Interactive comment on “New image measurements of the gravity wave propagation characteristics from a low latitude Indian station”

We thank reviewer for suggesting us the improvements in the manuscript. The responses and modifications made in the manuscript are in bold fonts.

Anonymous Referee #1

Individual scientific questions/issues ("specific comments"):

Q1.The paper does not detect wave sources, but can only suggest possible source regions with strong convection which show in the monthly mean OLR plots (items 46, 52, 58 in my list below). In one case, wind shear is mentioned as a possible source, but it is not clear whether the paper cited refers to this case (item 57).

Response: In order to identify the exact source mechanism we have use reverse ray tracing techniques also. These results are now discussed in detail. [specifically at pages Page : 5-6, line: 9-28; 1-12; and in section 3 result and discussion]

Q2.There is more papers with imager results from India in the literature than the one paper of 2013 which the authors mention (Mukherjee, 2003; Pragati et al. 2010; Mukherjee et al. 2010; Parihar and Taori, 2015, see item 15).

Response: Above mentioned articles are referred in this modified manuscript at Page: 2-3; line: 30-33; 1-10;

Q3.The maximum horizontal wavelengths observed may be more a result of the details of the image analysis and the reduced field-of-view, and not something requiring a geophysical explanation (item 12 and also items 20, 42).

Response: The geophysical explanation was removed and the manuscript has been modified at Page: 7; line: 23-26.

Q4. Instead of summarily stating that "most" waves go in a certain direction, numbers Should be given (item 49), and for the other months/years. Maybe in a table?

Response: Table 1 has been added as suggested

Additional Questions:
More technical (and language) corrections (most referring to style/clarity):

Nine of the reference in Table 1 are not in the refs list: item 72 (Takahashi 1999, Suzuki 2004, 2009ab, Medeiros 2007, Wrasse 2006, Li 2001ab, Matsuda 2014).

Response: References are added in the present manuscript.

Page by page list of issues/suggestions/comments:

1. Title: "New" is a bit provocative. Have there been previous imaging observations from Gadanki against which you need to discriminate? How about mentioning Gadanki, instead of "New"?

Response: Title of the present manuscript is changed.
Page: 1; line:1-2;

Remove all uninformative verboseness, as in some of the following items:

2. P8232 L2: better, change to read "We report on observations of O(1S) 558 nm airglow with a CCD based all-sky camera from the low lat station Gadanki...."

Response: Corrections have been done. Line 10-11;

3. L4: "Three years of ... data during March and April" change order -> "data during March and April over three years", to avoid false impression that you have "three years of data". Somehow, deal with the ’missing March 2013 problem’, maybe by adding "(except for March 2013)".

Response: Modified. Page: 1; line: 11-13;

4. L5: "We noted... to occur" is unnecessarily subjective (as if there might have been more events, but you did not notice). Better, "50 strong gw and 19 ripple events were detected".

Response: Modified. Page: 1; line: 13-14;

5. L7: "hor. wavel. from 12 to 42 km and phase velocities from 20 to 90 km were found". According to section 3 (and figure 3), the phase velocities are m/s, not km!

Response: Modified. Page: 1; line: 15;

6. L10: "most possible reason for the generation" -> "was probably the source..."

Response: Modified. Page: 1; line: 17-21;

7. L13: delete "be caused due to" -> "often attributed to the energy and momentum..."
(unless that sounds too tentative; alternative: "is due to energy and momentum deposition...").

Response: done. Page: 1; line: 24-25;

8. L15: "observe" does not go with "activities"; gws are observed, activity is measured
(or determined).

Response: Modified. Page: 1; line: 25-26

9. L17: observations are not techniques; radars, etc. are instruments. Better: "there
are many techniques... atmosphere. Radars, lidars, ...rocket and satellite instruments
have been used".

Response: Modification has been done at Page: 1; line: 26-29

10. L18: "lack of suitable instruments" sound as if imagers are completely new, but there is a considerable literature on imager observations from many places in the world. Your table 1 is testimony to this.

Response: modified: Page: 1-2; line: 29; 1-2;

11. L24: delete "characteristics" since "provides the temporal evolution" is enough.

Response: deleted. Page: 2; line: 5

12. L26: why only a horizontal distance of 200-250 km? Doesn’t that depend on the angular size of the field of view? The fov has no impact on observed periods and vertical wavelengths. It may help to point out that beyond the distance mentioned; there is loss of spatial resolution (if this is what limits horizontal range).

Response: Reviewer is correct that the horizontal distance is mainly limited by the angular size of the field of view. Though the FOV of the airglow imager is 180 degrees, our imager field of view is restricted by 117 degrees due to the background walls of our laboratory aimed to restrict the ambient illumination. Thus, the image covering area of the corresponding FOV at mesospheric altitude is ~200-250 km.

Modified at page 2 in line 8.

13. P8233,L2: change "Liu, 2003" to read "Liu and Swenson, 2003"

Response: done. Page: 2; line: 10-11

14. L3: "Since about a decade...", but you cite 1988, 1999, that’s almost three decades now!

Response: modified. Page: 2; line: 12

15. L22: "only one report" from India? The paper cited claims to be "the first study on the statistical characteristics of high frequency gravity waves over Indian sector covering all the seasons", though this is based on 35 nights of observation..

Response: Introduction of the present manuscript is modified according to the reviewer’s comments

16. L26: as in the abstract, also here a more "logical" (?) order is "during March and April, from 2012 to 2014". But, the lack of March 2013 observations and small number of April 2013 results should be mentioned early enough (here?). Spells of bad observing conditions cannot be avoided.

Response: modified. Page: 3 ; line: 15-22

17. L28: disadvantage of "for the said duration" is that the reader may feel he must now remember what the duration was and so interrupt his reading, while in fact the sentence is not meant to require this information to be understandable. So, better, change to read "...gravity wave characteristics and that the probable wave sources lie in the..." (there is no need to explain that the same waves are referred to).

Response: modification has been done. Page: 3; line: 15-22

18. P8234L1: sentence becomes too long, and the topic changes! Better, stop after "processes" and start next sentence about the information source "Thereby, we make use of daily mean outgoing....".

Response: modified. Page: 3; line: 15-22

19. L4: The only previous mention of "NARL" was in author affiliation. Not all readers can be expected to remember this, and not be confused by recent acronyms (OLR, NOAA), so better, explain or avoid this acronym, here. Hint: introduce the NAI (NARL Airglow Imager) acronym separately, in the next sentence. For example, like this: "The all sky airglow imager of the National Atmosphere Research Laboratory has been installed... in March 2012. Since then, this NARL Airglow Imager (NAI) has carried out...".

Response: Modifications have been done. Page: 3; line: 25-28

20. L7: aha! this 117 deg. fov must be the reason why the size of the observable field was earlier stated as being 200 to 250 km (however, that was in a general context, Without the space limitation of your laboratory!).

Response: Yes.

21. L13: "after passing through interference filters" is not useful; It is already understood that light must first pass a filter (not several filters, simultaneously), so, better delete this. Also, "to converge the optical rays" does not sound good (and the construction of the sentence is not logical, because what passes the filter is light, but the subject changes to "camera lense". Better stick to something simple like "A camera lens focuses the light on the PIXIS... CCD sensor, which is thermoelectrically cooled...".

Response: modified. Page: 4; line: 2-5

22. L15: "before the operation" must be some leftover from editing; delete! What is the "final" image? There is no previous, or preliminary one, so better, delete.

Response: deleted. Page: 4; line: 2-5

23. L18: IMHO, "among" is not appropriate in this context (which is not "one of the following", but "all of the following"); better, "between".

Response: changed. Page: 4; line: 6

24. L19, 20: It is understood that exposure times are those given, but may be modified. Then, it is not clear what "are like this" means. Several sentences (including those I have criticized above for wording) are literally copied from the Taori et al. 2013 paper. Therefore, some reformulation is also necessary to avoid auto-plagiarism (and, -some mild form of- copyright infringement): formally, such sentences would need to be cited with quotation marks and reference!

Response: reformulated. Page: 4; line: 7-10

25. L22, 23: this information has already been given in the previous section. If really necessary to repeat this here, the authors should add "as mentioned", to avoid that the surprised reader wastes time to check whether he has seen this before. However, I rather advise to shorten as much as possible to make relevant new information stand out.

Response: modified. Page: 4; line: 11

26. L26: change "Barrel" to "barrel" (since it’s not a personal name but an old-fashioned container with the shape of the distortion)

Response: have done. Page: 4; line: 14

27. P8235L: what is meant by "sustain"? Maybe, "persist"?

Response: modified. Page: 4; line: 18

28. L4, 5: "clear" and "prominent" expresses the same thing; so, either "clear wave events were observed", or "69 wave events were prominent", or "there were 69 prominent wave events".

Response: modified. Page: 4; line: 20

29. L5 (next sentence): could be shortened without loss of information to read "Among these, 19 events did not show...".

Response: have done. Page: 4; line: 20

30. L6: I do not understand how wave motion with the background is detected. It can’t refer to background wind, because waves moving with the background wind would suffer critical level filtering.

Response: Indeed reviewer is correct. However, we have noted no evolution of structures in the case we are referring. Full structure has been found moving together without any evolution. That is the prime reason we say that those 19 wave events looks like stationary.

31. L10: "elaborate"? You mean, "mark the wave fronts", or "make the wave fronts stand out"?

Response: modified. Page: 4; line: 24-25

32. L12: while from the figure it is clear that the wave propagation direction is defined with respect to the eastward direction, this is not clear from this sentence. There is not a single "the normal point", but arrows from any point of the wavefront in a direction normal to the wavefront can be drawn. At any rate, a better explanation appears in the next sentence (L14, 15). Avoid repetition.

Response: repetition has been removed.

33. L18: "perpendicular pixels of wave phase"?, "plot the gray count values"? This may refer to the image intensity versus distance from the reference point, but needs to be expressed more clearly.

Response: Yes, the plot is intensity Vs distance only. From that intensity plots distance between two maximum (or minimum) gray scale counts taken as wavelength of a particular event.

34. P8236L4: according to Table 1, horizontal wavelengths from 12 to 45 km were found. According to the abstract, it’s 12 to 42 km.

