Interactive comment on **"Response of OH airglow emissions to the mesospheric gravity waves and its comparisons with full wave model simulation at a low latitude Indian station"** ***by*** **R. N. Ghodpage et al.**

Response to the comments/suggestions made by Referee#2

Received and published: 11 January 2016 General Comments The paper presents an analysis of the experimental data obtained by the photometer in Kolhapur, (16.8 ◦N, 74.2 ◦ E), India, in order to detect variations in the characteristics of the hydroxyl radiation (intensity, temperature, time lag between them) at propagation of internal gravity waves (IGW) through the emission layer. It is not clear by what criteria, as the parameters characterizing the disturbance of characteristics of the observed emission of hydroxyl, the authors used Krassovsky's numbers η and Æ§. In the main conclusions of the article the authors present differences or coincidence of the obtained values of Krassovsky's numbers with the data of the numerical modelling executed for conditions of observation, and with the data, obtained in a number of others published works. Neither the analysis, nor discussion of the causes of revealed differences (coincidences) in this article is not presented. The article has no clear purpose and a problem on which solving the authors made efforts. The paper requires considerable revision before it can be published.

Response: We thank reviewer for the help rendered to us in improving the content of our manuscript. We have worked on the comments & suggestions made by the reviewer in the revised manuscript. Following are our point-by-point responses (bold fonts) to his/her comments (black fonts).Corrections made in the manuscript are reflected as bold letters.

Specific comments

1. There is no description of the organization of the hydroxyl emission monitoring - was the radiation observed at one point of the sky or at several points? To register IGWs using any emission (in this case - the hydroxyl emission) is required to satisfy the condition of observation necessary to identify them - simultaneous observations of variations in the intensity and temperature in the layer not less than in three sites of the sky.

Response: We have observed at one point of the sky over Kolhapur. Unless we need to get the vertical profile and propagation direction of observed gravity waves, observations at 3 sites are not

a require criteria. Kindly note that observations of gravity waves from a single locations with photometry are well documented and to get the kind of parameters we intend have been performed in the past as well (e.g., Takahashi et al., 2002; Reisin and Scheer, 2004; Lopez-Gonzalez et al. 2005).

2. There is no description of the methodology for determining the absolute values of the intensity of emission of hydroxyl, its variations, and accuracy. 3. There is no description of a technique of definition of the rotational temperature ofthe hydroxyl emission and accuracy of its definition. 4. There is no description of the analysis of statistical data providing satellite measurements, which are used together with ground-based measurements.

Response: In modified manuscript we have added description related to OH emission (in introduction section). As suggested we have now included the technique descriptions and statistical errors and significance at suitable places.

5. What criteria did the authors use, attributing observed variations in characteristics hydroxyl emissions as associated with IGW impact?

Response: In order to study the wave features present in the MLT region, we consider only those clear sky days having more than 5 hours of continuous data. After assuring that data is not contaminated by the passage of clouds, we have normalized data (mean intensity deviation / mean) for finding the wave feature in data. The long period wave estimates may be biased when the data length is comparable to that of the wave period and therefore in our study we have considered only those waves whose periods are substantially less than the length of the available data. Equation (2) is valid for the zenith observation and for plane waves and not valid for the evanescent waves. In this study, we have deduced the Krassovsky parameters and vertical wavelengths for the mesospheric OH band.

6. In Figures examples of variations of observed intensity and temperature in absolute values should be presented.

Response: In the absence of standard calibration source, we have used relative intensities in arbitrary units. Thus the derived temperatures are absolute while the intensity data is in relative units. In the Krassovsky analysis, we need the percentage amplitude variations instead the absolute values of intensity and temperature. Therefore, we have normalized data (mean intensity deviation / mean) for finding the wave amplitudes in data.

Response to the comments/suggestions made by Referee#1

[detailed] Review of Response of OH airglow emissions to the mesospheric gravity waves and its comparisons with full wave model simulation at a low latitude Indian station" by R. N. Ghodpage et al.by Ghodpage ,Hickey, Taori, Siingh, and Patil.

The paper presents the analysis of wave signatures present in OH airglow at Kolhapur in India, namely airglow brightness and (rotational) temperature, from a total of 105 nights of observation, in 2010 and 2011.The resulting values of Krassovsky's ratio scatter widely, but not considerably more than 10 previous literature reports, since the earliest analysis from Svalbard published 27 years ago until results from Hawaii published in 2008. Another comparison is done with respect to model results for long horizontal wavelengths published in the early 90s.However, since all this is shown in the same figure (but different figures for the different parameters), it is very hard to distinguish the symbols and follow the description in the text.The paper also reports on wave model simulations for the atmospheric background conditions corresponding to the observation site and time of year. These results based on the Hickey et al. model are expected to be comparable to the parameters observed (modulus and phase of Krassovsky's ratio), but it turns out to be successful only for a certain range of small model phase velocities. While the discussion in the text is well done, the corresponding figure suffers from the very wide scale chosen to accommodate some of the model results for short-period waves, and so isnot as instructive and easy to read as possible. No details are given about how rotational temperatures are determinedfrom the two spectral samples available from the airglow photometer, norany reference to other papers where this may have been described. Neither is there any mention about whether the intensities refer to the whole emission band (as required for meaningful and unbiased values of Krassovsky's ratio). There is a problem with figure 1 that I hope is only a scaling error. If the relative intensity and temperature amplitudes in Fig 1 are really plotted at the same scale (as the figure makes us believe), then they look too similar to explain eta values much different from the order of one. And indeed, the peak-to-peak distance of 12 mm I measure in Fig. 1aand 8.5 mm in 1b correspond to an eta of 1.4, but not 7 as the text claims, for the principal wave! For the residual wave, the situation does not look better, but it's harder to quantify from the -0.5 to +0.5 scale. The numerical result for the residual wave given in the text (3.7, see details on Line 165 (L165)) is however wrong (it is not even dimensionless but in relative intensity/kelvin).Figure 1 is also not a convincing example of the quality of the phase information (especially for the secondary wave) that can normally be obtained, and therefore casts doubt on the phases of eta obtained from the observations. For these reasons (some details are mentioned in the list below), I cannot recommend publication in the present form and think that a major revision (except for the excellent section 4) is needed. Details (mainly minor technical points but also some explanations of more serious stuff:

Response: Thanks for your suggestion. We have corrected it in our revised manuscript. Please check modified manuscript we have included description related to OH emission in our introduction section. We have normalized intensity data (mean intensity deviation / mean) and (mean temperature deviation / mean) for finding the wave feature in data.

L30: I do not understand what is gained by the words "In the present report", since there is no other topic in the abstract with which it could be confused.

Response: We have removed the text in abstract section.

L35: delete "the" before "propagating..." because it's generic (any gws!).

Response: We have deleted text as suggested on page number 4 (Line 57-58)

L37: "ambient" seems to stand for "mean flow", but that's not obvious for the general reader.

Response: Reviewer is correct. We have modified this word.

L40: Krassovsky (1972) did not include phase in his definition of eta. Better, replace "can be defined as" by "is now defined as".

Response: We have modified sentence as per reviewer suggestion on page number 4

L42: change "a phase" to "the phase difference".

Response: We have modified text as per reviewer suggestion on page number 4.

L68: Hickey et al. 1998 ref is missing. Do you mean Hickey, M.P., Taylor, M.J., Gardner, C.S., and Gibbons, C.R. (1998), Full-wave modeling of small-scale gravity waves using Airborne

Lidar and Observations of the Hawaiian Airglow (ALOHA-93) O(1S) images and coincident Na wind/temperature lidar measurements, J. Geophys. Res. 103, 6439-6453. -?

Response: Thanks for your suggestion. We included references as we miss it in our reference list.

L74: better, simplify -> "are made with the multispectral..."

Response: We have modified text as per reviewer suggestion on page number 6.

L75: I suggest change to read "We analyze the data from... to...".

Response: We have modified text as per reviewer suggestion on page number 6.

L76: delete "the availability of" to read "when clear sky conditions prevailed...".

Response: We have modified text as per reviewer suggestion on page number 6.

L77: "In particular" sounds as if only details follow, rather than new relevant info about the number of wave signatures found in 2010 and 2011; so, better start with "For 2010, 14 nights out of 45 nights of observation clearly showed....., while in 2011, 30 from 60 nights of data showed wavelike...".

Response: We have modified text as per reviewer suggestion on page number 6.

L83: correspondence between wavelengths and emissions is a little confuse; the essential information -the two wavelenghts at which the OH (8-3) band is sampled- is mixed up with the list of red and green atomic oxygen lines (which are not used in this paper).Better reorganize this sentence!

Response: We have modified text as per reviewer suggestion on page number 6.

L91, 92: "This output... processing" is not very informative. The message is simply that the corresponding time series are stored for further processing. And the other reviewer is right when saying that details about the determination of rotational temperatures should be given. The two wavelengths alone, without information on bandwidth and therefore, the rotational band components included in each of the two spectral samples, are insufficient to derive temperatures. In principle, also the spectral background intensity unaffected by the OH emission would be needed for good rotational temperatures (although I think this would be difficult, in the spectral vicinity of the 8-3 band)...

Response: Thanks for your suggestion. We have included information in introductions section in our revised manuscript.

L128, 129: Instrument and satellite names should be capitalized to match acronyms.

Response: We corrected text as per suggestion of referee in revised manuscript on page number 8.

L130: "orbital inclination" needs be added to "at 74°"; add missing word" atmosphere"

Response: We have corrected text as per suggestion of referee on page number 8.

L135; not clear what is gained by mentioning 2010 and 2011 again; what is meant by "to identify this"?

Response: We corrected text as per suggestion of referee on page number 8.

L136, 137: change to read "(obtained from SABER)" and delete the rest of the sentence (redundant).

Response: We have corrected text as per suggestion of referee on page number 8- 9.

L138: replace "representing" by "to represent", because the selected grids do not automatically represent Kolhapur (but are meant to).However, I wonder why the longitude interval is so much greater than the latitude interval, being so relatively close to the equator (where COS(17°)=0.956=~1).

Response: We corrected text as per suggestion of referee on page number 8-9.

L139-140: the two miss-time criteria just boil down to "night time (excluding twilight)" and do not require this two-item list.

Response: We have corrected text as per suggestion of referee on page number 9.

L146, 147: delete "with connecting lines", since that's not informative ;only circles can be clearly seen in figure 1.

Response: We have deleted text as per suggestion of referee on page number 9.

L149, 150: "mean airglow intensity", "mean temperature" is clear enough (delete "of", "of the").

Response: We have deleted text as per suggestion of referee on page number 9.

L153: an even better fit could be obtained if a constant term were included in equation (1).

Response: As per referee suggestion we tried to get best fit but did not seen many changes in wave periods, some phase difference values changes that effect on vertical wavelength values. We included it in our text on page number 10.

L150-154: too much information is given simultaneously in this long sentence, just to explain the red lines. Better, start simply: "Also, best-fit cosines are shown (red lines)." And then give details. The reason ("to identify...") is obvious.

Response: We have corrected text as per suggestion of referee on page number 9.

L155: then, this sentence ("Note that ... model") should be deleted.

Response: We have deleted text as per suggestion of referee on page number 9.

L157: see below (L161-162)!
L158: the argument is that the temperature and intensity oscillations correspond to the same physical wave, in spite of the small nominal difference in period (within combined errors).
L160: delete "(Figure 1c)" after "best-fit model values", because the next sentence is explicit enough. To explicit, in fact, since the information on the position of the panels ("bottom-left", etc.) is redundant.

Response: We deleted text as per suggestion of referee on page number 10.

L161-162, L165-166: but the correct order (Fig 1c, 1d) is intensity, temperature, respectively.

Response: We have mistakenly written wrong order. We corrected it on page number 10.
L164: while the figures 1a-d shows percentage amplitudes, the values in L165 are absolute amplitudes. Most importantly: the relative intensity and temperature amplitudes in Fig 1 look too similar to explain eta values of 7 (principal wave) and 3.7 (residual wave; but see the more serious error, below "L165-166"!).From the visual impression of figure 1, the principal wave has intensity and temperature nearly in phase, but for the secondary oscillation, visual inspection

does not lead to a clear conclusion, because of the ambiguity of relating 3 (nearly 4!) intensity maxima to 2 temperature maxima.

Response: In figure1 we have plotted mean intensity per mean verses time and mean temperature per mean verses time values. Not percentage amplitudes. If we reduce graph scale then you can see the phase difference in secondary wave. But as per referee suggestion we have again repots the figure 1 for intensity deviation and temperature deviation (you can see the scale values different for intensity and temperature deviation).

