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Key Points:
- Strong quasi 2-day wave in the mesosphere during January 2015
- Simultaneous presence of quasi 2-day oscillation in magnetic field with similar zonal structure
- Evidence for vertical coupling by quasi 2-day wave

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Imprint of Mesospheric Quasi 2-Day Wave in the Ground Geomagnetic Field Variations at Low Latitudes

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Abstract The strong quasi 2-day wave (Q2DW) event that occurred during January 2015 was studied by employing medium frequency and meteor radar observations of winds from three different locations at low latitudes with considerable longitudinal separation. The large-amplitude wave activity that occurred in mid-January is the focus of this study. Using the advantage offered by the longitudinal separation among the stations, the zonal structure of the Q2DW has been examined. The presence of a dominant westward propagating zonal wavenumber 3 (W3) mode was revealed in the analysis. The availability of geomagnetic field data from a number of stations at low latitudes enabled us to observe the wave event at ionospheric dynamo region heights. The phase-longitude cross-section of the quasi 2-day oscillation in the *Y* component of the geomagnetic field reiterates the presence of the dominant W3 mode observed at lower altitudes. Similar zonal characteristics and periods of the wave signatures found at mesospheric altitudes and in the manifestation of quiet-time ionospheric currents in geomagnetic field are in conformity with the notion of the wave coupling of the atmosphere-ionosphere system.

Plain Language Summary This study examines the strong quasi 2-day wave event that occurred during January 2015 at low latitudes using medium frequency and meteor radar observations. The analysis reveals the presence of a dominant westward propagating zonal wavenumber 3 mode. Geomagnetic field data from multiple stations at low latitudes show similar zonal characteristics and periods of the wave signatures, which suggests wave coupling of the atmosphere-ionosphere system.

1. Introduction

The quasi 2-day wave (Q2DW) is a transitory planetary-scale oscillation that plays an important role in determining the short-term variabilities of diverse phenomena in the mesosphere-lower thermosphere (MLT) region. The initial observational evidence for the presence of a Q2DW in the atmosphere (Muller & Kingsley, 1974; Muller & Nelson, 1978) led to the development of a strong theoretical basis for the wave origin and propagation. Salby (1981) suggested the Q2DW was a manifestation of the mixed Rossby-gravity (3, 0) normal mode of windless and isothermal atmosphere with a period of 2.25 days. Salby (1981) further examined the impact of non-uniform mean winds on the vertical propagation characteristics of the westward propagating zonal wavenumber 3 (W3, hereafter) mode. Model simulations indicated that the amplitude growth rate was higher in a region with higher refractive index (Yue, Liu, et al., 2012). Generally, wind fields with weak westward winds in the summer mesosphere at low and mid-latitudes favor amplitude growth of the Q2DW (Salby & Callaghan, 2001; Yue, Wang, et al., 2012).

The Q2DW exhibits some fundamental features that are well known now. Among the various wave modes, W3 is generally much stronger, particularly in the Southern Hemisphere (SH), than W2 and W4 (westward propagating wave numbers 2 and 4, respectively) modes, while in the Northern Hemisphere (NH) the W4 mode was reported to be stronger than W3 (Tunbridge et al., 2011). The presence of a weak W2 mode reported in an earlier work (Meek et al., 1996) was ascribed to the nonlinear interaction between W3 and stationary planetary waves (Rojas & Norton, 2007).

Pfister (1985) and Plumb (1983) came up with the suggestion that the Q2DW wave was forced by the baroclinic instability in the zonal jet at ~50°–60°N in the summer mesosphere. Studies now suggest that the amplification and propagation of the Q2DW cannot be explained solely by one or the other proposed mechanisms, but concurrently they can explain the Q2DW interhemispheric/seasonal variation (Norton & Thuburn, 1996; Salby & Callaghan, 2001).

The idea of a nonlinear interaction between thermal tides and Q2DW has been engaging the researchers for decades. According to the study by Teitelbaum and Vial (1991), the nonlinear interaction of two global-scale waves generates secondary waves with frequencies and zonal wavenumbers that are the sums and differences of those of the interacting waves. Observations and model simulations support the presence of secondary waves arising from the strong nonlinear interaction between Q2DW and the migrating diurnal tide (diurnal westward propagating wavenumber 1(DW1); Gurubaran, Sridharan, et al., 2001; Huang et al., 2013; Nguyen et al., 2016) causing considerable impact on the ionospheric electrodynamics (Forbes et al., 2021; Gu et al., 2018; Yue et al., 2016).

The vertical propagation of the planetary waves and their direct extension into the dynamo region are not well established. Various mechanisms have been proposed for the manifestation of mesospheric planetary-scale waves in the dynamo region (e.g., Elhawary & Forbes, 2016; Forbes, 1996). Direct propagation of the wave from the lower to the upper atmosphere is one of the mechanisms, which has been explained through simulations (Yue, Liu, et al., 2012). It was suggested that the Q2DWs could penetrate into the dynamo region and cause variations in ionospheric parameters at similar time periods. There was also a suggestion that tides carry the planetary wave periodicity into the dynamo region, and this was well supported by observations and simulations. Gravity wave filtering is another process by which the Q2DW periodicity can be imposed in the mesosphere and above. Gravity waves can be modulated at planetary wave periods at lower altitudes and the modulated gravity wave flux can impose periodicity at planetary wave periods at higher altitudes when they dissipate and deposit their momentum (Meyer, 1999; Smith, 2003). Earlier, Gurubaran, Sridharan, et al. (2001) reported the characteristics of QTDWs in the MLT region over the low latitude site, Tirunelveli (8.7°N, 77.8°E). The quasi 2-day oscillations (Q2DOs) in the equatorial electrojet and the role of mesospheric winds therein were reported in subsequent work by the same authors (Gurubaran, Ramkumar, et al., 2001).

The recent occurrence of the Q2DW during January 2015 was studied in detail by Fritts et al. (2019), wherein they used mid and high-latitude medium frequency (MF)/meteor radar stations along with the Earth Observing System Microwave Limb Sounder data at MLT altitudes over the SH. In the present study, we investigate the Q2DW in the tropical region at MLT heights and its signatures in the dynamo region during the January 2015 event. We discuss the probable conditions for the propagation of the Q2DW into the ionosphere that leaves its imprints in the solar quiet (Sq) ionospheric current system as manifested in ground geomagnetic field variations.

2. Data and Method of Analysis

The present work utilizes data sets from MF and meteor radars and ground-based geomagnetic field observations for the month of January 2015. The MF and meteor radars yield winds in the MLT region, that is, 70–100 km. The geomagnetic field variations, especially during magnetically quiet times, are known to represent the currents flowing in the ionospheric dynamo region at altitudes in the range of 100–120 km. The combined data sets thus make it possible to examine atmosphere-ionosphere coupling through planetary-scale waves.

