Investigation of sources of gravity waves observed in the Brazilian Equatorial region on 08 April 2005

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Abstract.

On 08 April 2005, a strong gravity wave activity (of more than 3 hours) was observed in São João do Cariri (7.4º S, 36.5º W). These waves propagated to the southeast and presented different spectral characteristics (wavelength, period and phase speed). Using the hydroxyl (OH) airglow images, the characteristics of the observed gravity waves were calculated; the wavelengths ranged between 90 and 150 km, the periods from ~26 to 67 min and the phase speeds ranged from 32 to 71 m/s. A reverse ray-tracing analysis was performed to search for the possible sources of these detected waves. The ray-tracing database was composed of temperature profiles from NRLMSISE-00 model and SABER measurements and wind profiles from HWM model and meteor radar data. According to the ray path, the likely source of these observed gravity waves was the Inter Tropical Convergence Zone with intense convective processes taking place in the northern part of the observatory. Also, the observed preferential propagation direction of the waves to the southeast could be explained using blocking diagrams, i.e. due to the wind filtering process.

Keywords. Gravity waves, Airglow, Reverse Ray Tracing, Troposphere, Mesosphere, ITCZ.

1. Introduction

Since the publication of the pioneering works of Hines in the 1960s on the detection of irregular motions ‘gravity waves’ in the upper atmosphere, there have been numerous improvement work-outpours. Gravity waves are results of disturbances that occur in atmospheric fluids with the upper mesosphere and thermosphere region being largely impacted (e.g., Fritts and Alexander, 2003). Potential sources of these waves are cold fonts (e.g Plougonven et al., 2017), troposphere convection (e.g., Vadas et al., 2009), wind shear (e.g Clemesha and Batista, 2008), topography and wave breaking (e.g., Sarkar and Scotti, 2017), as well as solar eclipse (e.g., Marlton et al., 2016). These atmospheric structures have been identified as a key component in the transportation of energy in the mesosphere and lower thermosphere (MLT) region (e.g., Fritts, 1993; Medeiros et al., 2007; Campos et al., 2016).

Internal GWs are generated as adjustment radiations whenever a sudden change in forcing causes the atmosphere to depart from its large-scale balanced state. Such a forcing anomaly occurs during a solar eclipse (Campos et al., 2016; Marlton et al., 2016). The intrinsic properties of the gravity waves (observed horizontal phase speed, propagation direction, observed period, horizontal wavelength) can be calculated directly from the airglow images by spectral analysis. Using the dispersion relation, the vertical wavelength can also be computed (Vargas et al., 2009). Gravity waves can be summarized as large-scale waves, medium-scale waves, and small-scale waves. Small-scale gravity waves are characterized by horizontal wavelengths in tens of kilometers (Medeiros et al., 2003), medium-scale gravity waves wavelength ranges from ~100-400 km, and large-scale waves have high phase speeds and travel farther horizontal distances compared to others (Vadas et al., 2009).

In the MLT region, there are several and continuous chemical reactions such as the OH airglow emissions (e.g., Sivjee et al., 1992; Taylor et al., 2009; Campos et al., 2016). These emissions among several others have been used by many authors as a proxy for investigating gravity wave activities. Airglow emissions are faint luminescence that are produced as a result of the emission of electromagnetic radiation by excited ionized or neutral atoms or molecules. These luminosities are usually captured by the all sky imagers (ASI) (e.g., Wallace, 1959; Krasovskij et al., 1965).

To identify source location of gravity waves, the reverse ray tracing method has been widely adopted. Several researchers have successfully implemented this technique to identify points of generation of these waves under different atmospheric conditions using airglow images (e.g., Hecht et al., 1994; Brown et al., 2004; Wrasse et al., 2006; Vadas et al., 2009; Pramitha et al., 2014, Sivakandan et al., 2016).

Wrasse et al., (2006) did a comprehensive study of gravity waves observed over Brazil and Indonesia and concluded that most of the studied waves have their sources in the troposphere. Similarly, Vadas et al. (2009) studied the propagation of gravity waves observed during the SpreadFEx campaign in Brazil and found out that the likely sources of those waves were deep convection in Brazil. In addition, Pramitha et al., (2014) identified that 64 % of observed GWs over Gadanki, India originated from the upper troposphere while the remaining were seen to have been ducted in the mesosphere. Sivakandan et al. (2016) also studied GWs observed in the southern part of India and associated the sources to convection.

The objective of the current study is to extensively study a strong activity of GWs observed in São João do Cariri (7.4^o S, 36.5^0 W) on 08 April 2005. More than three hours of GW activities were observed and the waves propagated exclusively to the southeast. Observation of different parameters of these gravity waves made during this time period indicates that the sources of these waves must be large having produces a wide spectrum of gravity waves. An explanation for this uncommon pattern is presented in this work investigating the combined effect of the location of the source and the wind filtering process.

2. Instrumentation

2.1 The all sky imager

The GWs detected in this study were observed using the ASI installed at the observatory in São João do Cariri. The ASI is an optical instrument that provides monochromatic maps of aurora and atmospheric airglow emission of different wavelengths. It has been designed to keep track of the spatial and temporal variations of OH, OI5577, 6300 nm airglow emissions (e.g. Paulino et al., 2010).

The present study however utilized only the OH airglow images captured by the ASI at an altitude of 87 km. This instrument comprises of a fish-eye (f/4) lens, a telecentric lens system, a field of view of 180^0, a computer-controlled filter wheel with several slots for the observation of different emissions, and a camera with a charged coupled device (CCD) used as a photodetector for increased sensitivity. More technical and operational details about this particular imager at São João do Cariri can be found in previous works (Medeiros et al., 2007; Paulino et al. 2012).

2.2 TIMED/SABER Satellite

The Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) is one of the four instruments onboard the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) satellite. The vertical temperature measurements from 20 to 108 km were observed on 08 April 2005 over São João do Cariri area (7.4^o S, 36.5^o W) from this instrument, SABER. Data from the Naval Research Laboratory Mass-Spectrometer-Incoherent-Scatter (NRLMSISE00) atmospheric model (Picone et al., 2002) was utilized for complementing the measurements at unavailable heights of 0-19 km, and 109-400 km. These measurements were used to provide vertical profiles of kinetic temperature, pressure, geopotential height, and volume mixing ratios for the trace species. (Mertens et al., 2001).

2.3 The SKiYMET Meteor Radar

The All-Sky Interferometric Meteor Radar (SKiYMET) system located at 7.4º S, 36.5º W São João do Cariri provided measurements of the horizontal wind speed and direction in the MLT (81-99 km). The radar which is composed of Yagi antennas- 5 receiving antennas and one transmitting antenna operate at 35.24 MHz with a maximum power of 12 kW. This instrument detects the trail left behind by vaporized meteors, determines the angle-of-arrival by using the phase difference between the receiving antennas, and then measures the radial velocity by using the derivation of the speed and direction of the atmospheric winds carrying the meteor trail at a specified altitude. The phase delay between the transmitted and received signal is used to determine the position of the trail. Further detail about this radar has been published in (e.g., Hocking et al., 2001; Egito et al., 2018; Paulino et al., 2015).

