Replies to Reviewer #1 Comments/suggestions

The paper presents backward ray-traces of GWs observed in two stations in India. Evidence is presented that these waves are generated by wind shear. The arguments presented are convincing, the paper is, in general, well structured and the findings very interesting. However, there are a number of points in the description of the data and the investigation which need to be improved. The English needs editing.

Reply: First of all we wish to thank the reviewer for going through the manuscript carefully, appreciating the actual content of the work and providing potential solutions for further improvement. We have taken care most of the issues suggested and tried to minimize the errors in English usage in the revised manuscript.

Major comment:
You discuss in your paper that the high phase-speed, high frequency GWs you observe in the MLT region are likely generated in the troposphere. You can rule out convection and orography as sources but find indication for strong wind shear. The generation of high phase-speed waves by wind shear I consider extremely interesting: to my knowledge most studies which relate high-phase speed GW observations in the MA to sources are about convection (e.g. Taylor et al., Planet. Space Sci., 1988, Wrasse et al., Vadas et al.) While literature which relates GWs to shear often focus on low phase-speed GWs (e.g. Pfister et al., JAS, 1993, Leena et al., JASTP, 2012, Preusse et al., ACPD, 2014; papers on the obstacle effect you have quoted).
Therefore I would like to suggest the following changes:

1. Change the title! For instance: Evidence for the excitation of high phase-speed gravity waves by wind shear in the troposphere from air glow observations over India. You can still explain the ray-tracing in the abstract. The abstract, however, should focus somewhat more on the source processes.
Reply: Thanks for suggestion. We have changed the title as suggested.

2. Do more (redo) literature research on evidence for shear generated GWs (e.g. starting from papers quoting Fritts, 1984). And on sources for waves observed in the airglow. Include a paragraph either in the introduction or in the discussion section or both highlighting a) which sources are identified for high phase-speed GWs in the MLT b) evidence for GWs from shear from measurements and which phase speeds they discuss. In this way you can better place your paper in a context.
Reply: We have provided few sentences related to sources of waves identified for high phase-speed GWs and also provided references related to the evidence of GWs from shear measurements as suggested in the revised manuscript. .

General comments:
1. Section 3 is a one-to-one copy of the ray-tracing equations as given in the appendix of Marks and Eckermann, 1995. Since you are not referring to these equations later, this can be completely omitted from the paper. A brief qualitative description what ray-tracing does would be more helpful to the reader. However, one essential information is currently missing: Did you use a program packet provided by others (e.g. GROGRAT) or did you do your own coding? If you did

your own coding you should have some validation. In this case, please mention which tests you performed (e.g. in an appendix).

Reply: In order to apply ray tracing we used the same ray tracing equations that is provided in the Eckermann, 1995. And we developed matlab code by using Runge-kutta fourth order method. For that we checked WKB parameter value less than one. This information is clearly mentioned in the revised manuscript (page 9).

2. P19600 L3, P19602 L10 and Figure 6 You use a threshold for the WKB parameter of 1 to terminate the ray, which is a default value in the GROGRAT settings(, too?). In this way you guarantee the accuracy of the backward ray-tracing. However, GWs propagate through regions where WKB is violated and terminating the rays at this altitude means loosing information on the true source location. The best example is the tropopause and the tropopause inversion layer. The very rapid change of the buoyancy frequency in a very narrow altitude layer violates WKB for almost all waves. This, I think, is what you observe in Figure 6: the rays stop at about 18km in plots 6a,b, Which corresponds to the rapid change of buoyancy frequency in panel c and hence indicates a ray termination by WKB violation. (On the other hand, if table 1 is correct: why do the rays in F6 not reach 13 km?) By the way, figure 6 therefore contradicts the interpretation presented in P19602 L10 though of course the extrapolated intrinsic frequency would be lower than the buoyancy frequency.

Reply: We have re-plotted this figure in the revised manuscript. Note that all the wave events which propagated down to the upper troposphere terminated between 10 and 14.5 km, except the case G2 which got terminated at 17 km due violation of the WKB approximation. As mentioned, the violation of the WKB approximation at 17 km could be due to sharp temperature gradients near tropopause. In the present study we have not calculated the propagation of past the level of violation of WKB approximation. This information is clearly mentioned in the revised manuscript (page 16)

3. My suggestion is to calculate past WKB violation but indicate at which altitude WKB violation occurs. You could include a further panel in Figure 6. On the other hand it may be helpful to have the buoyancy frequency and the intrinsic frequency in the same panel. Definitely it would be helpful to have a second x-axis (top-axis) for panels 6a and 6b which show the vertical wavelength and period of the wave. Also the horizontal wavelength would be interesting information. If you calculate past WKB violation then you can indicate also the altitude above which the source must be located, here 8 km. Of course this is now with some uncertainty as WKB was violated above this point, on the other hand WKB violation should much more affect the amplitudes because of partial reflection than the wave parameters.

Reply: We have included the altitude where WKB violation occurs and also provided buoyancy frequency and the intrinsic frequency in the same panel in Figure 6 as suggested. Note that in the present study we have not calculated the propagation of past the level of violation of WKB approximation.

4. Section 6 In order to identify the source altitude it would be helpful to provide one additional figure showing profiles of the Richardson number in the center of the terminal positions of the rays for both stations. The high phase speed and short period of these waves for which you identify shear as the most likely source is very interesting. This should be discussed! Which other evidence is there for waves from shear and which are the typical scales and phase speeds

of the waves identified in these studies? You could scan papers referring to Fritts 1984 and set your findings in relation. Also, even though you cannot determine the source amplitude, you may give a feeling which amplitude is necessary in order to be compatible to the observations.
Reply: In order to check the KH instability, we have used the radiosonde data available near to the termination point. For Gadanki we have used data VOMM (13^{0}N, 80^{0}E) observed on 17 March 2012 and for Hyderabad location we have used data from Goa (15.50^{0}N, 73.3^{0}E) observed on 8 March 2010. We have calculated the Richardson number profiles for both the stations and provided as additional figure (now figure 8) as suggested. We also included the discussion related to shear generated waves while relating to the Frits (1984) reports.

Specific comments
1. P19589 LL9 Of course you need to be selective in the references you are quoting (use e.g. or note that there are more studies than those quoted) but I would like to add a few further suggestions. Please add: depth of the heating: Salby and Garcia, JAS, 1987 obstacle effect: Pfister et al., JAS, 1993 topography: Queney, BAMS, 1948, Eckermann and Preusse, Science, 1999 geostrophic adjustment: O'Sullivan and Dunkerton, JAS,1995, Plugonven and Zhang, Rev. Geophys., 2014
Reply: We have included these references in the revised manuscript as suggested.

2. P19589 L18 remain a challenge (Geller et al., J.Clim., 2013)
Reply: Added.

3. P19589 LL19 This should be explained better: hodograph analysis may be used for two aims: a) to determine the wave parameters in which case it could be combined with other means like a ray-tracer; b) to discern between upward and downward propagation in which case it is indication though not final proof of a source at a specific altitude (e.g. the tropopause)
Reply: Modified these sentences as suggested.

4. P19590 L1 I think the real point is to identify the source of a GW which has already propagated for some distance, both in the vertical and the horizontal.
Reply: Modified.

5. P19590 L3 Please add also a few examples for the stratosphere: e.g. Hertzog et al., Ann. Geophys., 2001
Reply: Added.

6. P19590 L20 Applying a method to a new place is not really a "first time" and whether it is "successfully" we will see at the end of the paper: both phrases read strange in the introduction -> please delete them
Reply: Deleted.

7.P19590 Please add a few lines at the end of the introduction to outline the structure of the paper.
Reply: Added.

8.P19592 L2 You need the intrinsic phase speed to calculate the vertical wavelength. Please mention this (e.g. provide the equation)! This means you need the background wind. Please give the source for the wind data. omit "also" (in general: reduce the use of "also")

Reply: We have mentioned and provided the equation for the same in the revised manuscript. The background atmosphere used is the same developed background atmosphere. The dispersion relation is $\omega_{ir} = \omega - ku - lv$**,** $\omega_{ir}^2 = \dfrac{N^2(k^2+l^2)+f^2(m^2+\alpha^2)}{k^2+l^2+m^2+\alpha^2}$ **where** m **is the vertical wave number of the wave.**

9. P19592 L15 suggest to replace "elsewhere ncitep" by "by ncitet{}".

Reply: We are sorry to say that we do not understand what reviewer wants to convey here.