2.1. MF and Meteor Radars

The MF radars at Kolhapur (16.8°N, 74.2°E) and Pameungpeuk (7.6°S, 107.7°E) are similar instruments operating at ~2 MHz (Patil et al., 2007; Sridharan et al., 2007). The MF radar enables wind determinations using the spaced antenna technique in the 70–98 km height range at every ~2 min and at 2 km height intervals (Vincent & Lesicar, 1991). The data from the meteor radar at Cachoeira Paulista (22.7°S, 45°W) (CP) (Lima et al., 2012) provide information on winds from the western hemisphere in the altitude range of 81–99 km. The information regarding meteor positions is obtained from the relative phases of the echoes at various antennas together with the echo range. The Doppler shift of the returned signal is used to determine the radial velocity. In the equatorial MLT region, as the QTDW in meridional wind is almost 2–3 times stronger than in zonal wind (Pancheva et al., 2006), for the present work, we utilize meridional wind data sets for January 2015 from all three stations. The data from the three sites together can be used to retrieve the wavenumber characteristics of the dominant planetary wave mode. Figure 1 shows the locations of the radar sites along with magnetometer sites considered for the present study.

2.2. Geomagnetic Field Observations

In order to ascertain the ionospheric response to the Q2DW observed in the MLT region, we examine the ground geomagnetic field variations that are due to the superposition of various currents in the magnetosphere and E- and

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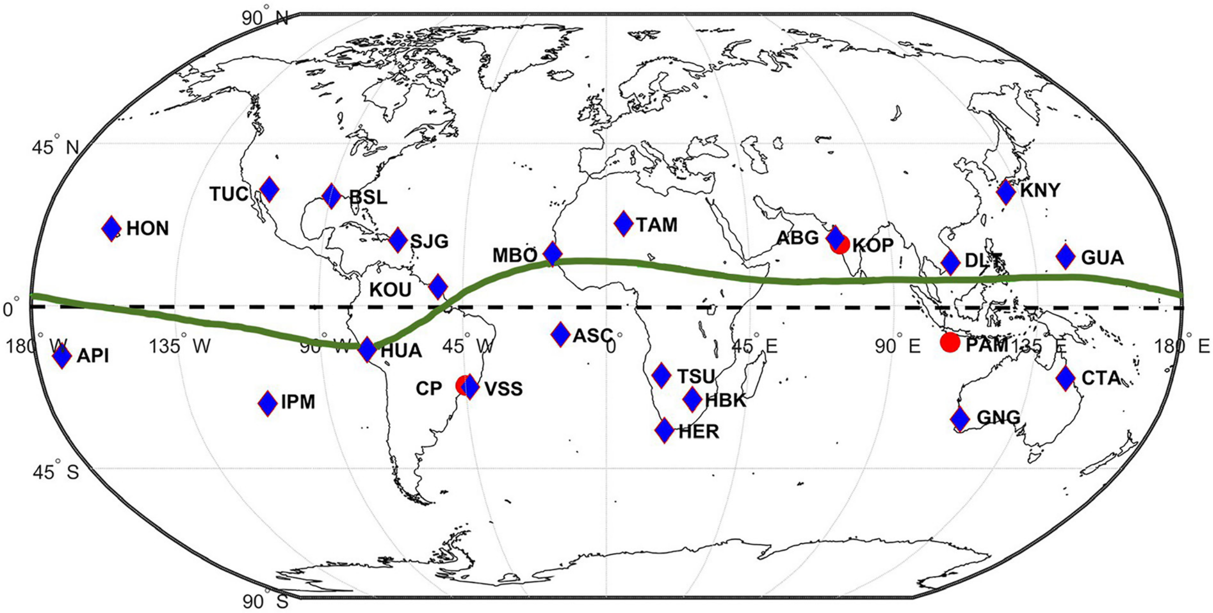

Figure 1. Station map showing the radar and magnetometer sites considered for this work. Blue markers indicate geomagnetic stations. Red markers indicate radar stations. Dashed and solid curves represent geographic and geomagnetic equators, respectively.

F-region ionosphere. Hourly geomagnetic data were obtained for the 22 stations from the International Real-time Magnetic Observatory Network (INTERMAGNET). The selected stations are listed in Table 1 together with their geographic and geomagnetic coordinates. The hourly variations of the geomagnetic field components archived in the IAGA 2002 format are used for this analysis. It is important to note that the amplitude of the perturbations detected in the geomagnetic field are not only dependent on the electric field driven by neutral winds but also on ionospheric conductivity. Moreover, the disturbed time currents, for example, those of magnetospheric origin, generated during geomagnetic storms, are superposed on the wind-driven quiet time ionospheric currents.

In order to assess the presence of any variability in the geomagnetic field in the periods corresponding to QTDW imposed by the disturbed time currents, we examined the Disturbance Storm Time (Dst) and ap indices for the period of interest. The hourly Dst reflects the symmetric part of the magnetospheric ring current, which produces a southward field on the ground, opposite to the daytime northward (X) component of the quiet-time daily variation of the geomagnetic field (Ebihara, 2019, for a recent work on geomagnetic storms). Using the S-transform (described later), we looked for the presence of a 2-day periodicity in Dst and ap indices. The results for the periods ranging from 1.5 to ∼5 days are gathered in Figure 2, wherein we do not see any significant 2-day variation in geomagnetic activity during the second half of January when the peak QTDW occurrence was observed in mesospheric winds. This implies that the role of disturbed time currents of magnetospheric origin in causing 2-day periodicity in the observed geomagnetic field variation was minimal during the time of QTDW occurrence.

Geomagnetic field variations from longitudinally separated stations can be used to differentiate the contributions from the sources originating in the magnetosphere and those having atmospheric origin. This is possible, because on the one hand, the solar-geomagnetic activity induced periodical signature, if any, should be present simultaneously across the globe, while the planetary wave induced variation in the corresponding period would show a phase difference between longitudinally separated stations. The nature of the disturbed current pattern is such that its contributions to the X component of the geomagnetic field are larger than those to the Y (East-West) component (Pancheva et al., 2006; Yamada, 2009). On the other hand, the planetary wave induced 2-day periodicity in the present exercise, is more pronounced in Y than in X and Z components. For these reasons, we have considered only the Y component for this work.