3. Methodology and data analysis

3.1 Determination of gravity waves parameters

To obtain the characteristics of the detected gravity waves, a two- dimensional Fast Fourier Transform (FFT) was used in specified batches of OH airglow images. The pre-processing of the airglow images can be summarized in the following procedures:

- Rotating the image to fit the top of the image with the north geographic region;
- Removing low frequency waves by applying the Butterworth high pass filter;
- Contrast enhancement and unwarping the airglow images for FFT analysis.

Figure 1(a) shows one of the raw OH image obtained from the São João do Cariri's ASI in the Observatorio de Luminescencia Atmosferica de Paraiba (OLAP). This image is a typical example of the wave events observed on this night. The ripples enclosed in the red box in Figure (1a) represents the gravity wave structure. This particular event was captured by the ASI at ~23:58 UT on 08 April 2005. This image however was contaminated with stars (bright circles), and the Milky Way (white streak running from the bottom North-West to South-East direction), tree branches/leaves (East-edge of the image), and building tops shown by the red arrow. Figure 1(b) portrays a clearer image after image processing. Figure 1(c) represents the unwarped version of previous image. Figure 1(d) shows the spectrum of the encapsulated event. The bright red circle which depicts the amplitude of the gravity wave and its positioning also provides the propagating direction of the wave. Table 1 presents a summary of all the wave events observed on this night. Additional information about the cross spectrum analysis used in the present study to obtain the characteristics of these waves can be found in (Wrasse et al., 2006).

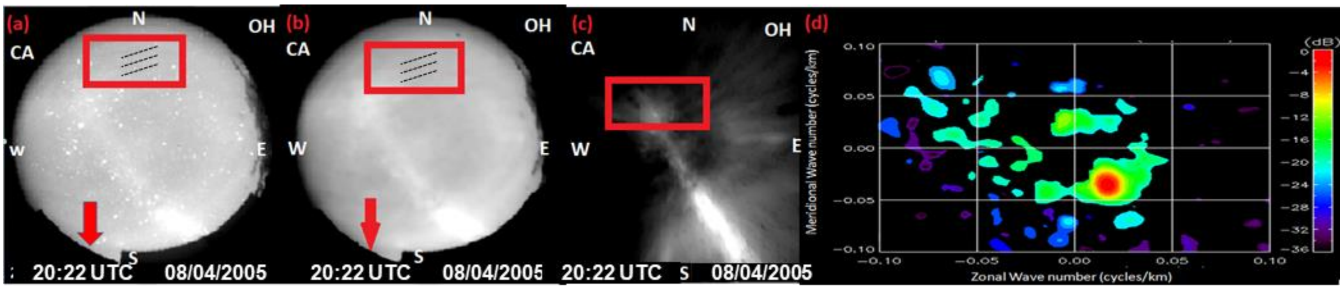

Figure 1: Illustration of the image processing. (a) Raw OH image collected from the ASI in São João do Cariri on 08 April 2005. For more details on the propagation of ripples, see the video clip in the supplement. (b) Filtered image (c) Unwarped & rotated image of the gravity wave event inside the red box area in previous images for FFT analysis (d) Cross spectrum applied to the GW enclosed in the box in (c).

Table 1: The observed properties of the 5 wave events

Event	Time (UTC)	τ (min)	λ_H (km)	Propagation direction (°)	cH (ms−1)	SD (km)
01	20:22	26.3	90.2	139.8	57.2	
02	21:33	66.9	144.5	131.2	36.0	
03	22:56	64.2	125.8	125.0	32.7	24.0
04	23:29	40.8	142.0	142.0	58.0	
05	23:58	35.0	149.2	150.9	71.0	

3.2 The atmospheric profile

The SABER instrument provided temperature measurement from 23h46 to 23h51 UT on 08 April, and from 08h35 to 08h40 UT on 09 April for altitudes 20-108 km. Then, linear interpolation between 23h51 (08 April) and 08h35 (09 April) was done for the same altitude range. In addition, numerical values for temperature were obtained from NRLMISIS model (https://omniweb.gsfc.nasa.gov/vitmo/msis_vitmo.html) for time (12h to 22h) on 08 April 2005 and for missing heights of (0-19km, 109-400km) to complement the SABER measurements. Finally, a 13-profile temperature data with a temporal resolution of 2 hours was constructed for the whole period. However, some discrepancies were observed at the combining points, hence the data were smoothened so that the model can seamlessly match the measurements at these junctions. This methodology was discussed by Paulino et al. (2012).

The SKYiMET radar provided the zonal and meridional wind measurements from 81-99 km every 3 km from 0h to 23h on 08 and 09 April 2005 with a resolution of 1h. Similarly, numerical interpolation was used to provide the spatial resolution of the wind with a 2 hours resolution like the temperature profile- with supporting data from the Horizontal Wind Model (HWM) (Drob et al., 2008) from 0 km to 80 km, and above 100 km.

From the temperature and wind measurements, other atmospheric parameters representing the atmospheric state of the period of study were obtained. The pressure $P(z) = P_o exp^{\left(-\int_0^z \frac{g}{RT} dz'\right)}$ was obtained using a combination of the ideal gas law $P = R\rho T$ and the hydrostatic balance equation $\frac{dP}{dz} = -gp$ where ρ is the density obtained from the MSIS model, and the molecular weight was estimated from $X_{MW} = \frac{1}{2}(X_{MW0} - X_{MW1})\left[1 - tanh\frac{s-a}{\Delta_a}\right] + X_{MW1}$ where X_{MW0}, X_{MW1}, $\Delta_a$and a are constants given by 28.90, 16.0, 4.20, and 14.90 respectively, while $s = ln\rho$ (Vadas et al., 2009). Additional details about the reverse-ray tracing parameters can be found in (Vadas et al., 2007; Vadas et al., 2009), T is the temperature, **g** is the acceleration due to gravity, $R = \frac{8314.5}{X_{MW}}$ is the gas constant, z is the altitude, and P_o is the static pressure.

The scale height $H = -\rho/d\rho/dz$ is obtained from the ratio of the density to the derivative with respect to the altitude, while the potential temperature is $\theta = T(P_o/P)^{R/C_p}$, C_p is the specific heat capacity at constant pressure, and the Brunt–Väisälä frequency is $N = \sqrt{\left(\frac{g}{\theta}\frac{d\theta}{dz}\right)}$. See further details in Vadas et al., (2007).

