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Key Points:

- AIRS observations demonstrate the presence of gravity waves generated by the polar night jet
- Downward propagating gravity waves were observed at altitudes below the polar night jet
- The polar night jet plays an important role in the growth of mountain waves in the stratosphere

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Observations of Stratospheric Gravity Waves Over Europe on 12 January 2016: The Role of the Polar Night Jet

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Abstract Observations during 12 January 2016 revealed a series of events of significant gravity wave (GW) activity over Europe. Analysis of derived temperatures from the Atmospheric InfraRed Sounder (AIRS) provides insight into the sources of these GWs, and include a new observation of stratosphere polar night jet (PNJ) generated GWs. Mountain waves were present during this time as well over the French Alps and the Carpathian Mountains and had maximum temperature perturbations, T', as large as 27 K over the French Alps. Further investigation of the mountain waves that demonstrated their presence in the stratosphere was determined not only by stratospheric conditions but also by strong winds in the troposphere and at the surface. GWs generated in the stratosphere by the PNJ had maximum T' of 7 K. These observations demonstrate multiple sources of GWs during a dynamically active period and implicate the role of the PNJ in both the vertical propagation of GWs generated in the troposphere and the generation of GWs from the PNJ itself.

1. Introduction

Gravity waves (GWs) play an important role in coupling across regions of the atmosphere through the vertical transport of momentum. It is well known that the deposition of momentum from breaking GWs in the mesosphere and lower thermosphere drives a residual circulation between the summer and winter hemispheres and thereby induces the cold summer mesopause and the warm winter stratopause, as well as a reversal of the summer mesospheric jet (Fritts & Alexander, 2003; Garcia & Solomon, 1985; Holton, 1982, 1983). While the influences of GWs on global circulation are well known from modeling efforts, there are still uncertainties in the parameterization of GWs in global-scale models regarding GW sources within the atmosphere and subsequent deposition of GW momentum into the middle atmosphere (Alexander et al., 2010). For example, the structure of the winter hemispheric mesospheric jet likely has dependence on secondary GWs generated in the stratopause region (Becker & Vadas, 2018), but secondary GWs are not included in conventional GW parameterizations.

Satellite measurements have led to global scale studies of stratospheric GWs, improving knowledge about GW sources and associated hotspot regions. Stratospheric GW measurements include global observations from the Atmospheric InfraRed Sounder (AIRS) (Eckermann et al., 2019; Gong et al., 2012; Hoffmann et al., 2013; Schmidt et al., 2016), the Cloud Imaging and Particle Size (CIPS) instrument (Randall et al., 2017), the High Resolution Dynamics Limb Sounder (HIRDLS) (Ern et al., 2018), the GPS Meteorology experiment (Tsuda et al., 2000), Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) (Liu et al., 2019), and the Microwave Limb Sounder (MLS) (Jiang et al., 2003; Wu & Eckermann, 2008). AIRS has provided the opportunity to study GWs through radiance perturbations (Alexander & Barnett, 2007). AIRS also allows for temperature retrievals both spatially and vertically through a high-resolution retrieval scheme detailed in Hoffmann and Alexander (2009). This temperature retrieval has previously been validated and used for the study of GWs (Ern et al., 2017; Meyer & Hoffmann, 2014; Wright et al., 2017). The AIRS high-resolution retrievals are limited to GWs with long vertical wavelengths with $\lambda_z > ~ 15$ km. Retrieved temperatures have a vertical resolution which changes with height, varying from a 7 km resolution near 20 km in altitude to a 12–14 km resolution near 55 km in altitude. AIRS observations have led

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to global studies of stratospheric GW hotspot regions associated with tropospheric GW sources including convectively and orographically generated GWs (Gong et al., 2012; Hoffmann et al., 2014, 2016; Jiang et al., 2005, 2012).

Favorable conditions within the stratosphere can allow for GW propagation to higher altitudes. The polar night jet (PNJ) plays an important role in filtering stratospheric GWs in winter time. Many observational and modeling studies have shown that under conditions of significant stratospheric winds such as those winds associated with a strong PNJ, mountain waves (MWs) can propagate into the stratosphere and meso-sphere (Bossert et al., 2015, 2017; Dörnbrack et al., 2002; Eckermann et al., 2016; Fritts et al., 2016; Krisch et al., 2017; Kruse et al., 2016; Vadas & Becker, 2019; Wagner et al., 2017). Strong stratospheric winds associated with the PNJ allow for growth to large vertical wavelengths and amplitudes (Alexander & Teitelbaum, 2007; Bramberger et al., 2017; Dörnbrack et al., 1999; Ehard et al., 2017; Gisinger et al., 2017; Heale et al., 2017; Wright et al., 2017). In addition, GWs having intrinsic horizontal phase propagation against the background wind are focused into the wind maximum due to horizontal refraction (Ehard et al., 2017; Jiang et al., 2019; Preusse et al., 2009; Senf & Achatz, 2011). Other observations have demonstrated a positive correlation between GW activity and wind speed in the stratosphere (Chu et al., 2018; Llamedo et al., 2019).

