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# The Mathematical characteristic of the Phase and Group Velocities of Pure Alfvèn Wave in the E Region of the Ionosphere for Low Latitudes

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## Abstract

In this study, we mainly focus our attention on mathematical analysis of the phase and group velocities of low-frequency Alfvèn waves in the E region of the ionosphere. According to observational conclusions it is known that the phase and group velocities of such waves are equal to each other when kinematic and magnetic viscosity are ignored. On the other hand, these velocities have different velocities when we take kinematic andmagnetic viscosities into account.

Since it is very difficult to analyze the group velocity analytically, we plan to discuss its numerical solutions in our future investigation. Thus, in the present study, we focus on the features of phase velocity of low-frequency of Alfvèn wave and analyze its nature in the E region of the ionosphere for low latitudes. we see that the trend of change of magnitudes of the phase velocities on on March 21$^{st}$and June21$^{st}$ resembles to the behavior of cosine function Moreover, it is concluded that the magnitudes of real and imaginary parts of the corresponding solutions arelarger than the ones obtained for March 21$^{st}$. The ma in reason of this case may be higher electron production in the ionosphere in June.

**Keywords:** Alfvèn waves, phase and group velocity, ionosphere

# Düşük Enlemlerde İyonosferin E bölgesinde Düşük Frekanslı Alfvèn Dalgalarının Faz ve Grup Hızlarının Matematiksel Karekteristiği

## Özet

Bu çalışmada, dikkatimizi esasen Iyonosferin E bölgesinde düşük frekanslı dalgaların faz ve grup hızlarının matematiksel analizini araştırmaya yönlendirdik. Elde edilen gözlemsel bulgulara göre, kinematik ve manyetik viskozite ihmal edildiğinde faz ve grup hızları böyle dalgalar için eşit değerlere sahip olmaktadır. Diğer yandan kinematik ve manyetik viskozite göz önüne alındığında ise faz ve grup hızları farklı değerler almaktadır.

Grup hızını analitik olarak analiz etmek oldukça zor olduğundan onun nümerik çözümlerini sıradaki araştırmamızda ele almayı planlıyoruz. Buradan hareketle sunulan bu araştırmamızda, temel olarak düşük frekanslı Alfvèn dalgaları için faz hızının özelliklerine ve orta enlemlerde iyonosferin E-bölgesi (140 Km) için doğasının analiz edilmesine odaklanılmıştır. 21 Mart ve 21 Haziran'da faz hızlarının büyüklüklerinin değişim trendinin kosinüs fonksiyonun davranışına benzediği görülmüştür. Öte yandan, karşılık gelen çözümlerin reel ve sanal kısımların büyüklüklerinin 21 Mart için elde edilenlerden daha büyük olduğu elde edilmiştir. Bu durumun esas nedeni iyonosferde Haziran ayındaki daha yüksek elektron üretimi olabilir
**Anahtar Kelimeler:** Alfvèn dalgaları, faz ve grup hızı, iyonküre

## INTRODUCTION

Until now, a large number of scientists haveperformed noteworthystudies about various properties, physical structure, and chemical structure of the Earth's ionosphere(Budden, 1988; Budden and Stott 1980; Hunsucker and Hargreaves 2003; Kaladze et al., 2019; Ratcliffe 1959). Since the ionosphere has a conductive structure, the behavior of electromagnetic waves in a such environment under various conditions, have been studied in literature (Budden, 1988; Budden and Stott 1980; Hunsucker and Hargreaves 2003; Kaladze et al., 2019; Ratcliffe 1959; Richard, 2014; Rishbeth, 1973;Swanson, 1989; Timucin et al., 2019; Timucin et al., 2014; Unal et al.,