3.3 The Reverse Ray Tracing technique

Every gravity waves gets influenced by the atmospheric winds with velocity **V** = (V_i, V_j, V_k) according to the following equations: Equation 1 describes the ray path while the refraction of the wave vector along the ray path is explained by equation 2. The tracing model employed in the study is based on Lighthill, 1978.

$$\frac{dk_i}{dt} = -k_j \frac{\partial V_j}{\partial x_i} - \frac{\partial \omega_{Ir}}{\partial x_i} \quad (1)$$

and

$$\frac{dx_i}{dt} = V_i + \frac{\partial \omega_{Ir}}{\partial x_i} = V_i + c_{gi} \quad (2)$$

Where i, j = 1, 2, 3 and the repeated indices imply a summation, V_i represents the zonal, meridional, and vertical wind components. The spatial position of the wave is represented by x, k is the wave vector, ω_{Ir} is the real part of the intrinsic frequency obtained using the dispersion relation in Equation 3 of (Pramitha et al., 2014), and c_g is the group velocity.

Numerical integration of the six ordinary differential equations (1)-(2) was performed using Runge-Kutta fourth order (Press, 2007). All the observed and intrinsic properties of the gravity waves and parameters representing the atmospheric condition were fed into the reverse ray-tracing (RRT) model. Four stopping conditions imposed constantly check the propagation of the GWs into the background winds. When any of the condition is violated, the ray tracing integration is terminated. The main stopping criteria are: (i) if the group velocity of the gravity wave is close to the speed of sound (c_g >= $0.9c_s$); (ii) when the real part of the intrinsic frequency tends to zero ($\omega_{Ir} \rightarrow 0$); (iii) when the vertical wavelength greater than viscosity length or dissipation of the gravity waves. (iv) if the momentum flow of the gravity wave $u_{GW}w_{GW}(z,t) \geq 10^{-5}u_{GW}w_{GW}$ at the height of OH airglow (87km). Extensive details of the reverse ray tracing algorithm employed in this study has been published by Paulino et al., (2012); and Pramitha et al., (2014).

4. Results and discussions

4.1 Spectral Analysis Result

The spectral results in Table 1 show that the horizontal wavelengths (λ_H) have a standard deviation of 24 km and mean value of 130 km with large variability among the detected waves while the propagating period (τ) of the waves ranged between 26 and 67 min. This result agrees with the reports of Medeiros et al., (2007) for waves detected at this observatory. Thus, it can be confidently concluded that the observed wavelengths are good representatives of the gravity waves in this observatory.

Figure 2 shows the traveling direction of the 5 events. From the polar chart, it is seen that all the waves are propagating Southeast with an approximate azimuth of ~134° from the north. This is in favorable agreement with the results obtained from previous studies for the same observatory (Essien et al. 2018). This anisotropicity will be discussed later on in this study.

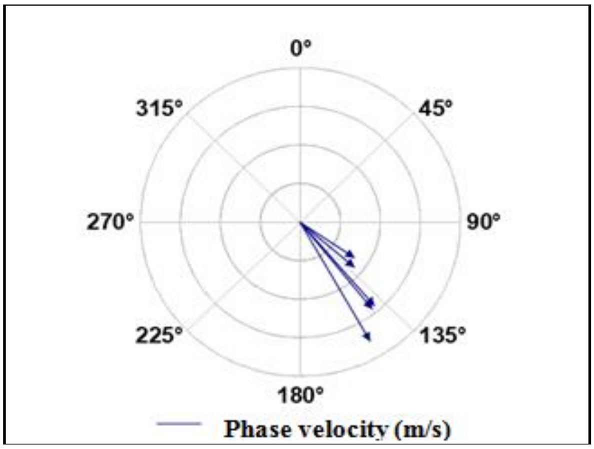

Figure 2: Compass graph showing wave velocities and direction of propagation- each circle denotes a velocity of 20m/s.

Figure 3 shows the impact of the atmospheric wind on the period of the waves. It reveals the difference between the intrinsic period of the waves which lacks atmospheric impact and the observed period which is susceptible to the influence of the atmospheric-winds. However, it can be seen that the winds accelerated almost all the gravity waves. The fluctuation in the period can be attributed to the variability of the horizontal winds. When the gravity wave is traveling anti-parallel to the wind direction, the second term on the left side of this equation $\omega_I = \omega_o - k_H.V_{GW}$ would become negative, consequently forcing the observed frequency to be smaller than the intrinsic frequency, this invariably results in increased observed periods.

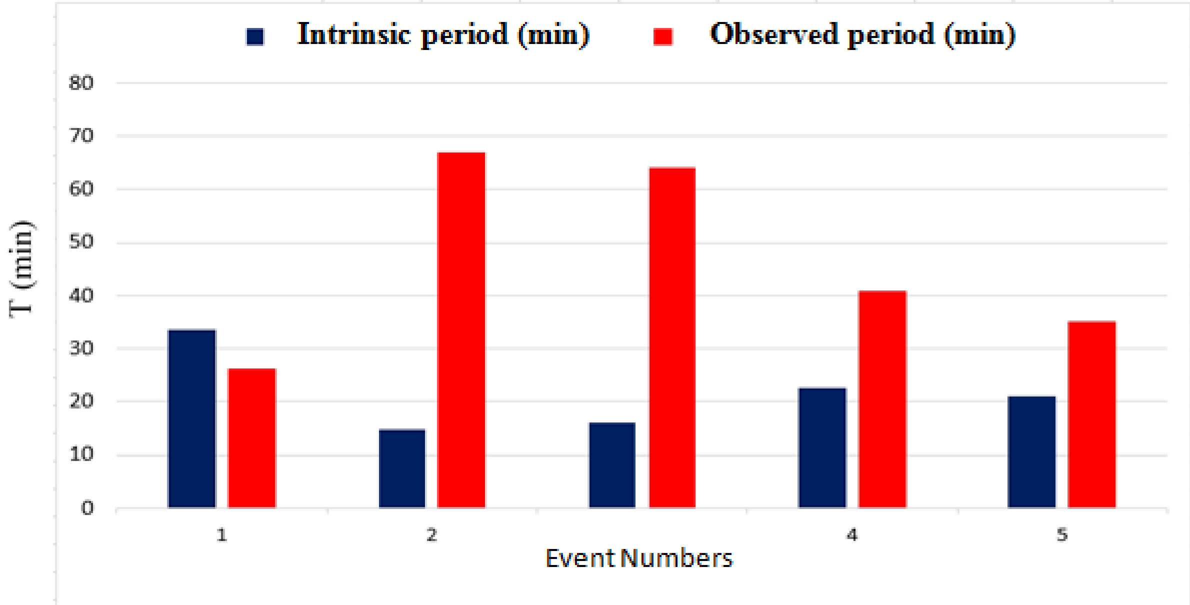

Figure 3: Bar chart graphs of intrinsic and observed periods.