To extract the short-term variabilities from the hourly geomagnetic data, we remove the baseline from each element of the time series (see Yamazaki & Maute, 2017 on the several ways to remove baseline values from ground geomagnetic data). Pancheva et al. (2006) introduced a novel method for extracting atmospheric perturbations

Table 1
Magnetometer Stations Considered in This Work

Station code	Geographic latitude	Geographic longitude	Geomagnetic latitude	Geomagnetic longitude
Stations in NH				
TAM	22.7	5.5	24.3	82.2
ABG	18.6	72.8	10.7	146.9
DLT	11.9	108.4	2.4	181.4
KNY	31.4	130.8	22.5	201.7
GUA	13.6	144.8	6	216.5
HON	21.3	202	21.6	270.9
TUC	32.17	249.27	39.1	317.6
BSL	30.3	270.3	39.1	341
SJG	18.1	293.8	27.3	7
KOU	5.2	307.2	14	20.5
MBO	14.3	343	19.4	58.1
Stations in SH				
TSU	−19.2	17.5	−18.8	87.2
HER	−34.4	19.2	−34	85.5
HBK	−25.8	27.7	−27	95.7
CKI	−12.2	96.83	−21.3	168.9
GNG	−31.3	115.7	−40.4	189.4
CTA	−20	146.2	−27.1	221.6
API	−13.8	188.2	−15	263.3
IPM	−27	250.5	−19.4	325.6
HUA	−12	284.6	−2.5	357.4
VSS	−22.4	316.3	−13.9	27.5
ASC	−7.9	345.6	−2.9	57.5

Note. The data for the three components of the geomagnetic field have been retrieved for the period of interest, that is, January 2015, from these stations.

from the geomagnetic field variations, wherein they considered the planetary wave activity as the modulation of the solar-quiet (Sq) diurnal cycle of the geomagnetic component. In this work, we adopt simultaneous harmonic fittings of Q2DW, 24 and 12 hr tides, and the mean wind over the radar sites in order to assess the temporal variations of the Q2DW amplitudes. The least squares fitting uses a 5-day sliding window with 1-day increment applied over the data for the period 1–31 January 2015. The harmonic analysis thus performed provides us with amplitude and phase information. To minimize the ambiguity caused by other longer period oscillations with the same zonal wave number, we filter the time series over the 40–60 hr period range before applying the harmonic analysis.

For time-varying signals, the traditional approach involving time-averaged amplitude spectra using Fourier transform is inadequate to track changes in signal amplitude, frequency, or phase. Rather, time-frequency based techniques are more useful than the techniques based on either time or frequency domain. Among the several approaches, the continuous wavelet transform (CWT) is widely being used, as it is seen as an extension of the traditional spectrogram. It can extract temporal variations in the amplitudes of desired frequencies present in the given time series. The S-transform (ST) (Stockwell, 1996) is one of the techniques, which is considered to be a hybrid of fast Fourier transform (FFT) and CWT. The low resolution of the FFT and the absence of phase information in the CWT led to the development of the ST, as the latter retains the absolute phase information while maintaining a good time-frequency resolution at all frequencies.

3. Results and Discussion

3.1. Q2DW in the MLT Region

Figure 3 shows the height-time cross-section of the amplitudes of Q2DW in meridional wind over KOP, PAM, and CP estimated using least squares fit applied to a window of 96 hr sliding at a step of 24 hr. Amplitudes exceeding 60 m/s are observed at altitudes between 85 and 88 km over all three stations. These larger amplitudes indicate a potential role of the Q2DW in driving short-term (in day-to-day time scales) variability in winds and thereby the overall circulation in the upper mesosphere during these times. Moreover, the wave activity over KOP and CP was comparable, while that over PAM, which is closer to the equator, but in the SH, the duration of the wave activity was comparatively shorter, though the activity occurred with similar amplitudes. Such larger amplitudes in the meridional wind at low latitudes were observed earlier in the ground and space-borne observations (e.g., Gurubaran, Sridharan, et al., 2001; Harris &

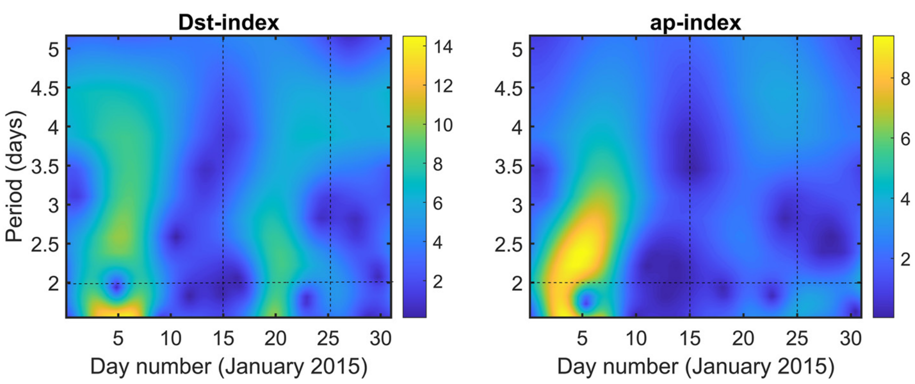

Figure 2. Frequency spectrum of Dst (left panel) and ap (right panel) indices for January 2015 (see text for details).

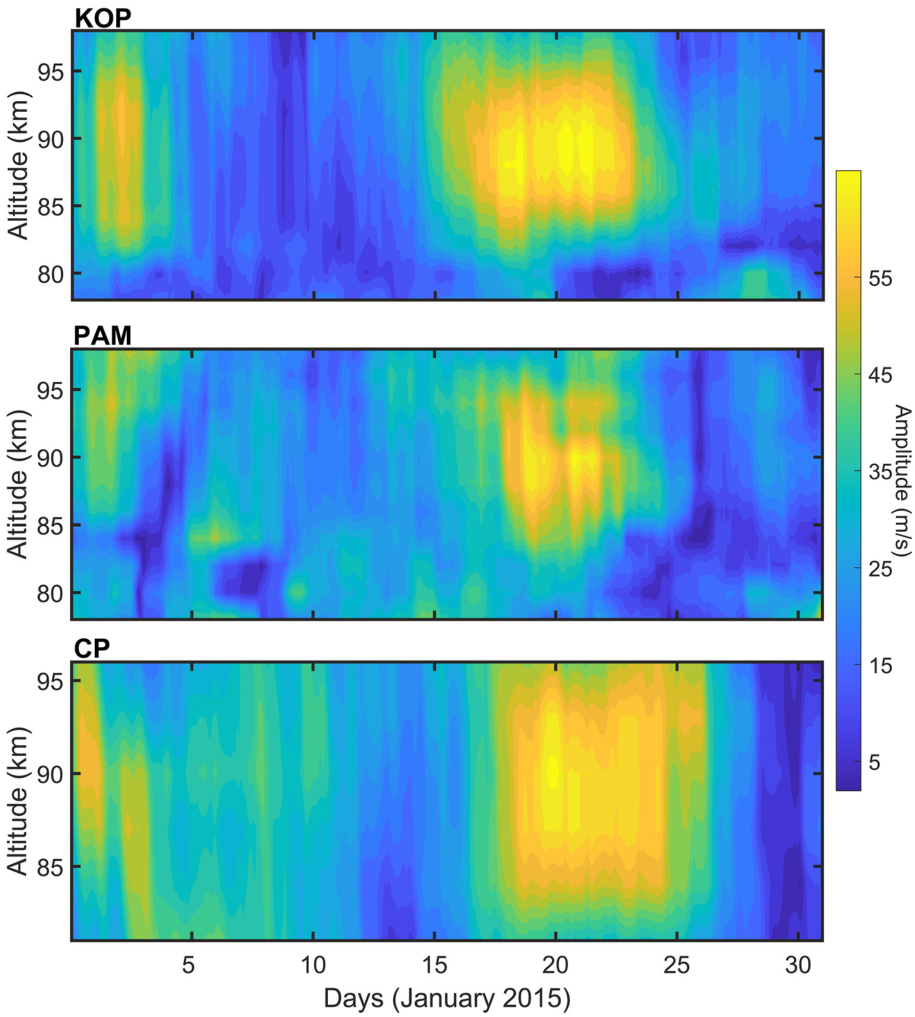

Figure 3. Altitude variation of amplitudes of quasi 2-day wave during the month of January 2015 over Kolhapur (top panel), Pameungpeuk (Middle panel), and Cachoeira Paulista (bottom panel).