L165-166: the temperature amplitude of 4.1K and intensity amplitude of15.1 units are insufficient information to arrive at the eta of 3.7 (but15.1/4.1=3.68 relative units/kelvin; hmmm). I hope that this is not how all the eta values have been determined, because they would be all wrong!

Response: In that text, we clearly wrote that it is percentage amplitude which is divided by their mean values. Further, we have calculated all eta values using the Krassovsky's equation (1) given in A. Guharay *et al.*, 2008 reference. We round up Eta value to keep on one digit after decimal point. Now, we corrected it and used two digits after decimal point in all Eta values calculation for plotting and text in manuscript.

L173: formula (2) is not from Hines' Fundamental Theorem paper of 1997,but can be deduced from eq 57 and 58 in Tarasick& Hines 1990 (not cited; that is: Tarasick, D.W., and Hines, C.O. (1990), The observable effects of gravity waves on airglow emissions, Planet. Space Sci. 38, 1105-1119); your formula (2) in the form how you cite it (and others have), may have first been given in Reisin & Scheer 1996 (which you cite). This is not an important point in itself. A simpler version (using a numerical factor 22 instead of 2 pi and the gamma terms) can also be obtained from eq 37 of Hines &Tarasick1987 (which you cite). Note that the sign conventions of H&T87 and T&H90are opposite to what Reisin &Scheer 1996 and Reisin &Scheer 2001 (not cited, but relevant to the context of your paper: Reisin, E.R., and Scheer, J. (2001), Vertical propagation of gravity waves determined from zenith observations of airglow, Adv. Space Res. 27(10), 1743-1748.) have used. With your formula (2), negative vertical wavelength corresponds to downward phase propagation (i.e., upward energy propagation, as your manuscript mentions only much later), and that means that temperature oscillations precede the intensity oscillations in phase (as, e.g., Takahashi, H., Sahai, Y., and Teixeira, N.R. (1990) , Airglow intensity and

temperature response to atmospheric wave propagation in the mesopause region, Adv. Space Res. 10, (10)77-(10)81) have shown mostly to be the case).
Since your paper compares with phase shifts from the literature, consistent phase conventions must be used. And since phase difference for waves with different period depends on time, corrections for frequency difference or time reference are needed, in general. Otherwise, considerable statistical errors can arise.

Response: We understand the reviewer's viewpoint. As these are geospatially different locations where latitude-longitude differences may be very large and more that they are not in same season and year, we think this should be highlighted in the manuscript. After reviewers comment we feel as we have no handle on these issues, we are now clearly mentioning this aspect in the manuscript.

L176: While formula (2) has not been derived for evanescent waves, this does not automatically imply that it is not at least approximately valid for Phi=0, since that leads to infinite vertical wavelength (i.e., constant phase with height), which is not unreasonable. By the way, for phi so close to zero that sign may change, also the sign of VW changes (simply as statistical errors), which is why for large values of VW, sign is meaningless! This is why it does not make sense to choose very wide scale for plots of VW.

Response: We change our vertical wavelength plot (figure 2c and 3c) as per referee suggestions.

L178: importantly, missing "the" before "long period and short period waves", because only the two cases of figure 1 are referred to (and it is not a general statement).

Response: We change text as stated.

L179: Note that the bias for long-period waves alluded to here could have been removed by simply including a constant term in the fit (eq 1).

Response: It is true that by adding a time varying constant we can remove the trend. The priory knowledge of the possible period is a tough call to take while fitting to address and varies case to case. For this reason, we avoid any confusion by considering only those waves whose periods are substantially less than the length of the available data.

L183, 184: "one may note that" and "in the data show" are unnecessary subjective aspects of an objective message ("During 2010... The principal wave components have periods between 5.2 and 10.8 h").

Response: We change text as stated.

L185: minimum temperature amplitudes of 0.2 K? Such small amplitude for a "principal wave" must be a chance exception meaning "no wave detected", and not a result to be taken seriously.

Response: We apologize for mistake, this day in our plot and text removed. Referee raised point is correct.

L190-198: these numbers are hard to digest without a figure to look at, but unfortunately, Figure 2 has too many different symbols to make the present results stand out clearly. I think, separate plots without the literature comparisons are needed (while including the black model curves would not hurt)! With respect to the comparisons with other observations, I doubt that the period ranges are all correct (that would be easy to repair by a statement like "also some of the results from other investigations are shown"). Some of the symbols in 2a and 2b differ, making it harder to interpret the plots (symbol 16 for Viereck &Deehr eta, but symbol 7 for Viereck& Deehr phi). Already from the present figure 2b it appears that Viereck &Deehr had many outliers (but if I remember correctly, several values were derived from the same spectral feature; note that their figure 7 with many strange phases is for O2!). Therefore, choosing such a wide phase angle scale to accommodate these "outliers" does not make sense. However, I can see no evidence for so many phase outliers in Viereck and Deehr's paper (which was, by the way, based on only three consecutive (24 -h) days of observation), especially if one ignores periods below 1h; see their figure 4).

Response: We corrected text and figures. As per referee suggestions we inserted separate plots without the others researchers values, in manuscript as figure (2a1) and (2b1) for eta and phi respectively. Symbol system used in plots makes similar in all plots. Thanks for the suggestion.

L199-205: I insist that comparisons should go to a separate Figure. Strictly speaking, the different results do not "vary", but each one is constant. However, they do "range from... to", or "fall in the range between... and...". Also in other places, the text abuses "vary", when referring to a range of fixed values.

Response: As per referee suggestion we included separate figures in modified manuscript on page number 11 and make changes in text also.

L215, 216: see my other comments about Viereck &Deehr's phases. I can see no such similarity with respect to the present results.

Response: As per referee suggestion we checked the phase values in Viereck and Deehr's paper and corrected it in modified manuscript.

L225: It is not true that Reisin &Scheer 2004 is for periods of 3000 sec and eta = 5.6. That number (5.6) was derived from mean variances of temperature and intensity averaged over several years, but does not refer to waves of any specific period. However, that paper did state that periods between 1000s and 3h correspond to an eta of 3.47±0.07 (for OH) according to Reisin & Scheer 2001 (which I have mentioned above, and which would make more sense to be cited here).

Response: As per referee suggestion we corrected text on page number 12.

L235: what is the reason to expect a latitudinal effect on the phases of eta? And, isn't Svalbard (Viereck & Deehr) even higher latitude than Sierra Nevada (Lopez-Gonzalez et al.)?

Response: In an earlier comment, reviewer has partially answered the reason for this. The reason can be because of time of wave occurrences, and more because of gas densities and temperature differences. Further, it is also remains to be seen that when mesopause altitude itself changes from low to high latitudes, how far the processes remain adiabatic. Only further experimental and theoretical efforts can resolve this.

L237: some word must be missing in this sentence.

Response: We corrected text on page number 13.

L239: Hines's Fundamental Theorem paper (1997; which you cite) uttered a different opinion.

Response: Reviewer is correct in saying that there are different opinions. However, a large data spread cannot be an aberration and has to be further ideas to explain them. Our aim is to point out that aspect by mentioning these statements.

L242: "Winds also affect" - citation needed!

Response: We have added the reference of Sonnemann G. and M. Grygalashvyly (2003) where they have elaborated the impact of wind on OH photochemistry.

L246: delete "the" before "upward"; also, citation needed about why this is thought to be so.

Response: Corrected sentence and included reference as suggested by reviewer on page number 13-14.

L263: The Offermann et al. (1981) paper has nothing to do with gravity waves and airglow and therefore must not be cited here. It only discussed the variability of measured atomic oxygen profiles.

Response: We removed cited reference as per referee suggestion.

L272: this information on propagation direction has already been given. Is this repetition warranted or just an oversight?

Response: We remove repeated sentence on page number 14-15.

L273: typo in "Krassovsky"

Response: We corrected typo mistake on page number 15.

L281, 282: Shouldn't the previous results by Ghodpage et al. based on data from other times or places be given more emphasis here?

Response: As suggested, we have explained more on the earlier results over Indian sector based on the earlier literature including our own work.

L288: -> "Full Wave Model results" (?)

Response: Sorry for writing it wrong way. It should be Full Wave Model results.

L289: what observations are you talking about? Isn't this section about model simulations?

Response: This is about running the model for the duration when we have made the observations reported in earlier section. We have mentioned it clearly in statement on page no. 15.

L310: lost single word "show" before "The observed..."

Response: We corrected it on page number 16.

L314: there is something incomplete in this sentence at "are 50-100 m/s". Maybe "at 50 and 100 m/s"?

Response: We corrected it on page number 16.

L321: delete excess "that" (after "that").

Response: We corrected it on page number 17.

L356: orphaned "for ."

Response: We corrected it on page number 18.

L363: please, correct strange "eta"-like font variant.

Response: Ok.

L367: correct typo in "constituents"; and if subject is "composition",then "were" -> "was"

Response: We corrected it on page number 19.

L369: missing "that" before arises" and missing final "s" in "a rises". my concluding remark to section 4: I wish the authors good luck to elevate the quality of the rest of the manuscript to the (language and argumentation) level of section 4!

Response: We corrected the text.

L386, 387: this section and the list of 4 items well deserves being called "conclusions"; "concluding remarks" implies that the results obtained are themselves clear enough, so that there is hardly a need to add more text. At any rate, "Following are the concluding remarks" sounds too obvious to be worth the spac.

Response: We corrected it on page number 20.

L391: reformulate so that is clear what is meant by "more magnitude of eta values". (Note that no error bars are given, so that quantitative comparisons are not necessarily conclusive).

Response: We have checked the errors in estimates and the differences are much above to be discounted as errors.

L393, 394: do you mean, "On the other hand, the phase values are greater than..."? Better, limit the use of "we note" to the minimum necessary and better stick to objective conclusions.

Response: We corrected it on page number 20.

L395: according to my impression with the corresponding figure (2b; see your symbols #7), some of the Viereck and Deehr phases differ considerably from your results, and from all the rest. But as stated above, I doubt that V&D really report those phases for OH.

Response: We corrected phase difference values (V and D) and repots figure 2b.

L408: better, delete after "under way", or reformulate to sound more reasonable.

Response: We corrected it on page number 20.

refs: in general, maintain chronological order of references! L440: missing space between "airglow" and subscript "2" in "O2"

Response: We corrected it on page number 22.

L448: missing hyphen in "T. -Y.", delete Walterscheid initial "L." (Paper only has "Richard").

Response: We corrected it on page number 22.

L452: wrong numbers! Correct is "148, 266-281, 2000".

Response: We corrected it on page number 23.

L460, 461: remove title capitalization and hyphen in "wave driven"

Response: We corrected it as suggested by referee on page number 23.

L494: is first author's naming "Pragati Sikha, R." (As mentioned in text)or Sikha Pragati, R. (as in the paper cited)? -it is not unusual that authors' names are spelled wrongly in published papers, so I ask.

Response: We corrected it as suggested by referee on page number 25 and apologize for mistake.

L495: delete final "s" in "Current Science"; 98(3).

Response: We corrected it as suggested by referee on page number 25.

I did not check all the references, so that's up to the authors.

Response: We checked all listed references.

L552: labeling indicates that (a) and (c) is intensity, (b) and (d) temperature, opposite to what caption (and text; see above) says.

Response: We corrected text on page number 29.

L555: info about meaning of the fits and "data ... Kolhapur" is redundant.

Response: We have corrected text as suggested by referee on page number 29.

L559: "A close resemblance..." contradicts the visual impression of wide scatter in figure 2b (but maybe the V&D outliers are O2, not OH; see above).

Response: We corrected text as suggested by referee on page number 29 and modified figure on page number 33.

L564, 571: typo in "Guharay".Each of the sections of figures 2 and 3 contains too much information to be part of a single figure!

Response: We corrected typo mistake. We have separately drawn plots for observed eta values and phi values as figure 2a1 and 2b1 on page number 32-33.

L576: Delete "Shown", because it's trivial that a figure shows something ; meaning of the sentence is hard to understand. Measured etas are compared with model?

Response: We corrected text as suggested by referee on page number 30 .

Figure 3a: model values for 100 and 150 m/s very nearly agree, so that the blue symbols are hardly visible. So, why are both ways plotted here?

Response: They are not always same when we look at amplitude and phase part and we wanted to show for clarity.

Figure 3b: most striking feature is that many of the highest phase velocity model phases are unrealistic.

Response: Reviewer's observation is correct. We like to showcase that most recent models are also unable to explain the observed values and large variations are persisting due to lack of a suitable photochemistry model which is dynamically coupled.

Figure 3c: symbols are here explained in a style that differs from all previous plots. Better, use consistent scheme everywhere. Space for positive vertical wavelengths (downward energy propagation) is kind of "wasted" for the 4 data points that occupy this region.