One important finding from the spectral analysis is that there is a wide spectrum of gravity waves being generated. It strongly suggests that the source of these GWs must be large (Vadas and Fritts, 2009). In order to investigate the likely sources of these waves, the next section of this work presents and discusses the results from the ray-tracing.

4.2 Reverse ray-tracing

These 5 waves have different spectral characteristics and they were all observed at different times as well. Using the reverse ray tracing technique to back trace these gravity waves from the point of observation in the airglow layer to their source of generation, we present the following results of the RRT analysis. During the backward tracing, we assumed critical levels are not encountered as explained in section 3.3.

The a-panels of Fig. (4-8) are the ray-paths as a function of the altitude and time and it describes the influence of various wind conditions on each GW event. The light blue line indicates the trajectory of the gravity wave under zero wind influence, while the black line shows the travel path of the wave under the HWM wind influence. This gave a better understanding of the roles played by the atmospheric winds in the traveling paths of GWs from the middle to the lower atmosphere. The blue and black shaded circles represents the time of generation of these waves under zero and modeled wind scenarios respectively. The dashed blue and solid black lines represents the trajectory of the waves under the zero winds and modeled winds conditions respectively.

The b-panels of Figure 4-8, however, describe the wave path as a function of longitude-latitude; thus providing a closer view of the exact generation point of these waves linearized over the map. The dark blue clouds represent the corresponding convective processes observed at the exact time that these gravity waves were detected. The black shaded triangle represents the precise location of the ASI at the OLAP.

Figure 4(b) shows a gravity wave propagating southeastward. Under the modeled wind conditions, this wave was generated at 17h00 UT of the same day, while under zero wind influence, it was triggered at 16h30 UT. Thus, the atmospheric winds were favorable as it accelerated the travel speed. The b-panel of Figure 4 zooms in on the actual source point of this wave. With a horizontal wavelength of 90 km, and phase velocity of 57.2 m/s, the reverse ray tracing result points to the source being in the northern region of the detection point (OLAP). Even though, the HWM-14 winds and zero winds are not equal, the gravity waves propagated through a similar path under both wind condition. Below 70 km, the GW propagates rapidly in the southeast direction which could be due to the strong winds.

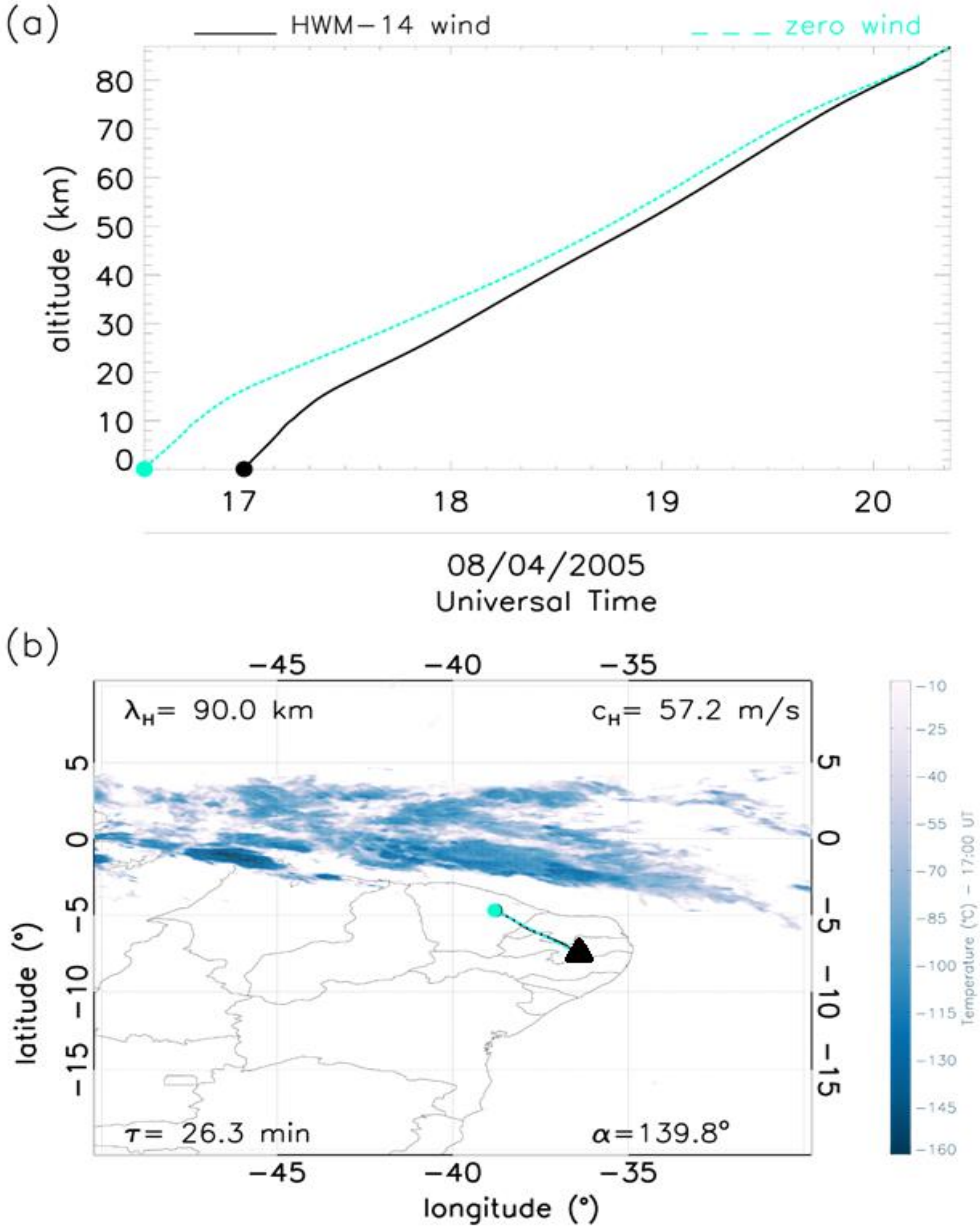

Figure 4: Reverse ray trace results for GW 1 (a-panels: Altitude as a function of time. Dashed blue and solid black lines show the ray paths for the zero winds and modeled winds respectively, and the time cross section with zero wind and modeled winds. (b-panels: Latitude-longitude cross section over convective cloud activities). Black and blue dots show the location of sources for zero winds and modeled winds respectively. The black triangle represents the exact location of the ASI, while the blue plumes represent convective activities in the region.

