**Authors' answer to Referee 2:**

**Reviewer comments in black, author's comments in blue.**

**Referee #2 Comments:**

The paper presents a new climatology of GWs inferred from airglow observations made at four stations at Antarctica. Such new observations could be publishable. Further scientific interpretations such as sources and secondary wave generation remain inconclusive. I hence recommend to focus on the observational part, but provide more detail which is needed to make the data useful for e.g. model comparison. This would need major revisions.

**Major points:**

The following points should be discussed: The observational filter of the four stations due to projection and pixel size for the horizontal wavelength. The observational filter due to the vertical extent of the OH layer. The conversion of relative intensity into GWMF. Which WACCM data are used and how realistic are they? What is the difference of the WACCM data over the four stations?

**Response:**

Information on the observational filter was included, and possible differences due to different instruments were discussed. The vertical extension of the OH layer is responsible for the cancellation of the wave’s amplitude with a dependence on the wavelength, implying that waves with wavelengths less than the layer thickness (i.e., ~8km) cannot be seen. Considering the OH layer 8 km thick, a value often seen in the literature, we are able to observe the waves in subject which implies, the observed waves attained the required condition for their signatures to be registered in the layer.

The conversion of relative intensity into GWMF.

**Response:**

The conversion of relative intensity into GWMF is achieved by equation 2.

$$MF = -\frac{1}{2}\frac{g^2}{N^4}\frac{m}{k}\;{}^2\left(\frac{I'}{Cf}\right)^2 \qquad \textit{Eqn 2 in the text}$$

This equation aids the said convection as stated. This is deemed necessary since relative intensity cannot give any dynamical information but only the wave parameters. In order to do this, the cancellation factor is vital for such conversion due unavailability of temperature observation. As a result of your question and the comment of referee 01, further details on the cancellation factor are provided in the main revised manuscript and the response to referee 01.

Which WACCM data are used and how realistic are they?

Estimation of the GW intrinsic parameters requires background fields such as wind and temperature. This is achieved by the use of Whole Atmosphere Community Climate Model Extension (WACCM-X). The model is a three-dimensional temperature, wind, composition and ionospheric structure from the surface to ~4.1E-10 (~500-700) at 0.9° in latitude x 1.25° in longitude and 130 pressure levels. To retrieve temperature and wind, inputs: locations (longitude, latitude, solar spectral irradiance, high-Latitude ionospheric inputs, interplanetary magnetic field e.t.c. In our case, we obtain neutral temperature and wind as the output. Details of WACCM-X can be found in Brown et al., 2026.

In addition to the above paragraph, more information on the used WACCM-X data was included.

The comparison section did not really help me. Is it needed?

The introduction needs to be rewritten from scratch. Perhaps one of the English native speakers can help

A new version of the introduction is presented.

**Comments as points occur in the paper:**

L15 First sentence is strange. You mean circulation, say it. Temperature distribution

L19 exciting topic ?

**Response:**

Based on your comment, the sentence had been rephrased as:

“The stratification of the Earth's atmosphere based on altitude variation of temperature leads to division into spheres, where each sphere (layer) plays a role in regulating the climate of the Earth and permitting the development of adequate environment for life. The stratification of the atmosphere is the primary mechanism that supports and sustains the generation and propagation of atmospheric waves. These waves are known to transport momentum and energy, thereby playing an essential role in the energy budget of the atmosphere."

L20 atmospheric layers differently than the air masses ???

**Response:**

Thank you very much for the correction! The entire sentence had been rephrased as:

Gravity waves study is an important subject in the atmospheric sciences due to their vertical energy and momentum transport, which connects the <u>different</u> atmospheric layers (Holton, 2004; Fritts and Alexander, 2003).

L47 recombination hypothesis ?

