

Review

"Observed large-scale trapping of gravity waves within the free troposphere" by Giovanni Biagioli, Alexis Aubel, Riwal Plougonven, and Sandrine Bony

General Remarks

The essence of the paper is the analysis of a single, about 7 min aircraft observation of trapped gravity waves at the upper edge of the Saharan dust layer over the eastern Atlantic on 15 August 2024. In addition, satellite images are used to document the gravity wave signatures with similar characteristics at various locations over the eastern Atlantic on that particular day. These topics constitute the first part of the paper. The second part of the paper is a statistical analysis of the environmental conditions conducive to gravity wave trapping at the ABL top. A simplified version of the Scorer parameter is used to define a Trapping Likelihood Index (TraLI). This index is computable over any chosen spatiotemporal domain using reanalysis data. Overall, this study successfully combines a rigorous case study analysis based on linear gravity wave theory with a broader climatological perspective. These two complementary approaches provide both a detailed mechanistic understanding of the observed event and a practical tool for evaluating the conditions for wave trapping.

The manuscript does not introduce any new physical principles: linear wave theory, the Scorer parameter, and the Taylor-Goldstein equation are well-established tools. Rather, its main strength lies in the rare combination of in situ, remote sensing, radiosonde, and satellite observations for a single event. The identified waveguide in the free atmosphere combined with the idealized cavity model represent a plausible conceptual framework. More on the explorative side, the trapping likelihood index might constitute a useful, albeit incremental, methodological contribution rather than a paradigm shift.

Specific Remarks

1. Title:

The formulation "... large-scale trapping ..." is somewhat misleading, as the paper does not provide direct evidence of trapping at large spatial scales beyond the visual similarity seen in the satellite imagery. On the other hand, "large-scale" could also be understood as referring to the observed wave packet itself being large in terms of its horizontal extent. The title could be revised to better reflect the content of the paper.

2. Abstract:

- "Gravity waves are a key dynamical feature of atmospheric flows, yet remain difficult to simulate and observe. However, on 15 August 2024, widespread wave signatures were observed over a broad region of the northeastern tropical Atlantic, with remarkable spatio-temporal coherence." This is too general, and there are numerous papers on numerical simulations (from linear to non-linear ones) and many many observations of gravity waves. Specify the first sentence. Also: Why do you use "However, ..." in the following sentence?

- "One such packet was sampled in situ by the research aircraft operated within the MAESTRO field campaign, providing an ideal case study." This sentence raises two issues. First, it is unclear why a single, spatially limited in situ sample should constitute an "ideal" case study of a phenomenon. Second, the reference point for the phrase "provides an ideal case study" is unclear: Since it appears immediately after "MAESTRO field campaign," it is not clear whether it is the measured wave packet, the measurement itself, or the campaign that "provides" the case study.

- the last sentence: the reference to "local climatologies" and "previous studies" is vague. Specify which climatologies and which previous studies are meant.

3. Introduction:

The introduction is generally well-written, provides a clear context for the study but lacks some references to the existing literature about trapped gravity waves.

- Observation of extended trains of short gravity waves in the free atmosphere is not new per se: see, e.g., Smith et al. (2008, J. Atmos. Sci., "Mountain Waves Entering the Stratosphere", T-REX, <https://doi.org/10.1175/2007JAS2598.1>) and, especially, Smith et al. (2016, J. Atmos. Sci., "Stratospheric Gravity Wave Fluxes and Scales during DEEP-WAVE", <https://doi.org/10.1175/JAS-D-15-0324.1>, their Fig. 9). It must be acknowledged that the term "wave trapping" was not explicitly mentioned in these studies apart from the considerable horizontal extent of the wave trains.

- Regarding the overview of recent wave trapping studies (ll. 45–56), the authors are encouraged to consider the closely related study by Dörnbrack (2024, J. Atmos. Sci., 'Transient Tropopause Waves'). Physically, contrasting its TIL-centered duct (likely triggered by stratospheric wave breaking) with the present study's free-tropospheric, non-orographic duct would provide an insightful comparison. Methodologically, the authors' strategy of identifying an 'extensive wave structure over a wide area [...] with remarkable spatiotemporal coherence' (ll. 63–64) via satellite data and verifying it in situ perfectly aligns with Dörnbrack (2024), who documented a similarly large-scale, coherent trapped wave event, additionally supported by downward-looking lidar measurements. In connection with the same discussion (ll. 45–56), the authors might also want to consider referencing the work by Eckermann et al. (2026, J. Atmos. Sci., 'Ground-to-Stratopause Trapped Lee Waves Observed Downstream of the Kerguelen and Heard Islands'). Including this recent paper would provide another excellent example of the growing interest in trapped wave dynamics and further strengthen the literature review.