Similarly, the ray-tracing results show backward propagation of the second wave event detected at 21h33 UT in Figure 5(a). This shows a similar analysis when compared to the first wave event. However, this wave suffered greater wind acceleration ~12 hours as did GW_3 ~10 hours. Thus, just as in GW_1, both GW_4 and GW_5 were accelerated by the modeled winds just by ~ 2 hours and 1 hour respectively.

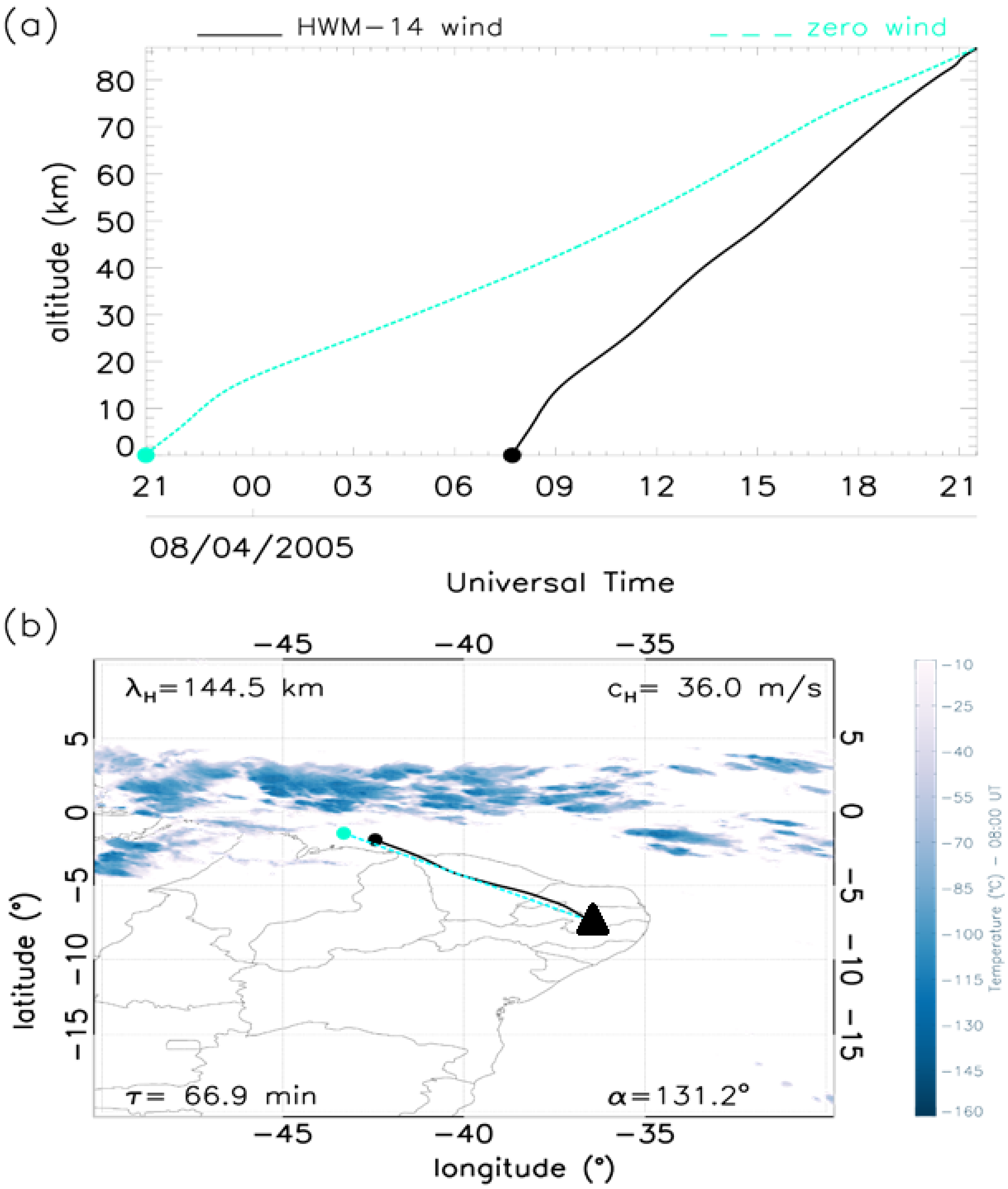

Figure 5: Same as in Figure 4 but for Event #2.

It was observed that the events 2, 3, 4, and 5 with a mean horizontal wavelengths of 140 km propagated more than ~1300 km from their source region. All these 4 events are believed to have originated from the same source due to the resemblance in their characteristics. In Event 1, in comparison to others, the bottom side of the convective sources (deep blue clouds) appear to be farther from the point where we traced the gravity wave source (black and blue dots). However, this particular wave is still linked to the convective processes as its source. According to Vadas and Fritts, 2009 the actual convective area is usually larger than the cloudy areas