Response: It is 12 to 42km only. Page: 6; line: 16 (see the table 2)

35. L7: replace "are having" by "have" (it is not about a process in action, just an objective statement ’after the fact’).

Response: done. Page: 6; line: 18

36. Here and anywhere else: avoid "it is noteworthy", "we note that", and similar expressions which would only be worth noting if that were not obvious. Just stating the facts is better, and usually enough.

Response: We have been careful in revised version such as to avoid such expressions.

37. L11: from figure 4 it is clear that "periodicity" just means to refer to observed periods, and should be stated like that. Formally, "periodicity" (in science) refers to the question whether something is periodical at all, but this is not a question raised in the present context.

Response: modification has done. Page: 6; line: 23

38. L15: Please, avoid expressions like "when it comes to..." which only distract from the point made (but are useful in oral presentations to give the speaker time to think and signal the audience a change of topic, but not in a written text, where a new paragraph does the job more efficiently).

Response: Modification has been done. Page: 6; line: 27

39. L16: the relevant information is in "most of the times", and "only few events". It would be more useful to give the numbers, because some of the arrows in figures 5 and 6 are not so easy to count.

Response: Tabulation has been made. Page: 16;

40. L26: "which further confirms our..."; no, an earlier paper cannot confirm a recent result, but your results may confirm an earlier one!

Response: those lines are removed from this manuscript. Page: 7; line: 11

41. L28: that table 1 does not claim to contain all existing papers is more or less obvious, so there is no need to draw the reader’s attention to the (distracting) fact. "a few earlier investigations" in the previous line already suggests such a thing (although, better change to "some earlier", because the 15 entries are more than just a few).

Response: Now, it is table 2. Relevant modification has been done as suggested by the reviewer at Page: 7; line: 17-20

42. P8237 L4,5: The most likely reason why some other researchers reported longer wavelengths may be that they used the full field of view of their imager, and a different analysis method (this is what Suzuki et al. 2004 did, if this JGR paper number D20S07 is what is referred to in your table 1, but not cited) or did not use an imager, but deduced wavelength from the phase shift between different fields of view of the three-field photometer (Ding et al. 2004).

Response: Agree, unwanted explanation has been removed.

43. L6 and many other places: replace "most of the" by "most", for brevity.

Response: done. Page: 7; line 21.

44. L12, 13: Holton and Alexander 1999 has already been cited a few lines before, in the same context (convection).

Response: removed.

45. L14, 15: replace "where based on the" by "based on".

Response: modified. Page: 7; line:28

46. L16-21: your search for plausible source locations in OLR patterns is not an "investigation" into "prime potential sources", but just a search for plausible source location candidates. This does not need to be introduced here, because the topic appears later.

Response: Modification has been done.

47. L22: replace "noted during" by "in" ("noted" is one of the examples referred to above).

Response: Modification has been done.

48. L25, 26: delete this sentence about the phase velocity scale, since it is same as figure 5

Response: removed.

49. L26, 27: shorten to read "Most of the waves propagate north-westward" (if that’s really so). Again, giving the numbers (not only for the southward cases) would be helpful.

Response: detail has been added. Page: 8; line: 24-27

50. P8238 L1, 3, 6, 8: delete "month" because "March", "April" is clear enough. It may be worthwhile to mention first of all that the information sought in the OLR patterns is deep convection corresponding to low OLR intensity, not the red that strikes the eye. The filled black circle is hardly visible in Figure 7, and looks more like a small asterisk, in Fig. 10.

Response: correction has been done. Page: 8; line: 8-22

51. L6: "It is interesting to note" distracts from the main point (though not a "fact"): the convective activity in the southwest may be the source region of the observed waves in April.
And,:
52. L9, 10: there are no "facts" about sources, only possibilities! Needs careful reformulation.

Response: With ray tracing results, we believe that the above questions have been answered.

53. L11, 12: change to read "The daily mean OLR data for this night are plotted [or rather, "shown"] separately in Fig. 8", and delete "We note that" before "There was some...".

Response: Modified. Page: 9; line: 1-7

54. L13: Delete "It is also important to note that" (also in L15), for reasons explained above.

Response: Deleted.

55. L24, 25: The lack of March 2013 data should have been mentioned much earlier, instead of creating the impression that March data for three years are available. Delete "We note that"

Response: Modification has been done.

56. L28: Delete "Important to note is that", unless it is convincingly explained why it is so important.

Response: Hope, now our content is convincingly explained by using ray tracing technique.

57. P8239 L1-4: replace "most possibly" by "may have"; wind shear source case needs a separate sentence. Did the Pramitha 2015 paper treat this case, or is the relation to that mechanism just a guess?

Response: Please note that the Pramitha et al. have investigated the source.

58. L10-15: Shouldn’t you admit that it is hard to make a convincing point from the different OLR scenarios in March and April, in the face of the similar observed wave propagation characteristics? Better, reformulate.

Response: We hope there is no need of reformulation now. Reverse ray tracing termination point and OLR were clearly support to our assumption.

59. L19: again, "10 to 45" conflicts with table 1 (and the abstract)

Response: Correction has been done. Page: 10; line: 20

60. L23-25: "which suggest that..." isn’t this rather what you assume, and which the OLR distribution does not contradict?

Response: modified.

61. L25-end of paragraph (next page): This topic of alleged ionospheric effects (?) of gravity waves comes as a surprise, without an evident relation to the content of this paper. If this is an expression of the opinion that ionospheric variability may owe a lot to gravity waves (that is, neutral dynamics), this would be a valid point, but the message does not come out as clear as it should.

Response: removed.

62. P8240 L2, 3: There is no need to point out what future studies might deal with, and it does not sound convincing that future studies will identify the sources of the present 50 (?) wave events more precisely.

Response: modification has been done. Page 10; line: 21-28.

References:

63. L10: missing initial "Alexander, M.J."; capitalize "Propagation from..."

Response: done.

64. L16: missing coauthors "Shiokawa, K., Ogawa, T., Igarashi, K., Nakamura, T., and Tsuda, T."

Response: co-authors names added.

65. L21: "convention" is a typo already in the Holton paper, but there can be no doubt that it should be "convection", as in Joan Alexander's web site. The journal version is Tellus A and B.

Response: correction has been done.

66. L23: correct to read "de Grandpré, J."

Response: correction has been done.

67. L26: missing hyphens in initials of Chung "J.-K.", Kim "J.-H.", and Chun "H.-Y."

Response:

68. P8241 L7: missing coauthor of Liu, "and Swenson, G.R."; missing start of title "A modeling study of O2..."

Response: correction has been done.

69. L13: capitalize "Propagation..."

Response: done.

70. L15: missing coauthors of Nakamura, T. (2003): Aono, T., Tsuda, T., Admiranto, A.G., Achmad, E., and Suranto

Response: done.

71. Table 1: better, change caption to read "Comparison of the present results with earlier small-scale wave measurements". "earlier investigators" is not correct, "other latitudes" is not to the point (there are inputs from latitudes not very different from Gadanki), and "using airglow imaging" is not true for all sites (example: Ding et al. 2004).

Response: title of the tabulation has been changed.

72. observed period "0-50"? Takahashi et al. 1999 not in refs list; did they really publish 0 min periods? not in refs list, Suzuki et al. 2004; Medeiros et al. 2007; Wrasse et al. 2006; Suzuki et al. 2009a, b; Li et al. 2011a, b; Matsuda et al. 2014.

Response: Takahashi et al was mistakenly taken. Remaining all references were added in this manuscript.

73. Fig. 1: shorten caption, "elaborate"-> "show", delete "noted", etc. (removing all uninformative verboseness)

Response: modified.

74. Fig. 2: delete "the month of", "from", and shorten caption correspondingly. Truth is that you have March and April in 2012 and 2014, and April in 2013. Is there an elegant way to signal that? Maybe, change caption -> "...waves in March and April 2012 and 2014, and April 2013"?

Response: all figure captions has been modified.

75. Fig. 3, 4: similarly...

76. Fig. 5, 6, 9, 11: correct typo in "direction"

Response: correction has been done.

77. Fig. 8: correct typo in "occurrence

Response: correction has been done.

Mesospheric gravity wave characteristics and identification of their sources near to the spring equinoxial months over Indian low latitudes

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Abstract

We report OI557.7 nm night airglow observation with the help of a CCD based all-sky camera from a low latitude station, Gadanki (13.5°N; 79.2°E). Based on the data collected during March and April over three year, from 2012 to 2014 (except March 2013), we characterize the small scale gravity wave properties. During this, 50 strong gravity wave events and 19 ripple events were detected. The horizontal wavelengths of the gravity waves are found to vary from 12 km to 42 km with the phase velocity ranging from **20 to 90 m/s**. In most cases, these waves were propagating towards north with only a few **occurrence** of southward propagation. **The outgoing long wave radiation (OLR) suggested that tropospheric convection was a possible source for generation of the observed waves. In the present novel investigation from Indian sector, each of the wave event were reverse ray-tracked to their sources. It was found that approximately 66% of the events were triggered directly by the convection.**

Introduction

The variability in the middle atmospheric parameters is often attributed due to the energy and momentum deposition by gravity waves [e.g., *Fritts and Alexander,* 2003]. There are many techniques to study the gravity wave activities in the middle and upper atmosphere, such as radio, optical and insitu as well as space borne. In order to observe the gravity wave parameters in the atmosphere, radars, lidars, photometers, rockets and satellite instruments have been used [e.g.,*Smith,* 2012]. However, **small scale gravity waves remain the least understood due to the instrumental limitation which can provide the** scale sizes, propagation direction together with its temporal evolution characteristics. In this regard, ground based airglow imaging is an important tool to estimate the gravity wave signatures. The primary advantage of the imaging is that it provides a 2 - dimensional view at the chosen airglow emission and thus it has the capability to determine the horizontal scales and propagation direction of the gravity waves. Further, at a given place it provides the temporal evolution of the gravity wave induced oscillations. As the field of view of imagers at mesospheric altitudes may cover a horizontal distance of **300 – 350 km**, such measurements are highly suited for the waves having small scales (horizontal wavelength < 150 km), short periods (periods < 1 hour) and long enough vertical wavelengths (>10 km**) [*Liu and Swenson*, 2003]**.