Response: We corrected figure 3c as suggested by referee on page number 36-37.

L586, 587: "are shown in plot" is no information. Where do these emission rate profiles come from? -> "solid lines: 2010, dashed lines: 2011".

Response: They are SABER observations corresponding to the duration of ground based data. We have clearly mentioned them now at this place together with existing explanations at section 2.3.

Response of OH airglow emissions to the mesospheric gravity waves and its comparisons with full wave model simulation at a low latitude Indian station

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Abstract:

The quasi-monochromatic gravity wave induced oscillations, monitored using the mesospheric OH airglow emission over Kolhapur (16.8°N and 74.2°E), India during January to April 2010 and January to December 2011, have been characterized using the Krassovsky method. The nocturnal variability reveals prominent wave signatures with periods ranging from 5.2-10.8 hr as the dominant nocturnal wave with embedded short period waves having wave periods 1.5-4.4 hr. The results show that the magnitude of the Krassovsky parameter, viz., $|\eta|$ ranged from 2.1 to 10.2 for principal or long nocturnal waves (5.2 to10.8 hr observed periods), and, from 1.5 to 5.4 for the short waves (1.5 to 4.4 hr observed periods) during the years of 2010 and 2011, respectively. The phase, i.e., Φ values of the Krassovsky parameters exhibited larger variability and varied from −8.1° to −167°. The deduced mean vertical wavelengths are found to be approximately −60.2 ± 20 km and – 42.8 ± 35 km for long and short wave periods for the year 2010. Similarly, for 2011 the mean vertical wavelengths are found to be approximately −77.6 ± 30 km and – 59.2 ± 30 km for long and short wave periods, respectively, indicating that the observations over Kolhapur were dominated by upward propagating waves. We use a full wave model to simulate the response of OH emission to the wave motion and compare the results with observed values.We discuss the observed wave characteristics and cause of the noted differences.

Keywords: OH emissions, Mesospheric gravity wave, Full wave model

1. Introduction

The airglow Hydroxyl emissions (OH) have been oftenly used for studying atmospheric temperature variation in the mesopause region since the pioneering work of Meinel (1950) and its usefulness (Greet et al., 1998, Bittner et al., 2000). The OH rotational temperature is one of useful parameters to monitor such variable atmospheric temperature in the mesopause region. The collision frequency of OH with the neutral atmosphere in the neighborhood of 90 km of altitude should be in an order to $10^4\,s^{-1}$ and the life time of the excited Hydroxyl emission is around 3 to 10 msec. (Mies, 1974). This ensures that the excited OH molecules in the rotational energy levels are in a thermal equilibrium with the atmospheric ambient gases (Sivjee & Hamwey, 1987, Takahashi et al., 1998). Thus, it is normally assumed that the rotational state of OH band is in Maxwell-Boltzmann distribution. The radiated light intensity provides a direct measure of OH quantum state distribution in the mesopause, if one knows the Einstein coefficients governing the emission. Meriweather (1975) arrived at an expression for the P1(2) and P1 (5) rotational lines of OH (8-3) band by making use of the vibration-rotation transition probabilities of Mies (1974). Therefore using two lines from a single band we can estimate the rotational temperature by the given quation (Mies, 1974):

$$T_{n,m} = \frac{E_{\nu'}(J'_m) - E_{\nu'}(J'_n)}{k \ln\left[\frac{I_n}{I_m}\ \frac{A(J'_m,\nu' \to J''_{m+1},\nu'')}{A(J'_n,\nu' \to J''_{n+1},\nu'')}\ \frac{2J'_m+1}{2J'_n+1}\right]}$$

Where *Tn,m* is the rotational temperature calculated from two line intensities, I_n and I_m, from rotational levels J'_n , J'_m in the upper vibrational level v', to J''_{n+1} , J''_{m+1} in the lower vibrational level v''. $E_v(J)$ is the energy of the level (*J*, v). $A(J'_n, v' \to J''_{n+1}, v'')$ is the

Einstein coefficient, for the transition from J'_n, v' to $J''m$, v''. The intensity ratio between P1 (2) and P1 (5) lines of the OH(8,3) band were used to obtain rotational temperature using the transition probabilities as given by Mies (1974)(Stubbs et al., 1983). Often the observed temporal variations in the mesospheric hydroxyl OH night airglow intensities and rotational temperatures are caused by propagating gravity waves from the lower to the upper atmosphere.

The interaction of these upward propagating waves with the ambient and other waves contribute to the dynamical variability, which in turn is reflected in observed airglow intensity and temperature perturbations (Hines, 1997). Krassovsky (1972) introduced a quantity 'η' to characterize the wave-induced perturbations. **This parameter, termed as 'Krassovsky's parameter', is now define as η** = $|\eta|\, e^{-i\Phi}$, where $|\eta|$ indicates the ratio of the amplitude variation between the emission intensity and temperature perturbations normalized to their time averages and Φ is **the** phase difference between the intensity wave and its temperature counterpart (e.g., Walterscheid et al., 1987; Taylor et al., 1991). It should also be mentioned here that apart from the pure dynamical processes η can also be affected by various other unknown parameters, such as the variation of local oxygen photochemistry (Hickey et al., 1993) and height variation of the emission layer which affects emission rates and temperature directly (Liu and Swenson 2003; Vargas et al., 2007). Although this can complicate studies of Krassovsky's parameter, it offers an opportunity to study the above aspects at the same time. Overall, once the physics and chemistry of emissions are well understood, the η values would offer a good tool to study the perturbations caused in a parameter (temperature, brightness/intensity) by measuring one under adiabatic conditions.

Utilizing the above, many investigators have carried out observational as well as the theoretical studies on the identification and characterization of gravity wave and tidal signatures with wave periodicities ranging from few minutes to several hours (e.g., Walterscheid et al., 1987; Hecht et al., 1987; Hickey 1988a, b; Taylor et al., 1991; Takahashi et al., 1992; Reisin and Scheer 1996; Taori and Taylor 2006; Guharay et al., 2008; Ghodpage et al., 2012, 2013). However, observational studies of the magnitude and phase of η over a range of wave periods for a given location and season are sparse. Some of the notable observations of η for the OH emission have been performed by Viereck and Deehr (1989) in the wave period range of ~ 1 - 20 hr and by Reisin and Scheer (1996) near to the semidiurnal tidal fluctuations.

In the present work, we utilize the mesospheric OH emission intensity and temperature data obtained during January - April 2010 and January - December 2011, when clear and moonless nights allowed observations to exceed 5 hours duration. We deduce the Krassovsky parameters as a function of observed wave period and also infer the vertical wavelengths for the observed mesospheric waves. Further, we compare our estimates with the earlier results reported by various investigators. We also employ a full-wave model to simulate the effects of wave motions on the OH airglow. This model has been used previously to compare observations and theory of airglow fluctuations (e.g., **Hickey et al., 1998**; Hickey and Yu 2005). Here, the model is used to estimate the values of the amplitudes and phases of Krassovsky's ratio which are compared to those derived from the observations, making the present study unique and first of its kind over Indian latitudes.

2. Instrumentation and Observations

The mesospheric OH observations **are made using the multispectral photometer** from Kolhapur (16.8°N, 74.2°E) (Ghodpage et al., 2013, 2014). **We analyze the data from** January - April 2010 and January-December 2011 when **clear sky conditions prevailed** for several nights.

For the year 2010, 13 nights out of 45 nights of observation clearly showed wavelike features, while in 2011, 29 from 60 nights of data exhibited wavelike variations.

2.1 The multispectral photometer

Regular observations of the night airglow emissions, OI 630.0 nm, OI 557.7nm and OH Meinel (731 nm and 740 nm) band have been carried out at the low latitude station Kolhapur. **We have operated multispectral photometer pointing to the zenith over Kolhapur. The fillers have a band width of 1 nm and their temperature is controlled by a temperature controller at 24 ^{0}C. The temperature coefficient of filter is 0.011 nm/ ^{0}C. At 24^{0}C the** transmission efficiency **of filters is** 40 - 70 %.We kept the integration time for each filter 15 seconds which results in repetition time of 90 seconds with an accuracy of approximately ±0.5% for line intensity. The photometer has F/2 optics with full field of view ~10°. The stepper motor rotation and sensing of the initial position is performed by computer controlled software. As the detector, the EMI9658B photomultiplier tube is used. An amplifier (high gain trans-impedance) is used to to convert and amplify photomultiplier's very weak (in the range of nA) output current in to corresponding voltage form. **In the absence of** standard **calibration** source, **we have used relative intensities (arbitrary units). In order to study the wave features present in the MLT region, we consider clear sky nights having more than 5 hours of continuous OH band data.**

2.2 Full Wave Model

The full-wave model is a linear, steady-state model that solves the linearized Navier-Stokes equations on a high resolution vertical grid to describe the vertical propagation of acoustic-gravity waves in a windy background atmosphere including molecular viscosity and thermal conduction, ion drag, Coriolis force and the eddy diffusion of heat and momentum in the mesosphere. The model description, including equations, boundary conditions and method of solution has been described elsewhere (Hickey et al., 1997; Walterscheid and Hickey 2001; Schubert et al., 2003). The neutral perturbations are used as input to a linear, steady-state model describing OH airglow fluctuations (Hickey and Yu 2005).

The model solves the equations on a high resolution vertical grid subject to boundary conditions, and allows quite generally for the propagation in a height varying atmosphere (non-isothermal mean state temperature and height varying mean winds and diffusion). The linearized equations are numerically integrated from the lower to the upper boundary using the tri-diagonal algorithm described by Bruce et al. (1958) and Lindzen and Kuo (1969). The lower boundary is set well below the region of interest and a sponge layer is implemented to avoid effects of wave reflection in the airglow response. In this study the lower boundary (the bottom of the lower sponge layer) is placed at 250 km below $z = 0$ (i.e., -250 km). The wave forcing is through the addition of heat in the energy equation. The heating is defined by a Gaussian profile with a full-width-at-half-max of 0.125 km. It is centered at an altitude of 10 km. A Rayleigh-Newtonian sponge layer in addition to natural absorption by viscosity and heat conduction prevents spurious reflection from the upper boundary. At the upper boundary (here 300 km altitude) a radiation condition is imposed using a dispersion equation that includes viscous and thermal dissipation (Hickey and Cole 1987). The mean state is defined using the Mass Spectrometer Incoherent Scatter (MSIS) model (Hedin 1991).

A set of linear perturbation equations for the minor species involved in the OH emission chemistry is solved using the approach described in Hickey (1988). This assumes that these minor species have the same velocity and temperature perturbations as the major gas (which are deduced from the full-wave model). A vertical integration of the volume emission rates through the vertical extent of the OH layer provides the brightness and brightness-weighted temperature perturbations, from which Krassovsky's ratio is determined. The OH chemistry we use is the same as that used previously (Hickey et al., 1997) and is for the OH (8-3) emission. We also determine the vertical wavelength at the peak of the OH emission layer evaluated from the phase variations of the temperature perturbations determined by the full-wave model.