**Response:**

The entire paragraph has been re-written as:

"Recent studies on secondary gravity wave generations indicated that these waves are excited from body forces created by the turbulence generated during the breaking/dissipation of primary gravity waves. From this standpoint, the generation and propagation of these secondary (or non-primary) waves becomes a platform for coupling extension of wave activities to higher altitudes, where primary waves from terrain or tropospheric phenomena are most likely not to reach and be observed. According to the non-primary wave concept, waves above the altitude of 70 km are secondary waves generated from the breaking of mountain waves or waves from waves from meteorological phenomena (Vadas et al., 2019). Efforts to test such a concept have been conducted by computational modeling and high-resolution observations (Wright et al., 2017; Vadas and Becker, 2019; Kogure et al., 2020), and evidence of their occurrence have been observed by simultaneous satellite profiles from different altitudes (Trinh et al., 2018). Another feature currently being discussed is the horizontal propagation of these waves. Several works have used it to examine the observational pattern of high atmosphere waves (Kogure et al., 2018; Wright et al., 2017; Perrett et al., 2021). Observations would require extensive horizontal observations to confirm the hypothesis. However, simulations can show the possibility of horizontal propagation as a dependence on the wind's influence on the waves' movement (Sato et al., 2012; Fritts et al., 2019)."

LL62 Instrument description: Provide the projected area on the sky and the size of a pixel => which horizontal wavelengths can be, in principle, observed

An (orography) map with the locations indicated would be helpful.

**Response:**

More information on the instruments, data resolution, and observational filter were included. The text below was included in the main manuscript.

Airglow imagers installed at the stations of McMurdo (77.8° S, 166.6° E, hereafter MCM), Davis (68.5° S, 77.9° E, hereafter DAV), Rothera (67.5° S, 68.1° W, hereafter ROT), and Commandant Ferraz's Brazilian Antarctic station at the Antarctic Peninsula (62° S, 58° W, hereafter CF) provided the primary data for this study. They measure the broadband hydroxyl (OH) emission originated from an ~8 km-thick layer at ~86 km altitude and is widely used as a tracer of the dynamical processes in the mesosphere and lower thermosphere (MLT) region. To ensure no direct light contamination or twilight, the cameras are controlled by a computer to work when the sun and moon are absent (with the Sun ~10 degrees below the horizon). The imagers installed at McMurdo and Davis are the Utah State University (USU) all-sky cameras, while multifilter all-sky imagers were used at Commandant Ferraz and Rothera stations. Furthermore, the imagers at McMurdo and Davis are owned and operated by USU.

The IR imagers located at McMurdo and Davis are fitted with a 320 × 256 pixel indium gallium arsenide (InGaAs) detector (from Xenics), sensitive from 900-1700 nm where contamination of auroral is smaller in wavelengths (visible–800 nm) to100 which CCD detectors are sensitive. The camera is sensitive to the desired spectra and has good efficiency, thus does not require an interference filter. The imagers observe several OH emission bands, specifically the (3,1) and (4,2) bands (>100 kR), thus permit the use of a short exposure time, 3s with acquisition cadence of 10s per every image. A Fujinon E185C046H-1 C-mount fisheye lens is used to observe the whole night sky. Further details can be found in Matsuda et al. (2017).

The instruments at CF and Rothera are Keo Scientific Sentri cameras, made out of CCD intercooled with a telecentric image system and a fish-eye lens. The efficiency is near 90% for all the near infrared emissions, corresponding to the used broad band filter of 700-900 nm; more information on the Keo cameras is available on their website (keoscientific.com/imagers). The effective field of view is about 145°. The resulting images were binned to a spatial resolution of 512x512 pixels for improving signal-to-noise ratio. The exposure time of the images was 15s and temporal resolution is 2 min at CF and 4 min at ROT, due to different filter wheel operation sequence. A detailed description of the imager and the required image acquisition modes can be found in previous studies (Nyassor et al., 2018; Paulino et al., 2020).

L90 what did you do to confirm that results were insensitive to the different resolution and processing. Synthetic data? Vary the parameters? Please be a bit more specific.

**Response:**

More information on the methodological tests was added as shown in the text below:

"As widely discussed in the above-mentioned paper, we used simulations made of synthetic images with traveling waves on them to test all the methodology, and applied image processing, as well as possible discrepancies on the results generated by the different images. The analysis tests showed errors in the estimation of the parameters below 5% for horizontal wavelengths and periods, and below 10% for phase speed, while the amplitudes remained around 20%."

