Observation of Thermospheric Gravity Waves in the Southern Hemisphere With GOLD

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Key Points:
1. First observations of thermospheric gravity waves from a GOLD special operational mode campaign are presented.
2. Signatures of perturbations are seen to propagate northward and appear to be atmospheric gravity waves.
3. Wave properties estimated from observations and GLOW model are consistent with a large-scale gravity wave.

Abstract
The middle thermosphere from ~150 to 250 km is characterized by rapid increase in temperature with altitude and rapid ionization. The entire thermosphere is believed to be home to atmospheric gravity waves that propagate through it, originating both in the atmospheric layers below and in the thermosphere itself. Within the middle thermosphere, direct observations of such waves are extremely sparse. The Global-scale Observations of the Limb and Disk (GOLD) far-ultraviolet imaging spectrometer is able to observe the middle thermosphere from geostationary orbit. During October 2018, a special observational campaign was performed, designed to identify atmospheric waves. Signatures in the 135.6-nm O airglow were seen that move northward with time, away from the southern polar region. These are consistent with a large-scale atmospheric gravity wave. These results are the first time 135.6-nm airglow has been used to track such a wave and highlight the ability of GOLD to observe such waves, even when at a modest amplitude, and track their motion.

Plain Language Summary
The upper region of the Earth's atmosphere, stretching from around 90–500 km above the surface, is known as the thermosphere. In this region, the temperature generally increases with altitude, but the strongest increase is in a region known as the middle thermosphere. The main source of heating in this region is absorption of ultraviolet light from the Sun, which also produces charged particles in this region, known as the ionosphere. Oscillations are observed in almost all the properties of the atmosphere at these altitudes, which are believed to result from waves within the atmosphere. In the middle thermosphere, there are very few direct observations of such waves. Global-scale Observations of the Limb and Disk (GOLD) is a new instrument that can observe the middle thermosphere by measuring emissions from the atmosphere call airglow. During a day in October 2018, GOLD observed what appear to be fluctuations in this airglow associated with such waves. The properties are determined, both from the GOLD observations and a theoretical model.

1. Introduction
The middle thermosphere, from around 150- to 250-km altitude, is characterized by a rapid increase in temperature and changing atmospheric composition with altitude, high rates of photoionization, and associated generation of photoelectrons. As in much of Earth's atmosphere, atmospheric waves are believed to play a key role in the dynamics of this region (e.g., Forbes, 2007). The spectrum of waves is observed to change at middle thermosphere altitudes, from the relatively small vertical wavelengths (tens of kilometers) seen in the mesosphere and lower thermosphere to the relatively long vertical wavelengths (>100 km) seen in the upper thermosphere (e.g., Djuth et al., 2010; Oliver et al., 1997). Atmospheric gravity waves (GWs) are believed to be a key component of the wave spectrum in the middle thermosphere and significantly impact this region, both in creating transient variations and in producing net acceleration, mixing, heating, and heat flux as they dissipate (e.g., Yiğit & Medvedev, 2015). The GWs in the middle thermosphere are believed to be a mixture of waves originating in the lower regions of the atmosphere (both primary and secondary waves; e.g., Vadas & Fritts, 2006; Vadas & Liu, 2009; Yiğit et al., 2014) as well as waves generated in the thermosphere, primarily via Joule heating in the auroral regions (e.g., Richmond, 1978).

