Tropical Wave Observations From the Reel-Down Atmospheric Temperature Sensor (RATS) in the Lowermost Stratosphere During Strateole-2

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Key Points:

- high-resolution observations in the lowermost stratosphere from a new instrument
- Instrument detected tropical waves at resolution limit of reanalyses
- ERA5 reproduces waves, but temporal evolution differs from observations

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Abstract

Tropical waves play an important role in driving the quasi-biennial oscillation (QBO) of zonal winds in the tropical lower stratosphere. In our study we analyze these waves based on temperature observations from the 2021-2022 Strateole-2 campaign when the Reel-down Atmospheric Temperature Sensor (RATS) was successfully deployed for the first time. RATS provides long-duration, continuous and simultaneous high-resolution temperature observations at two altitudes (balloon float level and 200m below) allowing for an analysis of vertical wavelengths. This separation distance was chosen to focus on waves near the resolution limit of reanalyses. Here, we found tropical waves with periods between about 6 hours and 2 days, with vertical wavelengths between 1.5 km and 5 km, respectively. Comparing our results to ERA5 reanalyses we found good agreement for waves with a period longer than one day. However, the ERA5 amplitudes of high-frequency waves are under-estimated, and the temporal evolution of most wave packets differs from the observations.

Plain Language Summary

We present measurements from the maiden flight of the RATS instrument (Reel-down Atmospheric Temperature Sensor) in November/December 2021. The instrument lowered a temperature sensor down to about 200 m from a balloon floating at about 18 km. By combining the temperature measurements at balloon floating level and RATS we analyze tropical waves with relatively small vertical wavelengths (<6 km). These waves are important as they drive the quasi-biennial oscillation in the east-west winds in the tropical stratosphere. This oscillation is acknowledged as an important process for seasonal forecasts, but it is currently not well resolved in weather or seasonal forecast models. In our study we compare the observed waves with waves in one weather model system (ERA5) and find that the spectral energies are similar for long-period waves (>1 day). However, the high-frequency waves (that provide about 25% of the necessary QBO forcing) are under-estimated by ERA5, which is likely related to the limited vertical resolution.

1 Introduction

Strateole-2 is a French-US project with a focus on dynamics, microphysics and composition in the tropical upper troposphere and lower stratosphere using long-duration superpressure balloons. Measurements include winds, temperatures, composition, clouds and aerosols from a variety of in situ and remote sensing instruments (Haase et al., 2018; Corcos et al., 2021; Kalnajs et al., 2021; Goetz et al., 2023). One goal is improved characterization of tropical waves, which drive variability in temperature and high cirrus clouds that have impacts on global stratospheric water vapor and decadal-scale climate variability (J.-E. Kim et al., 2016; Jensen et al., 2017; Solomon et al., 2010)

Tropical waves also drive the Quasi-Biennial Oscillation (QBO) in lower stratospheric zonal winds, a circulation with notable impacts on long-range prediction (Scaife et al., 2022). Global model systems struggle to simulate these climate processes (Richter, Anstey, et al., 2020; Davis et al., 2017), likely in part due to poor resolution of the short horizontal and/or vertical scales of important tropical waves (Holt et al., 2020; Richter, Butchart, et al., 2020; J.-E. Kim & Alexander, 2015; Bramberger et al., 2022).

To study the effects of tropical waves on QBO and cirrus clouds, global reanalyses provided by different centers for numerical weather prediction have been widely used (Ern et al., 2014; Y.-H. Kim & Chun, 2015; Pahlavan, Fu, et al., 2021; Pahlavan, Wallace, et al., 2021; Ueyama et al., 2023). Due to its higher horizontal resolution compared to its predecessors, the fifth generation European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis (ERA5) is capable to resolve a wider spectrum of tropical

waves. This also allows for an improved representation of the wave-mean flow interaction which is crucial for the generation of the QBO (Pahlavan, Fu, et al., 2021).

Recently, balloon studies have shown the importance of very short vertical wavelength 1-5 day intrinsic period gravity waves with momentum fluxes that will contribute substantial forces to the QBO in the lower stratosphere (Vincent & Alexander, 2020; Bramberger et al., 2022). These studies highlighted limitations of vertical resolution in reanalyses for representing short-vertical scale tropical waves, even for the high (∼350m) resolution of ERA5. Together with modeling studies these observations highlight the importance of high vertical resolution in the realistic representation of the QBO (Garfinkel et al., 2022).