2.3 Space borne measurements

The **Sounding of the Atmosphere using Broadband Emission Radiometry (SABER), on-board the Thermosphere Ionosphere Mesosphere Energetic and Dynamics (TIMED) satellite**, is a high-precision broadband radiometer which measures limb radiance (**orbital inclination at 74°) of the terrestrial atmosphere** at in 10 selected spectral bands ranging from 1.27 to 15 μm. In the present study, we note larger values of $|\eta|$ occur during 2011 compared to 2010 for long/principal waves, which indicates a larger intensity to temperature perturbation ratio over Kolhapur during the passage of the waves during 2011. This could be due to the differences in either the background atmosphere or the dynamical processes. **To identify the differences in the OH emission layer in year 2010 and 2011,** we scrutinize the OH volume emission rate profile for Kolhapur **region (obtained from SABER)** satellite. The selected latitude–longitude grids are 10°N to 20°N and 70°E to 90°E representing Kolhapur. The criteria for the selection of SABER data are such that: (i) the SABER pass should be during typical observation times **(excluding twilight time).**

3. Results and Discussion

To identify the wave structures in the data, we utilize the perturbation amplitudes normalized to their time averaged values (hereafter referred to as mean values) in the intensity and temperature data to calculate the Krassovsky ratio. To illustrate this, we show a typical example corresponding to the data obtained on 26-27 January 2011 in Figure 1. We plot the temperature deviations from their mean values in figure 1(a), while, the intensity deviations from their mean values are plotted in figure 1(b). We note that night airglow intensity variations show a long-period wave with embedded short-period oscillatory features. On this night, the mean airglow intensity is found to be ~ 1.83 arbitrary units and the mean temperature data is ~ 195.75 K. **To identify the nocturnal variability plotted together with data are the of best-fit cosine model (e.g., Taori et al., 2005) as follows. Also, best-fit cosines are shown (solid red lines).**

$$Y = A\cos\left[\pi\frac{(X - Xc)}{T}\right] \tag{1}$$

where, A is the amplitude of the fitted wave of half-period T with phase Xc , and X is the time. **The solid red** lines in figure 1 show the results of the best-fit cosine model. We observed the presence of ~ 8.2 ± 1.1 hr and 8 ± 1.3 hr waves with relative amplitudes **(normalized to their mean values and converted to corresponding % amplitude) ~ 3.60 K and 25.64%, in the nocturnal temperature and intensity variability, respectively**. Given the uncertainties involved in the observations, we consider these to be the same waves. Further, we compute the $|\eta|$ value for this wave to be 7.12 ± 1.2. To identify the shorter period features in the data we obtain residuals from the best-fit model values. **The figure 1c and 1d panels show the nocturnal variability of the residual intensity and temperature respectively**. The best-fit model reveals the presence of ~ 4.2 ± 0.2 and 3.0 ± 0.8 hr wave in the temperature and intensity residuals, respectively. Once again we treat these as the same wave for the reason explained above. The best-fit analysis shows the amplitudes of this wave to be ~ 1.019 K and 3.75% arbitrary units in the temperature and intensity data, respectively. Hence, the |η| value for short period waves is estimated to be **3.68 ±0.9**. **In general we note that in worst case, the maximum error in |η| values are <25%**. The phase difference between the intensity and temperature waves is obtained with the help of best-fit parameters which were also verified with a cross correlation analysis. The phase of the principal waves (maxima) (period ~8.2 hr) was ~ 24.88 hr in the temperature data and 24.4 hr in the intensity data, which results in the phase difference of ~ 0.48 hr, i.e., Φ values of −21.07±12°. Similarly, for the shorter period (period ~ 4.2 hr) the Φ values are estimated to be −114.3±20°.

We can also estimate the vertical wavelength with the help of Krassovsky's parameter following the **approach elaborated by Tarasick & Hines (1990).**

$$\lambda z = \frac{2\pi\gamma H}{(\gamma - 1)|\eta|\ \sin(\phi)} \tag{2}$$

where $\gamma = C_p / C_v = 1.4$ is the ratio of specific heats, and H = 6 km is the scale height. This formula is valid for zenith observations and for plane waves. It is not valid for the evanescent waves. Equation (2), **negative vertical wavelength corresponds to downward phase propagation (i.e., upward energy propagation**), and that means that temperature oscillations precede the intensity oscillations in phase **(e.g., Takahashi, H., et al. 1990).** Using the above relation we find that vertical wavelength for the two cases discussed above are ~ −51.5± 15 and −39.3± 40 km **for the long period and the short period waves**, respectively. Note that the long period wave estimates may be biased when the data length is comparable to that of the wave period and therefore in our study we have considered only those waves whose periods are substantially less than the length of the available data.

The above analysis was carried out on nighttime events recorded during 2010 and 2011 when the prominent wave features were visible. **During the** 2010 period, the principal nocturnal waves in the data show the wave periods vary from 5.2 to 10.8 hr with corresponding temperature amplitudes ranging from 2 to 13.8 K. Similarly for 2011, wave periods vary between 5.2 and 8.4 hr with corresponding temperature amplitudes lying between 1.1 K and 15.7 K. However, the intensity amplitudes of the principal waves vary from 7.9% to 49.9 % and 5% to 90% for 2010 and 2011, respectively. We note that the estimated $|\eta|$ values were found to range from 2.1 - 10.5 for the principal wave. In the case of the short period waves, the periods ranged from 1.5 to 4.4 hr (for 2010) and 2.8 to 4.4 hr (for 2011) with corresponding temperature amplitudes ranging from 0.68 K to 12.2 K and 0.4 K to 14.2 K. The corresponding intensity amplitudes fall in range between ~ 1.54% to 46.8% and 1.32% to 46.8 for 2010 and 2011, respectively. The phase (Φ) values also exhibit large variability for long (short) period waves, range in between −27° and −167° (−27° and − 150°) for 2010 and −8.1° and −65.2° (− 39.1° and −122.6°) for 2011. For 2010 the deduced vertical wavelengths **are found to vary from** – 32.2 km to −140 km and −24 km to −88 km for the long and short period waves, respectively. Similarly, for 2011 the deduced vertical wavelengths **are found to vary from** − 40 km to −102 km, and −26 km to −92.4 km for the long and short period waves, respectively.

In Figure 2a we plot our results for $|\eta|$ (hereafter η) with pink half-filled squares indicating the estimates for the year 2010 and olive half-filled squares for the year 2011. We plot Φ in Figure 2b **using the same symbols as used in Figure 2a**. For a **comparison, we also show the values of η and Φ of the results from other investigations are shown** (Viereck and Deehr 1989; Takahashi et al., 1992; Oznovich et al., 1995, 1997; Drob 1996; Reisin and Scheer 1996; Taylor et al., 2001; Lopez-Gonzalez et al., 2005). Also shown in the figure are the model estimates of Schubert et al. (1991), Tarasick and Shepherd (1992a, b), Walterscheid and Schubert (1995). **We also plot observed η and Φ values against there observed period in figure (2a1 and 2b1).** In general, we note that the parameter η increases with wave period. It is evident that the observed η and Φ values in our study show a large spread in their distribution as compared to the model values. A similar spread in the distribution of observed values of η (Figure 2a) from 1.03 to 7.85 has also been observed by other investigators (e.g., Takahashi et al., 1992). It may be noted that the values of η for the OH data in our study lie somewhere between the model estimates and the values observed by other investigators. Also noteworthy in this figure is that our η values are closer to the model values reported by Tarasick and Shepherd (1992a) for the waves with horizontal wavelength 500 km. The phase 'Φ' values, on the other hand show significantly larger deviations from this model for 2010, while for 2011 the match between measured and modeled phases appear to be better. We note that our measurements of Φ matches somewhat with those reported by Viereck and Deehr (1989), while large differences with other investigators can be easily noted. The variation of Φ values with respect to the wave periodicity, obtained in the 2010 year clearly shows that most of the time we observe values to be higher than those obtained by different models.

Of the importance is that Reisin & Scheer (2001) found η values of 3.47±0.07 corresponding to the wave periods between 1000s and 3h. Our observed values of η (arithmetic mean, 4.4± 1 for 2010 year and 5.7±1.7 for 2011 year) for OH measurements agree well with this report. In a further report, based on 5- year observations, Reisin and Scheer (2004), found the mean value of η to be ~5.6 for the nightly semidiurnal type waves and ~3.4 for the waves of 3000 s periodicity which is in agreement with our values. In another study based on long-term observations with a spectral airglow temperature imager (SATI) from a midlatitude station, Lopez-Gonzalez et al. (2005) reported a mean value of η of approximately ~ 8.6 for the OH measurements with a larger variability than our observations show. In another report, Guharay et al. (2008), found that for wave periods ranging from 6 hr to 13 hr, values of η in between 1.7 to 5.4, while the phase varied from -13^{o} to $-90°$. Similarly, Aushev et al. (2008) presented amplitudes of the Krassovsky parameter for wave periods of 2.2 to 4.7 hr which in range from 2.4 to 3.6 while the phase values in between -63^{o} to $-121°$. It is noteworthy that our derived values broadly agree with Guharay et al. (2008, 2009), **Reisin and Scheer (2001**, 2004) and Viereck and Deehr (1989) while they are somewhat different from the values reported by Lopez-Gonzalez et al. (2005) which may be due to the fact that their observations corresponded to higher latitude than ours because of, **it is also remains to be seen that when mesopause altitude itself changes from low to high latitudes.**

The results of (η and Φ) shown in Figure 2 emphasize that there are significant differences in the Krassovsky parameters derived from one study to another. This we suspect to be caused by the variations in the altitudinal profile of oxygen and its effect on the η through the complex OH chemistry (Walterscheid et al., 1994). Another possibility over low latitudes was discussed by Makhlouf et al. (1995) who suggested the quenching caused by the perturbed molecules during their transitions from several vibrational levels. Winds also affect the OH response to gravity waves and therefore they will also contribute to the spread of values seen between the various observation studies (e.g., **Sonnemann G. and M. Grygalashvyly, 2003**).

Note that our observations as well as models show the phase Φ for OH to be a negative value indicating upward propagating waves (**see Tarasick and Shepherd,1992a, b**). In general we note that our Φ values, although on some occasions are closer to Viereck and Deehr (1989) observations, show deviations from other investigators and are larger than the model values on most occasions. Differences in theory and observation may be due to the horizontal wavelength assumed in the model and or the Prandtl number (ratio of kinematic viscosity to thermal diffusivity) assumed. The Prandtl number is important in theoretical calculations and modeling, especially when in terms of dissipating waves owing to molecular viscosity and thermal diffusivity while they propagate in the atmosphere (Hickey 1988). An error in the Prandtl number assumption will affect the derived wave parameters (λ_z, η etc.), which will successively mask the actual ones. In this regard, Makhlouf et al. (1995) studied the variations in the η values by modifying the model proposed by Hines and using a photochemical dynamical model; however, they were still unable to explain the appearance of the negative phases appropriately. Hines and Tarasick (1987) found a wide range of η variability, a result supported by our measurements. Further, Hines and Tarasick (1997) subsequently discussed the necessary correction for thin and thick layer approximations for the calculation of η from airglow emissions due to gravity waves interaction. They also pointed out that OH emission intensity, which affects the derived η values, does not depend on the oxygen profile and other minor species, which contradicts the theory of Walterscheid et al. (1994), Schubert et al. (1991). The calculated vertical wavelengths (VW) for all the nights of the observation are shown in Figure 2c as pink half filled squares indicating the estimates for the year 2010 and olive half filled squares for the year 2011. Large differences exist from one night to another. The VW has a large variability ranging from – 41 km to −102 km (2010) and – 36.2 km to −140 km (2011) for long period waves, and, – 26 to −92.4 and – 24 to −88 km for short period waves period of 2010 and 2011 years respectively. In 2010 (and 2011) years, the mean VW values for long and short period waves are calculated to be −60.2 ± 20 km (−77.2 ± 40 km) and –42.8 ± 15 km (–59.2 ± 30) respectively. Further, unlike the clear dependency on the wave period noted in the

Krassovsky parameters (η and Φ) no clear trend is noted in the calculated VW. We also plot the values reported by Reisin and Scheer (1996) and Lopez-Gonzalez et al. (2005) for a comparison. It is noteworthy that for all the days the VW for the long period wave are higher than the VW of short period waves. We also observed that VW values calculated for 2011 year are larger than 2010 year calculated values.We note that the values reported by Reisin and Scheer (1996) are approximately −30 km with about 40 km variability, which is a good agreement with our values. However, Lopez-Gonzalez et al. (2005) observed VW values to be approximately −10 km deduced from their OH observations, which do not agree with our values. Further, Ghodpage et al. (2012) analyzed the long-term nocturnal data of 2004-2007 and also observed that the VW lies between 28.6 and 163 km. Recently, Ghodpage et al. (2013) studied the simultaneous mesospheric gravity wave measurements in the OH emission from Gadanki and Kolhapur, inferring mean VWs varying from – 26 to – 60 km for the Kolhapur observations. Takahashi et al. (2011) reported vertical wavelengths varying from 20 to 80 km, which is in agreement with our values.

4. Comparison with the Full Wave Model Results

Wave simulations were performed using the Full Wave Model **(FWM) for which the representative inputs were taken for the duration of observations reported in section 3**. The observations were conducted over an approximate one month period spanning February 8th and March 13th, and accordingly we used the middle date of this observation period (February 25th) in the MSIS model to represent the undisturbed mean state. The latitude used was 16.8° N, and the local time was midnight. Because the speed and direction of wave propagation were not determined from the observations, several simulations were performed for each wave period in which the direction of propagation (eastward, northward and westward propagation) and the phase speed (50 m/s, 100 m/s and 150 m/s) were varied. Note that the mean winds (not shown) in these simulations were derived from the Horizontal Wind Model (HWM) using the same input parameters as used for the MSIS model. The derived meridional winds (not shown) are far smaller than the zonal winds for the conditions considered here, and so while results for eastward and westward propagation differed quite markedly, those for northward and southward propagation did not. Hence we considered only a single direction (northward) for meridional propagation.

