Answers to the reviewers

Authors thank the reviewers for time and effort spent on evaluating the manuscript and providing suggestions which greatly improved the quality of the paper.

Anonymous Referee #1

Major comments:

Q1. **The structure of the manuscript**

To the best of my understanding, there are four major groups of experiments in this manuscript. They can be listed as below.

EXP A: 1) Detrend u and v from the time series; 2) Use a third order Butterworth filter with a bandpass between 36 and 44 h, which is a time-wise filter; 3) Use another bandpass filter between 1.5 and 4 km, which is a height-wise filter.

EXP B: The same as EXP A, except that Butterworth filter is replaced by a sixth order FIR1.

EXP C: 1) Obtain the fluctuation profiles by removing polynomial of different orders for each individual profiles. 2) Use a third order Butterworth filter between 1.5 and 4 km, which is a height-wise filter.

EXP D: The same as EXP C, except that Butterworth filter is replaced by FIR1.

Here, by assuming that the IGW characteristics are relatively stationary within 120 h, EXPs A&B could be considered as the reference for EXPs C&D. Also, in reality, EXPs A&B may not be possible due to the requirement of the continuous high-resolution observations in time. In contrast, EXPs C&D are easier to achieve since they only require individual profiles. The above classification and clarification are summarized by me, and I hope that they are correct. In the current manuscript, it is very hard for the readers to follow the manuscript due to its structure and the lack of the necessary clarification. I would suggest that the methodology part and the list of experiments should be introduced in details in a separate section before the results are shown.

A1. We have taken this valuable comment seriously and attempted to change the matter appropriately, though we have not written the methodology separately. We felt that the results in that case will become somewhat confusing. We request the reviewer to go through this revised portion now and to find out whether clarity is enough.

Q2. The clarification of the details in the methodology

Some of the details in the methodology should be clarified and given. Note that the other reviewer also gave similar comments on an earlier version, but I think that there is still room for improvement. Please check my below comments.

2.1 On the method of the filter: In addition to Figure 3, the authors should try to present a brief introduction on Butterworth filter and FIR1 filter. Please give the reference on the mathematical calculation of those two filters. Also, what is the meaning of the “order” for each filter? Why is the third order selected for the

Butterworth filter? Why is the sixth order selected for the FIR1 filter? Are the results sensitive to the selection of the order?

2.1 A. A brief introduction of the filters with corresponding references has been incorporated in the matter as per the suggestion of the reviewer.

The order of the filter refers to the number of components that affect the steepness or shape of the filter's frequency response. As the order of the filter increases, the cut-off become sharper, but the length of the data should be at-least 3 times the filter order. The length of our data is 20 (time-wise). So the maximum order of the filter which we could choose is 6. The filter order is normally judiciously chosen by the investigator depending on the efficacy of the filter. A Butterworth filter of order 3 is more efficient than a 6th order FIR1 filter.

2.2 Line 49: It seems to me that the measurement errors for wind and temperature could be very close to the wave-induced perturbation of wind and temperature. Please clarify it.

2.2 A. The fluctuations are almost of the same order of winds (±10 ms^{-1}) and temperature (±15 K) so the error (mentioned in the paper) is much less compared to the fluctuations

2.3 Lines 52-54: How many outliers or how many data gaps are there? The authors could try to give the ratio of the reliable data versus the interpolated data, if necessary.

2.3 A. Normally we adopt the method of visual inspection to remove outliers. But in this data we could hardly find 4 small outliers at 4 heights out of 20 profiles with 600 points (heights) each. Only one flight (4th May, 2012; 11:30 LT) data was missing and hence we had to interpolate one point at each height with time.

2.4 Line 58: In this work, the entire temporal duration is 120 h, and the temporal resolution is 6 h. Therefore, one should be careful about the period under 24 h due to the coarse temporal resolution, and one should also be careful about the period over 60 h due to the assumption of periodic boundary condition. Those similar clarifications should be given. Also, in order to capture a wide range of wave spectrum, it would be nice to have a much higher resolution in time. For example, in Wei et al. (2016, JAS), 1 minute is used as the temporal resolution for the analysis of wave period. This is also worth mentioning.

2.4 A. To avoid this problem, the time series data of 120 h with a gap of 6 h has been filtered between 36 h and 44 h. So waves under 24 h and above 60 h periods are eliminated.

The duration of each radiosonde flight is ~ 1½ h to 2½ h. It is not possible to fly radiosondes with very high time resolution. Wei et al (2016) is a simulation paper on gravity waves generated by baroclinic instability and it could be possible to take very high time resolution. The work is in the mesosphere which might not be relevant for this work.

2.5 Line 84-86: The temperature perturbation profiles are obtained slightly differently from the wind perturbation profiles. Why? Please clarify it.

2.5 A. The velocity and temperature perturbations are normally obtained differently in different papers. We have calculated velocity perturbations by removing different orders of polynomials and we find that removal of 4, 5 and 6 orders yield almost the same results.

Temperature fluctuations have been obtained by removing 4th order polynomial in Hu et al (2002), Allen and Vincent (1995) removed 2nd order polynomial. Chane-Ming et al (2010) removed 2nd and 3rd order polynomial from winds and temperature. No reasons are attributed in any of these papers.

2.6 In the current study, the authors apply a height-wise bandpass filter (between 1.5 and 4 km) in many calculations. In contrast, Zhang et al. (2004, GRL) actually don't have a height-wise filter. This may be due to the different vertical resolution between the observational studies in the current work and the numerical studies in Zhang et al. (2004, GRL). The authors should try to clarify those issues related to the above comparison. Is this height-wise filter necessary? What determines the window of the bandpass filter?

2.6 A. The height filter is necessary when we analyze individual altitude profiles of winds or temperatures. The vertical wavelength of IGW is short and generally between 2 – 3 km. The window of the filter is supposed to be selected judiciously by investigator. We have selected it between 1.5 – 4 km which is commonly taken for IGW studies.

Hodographs plotted with only time wise filtered fluctuations did not yield good hodographs showing some superposition of other waves and hence height wise filtering was needed.

2.7 Line 119: I am wondering how to determine the statistical significance with a large number of hodographs? What statistical method is used? What is the minimum sample number required for the significance test? Also, in reality, it may not be possible to have a large number of hodographs.

2.7 A. We have not used any statistical significance tests. We have only calculated the percentage of wave propagation in each direction and the maximum number is shown as the final direction of wave propagation. The percentage is mentioned.

2.8 Table 1&2: The direction of the propagation is a fixed number. It is strange to me, since the other parameters have a certain range. Please clarify it.

2.8 A. Parameters like intrinsic period, horizontal and vertical wavelengths etc are obtained from each of, say, 100 plus hodographs. The values obtained from each hodograph will differ but obviously will be within some range. The maximum and minimum of the ranges have been mentioned.

But the direction of propagation can be NE, SE, SW and NW. The maximum number showing a particular direction is mentioned and the percentage is written. The same is normally followed by other researchers as well.

<u>Minor comments:</u>

1. **Title: Instead of “IGW”, it is better to use “Inertial-Gravity Wave”.**

A. The word “IGW” in the title has been changed to “Inertia Gravity Wave”

2. **Line 8: When “IGW” is used for the first time in the abstract, please use its full name.**

A. The full name of IGW has been introduced in the abstract as per the suggestion of the reviewer.

3. **Line 10: When “FIR1” is used for the first time in the abstract (or in the main text), please use its full name.**

A. The full name of FIR has been introduced in the abstract.

4. **Figure 1: In the subplots, it is better to use “z=24.55 km”, instead of “24.55 km”. Similarly, please apply it to the other places as well.**

A. As per the suggestion of the reviewer we have mentioned “z=24.55 km” in the subplots and also applied to other places.