In addition to controlling the propagation and dissipation of GWs, both the PNJ and tropospheric jets can be a source of GWs due to spontaneous emission (Plougonven & Snyder, 2007; Plougonven & Zhang, 2014; Sato & Yoshiki, 2008; Uccellini & Koch, 1987). Observations have linked measured GWs to the tropospheric jets as a source region (Buss et al., 2004; Sato & Yoshiki, 2008; Wu & Zhang, 2004). Furthermore, modeling studies show GW generation from the tropospheric jets (O'Sullivan & Dunkerton, 1995; Sato, 2000; Sato et al., 1999; Wang et al., 2008; Zhang, 2004). Additionally, GWs can be generated from disruptions of the PNJ due to sudden stratospheric warmings (Dörnbrack et al., 2018; Yamashita et al., 2010, 2013).

This paper examines an active GW day over Europe on 12 January 2016. Data used include derived temperature perturbations from AIRS and the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) (Molod et al., 2015). During this case study, the PNJ and the tropospheric jet overlapped the region of observation, resulting in a strong west to east flow over the Alps. The sources of GWs are investigated and include MWs and stratospheric GWs generated by the PNJ. This study explores the concurrent nature of these different GW sources.

2. Airs Observations of GW Activity Over Europe on 12 January 2016

On 12 January 2016, the AIRS instrument observed significant temperature perturbations associated with GWs over central Europe. The temperature perturbations, obtained from the AIRS high-resolution temperature retrieval of Hoffmann and Alexander (2009), were visible over a range of altitudes from ~20–60 km, and over a range of times between 0.3 and 13.1 UT. Background average temperatures were subtracted across each latitude and altitude to obtain T'. Examples of GW-derived T' observed in AIRS for the two events in the earlier part of the day are shown in Figure 1. AIRS 4.3 µm daily average brightness temperature variances following Hoffmann et al. (2013) are plotted over the strength of the polar night jet at 30 km for this day and shown in Figure 2. The gray lines denote the polar vortex edge determined using the method described in Harvey et al. (2002). The locations of three separate events are labeled on this plot. Events 1 and 2 are discussed in this paper. Event 3 is not included in this discussion as the GWs may come from a different source than those GWs observed in Events 1 and 2 at earlier times in the day. However, Event 3 is labeled here as it contributes a significant variance in AIRS brightness temperatures over the daily average.

2.1. Event 1: Mountain Wave Generation Over the Alps

Near 2 UT on 12 January 2016, strong GWs were observed in AIRS with *T'* maximum amplitudes reaching ~27 K near 50 km in altitude. Plots of spatial *T'* at 42 km in altitude and vertical *T'* profiles along a longitude-altitude section are shown in Figures 3a and 3b. These GWs had horizontal wavelengths of ~230 km and are visible up to 60 km at this time. Later observations at 13.1 UT (Figures 3c and 3d) show that the measured *T'* associated with these GWs has significantly decreased, with T' < 5 K. Figure 3c shows that they are visible at 36 km with much weaker amplitudes, but are not visible above this region.





Figure 1. Two separate GW events observed in AIRS on 12 January 2016. Derived *T*' are plotted at 36 km. Granule swaths were taken at (a) 1.9 and 2 UT, (b) 11.5 and 11.6 UT. White lines in each plot denote the boundary of the granule from AIRS.

The large amplitude GWs shown in Figures 3a and 3b arise over the Alps during a time of overlap with the tropospheric jet. MERRA-2 wind vectors at 11 km plotted over the topography (Amante & Eakins, 2009) at 0UT on 12 January are shown in Figure 4a, and the wind magnitudes are plotted in Figure 4b. The wind vectors show the tropospheric jets are overlapped with the Alps, with wind vectors nearly perpendicular



Figure 2. The strength of the PNJ at 30 km plotted over the AIRS 4.3 μ m brightness temperature variance. Isotachs represent magnitude wind speeds in m s⁻¹, and the cluster of gray lines denote the edge of the polar vortex derived from MERRA-2 at 12 UT. Three regions of significant GW variance are numbered 1–3. Events from Regions 1 and 2 are shown in Figure 1.