GWs in the mesosphere and lower thermosphere region have been observed frequently via a variety of methods, including images of airglow (e.g., Swenson & Mende, 1994), lidar (e.g., Wilson et al., 1991), radar (e.g.,...
Vincent & Fritts, 1987), observations of noctilucent clouds (e.g., Thurairajah et al., 2017), and limb profiles from low-Earth orbit spacecraft (e.g., Preusse et al., 2009). GWs have also been detected frequently with in situ observations in the upper thermosphere (e.g., Bruinsma & Forbes, 2008; Garcia et al., 2016; Park et al., 2014). Despite the strong impacts GWs are believed to have in the middle thermosphere (e.g., Vadas & Fritts, 2006; Vadas & Liu, 2009; Yiğit et al., 2014), very few direct observations of GWs in this region have been made. The vast majority of observations of GW at middle thermosphere altitudes come from radar observations of electron density or motion, which identify traveling ionospheric disturbances (TIDs) that are the ionospheric counterpart to the GW in the neutral atmosphere (e.g., Djuth et al., 2010; Negrea et al., 2016). Where observations of both the GW and TID have been made in the same location in the thermosphere, it has been shown that the TID may be a very good proxy for the underlying neutral GW (e.g., Earle et al., 2008), and thus, observations of TIDs may provide a great deal of insight into the spectrum of GWs at this altitude, even if they do not reveal all the changes in the neutral atmosphere associated with the GW. Using a combination of ionospheric (airglow brightness) and thermospheric wind observations, Paulino et al. (2018) were able to deduce the intrinsic parameters of GWs in the middle thermosphere/bottomside $F$ region and confirm that the waves seen in the ionospheric response were consistent with upward propagating GWs that are filtered by the background winds, both at these altitudes and below.

Determining the characteristics of GWs in the thermosphere is important for understanding the energy and momentum balance of this region. As just one example, it is believed that GWs propagated upward from below can either heat or cool the thermosphere (e.g., Vadas et al., 2014; Yiğit & Medvedev, 2009), but their impact on the thermosphere depends on their properties, as well as the mean state. The characteristics of TIDs observed are typically grouped into two categories according to their horizontal spatial scales. Medium-scale TIDs, with horizontal wavelengths around 100–500 km, and horizontal phase speeds of around 100–200 m/s are believed to be associated with primary or secondary GWs from the lower levels of the atmosphere (e.g., Azeem et al., 2017), whereas large-scale TIDs, with horizontal wavelengths over 1,000 km, and horizontal phase speeds of around 500 m/s are believed to be associated with aurorally generated GWs (e.g., Bruinsma et al., 2006). Given the importance of GWs in the middle thermosphere, and the comparative lack of direct observations of these waves in this region, further examination of observations of GWs in the neutral atmosphere at these altitudes is warranted.

Global-scale Observations of the Limb and Disk (GOLD) is a National Aeronautics and Space Administration Mission of Opportunity, primarily focused on observing the far-ultraviolet airglow emissions from the Earth’s middle thermosphere and $F$ region ionosphere. Here we present the results from a special campaign of observations from GOLD, designed to reveal the impacts of GWs on the airglow originating from the middle thermosphere. While this data set is unique in that it represents a special campaign that has yet to be repeated, these results will highlight the capabilities of the GOLD instrument to observe such waves. We identify the impact GWs on the far ultraviolet (FUV) airglow during a geomagnetically quiet to moderate day, analyze the GOLD observations, and make use of an airglow model to estimate the intrinsic wave parameters in the neutral atmosphere. These results can also be used to help define future campaigns with the GOLD instrument.

2. Experimental Setup and Data

GOLD is a two-channel far-ultraviolet imaging spectrometer that observes the Earth from onboard the SES-14 geostationary communications satellite, which is located at 312.5° longitude (Eastes et al., 2017, 2019; McClintock et al., 2017). During regular operations, when the disk of the Earth is illuminated by the Sun, the instrument scans the disk of the Earth, building up an image of the Earth’s disk with a 30-min cadence. GOLD makes observations between ~134 and 167 nm, which allows identification of the prominent dayglow features of O at 135.6 nm and LBH band of N$_2$. During early operations on 13 October 2018, both channels of the instrument performed a special mode campaign, designed to identify the impacts of atmospheric waves on the middle thermosphere. Based on modeling by Greer et al. (2018), the anticipated changes in O dayglow at 135.6 nm were of order ±2 Rayleighs, requiring an integration time of ~400 s to clearly identify such perturbations, which is much longer than the typical dwell time when scanning the disk. To maximize the chance of seeing such a perturbation in the airglow, the special mode campaign...
involved pointing both channels close to nadir, with the mirror position set to view the Southern Hemisphere and stare continuously from ~12–18 hr UTC (see Figure 1). This has the effect of increasing the signal collected in this region by a factor of over 100 times compared to if the GOLD instrument were scanning across the disk but obviously limits the data availability to the two narrow strips shown. As the two channels are mounted in opposite directions on the spacecraft, the tilt of the slit with latitude is in the opposite direction for each channel such that the longitudinal separation of the fields of view is ~1° at the equator, increasing to ~9.9° toward the edge of the disk at ~61° latitude. It is this, currently unique ~6-hr long data set that will be considered here.