Motivated by these results, Strateole-2 balloons equipped with specialized sensors were launched in the tropics in late 2021 with flight levels within the TTL and lower stratosphere. A new measurement platform named the Reel-down Atmospheric Temperature Sensor (RATS), which senses temperature at the isopynic balloon level and hundreds of meters below the balloon level had its maiden flight November-December 2021. The goal of these measurements is to characterize tropical waves in the short vertical wavelength range that straddles the limits of ERA5 resolution. For this study we use RATS data in conjunction with balloon level Thermodynamical SENsor (TSEN) observations (Hertzog et al., 2004) to characterize tropical waves near 18 km in the lowermost tropical stratosphere. We use these unique measurements and ERA5 fields, to characterize tropical waves above the Indian Ocean in the lowermost tropical stratosphere and study their representation in ERA5.

2 Data and Instruments

2.1 Strateole-2 in situ TSEN observations

For Strateole-2, 25 super-pressure balloons were launched during two campaigns from the Seychelles. The first campaign took place from November 2019 to February 2020 and the second campaign from October 2021 to January 2022. These balloons circumnavigate the equator at 18 km or 20 km (Haase et al., 2018; Corcos et al., 2021). We focus on balloons C1-15-TTL4 (TTL4) and C1-16-TTL5 (TTL5) where both balloons are equipped with the TSEN temperature sensor at floating level (Hertzog et al., 2004) and the TTL5 balloon additionally carried the RATS instrument (see Fig. 1a). The TTL5 super-pressure flight duration was approximately 42 days and RATS was operational for the first 16 days of the flight. Due to closely spaced launch times (<2 hr) and near-identical float altitudes, the TTL4 and TTL5 balloons were floating in close proximity over the course of 10 days (see Fig. 1a and c). This permits combination of the in-situ observations of these two balloons for the purpose of analyzing the horizontal wavelengths of tropical waves.

In-situ balloon observations of ambient temperature, pressure and horizontal wind vectors at the isopycnic floating levels of the Strateole-2 balloons were done with TSEN. Wind speeds are calculated from the GPS position of the drifting balloon gondola. The temperature sensor accuracy is 0.1 K at night and 0.25 K during the day after correction for solar radiation (Hertzog et al., 2004). The precision of TSEN temperatures is on average about 4 mK for night-time measurements and about 20 mK for daytime, respectively (Wilson et al., 2023). The absolute accuracy and precision of the pressure sensor are ±2 hPa and 0.01 hPa. Winds are derived from position with 0.1 ms^{-1} precision. The temporal resolution of this data set is 30 s.

2.2 RATS

RATS is a platform designed to make simultaneous, continuous and fast-response measurements of temperature, pressure, and position at two altitudes from a drifting high-altitude balloon using the TSEN temperature and GPS (Fig. 1b). The temperature sensors were separated vertically by a reel-down cable, with one TSEN at the "Euros" control gondola flight level and the other at the end of the reel-down cable. The lower sensor was attached to a suspended sub-gondola, or end-of-fiber-unit (EFU). For the TTL5 flight, the separation length was about 200 m, but other lengths are possible on future flights. The flight level gondola contained the data and communications interface of RATS in addition to the mechanical reeling system used to deploy the EFU, which is identical to the reel system used by the FLOATS instrument (Goetz et al., 2023). The EFU design and implementation was also identical to FLOATS, with the TSEN probe located on a thin white PTFE wire about 1 m below the EFU sub-gondola. Other specifications can be found in (Goetz et al., 2023). Additionally, the same 600 µm diameter liquid crystal polymer (LCP) coated fiber optic cable used for FLOATS was used to suspend the EFU. Its UV radiation exposure rating and breaking strain meet the International Civil Aviation Organization (ICAO) regulatory standards (i.e. Rules of the Air ICAO Appendix 4 Annex 2). For TTL5 the EFU was configured to transmit GPS position and TSEN pressure and temperature every 10 to 30 s via Long Range (LoRa) radio to the flight level gondola interface system. The Euros level TSEN and GPS was configured to a sampling period of 30 s and the EFU data was synced to the same clock.