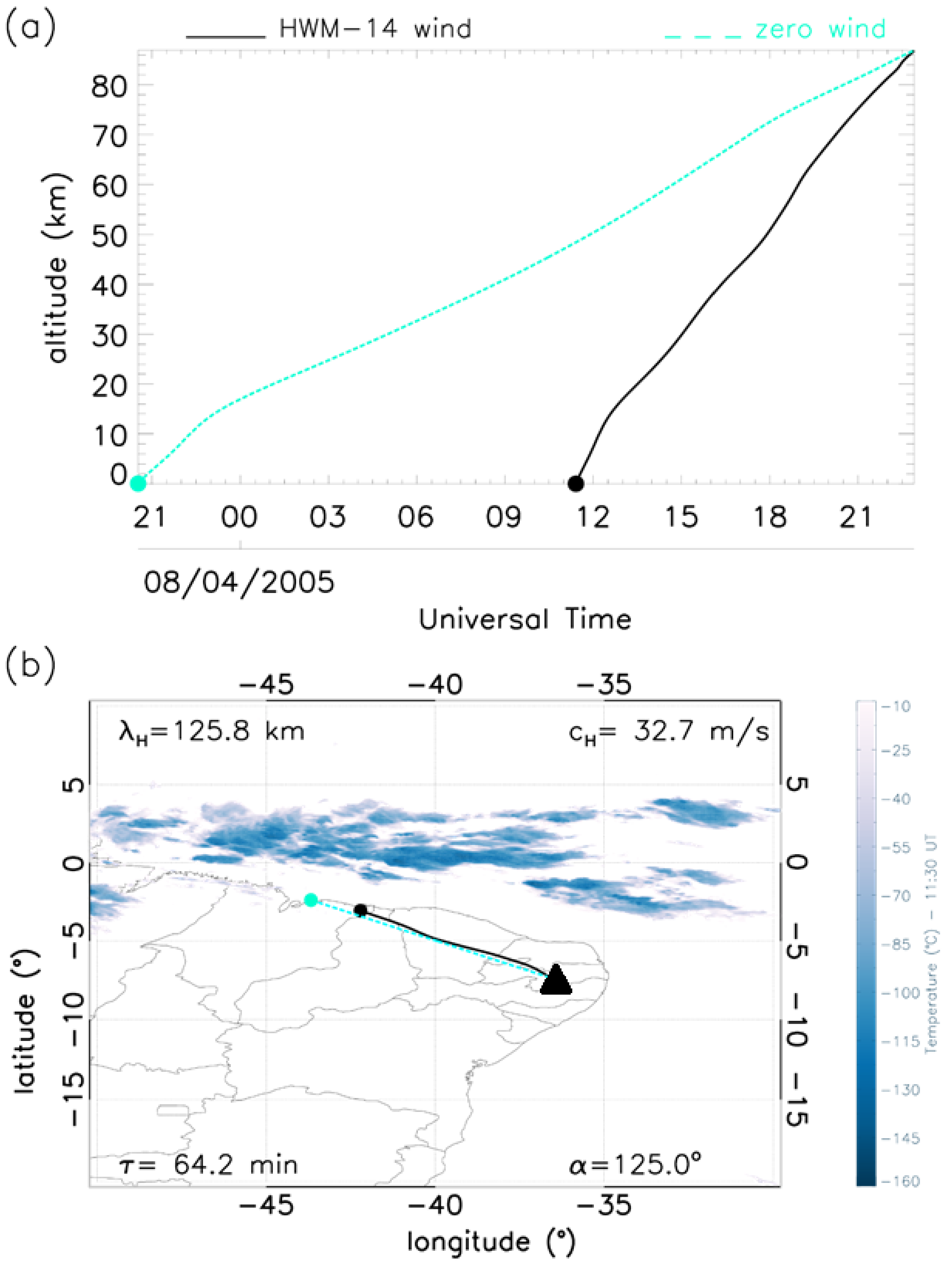

Figure 6: Same as Figure 4, but for the Event #3

Figures 4(b)-8(b) showed the ray paths for the wave events considering the normal and zero wind conditions. In the first panel of event 3, zero wind condition was applied, (blue line) and the modeled wind condition (black line) with a horizontal wavelength of 90 km, phase velocity of 57.2 m/s, propagating angle of 139.8º, 26.3-min period and a vertical wavelength of 90.2 km. It can be noticed in panel (a) of Event #3 that the GW attained the 87 km height for both wind conditions. A slight shift can be observed as there is a similarity between both conditions.

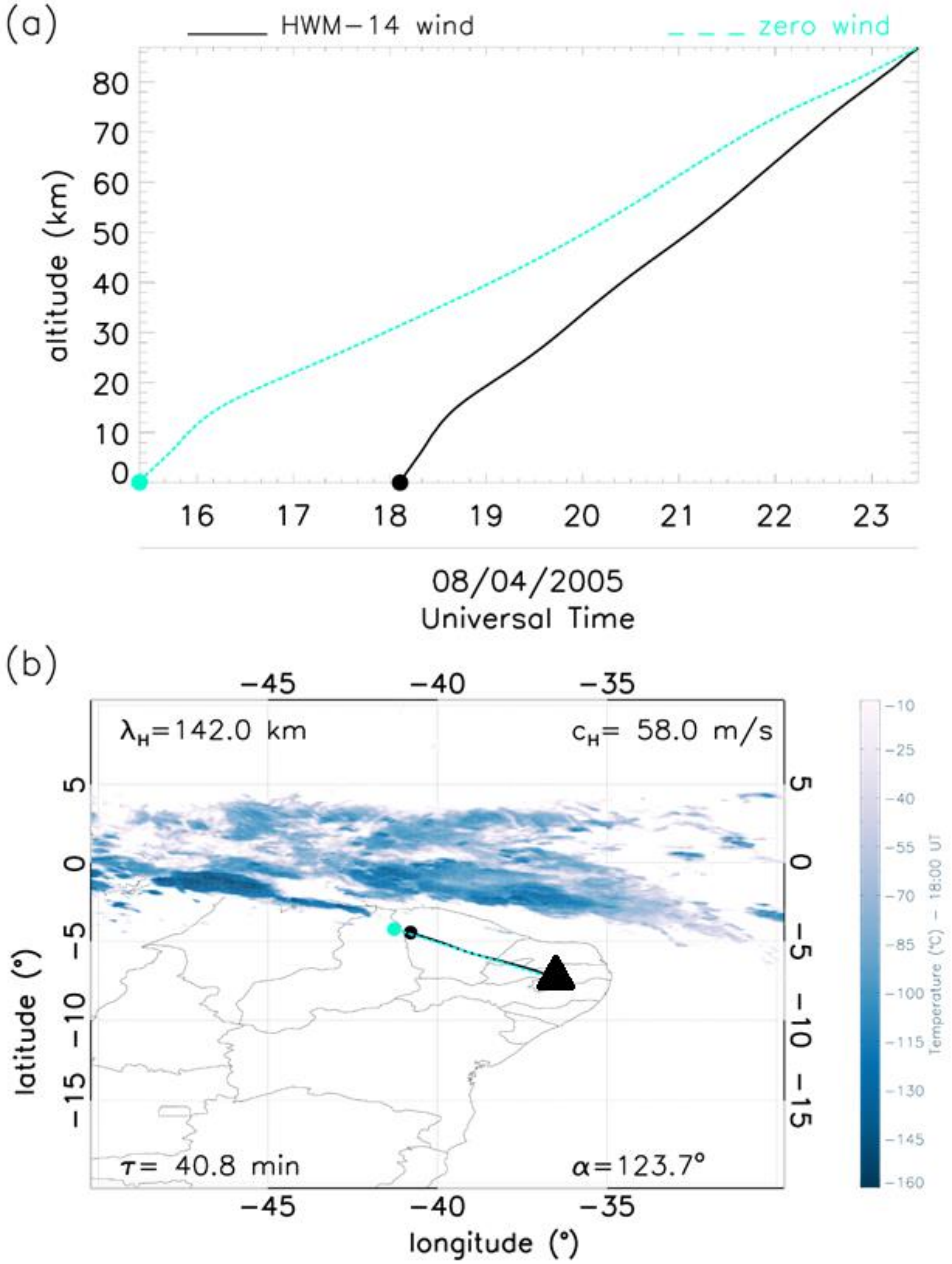

Figure 7: Same as Figure 4 but for Event #4.