While the special mode campaign was preplanned and not intended to align with any specific geophysical conditions, the conditions present on 13 October 2018 were geomagnetically quiet to moderate. \( F_{10.7} \) values on the day were low at \( 71.7 \times 10^{-22} \text{ W m}^{-2} \text{ Hz}^{-1} \), while the \( K_p \) values show moderate activity, reaching 4+ by later in the day, although it is worth noting that changes in the heating of the atmosphere are often delayed several hours from changes in \( K_p \), suggesting that this will have little impact during the time period of the campaign. Examining the real-time auroral AE index shows activity below 100 nT from 12–15 UT, with a pickup between 15 and 18 UT up to over 1,200 nT by the end of the period. It is worth noting that this heightened activity occurred several hours into the campaign.

This study focuses on Levels 1b and 1c (L1b and L1c) data from the GOLD instrument, which are described in the Data Products Users Guide (see https://gold.cs.ucf.edu). The L1b files are available for this campaign at 2-min cadence and provide the spectrum in instrument counts versus wavelength and latitude. The L1b processing includes geometric corrections for the detector and optics, filtering of the counts based on the detector pulse heights, a correction based on the detector dead time (maximum count rate), and data are binned on a regular wavelength scale. The L1c files are available at a 10-min cadence and provide the spectrum in radiance versus wavelength and latitude. The L1c processing additionally includes the radiometric conversion based on knowledge of the instrument flat field response, scattered light and dark current noise sources, and sensitivity versus wavelength.

### 3. Data Analysis

Given the low amplitude of the signal expected from an atmospheric GW described above, our analysis focuses on the bright O doublet feature near 135.6 nm, although it is worth noting that this overlaps the (3,0) emission from \( \text{N}_2 \) at 135.4 nm. Some of this can be excluded by not including the shortest wavelength bins in our computation of the 135.6-nm feature, as has been done here. To identify the perturbations associated with any atmospheric fluctuations such as GWs, we first isolate the 135.6-nm airglow from the background then detrend the variations associated with changes in local time and any that may be associated with changes in solar EUV brightness. This is done in three steps. To isolate the 135.6-nm airglow, we add up the signal at each pixel at each point in time in the range from 135.2–136.0 nm and perform a background subtraction using two out-of-band regions either side of this, at 134.4–134.8 and 136.4–136.8 nm (see Figure 2a). To remove the local time variations, a third-order polynomial fit is made to the signal at each pixel in each channel, and this smoothly varying signature is removed (see Figure 2b). Finally, changes associated with varying solar EUV brightness affect the signal at all latitudes on the disk simultaneously. As such, these are easily identified and removed by finding and removing the mean value of brightness across the image, after the local time variation is removed. This leaves a residual signal whose mean value is 0.

The atmospheric wave perturbations that may be expected in the middle thermosphere have periods of tens of minutes to several hours, so both the 2-min cadence L1b and 10-min cadence L1c data should have sufficient temporal resolution to capture these. At this 2-min cadence, the L1b residuals are
extremely noisy. To allow any longer-period signatures to be seen, we perform a 10-min rolling mean filter on these residuals at each latitude. This removes outlying high and low data points and puts these data on approximately the same temporal resolution as the L1c file. Figure 3 shows residuals for L1b and L1c for two channels, after this mean filter applied to L1b. In the residuals from both channels and both the L1b and L1c data, perturbations that appear to move northward with time are seen. Perhaps most clearly visible are a pair of higher count rates/brightnesses features between 12 and 14 hr UTC near −50° to −65° latitude. The locations of these were determined by eye, and their locations are given in Table 1.

