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Atmospheric
Chemistry
and Physics
Discussions

Interactive comment on "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)" *by* K. K. Kumar and K. N. Uma

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We are very much thankful to the reviewer for evaluating our manuscript and providing constructive comments. The responses to the reviewer's comments are typed in bold letters.

Comment: It is unclear for me how the authors distinguish in figure 1 what belong to the downdraft and what belong to the gravity wave. The downdraft at 17 km is followed

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by an equally intense updraft and the fact that intense updraft are not seen at lower levels cannot rule out the fact that we only see the propagation of a short gravity wave (especially in clear air). The propagation speed of about 4 m/s (5 km over 20 minutes) is within the admitted range for short gravity waves. It would require a sustained flux at the same speed to explain an intrusion.

Reply: This is a very intriguing question and reflects the reviewer's expertise in the gravity wave studies. Now, coming to the figure 1, what we observe is a downdraft initiated at 17 km and progressing in to the upper troposphere. This downdraft does two things (1) brings ozone rich lower stratospheric air in to the upper troposphere and (2) act as a seeding perturbation to the gravity waves. As a parcel of air descends, it is known that it warms up due to adiabatic compression and once it is warmer than the surrounding, it starts rising. This couplet of down and updraft is responsible for gravity wave generation. This couplet can be seen in the height region of 13-17 km height region with varying magnitude. The first question we put ourselves is how to know the existence of gravity waves as dynamical response of downdraft also can produce the similar kind of vertical velocity structure. This question led us to estimate the phase profile of the dominant gravity wave period using Fourier analysis, which is shown in figure 4(b). This phase profile clearly shows an upward propagating wave from 13-15 km height region. Based on this phase profile we confirmed the propagation of gravity wave. As correctly pointed out by the referee, it exhibits the small scale gravity wave characteristics. We completely agree with the referee that there should be a sustained flux at least for some time to explain the observed intrusion. What we envisage is, as the whole system is moving with the background wind including updraft and downdrafts, the source region also may have drifted with background wind. As the beam width of Indian MST radar is 3 degrees, there is every chance that it is out of Radar probing volume within a short time. However, the presence of gravity wave during the observational period is established by wavelet spectrum of vertical velocity and its vertical propagation is confirmed by the phase profile.

Comment: The uncertainty on the vertical velocity can be large in non homogeneous regions and should be assessed like in Astin (1997) or Choi et al. (2006).

Reply: The uncertainty in the vertical velocity can be accessed in terms of confidence interval proposed by Astin (1997). However, for evaluating the confidence intervals, more than three radar beams are required for each wind profile. The present radar experiment was carried out using zenith beam alone to have high temporal resolution vertical velocities and hence cannot be estimated. However, in the present study we are not using the magnitudes of vertical velocities to estimate any other parameters and no attempt is made to quantify the exchange process rather we are using vertical velocity measurements as proxy for upward and downward motion.

Comment: Such a deep intrusion induces a strong local heating and should affect more visibly the tropopause above.

Reply: As discussed earlier, a downdraft is initiated at 17 km and processes responsible for initiation of this drain is yet to be known. The downdraft across the tropopause is very often observed over this latitude during the passage of convective systems for example Jain et al, (2002) and Kumar (2006). What we emphasize here is the intrusion reported in the present study is a very localized and small scale. For example, Bellevue et al.,(2007) reported enhanced ozone values observed in the upper troposphere near intense tropical cyclones, surprisingly, the dynamical mechanisms involved in the enhanced tropospheric ozone values could not be explained by ECMWF meteorological analysis with 1.1250 horizontal resolution. The upper tropospheric ozone enhancement was then studied using a mesoscale model, which was able to reproduce a stratospheric PV filament into the troposphere. What we emphasize here is some of the small-scale atmospheric processes cannot be resolved/observed on some occasions, which can be attributed limitation of the observing tools.

Comment: Traces of the intrusion should be visible on the water vapour channel of geostationary satellite images.