- The historical account of the Scorer-parameter and lee-wave-trapping literature (ll. 34–44) cites the two founding references (Queney, 1948; Scorer, 1949) before jumping directly to recent tropospheric-waveguide studies, skipping the substantial body of intervening work that operationalized and extended Scorer's framework (e.g., Corby and Wallington, 1956; Corby and Sawyer, 1958; Vosper, 2004). This gap is particularly relevant for the TraLI introduced later in the manuscript (Sect. 4): Coney et al. (2025, QJRMS) recently published a regional climatology of lee-wave trapping conditions over Britain and Ireland, also derived from the Scorer parameter, albeit using a deep-learning classifier rather than a simplified threshold. Acknowledging and positioning TraLI relative to this very similar approach would strengthen the originality argument of Sect. 4.

- line 21: What is a " ... vertical view of atmospheric gravity waves ... "? The phrase is unclear and should be clarified.

- line 28: There is a dot behind Lane in the citation, which should be removed. Additionally, there is a nice case study by Heller, et al: Mountain waves modulate the water vapor distribution in the UTLS, Atmos. Chem. Phys., 17, 14853–14869, <https://doi.org/10.5194/acp-17-14853-2017>, 2017. which is an observational study of tracer transport.

- l. 54: "The occurrence of trapped waves appears more likely in the presence of significant shear in the upper troposphere..." It might be nice to also acknowledge the classic works of Kuettner (1971), Clark, Hauf and Kuettner (1986), and Kuettner, Hildebrand and Clark (1987) here. The presence of shear as a key condition enabling coherent, far-reaching propagation of gravity waves above convectively ABLs was indeed one of the central results of these foundational studies, and a brief nod to them would nicely connect this statement to this established body of work. By the way, every glider pilot knows the relationship between shear and wave propagation, as it is a key factor in the formation of wave lift above the convective boundary layer.