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2011; Yaşar, 2021; Yeşil et al., 2021; Yeşil and Sagir 2019; Yeşil 2006; Yeşil and Kurt 2019; Whitten and Popoff, 1971).But, low-frequency waves have been studied for a long time in ionosphere but these studies these studies are lacking due to some approaches(Richard, 2014; Rishbeth, 1973; Swanson, 1989; Timucin et al., 2019; Timucin et al., 2014; Unal et al., 2011; Yaşar, 2021; Yaşar, 2021; Yeşil et al., 2021; Yeşil and Sagir 2019; Yeşil 2006).Wave propagation in partially ionized plasma also plays an important role in the coupling between the ionosphere and magnetosphere. For example, the ionosphere may support very-low-frequency Alfvèn wave which can be caused by a balance between the bulk fluid inertia and the deformation of the magnetic field. The change in momentum caused by the collision between the plasma and neutral particles facilitates the transfer of magnetic stress to neutrals. Therefore, at the low frequency limit relative to the neutral-ion collision frequency, the waves undergo very little attenuation throughout the ionosphere. The frequency of these waves are very low and below few Hz. At lower frequencies below certain collision frequencies, the plasma behaves like a fluid. Generally, the magnetic field is present in all plasmas and a good conductor. Therefore, the magnetic field frozen in the fluid moves with the fluid. In MHD(Manyeto-Hidrodyamic) equations, generally high and low beta($\beta=P/(B2/2\mu0)$) distinction is made. in which, P represents plasma pressure and ($B2/2\mu0$) magnetic pressure, respectively. If $\beta>>1$, then plasma pressure is bigger than magnetic pressure and plasma drags magnetic field, otherwise magnetic field drags plasma. When plasma drags the magnetic field, the stresses occurring in the plasma propagate with the sound waves. Otherwise, this stress propagates Alfvèn waves(Richard, 2014; Richard, 2014; Rishbeth, 1973; Swanson, 1989; Timucin et al., 2019; Timucin et al., 2014; Unal et al., 2011; Yaşar, 2021; Yaşar, 2021; Yeşil et al., 2021; Yeşil and Sagir 2019; Yeşil2006). Why is it important for us to study group and phase velocity? Because when the wave enters a medium, it can lose energy or take energy from the medium, such as the ionosphere plate. Especially in remote sensing methods, group and phase velocity are generally studied when it is important for information about how much energy a wave loses or gains in the environment.

In this paper, it has been studied the group and phase velocity for the accepted conditions in the ionospheric plasma. As known, group carries energy in a wave, while phase velocity is the velocity of propagation of the wave in any direction. In many cases, it is the shape of a waveform. Sometimes the directions of group repetition and phase velocity are different. However, this information is not always correct if the wave is traveling in an absorbing medium. Many studies and experiments since the 1980s have shown that the group speed of laser light sent with specially prepared materials can exceed the speed of light in an air gap. In this case, faster-than-light communication is not possible because the signal speed remains slower than the speed of light in every way. It is also possible to reduce the group velocity to zero by stopping the current or creating a negative group velocity. In all cases, however, photons continue to propagate in the medium at the speed of light(Swanson, 1989; Timucin et al., 2019; Timucin et al., 2014; Unal et al., 2011; Yaşar, 2021; Yaşar, 2021; Yeşil et al., 2021; Yeşil and Sagir 2019).

## THE COMPLEX PHASE AND GROUP VELOCITY OF LOW-FREQUENCY ALFVÈN WAVES FOR IONOSPHERIC PLASMA AT NORTHERN HEMISPHERE

It is well known that MHD equations governing a compressible viscous conduction fluid immersed in a magnetic field are given by;

$$\frac{\partial \rho_m}{\partial t} + \nabla.\left(\rho_m \boldsymbol{U}\right) = 0 \quad (1)$$

$$\rho_m \frac{\partial \rho_m}{\partial t} + \rho_m\left(\boldsymbol{U}.\nabla\right)\boldsymbol{U} = -\nabla P + \boldsymbol{J}\times\boldsymbol{B} - \rho_{m0}\eta_k \nabla^2 \boldsymbol{U} \quad (2)$$

$$\nabla P = V_s^2 \nabla \rho_m \quad (3)$$

$$\nabla\times\boldsymbol{B} = \mu_0 \boldsymbol{J} \quad (4)$$

$$\nabla\times\boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t} \quad (5)$$

$$E + uxB = 0 (6)$$

If equations 1,3,4,5 and 6 are substituted in equation 2 after mathematical manipulation, using each other, the momentum equation,

$$\rho_{m0}\frac{\partial u_1}{\partial t} + V_s^2 \nabla \rho_{m1} + \frac{1}{\mu_0}\boldsymbol{B}_0\times(\nabla\times\boldsymbol{B}_1) = 0 \quad (7)$$