5. **Figure 6: Please double check the figure caption of Figure 6. (b) should be FIR1 filter, and (c) should be Butterworth filter. The related information is not consistent between figure subtitles and figure caption.**

A. Thanks, figure has been modified accordingly.

<u>Referee #2, Vladimir Gubenko</u>

<u>Aswers to the comments of Dr. Vladimir Gubenko</u>

This paper presents an attempt to overcome the inconsistency of hodograph method when retrieving the internal wave parameters from radiosonde measurements. It seems to me that the description of scientific methods and theoretical expressions used for calculations of wave characteristics and their uncertainties needs to be strongly improved. For this reason, I would advice MAJOR REVISION as the Anonymous referee #1, also. The paper may become suitable for publication in ACP following implementation of the following points.

<u>Major Comments:</u>

1. **Page 3, line 75. The values v’ and u’, in your Eq. 1, are not the meridional and zonal wind fluctuations, respectively. The values u’ and v’ are the complex perturbations for parallel and perpendicular components of wave-induced horizontal wind speed to the wave propagation direction [see for details, for example, Gubenko et al. (2008, JGR, p. 2); Gubenko et al. (2011, AMT, p. 2155); Gubenko et al. (2012, Cosm. Res., p. 22)]. Hu et al. (2002, GRL, p. 1) designate u’ as the in-phase wind along the wave propagation direction, and v’ as quadrature-phase wind perpendicular to the wave propagation direction.**

1A. We have followed the age old method of hodographic analysis. 'u' and 'v' are the profiles of zonal and meridional winds. Height variations of u and v are the profiles of zonal (E – W) and meridional (N – S) velocities only. Please refer to Tsuda et al 1994, (JGR, pg. 10508). "Gravity wave components were extracted…contour plots". Hodographs are plotted with these filtered eastward (zonal wind) and northward (meridional wind) components which are u' and v'. In page 10509, " The lengths of major and minor axes of an ellipse u' - v' correspond to the amplitude of wind velocity fluctuations due to gravity wave", and the formulae follows. Please check the above mentioned paper. The gravity wave fluctuations are normally computed in this manner from measure wind profiles. I am giving you two examples Dutta et al., 2008, JGR and Dutta et al., 2009, JGR. We followed the same procedure to extract gravity wave components.

2. **Page 3, line 77. Your Eq. 2 is wrong. The valid expression for the calculation of the inertial frequency f is following (Gubenko et al., 2008, JGR, p. 1). f = 2Ω sin ϕ, where Ω = 7.292 × 10-5 rad/s is the Earth's rotation rate, and ϕ is latitude.**

2A. Earth's rotation rate (Ω) can be calculated as

$$\Omega = \frac{1}{T} cycles/\sec$$

where 'T' is time period of Earth's rotation (=1day).

According to equation (3) of our paper,

$$f = \frac{\sin\varphi}{\frac{1}{2}day}$$

$$f = \frac{2\sin\varphi}{1day}$$

$$f = \frac{2\sin\varphi}{T}$$

$$f = 2\Omega\sin\varphi \qquad (\because \tfrac{1}{T} = \Omega)$$

which is the same equation that you have mentioned.

3. **Page 3, line 79. Your Eq. 3 is wrong. In the work of Gubenko et al. (2012, Cosm. Res., p. 23), the dispersion equation in the interval of intermediate intrinsic frequencies ($f^2 << \omega^2 << N^2$) is given: |k| = ω |m| / N. If we use this expression to calculate the value |k|, then calculated values of horizontal wave number |k| will be systematically overestimated by factor $(1 – f^2/\omega^2)^{1/2}$. This is connected with fact that the appropriate dispersion equation that is valid for internal waves with both low and intermediate intrinsic frequencies ($f^2 < \omega^2 << N^2$) has form (Gubenko et al. 2012, Cosm. Res., p. 23): $|k| = (1 – f^2/\omega^2)^{1/2} \times \omega |m| / N$. For this reason, the obtained results about horizontal wavelengths and wave numbers must be recalculated.**

3A. We thank Dr. Gubenko for pointing out this small mistake and giving his important reference paper. We have incorporated the correction factor which improved the quality of the paper.

4. Page 3, lines 86–87. You state that the final direction of wave propagation was calculated by using hodographs u' – v' and u' – t' (Hu et al., 2002). I don't understand your method, because Hu et al. (2002, GRL, p. 1) use for that the hodographs of the zonal wind versus meridional wind, and the in-phase wind versus temperature.

4A. Yes we have done with in-phase wind and temperature. But there is no clarification given in the paper. So now we have incorporated this clarification.

Minor Comments:

1. Page 2, line 71. For zonal and meridional perturbations it is necessary to introduce another symbols, for example, u_{we}' and u_{sn}'

1A. u' and v' are zonal (E – W) and meridional (N – S) wind fluctuations for us. We use in-phase wind and temperature perturbations in the other hodographs (Figure 7). It is not necessary to introduce the new symbols.

References:

Allen, S. J., and R. A. Vincent, 1995: Gravity wave activity in the lower atmosphere: Seasonal and latitudinal variations. J. Geophys. Res., 100, 1327–1350.

Chane-Ming, F., Z. Chen, and F. Roux, 2010: Analysis of gravity waves produced by intense tropical cyclones. Annales Geophysicae, 28, 531–547, doi: 10.5194/angeo-28-531-2010.

Dutta, G., M. C. Ajay Kumar, P. Vinay Kumar, M. Venkat Ratnam, M. Chandrashekar, Y. Shibagaki, M. Salauddin, and H. A. Basha (2009), Characteristics of high-frequency gravity waves generated by tropical deep convection: Case studies, J. Geophys. Res., 114, D18109, doi:10.1029/2008JD011332

Dutta, G., T. Tsuda, P. V. Kumar, M. C. A. Kumar, S. P. Alexander, and T. Kozu (2008), Seasonal variation of short-period (<2 h) gravity wave activity over Gadanki, India (13.5_N, 79.2_E), J. Geophys. Res., 113, D14103, doi:10.1029/2007JD009178.

Hu, X., Liu, A. Z., Gardner, C. S., and Swenson, G. R.: Characteristics of quasi-monochromatic gravity waves observed with Na lidar in the mesopause region at Starfire Optical Range, NM, Geophys. Res. Lett., 29 (24), doi:10.1029/2002GL014975, 2002.

Tsuda, T., Murayama, Y., Wiryosumarto, H., Harijono, S. W. B., and Kato, S.: Radiosonde observations of equatorial atmospheric dynamics over Indonesia, 2. Characteristics of gravity waves. J. Geophys. Res., 99, 10507-10516. 1994.

Retrieving characteristics of ~~IGW~~Inertia Gravity Wave parameters with least uncertainties using hodograph method

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Abstract. We have analyzed time series of wind velocities measured with high resolution GPS-radiosonde ascents continuously for 120 h from Hyderabad with an interval of 6 h. Hodograph method has been used to retrieve the ~~IGW~~Inertia Gravity Waves (IGW) parameters. Background winds are removed from the time series by detrending whereas polynomials of different orders are removed to get the fluctuations from individual profiles. Butterworth filter is used to extract monochromatic IGW component. Another filter Finite Impulse Response (FIR1) is tried in a similar manner to test the effects of filters in estimating IGW characteristics. Results reveal that the fluctuation profiles differ with the change of polynomial orders, but the IGW parameters remain same when Butterworth filter is chosen to extract the monochromatic wave component. FIR1 filter also produces acceptable results with a broader range. The direction of wave propagation is confirmed with additional temperature information which needs a large number of hodographs for statistical significance.

1 Introduction

It is well documented that gravity waves of different scales play an important role in maintaining the large-scale circulation of the middle atmosphere. A large number of studies have been carried out to characterize these waves by using different techniques. A very common, established and standard procedure of characterizing Inertia Gravity Waves (IGW) with frequencies close to Coriolis frequency is by hodograph method (Guest et al., 2000; Ogino et al., 2006; Niranjan Kumar et al., 2011). Radiosonde data of horizontal winds and temperature have been extensively used to study these waves (Tsuda et al., 2004; Vincent and Alexander, 2000; Gong et al., 2008; Chane-Ming et al., 2010, 2014; Murphy et al., 2014; Kramer et al., 2015). Nastrom and VanZandt (1982) reported good accuracy in gravity wave parameters derived using balloon measurements since balloons have good aerodynamic responses. In a simulation study Wei and Zhang (2014) have demonstrated that gravity waves with different frequencies and generated by different sources like jet-imbalance and convection can coexist together. The popular hodograph method demands the presence of a single coherent wave in the fluctuation profiles and does not yield good result when a mixture of various frequencies are present. The gravity wave

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Formatted: Heading 1, Space Before: 0 pt parameters extracted by hodograph method might also be inaccurate when multiple waves are present in the data (Eckermann and Hocking, 1989).