Since **about last three** decades, capabilities of airglow imaging have been widely utilized to analyze the gravity wave characteristics [e.g., *Taylor and Hapgood*, 1988; *Nakamura et al.*, 1999; *Walterscheid et al.*, 1999; *Medeiros et al.*, 2003; *Ejiri et al.*, 2003; *Kim et al.*, 2010; *Li et al.*, 2011a,b]. Particularly, *Nakamura et al.*, [1999] utilized 18 months of OH imager observations at Shigaraki (34.9° N, 136.1° E) and reported that the gravity waves propagated eastward (westward) in the summer (winter) with horizontal wavelength varying from 10 km to 45 km. *Medeiros et al.*, [2003] analyzed 12 months observation at Cachoeira Paulista (23° S, 45° W) and found that gravity waves exhibited preferential propagation directions, with southeast propagation in the summer and northwest in the winter with wavelength range 5-60 km. Using 1 year OH Meinel and OI (557.7 nm) band image data at Rikubetsu (43.5° N, 143.8° E) and Shigaraki (34.9° N, 136.1° E) in Japan from October 1998 to October 1999, *Ejiri et al.*, [2003] reported that gravity waves propagated mostly to the north or northeast during in summer at both sites with wavelengths in the range 10-58 km. However, gravity waves propagated to the west at Rikubetsu and to the southwest at Shigaraki in winter. In a more recent report, *Kim et al.*, [2010] used OH, O_2 and OI557.7nm data from Mt. Bohyun, Korea (36.2° N, 128.9° E) and found that gravity waves propagate westward during fall and winter and eastward during spring and summer. The wavelengths were found to be in 10-45 km range.

From Indian sector, there are few reports [*e.g.Mukherjee 2003, Mukherjee et al 2010, Pragati et al 2010, Lakshmi Narayanan and Gurubaran, 2013., Parihar and Taori 2015*] which documents the small scale gravity waves characteristics. For example, using five months of OH airglow imager data during January to May, 2008, at Allahabad (25.45°N, 81.85°E), *Pragati et al [2010]* reported that most of the small scale gravity waves propagates towrads North and North-East direction in March and May. Further, using the same data set *Mukherjee et al [2010]* studied the wind filtering effect of the gravity waves. Likewise,

using one year of airglow imager data during 2007 *Lakshmi Narayanan and Gurubaran, [2013]* reported the seasonal variation of the gravity waves characteristics over Tirunelveli (8.71° N, 77.81° E). Recently, *Parihar and Taori [2015]* investigated the long distance propagating gravity waves using the coordinated bi-station airglow data (Airglow photometer over Gadanki (13.5° N, 79.2° E), and all sky airglow imager over Allahabad (25.5° N, 81.9° E). They concluded that convection might be a source of the noted long distance gravity wave events. However, none of these reports addressed the exact sources of the waves.

It is important to note that being a tropical location, the availability of optically clear sky makes the statistics biased. Therefore, in the present report we have taken the data in March-April 2012 and 2014 and April 2013, when the maximum number of cloud free nights are monitored [e.g., *Taori et al.*, 2012] over Gadanki (13.5° N; 79.2° E). First time in indian sector, we show the gravity wave charactistics together with the reverse ray-traced sources of these waves. We use outgoing Long wave radiation (OLR) obtained from the National Oceanic and Atmospheric Administration (NOAA) and a reverse ray tracing analysis for the above purpose.

Instrumentation and data analysis

The all sky airglow imager of the National Atmosphere Research Laboratory (NARL) has been installed in March 2012 at Gadanki (13.5° N, 79.2° E) in March 2012. Since then, this NARL Airglow Imager (NAI) has carried out regular night airglow observations during moonless, cloudless nights. The front optics of NAI uses a fish eye lens **having a field of view (FOV) 180°** (**current FOV is limited to 117° due to NAI housing to avoid the background illumination at low elevation and to avoid nonlinearity of the pixels at higher zenith angles**). Its filter chamber contains three different interference filters, namely 840 nm for OH emission (peak altitude ~87 km), OI557.7nm emission (peak altitude ~97 km) and **OI630 nm** emission (peak altitude ~250 km). In order to maintain the constant temperature a thermo-electric temperature controller is attached to the filter chamber. **A camera lens focuses the light on the PIXIS-1024B CCD sensor, which is thermoelectrically cooled**. **In the present set-up, we bin the images to 2 x 2 pixels making an effective 512x512 super pixel image on the chip to enhance the signal-to-noise ratio**. Depending on the compromise **between** the background luminosity, interference filter transmission and actual airglow brightness, at **current** exposure time are **15s for OH and 110s for both, OI557.7nm and OI630 nm emission monitoring. The**

imager was optimized to view OI557.7 nm as well as OI630 nm emissions together with OH (840 nm). Further details about the NAI are given in *Taori et al.*,[2013].

In this present study, using earlier mentioned dataset, we could get 32 clear sky night data. From raw images we have cropped the images for 117° full field of view to remove the background walls of our laboratory from the images. Further, we **unwarped** the images for **barrel** distortions to linearize the scales. **This however, does not introduce any significant difference in the wavelength estimation as the error is a function of pixel size on which the image is focused, which in the present case is ~0.8 km.** At last **we enhance the wave fronts** by contrast adjustment (for better visibility). In order to remove the stars we **used a** median filters. In thus obtained, processed images, continuous bright and dark band which **persist** in more than three consecutive images are considered as the structure depicting a wave event**.** This analysis is performed on all the data. We note that in 32 days of data**, 69 wave events were prominent**. **Among these, 19 events** did not show any phase propagation and were moving with its background. Those wave events are considered as ripples (which may be arising due to Kelvin Helmholtz instability occurring due to the wave dissipation) and thus have not been considered as propagating gravity waves. An example of a gravity wave event is shown in **figure 1.** In this figure, **green color box emphasize the presence of consecutive bright and dark bands.** The propagation is identified by cross correlating the position of these fronts from one image to another in consecutive images. Further, the estimate of propagation angle is done by measuring the angle between the yellow line (shown as a yellow line with an arrow indicating the direction of propagation) with the horizontal line parallel to **the north** direction. In order to get the horizontal wavelength of the observed wave event, we took the perpendicular pixels of wave phase (yellow colored arrows) and plot the gray count values. The distance between two peaks provides the horizontal wavelength estimates (in this particular wave event horizontal wavelength is estimated to be ~14 km). To calculate **a** phase velocity (Vp=displacement/time-difference) of the wave event, first we calculate the phase displacement of the wave from one image to the other (for example, if the position of a wave phase is (x_1, y_1) in the first image and in the second image the position is (x_2, y_2), then the displacement is defined as, $d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$). In the case shown, the observed phase velocity is ~23 m/s, the angle of wave propagation is ~55°.

We performed this analysis on the full data set (i.e., 50 wave events of which 21 events in the year 2012, 5 events in the year 2013 and 24 events in the year 2014) and wave characteristics obtained as explained above are presented in this report.

2.1 Ray tracing method:

According to the formalism of *Lighthill [1978]*, if a gravity wave packet is propagating in a fluid with the background wind $\vec{V}(\vec{x}) = (u, v, w)$, then its evolution can be described by:

$$\frac{dx_i}{dt} = V_i + \frac{\partial \omega_{Ir}}{\partial k_i} = V_i + c_{gi} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

and

$$\frac{dk_i}{dt} = -k_j \frac{\partial V_j}{\partial x_i} - \frac{\partial \omega_{Ir}}{\partial x_i} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2)}$$

where $\omega_{Ir} = \omega_{Or} - \vec{k}.\vec{V}$ is the intrinsic frequency of the gravity waves, ω_{Or} is the observed frequency, $\vec{k}$ is the wave vector, $\vec{x}$ is the position of the wave in a given time, c_{gi} is the group velocity, $i, j = 1, 2, 3$ and repeated indices imply a summation. It means that the temporal evolution of a gravity wave in the atmosphere can be followed if its position and wave vector are known, in a given time, However, the knowledge of background wind and temperature are necessary as well.

In the present work, all of 50 observed gravity waves were reversed ray traced, in order to investigate the likely sources of them in the troposphere. The initial position of the gravity waves has been assumed to be equal to the geographic coordination of the observatory and the altitude of the OI557.7nm airglow layer peak, i.e., $\vec{x}(t = 0) = (x, y, z) = (79.2^o\text{E}, 13.5^o\text{N}, 97\ \text{km})$. The initial wave vector was taken from the OI557.7nm images and from the dispersion relation, that is, $\vec{k}(t = 0) = (k, l, m) = \left(\frac{2\pi}{\lambda_x}, \frac{2\pi}{\lambda_y}, m\right)$, where $\lambda_H^2 = \lambda_x^2 + \lambda_y^2$ is the horizontal wavelength. The vertical wave number at the OI557.7nm layer was obtained using the *Marks and Eckermann [1995*] dispersion relation, which excludes acoustic waves, i.e.,

$$m^2 = \frac{(k^2 + l^2)N^2}{\omega_{Ir}^2} - (k^2 + l^2) - \frac{1}{4H^2} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3)}$$

where N^2 is the buoyancy frequency and H is the scale height.

The background wind used as the input to the ray tracing model was based on the Horizontal Wind Model *[HWM-07; Drob et al., 2008]* and the temperature profiles were obtained from Naval Research Laboratory Mass Spectrometer and Incoherent Scatter Radar model *[NRLMSISE-00; Picone et al., 2002]*. In addition, comparison between the ray

paths for the gravity waves using the HWM model and no wind conditions were made in order to evaluate the effects of the wind in the propagation of the gravity waves. Further description about this ray tracing model can be found in [*Vadas and Fritts 2005,2009 and Paulino et al., 2012]*.

Results and Discussion

First, we present the composite results for the years 2012-2014 to show the overview of the results. We note that horizontal wavelengths of the observed wave events are found to vary from 10 km to **42 km** (**figure 2**). Among this distribution, about half of the wave events **have** their horizontal wavelengths in 10-25 km range and 22% wave events were noted in 30-35 km wavelength range. It is evident from **figure 2** that more than 90% wave events are **have** their wavelength less than 35 km. The estimated horizontal phase velocity distribution of the observed wave events is shown in **figure 3**. Phase velocity of the noted wave events are vary from 20 m/s to 90 m/s. From this ~78% of the wave events show the phase velocity less than 50 m/s. Using the observed horizontal wavelength and phase speed we have calculated the **phase period** of the observed wave events which is shown in **figure 4**. The periods of observed gravity waves are found to be in 4 min to 20 min range. And about 90% waves have their periods in 6 min to 15 min range with only 1% of waves having their periods more than 15 min.