Vincent, 1993; He et al., 2021; Norton & Thuburn, 1996; Wu et al., 1993). As reported by Fritts et al. (2019), the amplitudes over the mid-latitude stations, namely, Kingston and Adelaide, in the SH were twice the amplitudes over the corresponding high-latitude stations. It may be noted that the amplitudes reported in the present work are similar to those reported by Fritts et al. (2019) for the mid-latitude sites during the January 2015 Q2DW episode.

In order to bring out the temporal variation in wave periodicities and amplitudes in closer detail, the radar wind observations at 88 km were subjected to Stockwell transform, whose results for the meridional wind are shown in Figure 4. The spectra clearly show the presence of wave periodicities in the range of 45–52 hr. However, there was a difference noticed in the wave period at the time of the peak activity over the three sites. The observed period was ~48 hr over CP but closer to ~46 hr over PAM and KOP. One may argue that these differences were due to the latitudinal or longitudinal differences between the stations, but it may be noted that the periods reported by Fritts et al. (2019) over Kingston (43°S, 144°E) and Adelaide (35°S, 138°E) were very similar to the wave periods observed over PAM and KOP. The activity over CP was distinctly different in terms of period and in terms of the time of occurrence of the activity when compared to the other tropical stations, though possibly in a different background wind scenario.

Figure 5 plots the phase values (in degrees) from all three radar stations during the month of January 2015. The phases were estimated over a window length of 96 hr sliding at 1 hr intervals. As one follows through the three curves, it becomes evident that for the station pair CP-KOP (stations separated by ~120° in longitude), the phases are much closer to each other than those individually with PAM, clearly indicating a wavenumber 3 pattern for

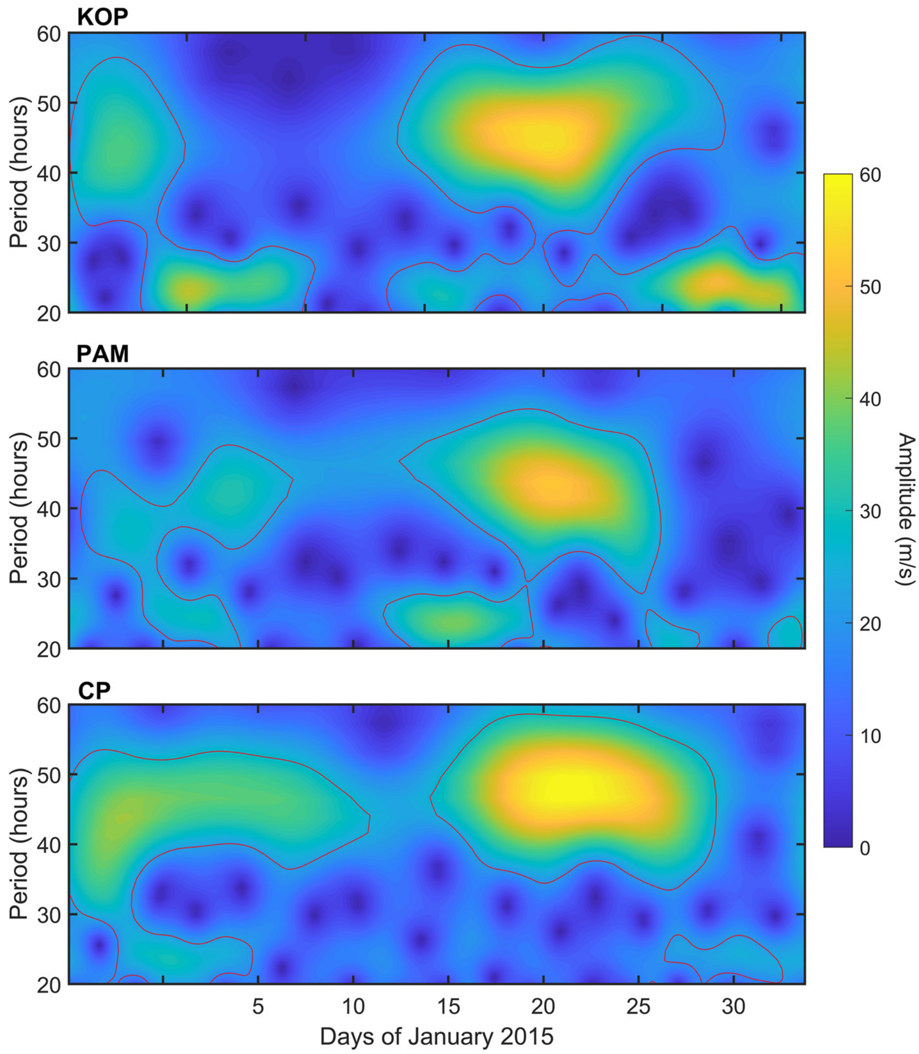

Figure 4. S-transform of meridional winds at 88 km for the month of January 2015 over Kolhapur (top panel), Pameungpeuk (middle panel), and Cachoeira Paulista (bottom panel). Solid contours indicate 95% confidence intervals.

the Q2DW over much of this duration. One would expect a small or negligible phase difference between those stations with a longitude separation of ∼120° for a wavenumber 3 mode having three maxima and three minima in its longitudinal structure. The phase difference observed between the stations PAM and CP with a longitudinal separation of ∼155° does confirm the presence of W3 as the dominant feature of the Q2DW during January 2015. This is in accordance with the earlier report of Fritts et al. (2019), who had identified W3 as the dominant mode of Q2DW for the same January 2015 period. As the activity receded after 24 January 2015, the phase differences between the stations do not conform to a wavenumber 3 behavior and there could be other wave modes present during the later period.