Assuming that the two channels are seeing the same feature in the atmosphere, which seems reasonable given the apparent similarity for the pair of features described above, and furthermore assuming this to be an atmospheric wave with plane wave fronts, it is possible to estimate a number of wave parameters. The mean residual brightness at the peak locations in Channel A for the first wave is 3.4 R, for the second wave is 6.0 R, and for the third wave is 6.8 R. The mean residual brightness for the first trough is −5.9 R, for the second trough is −5.5 R, and for the third trough is −6.7 R. The mean observed brightness in this region is 1,180 R, so using the average of the peak and the trough values listed above, the wave amplitude is around 0.48% or 5.7 R. Performing a linear least squares fit to the locations of the peaks of the first two waves in both channels, we can determine the wave period by the time between the first two peaks arriving at −52° latitude (chosen as this pair of waves is easily seen in both channels at this latitude). The estimated wave period from Channel A is

Figure 2. Panel (a) shows an example spectrum from the L1c data from Channel A at −39° latitude, 12:49–12:58 UTC. The area highlighted in green represents the in band, and those in blue represent the out-of-band signals used in the analysis. Panel (b) shows the variation in the 135.6-nm signal as a function of time for the same pixel shown in panel (a). The plus symbols represent the L1c values at 10-min cadence, and the solid line shows the third-order polynomial least squares fit to these data.

Figure 3. Panels (a) and (b) show the residual counts as defined in the text in the L1b data for Channels A and B, respectively, as functions of time and latitude. A 10-min rolling mean filter has been applied at each latitude for the L1b data. Panels (c) and (d) are as (a) and (b) but highlight the apparent wave peak, and trough features are marked by black triangles and white cross symbols, respectively. The locations of these symbols are given in Table 1. Panels (e) and (f) are as (a) and (b) but show the brightness in Rayleighs from the L1c data.
The wave properties will be discussed further in sections 4 and 5.

Using the amplitude of the perturbation to the 135.6-nm airglow, we can also see that observing the waves described here without the use of the special campaign mode would be extremely challenging. Given the background brightness of 1,180 $R$, the 10-min averaged data have a signal-to-noise ratio of 90 per bin. Taking a wave period of 1.2 hr, a single wave period spans approximately eight bins at a single latitude, meaning the lowest detectable wave amplitude is around 0.39% if only a single latitude is considered. The waves here have an amplitude of around 0.48%, meaning they are only just detectable if data from a single latitude are used. Given this, it is worth discussing further why we can be confident that the signatures seen here are real and not simply noise. First, the signatures are seen in both channels, the operation and analysis for which are independent. While both channels are not looking at exactly the same location on the ground, they are close (see Figure 1). Both appear to see the same number of perturbations, at approximately the same spacing in time (the first two peaks are clearly recognizable in both channels, given their spacing) and at the same longitudes. Importantly, the two channels see the signals at slightly different times, which is consistent with an atmospheric perturbation and not with an instrumental or background noise effect. Second, the apparent propagation rate is consistent between the three-wave peak and three-wave trough features in Table 1. Performing a linear least squares fit to these, we see that these features move at an angular rate of 8.0 ± 1.4°/hr in the meridional direction. Finally, the wave and trough features are seen spanning a region of ~20° latitude (substantially more than the single latitude bin at which we are close to the limit of detectability) and 4 hr of UTC. These three factors, taken together, provide confidence that real wave features are seen.

