view of 1.6 km at the earth limb. It uses the atmospheric transmission measurements in the 2.8- μ m CO₂ band for the retrieval of temperature profile. It provides data in the altitude range of about 15 to 130 km, depending on channel. Latitudinal coverage is from 80° S to 80° N. Detailed procedures for analysis of various atmospheric constituents from HALOE satellite observations and discussions have been reported by various groups (e.g., Russell et al. 1993; Singh et al. 1996; Randel et al. 1998; Remsberg et al. 2002a, 2002b, and reference therein). For the present study, we have selected temperature profiles from the closer passes of satellites ($\pm 5^\circ$ latitude-longitude grid) over both the locations, Mt. Abu (24.5° N, 72.7° E) and Gadanki (13.5° N, 79.2° E).

Results

Temperature profiles over Mt. Abu for nine nights (13–21 March 2004) and Gadanki for eight nights (19–26 March) have been shown in Fig. 1. The spread present at different heights shows day-to-day variability in the temperature, and it has been found ~ 10 K over both the stations. Day-to-day temperature profiles, given in Fig. 1, revealed that

the temperatures are higher over Mt. Abu than over Gadanki. The stratopause temperature is found between 280 and 290 K, with a mean of 284 K at an altitude of ~ 48 km over Mt. Abu, and the stratopause is found at ~ 47 km with a mean temperature of 266 K (varying between 260 and 272 K) over Gadanki. Thus, the mean stratopause temperature is 18 K higher over Mt. Abu than over Gadanki during the month of March 2004.

Figure 2a shows temperature profiles for the concurrent nights of 19–21 March 2004 at both the locations. Monthly mean temperatures for the years 2002 and 2003 along with CIRA-86 model temperature profiles are also shown in the figure. The temperature structure differs significantly from night to night over both the locations, and temperatures are found to be higher over Mt. Abu. The stratopause temperatures are 283, 286, and 283 K over Mt. Abu and 267, 270, and 267 K over Gadanki on 19, 20, and 21 March respectively. Height of the stratopause over Mt. Abu and Gadanki on these nights has been found ~ 48 km. The temperatures around the stratopause over Mt. Abu during these nights are higher than the average temperatures of March 2002 and 2003 (45–60 km on 19 March, 45–55 km on 20 March, and 45–65 km on 21 March). The temperatures



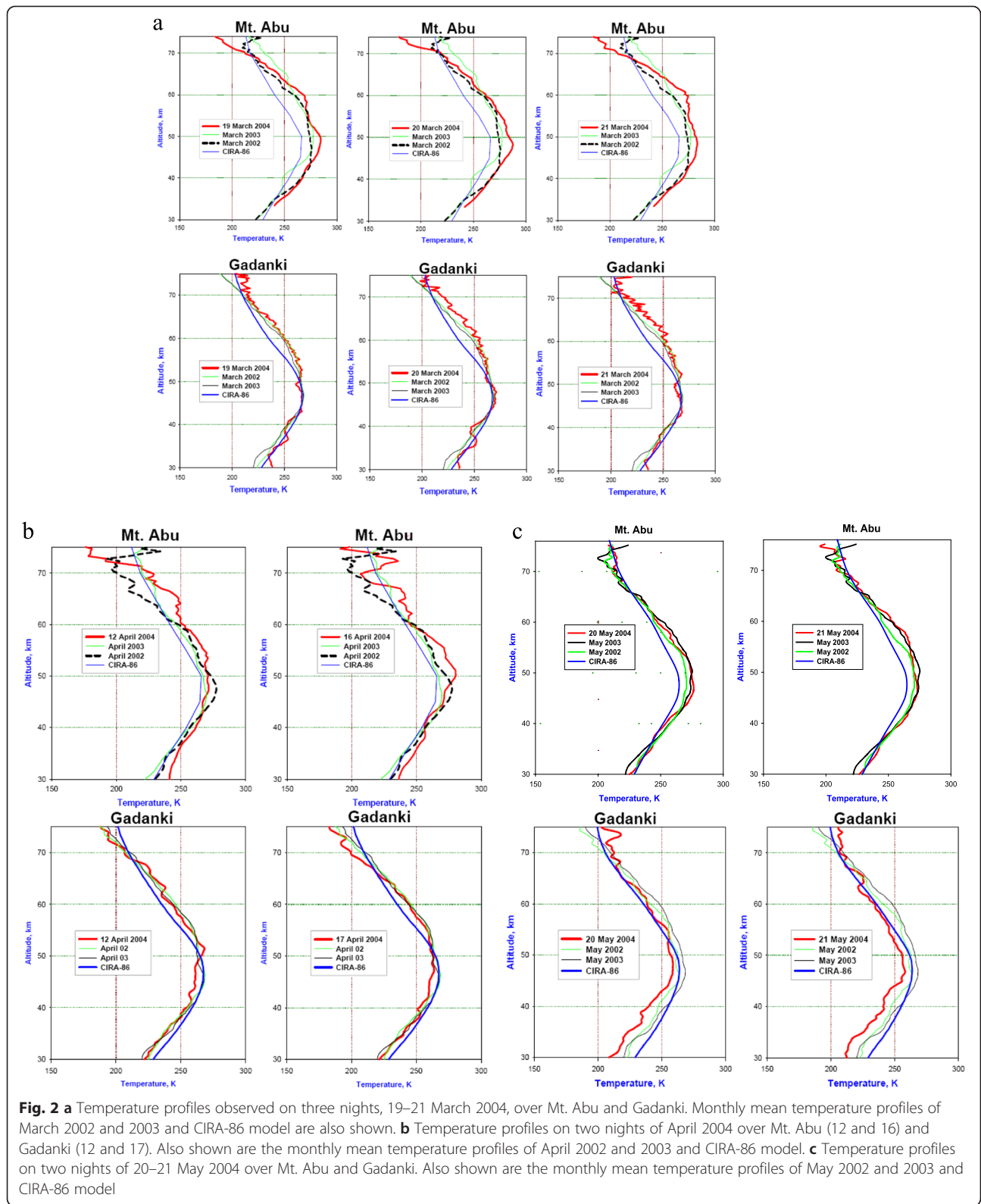
on these nights match fairly well with the average temperatures of March 2002 and 2003 over Gadanki.