Figure 6 depicts the height profiles of the phases of the Q2DW in meridional wind representing 96 hr time segments over the three radar sites (KOP (black), PAM (blue), and CP (red)) during the period 15–30 January 2015. As noted earlier, the phase differences between KOP and CP are much smaller (∼3 hr or less) than the phase differences corresponding to the other station pairs during peak wave activity (15–25 January 2015), thus confirming the wavenumber 3 behavior of Q2DW. However, there is an ambiguity in determining the direction of propagation with just a pair of stations. The latter can be resolved if one considers the third station in the determination of wave propagation direction. In this work, we confirm the presence of W3 with the third station, PAM. The dominance of W3 mode over cross-hemispheric stations indicates the absence of any steep latitudinal phase variation in the equatorial region during the activity, which was previously noted by Pancheva et al. (2006). The

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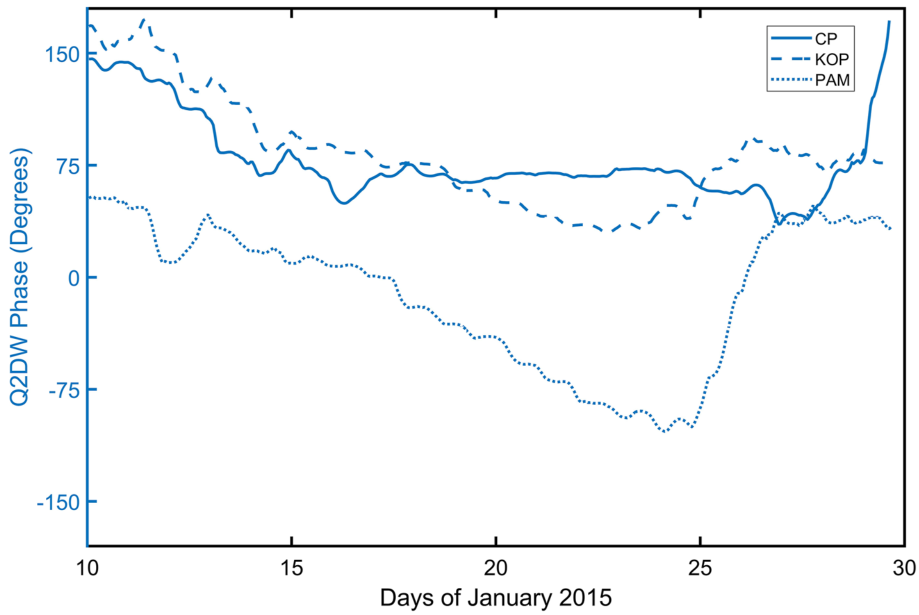

Figure 5. The phase (in degrees) of the quasi 2-day wave (Q2DW) (meridional winds) at 88 km during January 2015 over Pameungpeuk (dotted line), Kolhapur (dashed line), and Cachoeira Paulista (solid line).

phase descent noticed in the vertical phase profiles implies apparent upward propagation of the wave with vertical wavelengths in the range of 80–100 km.

3.2. Mean Zonal Winds and Q2DW

On the one hand, large-amplitude waves can have an impact on the background wind by accelerating or decelerating the mean flow, while on the other hand, the winds can favor or suppress vertical propagation of waves. To examine the interaction between mean zonal wind and Q2DW during January 2015, the zonal winds were averaged over a window length of four days sliding at one-day intervals. Figure 7 shows the mean zonal winds over KOP (left panel), PAM (middle panel), and CP (right panel) during this period. One can notice that there was a distinct change in the wind pattern during mid-January in both hemispheres. For example, the mean zonal wind at ~85 km over KOP during January 2015 was eastward (>50 m/s) prior to the activity, while during the activity, the wind direction had undergone a transition from east to the west. Over PAM, a similar feature was noticed, with the wind revealing eastward speeds (largest being ~20 m/s) prior to the activity and turning westward to reach speeds exceeding 40 m/s during the activity. Over CP, the eastward wind prior to the activity was weaker and there was an extended westward wind regime during the activity. Such variations in mean zonal circulation at these low latitudes are likely to be caused by the drag imposed by the westward propagating Q2DW.

It is also possible that the wave growth in the mesosphere is strongly affected by the background winds. Weak westward winds in the winter hemisphere and weak eastward winds in the summer hemisphere are expected to

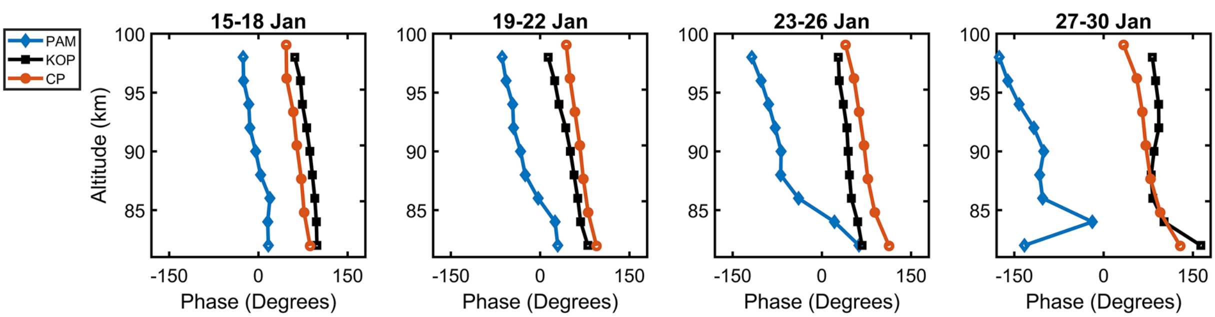

Figure 6. Altitude profiles of the phases of the quasi 2-day wave (meridional winds) in the month of January 2015 over Pameungpeuk (blue curve), Kolhapur (black curve), Cachoeira Paulista (red curve). Refer to text for further details.

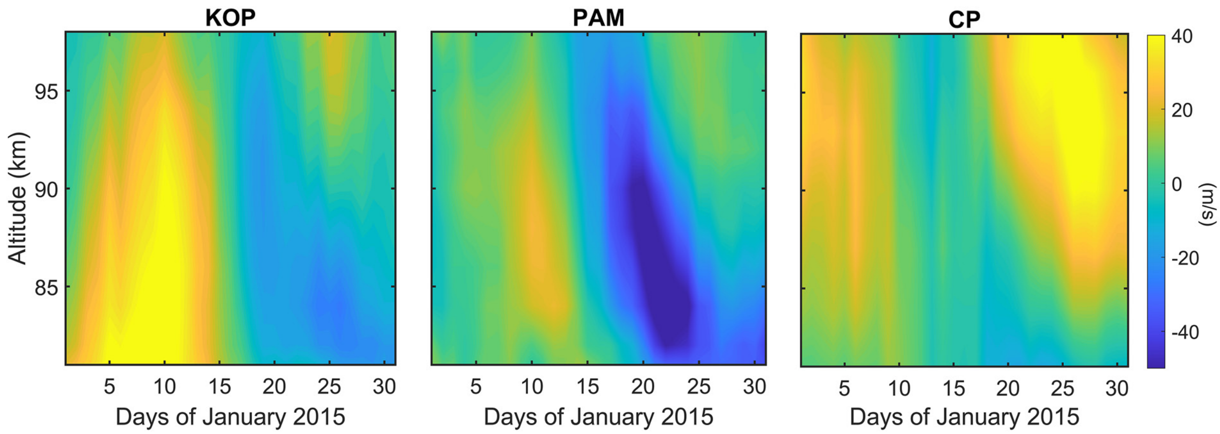

Figure 7. Altitude variation of mean zonal winds over Kolhapur (left panel), Pameungpeuk (middle panel), and Cachoeira Paulista (right panel) shown in the contour form for the period of interest. Note that the color scales are the same for all stations.