4. Section 3:

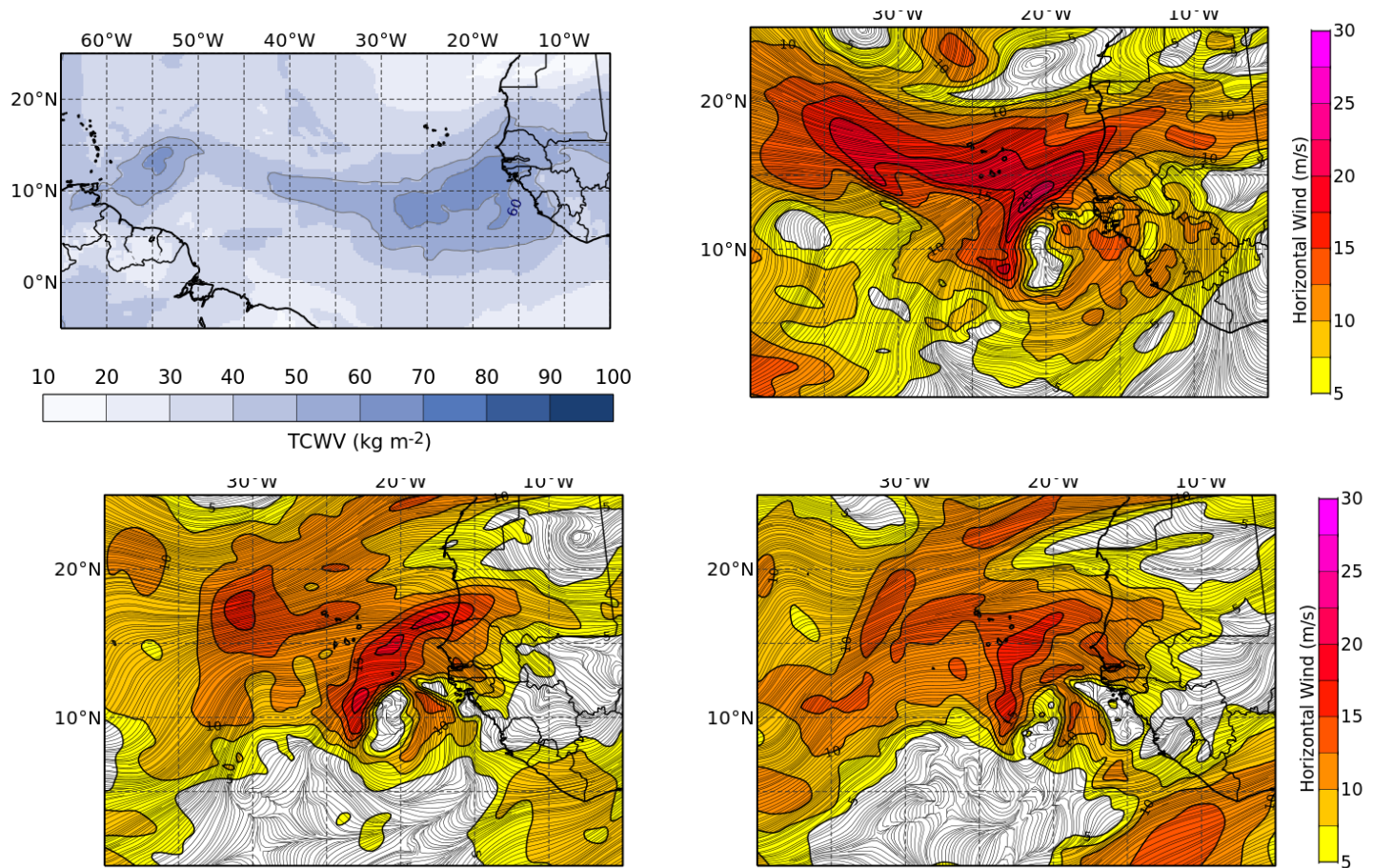
- Figure 1: Could you draw lines from the red boxes in panel a to the respective panels b–f?

- l. 112: delete "s" after the commata.
- l. 116: a reader would benefit if you explicitly state that these regions occur at different times and places.
- ll. 133/134: "must have been": can you provide evidence or it is just a speculation?
- Eq. 1 could be nicely combined with the direct computation of the vertical displacement via the purely kinematic relation used by Smith et al. (2008, 2016; see also the remark on Smith et al. above):

$$\zeta(x) = \int_0^x \frac{w'(x')}{U(x')} dx',$$

where w' is the perturbation vertical velocity and U is the along-track wind speed (Smith et al., 2016, their Eq. 12, following Smith et al., 2008). This would provide a useful, independent cross-check of $|\tilde{\zeta}|$ – obtained here from the polarization relation (Eq. 6) – without requiring prior knowledge of N or $\hat{\omega}$.

- l. 155: Which formulas are used to compute the ice and water saturation mixing ratios for RHw and RH_i? It would be helpful to provide the formulas or at least a reference.
- l. 156: replace "multiple" by "six"
- l. 156: The term "nearly monochromatic" caught my attention, given that the same signal is referred to as a "wave packet" elsewhere in the manuscript. Strictly speaking, a wave packet implies an amplitude-modulated wave train composed of a range of wavenumbers. If "wave packet" is instead used here in a more generic sense – simply meaning "a short train of waves" – rather than in this stricter technical sense, it would be helpful to clarify this to avoid ambiguity.
- Figure 3: The plot would benefit from an additional x-axis showing the distance in km.
- In Section 3.3, two different cases are combined to provide evidence that KHI can be ruled out for the case under consideration. The readability of this subsection could be greatly improved by integrating the relevant material from the appendix into the main text and by contrasting the two cases directly. Otherwise, the reader has to move back and forth between Section 3.3 and the appendix. Alternatively, this part (as it is important for the whole paper) could be an own new section.
- l. 194: What are "The unforced momentum ... equations". I assume, there is still Coriolis force, buoyancy, pressure gradient as forces in the equations. Please, clarify.
- Table 2: The vertical wavelength is rather small. How can this value be explained? By the thickness of the inversion layer or the depth the wave duct?
- ll. 280/281: The statement "Above this layer, dry static stability increases before decreasing again above roughly 10 km" oversimplifies the N^2 profile shown in Figure 5c, which also exhibits a secondary, weaker stratified layer between 11–13 km (as the authors themselves note a few sentences later). Consider rephrasing for consistency with this more detailed description.
- ll. 285–286: The statement that the stratification "was already evident in the radiosonde profiles from August 14 ... [and] that the well-mixed layer had decreased significantly by August 16" is not supported by Figure 5, which, according to the caption, shows only profiles from August 15, 2024. Either reference the correct supporting evidence (e.g. an additional panel or supplementary figure) or remove/qualify this comparison.
- Figure 5: Could you add ticks at the x-axis for N^2 ?
- Section 3.5: Although this subsection is remarkably clearly formulated, its scope warrants a separate and dedicated section. Furthermore, the manuscript would benefit from the inclusion of historical references to the theory of