2.3 ERA5 in Balloon Trajectory-Following Coordinates

ERA5 is an atmospheric reanalysis available at 6 hour intervals on 137 vertical levels up to 1hPa (Hersbach et al., 2020). The distance between the different vertical levels is about 400 m in the lower stratosphere and the horizontal resolution is 31 km. For this study the hourly ERA5 data was interpolated both in space and time to the balloon flight tracks of TTL4 and TTL5, respectively.

3 Methods

To determine the vertical or horizontal wavelengths we generally follow the approach of previous studies (Alexander et al., 2008; Wright et al., 2010; Ern et al., 2014; Alexander, 2015) who used adjacent satellite-borne temperature profiles to infer horizontal wavelengths. However for RATS analysis, we take into account covariance between two temperature time series rather than covariance between adjacent vertical profiles.

3.1 RATS vertical wavelength estimates

To calculate vertical wavelengths we use the temperatures measured with RATS (∼200 m below balloon flight level) and TSEN (at balloon floating level) systems. We decompose the temperature observations into time t and frequency ω spectrum applying the Stockwell transform (Stockwell et al., 1996). The covariance between the two spectra C_{TR} can be written as

$$C_{TR}(t,\omega) = \hat{T}_t \hat{T}_r^* \tag{1}$$

where the $\hat{T}_t$ and $\hat{T}_r^*$ are the complex temperature amplitude spectra observed by TSEN at balloon level and by RATS ∼200 m below the balloon, respectively. (See Fig.1b.) The star denotes the complex conjugate of $\hat{T}_r$. The phase shift is computed with

$$\Delta\phi_{TR} = arctan\left(\frac{Im(C_{TR})}{Re(C_{TR})}\right) \tag{2}$$

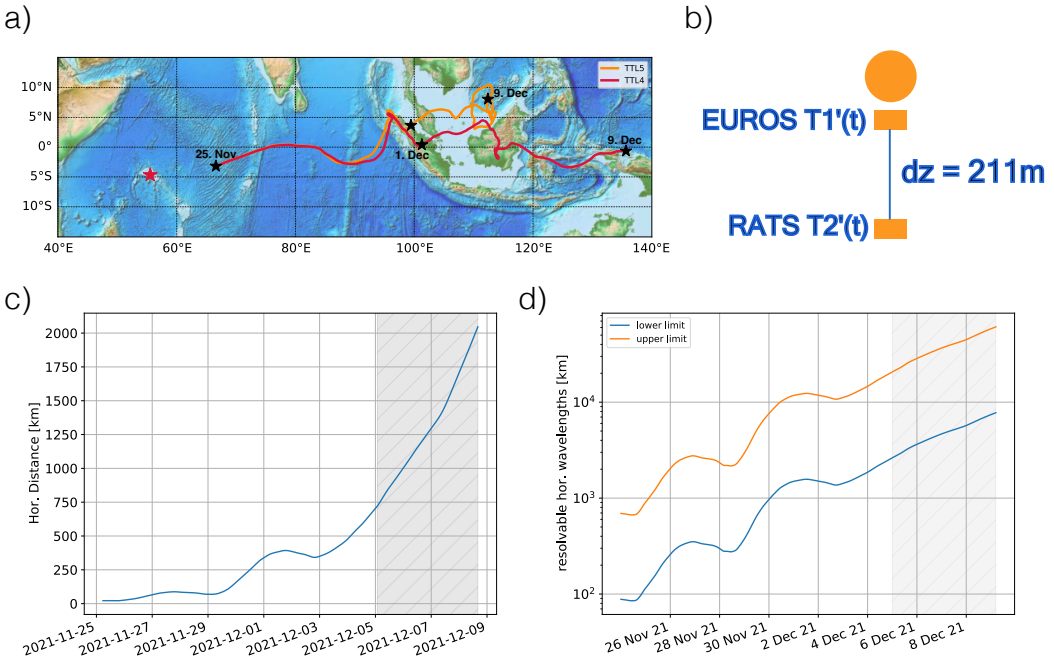

Figure 1. (a) Flight track of the TTL4 (red) and TTL5 (orange) balloons from 25th November to 9th December. The stars show the balloon positions on the 25th November, 1st December and 9th December, respectively. The red star highlights the Seychelles islands where the balloons were launched. (b) Schematic of TTL5 temperature measurements where RATS is on average 211m below the balloon. (c) Horizontal distance between the two balloons between 25th November and 9th December. (d) Theoretical upper and lower limits of horizontal wavelengths that can be resolved based on the horizontal distance of the balloons. Grey shading indicates the time period where the horizontal distance was too large and the data was excluded from the analysis.