Wave propagation and sources of the wave:

In Figure 5(a) (polar plot) shows the horozontal propagation direction of the small scale gravity waves (left panel) and Figures 5b, c (right side) show the reverse ray paths [with zero wind condition (Fig 5b) and with estimated HWM model winds (fig 5c)] and their termination points. In the polar plot, red colored arrows indicate the wave propagation angle in March 2012 and 2014 and blue color arrows indicate the wave propagation angle in April 2012, 2013 and 2014. The dotted circles denote the horizontal phase velocity of the observed wave events with an interval of 20 m/s. Similarly, in right side plots red line(dot) indicates ray path(termination point) in March and blue line(dot) indicates ray path(termination point) in April. Most of the time waves propagate towards north with only few events showing southward propagation (details of the wave propagation in different directions are given in **table 1**). An earlier report from Indian subcontinent by [*Lakshmi Narayanan and Gurubaran*, 2013] from Tirunelveli (8.7^{o} N), based on data corresponding to the year 2007 suggested that during equinox season waves mainly propagate towards the north**, presnet study also shows similar result**. As the waves propagate away from their source regions [e.g., *Pautet et al.*, 2005], it is prudent to suggest that the wave generations must be located somewhere in the south of the measurement location. In oder to identify the exact source mechanims we use reverse ray tracing technique that results are shown in righ side of the figure 5(b,c). Then we have compare the dermination points with NOAA daily mean OLR data. (the results are discussed in next paragaph).

A comparison of our results with some of the earlier small scale wave measurements is made in table 2 (please note that the list is not exhaustive). It is to note that, the wavelengths, phase velocity and observed wave periods are within the range reported by the earlier investigations. Further, as most small scale waves observed in mesosphere have their origin in lower atmospheric processes such as tropospheric convection, wind shear, wave-wave interaction or secondary wave generation [e.g., *Alexander*, 1996; *Holton and Alexander*, 1999; *Pandya and Alexander*, 1999; *Piani et al.*, 2000; *Fritts and Alexander*, 2003; *Taori et al.*, 2012; *Pramitha et al.*, 2015]. Numerous modelling as well as experimental evidences over equatorial latitudes suggest that most small scale waves with periods less than an hour have their sources in convective processes [e.g., *Horinouchi et al.*, 2003; *Nakamura*, 2003; *Pautet et al.*, 2005]. Of the particular relevance to our observations is the report by *Pautet et al.*, [2005], **based on** the 19 wave events it was clearly shown that waves were generated by the convection and propagated away from their sources (convective clouds). We investigate whether convection and associated processes are the prime potential sources for the perturbations noted in the middle atmosphere and ultimately were reflected in the upper mesospheric altitudes. For this, we carry out reverse ray tracing analysis (as mention earlier) and subsequently the termination points were compared with the daily mean NOAA-OLR**. The present investigation shows about ~66% wave events the soruces were located within the convective clouds and for another ~14% of wave events, source were located nearby the convective region. Remaining 20% wave events were generated purely by the non convective sources**. Further, to understand the monthly and yearly variation of the source region, we look into **average of the daily mean** NOAA-OLR for the days when airglow observations were made.

Figure 6a left side (polar polt) shows the propagation direction and phase velocity of the wave events noted in March-April 2012 and right side plots show the reverse ray tracing paths with their termination points (top panel show ray paths for zero wind condition-Figure 6(b) while the bottom panel show ray paths using HWM model wind Figure 6(c)). Similar to the figure 5 left side (polar plot), red colored arrows indicate the wave propagation angle in March and the blue color arrows indicate the wave propagation angle

in April. Likewise, in right side plots red line (dot) indicates ray path (termination point) in March and bule line (dot) indicates ray path (termination point) in April. Further, out of 21 wave events 14 wave events are propagating towards north-west. Few waves were travelling towards the north-east while only 2 wave events having their propagation towards south. Ray path also shows the similar result but in opposite direction. **The average of daily mean OLR data during the observations is plotted in Figure 7. In the OLR low intensity (<200) belongs to the deep convection. The left map shows the averaged OLR values for March month while the right map is for April 2012. The location of measurement is shown as asterick**. **It is clear that** during the March month there is a deep convection occurring at the **southeast part of the map** hence the waves propagating away from these sources shall have the propagation in the north-west direction which is consistent with the observations. It is interesting to note that during April month apart from the deep convection at the southeast location, there is a convective patch on the southwest **side of the map**. In this regard, observations suggesting that in the April month waves propagated in the north-east and northwest directions (in figure 6a) are consistent with the fact that their sources were associated with the convective plumes noted in the OLR data. There are two wave events which show southward propagation (on 27 March 2012) which we showcase as special case in the following.

On 27 March 2012, we noted four wave events, two of them propagating towards north-west and another two waves progressing to the south-east (as mentioned earlier). On this night, the daily mean OLR data and reverse ray paths are plotted in figure 8. There was some convective process occurring in the north-west locations as well as a strong convection in south-east location. Together with the OLR patches, the ray path also terminates nearby the convective locations. There were some isolated convective process at 20^{o}N,76^{o}E (source, http://www.mosdac.gov.in) which may have triggered these waves. We reemphasis that only those events which could overcome the wind filtering mechanisms could be observed. Typical zonal and meridional winds during March-April months over Tirunelveli (8.7^{o} N,77.8^{o} E) are reported to be ~15 m/s and 18 m/s [*Sivakandan et al.*, 2015] in 85- 100 km altitude range, and also that Horizontal Wind Model (HWM-07) wind estimates also suggest the maximum winds to be less than 20 m/s at these altitudes. Thus, waves having their phase velocity more than 20 m/s will not be blocked by the horizontal winds and may propagate to their preferred directions governed by the source properties. We believe that this is the reason we noted the waves have their phase velocity more than 20 m/s. Taking the above into the account, we believe that this event of abnormal wave propagation has been well captured by the reverse ray tracing analysis.

As mentioned earlier, the NAI could not be operated during March 2013 however, the propagation and phase velocity of the wave events noted in April **2013 as well as their reverse ray path results were plotted in Figure 9.** Out of 5 wave events, 3 waves were propagating to the northeast directions, 1 was propagating northwestward while 1 wave was propagating to the **southeast and the ray paths were derminates opposite to the wave propagation direction. Further, important think is that all** the waves had their phase velocity higher than 20 m/s. **The OLR data** corresponding to April 2013 events are plotted in **figure 10** where it is clear that there were convective regions in the southern side of the measuring site which most possibly triggered the waves which were propagating to the northeast and northwest directions with one of the event propagating to southeast direction, on this day **daily mean OLR shows convective region at around 20^0 N lat; 70^0E lon (figure not shown here). Furtther, as in earlier cases, for all these wave events ray path also terminates to the convective region**.

The left side (polar plot) plot depicting the gravity wave propagation direction and phase velocity and right side plot depicting the reverse ray tracing results corresponding March-April 2014 is shown in **figure 11a,b,and c**. This year wave directions show deviations compared to the year 2014. In year 2012 waves propagated dominantly to the northwest while in 2014 waves are moving towards northeast with a substantial number of waves in southward directions. Similarly, ray paths terminate opposite direction of the wave propagtion shown in figure11 b,c. The OLR corresponding to the March and April 2014 are shown in **figure 12**. It is to **note** that there are convective processes occurring in southward as well as northward directions and thus the waves triggered by these sources are reflected in our measurements. Our ray racing results also conforming this. However, from the ray tracing termination point it is clear that, the waves propagating almost in zonal directions are not generated by the **convective origin. Of this, one of the event was discussed earlier to be caused by the wind shears [*Pramitha et al.*, 2015]. Other sources may be mesospheric-thermospheric body forcing, secondary waves [*e.g., Fritts and Alexander, 2003; Vadas and Fritts, 2009; Vadas and Liu, 2011*], where convection may ramain as a prime source (~66%) of gravity waves.**

Summary

The image measurements of OI557.7nm nightglow during the spring season over Indian low latitudes show conspicuous signatures of upper mesospheric waves. The horizontal wavelengths ranged from 10 km to **42 km** and were mostly found to propagate towards the north side of the location of the measurements. Over the Indian subcontinent, often the lower atmospheric convection activities occur at the southern side of the location which we have also noted in the OLR data. The directions of wave propagation **and reverse ray tracing results were found to be consistent with the source being in the south, which suggest that ~66% observed wave events were purely generated by tropospheric convection and another 14% wave were coming from nearby the convective region. And remaining 20% waves were generated by purely non convective source mechanisms. Present investigation prominently shows that, convection and their associated process are the main source for the generation of small scale gravity wave over the low latitude Indian sector.**

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Table 1. Predominnent wave propagation directions in different months.

Month and year	wave propagations in different direction				Total
	East (46-135)	South (136-225)	West (226-315)	North (316-45)	
Mar-12	Nil	2	2	10	14
Apr-12	2	Nil	1	4	7
Apr-13	1	Nil	Nil	4	5
Mar-14	1	2	1	5	9
Apr-14	3	2	Nil	10	15
Total	7	6	4	33	50

Table 2. Comparison of the present results with earlier small-scale wave measurements.