Temperatures obtained on few concurrent nights over Mt. Abu and Gadanki during April 2004 are shown in Fig. 2b. The temperature over Mt. Abu on 12 April 2004 is higher than the temperature observed over Gadanki. Stratopause temperature is 277 K at an altitude of 47 km over Mt. Abu and 268 K at a height of 51 km over Gadanki. On 12 April 2004, stratopause temperature is higher over Mt. Abu, but height of the stratopause is more over Gadanki than over Mt. Abu. Observed mean temperatures over Gadanki during April 2004 are in close agreement with the temperatures observed during 2002 and 2003. Temperatures observed in April 2004 are modestly higher when compared to the mean temperatures during April 2002 and 2003 in the height range of 50–60 km over Mt. Abu.

The mesospheric temperature inversion (MTI) is an interesting feature, which was first reported from a rocket experiment (Schmidlin 1976). MTI was studied more extensively since then by using Rayleigh lidar and satellite-based observations at various locations (e.g., Hauchecorne et al. 1987; Jenkins et al. 1987; Whiteway et al. 1995; Fadnavis et al. 2007; Sridharan et al. 2008, and references therein). The observations of Hauchecorne et al. (1987) from two stations in the south of France showed that the occurrence of the inversion has semiannual variation with maxima in summer and winter. The deviation associated with the inversion was found to be as high as 40 K, and it occurs in the height range of 52–75 km in winter and 70–85 km in summer. The observed inversion was explained by the heating of

the turbulent layers generated by the continuous breaking of the upward-propagating internal gravity waves. Meriwether and Gerrard (2004) using the Rayleigh lidar observations made at Wright Patterson Air Force Base (Dayton, OH, USA), reported temperature inversions with amplitudes ranging from ~20 K to as much as ~100 K. The layer was located at 85 km during summer and at 70–75 km during winter. Closer examination of the temperature profile observed over Mt. Abu revealed MTI at ~65 km with magnitude of about 10 K. The second example shows a temperature profile on 16 April 2004 over Mt. Abu and 17 April 2004 over Gadanki. The temperatures are higher over Mt. Abu having stratopause temperature ~280 K and height at ~51 km compared to stratopause temperature ~262 K and height ~48 km over Gadanki. The mesospheric temperature inversion is found at Mt. Abu at an altitude of 66 km with a magnitude of ~16 K. In this case also, the temperature values at Gadanki agree fairly well with the mean values for April 2002 and April 2003. Over Mt. Abu, temperatures are higher by about 10 K between 50 and 58 km.