ERA5 analysis for 15 August 2024, 15 UTC: (top left) total column water vapour (TCWV); wind speed and streamlines at (top right) 600 hPa, (bottom left) 500 hPa, and (bottom right) 450 hPa.

multilayer linear gravity wave theory, such as those found in the textbook by Gossard and Hooke (1975). Explicitly highlighting the incremental progress or distinguishing this work from these pioneers would significantly strengthen its positioning within the field.

It might be also worthwhile to check the literature of trapped waves in the mesosphere and stratosphere. I vaguely remember papers seen at conferences and in the *J. Geop. Res.*

- Figure 6 reminds me of the figures 9-12 of Smith and Kruse (<https://doi.org/10.1175/JAS-D-16-0297.1>): w-power at small scales, u-power at large scales. A hint on this similarity in airborne observations in the free atmosphere close to inversion and shear layers (Smith: tropopause; here: ABL inversion layer) would be nice.

- either Section 3.1 or 3.4: Interested in this case study, I briefly analyzed the synoptic situation on the afternoon of August 15, 2024 (see figure above). The reason for doing so was simply to determine what caused the curved phase lines in the gravity wave field. This question was neither raised nor answered in the manuscript.

First, the event was located north of the ITCZ ($TCWV < 48 \text{ kg m}^{-2}$). Second the observations were conducted in a region where a low pressure system was located to the southeast. At its northwestern edge strong easterly winds with cyclonic curvature dominated. The curvature of the streamlines nicely corresponds to some of the gravity wave phase lines seen in the satellite imagery. A short discussion of this flow pattern in the manuscript would be great to place the observations in a meteorological context.

5. Section 4:

- l. 381: As far as I understand, your search for a "suitable approximation model" for S^2 ends here with the Scorer parameter, which essentially applies to atmospheric flow over mountains in the direction of the mean wind (Equation 14). Well, this can be done as a first step. Better would be to use a plausible range of phase speeds and directions. I agree, such an approach would be challenging but modern computer architectures should enable such a study. Moreover, the use of pressure levels instead of higher resolved model levels is critical as you compute vertical derivatives. In the text, most of the limitations are mentioned, so I see no need to change the text principally. However, I would like to see a more detailed mentioning of the limitations of the TraLI index in the conclusions, not just the rather qualitative and vague formulation " ... purposefully defines a conservative criterion ..."

6. Section 5:

I agree that the identification of the gravity wave sources is of secondary importance for the present study. What is unclear to me is the role of the Saharan dust layer in the dynamics of this event. There is the study by Chouza et al. (2016, Atmos. Chem. Phys., 16, 4675–4692, "Vertical wind determined using airborne lidar and analysis of island-induced gravity waves in combination with numerical models and in-situ particle measurements," <https://doi.org/10.5194/acp-16-4675-2016>). It seems that more than just the geographical proximity of the observation of trapped (resonant) waves serves as a further point of commonality.

These airborne coherent Doppler wind lidar measurements plus the in situ particle measurements and numerical modelling characterize gravity waves in the Saharan dust layer. This is a methodologically close approach to the combination of RASTA/LNG lidar, in situ microphysics, and model comparison employed here. Both the geographical overlap and the methodological similarity could also support the argument regarding regional representativeness that underlies the TraLI climatology discussed in Section 4.