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High temporal resolution VHF radar observations of stratospheric air intrusions in to the upper troposphere during the passage of a mesoscale convective system over Gadanki (13.5° N, 79.2° E)

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Abstract

A high temporal resolution VHF radar experiment, which was carried out to divulge the clear-air structure of a mesoscale convective system (MCS) at fine time scales over Gadanki, is discussed. The VHF radar was continuously operated for four hours with 11 seconds time resolution on 19 June 2006, which facilitated the study of finer details of stratospheric air intrusions into the upper troposphere during the passage of a MCS. Simultaneous GPS sonde and ground based optical rain gauge measurements are also used for the present study along with radar observations. The height-time section of range corrected signal to noise ratio (RSNR) revealed the convective cells reaching as high as 14 km altitude and the signature of the tropopause as a layered structure at around 16.5 km. The important observation from the radar RSNR is the time localized inclined echoes in the height region of 12–16 km region giving evidence for stratospheric air intrusion into the upper troposphere. Further, this observation is confirmed by the height–time section of vertical velocity, which showed the intense downdraughts in the height region of inclined radar echoes. A detailed examination of this down draft revealed an episode of high frequency gravity wave excitation, which is believed to be the consequence of intrusion of stable stratospheric air into the upper troposphere. Thus, the present study brings out for the first time, how the stratospheric intrusions will appear in the radar height-time sections and the consequences of such intrusions in the upper troposphere

1 Introduction

Stratospheric-tropospheric interactions have been the topic of research in the realms of atmospheric sciences for several decades. A seminal review by Holton et al. (1995) discussed the importance of dynamical, chemical, and radiative coupling between the stratosphere and troposphere. These authors also emphasized that these interactions are important processes that must be understood for the prediction of global change.

By now, it is well established that anthropogenic species transported from the troposphere into the stratosphere initiate much of the chemistry responsible for stratospheric ozone depletion. At the same time, downward transport from the stratosphere not only constitutes the main removal mechanism for many stratospheric species, but also represents a significant input of ozone and other reactive species into the tropospheric chemical system (Ramaswamy et al., 1992; Holton et al., 1995). Thus, in order to understand the physics and chemistry of the upper troposphere and lower stratosphere, quantitative information on the mass and chemical transport between these two regions is essential.

Jenkins et al. (2008) provided observational evidence for enhanced middle/upper tropospheric ozone through convective processes over the tropical Atlantic. These authors emphatically showed that the lightning associated with convective systems produced ozone through nitric oxide. There are other studies which also support upper tropospheric ozone enhancement through the lightning process (Martin et al., 2007; Sauvage et al., 2007). Thompson et al. (1997) provided observational evidence for the impact on ozone level in the upper troposphere by ozone transport from the lower stratosphere. Extensive studies were carried out on stratosphere-troposphere exchange over midlatitudes (Rao et al., 2008 and references therein). However, there are very limited observations over tropical latitudes, which show the downward transport of mass from lower stratosphere (Kumar, 2006). The lack of good number of observational evidences on downward transport of ozone and other trace gases from the lower stratosphere can be attributed to the dearth of direct vertical velocity measurements in the vicinity of the tropopause. However, there has been renewed interest in the atmospheric science community for quantifying the physical processes responsible for the upper tropospheric ozone enhancements.

Large-scale stratosphere-troposphere exchange (STE) is fairly well understood (Holton et al., 1995), but many aspects of smaller scale transport are yet to be studied in detail. Especially, the near-tropopause dynamical processes operative during the passage of mesoscale convective systems (MCS) are very crucial for better understanding of STE. However, there are very few instruments, which can observe near-tropopause dynamics and VHF radar is one among them. The VHF radar can directly observe three dimensional winds and turbulent motions with a good height and time resolution in the tropopause region. Recently, Hocking et al. (2007) by hourly monitoring the radar-derived tropopause height in combination with a series of frequent ozonesonde balloon launches, found numerous intrusions of ozone from stratosphere to troposphere and showed beyond any doubt that wind profiler observations can be used as a proxy for the possibility of ozone intrusions. Rao et al. (2008) reported the climatology of tropopause folds over European arctic station using VHF radar observations.