Station	Latitude, Longitude	Horizontal wavelength (km)	Phase speed (m/s)	Observed period (min.)	References
Shigaraki	35^{o}N,136^{o}E	5-60	0-100	0-30	Nakamura et al. (1999)
Rikubetsu	43.5^{o}N,143.8^{o}E	10-42 (OH) 10-58 (O^{1}S)	~0-100 ~10-110		Ejiri et al., (2003)
Cachoeira Paulista	23^{o}S,45^{o}W	5-60	10-80	6-34	Medeiros et al., (2003)
Tanjungsari	6.9^{o}S,107.9^{o}E	3-80	10-95	5-13	Nakamura et al., (2003)
Darwin	12.4^{o}S,131^{o}E	20-90	0-90		Suzuki et al., (2004)
Buckland Park	34.5^{o}S,138.5^{o}E	20-200	20-250	40-240	Ding et al., (2004)
Cariri	7.4^{o}S, 36.5^{o}W	~5-40	1-90	~5-30	Medeiros et al., (2007); Wrasse et al., (2006)
Resolute Bay,	74.7^{o}N,265.1^{o}E	~10-70	10-110		Suzuki et al., (2009a)
Kototabang	0.2^{o}S, 100.3^{o} E	25-95	5-125		Suzuki et al., (2009b)
Mt. Bohyun, Korea	36.2^{o}N,128.9^{o} E	10-45	0-80	5-45	Kim et al. (2010)
Xinglong	40.2^{o}N,117.4^{o} E	~10-55	10-100	2-20	Li et al., (2011a)
Maui	20.7^{o}N,156.3^{o}W	~10-120	~0-150	~5-30	Li et al., (2011b)
Syowa Station	69^{o}S,0-40^{o}E	10-60	0-150	3-65	Matsuda et al., (2014)
Tirunelveli	8.7^{o}N, 77.8^{o}E	5-45	10-140	3-20	Lakshmi Narayanan and Gurubaran, (2013)
Gadanki	13.5^{o}N, 79.2^{o}E	12-**42**	20-90	4-20	**Present Study**

Figure Captions:

Figure 1. A sample figure depicting the gravity wave signatures. One may see the propagation of features. The green color box show the dominant wave fronts, while the yellow arrows reveal their propagation direction at an angle ϴ.

Figure 2. The distribution of horizontal wavelengths of the observed waves in March-April 2012 and 2014 and April 2013.

Figure 3. The distribution of the observed phase velocity of waves in March-April 2012 and 2014 and April 2013.

Figure 4. The distribution of observed periods of the in March-April 2012 and 2014 and April 2013.

Figure 5. left side (figure 5a) depicting the observed phase speed and direction of horizontal propagation of gravity waves and right side plots depicting the reverse ray tracing results in (b) zero wind (top side) as well as in (c) HWM-07 model wind (bottom side) condition in March-April 2012 and 2014 and April 2013. The red color arrows (lines) indicate March events while blue arrows (lines) show the events noted in April month. In polar plot 0^o belongs to the North and the inner dotted circles indicate the horizontal phase speed of the observed wave at an interval of 20 m/s. In right side plots red (blue) dots indicate the ray termination point in March (April).

Figure 6. Same as figure 5 but only for the year 2012.

Figure 7. The average of daily mean OLR for the days when waves were observed in airglow image data in March and April 2012. The location of measurement is shown as **asterisk** in each map.

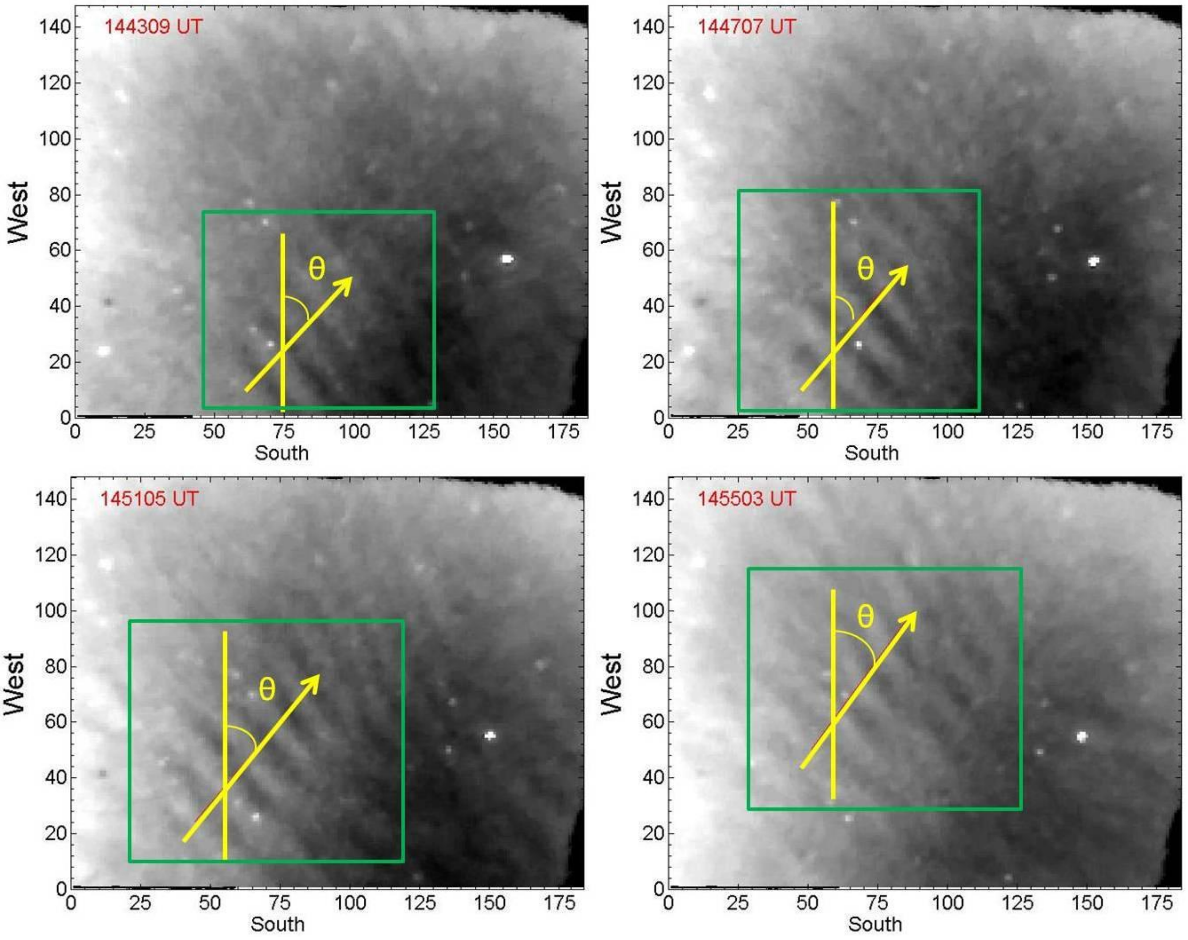
Figure 8. The daily mean OLR data and ray paths for different wave event noted in 27 March 2012. Ray tracing plots blue (red) color line indicates ray paths in model wind (zero wind) condition and the blue color triangle show observation location (Gadanki). Plus and filled square symbols indicate where the gravity waves have the maximum amplitude into the thermophere. Star and open square show where/when the gravity waves have less than 1% of their initial amplitude. From the OLR plot one may note the occurence of convective events at northern Indian locations.

Figure 9. Same as figure 5 but for the year 2013.

Figure 10. Same as figure 7 but for the year 2013.

Figure 11. Same as figure 5 but for the year 2014.

Figure 12. Same as figure 7 but for the year 2014.



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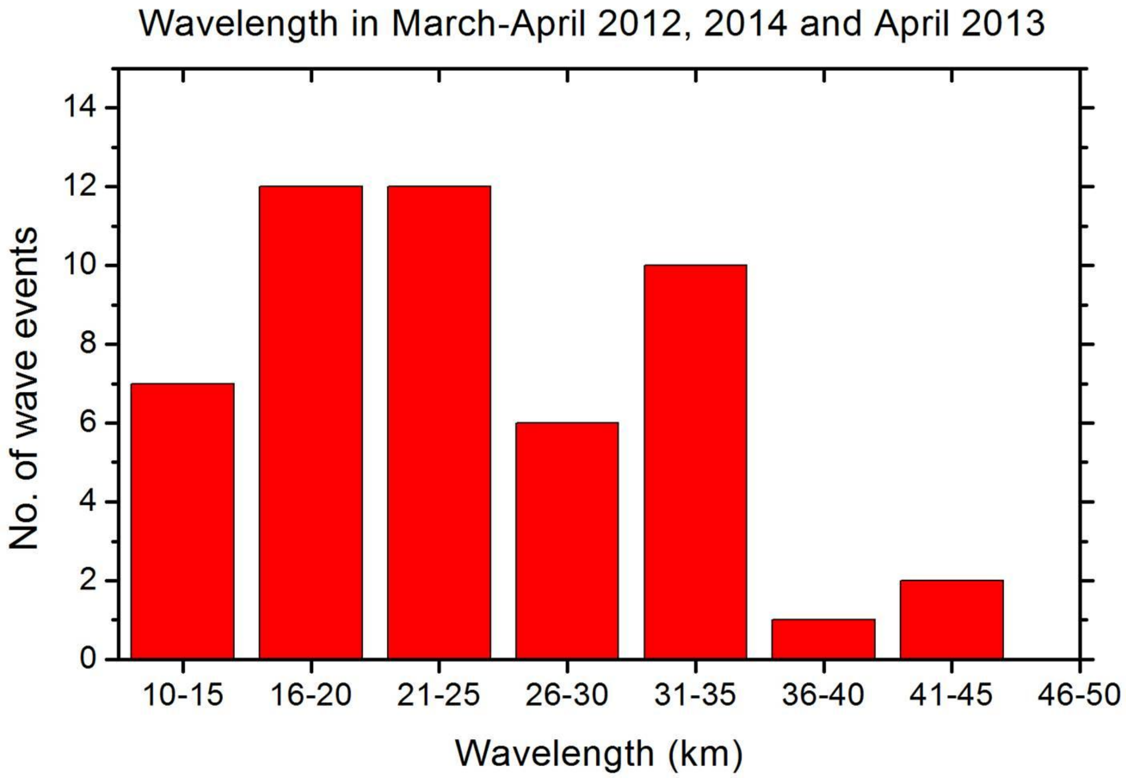


Figure 2. The distribution of horizontal wavelengths of the observed waves in March-April 2012 and 2014 and April 2013.