Hodograph method is based on linear theory of gravity waves whereas the dynamics of the flow is more complex and non-linear which introduces some uncertainties in the interpretation. There are several sources of errors in this method which have been described in Zhang et al., (2004). These authors compared the gravity wave characteristics obtained using hodograph method with the values derived from 4D output of their simulation study. A narrow bandwidth filter used by them to extract the fluctuations of a near-monochromatic wave resulted in large uncertainties in the horizontal wavelength which got reduced for waves with shorter vertical wavelengths. Even the spatial variations of the wave characteristics were found to be large. Moreover, since the hodographs are quite variable, a large number of hodographs (profiles) are required to get accurate results of gravity wave parameters with some statistical significance (Hall et al., 1995). This defeats the very advantage of the hodograph method which is capable of retrieving GW parameters from a single set of vertical profiles of zonal and meridional winds.

The present paper attempts to overcome the inconsistency of hodograph method in delineating the characteristics of IGW from velocity fluctuations obtained with radiosonde measurements.

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2 Experiment and Data

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An intensive campaign with high resolution (i-Met, USA) GPS–radiosonde flights was carried out from the campus of India Meteorological Department (IMD), Hyderabad (17.4 ºN, 78.5 ºE) with four flights a day at an interval of 6 h for 5 consecutive days (20 flights) between 30 April and 4 May, 2012 to study the characteristics of IGW. The timings of the flights were 05:30, 11:30, 17:30 and 23:30 LT. The accuracy of wind and temperature measurements provided by the manufacturer is ±1 ms^{-1} and ± 0.2 K respectively. There was one data gap at 11:30 LT on 4 May, 2012 which was linearly interpolated to get continuous time series of wind velocities. High resolution (~4 – 10 m) wind data obtained directly from balloon flights were first sorted in ascending order of height since the balloons occasionally drift downwards by a few meters. Wind profiles ~~were~~are then visually inspected for outliers and such outliers, if any, ~~were~~are removed. The gaps ~~were~~are filled up by linear interpolations. The wind profiles ~~were~~are then interpolated vertically to have a constant height resolution of 50 m. This method is useful to smooth the profiles and to maintain a good resolution in height.

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3 Analysis and Discussion

~~**Experiments were carried out for five days with a view to getting continuous horizontal wind velocities for 120 h with a regular interval of 6 h keeping in mind that the IGW period over the site is ~40 h.**~~

3.1 Time series analysis

IGW periods over low latitudes are quite large which makes their observations difficult by using common spectral analysis method. The normal procedure to find the frequency/period of an atmospheric wave is to have a continuous time series data with appropriate data gaps and subject it to Fast Fourier Transform (FFT) technique. The minimum length of data required for FFT analysis is double the period of the wave (Nyquist frequency) to be identified. Keeping this in mind, experiments were conducted as mentioned in section 2 to obtain wind velocities and temperatures continuously for 120 h with a regular interval of 6 h since the IGW period over Hyderabad is ~40 h and the data contains three cycles of the wave which satisfies the criterion of FFT technique. This time series data is capable of identifying IGW period after proper filtering and using spectral analysis method. The filtered time series data is considered as reference data for rest of the analyses.

We have used two types of filters. Butterworth filter and Finite Impulse Response (FIR) filter in the present work. Butterworth filter belongs to the Infinite Impulse Response (IIR) group of filters. It is a type of signal processing filter designed to have a very flat frequency response in the pass band with a monotonic amplitude response. FIR filters can be reliably designed with linear phase that prevents distortion. These filters can be easily implemented but with the disadvantage that they often require a much higher filter order than IIR filters to achieve a good level of performance. The details of these filters are available in Butterworth (1930) and Lake (1980).

3.1.1 Hodograph of wind perturbations using Butterwoth filter

The continuous zonal and meridional wind datasets are detrended (linear trend removed) to obtain time series of wind fluctuations. A third order Butterworth filter with a band-pass between 36 and 44 h is applied to the wind perturbations to retrieve the IGW fluctuations with zero phase distortion. The sufficiently wide band of the time filter is helpful to reduce the Doppler shift of IGW frequency (Niranjan Kumar et al., 2011). Ehard et al., (2015) also recommended the usage of Butterworth filter in extracting gravity waves over a wide range of periods from temperature perturbations measured by lidar. The filtered horizontal winds at particular heights are depicted in Fig. 1a – 1d which show the presence of IGW with a period of ~ 40 h. FFT analyses carried out with filtered wind ~~data~~fluctuations also reveal the presence of a clear monochromatic wave of the same period (Fig. 1e – 1h) which satisfies the requirement of hodograph method.

Hodographs plotted with this time-wise filtered zonal and meridional wind perturbations (u′, v′) are found to be quite noisy and it is difficult to identify proper closings. The fluctuation profiles are, therefore, further band-pass filtered using a Butterworth filter with a cut-off at 1.5 – 4 km which produced proper elliptic hodographs. The number of proper hodographs obtained from 20 pairs of vertical profiles of u′ and v′ are 124. A few IGW parameters have been extracted assuming linear dispersion relations (~~Cho, 1995;~~ Tsuda et al., 1994). The intrinsic wave frequency (ω) is calculated from the ratio of minor to major axes of the ellipse.

$$\frac{v\prime}{u\prime} = -i\left(\frac{f}{\omega}\right)\cancel{,} \qquad (1)$$

where f is the inertial frequency and ~~v′, u′~~ u′, v′ are the ~~meridional and zonal~~ amplitudes of wind velocity fluctuations ~~respectively~~due to gravity wave. f is computed as

$$f = \frac{\sin\varphi}{{}^{1}/_{2}day}\ cycles/sec \qquad (2)$$

where ~~φ~~ φ is the latitude of the place. The horizontal wave number k is found using the relation

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$k = \cancel{m\omega/N}\ m\omega/N$ (3)

N being the Brunt – Väisalä frequency and m is vertical wave number. Equation (3) is valid for $N \gg \omega \gg f$ (Fritts and Alexander, 2003). Gubenko et al., (2012) has reported that the dispersion equation which is valid for internal waves with both low and intermediate intrinsic frequencies ($f^2 < \omega^2 \ll N^2$) is given by

$$k = \left(1 - \frac{f^2}{\omega^2}\right)^{1/2} \frac{m\omega}{N} \qquad (4)$$

Intrinsic periods of IGW obtained using equation (4) from hodographs range between 20 – 28 h~~.~~ which are less than the inertial period and belongs to this intermediate range. The vertical and horizontal wavelengths inferred from the hodographs are between 2.0 to 2.8 km and between ~~493 – 846~~569 – 1171 km respectively.

3.1.2~~The direction of horizontal wave propagation is parallel to the major axis of the ellipse which is uncertain by 180°. This uncertainty can be removed with the help of additional temperature information. Temperature perturbation profiles are obtained by removing 5th order polynomial fits from the simultaneous temperature profiles and filtering them height-wise with a band-pass Butterworth filter between 1.5 and 4 km~~. Hodographs ~~of u′ – v′ and u′ – t′ are capable of deciding the final directions of propagation of the wave (Hu et al., 2002). The unambiguous direction of propagation of IGW is observed to be south-east (62%) in this analysis.~~using FIR1 filter

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Next we chose a different filter FIR1 of order 6 to test the effect of filtering on hodograph method since the vertical wavelength and intrinsic frequency are reported to be highly vulnerable to the filter used (Zhang et al., 2004). We followed the same procedure to delineate the IGW parameters as described ~~before~~in section 3.1.1 but by using ~~Butterworth~~FIR1 filter. The detrended and time-wise filtered horizontal wind profiles at a few heights and the corresponding FFT peaks are illustrated in Fig. 2a – 2d and 2e – 2h respectively. Both the time variation of wind fluctuations and the FFT peaks do not show distinct IGW periods. The frequency responses of Butterworth filter of 3rd order and FIR1 of 6th order are shown in Fig. 3. The Butterworth filter shows a sharp cut-off and also has the advantage of producing good result with a much lower filter order than the corresponding FIR1 filter. A few hodographs plotted with horizontal wind perturbations using both the filters are displayed in Fig. 4a – 4d. The IGW parameters derived from these hodographs are listed in Table 1. The ranges of horizontal wavelength, vertical wavelength and intrinsic period are observed to be broader using FIR1 filter compared to those obtained using Butterworth filter.