Over the present observational site Gadanki, a number of radar experiments were carried out to study the STE processes during the passage of a MCS (Jain et al., 2000; Kumar, 2006). Both these studies identified the weakening of the tropopause as a causative mechanism for initiation of STE during the passage of MCS. Kumar (2006) argued that, continuous impinging of air parcels on the tropopause will decrease the strength of the temperature gradient at that level and initiate the STE. Also, the author quantified the mass flux during disturbed tropopause conditions, which showed significant enhancements across the tropopause. However, both the studies Jain et al. (2000) and Kumar (2006) did not show how the signature of STE appears in radar reflectivity and their consequences, which can be attributed to lack of high temporal resolution observations. The central objective of the present study is to report the signature of stratospheric air intrusion into the troposphere in the height-time section of radar reflectivity for the first time during the passage of MCS. An attempt is also made to study the consequence of such intrusions in terms of the excitation of atmospheric waves. Section 2 provides the experimental details, results are discussed in Sect. 3 and summary is presented in the Sect. 4.

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2 Experimental setup

The VHF radar was operated continuously during the passage of a MCS over Gadanki on 19 June 2006. The VHF radar located at Gadanki operates at 53 MHz (signal wavelength is 5.66 m and hence this instrument detects the backscattered echoes from irregularities of ~3 m), with an average power aperture product of $\sim 7.7 \times 10^8$ Wm^2 and an altitude resolution of 150 m in the vertical direction. This system uses phased-array antennas (32×32) for transmitting and receiving the signals using a duplexer. The radar system details are given by Jain et al. (1994) and Rao et al. (1995). The measurements of vertical velocity were the main emphasis of this particular experiment. A high temporal resolution of ~11 s was obtained using these specifications, which facilitated the observation of fine-scale structures in the radar reflectivity associated with STE. Apart from radar observations, GPS sondes were carried out with Väisälä RS-80 radiosondes at 17:30 h LT (LT = UT + 05:30 h) along with ground based precipitation measurements using an optical rain gauge.

3 Results and discussion

The top panel of Fig. 1 shows the height-time section of radar range corrected signal to noise ratio (RSNR) during the passage of a deep convective system on 19 June 2006. There are three noticeable features in this height-time section. (1) The RSNR patterns during 17:34–18:34 h show convective turrets reaching as high as 14-15 km height region thus giving evidence for deep convective system passage over the radar site. (2) There are two distinct layered structures in the height region of 16–19 km. The lower layered structure at ~16.5 km corresponds to the tropopause. By now, it is well established that VHF radar gets strong return signals from tropopause, owing to the sharp temperature gradient existing over this height region. The height of the tropopause is determined from the GPS sonde observations carried out at the observational site as mentioned the Sect. 2. Kumar (2006) discussed the causative mechanism for the ob-

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served layer structure in the height-time section of radar echo power at the tropopause region. The upper layered structure at 18.5 km region, is due to the thin temperature sheets present in the lower stratosphere (Kumar, 2006) shown later. (3) The third noteworthy feature in the height-time section of RSNR is the inclined echoes at 12–16 km height region observed during 20:15–21:00, which is the topic of the present communication. More discussion on these inclined echoes will be presented later.

The bottom panel of Fig. 1 shows the height-time section of vertical velocities, a unique capability of VHF radar. This height-time section readily reveals the episodes of updrafts and downdraughts throughout the observational period. Vertical velocities of the order of 4–5 ms^{-1} were observed in this particular MCS. A detailed study on vertical velocity characteristics in several deep convective system over present observational site were reported by Kumar et al. (2005) and more recently by Uma et al. (2009). It is known that downdraughts above the freezing level (~ above 5 km for this latitude) are due to sublimation/condensate loading and also due to pressure perturbations induced by the strong updrafts. Similarly, the downdrafts below the freezing level are mainly due to precipitation loading and evaporative cooling.

Figure 2a shows the height profiles of zonal and meridional wind along with temperature from GPS sonde measurements. As the MCS in discussion was observed during the south-west monsoon a tropical easterly jet can be observed around ~16 km height in the zonal wind profile with magnitude ~35 ms^{-1}. The height profile of temperature shows two sharp gradients, one at ~16 km and another at ~18 km. As discussed earlier, layered structures observed in the height-time section of RSNR are believed to be due to these sharp gradients in the temperature. Figure 2b shows the rainfall measurements from the optical rain gauge, which confirms the passage of the MCS over the observational site.