We also performed a tidal simulation using an equivalent gravity wave model (Lindzen 1970; Richmond 1975), as implemented in an earlier study (Walterscheid and Hickey 2001). The horizontal wavelength and Coriolis parameter are adjusted to give maximal correspondence with a given tidal mode. Here, we performed calculations for the terdiurnal (3,3), (3,4), (3,5) and (3,6) modes using parameters provided by Richmond (1975). The simplifications inherent in this approach are discussed by Walterscheid and Hickey (2001).

Comparisons between the full wave model results for η, Φ and λ_z and the values inferred from the observations are shown in figure 3a, 3b and 3c, respectively. In figure 3a we compare the observed values of η for 2010 and 2011. The observed values of η are represented as pink and olive lower half-filled squares for 2010 and 2011, respectively. In figure 3a we note that at few of the longer wave periods, the observed values of η are in good agreement with the full wave model results. For short period waves the values of η inferred from the observations appear to be bounded by the model values for waves with horizontal phase velocities are 50 **and** 100 m/s, respectively. For example, for 3.6 hr wave periods, the average of the values of η inferred from the observations is 3.7, while the full wave model values lie between about 0.5 (for the 100 m/s wave) and 7 (for the 50 m/s, eastward propagating wave). For the 8 hr wave periods, the average of the values of η inferred from the observations is 5.7, which is bounded by the full wave model estimates for waves having a horizontal phase velocity of 50 m/s and different propagation directions.

Overall, we note that the comparison between the observed η values and the modeled values can be explained by gravity waves whose horizontal phase velocities range from 50 m/s to 100 m/s. In this regard, an earlier investigation by **Pragati Sikha et al. (2010)** reported observed gravity wave horizontal phase speeds (for periods 5 min to 17 min) varying between 10 m/s and 48 m/s. The propagation directions were reported to be preferentially towards the north. More recently, Taori et al. (2013) studied mesospheric gravity wave activity in the OH and OI 558 nm emissions from Gadanki. They observed that the gravity waves were moving in the north–west direction. The average phase velocity of the ripple-type waves was found to be 23.5 m/s. The other, band-type waves, with horizontal scales of about 40 km, were found to be propagating from south to north with an estimated phase speed of 90 m/s.

The vertical wavelengths (λ_z) calculated using the observed values of η and Φ differ significantly from the full wave model estimate for waves with phase velocities below 100 m/s. More typically, a comparison between those values inferred from the observations and those derived from the model tend to agree for phase velocities in the 100 - 150 m/s range. However, it should be noted that vertical wavelengths inferred from the observations are based on the use of the inferred Krassovsky's ratio, η, in Eq. (2). **Please note that the errors in the determination of the phase (Φ) of η may lead to significant errors (proportional to cotΦ) in the determination of λ_z, especially as Φ approaches $\pm 180^o$.**

The differences noted in the observed and modeled estimates of Krassovsky ratio magnitudes η and phase (Φ) may be associated with the limitation arising due to dynamics as well as the measurements. In terms of measurements limitation, the parameters achieved with the best fit method may have leaked contribution from other wave components which may be dynamically varying within a wave period. In terms of dynamics, that full wave model uses climatological density (both major gas and minor airglow-related species) and wind profiles which will introduce uncertainties. This point has been previously elaborated by Walterscheid et al. (1994) with respect to the effect of a change in the [O] profile on the OH response to wave motions.

It is interesting to note that the arithmetic mean values of $|\eta|$ for the years 2010 and 2011 were 4.4 and 5.7 respectively. **When we look at each $|\eta|$ value from one wave period range to other, the difference is found to be more than 30% which is well above the maximum errors in the estimation. One may further argue that this difference may not be significant. For this, we looked at the mode of the values for periods ranges 1-4 hr, 4-6 hr, 6-8 hr and 8-10 hr. We found that in each case in the year 2011 mode values are larger than the year 2010.** The differences noted in the magnitude of the observed Krassovsky ratio η between 2010 and 2011 may be associated with variations in the height and shape of the undisturbed OH emission profile. **We use the SABER data to investigate this aspect**. To check whether there was a difference in the OH emission layer structure, we selected the nighttime OH emission profile for a grid encompassing 10^{o}N to 20^{o}N latitudes and 70^{o}E to 90^{o}E latitudes during February, March and April months of the years 2010 and 2011. We have selected the February to March period because the optical airglow data used in this study was acquired primarily during these months. The monthly mean values of OH emission rates are plotted in

Figure 4. The solid curves correspond to 2010 data while the dashed curves correspond to 2011 data. We note that the peaks of OH emission layer during February, March and April of 2010 occurred at 84.2 km, 82.8 km and 85.1 km altitude, respectively, while the corresponding peaks for 2011 were found to occur at 85.8 km, 85.6 km and 85.2 km altitude. This suggests that the peak of the emission layer occurred at a somewhat lower altitude in 2010 compared to 2011. Also, the mission rates during February and March were found to be higher in 2010. It is important to note that in an earlier study, Ghodpage et al. (2013) compared the Krassovsky ratios at two different latitudes, Gadanki (13.5 N, 79.2E) and Kolhapur (16.8°N and 74.2°E) and noted a lower OH emission layer peak over Kolhapur and also larger estimated **η** values over Kolhapur. In the present case, instead of the location, it is the difference in the measurement year where the peak emission altitudes of the OH emission layer are somewhat diffterent. As the peak emission layer arise due to the chemical reactions involving odd oxygen, it is proposed that chemical constutents composition **was** different from the year 2010 to the year 2011. Therefore, the noted emission rates may be responsible for the observed differences in the Krassovsky parameters. A further question **that arise** here is why the peaks should be different from one year to the other. As these months are pre-monsoon, when a large scale oscillation namely,El Niño/Southern Oscillation (ENSO) sweeps through the south Asian continent, we looked at the ENSO strength based on the Multivariate ENSO Index (MEI). This index is shown in table 1, where it is noteworthy that the MEI index for 2010 (January to May) is of opposite sign to that for the corresponding months in 2011. We postulate that these large scale processes have a profound impact on the observed wave energetics and dynamics at mesospheric altitudes. Large scale processes induced the wave oscillations associated with the ENSO. The ENSO generates a spectrum of waves which are of planetary scales. These are expected to generate a secular

variation in temperature and density structure throughout the atmosphere. A difference in ENSO suggests that these forcing are different in the two years (2010, 2011). At present, we do not know through which process the ENSO may have implications in the observed wave characteristics. However, we believe that further investigation is required in order to confirm whether or not any such associations really do exist.

5. Conclusion:

We report the Krassovsky parameters for the observed gravity waves from Kolhapur (16.8°N and 74.2°E) and their comparison with the full wave model.

1) It is evident that the observed values of Krassovsky parameters in our study show a large spread in their distribution as compared to the model values (shown in Figure 2a). A similar spread in the distribution has also been reported by other investigators. We have also observed magnitude of η values is larger in the year 2011 than 2010.
2) It is also notable that the values of η for the OH data in our study lie between the model estimates and the values observed by other investigators. Whereas the phase values are more than the model values on most occasions. We note that our Φ measurements match with those reported by Viereck and Deehr (1989), while they show large differences with other investigators values.
3) Observed vertical wavelength (VW) values broadly agree with the range reported by other investigators and are found to vary from −26 to −140 km.We also noted that VW values calculated for 2011 year are larger than 2010 year calculated values. Most of wave propagating upward in direction.

4) Comparison of observed η and Φ values agree fairly well with the full wave model results for waves with 50 **and** 100 m/s horizontal phase velocities. Vertical wavelengths tend to agree for waves with 100 **and** 150 m/s horizontal phase velocities, except for the longest period waves for which vertical wavelength cannot be reliably inferred from the observations.

The database used in the present study is limited in terms of the length and locations. Based on the above conclusions we emphasis that more rigorous study using coordinated observations and modeling are required to uncover the physics occurring at upper mesosphere.

Acknowledgements

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6. References

Aushev, V. M., Lyahov, V. V., Lopez-Gonzalez, M. J., Shepherd, M. G., and Dryna, E. A. :Solar eclipse of the 29 March 2006: results of the optical measurements by MORTI over Almaty (43.03°N, 76.58°E), J. Atmos. Sol. Terr. Phys., 70, 1088–1101, 2008.

Bruce, G. H., Peaceman, D. W., Rachford, Jr. H. H., and Rice, J. D.: Calculations of unsteady-state gas flow through porous media, Petrol. Trans. AIME, 198, 79-92, 1953.

Bittner, M., Offermann, D., Graeft.: Mesopause temperature variability above a midlatitude station in Europe. Journal of Geophysical Research, 105(D2): 2045–2058, 2000.

Drob, D. P.: Ground-based optical detection of atmospheric waves in the upper mesosphere and lower thermosphere, Ph. D. Thesis, University of Michigan, Ann Arbor, MI., 1996.

Ghodpage, R. N., Singh, D., Singh, R. P., Mukherjee, G. K., Vohat, P., and Singh, A. K.: Tidal and gravity waves study from the airglow measurements at Kolhapur (India), J. Earth Syst. Sci.121, 6, 1511–1525, 2012.

Ghodpage, R. N., Taori, A., Patil, P. T., and Gurubaran, S.: Simultaneous mesospheric gravity wave measurements in OH night airglow emission from Gadanki and Kolhapur – Indian low latitudes, Currents Science, 104, 1, 98-105, 2013.

Ghodpage, R.N., Taori, A., Patil, P. T., Gurubaran, S., Sharma, A. K., Nikte, S., and Nade, D.: Airglow Measurements of Gravity Wave Propagation and Damping over Kolhapur (16.8^{o} N, 74.2^{o} E), International Journal of Geophysics (IJG), Volume 2014,1-9, http://dx.doi.org/10.1155/2014/514937, 2014.

Greet, P.A., French, WJR., Burns, G B., Williams, PFB., Lowe, R. P., & Finlayson, K. :OH (6-2) spectra and rotational temperature measurements at Davis, Antarctica, Annales Geophysicae, 16(1), 77–89, 1998.

Guharay, A., Taori, A., Bhattacharjee, B., Pant, P., Pande, P., and Pandey, K.: First ground-based mesospheric measurements from central Himalayas, Current Science, 97, 664-669, 2009.

Guharay, A., Taori, A., and Taylor, M.: Summer-time nocturnal wave characteristics in mesospheric **OH and O_2 airglow emissions**, Earth Planets Space, 60, 973–979, 2008.

Hecht, J. H., et all.: Observations of wave-driven fluctuations of OH nightglow emission bfrom Sondre Stromfjord, Greenland, J. Geophys. Res., 92, 6091-6099, 1987.

Hedin, A. E. :Extension of the MSIS thermosphere model into the middle and lower atmosphere, J. Geophys. Res., 96, 1159 – 1172, 1991.

Hickey, M. P., and Yu, Y.: A full-wave investigation of the use of a "cancellation factor" in gravity wave-OH airglow interaction studies, J. Geophys. Res., 110, A01301, doi:10.1029/2003JA01372, 2005.

Hickey, M. P., Huang, T.-Y., and Walterscheid, R.: Gravity wave packet effects on chemical exothermic heating in the mesopause region, J. Geophys. Res., 108(A12), 1448, doi:10.1029/2002JA009363, 2003.

Hickey, M. P., Walterscheid R. L., and Schubert, G.: Gravity wave heating and cooling in Jupiter's thermosphere, Icarus, **148, 266-281, 2000.**

Hickey, M. P., Walterscheid, R. L., Taylor, M. J., Ward, W., Schubert, G., Zhou, Q., Garcia, F., Kelley, M. C., and Shepherd G. G.: Numerical simulations of gravity waves imaged over Arecibo during the 10-day January 1993 campaign, J. Geophys. Res., 102, 11,475-11,489, 1997.

Hickey, M.P., Schubert, G., and Walterscheid, R. L.: Gravity wave-driven fluctuations in the O_2 atmospheric (0-1) nightglow from an extended, dissipative emission region, J. Geophys. **Res., 98(13),717-730, 1993.**

Hickey, M. P.: **Effects of eddy viscosity and thermal conduction and coriolis force in the dynamics of gravity wave driven fluctuations in the OH nightglow, J. Geophys. Res., 93, 4077, 1988.**

Hickey, M.P., Taylor, M.J., Gardner, C.S., and Gibbons, C.R. Full-wave modeling of small-scale gravity waves using Airborne Lidar and Observations of the Hawaiian Airglow (ALOHA-93) O(1S) images and coincident Na wind/ temperature lidar measurements, J. Geophys. Res. 103, 6439-6453,1998.

Hickey, M. P., and Cole, K. D.: A quartic dispersion equation for internal gravity waves in the thermosphere, J. Atmos. Terr. Phys., 49, 889-899, 1987.