support the growth and propagation of Q2DW in the MLT region. The westward accelerated winds by the Q2DW can act like a self-generated critical layer, where the wave can become evanescent. If one considers propagation into the thermosphere, the easterly jet in the thermosphere is not known to be so strong for the formation of a critical layer at those altitudes. Thus, with the same molecular diffusion the wave can extend much higher into the thermosphere (e.g., Yue, Liu, et al., 2012). Accordingly, there is a possibility of the wave propagating through the lower thermosphere and into the ionospheric dynamo region without considerable reduction in the wave amplitude, as we do observe strong signatures of 2-day periodicity in the quiet-time dynamo region currents manifested in the ground geomagnetic field variations (discussed in the next section).

3.3. Q2DO in Geomagnetic Field

Figure 8 shows the hourly time series of the *Y* component of the geomagnetic field over the low latitude station, Kourou (KOU) (refer to Table 1 for station coordinates) and the meridional wind at 88 km over KOP (shown in the top two panels) and the corresponding filtered wind (shown in the bottom panel). These two stations are located ∼120° apart in longitude. Despite this, the wave structures in the winds and in the geomagnetic field were very similar and there was little phase difference between the observed 2-day oscillations. This could be due to one or both of the following: (a) The activity was imposed by the solar-geomagnetic activity and was independent of longitude; (b) The activity owes its existence to the forcing from the mesospheric planetary wave with a wavelength equal to the longitudinal separation (∼120°) between the two stations. As the Dst index does not reveal any pronounced 2-day variation during this period, we rule out the first possibility. To confirm the role of the planetary wave in causing the observed quasi 2-day type oscillation observed in geomagnetic field variation, the phase structure of the Q2DO from multiple sites is examined and compared with the mesospheric wave activity.

The S-transforms of the geomagnetic time series for the selected stations from both hemispheres are shown separately in Figures 9 and 10. One can immediately notice the presence of 2-day activity during 20–25 January 2015 over all stations, though with different amplitudes. An enhanced power at a period of ∼46 hr was observed over almost all stations, which was close to the wave periods observed over the radar sites, KOP and PAM. From the features noticed in the S-transforms of the *Y* component shown in Figures 9 and 10, we reaffirm that the periodicities showing up as enhanced activity in the geomagnetic field were due to the mesospheric Q2DW. Despite similarities in the features observed, there were differences in the time of occurrence of the peak amplitude, which need to be examined separately.

To estimate the zonal wavenumber and assess the overall zonal structure of the observed Q2DO in the geomagnetic *Y* component, the phases of the Q2DO are retrieved from the geomagnetic data using least squares fits. The results are plotted in Figure 11 (left panel (middle panel) for Northern (Southern) Hemispheric stations). The straight lines passing through the phase values represent the best fit for the corresponding wavenumber feature. It is encouraging that a linear trend is clearly evident in how the phase of the Q2DO varied with longitude, indicating a consistent westward wavenumber, which was ∼3 for the NH and 2.8 for the SH. The W3 phase structure

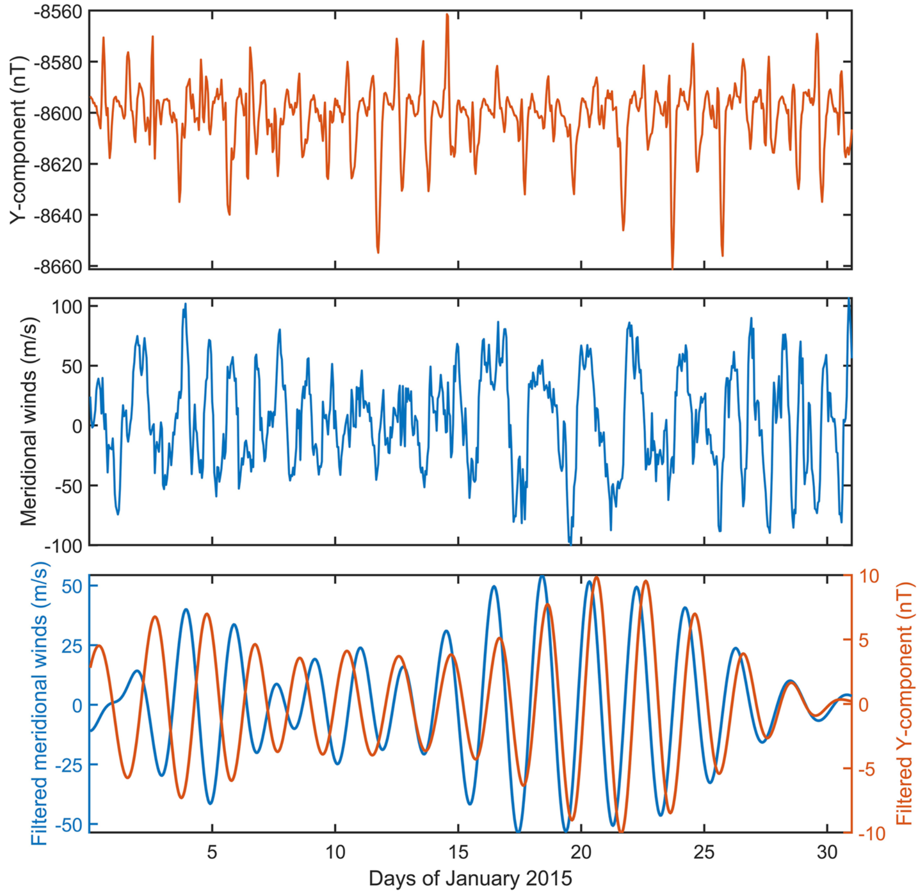

Figure 8. Hourly *Y* component of the geomagnetic field over Kourou (KOU) (top panel), hourly winds over Kolhapur at 88 km (middle panel), and filtered meridional winds along with the filtered time series of *Y* component (bottom panel).

was retained throughout the NH during this January 2015 Q2DW wave event. Over the SH, however, W3 was not so well expressed. Whether the latter was caused by the background winds at lower thermospheric altitudes or whether there were additional modes present besides W3 that might have caused a shift in the observed zonal wavenumber in the Southern Hemisphere is not known. Taking note of the longitude dependence of the phase of the Q2DW in meridional wind at mesospheric altitudes (shown in the right panel in Figure 10 for comparison), the results presented in this work strongly indicate a direct penetration of the Q2DW to the dynamo region, the possible reasons for which are examined below.