From the vertical phase shift $\Delta\phi_{TR}$ and the vertical distance Δ_z =211 m we can then estimate the vertical wavelength

$$\lambda_z = \frac{\Delta\phi_{TR}}{\Delta_z}. \tag{3}$$

Due to the sensitivity of the instrument and to avoid aliasing effects we define wave packets with a covariance threshold $> 0.5\,\mathrm{K}^2$ and only compute vertical wavelengths where the observed phase difference $|\Delta\phi_{TR}|$ is in the range $0.2 - \pi$.

As the vertical distance between the RATS and balloon observed temperatures is a constant the resolvable vertical wavelengths range from ∼420 m to 6.6 km throughout the observation period.

3.2 Dual-balloon horizontal wavelength estimates

As the balloons TTL4 and TTL5 were floating in close proximity over 10 days we can also estimate the horizontal wavelength λ_x analogous to the vertical wavelength. In this case the equation changes to

$$\lambda_x = \frac{\Delta\phi_{45}}{\Delta_x(t)} \tag{4}$$

where $\Delta\phi_{45}$ is the phase shift derived from the co-spectral analysis of TTL4 and TTL5 measured in-situ temperatures at the Euros gondola level and $\Delta_x(t)$ is the horizontal distance between the two balloons which varies with time (see Fig.1c). As the horizontal

distance between the two balloons varies with time the resolvable horizontal wavelength range changes accordingly (see Fig.1d). Note, we limit the application of this method to times where Δ_x is smaller than 750 km and where the change in time of Δ_x is also small. Also note that compared to their horizontal separation, the mean vertical distance between the two balloons was negligibly small and is neglected in the analysis.

4 Results

4.1 Vertical and horizontal wavelength estimates from balloon observations

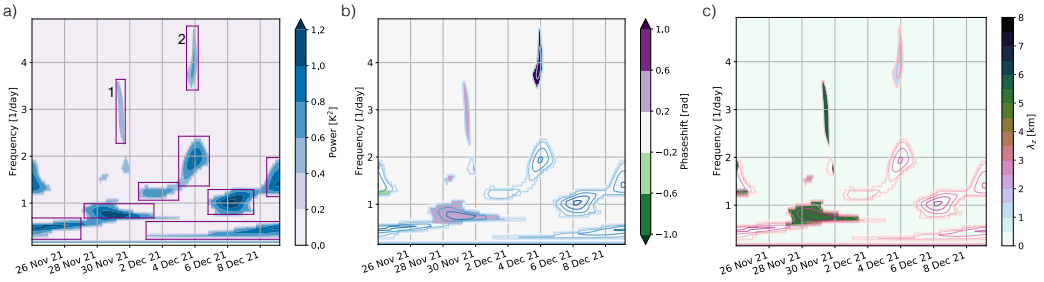

Figure 2. (a) Covariance of the temperatures measured by RATS and TSEN with a mask to only show significant amplitudes (power $> 0.5\mathrm{K}^2$). (b) Phase shift for significant wave packets with overlain covariance contours for reference. (c) Vertical wavelength for wave packets with detectable signals (where phase shift >0.2 radians). All spectra are shown as a function of time and wave frequency.

The covariance calculated from RATS and balloon flight-level observed temperatures shows enhanced power for waves with periods between 12 hours and 2.5 days between 25th November 2021 and 8th December 2021 (Fig. 2a). Boxes on the figure identify potential candidate wave packets for analysis. The corresponding phase shifts, computed as amplitude-weighted averages for each packet, reveal two high-frequency waves and one low-frequency wave packet with detectable phase shifts in these measurements (Fig. 2b). For these wave packets the vertical wavelengths range from 1.5 km to 5.5 km (Fig. 2c). For wave packets with a vertical wavelength larger than 6.6 km the phase shift becomes so small that it cannot be detected with the deployed instrument configuration.