10. 2.2. I guess from your text that you use a 2D detector and use one direction for the spectral resolution and one direction for 1D spatial imaging, correct? If yes, please say so explicitly. In addition, please specify the spatial extent and resolution of the imaging. This defines the observational filter and is therefore essential to the interpretation of the results.

Reply: Yes, we use a 2-D detector. Further, the spatial extent of the measurement in the E-W direction is ~170 km, with a spatial resolution of ~11 km. In the N-S direction the spatial extent and resolution are 330 km and 50 km, respectively. We have included this information as suggested.

11. P19593 LL5 These are geostationary satellites, so it should be particularly one of them which is mainly providing the data for India. Mentioning geostationary is important because in this way you get complete coverage at short temporal sampling (the 1 hour data you are referring to later).

Reply: We have mentioned clearly about the geostationary satellite as suggested.

12. P19597 L5 What do you mean here? Since the waves are high frequency they don't propagate far and a region of 5X 5 is sufficient? Or: since the waves are high frequency, you need a resolution of at least 5 to capture the relevant variations of the background.

Reply: Since these are high frequency waves they will propagate very fast with less horizontal wavelengths and thus maximum of 5°X5° grids is enough.

13. Figure 3: Why do you compare a single snapshot from ERA-interim with climatologies? It would be helpful to have a) also a comparison based on an ERA monthly mean and b) a motivation in the text why a single-day comparison is also helpful.

Reply: In order to check whether ERA interim data is suitable to Gadanki location we checked this data with climatology developed data. As suggested we also provided the discussion related to monthly mean from ERA-Interim.

14. P19599 L15 How did you obtain molecular diffusivity?

Reply: Molecular diffusivity D_{mole} **is given by** $D_{mole} = 2.4\mu / \rho$ **(Chester S. Gardner 1995) where Coefficient of molecular viscosity** μ **is given by** $\mu = 3.34*10^{-4} T^{0.71} gmm^{-1}s^{-1}$ **(S.L.Vadas 2009 et al).**

Gardner, C.S., (1995), Scale-Independent Diffusive Filtering Theory of Gravity Wave Spectra in the Atmosphere, Geophysical Monograph 87.

15.Section 6: I would like to suggest to modify the title of this section: Discussion of potential source processes

Reply: Modified as suggested.

16. P19603 L11 A presumable source altitude larger 10km is the second argument that rules out topography. I think at this point you should omit a reference, since a) the arguments are very clear and b) you could quote quite a large number of references, so highlighting one is not really appropriate.

Reply: Reference is omitted as suggested.

17. P19603 L17 I don’t think that this is a good argument even to be discarded. Deep convection is very frequently accompanied to clear sky in the vicinity. The DAWEX campaign would be a further example.

Reply: Deleted this sentence in the revised manuscript.

18. P19603 LL20 Please first discuss the potential source time. For this you should include in Figure 6 an altitude profile of the time, most helpful for the further discussion would be of course absolute times, i.e. the observation time at the ray-start and according times along the ray (GROGRAT would provide relative times with respect to the ray start).

Reply: Altitude profile of the time is also provided in the revised manuscript as suggested.

We once again thank the reviewer for going through the manuscript carefully as providing constructive comments which made us to improve the manuscript content further.

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Replies to Reviewer #2 Comments/suggestions

To identify the sources of gravity waves observed by optical airglow measurements over Gadanki (13.5^0 N) and Hyderabad (17.5^0 N) at altitudes of about 97 km, reverse ray tracing methods based on the equations described by Marks and Eckermann (1995) are successfully applied. In 9 of 14 investigated events the authors could identify that these waves are launched in the upper troposphere (10 – 12 km) at regions with large vertical shears of horizontal winds. In all cases studies investigated here, tropical deep convection has been excluded as possible sources for the upward propagating gravity waves. To get confidence to the results, the backward ray tracing estimations have been done by considering a realistic variability of winds and temperatures caused by tidal waves. The derived results are very interesting. Before publication in ACP the authors should extend their discussion, consider the following remarks:
Reply: First of all we wish to thank the reviewer for going through the manuscript carefully, appreciating the actual content of the work and for providing potential solutions for further improvement. We have taken care most of the issues suggested.

1. A broader discussion in connection with previous results is recommended.
Reply: As also suggested by other reviewer we have included discussion related to wind shear generated waves while quoting relevant references in the revised manuscript.

2. As an example: Preusse et al., (2008) used GROGRAT to discuss the propagation properties of high frequency waves with short horizontal wavelengths and questioned whether these could possibly reach the mesopause region. In their Figure 2 they show that most GW with horizontal wavelengths smaller than 50 km propagating upward from the troposphere (5 km) or stratosphere (20 km), respectively, are evanescent at the sources or are reflected by wind shears and hence cannot reach altitudes of 80 km or higher during summer. How are their results related to the findings during these case studies?
Reply: We have compared our findings with that reported by Preusse et al., (2008) as suggested. Preusse et al. discussed the transparency of the waves to the atmosphere in different seasons. They reported that during equinox times atmosphere is more transparent to the high phase speed and shorter horizontal wavelength waves than that in the solstices. Further, horizontal wavelength less than 10 km and slow phase speed waves are less likely to reach MLT regions. However, the number of rays penetrating to the MLT peaks at the tropical latitude where wind speed is low in comparison to the mid and high latitudes. In our case, whenever phase speed is low for short horizontal wavelength waves, ray didn't reach up to the troposphere and it got stopped at mesospheric altitude itself. This has been discussed in revised manuscript.

3. Five of the total 14 wave events are restricted to mesospheric altitudes. A stronger discussion on the origin of these waves, e.g. as secondary waves, is recommended.
Reply: Thanks for this suggestion. We have included discussion related to secondary waves while quoting relevant references in the revised manuscript.

4. Following the suggestions given by the first interactive comment, it is recommended to delete Section 3 (which follows the appendix of Marks and Eckermann, 1995) and substitute it by an explanation and evaluation of the used program packet.

Reply: As also suggested by other reviewer, we have reduced the content of section 3 and tried to explain the used code to the maximum possible extent.

5. The English needs a revision.
Reply: We tried our level best to reduce the errors in the English usage in the revised manuscript.

6. P19592 L3 : The zonal, meridional and vertical wavelength are not provided in table 1 but can be derived using the values provided in table 1
Reply: Modified.

7. P 19593 Sect 2.3 To improve the readability it is recommended to explain that the OLR values are later shown in Fig 8.
Reply: Explained.

8. Page 19599 line 25 Runge-Kutta
Reply: Modified.

9. Page 19600 line 28 is nearly identical to page 19598 line 16
Reply: Deleted the repeated sentences.

10. Page 19606 line 18 Rayleigh
Reply: Modified.

11. Figure 5c and f please add “at 97 km”
Reply: Added.

References: Preusse, P., S. D. Eckermann, and M. Ern (2008), Transparency of the atmosphere to short horizontal wave-length gravity waves, J. Geophys. Res., 113,D24104, doi:10.1029/2007JD009682.Interactive comment on Atmos. Chem. Phys. Discuss., 14, 19587, 2014.
Reply: We have included this reference in the revised manuscript.

We once again thank the reviewer for going through the manuscript carefully as providing constructive comments which made us to improve the manuscript content further.