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$$\frac{\partial \boldsymbol{B}_1}{\partial t} - \nabla \times (\boldsymbol{u} \times \boldsymbol{B}_0) - \eta_m \nabla^2 \boldsymbol{B}_1 = 0 \quad (8)$$

In which, all fields change as follow.

$$\boldsymbol{B}(\boldsymbol{r}, t) = \boldsymbol{B}_0 + \boldsymbol{B}_1(\boldsymbol{r}, t) \quad (9)$$

$$\rho_m(\boldsymbol{r}, t) = \rho_{m0} + \rho_{m1}(\boldsymbol{r}, t) \quad (10)$$

$$\boldsymbol{u}(\boldsymbol{r}, t) = \boldsymbol{u}_1(\boldsymbol{r}, t) \quad (11)$$

Lowercase u is the fluid's velocity, $\rho_m$ mass density, and B is the magnetic field. Under equilibrium conditions, the fluid is assumed to be spatially uniform with constant density $\rho_{m0}$, the equilibrium velocity is accepted zero and throughout the fluid the magnetic induction $B_0$ is uniform and constant (Swanson, 1989; Timucin et al., 2019; Timucin et al., 2014; Unal et al., 2011; Yaşar, 2021; Yaşar, 2021; Yeşil et al., 2021; Yeşil and Sagir 2019). If both electrical and fluid equations are used within each other (Equations (1-3)), Eq.(7) is obtained by, Some expressions in this equation, respectively,
ω: Wave Frequency, k= wave vector, $V_A$ ; Alfvèn Velocity and $Vs$ ; Adiabatic sound speed

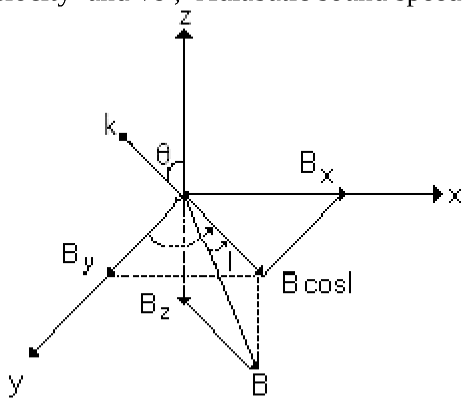


**Figure1.** The geometry of Earth's magnetic field for the Northern hemisphere [1-5,9-10]].

$$B = B_x a_x + B_y a_y + B_z a_z \quad (12)$$

Where $B_x = B_0 CosI\ Sind$, $B_y = B_0 CosI\ Cosd$ and $B_z = -B_0 SinI$. I and d are the magnetic dip and the magnetic declination angles, respectively. Wave vector $k = k_y + k_z = k sin(\theta) y + k cos(\theta) z$,
Besides, $V_A$ and components of its velocity by using the geometry of magnetic field in Fig.(1)

$$\boldsymbol{V}_A = \frac{\boldsymbol{B}}{\sqrt{\mu_0 \rho_{m0}}} = V_{Ax}\,\boldsymbol{i} + V_{Ay}\,\mathbf{j} + V_{Az}\,\mathbf{k} \quad (13)$$

In which $V_{Ax} = V_A\, CosI\ Sind$, $V_{Ay} = V_A\, CosI\ Cosd$ and $V_{Az} = -V_A\, SinI$ are and $V_s = (\gamma k_b\, T/\rho_m)(1/2)$(Adiabatic sound speed), $\gamma$; degrees of freedom , $k_b$=Boltzmann constant and $T$= Fluid temperature.
If d=0 becomes with respect to Fig.1, the phase velocity of Alfvèn wave could be obtained as follow.

$$\frac{1}{V_p^4}\eta_m\eta_k - \frac{1}{\omega^2} + \frac{1}{V_p^2}\left\{\left[\left(\frac{V_A}{\omega}\right)(\mathrm{Sin}(\theta - I)\right]^2 + i\frac{1}{\omega}(\eta_k + \eta_m)\right\} = 0 \quad (14)$$