Hines, C. O.: A fundamental theorem of airglow fluctuations induced by gravity waves, J. Atmos. Sol. Terr. Phys.,59, 319–326, 1997.

Hines, C. O., and Tarasick, D. W.: Layer truncation and the Eulerian/ Lagrangian duality in the theory of airglow fluctuations induced by gravity waves, J. Atmos. Sol. Terr. Phys., 59, 327–334, 1997.

Hines, C. O., and Tarasick, D. W. : On the detection and utilization of gravity waves in airglow studies, Planet Space Sci., 35, 851–866, 1987.

Krassovsky, V. I.: Infrasonic variation of OH emission in the upper atmosphere, Ann. Geophys., 28, 739–746, 1972.

Lindzen, R. S.: Internal gravity waves in atmospheres with realistic dissipation and temperature, part I: Mathematical development and propagation of waves into the thermosphere, Geophys. Fluid Dyn., 1, 303-355, 1970.

Lindzen, R. S., and Kuo, H. L.: A reliable method for the numerical integration of a large class of ordinary and partial differential equations, *Mon. Wea. Rev.*, **97,** 732-734, 1969.

Liu, A. Z., and Swenson, G. R.: A modeling study of O_2 and OH airglow perturbations induced by atmospheric gravity waves, J. Geophys. Res, 108, D4, 4151, doi:10.1029/2002JD002474, 2003.

Lopez-Gonzalez, M. J., et al.: Tidal variations of O_2 Atmospheric and OH(6-2) airglow and temperature at mid-latitude from SATI observations, Ann. Geophys., 23, 3579–3590, 2005.

Makhlouf, U. B., Picard, R. H., and Winick, J. R.: Photochemical-dynamical modeling of the measured response of airglow to gravity waves, 1: basic model for OH airglow, J. Geophys. Res., 100, 11,289–11,311, 1995.

Mies, F. H.:Calculated vibrational transitions probabilities of OH ($X^2\pi$). Journal of Molecular Spectroscopy, 53, 150–188, 1974.

Meinel, A. B.:OH Emission bands in the spectrum of the night sky. American Geophysical Union, 31 (21), 1950.

Meriwether, J. W.: High latitude airglow observations of correlated short term fluctuations in the hydroxyl Meinel 8-3 band intensity and rotational temperature, Planet. Space Sci., 23, 1211–1221, 1975.

Oznovich, I., Walterscheid, R. L., Sivjee, G. G., and McEwen, D. J.: On Krassovsky's ratio for ter-diurnal hydroxyl oscillations in the winter polar mesopause, Planet Space Sci.,45(3), 385–394, 1997.

Oznovich, I., McEwen, D. J., and Sivjee, G. G.: Temperature and airglow brightness oscillations in the polar mesosphere and lower thermosphere, Planet Space Sci., 43, 1121–1130, 1995.

Pragati, R.S., Parihar, N., Ghodpage, R., Mukherjee, G.K.: Characteristics of gravity waves in the upper mesosphere region observed by OH airglow imaging, Current Science 98, 392–397,2010.

Reisin, E.R., and Scheer, J.: Vertical propagation of gravity waves determined from zenith observations of airglow, Adv. Space Res. 27(10), 1743-1748, 2001.

Reisin, E. R., and Scheer, J.: Gravity wave activity in the mesopause region from airglow measurements at El Leoncito, J. Atmos. Sol. Terr. Phys., 66, 655–661, 2004.

Reisin, E. R., and Scheer, J.: Characteristics of atmospheric waves in the tidal period range derived from zenith observations of O_2(0-1) Atmospheric and OH (6-2) airglow at lower mid latitudes, J. Geophys. Res., 101, 21,223–21,232, 1996.

Richmond, A. D.: Energy relations of atmospheric tides and their significance to approximate methods of solution for tides with dissipative forces, J. Atmos. Sci., 32, 980-987, 1975.

Schubert, G., Hickey, M. P., and Walterscheid, R. L.: Heating of Jupiter's thermosphere by the dissipation of upward propagating acoustic waves, Icarus, 163, 398-413, 2003.

Schubert, G., Walterscheid, R. L., and. Hickey, M. P.: Gravity wave-driven fluctuations in OH nightglow from an extended, dissipative emission region, J. Geophys. Res., 96 (A8), 13,869–13,880, 1991.

Sivjee, G. G., & Hamwey, R. M.: Temperature and chemistry of the polar mesopause OH. Journal of Geophysical Research, 92(A5): 4663–4672, 1987.

Stubbs, L. C., Boyd, J. S., and Bond, F. R.: Measurement of the OH rotational temperature at Mawson, East Antarctica, Planet. Space Sci., 31 (8), 923–932, 1983.

Sonnemann G. and Grygalashvyly, M.: The zonal wind effect on the photochemistry within the mesosphere / menopause region, Adv. Space Res. Vol. 32 (5), 719-724, 2003.

Takahashi, H., Buriti, R. A., Gobbi, D., and Batista, P. P.: Equatorial planetary wave signatures observed in mesospheric airglow emissions, J. Atmos. Sol. Terr. Phys., 64, 1263–1272, 2002.

Takahashi, H., Sahai, Y., Batista, P. P., and Clemesha, B. R.: Atmospheric gravity wave effect on the airglow O2(0-1) and OH (9-4) band intensity and temperature variations observed from a low latitude station, Adv. Space Res.,12(10), 131–134, 1992.

Takahashi, H., Sahai, Y., and Teixeira, N.R.: Airglow intensity and temperature response to atmospheric wave propagation in the mesopause region, Adv. Space Res. 10, (10)77-(10)81, 1990.

Tarasick, D. W. and Hines, C. O.: The observable effects of gravity waves in airglow emission, Planet. Space Sci., 38, 1105–1119, 1990.

Takahashi, H, Batista, P. P, Buriti, R. A, Gobbi, D, Nakamura, T, Tsunda, T & Fukao S. Simultaneous measurements of airglow OH emission and meteor wind by a scanning photometer and the MU radar. Journal of Atmospheric and Solar-Terrestrial Physics, 60(17): 1649–1668, 1998.

Taylor, M. J., Gardner, L. C., and Pendleton, Jr. W. R.: Long-period wave signatures in mesospheric OH Meinel (6,2) band intensity and rotational temperature at mid-latitudes, Adv. Space Res., 27(6–7), 1171– 1179, 2001.

Taylor, M. J., Turnbull, D. N., and Lowe, R. P.: Coincident imaging and spectrometric observations of zenith OH nightglow structure, Geophys. Res. Lett., 18, 1349–1352, 1991.

Taori, A., and Taylor, M. J.: Characteristics of wave induced oscillations in mesospheric O2 emission intensity and temperatures, Geophys. Res. Lett., 33, L01813, doi:10.1029/2005GL024442, 2006.

Taori, A., Taylor, M. J., and Franke, S.: Terdiurnal wave signatures in the upper mesospheric temperature and their association with the wind fields at low latitudes (20◦N), J. Geophys. Res., 110, D09S06, doi: 10.1029/2004JD004564, 2005.

Taori, A., Jayaraman, A., Kamalakar, V.: Imaging of mesosphere–thermosphere airglow emissions over Gadanki (13.51N, 79.21E)-first results, J. Atmos. Sol. Terr. Phys. 93, 21–28, http://dx.doi.org/10.1016/j.jastp.2012.11.007, 2013.

Tarasick, D. W., and Shepherd, G. G.: Effects of gravity waves on complex airglow chemistries: 1. $O_2(b^1\sum^+{}_g)$ emission, J. Geophys. Res., 97, 3185–3193, 1992a.

Tarasick, D. W., and Shepherd, G. G.: Effects of gravity waves on complex airglow chemistries: 2. OH emission, J. Geophys. Res., 97, 3195–3208, 1992b.

Vargas, F., Swenson, G., Liu, A., and Gobbi, D.: $O(^1S)$, OH, and $O_2(b)$ airglow layer perturbations due to AGWs and their implied effects on the atmosphere, J. Geophys. Res, 112, D14102, doi:10.1029/2006JD007642, 2007.

Viereck, R. A., and Deehr, C. S.: On the interaction between gravity waves and the OH Meinel (6-2) and O2Atmospheric (0-1) bands in the polar night airglow, J. Geophys. Res., 94, 5397–5404, 1989.

Walterscheid, R. L., and Schubert, G.: Dynamical-chemical model of fluctuations in the OH airglow driven by migrating tides, stationary tides, and planetary waves, J. Geophys. Res., 100, 17,443–17,449, 1995.

Walterscheid, R. L., and Hickey, M. P.: One-gas models with height-dependent mean molecular weight: Effects on gravity wave propagation, J. Geophys. Res., 106, 28,831-28,839, 2001.

Walterscheid, R. L., Schubert, G., and Hickey, M. P.: A Comparison of Theories for Gravity Wave Induced Fluctuations in Airglow Emissions, J. Geophys. Res., 99, 3935, 1994.

Walterscheid, R. L., Schubert, G., and Hickey, M. P.: Comparison of theories for gravity wave fluctuations in airglow emissions, J. Geophys. Res., 99, 3935–3944, 1994.

Walterscheid, R. L., Schubert, G., and Straus, J. M.: A dynamical chemical model of wave-driven fluctuations in the OH nightglow, J. Geophys. Res., 92, 1241 – 1254, 1987.

Figure captions:

Figure 1. Nocturnal variability in the mesospheric OH emissions on 26-27 January 2011. The upper panels represent the mean deviations in **(a) intensity and (b) temperature data. Bottom panels represent (c) intensity and (d) temperature residuals.** Solid line curves in each plot show the result of simple best-fit cosine model.

Figure 2 (a) A comparison of Krassovsky parameters of data to their respective wave periods. The x -axis shows the wave periodicity and the y-axis is for Krassovsky parameters (η and Φ) in each plot. A close resemblance between the observational values and discrepancy between the observational and theoretical estimates are notable. The legends in the figure are as following: ((η : 1 (for 2010 year), 2 (for 2011 year), present study ; 3,Schubert et al. 500 km; 4, Schubert et al. 1000 km; 5, Tarasick and Shepherd 500 km; 6,Tarasick and Shepherd 1000 km; 7, Takahashi et al. (1992); 8, Oznovich et al. (1995); 9, Drob et al. (1996); 10, Reisin and Scheer (1996); 11, Taylor et al. (2001); 12,**Guharay et al** (2008); 13, Walterscheid and Schubert (1995); 14, Lopez-Gonzalez et al. (2005); 15, Oznovich et al. (1997)); 16, Viereck and Deehr (1989).

Figure 2 (a1) Observed values of η verses wave period.

Figure 2 (b) A comparison of phi values to their respective wave periods (Φ: 1, 2, present study; 3,Schubert et al. 500 km; 4, Schubert et al. 1000 km; 5, Tarasick and Shepherd 500 km; 6, Tarasick and Shepherd 1000 km; 7,Viereck and Deehr (1989); 8, **Oznovich et al. (1995); 9, Drob et al. (1996); 10, Reisin and Scheer (1996); 11, Taylor et al. (2001); 12, Guharay et al.(2008); 13, Walterscheid and Schubert (1995); 14, Lopez-Gonzalez et al. (2005); 15, Oznovich et al. (1997); 16,Viereck and Deehr (1989);).**

Figure 2 (b1) Observed values of Φ verses wave period.

Figure 2(c) Deduced vertical wavelength (VW) for both the short and long period wave as function of wave periodicity. Also shown comparison with values obtained by other investigators.

Figure 3(a) Comparison with η calculated by observation of both year and Full wave model simulation with their respective wave period. Pink and olive lower half filled square shows the 2010 and 2011 year η observations **(1 and 2 present study η: 3,FWM simulation of η for 50 m/s horizontal phase velocity; 4, FWM simulation of η for 100 m/s horizontal phase velocity; 5, FWM simulation of η for 150 m/s horizontal phase velociy)**.

Figure 3(b) Simillar as figure 3(a) but for phase values for both the short and long period wave.

Figure 3(c) Simillar as figure 3(a) but for deduced vertical wavelength (VW).