"As the images of the USU cameras are smaller and have different time resolution, a slightly different processing was necessary as follows. The vertical series composing the keograms were re-gridded to a 512 x 512 -pixel grid (resolution) to fit in the analysis code, and temporal binning to a resolution of 1 min was performed with no loss of quality in the analysis procedure. Time-difference images were not used, as the short-period gravity waves (20-120 min) showed a good response to the wavelet transform. Possible inaccuracies due to this different treatment were tested with synthetic images as described above, and no considerable differences were observed in the results."

L91 Which configuration of WACCM did you use? WACCM-DART, i.e. with assimilation? Up to which point can the WACCM data reflect the actual atmospheric conditions of the observations?

**Response:**

The WACCM-X configuration was used. As attested by the text the model represents the atmospheric conditions in an averaged way, giving a rough estimation of the environment the waves were subject to.

L100 Again, which tests? Which uncertainties do you assume for the model winds?

**Response:**

We verified the behavior of the m2 equation in relation to the scale of each of the terms of the equation and found similar values, thus all terms are significant and relevant for the adequate calculation. We attested that because of the considerably larger dimensions of the waves in the study, wind curvature and shear affect the calculation, so they can not be disregarded.

L108 What are "the observations theoretical layers"? You need to explain the variables, in particular \omega (ground-based? frequency), I' , I_%' and T_%

Using CF both for correction factor and Commandant Ferraz is a bit confusing

Fig 2: What is relative amplitude?

**Response:**

This entire part has been re-written to implement your suggestion and Referee 01 suggestions. Also, relative amplitude was defined and explained how it was calculated, and how it is used for the momentum flux estimation. Please refer to Lines 125-129, and 153-168 for the new version.

In all the text $C_f$ is defined as cancellation factor and CF as Comandante Ferraz.

The relative amplitude is the wave amplitude delivered by the wavelet transform divided by the average brightness of the night excluding twinlight time and auroras (if present).

**L163** ... we should expect that mostly non-irregular values were identified for the calculated parameters.

Sorry, I don't get this: Do you mean that using smoothed parameters underestimates the values? Leads to less extremes? Or that you have identified irregular values afterwards?

**Response:**

The authors thank you for pointing out this issue and we acknowledge the confusing phrase. As a result, we have paraphrased the part for clarification. Please refer to Lines 225-229 for the new version.

**L175** Given the layer thickness: What are the shortest waves observable? Likely the 0-10 km bin should be non detectable, thus the strong decrease in this bin. That there are waves at all, probably tells you something of the accuracy of your method.

**Response:**

We are grateful for the suggestion. More information on the observation filter was included as part of the description of the cancellation factor. Following that theory, only waves with vertical wavelengths larger than 8 km should perturbate the airglow layer, otherwise they are fully cancelled. We consider the possibility of error propagation and inaccuracy of the used method as a possible explanation for the presence of such smaller waves, which are few cases. Besides the possibility of the inaccuracy of the method used, the layer can register evanescent waves and small turbulent generated waves if such waves are close enough to the layer surface, as some works on ripples and small waves have presented.

**Fig 5:** According to equation 1, the ground-based phase speed is directly taken from your observations, the ground-based phase speed needs the WACCM wind velocities and the vertical wavelength the 1st and 2nd derivatives of the winds. In mid-frequency approximation you would assume that vertical wavelength and intrinsic phase speed are proportional, thus that vertical wavelength and phase-speed distribution have the same shape. That is roughly the case for CF, MCM and DAV, but not for ROT. Which leads to two questions: what is so unusual at ROT and, since this is WACCM-based, is it real?

**Response:**

We assume that you mean movement-based phase speed on the second line. We do not expect the described behavior because the m2 calculation generally present two behaviors, as described below:

Case 1: The vertical wavenumber is largely dependent on the wind speed (eq 1 is valid for a ground-based description, following the reference) when the wave phase speed is close to the wind speed, which is the case for a dissipating wave near a critical level. The equation indicates a singularity for this situation, wavenumber going to infinity, thus wavelength going to zero, which represents a wave vanishing.