The examples of the temperature profiles on 20 May and 21 May of 2004 are shown in Fig. 2c. On 20 May, the profile at Mt. Abu matches fairly well with the mean profiles for May 2002 and May 2003. The maximum temperature is found at 47 km with a value of 277 K, which is again higher than the value of 258 K at 47 km for Gadanki. However, the values for Gadanki on this night are lower than the mean values during May 2002 and May 2003 in the altitude region of 30 to 52 km. On 21 May 2004, the stratopause is located at 46 km with a temperature of 273 K at Mt. Abu compared to 48 km



with a temperature of 257 K at Gadanki. The temperature profile on 21 May follows closely the monthly mean profiles of May 2002 and May 2003. However, at Gadanki, the

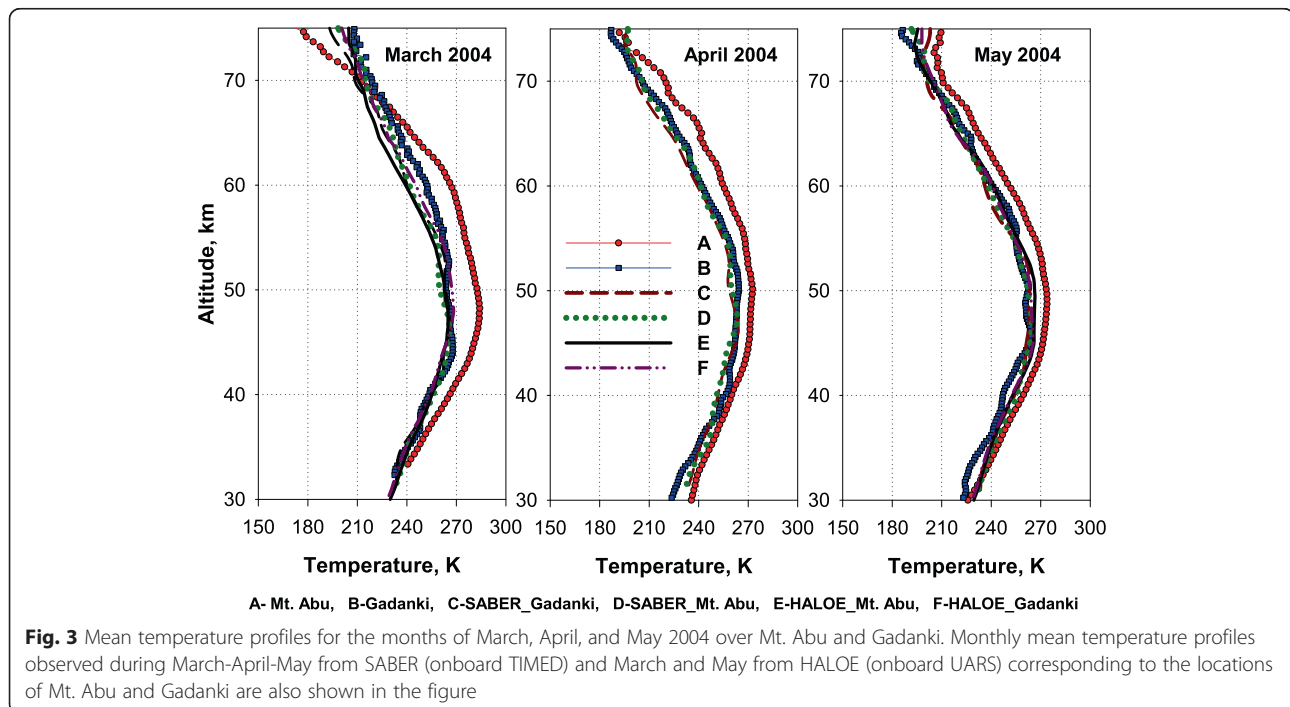
temperatures on this night are lower by about 10–12 K than the mean temperature values of May 2002 and May 2003 for altitudes below 63 km.