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Evidence for tropospheric wind shear excitation of high phase-speed gravity waves reaching the mesosphere using ray tracing technique

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Deleted: Identification of gravity wave sources using reverse ray tracing over Indian region

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Abstract

Reverse ray tracing method is successfully implemented in the Indian region for identification of the sources and propagation characteristics of high frequency gravity waves observed in the mesosphere using airglow emissions from Gadanki (13.5°N, 79.2°E) and Hyderabad (17.5°N, 78.5°E). Wave amplitudes are also traced back by including both radiative and diffusive damping. Background temperature and wind data obtained from MSISE-90 and HWM-07 models, respectively, are used for the ray tracing. For Gadanki region suitability of these models is tested. Further, a climatological model of background atmosphere for Gadanki region has been developed using a long-term of nearly 30 years of observations available from a variety of ground-based (MST radar, radiosonde, MF radar), rocket-, and satellite-borne measurements. For considering real-time atmospheric inputs, ERA-Interim products are utilized. By the reverse ray tracing method, the source locations for nine wave events could be identified to be in the upper troposphere, whereas, for five other events the waves got terminated in the mesosphere itself. Uncertainty in locating the terminal points in the horizontal direction is estimated to be within 50-100 km and 150-300 km for Gadanki and Hyderabad wave events, respectively. This uncertainty arises mainly due to non-consideration of the day-to-day variability in tidal amplitudes. As no convection in-and-around the terminal points are noticed, it is unlikely to be the source. Interestingly, large (~9 m/s/km) vertical shears in the horizontal wind are noted near the ray terminal points (at 10-12 km altitude) and are identified to be the source for generating the observed high phase speed, high frequency gravity waves. Conditions prevailing at the terminal points for each of the 14 events are also provided.

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Key words: Gravity wave sources, reverse ray tracing, wave action, airglow, model outputs.

1. Introduction

Atmospheric gravity waves (GWs) play an important role in the middle atmospheric structure and dynamics. They transport energy and momentum from the source region (mainly troposphere) to the upper atmosphere. The waves are dissipated on encountering critical level, transferring energy and momentum to the mean flow and leading to changes in the thermal structure of the atmosphere (Fritts and Alexander 2003). Several sources are identified for the generation of GWs which include deep convection, orographic effect, vertical shear of horizontal wind and geostrophic adjustment. For GW generation from deep convection, basically three mechanisms are considered (Fritts and Alexander 2003). These are (i) pure thermal forcing (e.g. Salby and Garcia 1987; Alexander et al., 1995; Piani et al., 2000; Fritts and Alexander 2003; Fritts et al., 2006), (ii) mechanical oscillator effect (e.g. Clark et al., 1986; Fovell et al., 1992), (iii) obstacle effect (e.g. Clark et al., 1986; Pfister et al., 1993; Vincent and Alexander 2000). The importance of these depends upon the local shear vertical profile and time dependence of latent heat release. GWs from the convection source can have a wide range of phase speeds, frequencies and wavelengths unlike those from orography, which are generally confined to a particular frequency and phase speed (low) (e.g. Queney., 1948; Lilly and Kennedy 1973; Nastrom and Fritts 1992; Eckermann and Preusse 1999; Alexander et al., 2010). In the shear excitation mechanism two processes namely sub-harmonic interaction and envelope radiation (Fritts and Alexander 2003) exists. The latter process can yield horizontal scales of a few tens of kms and phase speeds comparable to the mean wind. The geostrophic adjustment source is effective mainly in high latitudes (e.g. O'Sullivan and Dunkerton 1995., Shin Suzuki et al., 2013; Plougonven and Zhang 2014).

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In general, significant progress has been made in the understanding of the physical processes for generating the spectrum of GWs through both observations and modeling. However, identification of the exact sources for the generation of GWs and their parameterization in the models still remains a challenge (Geller et al., 2013). In order to identify the gravity wave sources, hodograph analysis has been widely used. Hodograph analysis can be used to identify the gravity wave parameters and which can be used as input parameters to the ray tracing. Using hodograph we can find whether the wave is propagating upward or downward and in this way indirectly we can locate the source at a particular altitude. However, this method is applicable only for medium and low frequency waves, as for the high frequency GWs the hodograph would not be an ellipse but nearly a straight line. Further, as it assumes monochromatic waves, it is not always applicable in the real atmosphere. Notwithstanding this limitation, using this method convection and vertical shear have been identified as the possible sources of the observed medium and low frequency GWs in the troposphere and lower stratosphere over many places (e.g., Venkat Ratnam et al., (2008)). It becomes difficult to apply this method for GWs that are observed in the MLT region where simultaneous measurements of temperatures (with wind) would not be available.

A more appropriate method in such cases is ray tracing (Marks and Eckermann 1995), which is widely being used to identify the sources of GWs observed at mesospheric altitudes. Several studies (Hecht et al., 1994; Taylor et al., 1997; Nakamura et al., 2003; Gerrard et al., 2004; Brown et al., 2004; Wrasse et al., 2006; Vadas et al., 2009 and references therein) have been carried out to identify the sources for the GWs observed in the mesosphere using airglow images and in the stratosphere using radiosonde and lidar data (Guest et al., 2000; Hertzog et al., 2001). In mesospheric studies, important GW parameters, such as, periodicities and horizontal

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wavelengths (and sometimes vertical wavelengths when two imagers are simultaneously used) are directly derived. A major limitation to the ray tracing method is the non-availability of realistic information of the background atmosphere, which is difficult to obtain with available suite of instrumentation and so identifying the source of the waves which propagate horizontally as well as vertically is difficult. Nevertheless, possible errors involved in identifying the terminal point of the waves with and without realistic background atmosphere have been estimated (e.g., Wrasse et al., 2006; Vadas et al., 2009).

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Over the Indian region, several studies (Venkat Ratnam et al., 2008 and references therein) have been carried out for extracting GW parameters using various instruments (MST radar, Lidar and satellite observations). In a few studies (Kumar 2006., 2007; Dhaka et al., 2002; Venkat Ratnam et al., 2008; Debashis Nath et al., 2009; Dutta et al., 2009) possible sources in the troposphere for their generation are identified which include convection, wind shear, and topography.

In the present investigation, reverse ray tracing method is implemented to identify the sources of the GWs at mesospheric altitudes observed from an airglow imager located at Gadanki (13.5^{o}N, 79.2^{o}E) and from a balloon experiment which carried an ultraviolet imaging spectrograph from Hyderabad (17.5^{o}N, 78.5^{o}E). Using this we have traced the wave parameters and wave amplitudes along the ray path after including the radiative and turbulent damping and tried to find the sources for the observed waves. In Section 2 we described the instrumentation, in Section 3 the theory behind ray tracing, in Section 4 the background atmosphere used for ray tracing, in Section 5 application of the ray tracing method and in Section 6 identification of the sources for the observed waves.

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2. Database

2.1. Airglow imager observations at Gadanki and methodology for extracting GW characteristics

The NARL Airglow Imager (NAI) located at Gadanki is equipped with 24 mm of Mamiya fish eye lens. It can monitor OH, O(^{1}S), and O(^{1}D) emissions and has a 1024x1024 pixels CCD as the detector, and a field-of-view of NAI is 90^o avoiding non-linearity arising at higher zenith angles. In present study, only observations of O(^{1}S) emission which originate at ~93-100 km (with a peak emission altitude of ~97 km) are used. The exposure time used to measure the intensities of emissions was 70 s. After capturing the image it has been analyzed and corrected for the background brightness, star brightness and actual coordinates. The area covered in the image is 200 km x 200 km with a spatial resolution of 0.76 km near zenith and 0.79 km at the edges. More details of the NAI are discussed by Taori et al. (2013).

We have observed three wave events between 14:29-14:51 UTC, 15:44-15:50 UTC and 20:45-21:17 UTC on 17 March 2012 (Figure 1) and two wave events between 15:47 - 16:27 UTC and 16:31 - 16:54 UTC on 19 March 2012 in the O(^{1}S) airglow emission intensities. In these images crests of the waves are emphasized by yellow freehand lines and motion of the waves are apparent in the successive images shown one below the other. Red arrows indicate the direction of the propagation of the waves. Horizontal wavelengths of the GWs are determined by applying 2D FFT to the observed airglow images. The periods of the GWs are estimated by applying 1D FFT in time to the complex 2D FFT in space. Direction of propagation and phase speed of GWs are identified using successive images. More details of the methodology for estimating the GW parameters from NAI observations are provided in Taori et al. (2013). Table 1 summarizes the GW parameters extracted for the five wave events (G1 to G5) mentioned above. In general, the waves corresponding to these events are moving north, north-west

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$$\omega_{ir}^2 = \frac{N^2(k^2+l^2)+f^2(m^2+\alpha^2)}{k^2+l^2+m^2+\alpha^2} \qquad (1)$$

where ω$_{ir}$ is the intrinsic frequency of the wave, N is the Brunt- Väiäsälä frequency, *f* is the coriolis frequency and m is the vertical wave number, Zonal, meridional and vertical wavelengths can be derived from the parameters given in Table 1 Preusse et al.(2008) reported that around 60% of the waves which are launched around 20 km with horizontal wavelength greater than 20 km and high phase speed can reach MLT altitudes and we try to explore our findings related to this. The background atmosphere used for ray tracing is developed using 30 years of observations from various sources and will be discussed more in section 4.