The noteworthy feature of the height-time section of vertical velocity is an episode of downdraft of the order of 4 m/s in the height region of 12–16 km during 20:15–21:00 h. The interesting part of this high altitude downdraft is, it coincides with the fine inclined echoes observed in the height-time section of RSNR. As the VHF radar used for the present study operates at 50 MHz, it is generally insensitive to ice fall-streaks. We have examined the radar spectra and are sure that the echoes are from clear-air rather than fall-streaks. These two observations, the inclined echoes and downdraft occurring at the same height region, provide evidence for possible intrusion of stratospheric air into the upper troposphere. To examine this episode in more details, the time series of vertical velocity around the tropopause and RSNR at around 14 km are shown in Fig. 3a and b respectively. This figure readily reveals that the two above-mentioned processes are happening around the same time. When stratospheric air intrudes into the upper troposphere, it may take definite time to mix with the surrounding air mass and thus retains its stratospheric identity for some time. As the stratospheric air is more statically stable as compared to upper tropospheric air, the potential refractive index gradient (M) of this air mass will be more than that of upper tropospheric air mass. Thus a gradient in potential refractive index will be formed along the path of the stratospheric air entering into the upper troposphere and this gradient is believed to be responsible for the enhanced echoes in the height region of 12–16 km as observed in the height-time section of RSNR. The total potential refractive index gradient is given by (Van Zandt et al., 1978),

$$M = M_d + M_w$$

Where $M_d = -77.6 \times 10^{-6} \dfrac{PN^2}{Tg}$

and $M_w = -77.6 \times 10^{-6} \dfrac{PN^2}{Tg} \left[15500 \dfrac{q}{T} - 7750 \dfrac{g}{N^2 T} \left(\dfrac{\partial q}{\partial z} \right) \right]$

where, T is temperature, P is pressure, q is specific humidity and g is acceleration due to gravity. Of all the parameters on which M has dependency, the static stability parameter is very significant for the present discussion. The magnitude of N^2 in the stratosphere is approximately twice that of the troposphere. It is also evident from the above equation that the dry part of M will be dominant in the upper troposphere and

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lower stratosphere as compared to wet part as humidity is negligible at these height regions. However, the humidity in the present case in the upper troposphere can not be neglected as it is a case of deep convection, but, it will be smaller in magnitude as compared to mid and lower troposphere. Thus from the above equation and discussion, it is evident that the lower stratospheric air will have lager M_d values as compared to upper tropospheric air. As lower stratospheric air enters into the upper troposphere, the gradients in M will be formed along its path, which results in enhanced radar echo power. As these trails of enhanced M will be carried by the background wind, the echoes from these regions appear slanted as shown in the Fig. 1a. Thus the present study shows the intrusion of lower stratospheric air into the upper troposphere and its signature in the radar time-height sections.

Thompson et al. (1997) reported the various physical processes that contribute to the upper tropospheric ozone budget. These authors successfully accounted the excess ozone concentration in the upper troposphere to deep convection and associated transport of pollutants into the upper troposphere. Recently, there were observational evidences for upper tropospheric ozone enhancement through the lightning process associated with deep convection (Jenkins et al., 2008). However, little attention was paid to the intrusion of stratospheric air in to the upper troposphere during the deep convection episodes as discussed in the present study. This can be attributed to limited observations of downdrafts from lower stratosphere to upper troposphere during the deep convection episodes, which is provided lonely by wind profilers. Thus the present study emphasizes the consideration of stratospheric air intrusion episodes during the deep convection events in accounting for the upper tropospheric ozone budgets.

Apart from stratospheric air intrusion, there is one more consequence of these high altitude downdrafts observed in the present study. These perturbations in the vertical velocity can act as a seeding mechanism for gravity wave excitation. There are few studies reported from the present observational site on the convectively generated gravity waves (Kumar, 2006; Kumar, 2007). All these studies have shown the convective updrafts in the mid-troposphere as source mechanism for gravity waves. However,

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in the present study, the high altitude downdrafts observed in 12–16 km height region seems to be the source for the observed gravity wave signature in the lower stratosphere. To examine this aspect in details, the lower stratospheric vertical velocity time series is subjected to wavelet analysis and the resulting spectrum is shown in Fig. 4a. This figure readily reveals a short burst of gravity wave with a time period 25–30 min and having amplitude of the order of 0.6 ms^{-1}. To examine the vertical structure of this gravity wave, the phase profile is constructed and is shown in Fig. 4b. From this figure it can be noted that the phase is more or less constant in the height region of 13–15 km and the phase is propagating downwards in the 15–20 km and is propagating upwards in 10–13 km height region. This phase structure indicates that the wave source lies in 13–15 km and from this region wave is propagating both upwards and downwards thus confirming the presence of gravity waves. For more discussion on the phase structure of convectively generated gravity waves and their propagation direction, refer to Kumar (2006). Thus the high altitude downdrafts observed during the deep convection play a role not only in stratosphere-troposphere exchange but also in exciting the gravity waves.