Monthly mean profiles for the months of March, April, and May 2004 observed over Mt. Abu and Gadanki are shown in Fig. 3. A significantly higher temperature is found during the month of March 2004 as compared to temperatures during April and May 2004 over Mt. Abu. Maximum temperature difference is found at an altitude of ~ 60 km, though such temperature difference is not noted during March, April, and May 2004 over Gadanki. The stratopause temperatures are found to be 285, 272, and 274 K over Mt. Abu and 267, 263, and 263 K over Gadanki for the months of March, April, and May respectively. The stratopause temperature over Mt. Abu is ~ 18 K higher than the temperature over Gadanki during March 2004, and it is higher by ~ 11 K and ~ 9 K higher during April 2004 and May 2004 respectively. Figure 3 also contains the average temperature profiles for March, April, and May 2004 from SABER and March and May 2004 from HALOE (e.g., Killeen et al. 1999; Azeem et al. 2000; Russell et al. 1993; Remsberg et al. 2002a, 2002b, and reference therein). Satellite observations are taken from the nearby passes ($\pm 5^\circ$ latitude/longitude from the lidar locations) over Mt. Abu and Gadanki. Lidar- and satellite-observed temperatures show better agreement over Gadanki than over Mt. Abu. Differences between lidar- and HALOE-observed temperatures over Mt. Abu are larger during March than May 2004 (HALOE data was not available for April 2004). This difference could be due to the wave-associated perturbations, which are not mapped by satellite observation owing to poor vertical resolution and difference in time of the

observations and sampling volume ($\pm 5^\circ$ latitude/longitude from the lidar locations). Hervig et al. (1996) presented the HALOE-observed temperature profiles to those of lidar and rocket and found that the measurements have differences less than 5 K for altitudes below 60 km. In the upper mesospheric region (65–80 km), significant differences were noted between lidar and satellite measurements (e.g., LeBlanc et al. 1995; LeBlanc and Hauchecorne 1997; Sharma et al. 2012 and references therein).

Though CIRA-86 and MSISE-90 model temperatures over the Gadanki (15° N) and Mt. Abu (25° N) are not shown in Fig. 3 as it was getting congested, model temperatures have differences from lidar-observed temperatures over both the locations. Sivakumar et al. (2003) have reported differences between models (CIRA-86 and MSISE-90) and lidar-observed temperatures over Gadanki. Batista et al. (2009) have also reported large differences between lidar-observed temperatures and MSISE-90 model temperatures over a subtropical station in the southern hemisphere using 14 years of lidar observations over Sao Jose dos Campos (23° S, 46° W).

Comparing the monthly mean temperature profiles for the three months, the temperatures are higher in March than in the other two months for Mt. Abu. This observed difference is attributed to different local processes and dynamics over the tropical and subtropical regions. This is in agreement with the earlier climatological study of the middle atmospheric thermal structure over Gadanki, which showed equinoctial maxima at Gadanki (Sivakumar



et al. 2003), and over Mt. Abu, summer maximum was reported (Chandra et al. 2005).

The differences in the observed monthly mean temperatures over both the locations for the months of March, April, and May 2004 at 5-km intervals from 35 to 70 km are given in Table 2 along with the standard errors (1σ). The values are higher at Mt. Abu for all the three months, and the differences are higher (up to about 20 K) during March 2004, as compared to up to 10 K during April and May 2004. A maximum temperature difference of 22 K is found at 50 km in the month of March 2004. Considering the errors of <5 K in this altitude region, the differences are significant. A minimum temperature difference of 4 K has been found at 40 km during the month of April. Observed temperature differences above 60 km may not be very significant whenever these are less than or comparable to 8 K, which is the order of the error in these altitude regions.

Figure 4 shows day-to-day variations in the temperature at fixed altitudes from 35 to 60 km, at every 5 km, for both the locations during March 2004 (nine night observations at Mt. Abu and eight nights at Gadanki). A wave-type structure is observed in the temperatures at different altitudes over both the stations. Observed temperatures at fixed altitudes from 35 to 60 km at an interval of 5 km are subjected to Lomb-Scargle periodogram analysis (Lomb 1976, Scargle 1982) to find the wave periods over Mt. Abu and Gadanki. The advantage of this method is that it can be applied for evenly as well as unevenly spaced data sets (Press et al. 1992). Compared to the other methods, the Lomb-Scargle periodogram method weights the data on a per-point basis, instead of per-time basis. Further, this method can provide an estimate of the significance of each peak by examining the probability of it arising from a random fluctuation (Luo et al. 2002). The Lomb-Scargle periodogram method has also been used by other authors for studying wave activity and atmospheric oscillations (e.g., Kishore et al. 2006; Sivakumar et al. 2011).