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2.2. Daytime GW observations at Hyderabad obtained through optical emissions

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A multi-wavelength imaging echelle spectrograph (MISE) is used to obtain daytime emission intensities of oxygen emissions at 557.7 nm, 630.0 nm and 777.4 nm in the MLT region at Hyderabad. MISE obtains high resolution spectra of daytime skies which are compared with the reference solar spectrum. The difference obtained between the two yields information on the airglow emissions. The details of the emission extraction process and calibration procedures of the emission intensities and the salient results obtained in terms of wave coupling of atmospheric regions demonstrating the capability of this technique have been described elsewhere (Pallamraju et al., 2013; Laskar et al., 2013). In the present experiment, the slit oriented along the magnetic meridian enabled information on the meridional scale size of waves (λ_y) at O(^{1}S) emission altitude of ~ 100 km (in the daytime). An ultraviolet imaging spectrograph (UVIS) with

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its slit oriented in the east-west direction was flown on a high-altitude balloon (on 8 March 2010) which provided information on the zonal scale sizes of waves (λ_x) using the OI 297.2 nm emissions that originate at ~ 120 km. Both MISE and UVIS are slit spectrographs with array detectors providing 2-D information with one direction yielding high spectral resolution spectrum (0.012 nm @ 589.3 nm; and 0.2 nm @ 297.2 nm for MISE and UVIS), and the orthogonal direction yielding information on the dynamics over 330 km (in the y-direction for OI 557.7 nm emission) and 170 km (in the x-direction for the OI 297.2 nm emission). The spatial resolutions of these measurements are around 50 km and 11 km, respectively. The details of the experiment and the wave characteristics in terms of λ_x, λ_y, λ_H (horizontal scale sizes), time periods (τ), propagation speeds (c_H) and propagation direction (θ_H) obtained by this instrument at a representative altitude of 100 km are described in detail in Pallamraju et al. (2014). Nine events from this experiment occurred on 8 March 2010 are considered in the present study for investigating their source regions and are marked as H1 to H9 in Table 1. All the observed wave events at Gadanki and Hyderabad whose parameters are given in Table 1 correspond to high frequency high phase speed gravity waves as seen from their large vertical wavelengths, small periods and high phase speeds (Table 1).

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2.3. Outgoing Long-wave Radiation (OLR) and Brightness Temperature in the Infrared band (IR BT)

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Satellite data of OLR / IR BT are used as proxy for tropical deep convection. In general, the daily NOAA interpolated OLR can be used to obtain information on synoptic scale convection. However, for local convection on smaller spatial and temporal scales, the IR BT data merged from all available geostationary satellites (GOES-8/10, METEOSAT-7/5 GMS) are obtained from Climate Prediction Center, National Centre for Environment Prediction (NCEP) (source: ffp://disc2.nascom.nasa.gov/data/s4pa/TRMM_ANCILLARY/MERG/). The merged IR BT with a pixel resolution of 4 km is available from 60^{o}N to 60^{o}S (geo-stationary). The data in the East-west begins from 0.082^{o} E with grid increment of 0.03637^{o} of longitude and that in the North-South from 59.982^{o} N with grid increment of 0.03638^{o} of latitude (Janowiak et al., 2001). The BT dataset is retrieved for every half an hour interval over regions of ±5° around Gadanki and Hyderabad on 17 March 2012 and 8 March 2010, respectively, to see whether any convective sources were present over these locations. Since the waves under study are high frequency waves propagating at high phase speeds with smaller horizontal wavelengths, a maximum of 5^{o}X5^{o} grid is considered to be adequate. In general, the regions with OLR < 240 W/m^2 is treated as convective areas.

3. Reverse ray tracing method

We followed basically the treatment of ray tracing given by Marks and Eckermann (1995). Note that the ray tracing theory is applicable only when WKB approximation is valid. When the WKB parameter δ given by

$$\delta = \frac{1}{m^2}\left|\frac{\partial m}{\partial z}\right| \approx \left|\frac{1}{C_{gz} m^2}\frac{dm}{dt}\right| \qquad (2)$$

where C_{gz} is the vertical group velocity, m is the vertical wave number, t is the time and z is the altitude, is less than unity, the approximation is taken to be valid.

In order to calculate the wave amplitude we used the wave action equation of the form

$$\frac{\partial A}{\partial t} + \nabla.(C_g A) = -\frac{2A}{\tau} \qquad (3)$$

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where $A = E/\omega_{ir}$ represents the wave action density, C_g represents the group velocity vector and $E = \frac{\rho_0}{2}[\overline{u'^2} + \overline{v'^2} + \overline{w'^2} + N^2\overline{\zeta'^2}]$ represents the wave energy density being the sum of kinetic and potential energy components, as described by wave perturbations in zonal, meridional and vertical velocities (u', v', w'), and vertical displacement (ζ'). Here ρ_0 is the background density and τ is the damping time scale (Marks and Eckermann, 1995). Using the peak horizontal velocity amplitude along the horizontal wave vector we can calculate the wave action density using the equation:

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$$A = \frac{1}{4}\frac{\rho_0 |\hat{u}_{\backslash\backslash}|^2}{\omega_{ir}}\{1 + \frac{f^2}{\omega_{ir}^2} + \frac{N^2 + \omega_{ir}^2}{N^2 - \omega_{ir}^2}(1 - \frac{f^2}{\omega_{ir}^2})\} \qquad (4)$$

In order to avoid spatial integration in the wave action equation we can write Equation (3) in terms of the vertical flux of wave action $F = C_{gz}A$, where F is the vertical flux of wave action and C_{gz} is vertical component of the group velocity. Assuming negligible contribution from the higher order terms, the Equation (4) can be written as:

$$\frac{dF}{dt} = -\frac{2}{\tau}F \qquad (5)$$

As the wave moves through the atmosphere, amplitude damping takes place which is mainly due to eddy diffusion and infrared radiative cooling by CO_2 and O_3. At higher altitudes (above about 100 km) molecular diffusion becomes important as compared to the eddy diffusion. We can calculate the damping rate due to diffusion using:

$$\tau_D^{-1} = D(k^2 + l^2 + m^2 + \alpha^2) \qquad (6)$$

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Where, $D = D_{Eddy} + D_{molecular}$, represents the sum of eddy and molecular diffusivities. In order to calculate the infrared radiative damping we used Zhu (1993) damping rate calculation method from 20-100 km. The total damping rate is calculated using the following equation:

$$\tau^{-1} = \frac{\tau_r^{-1}\left(\frac{1-f^2/\omega_{ir}^2}{1-\omega_{ir}^2/N^2}\right) + \tau_D^{-1}\left(1+\frac{f^2}{\omega_{ir}^2} + \frac{1-f^2/\omega_{ir}^2}{N^2/\omega_{ir}^2-1} + \mathrm{Pr}^{-1}\frac{1-f^2/\omega_{ir}^2}{1-\omega_{ir}^2/N^2}\right)}{\left\{1+\frac{f^2}{\omega_{ir}^2} + \frac{N^2+\omega_{ir}^2}{N^2-\omega_{ir}^2}\left(1-\frac{f^2}{\omega_{ir}^2}\right)\right\}} \qquad (7)$$

Where Pr is prandtl number. Note that for high frequency waves diffusion damping effect will be less.