From here, after some mathematical operations, the propagation speed of Alfvèn wave

$$\frac{1}{V_p^2} = \frac{-\mu \pm \left(K_{1R}^2 + K_{1S}^2\right)^{1/2} \mathrm{Cos}\left(\frac{\alpha}{2}\right)}{2\eta_k\eta_m} + i\frac{-\chi \pm \left(K_{1R}^2 + K_{1S}^2\right)^{1/2} \mathrm{Sin}\left(\frac{\alpha}{2}\right)}{2\eta_k\eta_m} \quad (15)$$

In which, $\eta_k = \frac{nk_bT}{v}$ *kinematic viscosity*

$\eta_m = \frac{1}{\mu_0\sigma_0}$ *magnetic viscosity* . This speed(Eqn.(15)) is occurring in both the real and imaginary parts. The real part represents the progressing imaginary part of the wave, the damping part of the wave.

$$\left.\begin{aligned} K_{1R} &= \mu^2 - \chi^2 + 4\sigma \\ K_{1s} &= -2\mu\chi \\ \chi &= \frac{1}{\omega}(\eta_k + \eta_m) \\ \sigma &= \frac{\eta_k\eta_m}{\omega^2} \\ \mu &= \left[\frac{V_A\,\mathrm{Sin}(\theta - I)}{\omega}\right]^2 \end{aligned}\right\}. \quad (16)$$

If we rearrange the phase velocity equation above in terms of the wave propagation vector and we neglect fluid and magnetic viscosity, Eqn.(15) turns into the following expression.

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$$\omega^2 = k^2 V_A^2 (\mathrm{Sin}(\theta - I))^2 \; and \; V_P^2 = V_A^2 (\mathrm{Sin}(\theta - I))^2 \quad (17)$$

$$V_P^2 = \frac{B_0^2}{\mu_0 \rho_{m0}} (\mathrm{Sin}(\theta - I))^2 \quad (18)$$

The relationship between group and phase velocity are given by;

$$V_g = \frac{c}{n + \omega \frac{\partial n}{\partial \omega}} = V_P + k \frac{\partial V_P}{\partial k} \quad (19)$$

If θ=I takes (perpendicular case), then from Eqn.(15) is obtained as follow

$$V_g = \frac{1}{\sqrt{\frac{-i(n_k + n_m)}{\omega(n_k \cdot n_m)}} + \frac{\frac{-i(n_k + n_m)}{\omega(n_k \cdot n_m)}}{\sqrt{\frac{-i(n_k + n_m)}{2\omega(n_k \cdot n_m)}}}} \quad (20)$$

According to Fig.1, Eqn.(15), when the magnetic field is parallel to the propagation vector (**k**),

That is; θ=90+I, the phase velocity of Alfvèn wave is obtained by

$$\frac{1}{V_p^2} = \frac{-\left[\left(\frac{V_A}{\omega}\right)^2\right] \pm \left[\frac{\pi_R \pm \sqrt{\pi_R^2 + \pi_I^2}}{2}\right]^{1/2}}{2\eta_k \eta_m} + i \frac{-\left[\left(\frac{1}{\omega}\right)(\eta_k + \eta_m)\right] \pm \left[\frac{-\pi_R \pm \sqrt{\pi_R^2 + \pi_I^2}}{2}\right]^{1/2}}{2\eta_k \eta_m} \quad (21)$$

$$\pi_R = \frac{V_A^4}{\omega^4} - \frac{1}{\omega^2} (\eta_k - \eta_m)^2, \qquad \pi_I = \frac{1}{\omega} (\eta_k - \eta_m) \left(\frac{V_A}{\omega}\right)^2 \quad (22)$$

$$\frac{1}{V_p^2} = \Pi_R + i\Pi_I \Rightarrow \frac{1}{V_p} = \sqrt{\Pi_R + i\Pi_I} = \Gamma_R + i\Gamma_I \quad (23)$$

$$\Gamma_{R\,1,2}^2 = \frac{1}{2} \left[ \frac{-\left[\left(\frac{V_A}{\omega}\right)^2\right] \pm \left[\frac{\pi_R \pm \sqrt{\pi_R^2 + \pi_I^2}}{2}\right]^{1/2}}{2\eta_k \eta_m} \pm \sqrt{\left( \frac{-\left[\left(\frac{V_A}{\omega}\right)^2\right] \pm \left[\frac{\pi_R \pm \sqrt{\pi_R^2 + \pi_I^2}}{2}\right]^{1/2}}{2\eta_k \eta_m} \right)^2 + \left( \frac{-\left[\left(\frac{1}{\omega}\right)(\eta_k + \eta_m)\right] \pm \left[\frac{-\pi_R \pm \sqrt{\pi_R^2 + \pi_I^2}}{2}\right]^{1/2}}{2\eta_k \eta_m} \right)^2} \right] \quad (24)$$