### 4. Airglow Simulations

From the measured amplitude of the brightness perturbation, it is possible to estimate the amplitude of a GW that would be required to produce such a signature. Following the methodology of Greer et al. (2018), we use a background atmosphere from the thermosphere-ionosphere-electrodynamics GCM (TIEGCM v2.0; Maute, 2017) and the Global Airglow model (Solomon, 2017) to simulate the 135.6-nm O and (3,0) N$_2$ airglow GOLD would observe at ~50° latitude for the conditions present on 13 October 2018. This is then perturbed with a sinusoidal function that modifies the atmospheric density and temperature, as described in section 2 of Greer et al. (2018). By varying the amplitude of this perturbation, we can find the amplitude of a wave in the middle thermosphere that would produce a perturbation in the airglow of the same amplitude as observed by GOLD. Figure 4 shows the results of seven simulations at varying wave amplitude, at both 9 a.m. and 12 p.m. local time (corresponding approximately to 12 and 15 UT in the GOLD observations). At these relatively small amplitude perturbations in the atmosphere, the response in the airglow is very close to linear, and a linear least squares fit is used to identify the best fit wave amplitude that corresponds to the observed airglow signature. The 5.7 $R$ or 0.48% amplitude variation seen by GOLD near

| Channel | Feature       | Time, UTC hours | Latitude, degrees |
|---------|---------------|-----------------|-------------------|
| A       | First wave peak | 12.4            | −57.5             |
|         |                | 12.9            | −53.8             |
|         |                | 13.3            | −51.3             |
|         |                | 13.6            | −48.9             |
|         |                | 14.0            | −46.6             |
|         | Second wave peak | 13.0           | −62.1             |
|         |                | 13.4            | −58.5             |
|         |                | 13.8            | −56.8             |
|         |                | 14.1            | −54.3             |
|         |                | 14.4            | −52.8             |
|         |                | 14.8            | −50.7             |
|         | Third wave peak | 14.6            | −67.0             |
|         |                | 15.3            | −62.5             |
|         |                | 15.6            | −60.5             |
|         |                | 16.0            | −58.0             |
|         |                | 16.3            | −55.0             |
|         | First wave trough | 12.9          | −57.7             |
|         |                | 13.2            | −55.6             |
|         |                | 13.6            | −53.1             |
|         |                | 13.9            | −51.1             |
|         | Second wave trough | 12.4          | −54.0             |
|         |                | 12.9            | −50.5             |
|         |                | 13.2            | −47.5             |
|         |                | 13.6            | −45.5             |
|         | Third wave trough | 13.4           | −66.5             |
|         |                | 13.8            | −62.5             |
|         |                | 14.2            | −58.5             |
|         |                | 14.6            | −56.0             |
| B       | First wave peak | 12.5            | −65.5             |
|         |                | 12.7            | −62.5             |
|         |                | 13.1            | −59.5             |
|         |                | 13.7            | −53.5             |
|         |                | 13.9            | −51.0             |
|         | Second wave peak | 12.4           | −54.4             |
|         |                | 12.8            | −50.6             |
|         |                | 13.1            | −48.4             |
|         | Third wave peak | 14.1            | −68.5             |
|         |                | 14.5            | −65.5             |
|         |                | 14.8            | −61.5             |
|         |                | 15.0            | −59.0             |
these local times could be explained by a wave with an amplitude of 34 K, corresponding to 8.5% density fluctuation.

It is worth noting that the 135.6-nm O dayglow also includes a minor contribution from O⁺ radiative recombination. This is expected to be small at −50° latitude, but nonetheless, it is worth determining if an ionospheric perturbation, either instead of or in addition to an atmospheric perturbation, could explain the GOLD observations. Using an estimate of the ionospheric O⁺ density in the region of the observed wave from the TIEGCM simulations described above, and the radiative recombination airglow coefficients from Melèndez-Alvira et al. (1999), the total brightness of O⁺ radiative recombination near 12 UT is estimated to be 14 R. Using an estimate of the ionospheric O⁺ density in the region of the observed wave from IRI-2016 (Bilitza, 2018) instead, the total brightness of O⁺ radiative recombination near 12 UT is estimated to be 20 R. Using either the TIEGCM or IRI-2016 estimate of the ionospheric contribution to the 135.6-nm airglow, only an extremely large amplitude variation in O⁺ in the ionosphere could produce the 10.5 R peak-to-trough variation seen by GOLD. While it is likely that some portion of the observed signature is associated with ionospheric O⁺ perturbations, it seems likely that the majority of the observed signal is associated with variations in the neutral middle thermosphere.