4. Background atmosphere

In order to carryout reverse ray-tracing, information on background atmospheric parameters (U, V and T) is required right from the initial point (mesosphere) to the termination point (usually the troposphere). In general, there is no single instrument which can probe the troposphere, stratosphere, and mesosphere simultaneously. Note that in order to trace the ray we require atmospheric parameters for a specified latitude-longitude grid. Since the observed wave events belong to high frequencies (GWs with short horizontal wavelengths), we require the background information at least for grid sizes of 5° x 5° around Gadanki and Hyderabad. For the information on temperature and density at the required grids, we used Extended Mass Spectrometer and Incoherent Scatter Empirical Model (MSISE-90) data (Hedin, 1991) from surface to 100 km with an altitude resolution of 0.1 km for 0.1°x0.1° grid around these locations. Note that the MSISE-90 model is an empirical model which provides temperature and density data from the surface to the thermosphere. For horizontal winds at required grids, we used the outputs from the Horizontal Wind Model (HWM-07) (Drob et al., 2008) data. This model has

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been developed by using a total of 60 x 10^6 observations available from 35 different instruments spanning 50 years. Further, long-term data available from a variety of instruments (MST radar, MF radar, Rocketsonde, radiosonde, HRDI /UARS and SABER/TIMED satellites) in-and-around (±5°) Gadanki have been used to develop a background climatological model profiles of U, V, and T on monthly basis. Details of the data used to develop the background temperature and horizontal winds are provided in Table 2. Monthly mean contours of temperature, zonal and meridional winds obtained from the climatological model (hereafter referred to as the Gadanki model) are shown in Figure 2. In general, major features of the background atmospheric structure for a typical tropical region can be noticed from this figure. Tropopause, stratopause, and mesopause altitudes are located at around 16-18 km, 48-52 km, and 98-100 km with temperatures 190-200 K, 260-270 K and 160-170 K, respectively. Mesospheric semi-annual oscillation around 80-85 km is also seen (Figure 2a). Tropical easterly jet at around 16 km during the Indian Summer Monsoon season (June-July-August) and semi-annual oscillation near the stratopause (and at 80 km with different phase) are also clearly visible in the zonal winds (Figure 2b). Meridional winds do not exhibit any significant seasonal variation in the troposphere and stratosphere but show large variability in the mesosphere (Figure 2c). These overall features in the background temperature and wind match well with those reported considering data from different instruments by Kishore Kumar et al., (2008a,b).

The profiles of T obtained from MSISE-90 model and U and V from HWM-07 for 17 March 2012 are shown in Figure 3(a)-(c), respectively. The Gadanki model mean temperature profile for the month of March and the temperature profile obtained from TIMED/SABER and mean temperature obtained from ERA-Interim for the month of March 2012 are also superimposed in Figure 3a for comparison. A very good agreement between the profiles can be

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noticed. The profiles of U and V obtained from the Gadanki model for the month of March and also monthly mean of the ERA-Interim are also superimposed in Figure 3b and 3c, respectively. In general, a good match is seen between the Gadanki model and ERA-Interim and HWM-07 models up to the altitudes of stratopause. The differences between the two above the stratopause could be due to tidal winds which have large amplitudes at mesospheric altitudes. Though tidal amplitudes are already included in the HWM-07 model, their day-to-day variability may be contributing to these differences. In order to avoid any bias due to day-to-day variability of the tides at mesospheric altitudes, we have considered tidal amplitudes of 5 K, 10 K, 15 K and 10 m/s, 20 m/s, 30 m/s in temperature and winds, respectively, at 97 km to represent day-to-day variability.

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In general, troposphere is a highly dynamic region though the amplitudes of tides are considerably low. In order to consider more realistic horizontal winds in the troposphere and stratosphere, we further considered the ERA-Interim products (Dee et al., 2011). This data is available at 6 h intervals with 1.5^0 x 1.5^0 grid resolution at 37 pressure levels covering from surface (1000 hpa) to the stratopause (~1 hPa). The profiles of T, U and V from ERA-Interim for 17 March 2012 for 12 UTC are also superimposed in Figures 3(a), 3(b) and 3(c), respectively. In general, good agreement between the other models and ERA-Interim model can be noticed particularly in V in the lower and upper levels except between 10 and 20 km. Summarizing, we have considered the following wind models: (1) ERA-Interim (from surface to 40 km) and HWM 07 models from 40-100 km, (2) Gadanki model, (3) zero wind (U=0 and V=0). Using these background atmosphere profiles, we calculated the relevant atmospheric parameters like N^2 and H. Profiles of T, U, and V obtained using ERA-interim data products for 8 March 2010, 6 UTC over Hyderabad region are shown in Figures 3(c)-(f), respectively. T, U, and V profiles as

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obtained from MSISE-90 and from HWM-07 for the same day are also provided in the respective panels. The background atmosphere information for wave events over Hyderabad is obtained in a manner similar to that mentioned above for Gadanki.

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In order to calculate diffusive damping we used eddy diffusivity profiles for troposphere and lower stratosphere and mesosphere which are obtained using MST Radar (Narayana Rao et al., 2001) at Gadanki as shown in Figure 4a. In the altitude regions where there are data gaps, we extrapolated/interpolated the diffusivity profiles and the approximated profile with different analytical exponential functions is also shown in Figure 4a. The eddy diffusivity profile of Hocking's (Hocking, 1991) that is presented in Marks and Eckermann (1995) is also superimposed for comparison. Note that Hocking's profile corresponds mainly to mid latitudes. In general, eddy diffusivity is relatively higher in Hocking's profile than in the Gadanki profile. This same (Gadanki) profile is used for Hyderabad events also. In Figure 4b molecular diffusivity is shown. It is seen that the molecular diffusivity exceeds the eddy diffusivity at altitudes > 80 km. We have taken into account molecular diffusivity also in the ray tracing calculation while considering the total diffusivity above 80 km and the total diffusivity profile is shown in Figure 4b. Radiative and diffusive damping rates corresponding to Event G1 observed over Gadanki are shown in Figure 4c for illustration. It is seen that radiative damping rate is higher than the diffusive damping rate below 95 km. This is so for the other 13 events (G2-G5 and H1-H9) as well.

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5. Application of reverse ray tracing for the wave events

By using the background parameters and the ray tracing equations, we trace back the ray path(s) to identify the GW source region(s). We used Runge-Kutta fourth order method for numerical integration at the time step of $\delta t = 100\ \mathrm{m}/C_{gz}$ where 100 m is the height step

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downwards from 97 km (the peak altitude of the airglow layer) and C_{gz} is the vertical group velocity. As the ray tracing treatment is valid only when WKB approximation holds good, the ray integration is terminated whenever the WKB approximation is violated. We terminated the ray when 1) m^2 becomes negative, which means that the wave cannot propagate vertically, 2) intrinsic frequency < 0 or approaching zero, which mean that the wave reached a critical layer and is likely to break beyond this 3) WKB parameter approaching values greater than one (beyond which WKB approximation breaks) and 4) vertical wave number becoming greater than 1 x10^{-6} (approaching critical level) (Wrasse et al., 2006). Background wind in the direction of wave propagation is checked with the horizontal phase speed of the wave and the ray integration is terminated whenever it approaches the critical level. We calculated the wave action and thus the amplitude along the ray path by including the damping mechanisms. As information on wave amplitudes can not be unambiguously determined from the optical emission intensity measurements, we assumed the GW amplitude as unity (at 97 km) and traced back the relative amplitudes along the ray path. Further, as we have not considered the local time variation of the background parameters, the ground-based wave frequency will be a constant. However, note that the intrinsic frequency still varies with altitude because of the varying background horizontal winds.

The observed and calculated GW parameters (intrinsic frequency, wave period, zonal, meridional, and vertical wave numbers) for all the wave events measured at the peak airglow emission altitudes as described in Sections 2.1 and 2.2 are given as initial parameters to the ray tracing code. We considered all the different combinations of observed wave parameters including the errors in the observations for obtaining the ray paths and the uncertainties in them. Note that atmospheric tides have large amplitudes in the MLT region which, at times, can be

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comparable sometimes to those of the background wind. As mentioned earlier, though tidal amplitudes are considered in the HWM-07 model, their day-to-day variability is not taken into account in the model. Amplitudes of the tides may reach values as high as 20 m/s over equatorial latitudes (Tsuda et al., 1999). As already mentioned we have included day to day variability of tidal amplitudes into temperature and winds. In general, above the stratopause, tidal amplitudes are large and increase exponentially with altitude. It is interesting to note that (figure not shown) the variabilities in the background atmospheric parameters developed using data from a suite of instruments as mentioned above lies within the variability due to tides. Ray path calculations are also carried out for these background profiles.