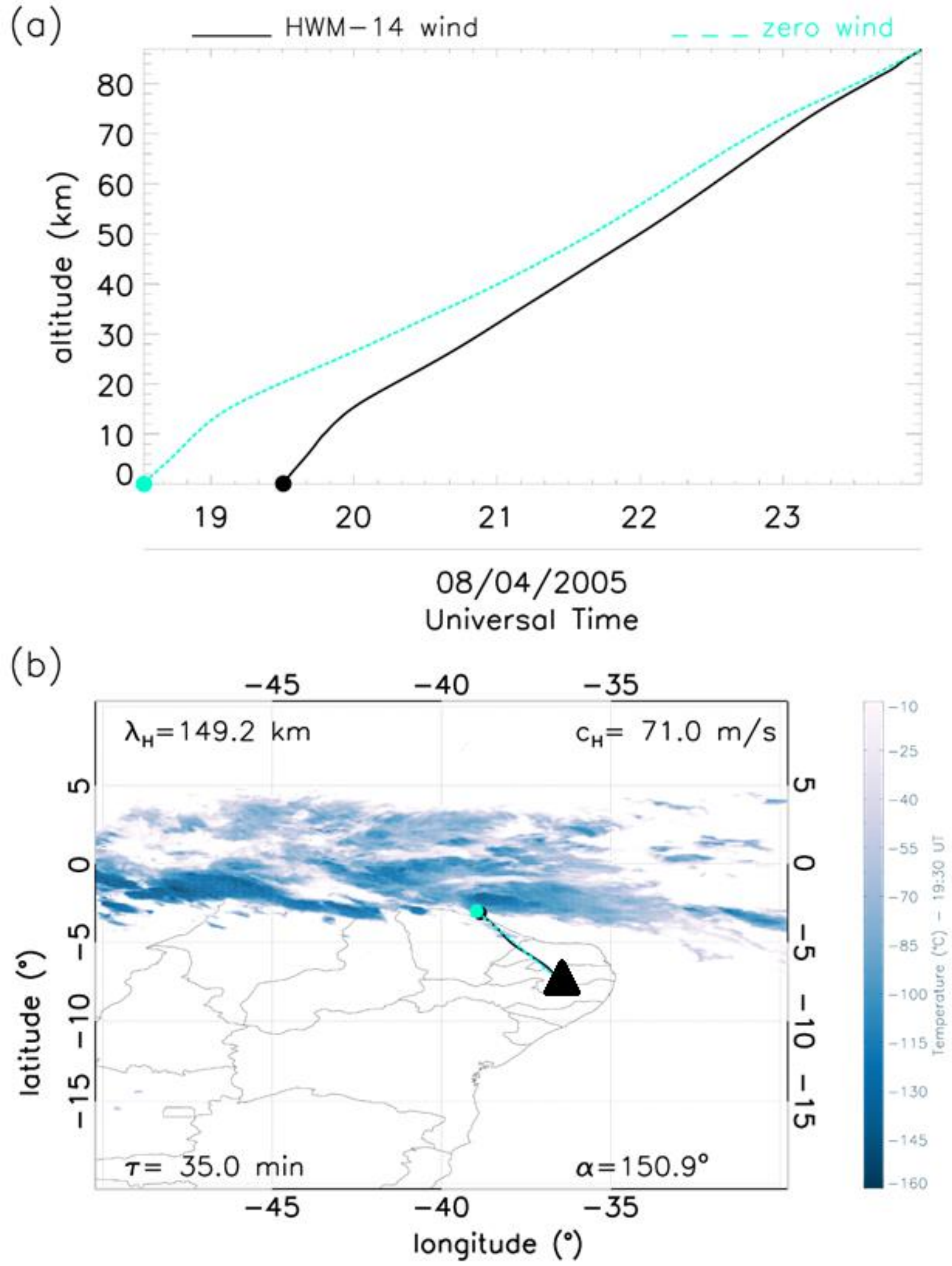

Figure 8: Same as Figure 5 but for event #5.

All the 5 wave events were reverse traced to some convection activities occurring in the northern region of the OLAP observatory. These have been identified as possible generators of these waves. One question is evident, why is the propagation direction of all the waves southeastward, since the Inter Tropical Convergence Zone (ITCZ) extends horizontally and covers the northern-region of the observatory? These results are in close agreement with previous results of different studies obtained at this laboratory (e.g., Medeiros et al., 2003 and Essien et al., 2018). It is expected that the gravity waves should propagate across all directions in accordance to the location of the ITCZ. Thus, further investigation was done to explain this anisotropy phenomenon. To better understand the physical mechanism that is producing the anisotropy, blocking diagrams have been used to investigate the role of the wind in the filtering process of these gravity waves.

Atmospheric winds are the default features of a real atmosphere. As these gravity waves propagate in the wind direction into the upper atmosphere, they would be susceptible to the Doppler's effect and critical level dissipation (Bretherton, 1966). The critical level marks the region where the horizontal wind component annuls the wave's horizontal phase speed (Medeiros et al., 2003). This region is very important as it decides how and if a traveling wave would propagate further. To understand the anisotropy of these GWs, we apply the critical level theory of the atmospheric gravity waves filtering (Fritts and Geller, 1976; Fritts, 1979). From Gossard and Hooke (1975) relation, the intrinsic frequency of the gravity wave under the influence of both horizontal wind components can be described by equation 3 below.

$$\omega_I = k.(c - V) \qquad (3)$$

where k is the magnitude of the horizontal wave vector, **V** represents the two horizontal wind components, and c is the horizontal phase speeds of the gravity waves. Equation (4) can also be re-expressed in terms of the zonal and meridional components. Further details can be found in the works of Medeiros et al. (2003), Campos et al. (2016) and Paulino et al. (2018). According to $cH = U\cos\emptyset + V\sin\emptyset$, where cH represents the phase speeds of these waves, U is the zonal wind component and V is the meridional wind component, we constructed blocking diagrams using the azimuthal angles (ø). With input winds from the Horizontal Wind Model, we aimed to understand the wind filtering effects on the gravity waves, investigate why all the waves have a preferential propagation direction, and also to detect regions where the phase speed of the GW is ≤ the velocity of the winds. The results of the 3-D blocking diagrams are shown in the following figures.