Table 2 Differences (Mt. Abu-Gadanki) in observed temperatures at every 5 km along with standard errors (1σ) at both the locations

Height (km)	Temperature difference (Mt. Abu-Gadanki) (K)			Standard error (1σ) (K)
	March 2004	April 2004	May 2004	
35	8	9	8	~ 0.2
40	12	4	13	~ 0.5
45	18	9	8	~ 0.8
50	22	8	9	~ 1.5
55	17	11	10	~ 3.0
60	15	14	11	~ 4.0
65	6	15	8	~ 8.0
70	-7	11	6	~ 10.0

The periodograms (the power, in arbitrary units, as a function of periodicity in days) at different altitudes over Mt. Abu and over Gadanki are shown in Fig. 5a, b. A quasi-3-day wave type of structure is seen over Mt. Abu, and it is also noted that the power is increasing up to an altitude of 45 km. In contrast to Mt. Abu, a little longer period wave type of structure is present at 35 km, and at 45 km, no clear wave feature is seen over Gadanki. In the mesosphere (at 50–60 km), a 3-day wave type of structure is present over both the locations. Lima et al. (2008) have also found the 3–4-day oscillations in the mesosphere and lower thermosphere (MLT) region at a low-latitude Brazilian station in Sao Joao do Cariri, PB (7.4° S, 36.5° W), using meteor wind measurements.

Discussion

In this work, we briefly presented the differences and discrepancies in the observed temperatures over two locations and compared with the satellite observations. Thermal structure during March, April, and May 2004 over a subtropical location, Mt. Abu, and over a tropical location, Gadanki, revealed significant day-to-day differences. These differences are plausible either because of instrument differences and/or different geographical location. Instrumental differences are mostly taken care of as the lidar systems at both locations are very much similar in terms of laser power, aperture of the telescope, and other peripherals (given in Table 1). Further, over both the locations, lidar measurements were made only in nights without visible clouds. As far as it is possible, the temporal sampling interval was also kept similar. Therefore, the observed day-to-day variability in the thermal structure between the two stations, which are separated by about 11° in latitude, could be attributed to the difference in the local processes operative in these regions. Gadanki, a tropical location, is very much influenced by low-latitude processes, and the other location, Mt. Abu, is located in the subtropical region. The subtropics are mostly having the imprint of the mid-latitude and at times low-latitude processes also do modulate the local processes over the subtropics (Sharma et al. 2012). Observed differences in the temperature are greater during the month of March than in April and May as March is the closest month to the local winter. Funatsu et al. 2011 studied seasonal and inter-annual stratospheric temperature variability at two relatively close by lidar stations, the Observatoire de Haute-Provence (France) and the Hohenpeissenberg Observatory (Germany) using lidars and the Advanced Microwave Sounding Unit (AMSU) satellite data. They suggested that in wintertime, differences are to a great extent the result of different local atmospheric dynamics. Further, they emphasized that these studies are important for the estimation of

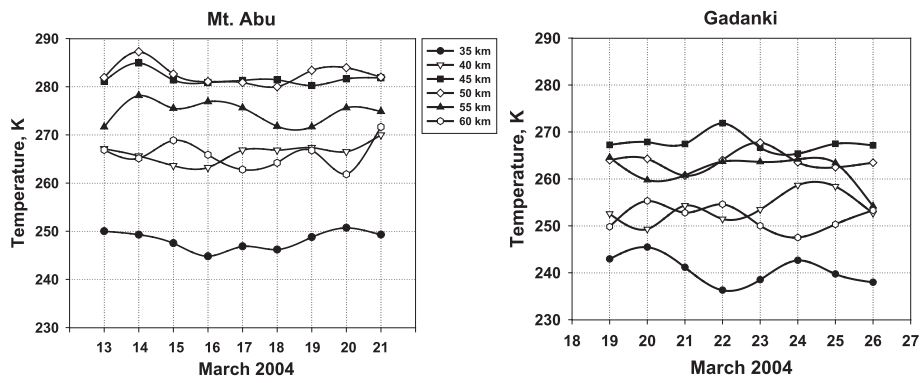


Fig. 4 Day-to-day temperature variations at fixed altitudes (at every 5 km, from 35 to 60 km) over Mt. Abu and Gadanki