Over the course of 10 days the balloons TTL4 and TTL5 floated in close proximity (Δx <750 km) allowing the analysis of horizontal wavelengths (see Fig. 3). Again the covariance shows wave packet signals for periods between 5 hours and 2 days and phase shifts are detectable (>0.2) especially for wave packets after 30 November 2021. The estimated horizontal wavelengths range between 500 km and 3000 km (see Fig. 3c). Note, that the horizontal distance between the two balloons varies with time (see Fig. 1a and c) which means that changes in the derived horizontal wavelengths over a wave packet could be related to the change of horizontal distance between the balloons with time if the wavelength shifts in or out of the observable range (see Eq.4 and Fig.1d).

4.2 Comparison to ERA5 reanalyses

As a next step we compare the observed covariances with ERA5 temperature covariances. For the comparison with the vertical RATS-TTL5 covariances we choose the two ERA5 model levels that are closest to the balloon and RATS floating level. Please note that the vertical grid spacing of ERA5 at this altitude region is about 350 m whereas

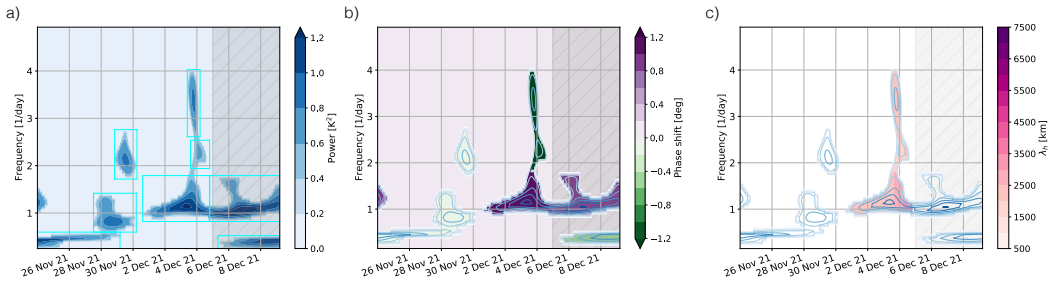

Figure 3. (a) Covariance of the temperatures measured by TTL4 and TTL5 TSEN with a mask to only show significant amplitudes (power $> 0.5\mathrm{K}^2$). (b) Phase shift between the temperatures for significant wave packets. (c) Resulting horizontal wavelength for significant wave packets and phase shift >0.2 radians. All spectra are shown as a function of time and wave frequency. Grey shaded areas highlight the time where the horizontal distance exceeds the threshold.

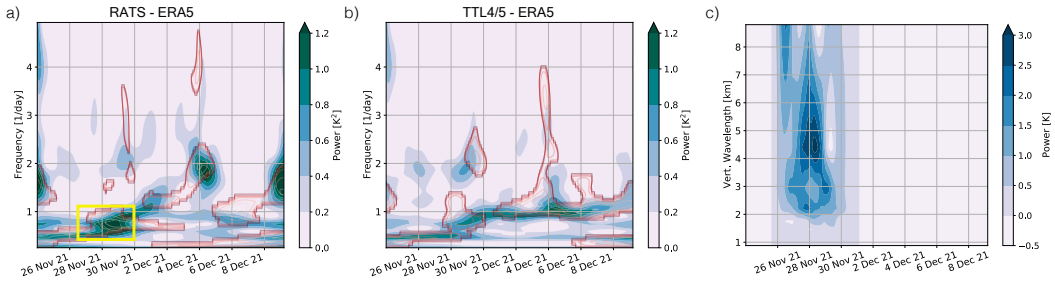

Figure 4. (a) Covariance of ERA5 temperatures between the two model levels that are closest to the balloon and RATS floating levels (blue and green contours). (b) Covariance of ERA5 temperatures interpolated to the TTL4 and TTL5 flight tracks. For both panels (a) and (b) the red contours identify where observed covariances$>0.5\mathrm{K}^2$ as presented in Fig. 2a and 3a. (c) ERA5 vertical wavelength spectrum for the wave packet for which the best agreement between measurements and ERA5 was found (yellow box in panel (a)). The spectra in a) and b) are shown as a function of time and wave frequency.

RATS is only about 200 m below the balloon. For the comparison with the observed TTL4 and TTL5 covariances we use ERA5 data interpolated in space and time to the respective balloon flight tracks.

Fig. 4a shows that for frequencies lower than 2 cycles/day the ERA5 simulated covariances have similar structures and energies as the observed ones. This is especially true for the wavepacket observed on 29th November 2021 with a frequency of ∼0.6 cycles/day (see yellow box in Fig 4a). This similarity gives confidence in the wave-packet analysis based on RATS observations, since the two figures Fig.2a and Fig. 4a show correlations obtained with independent datasets. However, most of the ERA5 wave packets seem to evolve differently in time compared to observations and the observed high-frequency wave packets (29th November and 3rd December) are not resolved at all in ERA5.