Figure 4. The monthly (February, March and April) mean values of OH emission rates are shown in plot (which are obtain from SABER data) . **The solid lines plot the data for the year 2010 while the dashed lines represent the year 2011.**

Table 1. Comparisons of deduced wave parameters in 2010,2011 years with MEI index and OH altitudes. The observed quantities are mean for their representative wave periods. (JFM-January, February and March months like this)

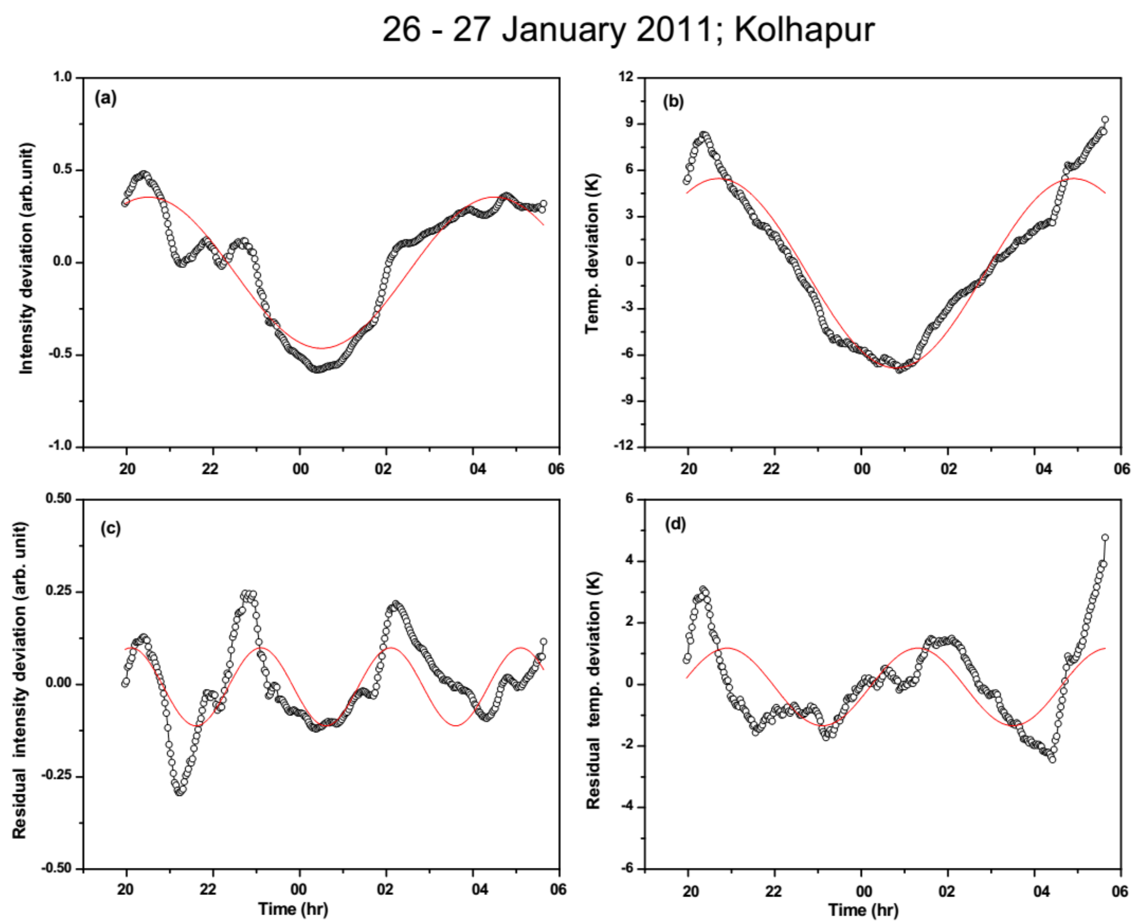

26 - 27 January 2011; Kolhapur
(a)
Intensity deviation (arb.unit)
(b)
Temp. deviation (K)
(c)
Residual intensity deviation (arb. unit)
Time (hr)
(d)
Residual temp. deviation (K)
Time (hr)

Figure 1.

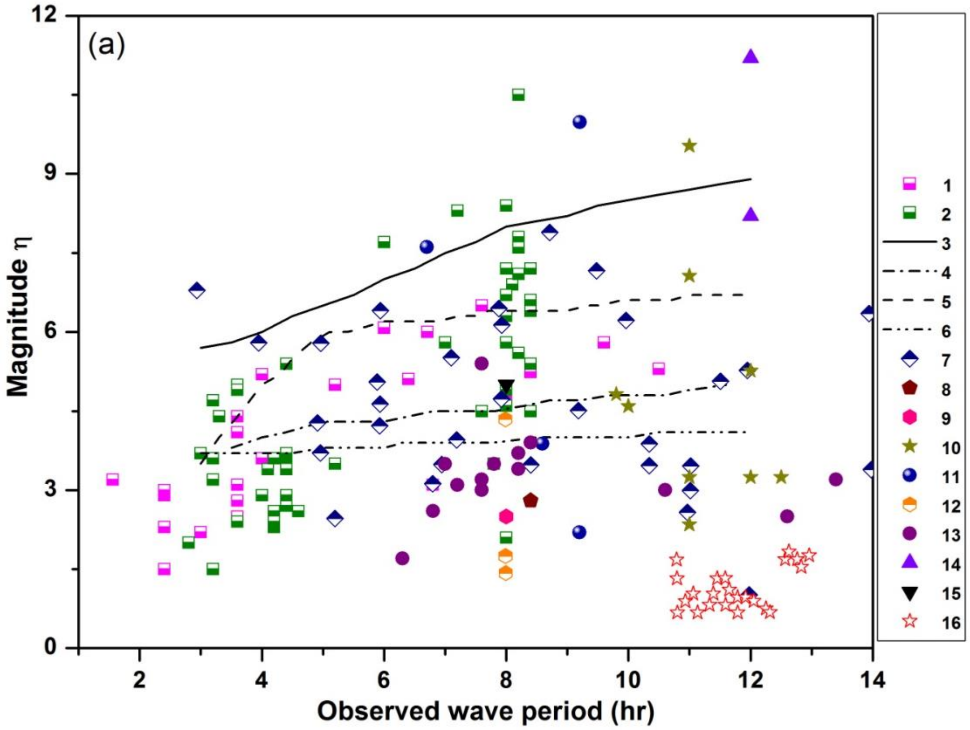


Figure 2(a)

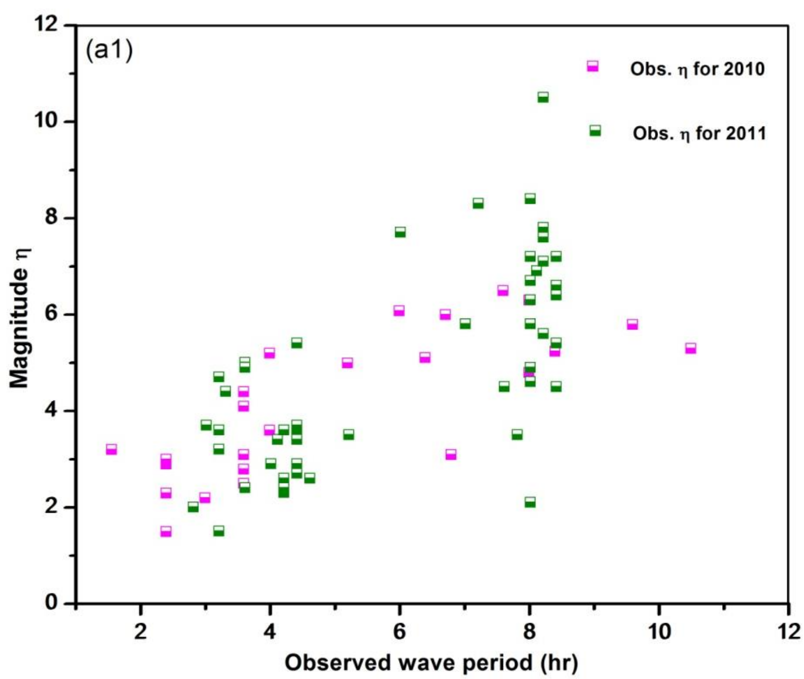


Figure 2(a1)

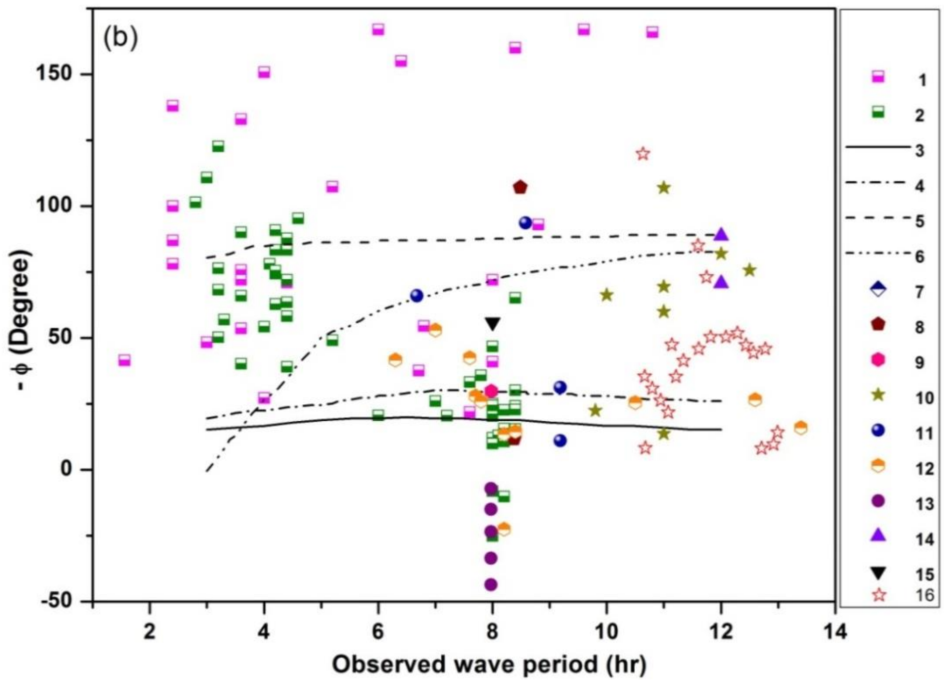


Figure 2b

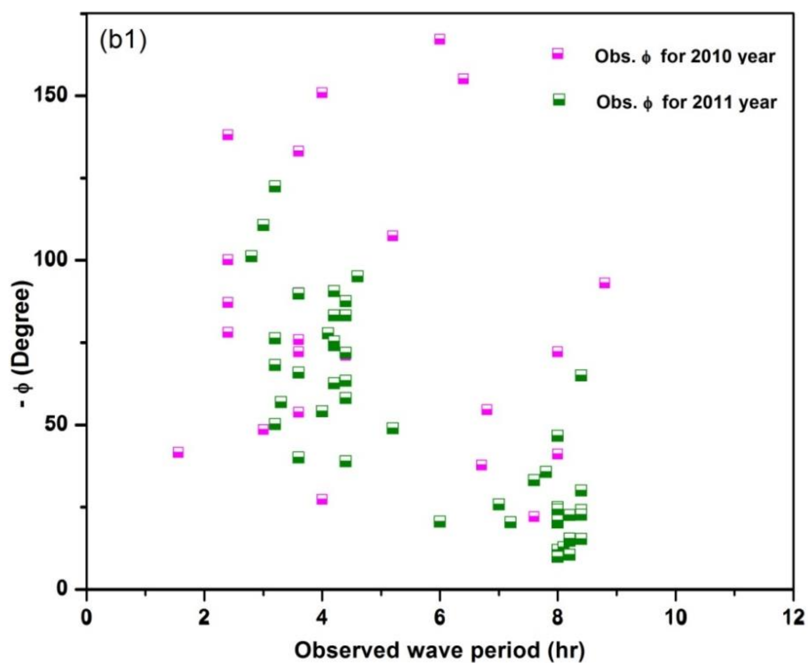


Figure 2(b1)

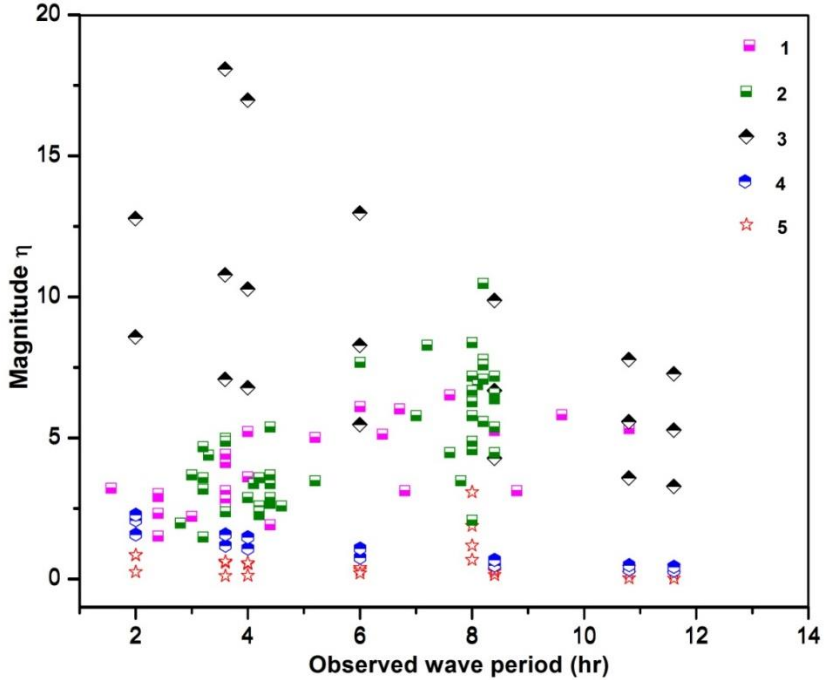


Figure 2(c)