4 Summary and concluding remarks

VHF radar observations of a MCS with 11 s temporal resolution were discussed. The height-time section of RSNR showed the inclined echoes in the height region of 12–16 km. Co-incident with the inclined echoes, the height-time section of vertical velocity showed a downdraft of the order of 4 ms^{-1}. These two observations in RSNR and vertical velocity provided the first clue for stratospheric air intrusion into the upper troposphere. Subsequent analysis showed that the inclined echoes are due to the stratospheric air having relatively large M compared to upper tropospheric air. It was proposed that the air mass of two different regions having varying M values may generate gradients in M to which VHF radar is sensitive. Thus, the inclined echoes observed in the present study in the 12–16 km region was regarded as the signature of stratosphere-troposphere exchange, which has implication in accounting the physical process responsible for upper tropospheric ozone budget. Earlier observations reported from the present experimental site showed the evidence from stratosphere-troposphere exchange and the present observations for the first time showed how this process appears in the height-time section of RSNR. The present study using the wavelet spectrum of lower stratospheric vertical velocity and its phase structure showed that the high-altitude downdraft can trigger the gravity waves. Thus the present study provided the radar signature of stratospheric air intrusion into the upper troposphere and its consequences. However, the origin of the observed downdrafts near the tropopause is not addressed in the present study and it will be the focus of our future studies.

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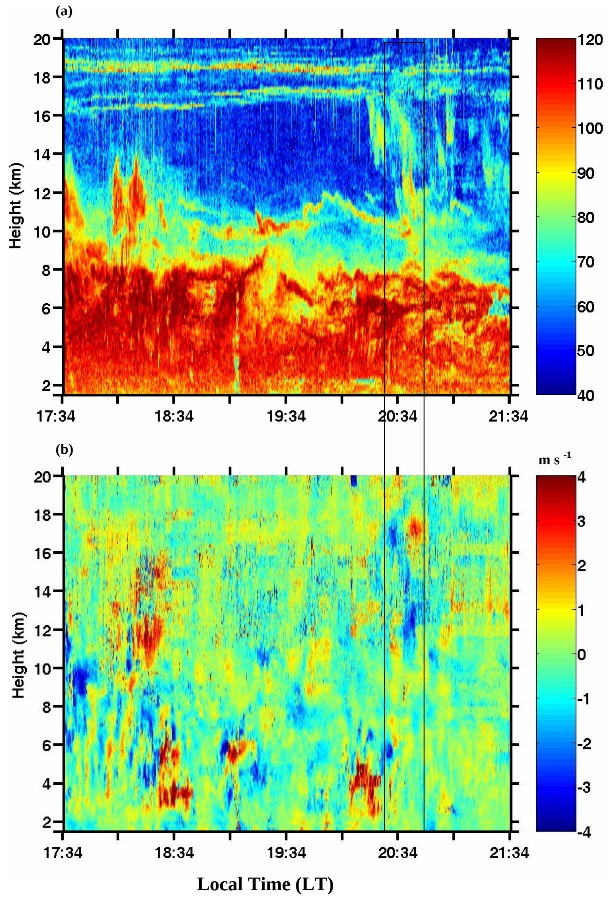

Fig. 1. Height-time section of **(a)** range corrected SNR and **(b)** vertical velocity (ms^{-1}) as observed by the VHF radar on 19 June 2006. The rectangle highlights the intrusion event.

