General comments

The study presents detailed observations of intense concentric gravity waves (CGWs) in the mesosphere and thermosphere over southern Brazil during 17–18 September 2023, triggered by fast-moving severe thunderstorms. Utilizing dual-channel ground-based airglow imaging (OH and OI 630.0 nm) alongside multi-satellite data (GOES-16, AIRS, VIIRS, SABER), the authors documented three CGW events lasting over 10 hours, with amplitudes exceeding 24% and horizontal movements over 400 km. The findings highlight exceptional momentum flux and vertical energy transport from the troposphere to the mesosphere–lower thermosphere (MLT) region. The study also addresses contamination in 630.0 nm thermospheric imaging due to OH emissions and explains the observed asymmetric wave propagation via Doppler effects from background winds. This work advances understanding of atmospheric coupling and underscores the value of coordinated multi-layer observations.

The study is scientifically sound and presents a comprehensive and well-supported analysis of extreme concentric gravity waves using an impressive combination of ground-based and satellite observations. The paper is well written, generally concise, and includes clear figures that support the findings. However, in a few instances, the inclusion of additional details, particularly regarding data interpretation and methodological assumptions, could enhance clarity and aid reader comprehension. I recommend accepting the paper for publication, subject to minor revisions.

We sincerely appreciate your time and effort in reviewing our manuscript, as well as your constructive feedback, which has greatly helped us improve the quality of our work. We have carefully addressed all your comments and revised the manuscript accordingly.

Specific comments

lines 33-34: Might be helpful to mention the typical height of the OH airglow layer (~87 km) and OI airglow layer (~250 km).

Reply: Thank you for your suggestion. The modifications we have implemented are as follows:

“The same CGW event was observed propagating from the OH airglow layer (~87 km) to the thermospheric OI 630.0 nm airglow layer (~250 km).”

lines 40-46: While the discussion provides useful context on the sources of atmospheric gravity waves (AGWs), it would benefit from the inclusion of some earlier and potentially more foundational references. Citing key historical studies on different atmospheric gravity wave types and generation mechanisms would help establish a more comprehensive background for the reader.

Reply: Thank you for your suggestion. The following references were added to the reference list.

Fovell, R., Durran, D., and Holton, J. R.: Numerical simulations of convectively generated stratospheric gravity waves, J. Atmos. Sci., 49, 1427-1442, https://doi.org/10.1175/15200469(1992)049<1427:NSOCGS>2.0.CO;21992.

Fritts, D. C.: Shear excitation of atmospheric gravity waves, J. Atmos. Sci., 39, 1936–1952, https://doi.org/10.1175/1520-0469(1982)039<1936:SEOAGW> 2.0.CO;2, 1982.

Fritts, D. C., and Nastrom, G. D.: Sources of Mesoscale Variability of Gravity Waves. Part II: Frontal, Convective, and Jet Stream Excitation, Journal of the Atmospheric Sciences 49, 111–127, https://doi.org/10.1175/1520-0469(1992)049 <0111:SOMVOG>2.0.CO;2, 1992.

Nastrom, G. D., and Fritts, D. C.: Sources of Mesoscale Variability of Gravity Waves. Part I: Topographic Excitation, Journal of the Atmospheric Sciences 49, 101–110, https://doi.org/10.1175/1520-0469(1992)049<0101:SOMVOG>2.0.CO;2, 1992.

Piani, C., Durran, D., Alexander, M. J., and Holton, J. R.: A Numerical Study of Three-Dimensional Gravity Waves Triggered by Deep Tropical Convection and Their Role in the Dynamics of the QBO, J. Atmos. Sci., 57, 3689-3702, https://doi.org/10.1175/1520-0469(2000)057%3C3689:ansotd%3E2.0.co;2, 2000.

Plougonven, R., and Zhang, F.: Internal gravity waves from atmospheric jets and fronts, Rev. Geophys., 52, 33-76, https://doi.org/10.1002/2012RG000419, 2014.

lines 68-73: The authors should briefly explain what is meant by “dual-layer airglow observations” to provide clearer context for readers who may not be familiar with this technique. Specifically, clarifying that it involves simultaneous observations of airglow emissions from the mesosphere and thermosphere (e.g., OH and OI 630.0 nm layers) would help highlight the significance of this method for studying vertical wave propagation and atmospheric coupling.