Case 2: When the wind speed is smaller (or oriented in a different direction), the wavenumber will rely on buoyancy (temperature rate of change), or wind curvature or shear. Which one of these can be inferred by a scale analysis of the environment for each wave.

None of the above-mentioned situations happens for the waves understudy: on case (1), they have large phase speeds, so no critical levels are encountered. For case (2) the model provides a small rate of change for temperature and wind, it is meant to be smooth, so no singular values of wavenumber or wavelength are seen.

In conclusion, the calculation of vertical wavelength is following the terms of Equation 1: buoyancy, wind shear and curvature, in a balanced way, thus no general situation was perceived. We kept all the terms, as argued above in other points, because of this behavior. In addition, the statement about the model representing the atmospheric behavior in a smooth way is valid for this point also.

In connection to this: WACCM also may resolve some GWs, depending on the spatial resolution of the run. These should be removed e.g. by spatial filtering before calculation of eq. 1

**Response:**

The model we used does not include resolved waves but parameterized GW. We believe that the model is smooth enough for the kind of waves we are working.

**L255:** With these horizontal wavelengths and these phase speeds the wave could originate from sources very far away. You have ray-tracing tools available in your group, did you try? Best with some spread for uncertainties.

**Response:**

The RT model was used and no great conclusion was taken from its results, besides the fact that the model propagated the waves to very far regions, especially those with phase components parallel to the polar vortex wind. The estimation of the wave sources would require more observational data capable of relating atmospheric conditions along the ray paths to the wave source mechanisms. That would need an entire new analysis and would be out of the objectives of this study.

The RT shows the waves able to come from far regions when they pass through the polar vortex, and the vertical wavelength gets a very small value in that region. Besides the model does not stop the ray due to this condition, it is not possible that the waves could exist with such small wavelengths. Maybe that is another point indicating they are secondary waves generated somewhere above the polar vortex.

Another point to the interpretation: I don't think that waves with ground-based phase-speeds > 50m/s can be mountain waves. There would need to be a lot of refraction going on. Secondary waves from MWs might be possible?

**Response:**

Secondary generation is the most probable, we agree. The challenge here is the limited observation to prove they are secondary gravity waves. At this point, we could only gather some evidence that these waves are not primary, like comparing the known spectrum of primary GWs in literature.

**LL300** I do not find the comparisons very helpful: there are too many, but without detail. For instance, there is no discussion of different observational filters etc. If you have in mind some general picture which brings all these observations together I don't get it from the discussions.

**Response:**

The authors thank you for pointing out this issue and we acknowledge the confusing discussion. We have intended to point out that each study had a similar aspect to our study to give the available hints about the waves characteristic regarding generation and role in the atmosphere. That was unfortunate, as not everything got tightly connected for pointing to the intended conclusion.

A new version of the discussion is proposed in which we present the points and then expand the comparisons, thus guiding the reader to the conclusion.

**L334** If you would dissipate these waves in an 10km altitude interval you would have 170 m/s/day, probably everywhere in this lat-region (unlike shorter waves I would not assume them to be localized in regions), so they could have significant influence. Anyway, your observational filter lets you see only part of the wave spectrum. Without further study you do not know, whether and where these waves are important.

**Response:**

Thanks very much for the suggestion. That was rephrased.

**L340** Indeed, you would need some source identification, e.g. by backtracing.

**Response:**

Thanks very much for the suggestion. Identification of sources is intended to be carried out in the follow-up paper.

Data source is provided only for FC.

**Response:**

Thanks very much for noticing. Other data was obtained from private conversation.

References

Brown, M. K., Elvidge, S., Allanson, O., &Themens, D. R. (2026). WACCM-X simulation of the atmosphere from 1950through 2024 at an hourly resolution.Journal of Geophysical Research: SpacePhysics, 131, e2025JA034630