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Figure 3. AIRS T' derived for (a) 42 km in altitude at 2 UT, (b) a vertical section along 47.5 N at 2 UT, (c) at 36 km altitude at 13.1 UT where there is still some evidence of a MW, and (d) a vertical section along 47.5°N similar to (b) and plotted on the same scale, demonstrating the difference in *T*' amplitudes between the two times.



Figure 4. Plot (a) shows MERRA-2 wind vectors in red at 11 km and 0 UT plotted over a topographic map of Europe, and plot (b) shows MERRA-2 wind magnitudes at 11 km. The wind vectors show the tropospheric jets are overlapped with the Alps during this time.





Figure 5. MERRA-2 zonal and meridional winds averaged from $5-10^{\circ}$ E, $45-50^{\circ}$ N at 0 UT and 12 UT near the observation times and regions of the strong MWs and weak MWs, respectively.

to the western Alpine ridge near 8°E, 47.5°N. The orientation of the large amplitude GWs observed by AIRS in Figure 3b indicates a westward propagation direction assuming upward propagating MWs, which is against the eastward winds shown in Figure 4a. The propagation against the direction of the wind in the upper troposphere in combination with the orientation of the GW over the Alpine ridge indicates that the observed wave is a mountain wave (MW). Additionally, the winds shown in Figure 5 indicate for a MW (c = 0 m/s), the vertical wavelength near z = 40 km would be ~20 km, which is in line with AIRS observations given in Figure 3b. This MW event and subsequent propagation into the mesosphere and lower thermosphere was the subject of a modeling study by Heale et al. (2020), which predicted MW breaking occurring from 60–80 km.

A significant change in MW *T'* amplitudes was observed between 2 UT and 13.1 UT, which may be due to changes in the background winds or forcing conditions. MERRA-2 zonal winds at 0 UT and 12 UT over 5–10°E and 45–50°N are plotted in Figure 5. While MERRA-2 shows wind profiles which are similar in the stratosphere between the two times, another possibility contributing to the difference in observed MWs is a change in the wind forcing of MWs near the surface. Figure 6 gives a comparison of MERRA-2 winds between 11 and 12 January near the surface on the western side of the French Alps at 6.25°E and 45°N. The highest peaks in the Alps are above 4 km, with the ridge being above 3 km. The location chosen in Figure 6 shows winds for altitudes above 2 km, which is about halfway in altitude of the highest peaks on the French Alps. Figure 6 demonstrates a strengthening in the zonal winds in the lower troposphere starting near 12 UT on 11 January, maximizing near 21 UT, and followed by winds decreasing to less than half of the previous magnitude by 6 UT on 12 January. During this time duration on 11 January, meridional winds are close to zero near the surface, thus the forcing is largely dominated by zonal winds. In order to determine the duration it took for MWs to propagate to ~50 km in altitude of a MW, the midfrequency approximation for

GWs was used (e.g., Fritts & Alexander, 2003) to determine the vertical group velocity, $c_{gz} \approx \frac{k_H}{N} U^2$, where k_H

is the horizontal wave number, N is the buoyancy frequency, and U is the zonal wind, and the MW is assumed to be propagating approximately zonally. The vertical group velocity was calculated using MERRA-2 winds and temperatures, then integrated over each altitude bin to obtain an approximate time

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Figure 6. Altitude-time section of MERRA-2 (left) zonal winds and (right) meridional winds plotted every 3 hr from 00 UT 11 through 12 January from the surface to 4.7 km.

of propagation from the surface to ~50 km at launch times of 15UT and 21UT on 11 January, and 0UT on 12 January. The propagation times were found to be 4.5, 5.7, and 5.3 hr, respectively, indicating that the observed MW at 2UT on 12 January was most likely forced near the time of the surface wind maximum on 11 January. Given that the observed MWs ranging from the entire AIRS vertical observation altitudes of z = 20-60 km, MWs were likely forced over several hours during this time period of maximized surface winds on 11 January. The weakening surface winds on 12 January are likely the reason for the lack of MWs observed at 13.1UT.

2.1.1. Trailing Mountain Waves and Gravity Waves Toward the East

Shortly before the observation of the MWs at 2UT, AIRS observed GWs further toward the east at 0.3UT. The GW *T'* measurements from AIRS are shown with the MW measurements at altitudes of 30 and 48 km with wind vectors from MERRA-2 in Figure 7. For trailing GWs to be present, one would expect these waves to be downwind of the wind vector (Jiang et al., 2019), and this is indeed the case for these observations.