Past work had indicated modulation of diurnal and semidiurnal tides at Q2DW periods at upper mesospheric altitudes and the modulated tides, in turn, would have caused perturbations of the quiet-time currents at those periods (Liu et al., 2010; Pancheva et al., 2000; Teitelbaum & Vial, 1991). In the present study, however, we do not observe any significant modulation of tides at MLT altitudes during the January 2015 episodic event as shown in Figure 12. To assess tidal modulation, we first removed the dominant Q2DW component from the observed meridional wind and the residual wind was filtered with a bandpass of 40–60 hr. As can be seen in Figure 12, large-amplitude diurnal tide signatures can be clearly seen between 14 and 18 January 2015, that is, prior to the peak occurrence in QTDW activity, but there is no obvious 2-day modulation of these tidal signatures. Rather, the bandpass filtered wind only indicates a weak 2-day oscillation with speeds of a few m/s, which is far less in order to have any impact on the E-region dynamo. Hence, the possibility of modulated tides causing Q2DW signatures at ionospheric altitudes did not arise at least for this event.

On the other hand, from their numerical simulation experiments, Yue, Liu, et al. (2012) reported direct propagation of Q2DW to the thermosphere, and as suggested by them the easterly jet in the thermosphere was not so strong for a critical layer to form and that would have permitted the upward propagation of planetary wave. In the

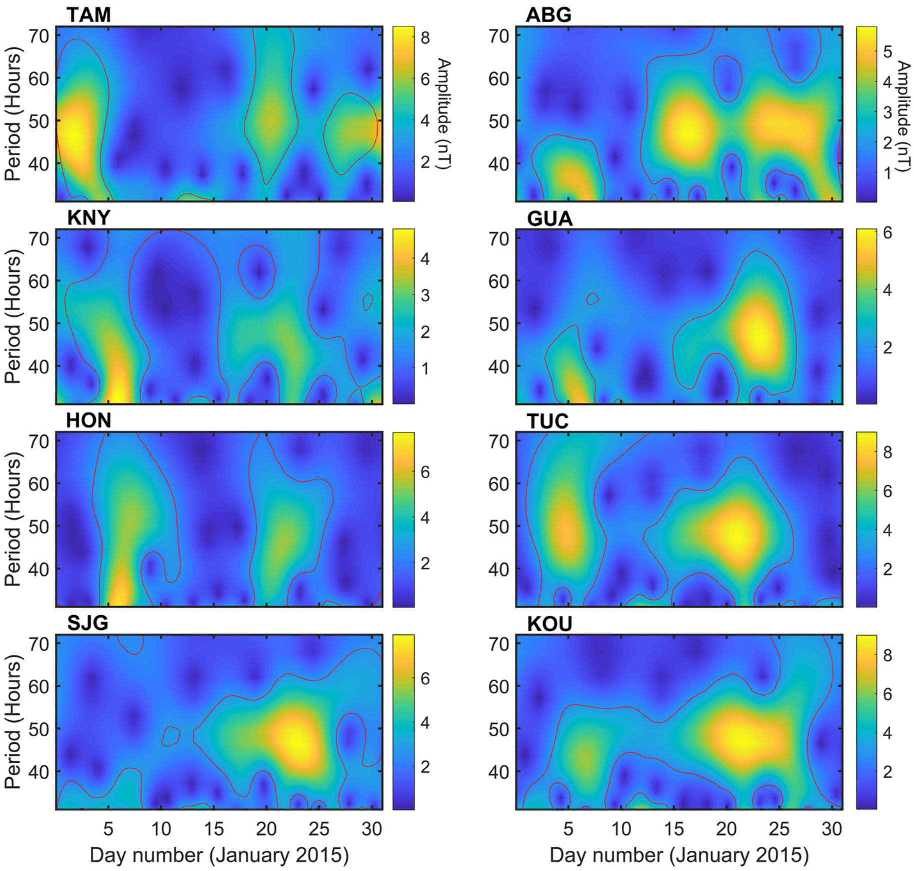

Figure 9. Stockwell transform of *Y* component of geomagnetic field for the Northern Hemisphere. Solid contours indicate 95% confidence intervals.

absence of a critical layer, the Q2DW would have remained active at those altitudes despite molecular diffusion tending to dissipate the wave. Moreover, larger vertical wavelengths observed for the Q2DW are a good indicator for the wave propagation to extend well into the ionospheric dynamo region. Similar to the Ultra-Fast Kelvin Waves and DE3 tides, a large amplitude Q2DW, on propagation to the E region, would modulate the dynamo winds at those altitudes under favorable conditions (Yue, Wang, et al., 2012 and references therein) and could cause the observed Q2DO in the ionospheric currents, and in turn, the ground geomagnetic field variations. Elhawary and Forbes (2016) had argued for the interaction between solar periodicities in electrical conductivity and planetary wave periodicities in electric field to account for the variations in geomagnetic field with periods less than 20 days.

Besides a strong Q2DW peak in the mesosphere, past satellite observations (Limpasuvan et al., 2005; Ward et al., 1996; Wu et al., 1993) and numerical experiments (Chang et al., 2011; Palo et al., 1999) had revealed another maximum in Q2DW activity at 110–115 km. This double-peak structure, with a secondary maximum in the lower thermosphere, was attributed to the internal wave-like propagation into the upper mesosphere and thermosphere from the barotropically/baroclinically unstable region over summer midlatitudes with enhanced refractive index. In case the wave dissipates at these altitudes, the Q2DW winds superimposed on the background winds would drive additional plasma motions across the geomagnetic field lines causing the modulation of the E-region dynamo at a period of ~2 days.

4. Summary and Conclusion

This paper demonstrates the role of Q2DW in the vertical coupling of the atmosphere-ionosphere system at low-to-middle latitudes. Strong Q2DW activity observed over KOP, PAM, and CP during January 2015 was analyzed in detail using observational data from MF and meteor radars. The activity exhibited similar wave