Reply: Thank you for your suggestion. We have provided a brief clarification regarding dual-layer airglow observations as follows:

“Although the observation of AGWs by airglow imagers has been widely documented in previous studies (Dalin et al., 2024; Nyassor et al., 2021, 2022; Suzuki et al., 2007; Vadas et al., 2012; Vargas et al., 2021; Wüst et al., 2019; Xu et al., 2015; Yue et al., 2009), dual-layer airglow observations, which involve observing airglow emissions from a hydroxyl radical (OH) layer (~87 km) in the mesosphere and an atomic oxygen emission layer at 630 nm (OI 630.0 nm) (~250 km) in the thermosphere, offer a unique opportunity to simultaneously investigate CGWs in both the mesosphere and thermosphere. This configuration enables comprehensive studies of gravity wave vertical propagation and their role in vertical atmospheric coupling. However, due to past limitations in observational capabilities, simultaneous detection of CGWs across both the OH and OI 630.0 nm layers was rare.”

lines 77-82: It would be helpful to clearly state where and when the observations were conducted to orient the reader. Additionally, the reported 24% amplitude is striking, providing context by specifying which previous studies or typical values this is being compared to would clarify its significance.

Reply: Thank you for your suggestion. We have made the following revision:

“In this study, we observed multiple strong CGW events using airglow measurements in southern Brazil on 17-18 September 2023, with a maximum amplitude reaching 24%, which is far higher than previously reported events with average amplitudes of 2-3% (Li et al., 2016; Tang et al., 2014; Suzuki et al., 2007a). Through ground-based dual-layer and multi-satellite joint observations, we conducted a comprehensive analysis of these events to reveal their role in vertical energy transfer and atmospheric coupling.”

lines 104-116: The authors should clarify what is actually done in step #2 of the image processing chain. Specifically, more detail is needed on how the van Rhijn effect and atmospheric extinction are corrected, what parameters are used, and how the corrections are applied to the data. This would help readers better understand the methodology.

Reply: Thank you for your suggestion. We provide a detailed description as follows:

Second, we corrected for the van Rhijn effect and atmospheric extinction using the approach described in Kubota et al. (2001). The observed airglow intensity $I(\theta)$ from the ground is not uniform across different zenith angles. This non-uniformity is due to the van Rhijn effect. Additionally, the observed airglow intensity is influenced by atmospheric extinction, which results from absorption and scattering along the line of sight.

Since airglow observations are subject to the van Rhijn effect, the measured emission intensity at a specific zenith angle (θ) follows the relation **(**Kubota et al., 2001**):**

$$I(\theta)=I(0)\cdot V(H,\theta),$$

$$V(H,\theta)=\left[1-\left(\frac{R}{R+H}\right)^2\sin^2(\theta)\right]^{-1/2}, \quad (1)$$

where $I(0)$ is the emission intensity at zenith. $V(H,\theta)$ is the van Rhijn correction factor. R is the earth radius and H is the height of OH airglow layer. The relationship between the observed emission intensity $I(\theta)$—affected by atmospheric extinction—and the true emission intensity $I_{true}(\theta)$ at the airglow layer is described by Kubota et al. (2001).

$$I(\theta) = I_{true}(\theta) \cdot 10^{-0.4 \cdot a \cdot F(\theta)},$$
$$F(\theta) = [\cos\theta + 0.15 \cdot (93.885 - \theta \cdot \frac{180}{\pi})^{-1.253}]^{-1}, \quad (2)$$

where a is the atmospheric extinction coefficient, $F(\theta)$ is an empirical equation.

Consequently, the image correction factor, obtained from the combination of Eqs. (1) and (2), takes the form:

$$K = V(H, \theta) \cdot 10^{-0.4 \cdot a \cdot F(\theta)}. \quad (3)$$

The parameter a depends on the atmospheric observing conditions. For the observed CGW events, we treat a as temporally constant. By averaging the images over the observation period, we derive the zenith-angle-dependent airglow intensity profile. The optimal value of a is determined by matching this observed profile with theoretical K profiles across varying a. The fitted value of parameter a is approximately 0.42. Finally, we apply the flat-field correction by dividing the raw images by the corresponding K factor.

line 120: It seems the subsection introducing the SABER/TIMED measurements is missing?

Reply: Thank you for your suggestion. We added the following description to section 2.2 of the main text.

"Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) is one of four instruments on NASA's Thermosphere Ionosphere Mesosphere Energetics Dynamics (TIMED) satellite (Russell et al., 1999), launched on December 7, 2001. TIMED focuses on exploring the energy properties and redistribution in the MLT region, providing data to define the basic states and thermal balance of this area. SABER is a 10-channel broadband limb-scanning infrared radiometer (1.27-17 μm). It measures kinetic temperature through CO_2 emissions (15 μm Local Thermodynamic Equilibrium (LTE) below 90 km; 4.3 μm non-LTE above 90 km) with ±2-5 K accuracy. Simultaneously observing O_3 (9.6 μm), OH (1.6-2.0 μm), and O_2 (1.27 μm) emissions, it quantifies radiative cooling (up to 150 K/day) and chemical heating (~8 K/day) in the MLT region with 2-4 km vertical resolution."

lines 122-129: The authors are kindly requested to provide a reference for the ABI (Advanced Baseline Imager) instrument onboard GOES-16 to support the description of its capabilities

Schmit, T. J., M. M. Gunshor, W. P. Menzel, J. J. Gurka, J. Li, and A. S. Bachmeier, 2005: INTRODUCING THE NEXT-GENERATION ADVANCED BASELINE IMAGER ON GOES-R. Bull. Amer. Meteor. Soc., 86, 1079–1096, https://doi.org/10.1175/BAMS-86-8-1079.

Reply: Thank you for your suggestion. The recommended reference has been incorporated into the text.

lines 133-135: The swath width of AIRS is approximately 1765 km, not 1600 km as stated (Hoffmann et al., 2014). I recommend citing Hoffmann et al. (2014) here, as their study offers important additional details on data processing methods—such as detrending—and discusses the sensitivity of AIRS stratospheric gravity wave observations, which are currently missing in this manuscript.

Hoffmann, L., Alexander, M. J., Clerbaux, C., Grimsdell, A. W., Meyer, C. I., Rößler, T., and Tournier, B.: Intercomparison of stratospheric gravity wave observations with AIRS and IASI, Atmos. Meas. Tech., 7, 4517–4537, https://doi.org/10.5194/amt-7-4517-2014, 2014.

Reply: Thank you for your suggestion. The recommended reference has been incorporated into the text.

lines 255-257: The relatively weak brightness temperature fluctuations observed by AIRS may result from the instrument's limited sensitivity to short vertical wavelengths (see, e.g., Hoffmann et al., 2024). Consequently, the observed brightness temperature amplitudes are typically much lower than the actual stratospheric temperature fluctuations, especially for convective wave events with short vertical wavelengths.

Reply: Thank you very much for your constructive suggestions. Your suggestions have been incorporated into the main text as follows:

"The relatively weak brightness temperature fluctuations observed by AIRS may result from the instrument's limited sensitivity to short vertical wavelengths (Hoffmann et al., 2014). Consequently, the observed brightness temperature amplitudes are typically much lower than the actual stratospheric temperature fluctuations, especially for convective wave events with short vertical wavelengths."

line 260: In Figure 6, the convective gravity waves (CGWs) might become more visible if the colorbar range is adjusted, for example, by using a fixed, symmetric range of ±0.5 K. Additionally, the colorbar label should be corrected to read "Brightness temperature perturbation (K)" instead of "Temperature perturbation (k)" to avoid confusion between measured radiance (brightness temperature) and actual atmospheric temperature.

Reply: Based on your suggestions, we have revised Figure 6 as shown in the figure below.