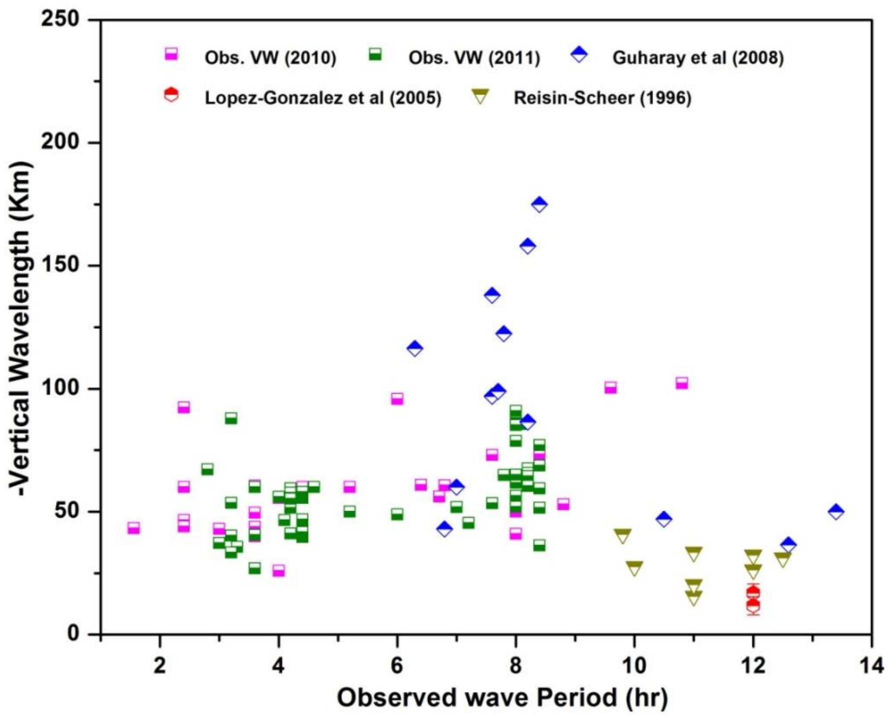
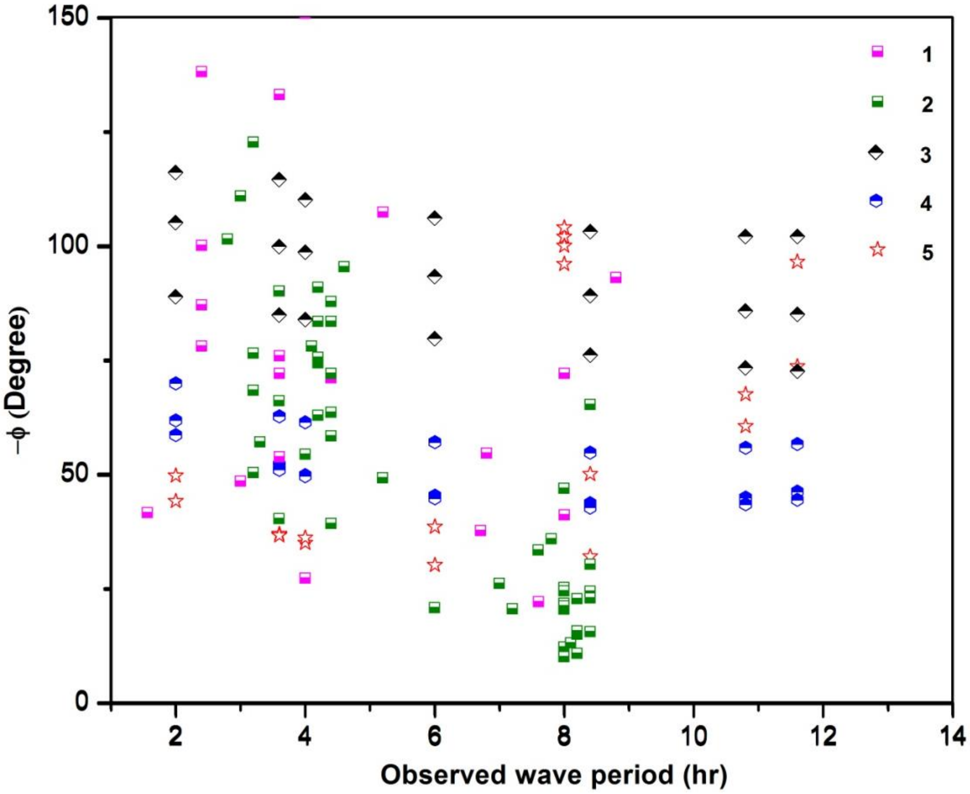
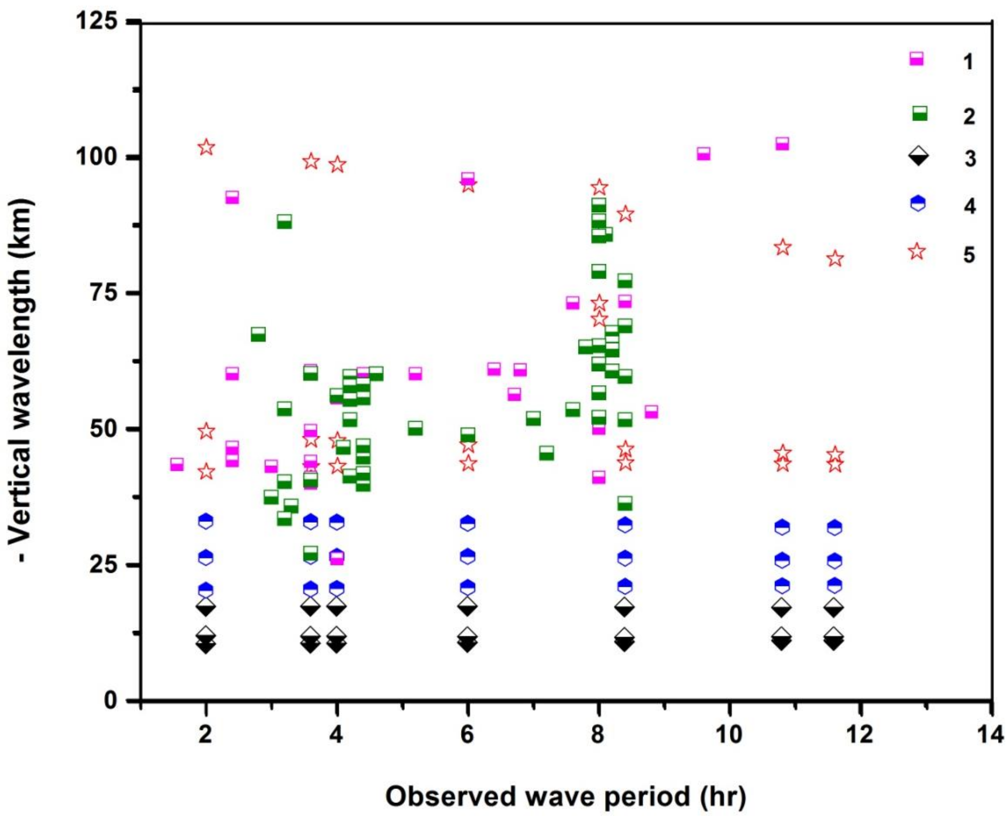


Figure (3a)



150
100
50
0
2
4
6
8
10
12
14
−ϕ (Degree)
Observed wave period (hr)
1
2
3
4
5

Figure 3(b)



125
100
75
50
25
0
2
4
6
8
10
12
14
- Vertical wavelength (km)
Observed wave period (hr)
1
2
3
4
5

Figure 3 (c)

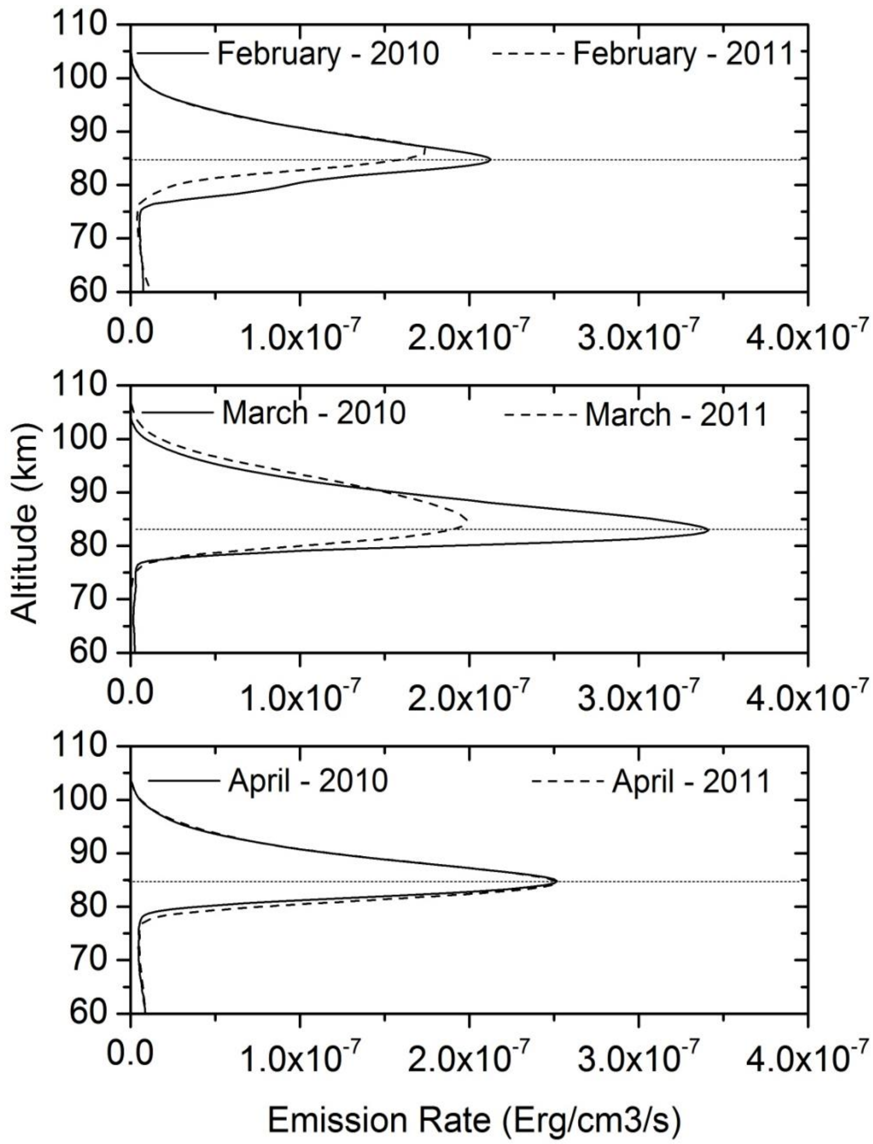

February - 2010
February - 2011
March - 2010
March - 2011
April - 2010
April - 2011
Altitude (km)
Emission Rate (Erg/cm3/s)
110
100
90
80
70
60
0.0
1.0x10-7
2.0x10-7
3.0x10-7
4.0x10-7

Figure 4.

Table 1.

Year	**Mean η** (± Errors)		**Mean (-Φ)** (Deg.)		**Mean (-VW)** (km)		**OH altitude** (km)	**MEI index**				
	Long wave period	Short wave period	Long wave period	Short wave period	Long wave period	Short wave period		JFM	FMA	MAM	SON	OND
2010	4.4 ± 1	2.3 ±0.9	90.6±40	70.4± 45	60.2 ± 20	42.8 ± 15	82 km to 85.1 km during February – April	1.1	0.8	0.5	-1.4	-1.3
2011	5.7 ± 1.7	2.7 ±0.6	33.8±40	64.4± 40	77.6 ± 40	59.2 ± 30	85.1 km to 86 km during February – April	-1.1	-0.8	-0.6	-0.9	-0.9