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Reply: The mesoscale system observed in the present study is highly localized and we doubt whether this small scale process will be resolved by the geo-stationary satellite. However, the Geostationary Operational Environmental Satellite (GOES 9) (Miyakawa and Satomura 2006) Tbb (brightness temperature) maps are generated for every hour; around the time of appearance of convective core in the Indian MST radar are presented in figure1 (reply). Black dot indicates the location of Gadanki. It is clear from the figure that as the time progresses, deep clouds are slowly advecting over the observational site. One interesting feature is that at the time and after the intrusion, deep convective clouds are clearly visible from these Tbb maps. This imagery confirms the presence of a MCS over radar site, which is also supported by the rainfall measurements shown in figure 2(b) in the manuscript. We are also providing the watervapor imagery from metosat observations in the revised manuscript. The figure 2 (reply) shows the water vapor channel image at 1200(left panel) and 1800 UT (right panel). The location of Gadanki is marked in the figure. However radar observations are during 1204-16:04 UT. From this figure it is evident that at 1200 UT, which is closer to radar observational time period, there is highly localized accumulation of water vapor over the radar site.

Comment: Although, it is likely that a downdraft at tropopause level would induce stratosphere-troposphere exchange there is no independent data to support it and this cannot be presented as a result.

Reply: We are very happy that referee agrees that downdraft at tropopause level would likely to induce stratosphere-troposphere exchange. Unfortunately, we do not have any simultaneous measurements like ozonesonde at the radar site. But, we are very sure about the results presented in the manuscript for the following reasons,

(1) In the present study, we have observed the slanted echoes during an episode of downdraft in the vicinity of the tropopause. Earlier studies from this latitude reported the downdrafts across the tropopause as an indicator of stratosphere-troposphere exchange, which is clearly seen in the present results. (2) On a clear-air conditions,

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the signal to noise ratio profiles always show a dip in 13-16 km region over this latitude. However, during the passage of deep clouds coherent enhanced SNR structures reaching as high as 17 km can be noticed. The enhancement in the SNR is attributed to the gradients in refractive index of air, which is a function of temperature and humidity in the lower atmosphere. In the present study, the echoes observed in the 13-16 km altitude are not due to deep cloud, which is obvious from height-time section of SNR. The only reason we find for this localized enhancement in the SNR is the mixing of two air masses of different refractive index. The downdraft observed during the same period substantiates our interpretation of stratospheric air intrusion in to the troposphere.

At this juncture, where VHF radar applications are extending to operation meteorology, what we believe is VHF radar measurements can be used as an independent tool for understanding some of the atmospheric processes in finer details. By now, it is showed by several researches across the globe that VHF radar observations can be independently used to study the stratosphere-troposphere exchange [e.g., Hocking et al., 2007].

Bellevue, J. L, J.L. Baray, S. Baldy, G. Ancellet, R. Diab, F. Ravetta, Simulations of stratospheric to tropospheric transport during the tropical cyclone Marlene event

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Interactive comment on Atmos. Chem. Phys. Discuss., 9, 13843, 2009.

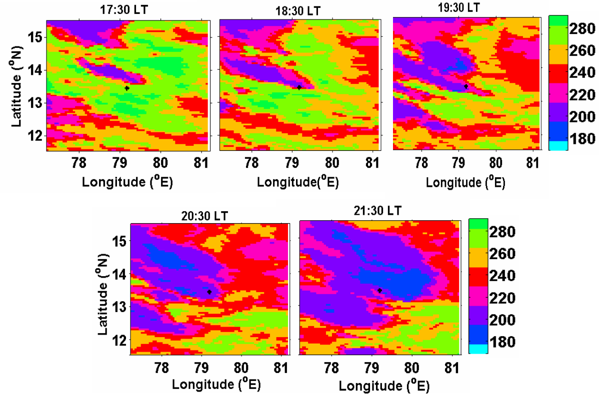

Figure 1: T_{bb} maps generated from GOES 9 observations over Gadanki

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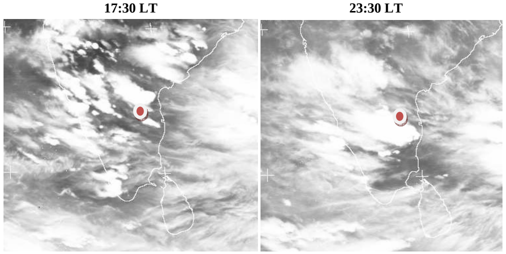

Figure 2: Water vapor imagery from Meteosat observations

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