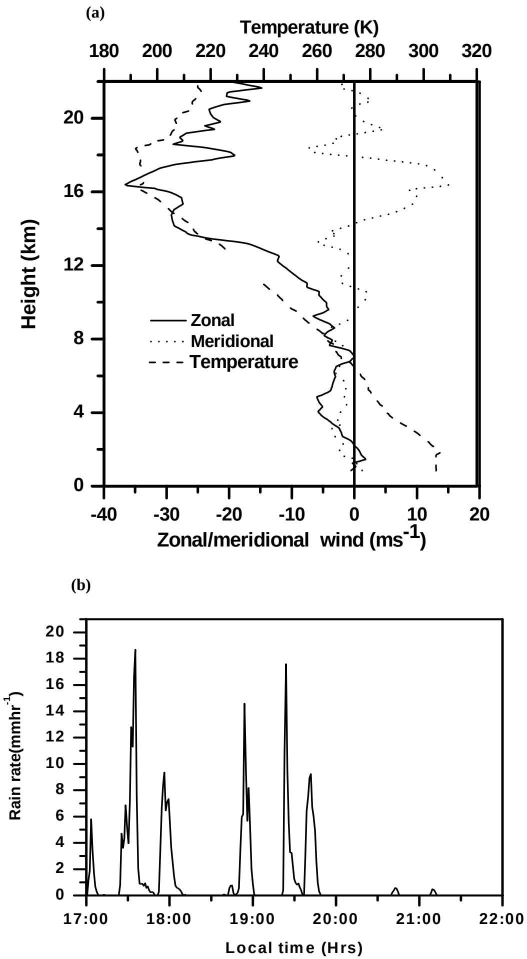

Fig. 2. **(a)** Height profile of zonal winds, meridional winds and temperature derived from the GPS sonde observations and **(b)** Time series of rainfall measurements using optical rain gauge observations on 19 June 2006.

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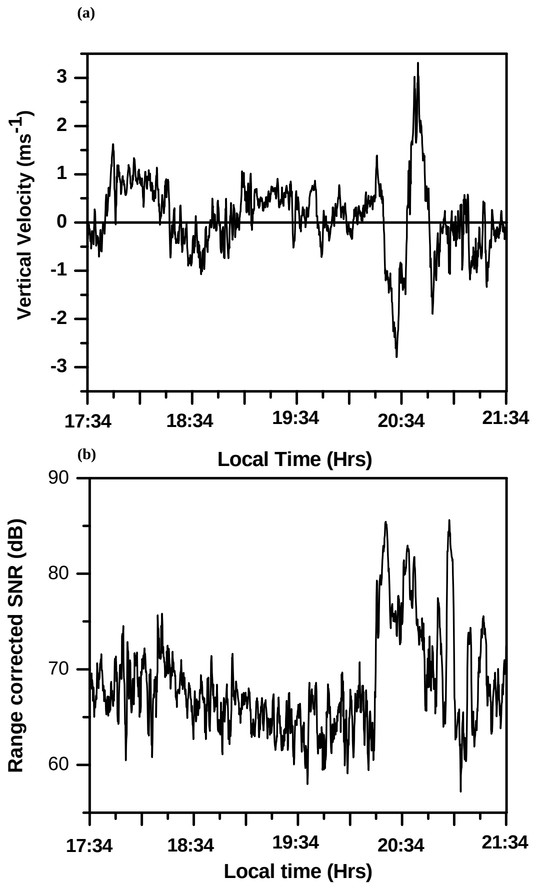

Fig. 3. (a) Time series plot of (a) vertical velocity around the tropopause and **(b)** range corrected SNR around 14 km altitude.

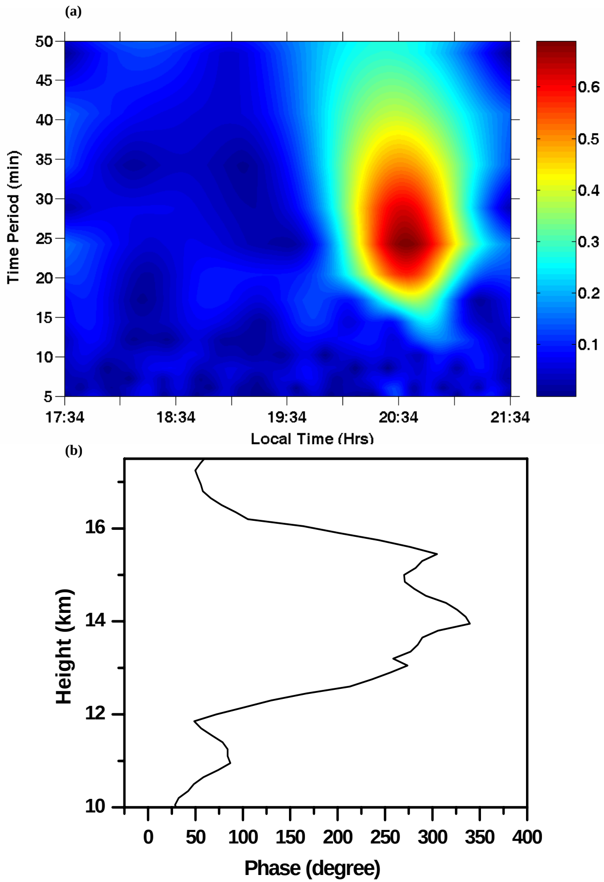

Fig. 4. (a) Wavelet spectra of vertical velocity in the lower stratosphere and **(b)** Phase profile of dominant gravity wave.

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