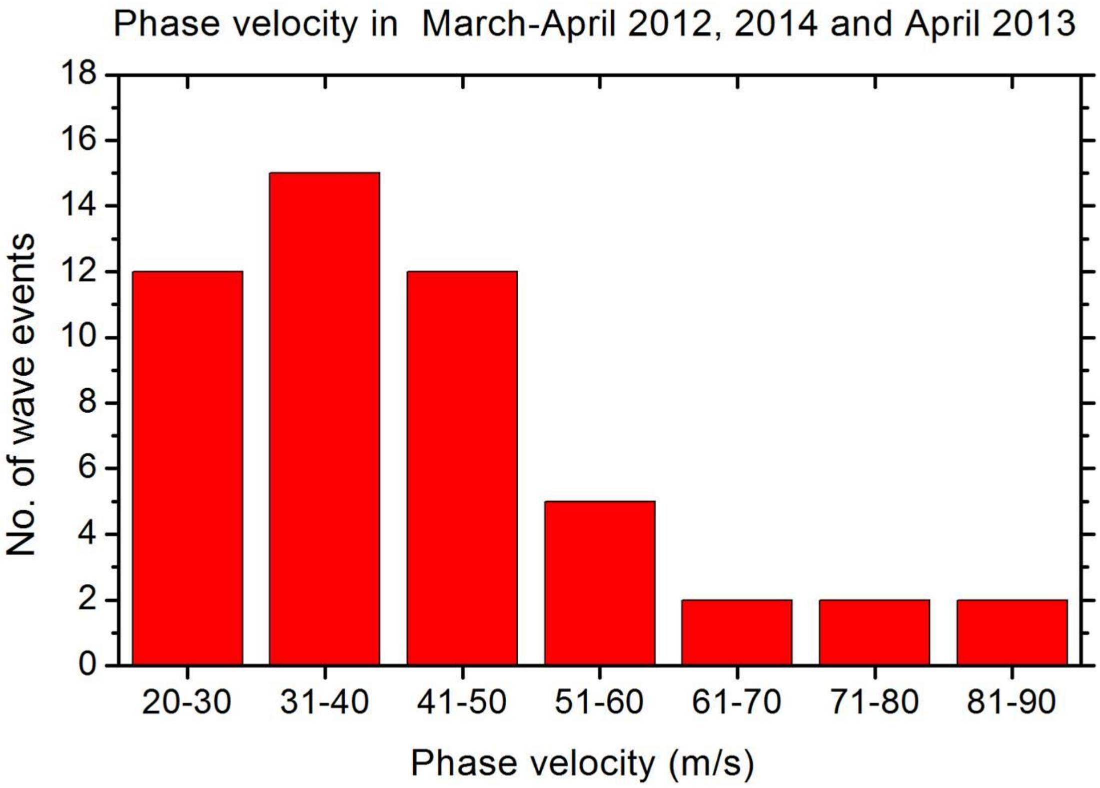


Figure 3. The distribution of the observed phase velocity of waves in March-April 2012 and 2014 and April 2013.

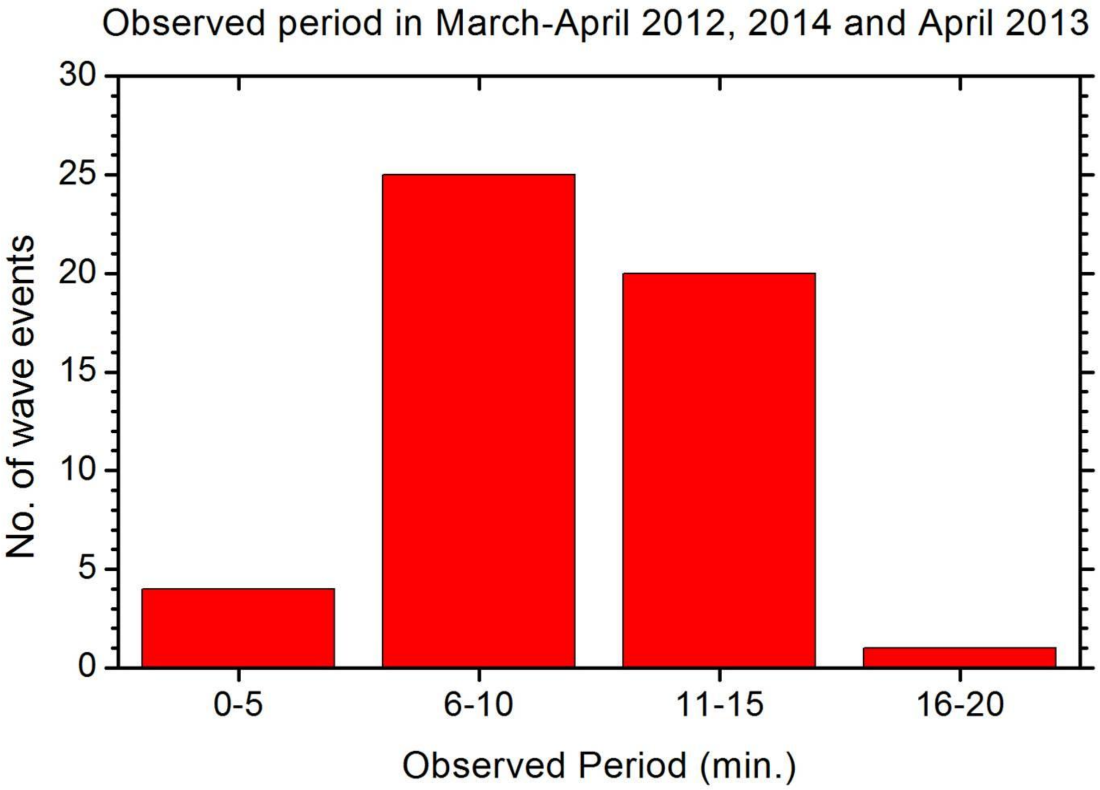
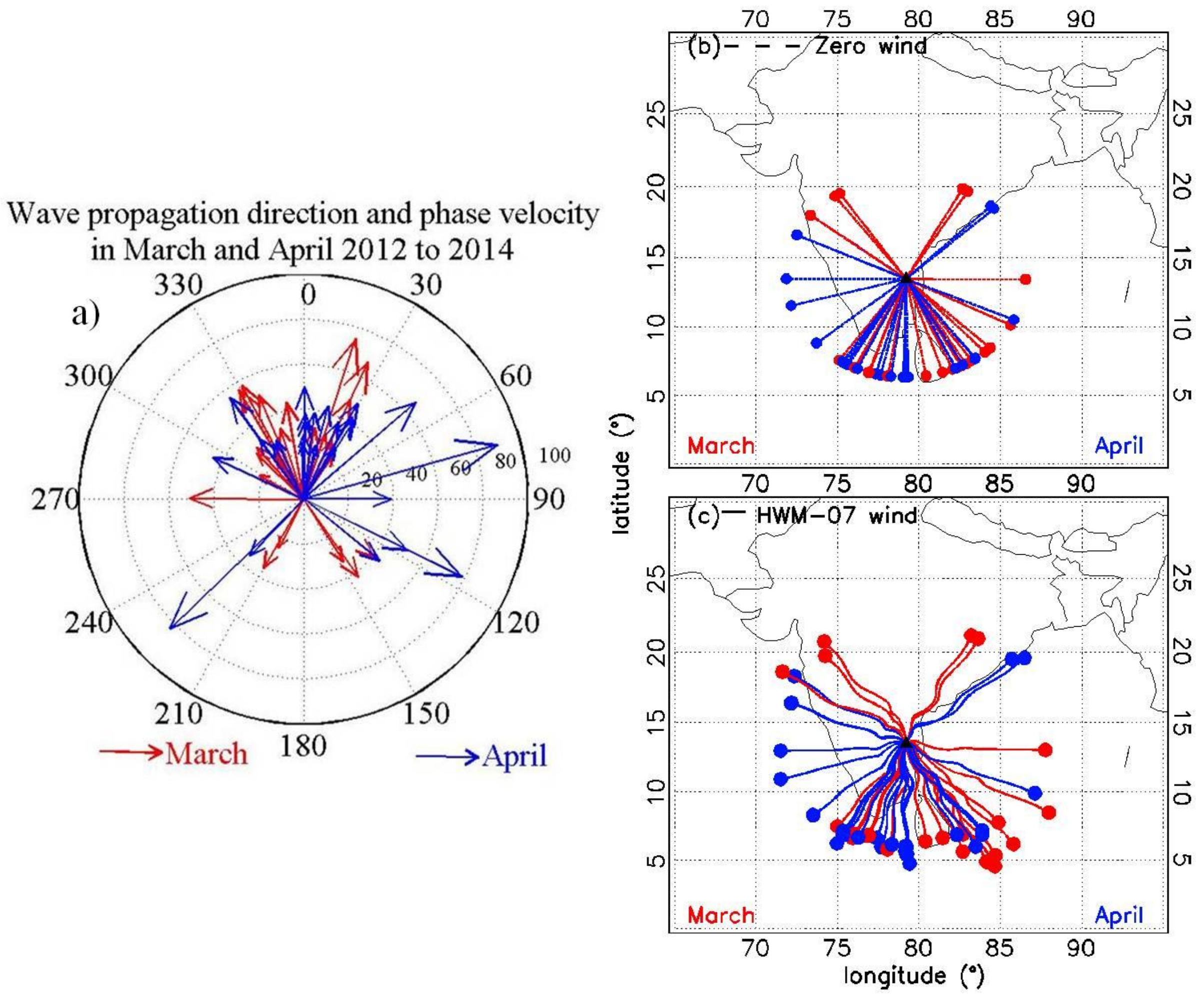


Figure 4. The distribution of observed periods of the in March-April 2012 and 2014 and April 2013.