We traced the ray path using the above initial parameters from the initial latitude (13.5^{o}N/17.5^{o}N) and longitude (79.2^{o}E/78.5^{o}E) and altitude (97 km). The ray paths for the wave events G1 with the longitude-altitude, latitude-altitude and longitude-latitude are shown in Figures 5(a)-(c), respectively, for Gadanki and in Figures 5 (d)-(f) for (H1) Hyderabad. Ray paths obtained while considering different background conditions (normal wind, zero wind and Gadanki model wind) and the day-to-day variability of tides are also superimposed with dotted lines. When we considered zero (Gadanki) wind, a shift of 71 km (25 km) in the horizontal position of the terminal point is observed with respect to that for normal wind for wave event G1. The shift reduced to 19 km and increased to 47 km and 97 km when we considered the tidal variability of +5K, +10 m/s and +10 K, +20 m/s, +15 K, +30 m/s, respectively, with respect to the normal wind. The shift is ~15 km for the tidal variability of -5 K, -10 m/s. The ray terminated in the mesosphere itself for tidal variability of -10 K, -20 m/s and -15 K, -30 m/s (figure not shown).

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Over Hyderabad, for the wave event H1, shown in Figures 5(d)-(f), the shifts in the horizontal location of the terminal point are 305.6 km (148.7 km) for tidal variability of +10, +20 m/s (-10 K, -20 m/s), respectively, with reference to zero wind. This difference is only 59.5 km for tidal variability of -10 K, -20 m/s with respect to the normal wind. The terminal point locations for the rest of the wave events for normal winds are listed in Table 1. Note that out of the five wave events over Gadanki two wave events (G3 and G4) got terminated in the upper mesosphere itself and one (G5) got terminated at 67 km. Over Hyderabad, out of the nine wave events, two wave events (H4 and H7) got terminated at ~ 67 km. In general, all the wave events which propagated down to the upper troposphere terminated between 10 and 14.5 km, except the case G2 which got terminated at 17 km due violation of the WKB approximation. The violation of the WKB approximation at 17 km could be due to sharp temperature gradients near tropopause.

Profiles of square of vertical wave number (m^2), intrinsic frequency (ω_{ir}) and Brunt Väiäsälä frequency (N), horizontal wavelength (λ_h), zonal, meridional, and vertical group speed for the event G1 are shown in Figures 6(a)-(f), respectively. Profiles of these parameters obtained for different background wind conditions (normal wind, zero wind, and Gadanki model wind) and for the day-to-day variability of tides are also superimposed in the respective panels. The differences with and without the variability of tides in the above mentioned parameters are small below the stratopause, and are quite high above. Note that the effect of Doppler shifting of the wave frequency is larger at higher altitudes due to higher wind amplitudes. Around 13 km, Brunt Väisälä frequency is less than that of the intrinsic frequency and so the square of the vertical wave number is negative there (Figure 6b). There is not much variation in the horizontal wavelength with height (Figure 6c). Zonal group speed shows (Figure 6d) nearly the same

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behaviour as that of the zonal wind. The intrinsic frequency, $\omega_{ir,}$ exceeded N at 13 km altitude and due to this m^2 became negative and the ray path got terminated there. The observation time at the ray-start and according times along the ray time shown in Figure 6(a) reveals that it has taken 63 minutes.

As mentioned earlier, the information on the wave amplitudes is not available from the observations. So we used the GW amplitude as unity (at the altitude of observation) and traced back the relative amplitudes along the ray path. Profiles of amplitudes of GWs observed for the wave events G1 and H1 over Gadanki and Hyderabad are shown in Figures 7(a) and 7(b), respectively. Amplitudes with three different background wind conditions along with different tidal amplitudes are also shown in the respective panels. A unit wave amplitude at the observed region, translates to an amplitude of 10^{-3} near the source region. Amplitude growth is found higher when either Gadanki or zero wind models are considered and slightly lower for the normal wind. The growth is highly reduced when tidal variability in the background wind is considered. However, higher amplitude growth rates are obtained over Hyderabad when we considered normal wind along with tidal variability than zero wind. Similar growth rates are also obtained for other wave events (not shown). Thus, background winds play an important role in the growth rates of GWs.

6. Discussion on potential source(s) for the GW events

The geographical locations of the terminal points for different combinations of background winds along with different combinations of tidal variability are shown in Figures 8 and 9 for Gadanki and Hyderabad wave events, respectively. In this figure, the contour encircling all the points (not drawn in the panels of the figure) represents the horizontal spread of uncertainty due to background conditions (including tidal variability). Terminal point of the ray

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(in the troposphere) is expected to be the location of GW source. Since 9 out of 14 wave events got terminated between 10 and 17 km, we search for the possible sources around this altitude at the location. In general, major sources for the GW generation over tropics are orography, convection, and vertical shear in the horizontal winds. In the present case, GWs are unlikely to be orographic origin as the observed waves have phase speeds much greater than zero. Tropical deep convection is assumed to be a major source for the generation of wide spectrum of GWs in the tropical latitudes. As mentioned earlier, OLR/IR BT is assumed to be proxy for the tropical deep convection. Lower the OLR/BT values, higher the cloud top and hence the deeper the convection. OLR (IRBT) < 240 W/m^2 (K) is taken to represent deep convection. However, convection may exist at locations away from the observational site and waves generated at those locations can propagate to the mesospheric altitudes over the site. In order to see the presence or otherwise of convection in the vicinity of the termination location, latitude-longitude cross section of NOAA interpolated OLR obtained for 17 March 2012 (8 March 2010) is shown in Figure 8a (Figure 9a) for Gadanki (Hyderabad) region. The terminal points of the rays for the wave events G1 and G2 (H1-H9 except H4 and H7) with different background wind conditions and different combinations of variability of the tides are also shown in the figure. As expected, no convection in-and-around Gadanki (Hyderabad) region can be noticed in this figure. Note that this plot is with a coarse grid (2.5^o x 2.5^o latitude-longitude) averaged for a day. The observed GWs could be generated due to localized sources having shorter temporal and spatial scales than those seen from the NOAA OLR data used. In order to examine this, we have used IR BT data which is available at 4 km x 4 km grid size and at half an hour basis. Latitude and longitude section of hourly IR BT at 14 UTC (10 UTC), 15 UTC and 16 UTC is shown in Figures 8(b)-(d) (Figure 9b), respectively. The terminal points with and without variability of the tides are also

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shown. Interestingly no cloud patches are seen at any of the times mentioned above. Thus, convection as a possible source for the observed wave events can be ruled out.

The other possible source for GW generation is the vertical shear in the horizontal wind. The vertical shear in horizontal winds at an altitude of 10 km (8 km) on 17 March 2012 (8 March 2010) as a function of latitude-longitude is shown in Figure 10a (Figure 10b). The terminal points of the rays for both the wave events with and without the day-to-day variability of the tides are also shown in the figure. Interestingly, at all the terminal points (in the troposphere), strong vertical shear in the horizontal wind which is quite high (8-9 m/s/km) is seen. In order to see whether these waves could be generated due to non-linear interaction (through Kelvin Helmholtz Instability, KHI), the Richardson number ($Ri = \frac{N^2}{(dU/dz)^2}$) for this location is calculated (using nearby radiosonde data) and is shown in Figure 11. From figure it can be noticed that Ri is < 0.25 showing that Ri satisfies the condition for instability for the observed waves at both the stations. Thus, the shear is unstable and hence conducive for the excitation of KHI leading to the generation of the propagating GWs through non-linear interaction. Note that shear excitation of the GWs has been examined theoretically using both linear and non-linear approaches (e.g., Fritts, 1982; 1984; McIntyre, 1978). For the excitation of radiating GWs by KH instabilities at a shear layer, the two mechanisms that are examined are the vortex pairing (sub-harmonic interaction) and envelope radiation (Fritts, 1984). The vortex pairing is found to be highly dependent on the minimum Ri, whereas, the envelope radiation mechanism is found to provide efficient radiating wave excitation in the absence of propagating unstable modes (Fritts, 1984). Theoretical and numerical simulation work needs to be carried out to examine which of these mechanisms is effective for the observed events in the present study. This aspect is beyond the scope of the present study and is planned to be taken up in the future.