3.2. Height series analyses

Hodographs are generally plotted with the fluctuations derived from data of individual sounding by removing polynomials of 1st or 2nd order. We treated the measured vertical profiles of zonal and meridional winds as single individual set (not time series) and approximated the backgrounds by polynomials of different (2 to 9) orders. Fig.5 depicts the different fits and the corresponding wind profiles. The fluctuation profiles obtained by removing polynomials of 4, 5 and 6 orders show close agreements whereas appreciable differences could be noticed for others (figure not shown). ~~These profiles are then~~These fluctuation profiles are then subjected to different filtering process and hodographs are plotted. They are consequently analyzed to derive IGW parameters.

3.2.1 Hodographs using Butterworth filter

The perturbation profiles are filtered with a 3rd order Butterworth filter height-wise to retain IGW oscillations with short vertical wavelengths (1.5 – 4 km). IGW parameters obtained from the hodographs plotted with these fluctuations match extremely well with those ~~delineated from the previous computation where the background was removed from the time series by detrending and filtering was done both time-wise (36 – 44 h) and height-wise (1.5 – 4 km).~~described in section 3.1.1

3.2.2 Hodographs using FIR1 filter

The individual profiles of winds and temperature are then analyzed in a similar manner as mentioned in section 3.2.1 but by using FIR1 filter with height instead of Butterworth filter. The perturbation profiles (after removing backgrounds with different orders) and the filtered fluctuation profiles using both Butterworth and FIR1 filters are shown in Fig. 6a – 6c and 6d – 6f for both the wind components, respectively. It is clearly observed that the Butterworth filter can extract the monochromatic IGW fluctuations very efficiently. The retrieved IGW parameters retain same numerical values (except after decimal points) irrespective of the background removals. Results obtained with FIR1 filter also belong to the same range but with a broader band which is illustrated in Table 2 for different orders. ~~The direction of propagation of IGW inferred from different ways of computation is unambiguously south east. This demands a large number of hodographs to finalize the direction with some statistical significance.~~

3.3. Direction of wave propagation

The direction of horizontal wave propagation is parallel to the major axis of the ellipse which is uncertain by 180º. This uncertainty can be removed with the help of additional temperature information. Temperature perturbation profiles are obtained by removing 5th order polynomial fits from the simultaneous temperature profiles and filtering them height-wise with a band-pass Butterworth filter between 1.5 and 4 km. In-phase wind is calculated as Ucosθ where U is the total wind and θ is the corresponding orientation angle of the u′ – v′ hodograph. A few hodographs plotted with in-phase winds and temperature fluctuations are illustrated in Fig. 7 (a –d) which help in resolving the ambiguity to determine the wave propagation direction (Hu et al., 2002). The unambiguous direction of propagation of IGW is observed to be south-east (58%) in this analysis. It is necessary to analyze a large number of hodographs to finalize the direction of propagation with some statistical significance

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4 Summary

Balloon borne experiments have been conducted for five days with an interval of 6 h to characterize IGW using hodograph method. The method is helpful in identifying low-frequency IGW but suffers from several uncertainties. We have utilized the time series of wind fluctuations to extract IGW component by filtering and confirmed it with spectral analysis. Results obtained by using Butterworth and FIR1 filters are compared. A band-pass Butterworth filter with a sharp cut-off is found to isolate the monochromatic IGW component very efficiently. Backgrounds of individual wind profiles have been approximated with polynomials of different orders when the perturbation profiles show reasonable differences. The differences are observed to get reduced when Butterworth filter is used to isolate the IGW components, whereas differences still persist with FIR1 filter. IGW parameters delineated from the corresponding hodographs using the former filter agree extremely well for different order polynomial removal. Results obtained with FIR1 filter also show reasonable agreement but with a broader range. Filtering appears to be of great importance in removing uncertainties of hodograph method. The unambiguous direction of wave propagation can be ascertained using additional and simultaneous temperature information but a large number of hodographs are needed to confirm it with statistical significance.

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Acknowledgements

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References

Butterworth, S.: On the theory of filter amplifiers, Experimental wireless and the wireless engineer, 7, 536-541, 1930.

Chane-Ming, F., Chen, Z., and Roux, F.:~~–~~ Analysis of gravity-waves produced by intense tropical cyclones, Annales Geophys., 28, 531-547, 2010.

Chane-Ming, F., Ibrahim, C., Barthe, C., Jolivet, S., Keckhut, P., Liou, Y.-A., and Kuleshov, Y.: Observation and a numerical study of gravity waves during tropical cyclone Ivan (2008), Atmos. Chem. and Phys., 14, 641–658, 2014, doi:10.5194/acp-14-641-2014, 2014.

~~Cho, J. Y. N.: Inertio-gravity wave parameter estimation from cross-spectral analysis, J. Geophys. Res., 100, D9, 18727-18737, 1995.~~

Eckermann, S. D., and Hocking, W. K.: Effect of superposition on measurements of atmospheric gravity waves: a cautionary note and some reinterpretations, J. Geophys. Res., 94, 6333-6339, 1989.

Ehard, B., Kaifler, B., Kaifler, N., and Rapp, M.: Evaluation of methods for gravity wave extraction from middle-atmospheric lidar temperature measurements, Atmos. Meas. Tech., 8, 46454655, doi:10.5194/amt846452015, 2015.

Fritts, D. C., and Alexander M. J.: Gravity wave dynamics and effects in the middle atmosphere, Rev. Geophys., 41(1), 1003, doi:10.1029/ 2001RG000106, 2003.

Gong, J., Geller, M. A., and Wang, L.:Source spectra information derived from U.S high-resolution radiosonde data, J. Geophys. Res., 113, D10106, doi:10.1029/2007JD009252, 2008.

Gubenko, V. N., Pavelyev, A. G., Salimzyanov, R. R., and Andreev, V. E.: A method for determination of internal gravity wave parameters from a vertical temperature or density profile measurement in the Earth's atmosphere, Cosmic Res., 50 (1), 21-31, 2012.

Guest, F., Reeder, M. J., Marks, C. J., and Karoly, D. J.: Inertia-Gravity wave observed in the lower stratosphere over Macquarie Island, J. Atmos. Sci., 57, 737-752, 2000.

Hall, G. E., Meek, C. E., and Manson, A. H.: Hodograph analysis of mesopause region winds observed by three MF radars in the Canadian prairies, J. Geophys. Res., 100, 7411-7421, 1995.

Hu, X., Liu, A. Z., Gardner, C. S., and Swenson, G. R.: Characteristics of quasi-monochromatic gravity waves observed with Na lidar in the mesopause region at Starfire Optical Range, NM, Geophys. Res. Lett., 29 (24), doi:10.1029/2002GL014975, 2002.

Kramer, R., Wüst, S., Schmidt, C., and Bittner, M.: Gravity wave characteristics in the middle atmosphere during the CESAR campaign at palma de Mallorca in 2011/2012: Impact of extratropical cyclones and cold fronts, J. Atmos. Sol. Terr. Phys., 128, 8-23doi:10.1016/j.jastp.2015.03.001, 2015.

Lake, R.: Programmes for digital signal processing, IEEE Xplore, DOI: 10.1109/MSP.1980.237616, 1980.

Murphy, D. J., Alexander, S. P., Klekociuk, A. R., Love, P. T., and Vincent, R. A.: Radiosonde observations of gravity waves in the lower stratosphere over Davis, Antarctica, J. Geophys. Res., 119, 11,973–11,996, 10.1002/2014 JD022448, 2014.