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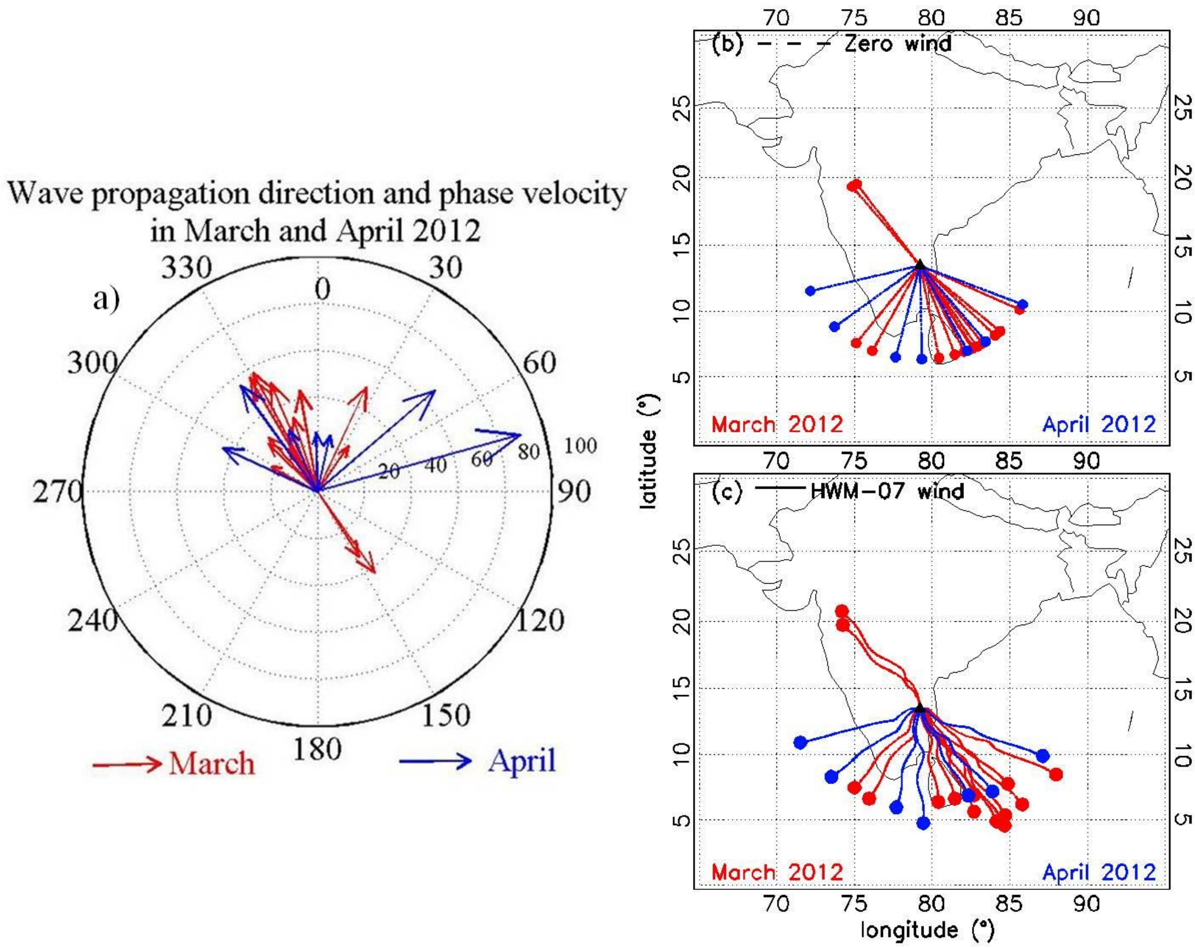
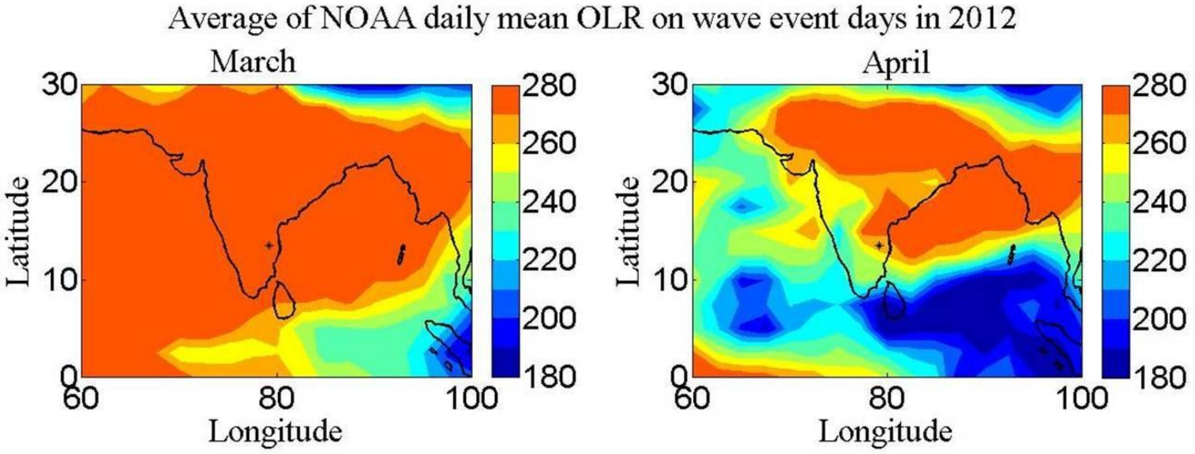


Figure 6. Same as figure 5 but only for the year 2012.



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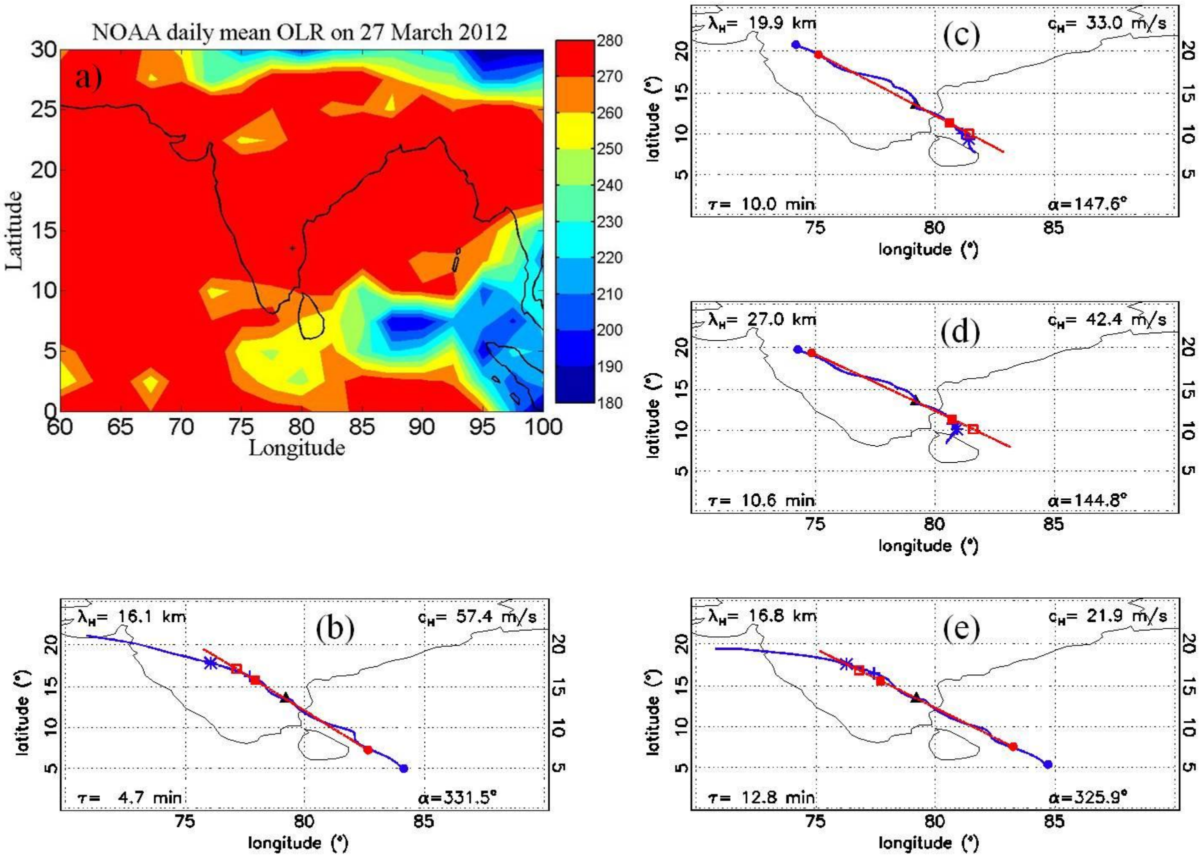

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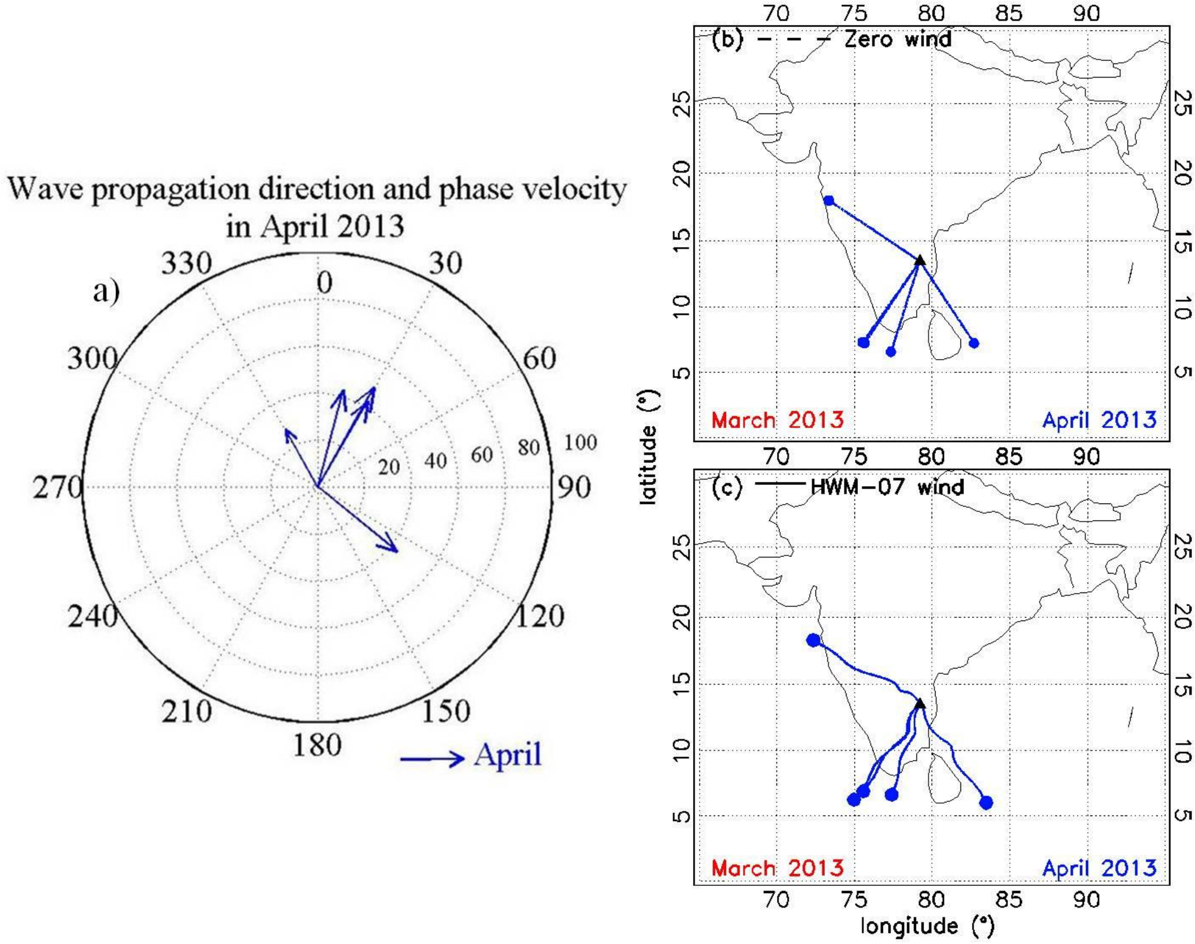

Figure 9. Same as figure 5 but for the year 2013.