**5. Discussion and Conclusions**

During the observing campaign on 13 October 2018, GOLD observed perturbations in the 135.6-nm dayglow in the Southern Hemisphere. As described in section 3, these features were identified from visual inspection from data with a low signal-to-noise ratio. Following our visual identification of the airglow brightness perturbations, these features were seen to move northward with time and were seen with both channels of the instrument, providing confidence that they represent the response to structures in the thermosphere. The structures appear to be atmospheric GWs or Traveling Atmospheric Disturbance (TADs), and if so, this would be the first time that the properties of such waves, including their propagation, have been identified in 135.6-nm airglow. It is worth restating that these features are identified, and their motion determined via visual inspection, which is open to some degree of subjectivity and other interpretations, may be valid. Nonetheless, several checks described in section 3 have provided confidence that these perturbations are associated with atmospheric waves. Using data from both channels and approximating the wave as plane wave, it is possible to identify the best fit horizontal wavelength of 1,800 km, period of 1.2 hr, phase speed of 400 m/s, and azimuth of propagation of 300°. These characteristics are broadly consistent with those reported for large-scale TADs seen in the upper thermosphere (e.g., Bruinsma et al., 2006) and the larger-scale TIDs seen in the ionosphere at middle thermosphere altitudes (e.g., Negrea et al., 2016). Utilizing a model of the airglow, it is possible to estimate the approximate amplitude of the atmospheric perturbation associated with this wave. The best fit to the observed airglow perturbation was found from a wave in the neutral atmosphere with a temperature amplitude of 33 K and a density amplitude of 8.5%, which is consistent with in situ observations of TADs in the middle-upper thermosphere (e.g., Earle et al., 2008).
The direction of propagation suggests a wave source that is south and east of the observed region, that is, to the east of the Antarctic Peninsula. The GOLD data do not uniquely identify the wave source, but there are perhaps three types of broad source locations one could consider—GWs of tropospheric origin (primary GWs), secondary GWs produced at some higher altitude where a primary wave dissipates, or waves of thermospheric origin. As described in Azeem et al. (2017) (following Vadas, 2013), the maximum phase speed for a wave of tropospheric origin is around 255 m/s, which appears to exclude this as the direct origin of the wave observed by GOLD, leaving the other two as possibilities in this case. Comparison to other observations, such as from ground-based instrumentation, would be one possible way to determine the wave source but is beyond the scope of this study. It is worth noting that other ground-based observations could provide some independent verification of the presence of a TAD or TID, but the portion of the GOLD observations that are over the land is northward of −25° latitude (see Figure 1), which is beyond where we see clear wave signatures during this campaign. Thus, while no ground-based data have been included in this study, the desire to have such supporting data will inform the design of future campaigns.

The results highlight the ability of GOLD to observe atmospheric waves. From its geostationary vantage point, GOLD is perhaps ideally suited to tracking such waves over large horizontal distances. The ability to detect a wave of relatively modest amplitude, not in response to a geomagnetic storm, suggests opportunities for similar observing campaigns to be planned in the future. GOLD’s field of regard includes several regions believed to be important sources of atmospheric GWs, including the Andes mountain range, the Antarctic Peninsula, and strong convective sources over the Amazon rainforest. The results described here are only for the first special mode campaign performed with GOLD. Additional campaigns that repeat this basic type of observations and utilize lessons learned from this are planned. The results from these follow-on campaigns are expected to further solidify and expand on the finds described here.

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