Nastrom, G. D., and VanZandt, T. E.: An analytical study of nonlinear responses of rising balloons in horizontal winds, J. Appl. Meteorol., 21, 413-419, 1982.

Niranjan Kumar, K., Ramkumar, T. K., and Krishnaiah, M.: MST radar observation of inertial-gravity waves generated from tropical cyclones, J. Atmos. Sol. Terr. Phys., 73, 1890-1906, doi:10.1016/j.jastp.2011.04.026, 2011.

~~Nastrom, G. D., and VanZandt, T. E.: An analytical study of nonlinear responses of rising balloons in horizontal winds, J. Appl. Meteorol., 21, 413-419, 1982.~~

Ogino, S. Y., Sato, K., Yamanaka, M. D., and Watanabe, A.: Lower stratospheric and upper-tropospheric disturbances observed by radiosondes over Thailand during January, 2000, J. Atmos. Sci., 63, 3437-3447, 2006.

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Tsuda, T., Murayama, Y., Wiryosumarto, H., Harijono, S. W. B., and Kato, S.: Radiosonde observations of equatorial atmospheric dynamics over Indonesia, 2. Characteristics of gravity waves. J. Geophys. Res., 99, 10507-10516. 1994.

Tsuda, T., Ratnam, M. V., May, P. T., Alexander, M. J., Vincent, R. A., and MacKinnon, A.: Characteristics of gravity waves with short vertical wavelengths observed with radiosonde and GPS occultation during DAWEX (Darwin Area Wave Experiment), J. Geophys. Res., 109, D20S03, doi:10.1029/2004JD004946, 2004.

Vincent, R. A., and Alexander, M. J.: Gravity wave in the tropical lower stratosphere: An observational study of seasonal and inter-annual variability, J. Geophys. Res., 105, 17971-17982, 2000.

Wei, J., and Zhang, F.: Mesoscale gravity waves in moist baroclinic jet–front systems. J. Atmos. Sci., 71, 929–952, doi:10.1175/JASD130171.1, 2014.

Zhang, F., Wang, S., and Plougonven, R.: Uncertainties in using the hodograph method to retrieve gravity wave characteristics from individual soundings, Geophys. Res. Lett., 31, L11110, doi:10.1029/2004GL019841, 2004.

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Figure Captions

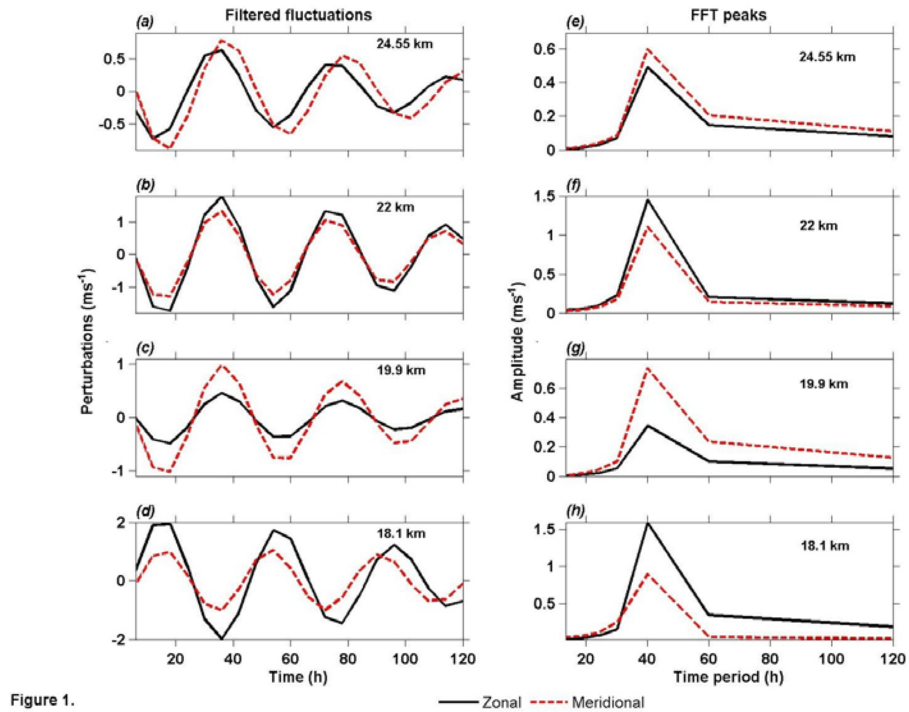

Figure 1. Time series of filtered (Butterworth filter) fluctuations (ms^{-1}) of zonal and meridional winds (a – d) and corresponding FFT spectra (e – f) at a few heights.

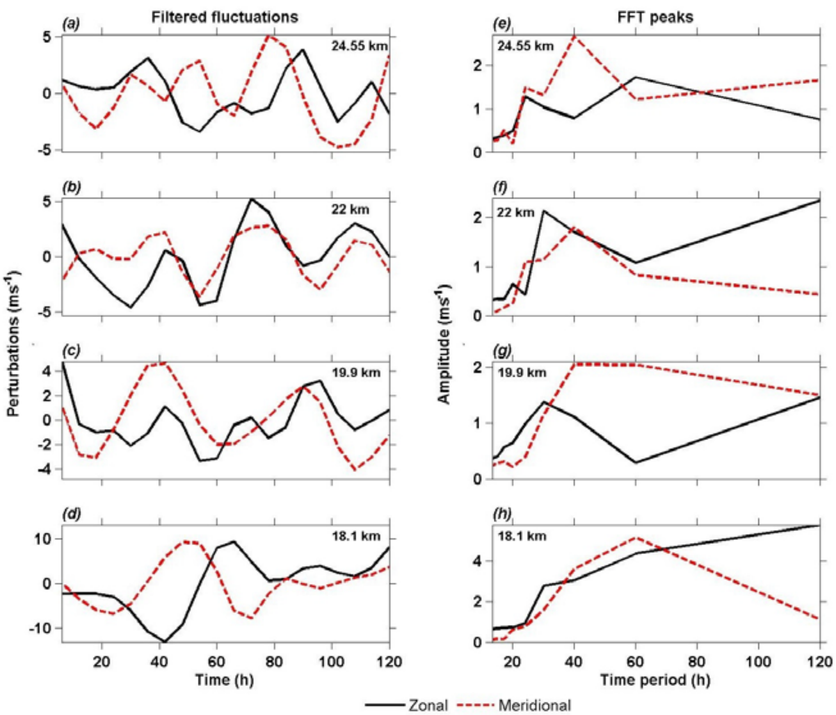

Figure 2. Same as in Figure 1 but with FIR1 filter.

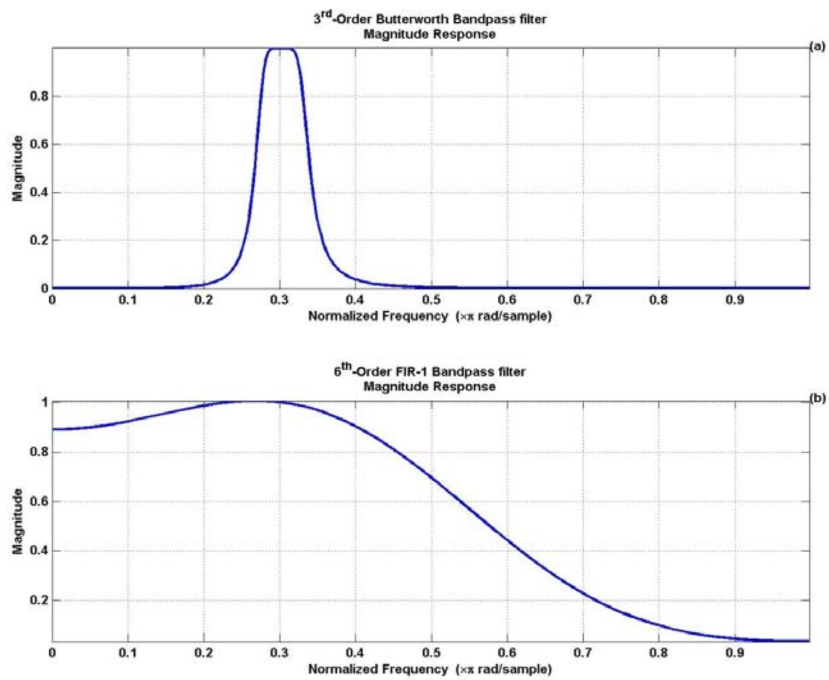

Figure 3. The filter responses of Butterworth (a) and FIR 1(b) filters.