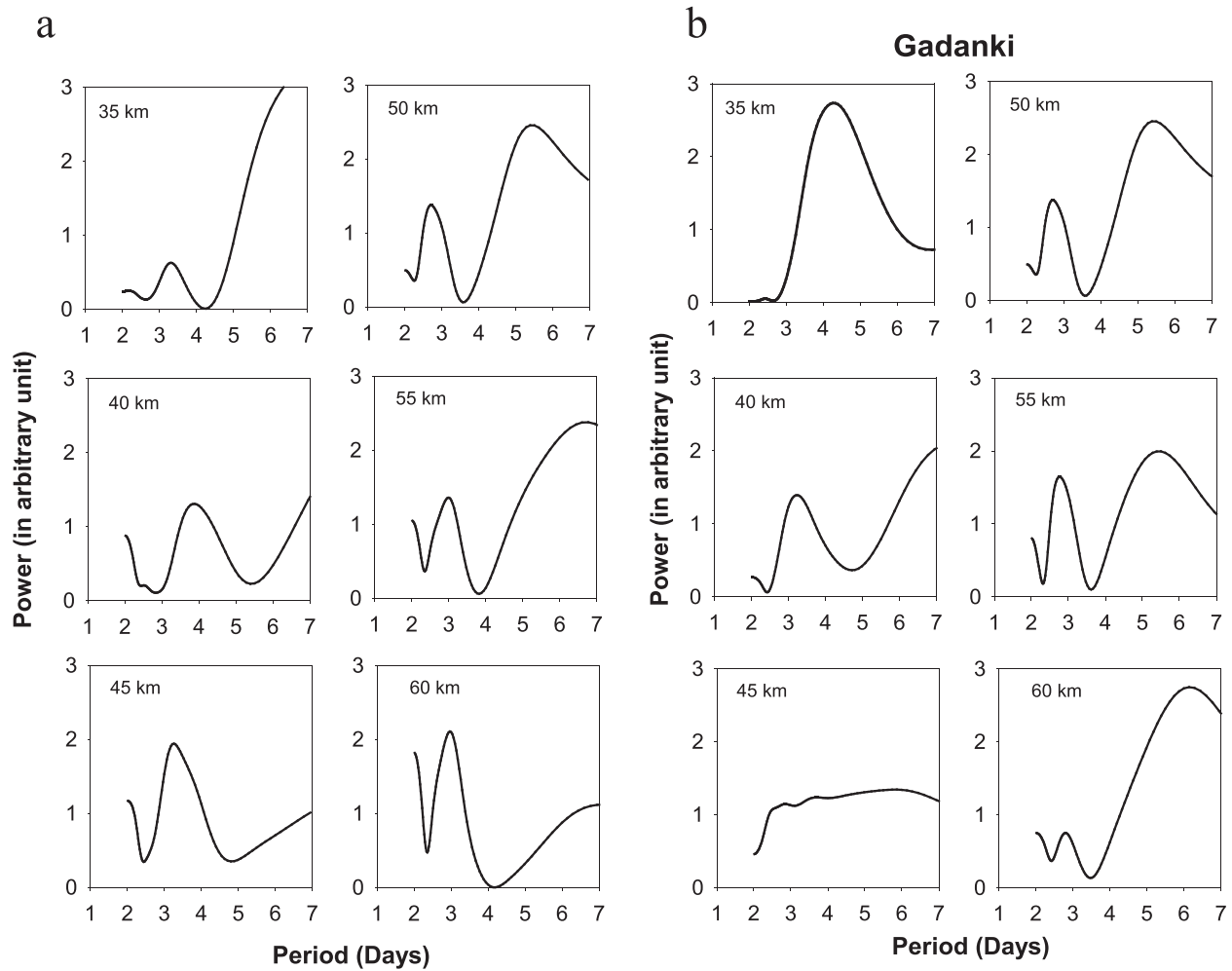


Fig. 5 a Periodograms showing the power at different periodicities at heights of 35, 40, 45, 50, 55, and 60 km for the period of 13–21 March 2004 observed over Mt. Abu. **b** Periodograms showing the power at different periodicities at heights of 35, 40, 45, 50, 55, and 60 km for the period of 19–26 March 2004 observed over Gadanki

stratospheric temperature trends and can partially explain discrepancies observed in lidars at different locations.