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Note that five wave events terminated at mesospheric altitudes. We examined the background atmospheric condition which can lead to the termination for these wave events at such high altitudes. The ray paths for two wave events observed on the same day over Gadanki could propagate down below with the same background atmosphere. When wave parameters related to this event are examined (Table 1) it can be seen that the phase speeds are small when compared to the other two wave events. When the wave is introduced at around 15 km with all the wave parameters similar to that observed at 97 km for this event and forward ray tracing is carried out, it is seen that the ray propagated up to 50 km terminating there. Note that strong vertical shear in the background wind is seen at this altitude (Fig. 3). To investigate the role of shear in the process of propagation of waves, the shear is reduced to almost 0 in the 50 – 80 km altitude region. Under such conditions this wave event also could propagate to ~16 km (in the reverse ray tracing). This reveals that the background wind shear is obstructing the ray path. It is quite likely that the wave got ducted between 50 and 80 km and similar results are obtained for the other cases which got terminated in the mesosphere. This indicates that wind shears at mesospheric altitudes are responsible for termination at mesospheric altitudes for these events.

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7. Summary and conclusions

Identification of the GW sources for the 14 wave events observed over Gadanki and Hyderabad using optical airglow measurements is presented. Reverse ray tracing method is developed to obtain the location of the source regions of the GWs in the troposphere/mesosphere. We made use of the MSISE-90 model for temperature and the HWM-07 for the zonal and meridional winds in addition to the ERA-Interim products in the lower atmosphere (1000 hPa to 1 hPa pressure levels), Gadanki climatological model, and zero wind model for the background atmosphere. We have incorporated also the expected variability of tidal amplitudes of 5 K, 10 K, 15 K and 10 m/s, 20 m/s, 30 m/s in temperature and winds, respectively. The terminal points lie in the range of 50-100 km and 60-300 km for Gadanki and Hyderabad, respectively when different wind and tidal variabilities are used. Wave action is successfully implemented taking into account the radiative and diffusive damping. Considering the wave amplitude as unity at 97 km, amplitude of the wave is traced back to the source region for different wind models. Out of the 14 events examined, 9 ray paths terminated in the troposphere. The remaining 5 events got terminated in the mesosphere itself. We examined for possible sources for the 9 events for which the ray paths terminated in the troposphere.

Orography as the possible source was ruled out as wave events have high phase speeds. No tropical deep convection in-and-around Gadanki and Hyderabad was noticed near the ray terminal points. Interestingly, strong vertical shear in the horizontal wind is observed near the terminal points and these large shears are attributed to be the source for the GW events observed at the mesospheric altitudes. Preusse et al., (2008) discussed the transparency of the waves to the atmosphere in different seasons. They reported that during equinox times atmosphere is more transparent to the high phase speed and shorter horizontal wavelength waves than that in the solstices. Waves with shorter (<10 km) hhorizontal wavelengths tend to be removed by vertical reflection or evanescence at the source and slower phase speeds are more prone to critical level removal. This leads to a preference for waves with longer horizontal wavelengths and faster ground-based phase speeds to reach the MLT. However, they observed that many rays penetrated to the MLT at the tropical latitude where wind speed is low in comparison to the mid and high latitudes. In our case, whenever phase speed is low for short horizontal wavelength waves, ray didn’t reach up to the troposphere and it got stopped at mesospheric altitude itself. While there is strong evidence for convectively generated gravity waves, evidence for tropospheric wind shear

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generated GWs is rather sparse (Mastrantonio 1976; Fritts and Alexander 2003). The present study clearly demonstrated that high frequency high phase speed GWs observed in the mesosphere can be generated by tropospheric wind shear. Examination of the background wind conditions and wave parameters for the events that got terminated in the mesosphere revealed that the phase speeds were quite low for these strong vertical shears in the 50-80 km region (and at 95 km) resulted in the termination of the ray paths. It is likely that the waves generated in the troposphere are ducted between 50-80 km and the waves observed above this region are due to leakage of waves from the duct. It is also likely that the observed GWs in these cases (G3,G4,G5,H5 and H7) are from secondary wave generation due to wave breaking at the termination region. While secondary wave generation due to convectively generated waves has been investigated (e.g. Zhou et al., 2002; Chun and Kim 2008) such investigations have not yet been carried out for GWs of shear origin. This aspect needs further investigation. Note that we have tested reverse ray tracing method successfully for fourteen wave events. Further, wave action is also implemented successfully by assuming the wave amplitudes as unity as information on the same is not available from optical observations. However, more number of cases are needed to be examined, particularly for the events that occur during Indian Summer Monsoon season where convection and strong vertical shears in the horizontal winds co-exist due to prevailing tropical easterly jet (Venkat Ratnam et al., 2008). A few experiments are planned to be conducted at Gadanki by operating simultaneously MST radar, Radiosonde, Rayleigh Lidar, Airglow imager and Meteor radar which provides information right from the troposphere to the MLT region. Note that such a study on the vertical propagation of meso-scale gravity wave from lower to upper atmosphere was made recently by Shin Suzuki et al. (2013) using Airglow Imager and Lidar over Arctic region.

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Acknowledgements: This work is done as a part of SAFAR and CAWSES India phase II programs. We thank NARL staff for providing data used in the present study. We deeply appreciate NOAA, HWM-07, ERA-Interim for providing data used in the present study through their ftp sites. This work is supported by Department of Space, Government of India.

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Figure 1. Identification of three wave events (left to right) obtained from the airglow emission intensities originating from O(^{1}S) emissions from Gadanki. The wave crests are emphasized by yellow freehand lines. Motion of waves can be obtained by successive images and the direction of propagation is shown by red arrows. Time of occurrence of events is shown in each image in UT (hh:mm).

Figure 2. Climatological monthly mean contours of (a) temperature, (b) zonal wind and (c) meridional wind obtained over Gadanki region combining a variety of instruments listed in Table 2.

Figure 3. Profiles of (a) temperature (b) zonal wind and (c) meridional wind obtained using ERA-interim data products for 17 March 2012, 12 UTC over Gadanki region. Profiles obtained from variety of sources over Gadanki (Gadanki model) listed in Table 2 are also superimposed in the respective panels for comparison. Plots (d)-(e) are same as (a)-(c) but obtained for Hyderabad on 8 March 2010. Temperature profile obtained from MSISE-90 and zonal and meridional winds obtained from HWM 07 for the same day are also provided in the respective panels.

Figure 4. (a) Profile of eddy diffusitvity (thick red line) obtained from Gadanki MST radar (Rao et al., 2001) in the tropopshere, lower stratopshere and mesopshere. Fitted profile (dotted line) with exponetial function is also shown. Hocking's (Hocking 1991) analytical curve (extrapolated) is also superimposed for comparsion. (b) Profiles of eddy, molecualr, and total diffusivity. (c) radiative, and diffusive damping rates.

Figure 5. Ray paths for the wave event G1 (started at 97 km) in the (a) Longitude-Altitude, (b) Latitude-Altitude, and (c) Longitude-Latitude cross sections. Ray paths obtained while

considering different background wind conditions (normal wind, zero wind and Gadanki model wind) and the day-to-day variability of tides are also superimposed (dotted lines). (d)-(f) same as (a)-(c) but for the wave event H1. Note that Gadanki atmospheric model wind is not used for the wave events over Hyderabad.

Figure 6. Profiles of (a) square of vertical wave number (m^2), (b) intrinsic frequency (ω_{ir}) and Brunt Väisälä frequency (N) (green), (c) horizontal wavelength (d) zonal, (e) meridional, and (f) vertical group velocities for the wave event G1. Profiles of the same obtained while considering the three different background winds (different colored lines) and the day-to-day variability of tides are also superimposed (dotted lines) in the respective panels. The observation time at the ray-start and according times along the ray time is also shown in (a) with axis on the top.

Figure 7. Normalised amplitudes of gravity waves observed for the wave events (a) G1, and (b) H1, over Gadanki and Hyderabad, respectively. Amplitudes with three different background wind conditions along with different tidal amplitudes are also shown.