$$\Pi_R = \frac{-\left[\left(\frac{V_A}{\omega}\right)^2\right] \pm \left[\frac{\pi_R \pm \sqrt{\pi_R^2 + \pi_I^2}}{2}\right]^{1/2}}{2\eta_k \eta_m} \quad (25)$$

$$\Pi_I = \frac{-\left[\left(\frac{1}{\omega}\right)(\eta_k + \eta_m)\right] \pm \left[\frac{-\pi_R \pm \sqrt{\pi_R^2 + \pi_I^2}}{2}\right]^{1/2}}{2\eta_k \eta_m} \quad (26)$$

## NUMERICAL ANALYSIS AND RESULTS

In this context, the pure Alfvèn waves for the considered conditions in Northern-hemisphere at E-region ( for height 140 km) of ionospheric plasma were calculated with low latitudes by using Eq.(16, 17-18), at hour 12.00 LT for 1990 year. We have studied special days March21st (Northern and Southern Hemispheres. Sun rays fall at noon at 90° to the Equator. From this date, the sun's rays begin to fall perpendicular to the Northern Hemisphere. The nights begin to be longer than the days in the Southern Hemisphere) and June21st (the Summer Solstice is the longest day of the year. The longest day affects not only the Northern hemisphere but also the Southern hemisphere. On this date, winter begins in the Southern Hemisphere. Longest night and shortest day in the Southern Hemisphere) for

Alfvèn wave modes. The ionosphere parameters (16, 17-18) used for calculation were obtained by using the IRI model, according to the accepted conditions. We investigated the seasonal change of eqns. with respect to latitude for 12.00 LT. According to the results of the numerical calculations, the real and imaginary parts of the phase velocity for March

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21st are shown in figures 3 and 4 when the wave propagation vector is perpendicular and parallel to the magnetic field. If the magnetic field is parallel to the propagation vector (θ=90+I), it shows an approximately symmetrical variation for its perpendicularity((θ=I)). When (θ=90+I), the change of the real part of phase velocity approximately looks like the cosines function. The same trend is also seen when θ = I. But it is symmetrical when the magnetic field is perpendicular to the propagation vector. That is, the imaginer part is maximum when k//B is, the magnitude of the real phase velocity is minimum when **k** is perpendicular to B. The trend of change with the latitude of the magnitude of the imaginary part of the phase velocity is similar to the real part but different in magnitude. It is slightly smaller than the real part (Fig.3). Actually, If the magnetic field is perpendicular or parallel to the wave propagation vector on June 21, the change in the phase velocity of the real and imaginary parts at mid-latitudes is as given in figures 4 and 5. accordingly, the latitude changes of both the real and imaginary parts are similar as a trend for the 21 March situation. However, on June 21, the values are expected to increase. It is likely that dynamic processes in the ionosphere are more frequent in this month since the sun's rays are more and ionization is more.