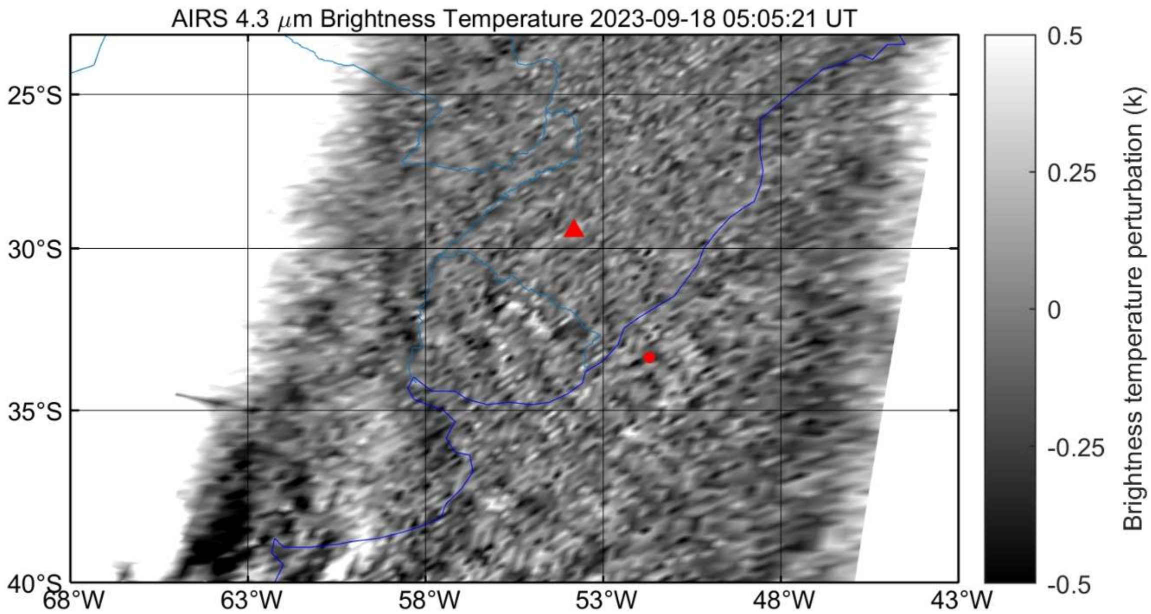

Figure 6. Aqua satellite 4.3 μm brightness temperature observations of CGWs at 05:05:21 UT on 18 September 2023. Brightness temperature is derived from 4.3 μm radiance at an altitude range of 30–40 km. The red triangle and dot mark the SMS station and fitted wave center, respectively.

lines 376-378: The statement "These events represent the most intense vertical transport cases ever recorded" should be better contextualized. Please clarify the criteria or dataset scope that support this claim to avoid potential overgeneralization.

Reply: Thank you very much for your comment.

We have removed the phrase "These events represent the most intense vertical transport cases ever recorded" from text to avoid potential overgeneralization.

lines 388-393: Another relevant study for comparison is Yue et al. (2013), which also presents multi-layer observations of convective gravity waves and estimates propagation times from the troposphere to the airglow layer, similar to the approach in this study. Including a discussion of their findings could provide valuable context and strengthen the interpretation.

Yue, J., L. Hoffmann, and M. Joan Alexander (2013), Simultaneous observations of convective gravity waves from a ground-based airglow imager and the AIRS satellite experiment, J. Geophys. Res. Atmos., 118, 3178–3191, doi:10.1002/jgrd.50341.

Reply: Thank you very much for your comment. The following discussion has been incorporated into the main text.

"Yue et al. (2013) conducted multilayer observations of convective gravity waves over the western Great Plains of North America and estimated that the time from the convective source to the airglow layer was ~45 min.”

lines 422-424: The authors should please clarify the actual detection threshold of the vertically integrated airglow observations, specifically the limit in terms of vertical wavelength.

Reply: Thank you very much for your comment. The following discussion has been incorporated into the main text.

“This strong eastward wind likely suppresses the visibility of eastward-propagating thermospheric CGWs in airglow imaging. We use Eq. 5 to estimate that the vertical wavelength of thermospheric CGWs propagating in the northwest direction is approximately 236 km, while that of thermospheric CGWs propagating eastward is approximately 62 km. The Doppler shift reduces their vertical wavelengths, causing them to fall below the detection threshold of the vertically integrated airglow observations, which is approximately 100 km from 200 km to 300 km during nighttime (Chiang et al., 2018).”

Chiang, C.-Y., Tam, S. W.-Y., and Chang, T.-F.: Variations of the 630.0 nm airglow emission with meridional neutral wind and neutral temperature around midnight, Ann. Geophys., 36, 1471–1481, https://doi.org/10.5194/angeo-36-1471-2018, 2018.

Technical corrections

line 18: The acronym "CGW" (Concentric Gravity Wave) should be introduced in full when first mentioned.

Reply: It has been revised.

line 28: change to “fast-moving deep convection” (singular)

Reply: It has been revised.

lines 304-307: Remove redundant sentence “Figure 9c present…”

Reply: It has been revised.

line 312: replace “ERA-5” by “ERA5”

Reply: It has been revised.

line 332: replace “saber” by “SABER”

Reply: It has been revised.

line 358: is _the_ cancellation factor

Reply: It has been revised.

lines 386-387: from _the_ troposphere to _the_ airglow layer

Reply: It has been revised.