Figure 8. Daily mean latitude-longitude section of (a) OLR observed using NOAA products over Indian region on 17 March 2012. (b)-(d) same as (a) but for IRBT observed at 14 UTC, 15 UTC, and 20 UTC, respectively. Open (closed) circles in (a) (b-d) depict the terminal points of the ray paths shown in Figure 4.

Figure 9. Same as Figure 8 but for wave events observed over Hyderabad on 8 March 2010. Note that IRBT is shown only for 10 UTC.

Figure 10. Latitude-longitude section of vertical shear in the horizontal wind observed using ERA-Interim data products on (a) 17 March 2012 at 10 km, (b) 8 March 2010 at 8 km. Filled

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circles depicts the terminal points of the ray paths estimated using three different wind conditions and tidal amplitudes.

Figure 11. Profiles of Richardson number calculated close to the termination point using radiosonde data for (a) Gadanki and (b) Hyderabad locations.

Table captions:

Table 1. GW characteristics (direction of propagation (φ), horizontal wavelength (λ_h), period (T), phase speed (C) and intrinsic frequency (ω_{ir})) for events observed over Gadanki (G) and Hyderabad (H). The terminal point locations (latitude, longitude and altitude) are also shown for each event. Conditions leading to the termination for each wave event are also shown. Events for which ray paths terminated at mesospheric altitude are indicated with an asterisk.

Table 2. Details of instruments, parameters measured, altitude range in which data is available and the duration of the data considered for developing the Gadanki atmospheric model.

Tables:

Events	φ (degrees)	Λh (km)	T (min)	C (m/s)	Longitude (degrees)	Latitude (degrees)	Altitude (km)	ω_{ir} (rad/s)	Termination condition
				Gadanki location					
G1	102	85 (26)	18	78	79.9	10.8	13	0.00058	$m^2 < 0$
G2	98	34 (28.9)	9	63	79.4	12.3	17	0.0116	WKB > 1
G3	132	12 (13.6)	6	33	79.2	13.37	96.9*	0.0006	Intrinsic frequency approaching zero
G4	62	134 (40)	12	186	79.14	13.2	92.9*	0.0093	WKB >1
G5	142	16 (2)	8	33	79.9	12.7	66.9*	0.0156	WKB >1 and $m^2<0$
				Hyderabad location					
H1	11	39 (23.7)	16	41	70.2	15.8	10.5	0.0028	WKB >1
H2	16	57 (31.5)	16	59	75.3	16.4	13.5	0.0046	WKB >1
H3	21	74 (39)	16	77	75.9	16.3	14.5	0.0049	WKB >1
H4	11	39 (19.6)	20	32.5	76.3	17.1	67.6*	0.00083	m^2 > limiting condition and intrinsic frequency approaching zero
H5	16	57 (25)	20	48	72.7	15.7	12.5	0.0029	WKB >1
H6	21	74 (31)	20	61.7	74.7	15,8	13.5	0.0035	WKB >1
H7	11	39 (17.7)	23	28	75.8	16.9	68.5*	0.00087	m^2 > limiting condition and intrinsic frequency approaching zero
H8	16	57 (23)	23	41	68.3	14,8	11.5	0.0022	WKB >1
H9	21	74 (27)	23	54	73.4	15.4	13.5	0.0032	WKB >1

Table 1. GW characteristics (direction of propagation (φ), horizontal wavelength (λ_h) (vertical wavelength (λ_z)), period (T), phase speed (C) and intrinsic frequency (ω_{ir})) for events observed over Gadanki (G) and Hyderabad (H). The terminal point locations (latitude, longitude and altitude) are also shown for each event. Conditions leading to the termination for each wave event are also shown. Events for which ray paths terminated at mesospheric altitude are indicated with an asterisk.

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Instrument (parameter(s) obtained)	**Altitude range covered**	**Duration of the data considered**
Indian MST radar (U,V)	4-21 km and 65-85 km	1996-2012
Radiosonde (U, V, T)	1-30 km	2006- 2012
Lidar (T)	30-75 km	1998- 2012
Rocket (U, V, T)	22-80 km	1970-1991, 2002-2007
HALOE, HRDI / UARS (T, U, V)	65-110 km	1991- 2000
SABER/TIMED (T)	30-110 km	2002-2012

Table 2. Details of instruments, parameters measured, altitude range in which data is available and the duration of the data considered for developing the Gadanki atmospheric model.

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The reverse ray tracing method (Lighthill, 1978; LeBlond and Mysak, 1978; Schoeberl, 1985), which is widely used to trace back to the GW sources is utilized in the present study. For ray tracing description to be valid for $\psi = \psi_0 e^{i\theta}$ (where ψ is the amplitude and θ is the phase) the phase has to vary rapidly when compared to the amplitude and the phase changes by 2π when it moves through one wavelength (Landau and Lifshitz, 1962). In an inhomogeneous anisotropic atmosphere, $\omega = \omega(\vec{k}, \vec{x})$, where ω, $\vec{k}$, $\vec{x}$ are frequency, wave number vector and position vector, respectively. Using ray tracing theory, the equations describing the ray path and refraction of the wave vector along the ray are given by:

$$\frac{dx}{dt} = \frac{\partial \omega}{\partial k} = c_g(k) \qquad (1)$$

$$\frac{dk}{dt} = -\frac{\partial \omega}{\partial x} \qquad (2)$$

The ray tracing equations for GW are derived (Jones, 1969; Eckermann, 1992; Marks and Eckermann, 1995; Vadas, 2009) using the dispersion relation:

$$\omega_{ir}{}^2 = \frac{N^2(k^2 + l^2) + f^2(m^2 + \alpha^2)}{k^2 + l^2 + m^2 + \alpha^2} \qquad (3)$$

where $\omega_{ir} = \omega - kU - lV$ is the intrinsic frequency (frequency relative to the mean wind), U and V are the zonal and meridional winds and N is the Brunt-Väisälä frequency, k, l and m are the wave number vectors components in the zonal, meridional and vertical directions, respectively. $f = 2\Omega \sin\phi$ is the coriolis parameter $\alpha = 1/2H$ and H is the density scale height of the atmosphere. The ray tracing equations for gravity waves propagating through 3D space are given below:

$$\frac{dx}{dt} = U + \frac{k(N^2 - \omega_{ir}^2)}{\omega_{ir}\Delta} \qquad (4)$$

$$\frac{dy}{dt} = V + \frac{l(N^2 - \omega_{ir}^2)}{\omega_{ir}\Delta} \qquad (5)$$

$$\frac{dz}{dt} = -\frac{m(\omega_{ir}^2 - f^2)}{\omega_{ir}\Delta} \qquad (6)$$

$$\frac{dk}{dt} = -k\frac{\partial U}{\partial x} - l\frac{\partial V}{\partial x} - \frac{1}{2\omega_{ir}\Delta}[\frac{\partial N^2}{\partial x}(k^2 + l^2) - \frac{\partial \alpha^2}{\partial x}(\omega_{ir}^2 - f^2)] \qquad (7)$$

$$\frac{dl}{dt} = -k\frac{\partial U}{\partial y} - l\frac{\partial V}{\partial y} - \frac{1}{2\omega_{ir}\Delta}[\frac{\partial N^2}{\partial y}(k^2 + l^2) - \frac{\partial \alpha^2}{\partial y}(\omega_{ir}^2 - f^2)] - \frac{f}{\omega_{ir}\Delta}\frac{df}{dy}(m^2 + \alpha^2) \qquad (8)$$

$$\frac{dm}{dt} = -k\frac{\partial U}{\partial z} - l\frac{\partial V}{\partial z} - \frac{1}{2\omega_{ir}\Delta}[\frac{\partial N^2}{\partial z}(k^2 + l^2) - \frac{\partial \alpha^2}{\partial z}(\omega_{ir}^2 - f^2)] \qquad (9)$$

where, $\Delta = k^2 + l^2 + m^2 + \alpha^2$ and U and V are the zonal and meridional velocity.

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WKB approximation is valid whenever

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Events	φ (degrees)	Λh (km)	T (min)	C (m/s)	Λz (km)	Longitude (degrees)	Latitude (degrees)	Altitude (km)	ω_{ir} (rad/s)	Termination condition
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