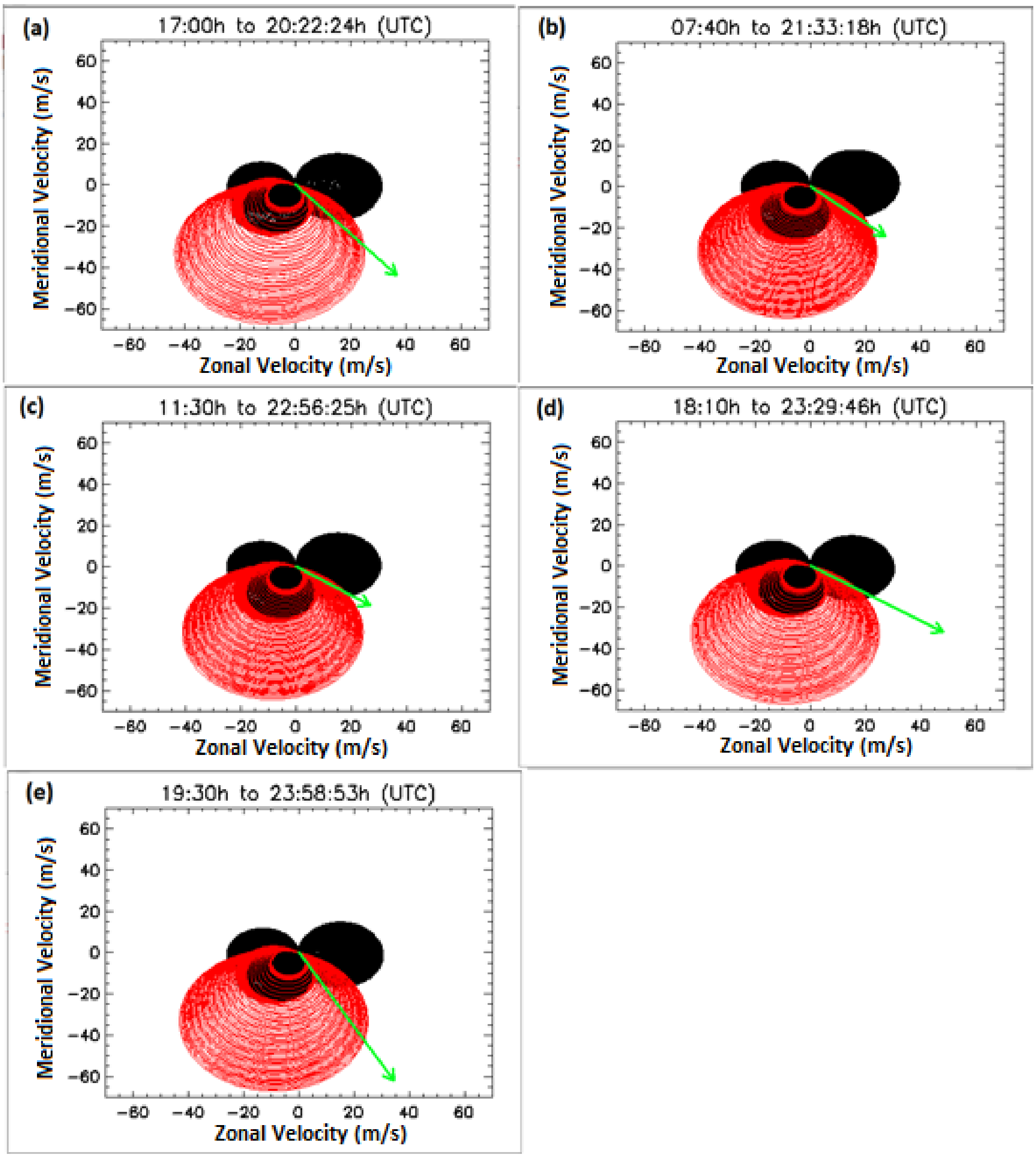

Figure 9: (a) Two-dimensional blocking diagrams for GW #1, (b) GW #2, (c) GW #3, (d) GW #4, and (e) GW #5 events observed at the OH layer (87 km). The green arrow depicts the magnitude and direction of the phase velocity of each gravity wave. The meshed region in red and black represents the magnitude and the direction of the restricted area for the propagation of the wave to the (OH) layer.

Constructing a polar chart as a function of the azimuthal angles and phase speeds using the wind data from HWM and the SkiYMET radar, we show where the phase speeds of these gravity waves equaled the wind speed of the background. The critical levels were projected into the blocking diagram showing for each horizontal wind speed and azimuths of the corresponding GWs. If the phase speed of the GW is trapped in the blocking lines, it represents that the wave is prohibited to propagate upwards.

The above blocking diagram allows the detection of regions where $\omega_I \leq 0$ on the night of 08 April 2005 for the OH emission layer. Every circle in this diagram shows the critical level of the vertical propagation of these waves. The red and black mesh signify the measured and modeled wind components respectively while the green arrow represents the magnitude and direction of the detected GW. The theory of filtering process of gravity waves disallows waves propagating into the shaded region due to the effect of the critical levels (Paulino et al. 2018).

Similarly, we observed that the phase velocity of all the GW events were indeed greater in magnitude than the blocking area. They had strong speed and momentum, enough to escape and propagate through the critical levels easily. It is important to note the main contributions to the blocking area were due to the measured wind in the mesosphere and lower thermosphere, making this analysis strongly confident.

Thus, these detected waves avoided and escaped absorption in the forbidden regions by traveling at these interesting angles. The anisotropy of these waves furthermore compels the source location of the wave to be in the Northwest because the location of this wave source played a key role in this preferential traveling (Fritts et al., 2008; Campos et al.; 2016). The sources of these waves were identified as the convective processes in the ITCZ zone.

5. Conclusions

Using OH airglow images captured by the ASI at São João do Cariri, we investigated the sources of some gravity waves observed on the night of 08 April 2005 in the OH airglow layer. Employing the spectral analyzing method, we obtained the characteristics of 5 major gravity wave events with horizontal wavelengths concentrated between 90 km and 149 km. The phase speeds were distributed between the range of 32 m/s and 71 m/s, and the observed periods extended from 26 min to 67 min. These waves presented spectral characteristics that are very compatible with waves previously observed in the same site. In addition, southeast propagation suggested possible sources in the northwest of the observatory.

Focusing on the possible sources of these waves, we back-traced the trajectory of each of these waves from the OH layer ($87km$) into the troposphere using the meteor radar wind data, the HWM model winds, and zero winds. We found out that the RRT put the source as active convective processes (in the ITCZ) in the northwest of the laboratory as shown in the back tracing results presented above. However, the ITCZ was extended by a long strip in the northern part of the observatory which suggested generation of other GWs that should have been observed in the south and southwest of the observatory. Thus, the construction of blocking diagrams showed that only the spectrum of waves with propagation to the southeast were able to propagate vertically to altitudes of the OH layer. Therefore, the filtering effect of gravity waves was decisive for explaining the presence of observed waves propagating to the Southeast.

Data availability: All sky image data used in the course of this study can be requested from Aerolume (UFCG) or Lume (INPE) Groups by mailing igo.paulino@df.ufcg.edu.br.

Author contributions: OD-I has written the manuscript. IP has revised the manuscript and supervised the research. CAOBF has calculated the deep cloudy convection over the OLAP area. ARP has provided wind measurements from the meteor radar, and revised the manuscript. RAB and AFM have revised the full text. CMW has provided the spectral analysis for the observed gravity waves.

Competing interests: All the authors declare that they do not have any competing interests.

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