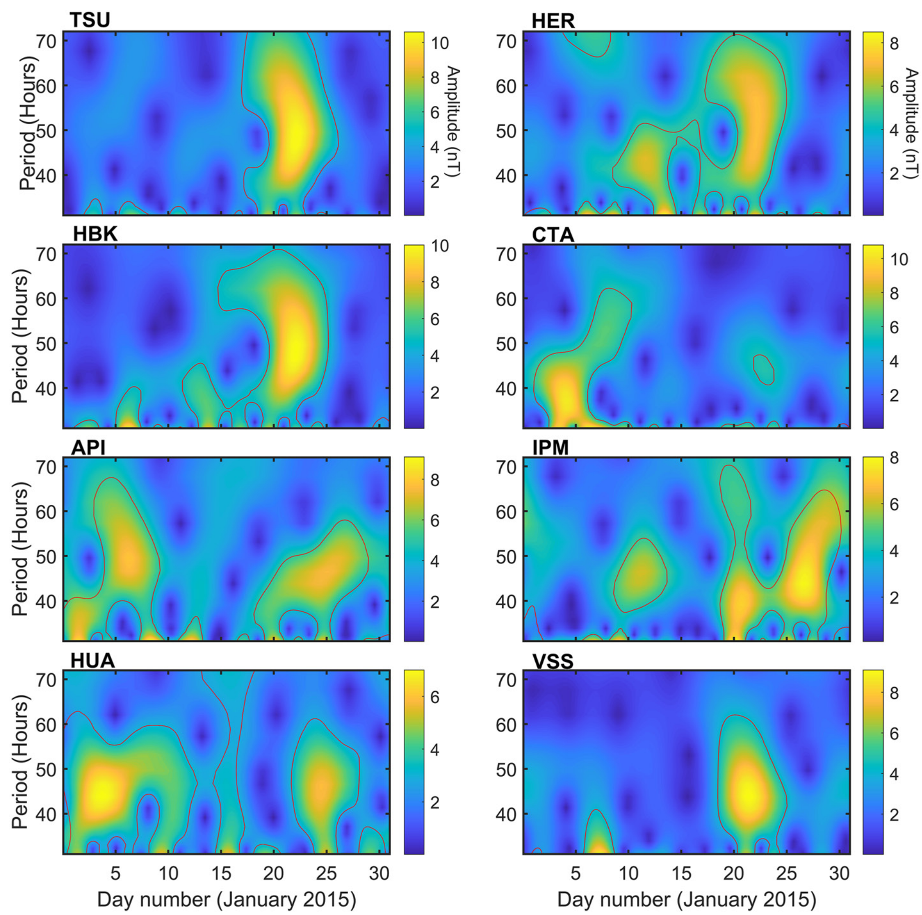

Figure 10. Similar to Figure 9 but for the Southern Hemisphere.

features like amplitudes, time of occurrence and zonal structure in both the hemispheres. The same Q2DW burst was also observed in ground geomagnetic data over 22 low-latitude stations from both Northern and SHs. We had chosen the *Y* component of the geomagnetic field for this study as it is less influenced by geomagnetic disturbances. The phase-longitude cross-section depicting the zonal structure of the wave in MLT winds yielded a linear fit with a slope of ∼−3 indicating the dominant W3 mode.

An important finding from the present work is the presence of the Q2DO in geomagnetic field variations with the same westward propagating zonal wavenumber 3 structure, more so for the NH stations, as was observed in the

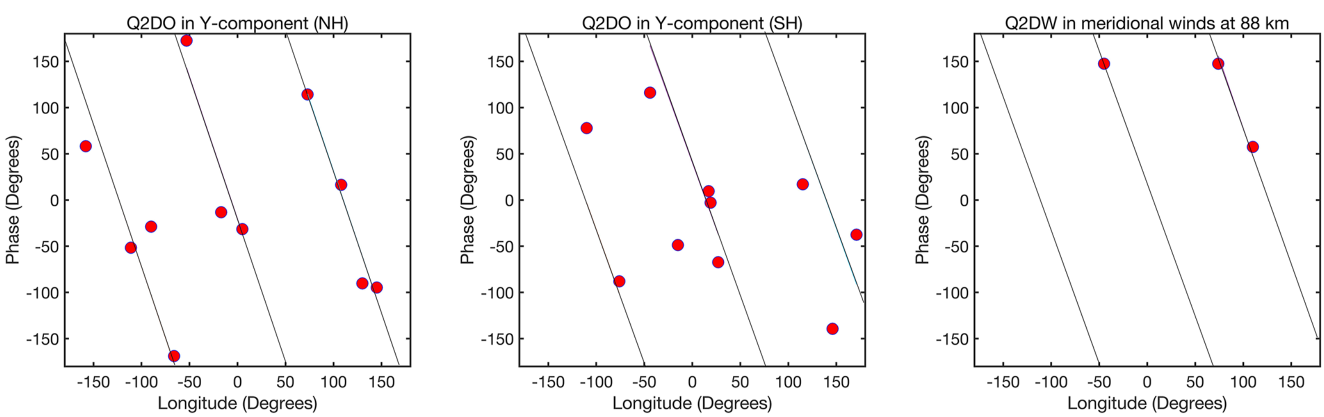

Figure 11. Longitudinal variation of phase of quasi 2-day wave (Q2DW) over geomagnetic stations in NH (left panel) and SH (middle panel). The right panel shows the results for the mesosphere-lower thermosphere winds from three radar stations.

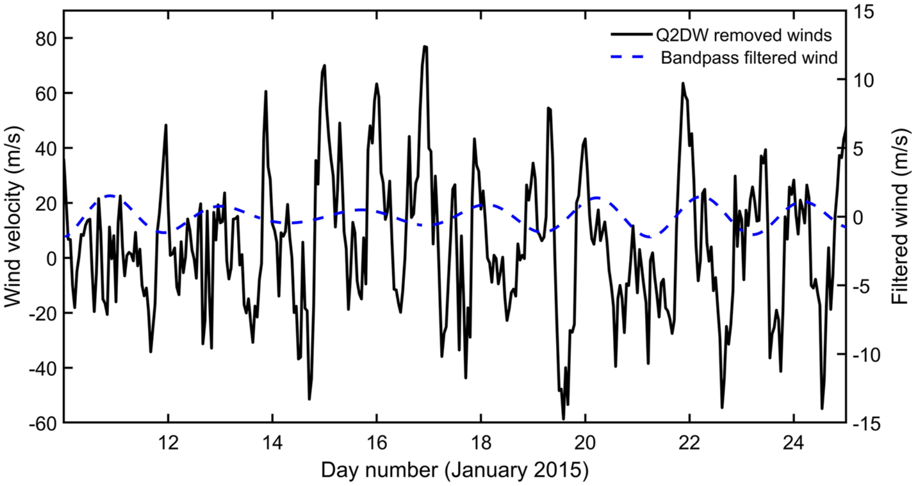

Figure 12. Meridional wind at 88 km with QTDW component removed (solid curve) along with the filtered component (red curve).

MLT region. These results are suggestive of a direct vertical propagation of the Q2DW on this occasion. There does not appear to be any signature of tidal modulation in the generation of Q2DO at ionospheric altitudes. It appears the zonal structure was carried up to the thermosphere from the mesosphere as it was in this scenario. This was quite different from the earlier reports which showed different zonal structures in these two height regimes. Reliable measurements on neutral winds from lower thermospheric heights (∼110 km) would throw more light on such intriguing features reported in this work.

Data Availability Statement

The authors thank INTERMAGNET for maintaining geomagnetic records with high standards and for making them available (https://intermagnet.org). The authors are also thankful to RISH, Kyoto University, Japan for making the Pameungpeuk MF radar data available through http://database.rish.kyoto-u.ac.jp/arch/iugonet/, the distribution of the data having been partly supported by the IUGONET (Inter-university Upper atmosphere Global Observation NETwork) project (http://www.iugonet.org/) funded by the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan. The data sets for Kolhapur and Cachoeira Paulista used in this work are available here: https://iigm.res.in/content/mf-meteor-radar-data.

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