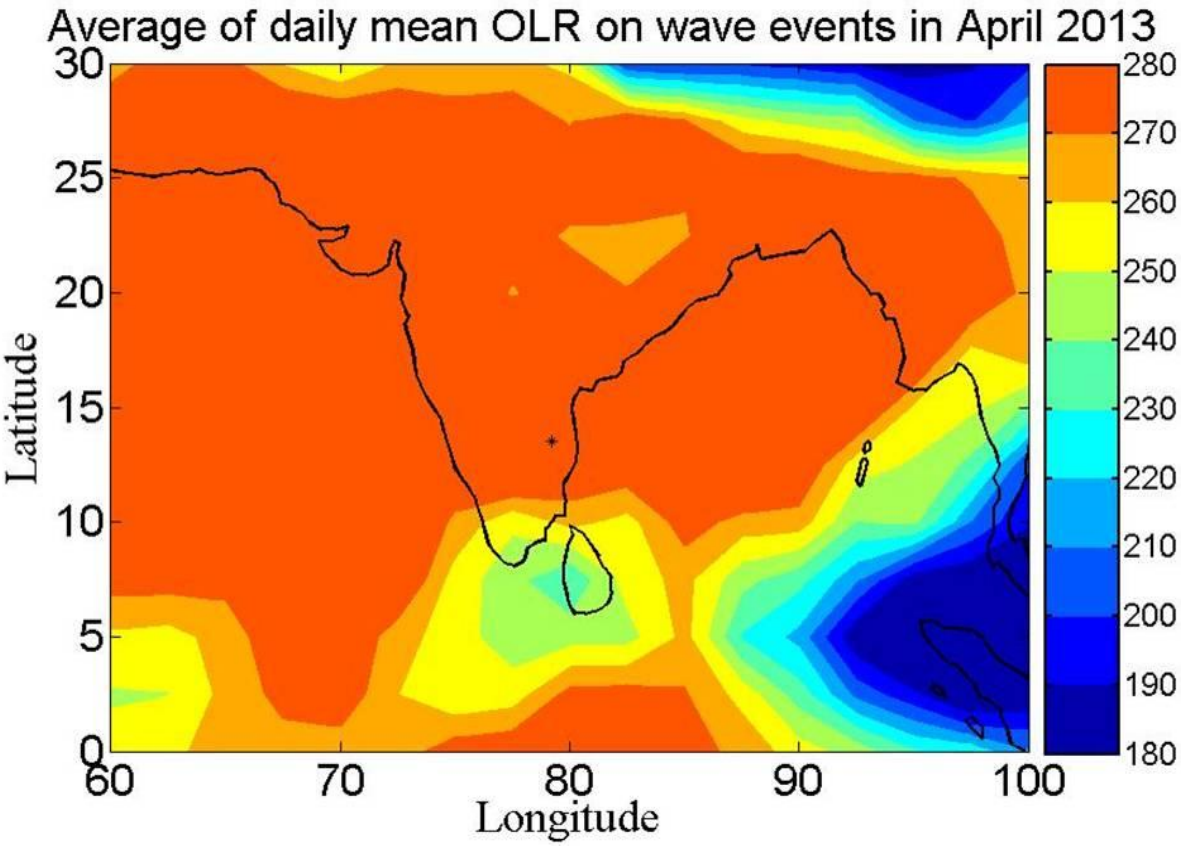

Figure 10. Same as figure 7 but for the year 2013.

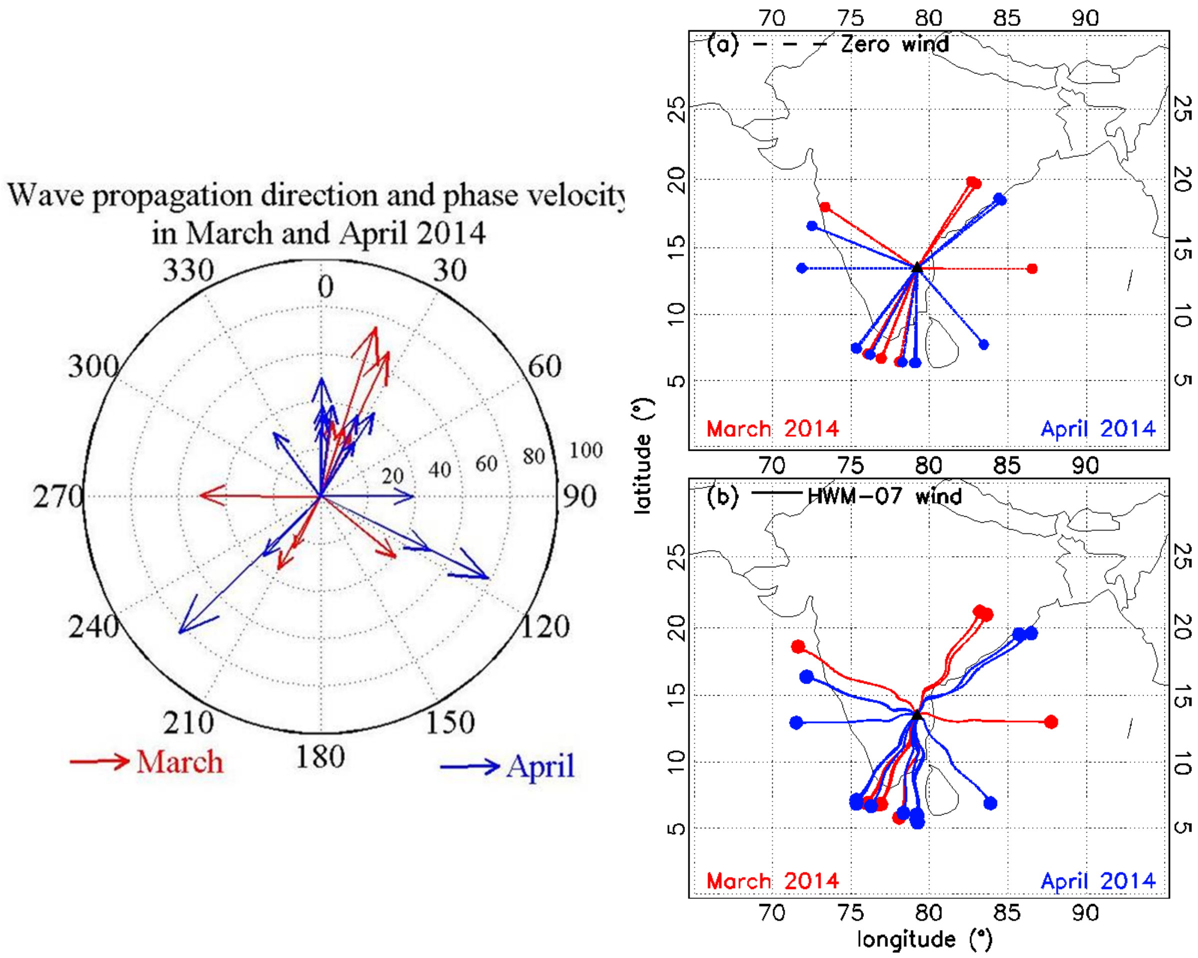

Figure 11. Same as figure 5 but for the year 2014.

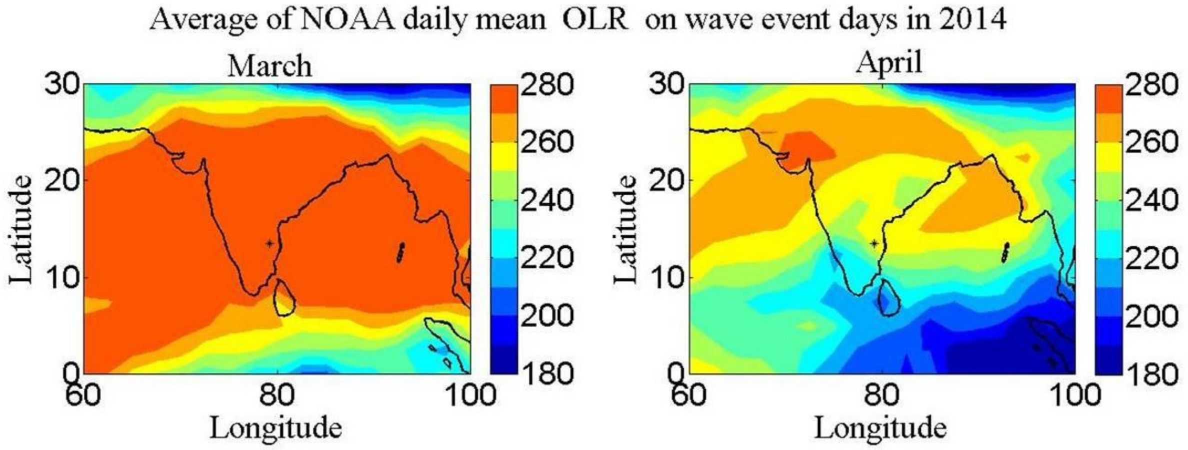

Figure 12. Same as figure 7 but for the year 2014.