The temperature modulations (noted from the temperature variations over fixed altitudes) over Gadanki are more prominent than over Mt. Abu. This can be attributed to the fact that Gadanki, being a low-latitude location, is more affected by equatorial waves. Holton and Alexander (2000) observed that in the winter, the stratosphere latitudinal temperature gradient is much weaker than the radiative equilibrium gradient. Therefore, the zonal winds in this region of the atmosphere tend to be much weaker than those that would be in thermal wind balance with the equilibrium temperature distribution. This departure from the mean zonal flow from its radiatively determined state strongly suggests that some significant decelerating force must influence the mean zonal flow distribution in the winter stratosphere. They also stated that the planetary waves in the northern winter stratosphere may amplify dramatically over a short period of time and produce rapid meridional transport, which leads to rapid deceleration of the mean zonal flow and accompanying sudden stratospheric warming in the high-latitude regions. Similar to findings reported in the present study, Sridharan et al. (2002) have found the 3.5-day Kelvin waves in the mesopause region over Tirunelveli (8.7° N, 77.8° E) and over Ascension Island (7.8° S, 14.3° W). In the southern hemisphere, Yoshida et al. (1999) reported 3.0–3.8-day ultrafast Kelvin waves over Jakarta (6.4° S, 106.7° E) using meteor wind radar observations and over Badung (6.9° S, 107.6° E) using radiosonde profiles. Furthermore, Lima et al. (2008) also reported 3–4-day waves over a Brazilian station using wind measurements in the MLT region. Using lidar and Microwave Limb Sounder (MLS) observations, Guharay et al. (2011) reported a dominant component of the 3–5-day-period wave at altitudes between 50 and 80 km over two low-latitude stations in Gadanki (13.5° N, 79.2° E) and over a site in north America (23.5° N, 100° W).

Nee et al. (2002) showed that the observed temperatures over Gadanki are higher than the temperatures observed by HALOE onboard UARS. In the present study, also we have found a maximum difference of ~22 K (between the lidar- and HALOE-observed temperature) in the stratopause region. Similar to the finding reported in the present study, Nee et al. (2002) also found maximum temperature differences in the stratopause region. During the month of May, observed differences are less as local phenomena are different during summer months. Prominent gravity wave and planetary wave activities are also equally imperative in modifying thermal structures in the low-latitude region (e.g., Sivakumar et al. 2006; Kishore et al. 2006). These are the plausible causes for the higher temperatures recorded during these months over both the locations. Furthermore, the contributions

of the local dynamical processes operative in the equatorial middle atmosphere cannot be ruled out.

Conclusions

Coordinated Rayleigh lidar observations carried out over Mt. Abu and Gadanki during March–May 2004 show higher temperatures at Mt. Abu than at Gadanki by 10–20 K in the altitude range 40–65 km during March 2004. The stratopause temperature at 46 km is ~18 K higher at Mt. Abu than at Gadanki during March 2004. The temperature was also higher at Mt. Abu during April 2004 and May 2004. Temperatures, in the altitude region of 30–47 km are higher in March 2004 than in April and May 2004 over Mt. Abu. However, over Gadanki, the temperature is lower in March 2004 than the temperatures in April and May 2004. In the mesosphere, observed temperatures are higher during March 2004 over Mt. Abu and over Gadanki as compared to mean temperatures during March 2002 and 2003. Day-to-day temperature variations at fixed heights during March 2004 showed wave types of oscillations over both the locations.

We wish to emphasize that the present study addressed few scientific issues related to the middle atmospheric thermal structure in the tropical and subtropical regions during March, April and May. Further scientific issues, covering different seasons, will be resolved by longer periods of simultaneous measurements at both the locations. The present results provide the direction and may have implications on the planning of measurement strategies using lidars for further detailed investigations of the low-latitude regions, with a larger lidar network, which are relatively less explored.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

SS and HC analyzed Mt. Abu data and wrote paper. SL contributed in writing and discussions and YBA in writing and in up-keeping lidar at Mt. Abu. AJ, HG and SS provided lidar data from Gadanki and contributed in writing and discussions. SC helped in satellite data analysis. All the authors' read and approved the final manuscript.

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