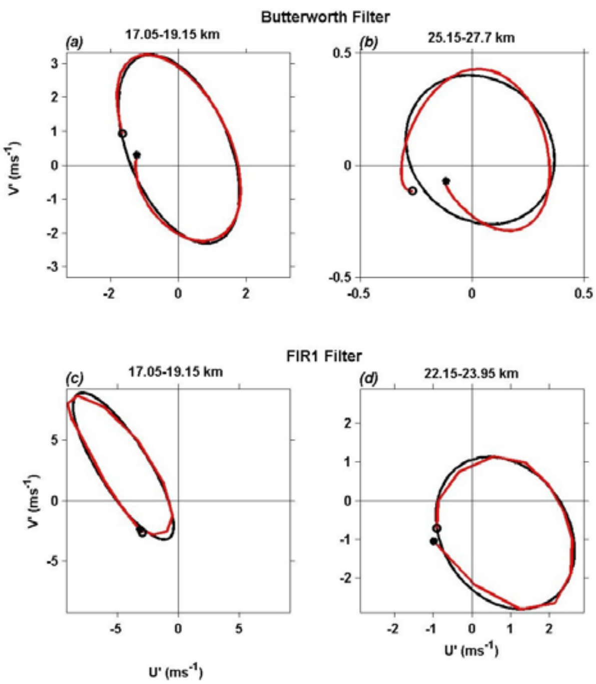

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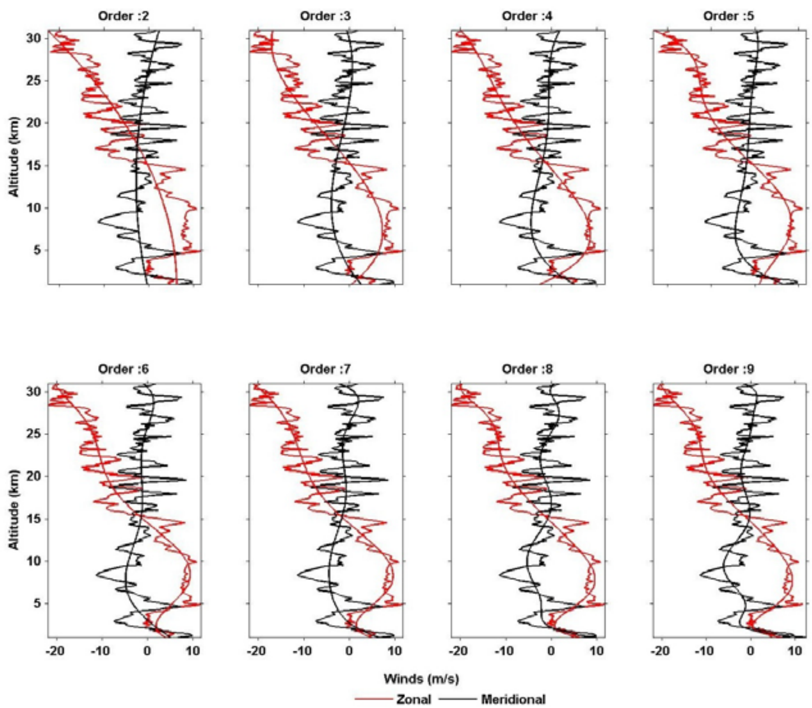
Figure 4. Hodographs of horizontal wind fluctuations (ms^{-1}) obtained using Butterworth (a, b) and FIR1 (c, d) filters. An open circle and a solid circle in each hodograph indicate the lowest and highest altitudes, respectively. The thin curves represent the elliptical fits.



-Figure 5. Profiles of zonal and meridional winds (ms^{-1}) and their fits with different orders.

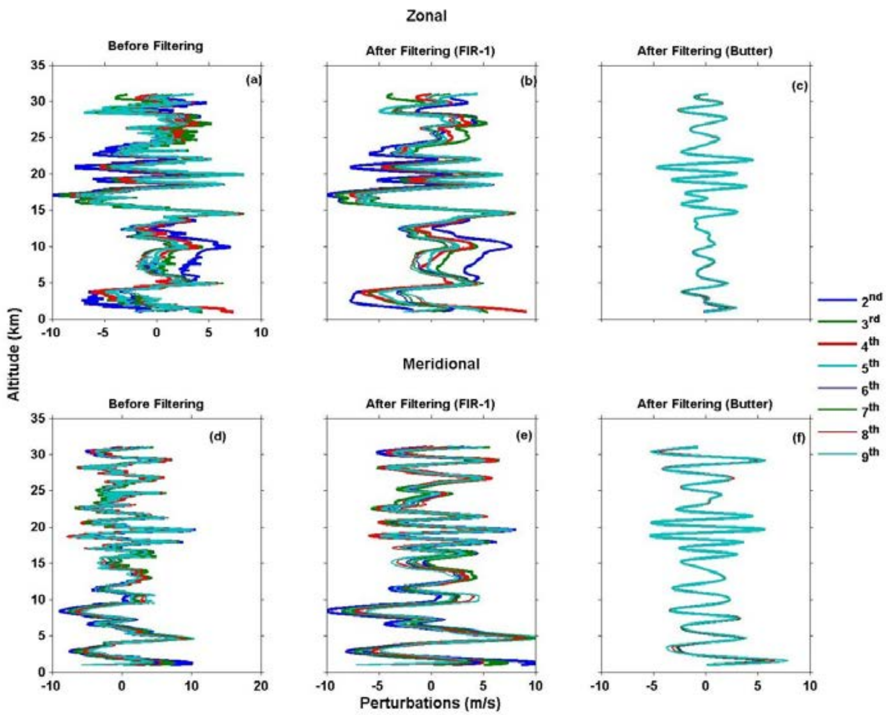
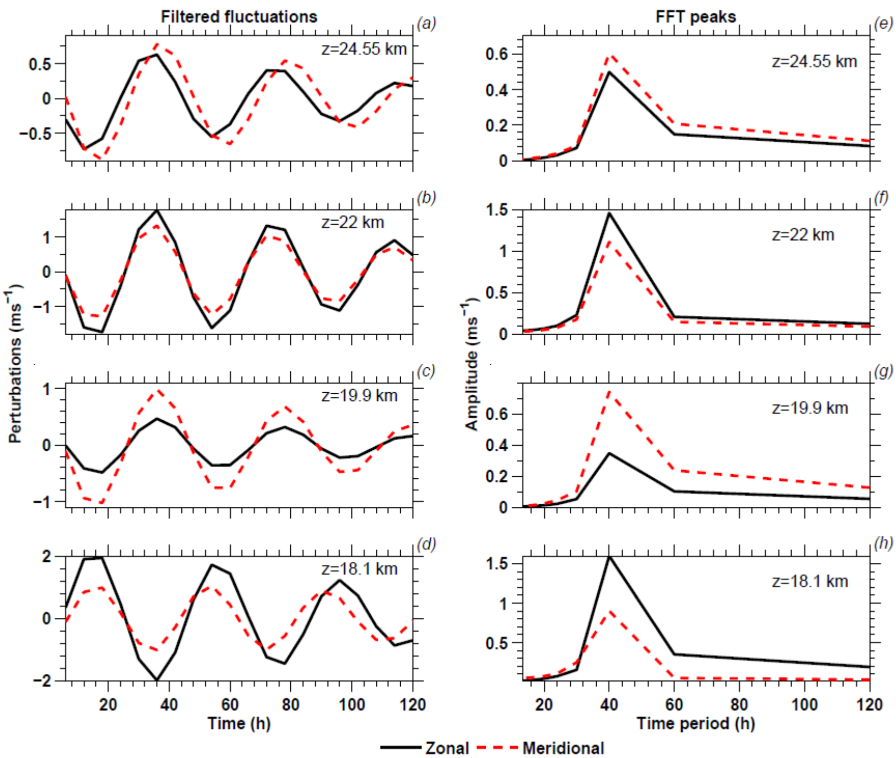


Figure 6. Upper panel: Vertical profiles of zonal wind fluctuations (ms^{-1}) after approximating the backgrounds with different order (2nd – 9th) polynomials (a) and filtering height-wise with Butterworth filter (b) and FIR1 filter (c). **Lower panel:** Same as upper panel but for meridional wind fluctuations.