For the wave packed that is well reproduced in ERA5 (yellow box in Fig 4a) we calculated the vertical wavelength for comparison with vertical wavelength estimates from RATS. For this analysis we interpolated ERA5 data on an equal-spaced vertical grid and then calculated the power spectrum of the vertical wavelength as a function of time (see

Fig. 4c). Most of the power is concentrated at a vertical wavelength of about 4.5 km which is similar to the estimated 5 km vertical wavelength derived from RATS observations.

Comparing the ERA5 and observed covariances of TTL4 and TTL5 (Fig.4b) we draw similar conclusions. Again, for low frequencies, less than 1/day, there is similar power and temporal evolution, but the power for higher-frequency wave packets is underestimated in ERA5 and temporal evolution does not much resemble the observations. As ERA5 does not reproduce the observed packets that were well-resolved ($\sim$ 3 December in Fig.4b), we do not attempt to compare the horizontal wavelengths between ERA5 and observations.

5 Conclusions & Discussion

In this study we present first results of a newly developed instrument RATS (Reeldown Atmospheric Temperature Sensor). RATS was developed during the second Strateole-2 campaign in 2021 and this study provides a proof-of-concept analysis of first measurements with this instrument. In its current design RATS was deployed about 200 m below the balloon gondola thus enabling observations of tropical waves with vertical wavelengths between $\sim$400 m and 6 km. A previous study of long-duration balloon observations (Bramberger et al., 2022) found significant gravity waves with vertical wavelengths $<$1 km. In the present case study, we observed tropical waves with vertical wavelengths between 1.5 km and 5 km. To extend the range of observable tropical waves future plans include the development of several RATS instruments allowing different vertical distances. These different RATS instruments can be deployed on several balloons in the next Strateole-2 campaign planned for late 2025.

The comparison to ERA5 reanalyses shows that the power distribution in the covariances at frequencies $\leq$ 1cycle/day is similar to the observations, both for the RATS and the TTL4/TTL5 comparisons. However, the power is underestimated for high-frequency waves with frequencies $\geq$ 2 cycles/day, and some prominent observed higher frequency waves are absent in ERA5. Given the limited 10-day time series in this study, it is possible some higher frequency wave events may appear in ERA5 but with different timing than in the observations. The differences might be related to modeling limitations due to limited vertical resolution or differences in ERA5 representation of convection, which is the likely source of these tropical gravity waves (Corcos et al., 2021). Nevertheless, one low-frequency wave packet compared very well between ERA5 and RATS observations and we could therefore compare the respective vertical wavelengths. The found wavelengths agree well between ERA5 and RATS which adds confidence to the analysis technique applied to the RATS data.

Momentum fluxes calculated with a previously published method (Corcos et al., 2021) for the two high-frequency wave packets 1 and 2 in Fig.2a are modest with about $\sim$1 mPa and $\sim$5 mPa, respectively. The found momentum fluxes are in concurrence with Corcos et al. (2021) where 1-5 mPa were the most commonly observed values and the global average momentum flux was $\sim$5 mPa. In their study they found that collectively the high-frequency waves ($>$1 cycle/day) contribute at least 25%, and possibly more than 50%, to the total force required to drive the QBO.

In general, there is good correspondence in the temperature covariance time series comparing the balloons to ERA5 for inertia-gravity waves with periods in the 1-2 day range. Similar signals were analyzed in ERA5 in detail over decades (Pahlavan, Fu, et al., 2021), and finding their contribution to forcing the QBO. Our comparison to these balloon data suggests these low-frequency gravity waves may be quite realistic in ERA5, both in their locations, timing, and amplitude (Fig.4). However, although this is only a limited case study comparison, the ERA5 reanalysis appears to be deficient in gravity waves at higher frequencies. Additionally, ERA5 vertical resolution limitations were

implicated in missing waves seen in a previous balloon study (Bramberger et al., 2022) that should otherwise have been resolvable. Future comparisons between Strateole-2 balloon observations and reanalyses should further illuminate the strengths and limitations of the reanalysis datasets for representing tropical gravity waves.

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