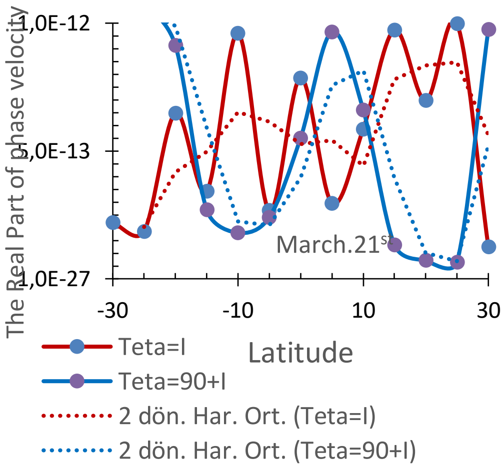


**Fig.2.** The real part of phase velocity of Alfvèn waves **k//B** and k⊥B (March21, 12:00 LT).

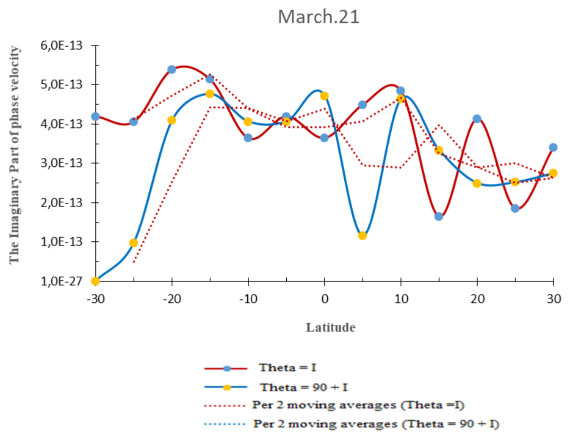


**Figure 3.** The imaginary part of phase velocity of Alfvèn waves **k//B** and **k⊥B** (March21st, 12:00 LT).

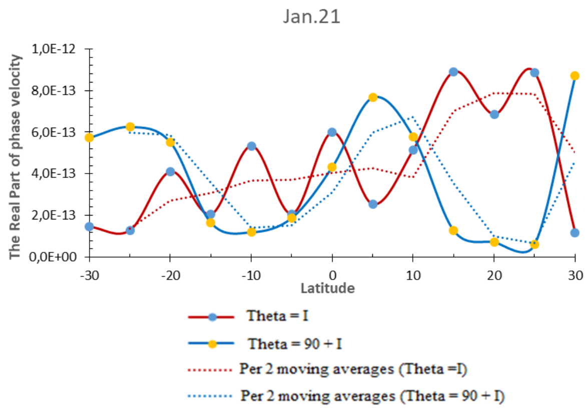


**Figure 4.** The real part of phase velocity of Alfvèn waves **k//B** and **k⊥B**(June21st, 12:00 LT).

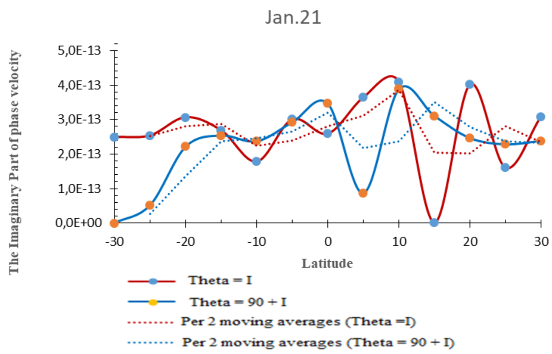


**Figure 5.** The imaginary part of phase velocity of Alfvèn waves **k//B** and **k⊥B**(June21st, 12:00 LT)

## CONCLUSION

In this study, Alfvèn waves for the accepted conditions in Northern-hemisphere at E-region of ionosheric plasma was calculated with low latitudes

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by using Eqn.(15-17), at hour 12.00 LT for 1990 year. When the results are evaluated in this article, the outstanding results are; In fact, it has been shown that all modes of all Alfvèn waves (Pure Alfvèn, fast and slow MHD) depend on the angle between the magnetic field and the wave propagation vector, as well as on the declination and magnetic dip angle. the values of NmF2 during the night as a function of the latitude exhibit a condition so-called "cavity" focused on the lowest magnetic point of the equator with "peaks" in 15 $^{o}$N - 20 $^{o}$S latitudes in the northern hemispheres. Electromagnetic drift (⊥B) and diffusion (//B) combine and cause an upward increase in plasma motion like a "fountain". As can be seen from the analytical and numerical solution, if the viscosity coefficients are not taken into account, the real and group velocities of all waves are equal to the phase velocities. Besides, just like in cold plasma, when collisions, kinematic viscosity, and magnetic viscosity are taken into account, all parameters of the medium, group velocity, and phase velocity of the wave are complex. As it can be understood from the numerical calculations, the behavior of the phase velocity of the wave in mid-latitudes is almost similar to a cosines function, but the magnitudes of both the real and imaginary parts are different in both seasons.

## STATEMENT OF CONFLICT OF INTEREST

Author(s) do not declare any conflict of interest regarding this article.

## STATEMENT OF RESEARCH AND PUBLICATION ETHICS

Author(s) declare that this study is in compliance with research and publication ethics.

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