Figure 7. Hodographs of in-phase wind (ms^{-1}) verses temperature fluctuations (K) obtained using Butterworth (a, b) and FIR1 (c, d) filters. An open circle and a solid circle in each hodograph indicate the lowest and highest altitudes, respectively. The thin curves represent the elliptical fits.



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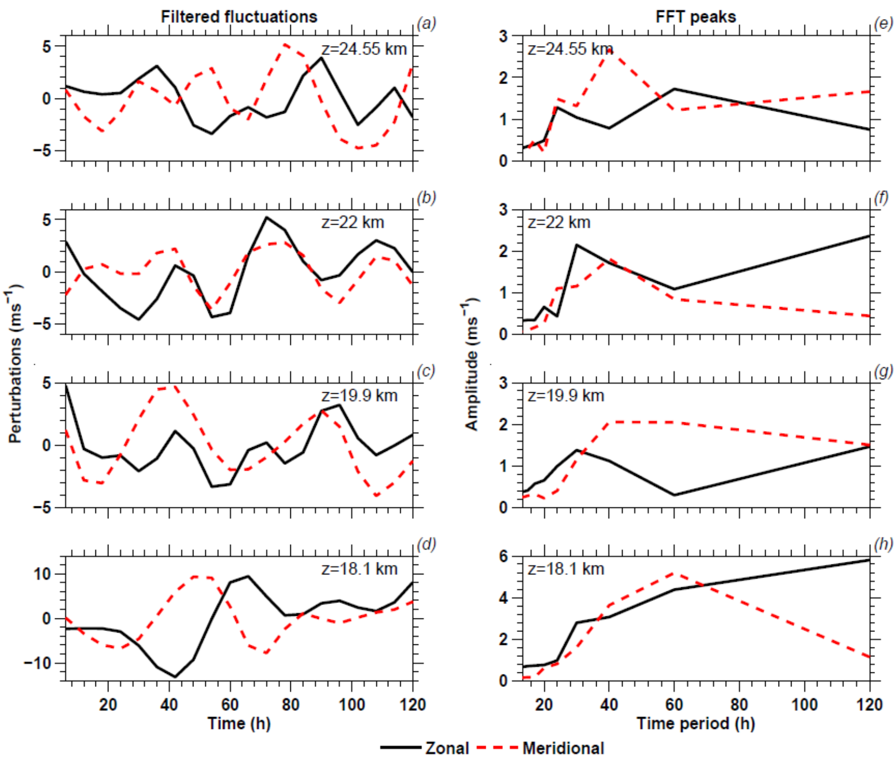
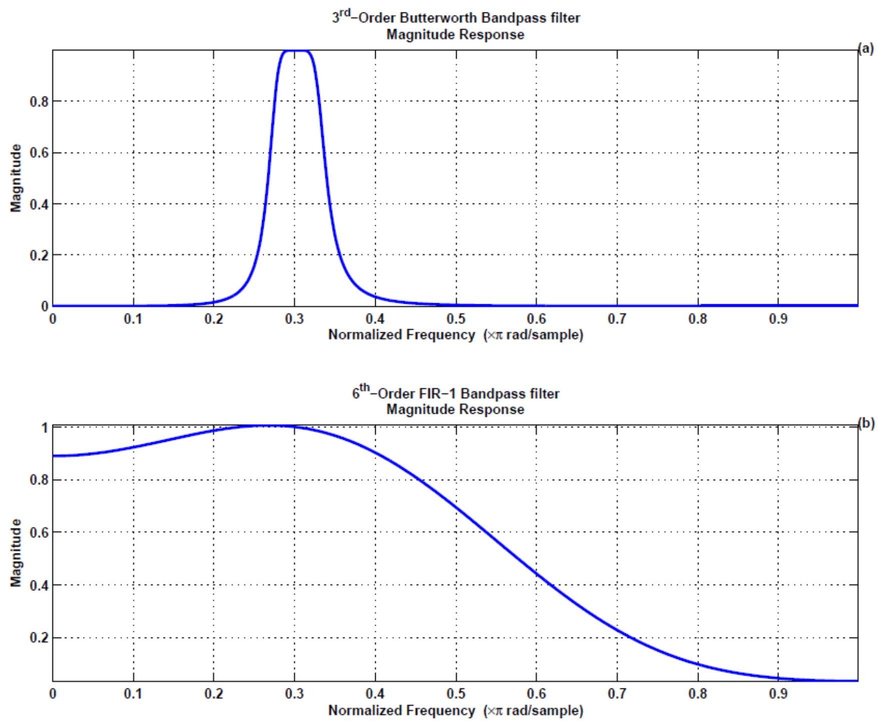


Figure 2: Same as in Figure 1 but with FIR1 filter.



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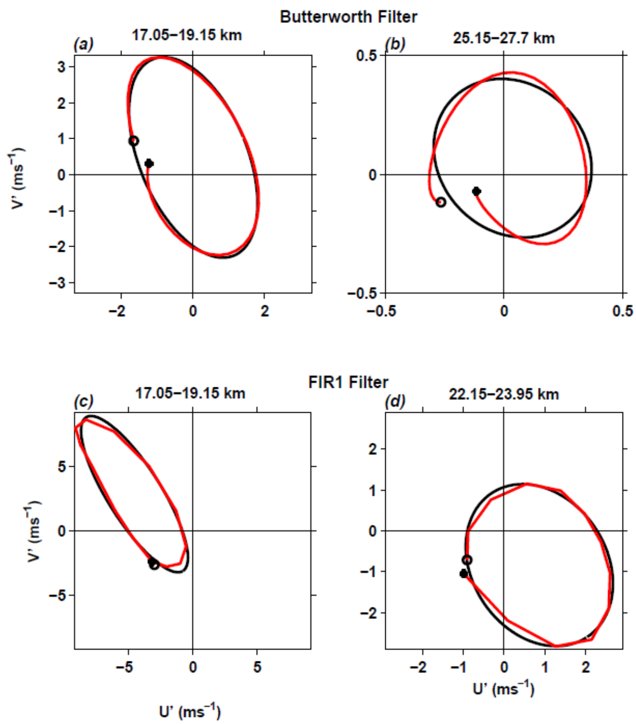


Figure 4: Hodographs of horizontal wind fluctuations (ms^{-1}) obtained using Butterworth (a, b) and FIR1 (c, d) filters. An open circle and a solid circle in each hodograph indicate the lowest and highest altitudes, respectively. The thin curves represent the elliptical fits.

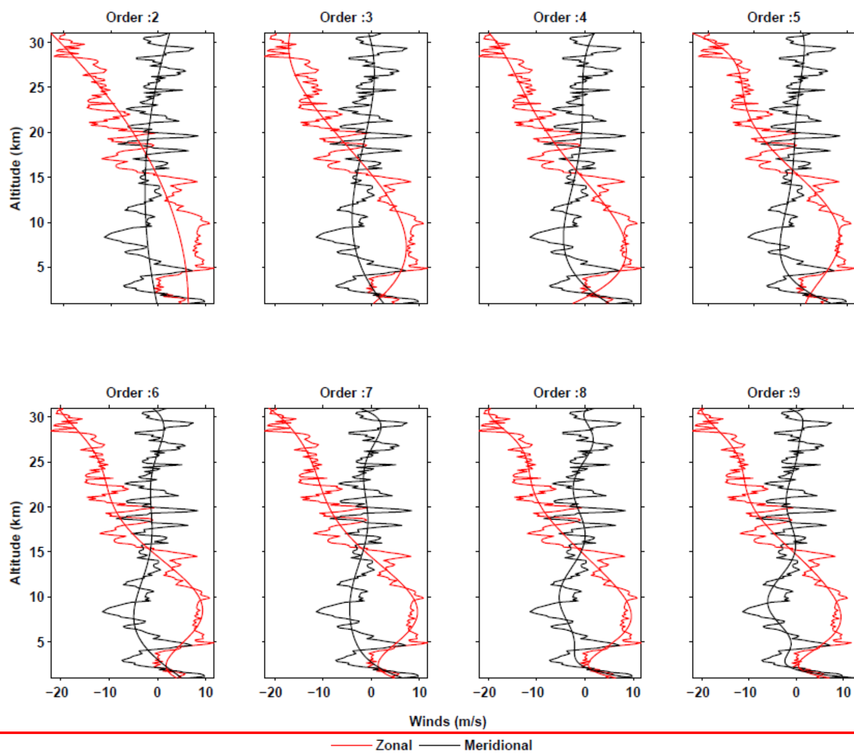
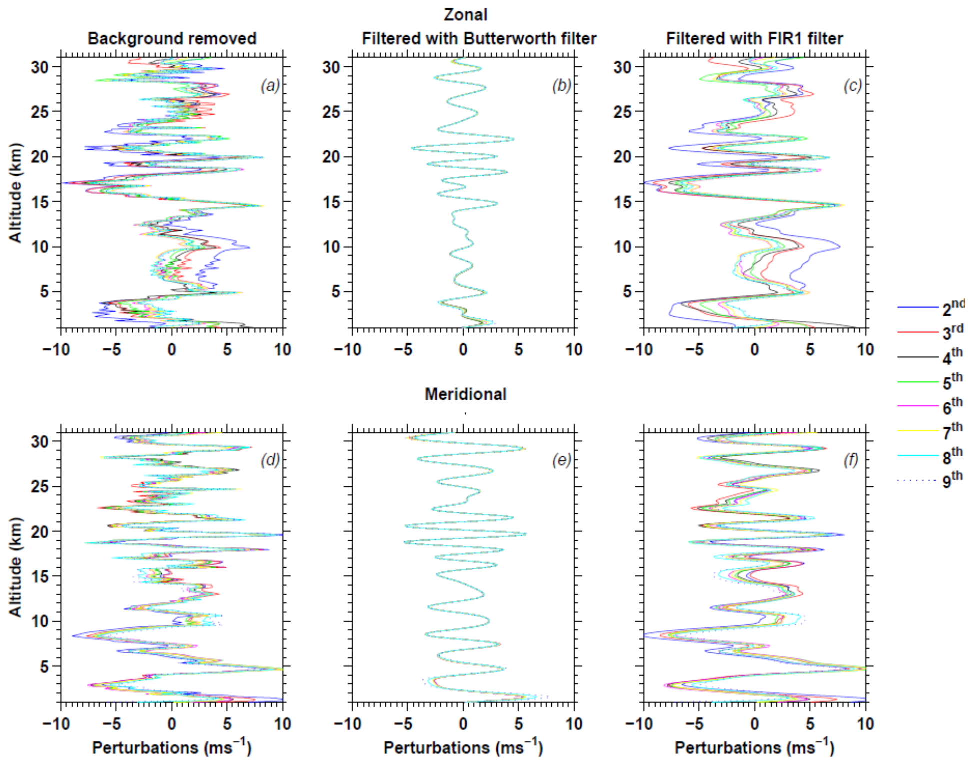


Figure 5: Profiles of zonal and meridional winds (ms^{-1}) and their fits with different orders.



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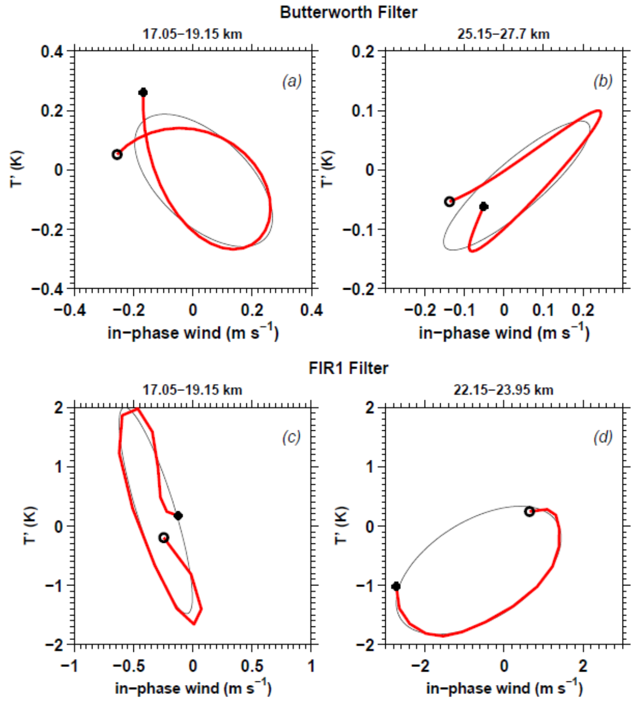

Figure 7: Hodographs of in-phase wind (ms^{-1}) verses temperature fluctuations (K) obtained using Butterworth (a, b) and FIR1 (c, d) filters. An open circle and a solid circle in each hodograph indicate the lowest and highest altitudes, respectively. The thin curves represent the elliptical fits.

Table 1: Comparison of IGW parameters using detrended time series fluctuations and obtained with different filters

Parameters	Butterworth filter	FIR1 filter
Horizontal wavelength (km)	~~493 – 836~~569 – 1171	~~227 – 800~~237 – 1209
Vertical wavelength (km)	2.0 – 2.8	1.5 – 3.5
Intrinsic Period (h)	20 – 28	10 – 30
Ratio of minor to major axis	0.44 – 0.76	0.35 – 0.87
Direction of propagation	South-East (~~62~~58%)	South-East (~~63~~55%)

Table 2: Comparison of IGW parameters using individual set of wind fluctuation profiles by removing the backgrounds with different order polynomial fits and using both the filters.

Parameters		Horizontal wavelength (km)	Vertical wavelength (km)	Intrinsic Period (h)	Ratio of minor to major axis	Direction of propagation
Filter	Order number					
Butterworth	2 to 9	~~388-770~~423 – 986	2.0~~-~~ – 2.6	16.0 – 25.0	0.34~~-~~ – 0.71	South~~-~~ – East (52%)
FIR1	2	~~300-722~~324 – 882	1.7~~-~~ – 4.0	15.0 – 23.0	0.34~~-~~ – 0.71	South~~-~~ – East (~~63~~51%)
	3	~~426-663~~472 – 827	1.7~~-~~ – 4.0	17.3~~-~~ – 23.9	0.32~~-~~ – 0.71	South~~-~~ – East (~~65~~58%)
	4	~~371-683~~404 – 844	1.7~~-~~ – 3.2	15.8~~-~~ – 23.5	0.32~~-~~ – 0.71	South~~-~~ – East (~~64~~60%)
	5	~~250-850~~273 – 1090	1.8~~-~~ – 3.1	16~~-~~.0 – 25.0	0.32~~-~~ – 0.~~7~~70	South~~-~~ – East (~~60~~64%)
	6	~~332-712~~361 – 905	1.7~~-~~ – 4.0	15.8~~-~~ – 24.7	0.3~~3-~~30 – 0.69	South~~-~~ – East (~~66~~61%)
	7	~~403-711~~440 – 920	1.7~~-~~ – 4.0	16.1~~-~~ – 25.4	0.3~~3-~~30 – 0.69	South~~-~~ – East (~~65~~56%)
	8	~~330-685~~360 – 878	1.8~~-~~ – 3.1	16~~-~~.0 – 25.0	0.32~~-~~ – 0.68	South~~-~~ – East (~~63~~55%)
	9	~~322-577~~352 – 739	1.7~~-~~ – 4.0	16.2~~-~~ – 25.0	0.31~~-~~ – 0.68	South~~-~~ – East (~~66~~51%)

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