Vertical profiles of the AIRS measurements plotted with MERRA-2 winds and temperatures over the same region are given in Figure 8. While MERRA-2 does not have the resolution to detect all GWs present and may also be presenting data from assimilated instruments, it is noted here that GWs with a similar characteristic to the observed MWs at 2UT are present in the MERRA-2 reanalysis data at much lower amplitudes



Figure 7. AIRS-derived T' swaths at 2UT and 0.3UT with wind vectors at 30 km (left) and 48 km (right).











Figure 9. Swaths of AIRS-derived T' over eastern Europe at altitudes ranging from (a–f) 30–51 km at ~11.5–11.6UT on 12 January 2016. Red lines marked 'a', 'b', and 'c' in panel (b) indicate the location of the longitude-altitude and latitude attitude transects shown in Figure 10.

(Figure 8a). These waves appear to be present from 6–30°E with decreasing λ_z going further toward the east. This would be unsurprising for trailing MWs given the decreasing zonal winds in the stratosphere changing from 100 m s⁻¹ near 5°E at z = 45 km to 50 m s⁻¹ near 25°E shown in Figure 8b. This decrease in λ_z along with likely dissipation of trailing waves as they travel further from the source would contribute to a smaller T' observed by AIRS due to the vertical averaging associated with AIRS temperature retrievals. Evidence of shorter λ_z waves (~12 km) is observed between 15° and 20° longitude in the AIRS measurements (Figure 8d). These GWs are potentially trailing MWs. However, also apparent in these AIRS measurements are GW perturbations between 25 and 30°E which are superimposed on top of the presumed trailing waves. Plotted topography just to the south in Figure 8e demonstrates two distinct regions of mountains which would both independently generate MWs. The waves further to the east overlap the Carpathian Mountains. Given the distinct location of these waves over mountains, and the lack of significant T' observed in between these two mountainous regions, it is unlikely that these waves between 25 and 30°E are trailing waves. Instead these are likely MWs generated directly from topography nearby.

2.2. Event 2: Stratospheric Vortex Generated Waves

About 9 hr after AIRS observed the large amplitude MW, the instrument sampled nonorographic PNJ-generated GWs extending from ~17–27°E and 50–57°N. At 11.6UT, AIRS *T*' indicated the presence of GWs with horizontal wavelengths of ~300 km. Figures 9a–9f show swaths of AIRS derived *T*' at six different altitudes. No discernable *T*' are visible near 42 km in Figure 9d. However, *T*' associated with the observed GW are visible above and below this altitude with similar spatial orientation and horizontal wavelengths. Figure 9b shows traces of spatial paths used for vertical slices, which are shown in Figure 10. Figures 10a and 10b show west-to-east transects following the 52°N and 54°N latitude circles. Figure 10c shows a south-to-north transect along the 23°E meridian. All three perspectives demonstrate waves that



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Figure 10. Panels (a) and (b) show longitude-altitude sections of AIRS T' at 52°N and 54°N, respectively. Panel (c) shows a latitude-altitude section along the 23°E longitude. The white dotted lines in panel (c) denote a region of large dU/dy and dV/dy shown in Figures 11b and 11c.

disappear near 42 km, with a changing orientation and propagation direction above and below 42 km. This indicates that the generation region of the observed GW may be near 42 km. Figure 10c shows that the strongest T' appear between 50 and 55°N in latitude, with maximum $T' \sim 5-7$ K. Figure 11a shows MERRA-2 vertical profiles of meridional and zonal winds at a latitude equatorward of the PNJ (48°N) and at a latitude within the PNJ core (54°N) averaged longitudinally from 8–33°E over the region of GWs observed in AIRS. Figures 11b and 11c show latitude-altitude sections of zonal and meridional winds. The strongest observed T' between 50 and 55°N also coincide with a region of strong meridional shear in the horizontal winds (both dV/dy and dU/dy). It is noted that there are multiple regions of shear, and consequently, several regions where wave generation may be possible. AIRS is most sensitive to larger vertical wavelengths, thus will observe those GWs with a larger vertical wavelength. A plot of MERRA-2 wind magnitudes and vectors at 42 km and 12UT is shown in Figure 12. This wind view demonstrates the larger-scale dynamics at play causing disruptions to the PNJ through planetary wave disturbances in the region of the AIRS-observed GWs.

The MERRA-2 wind vector at 42 km and 12UT plotted over AIRS T' at 36 km and 11.5–11.6UT is shown in Figure 13. The GWs generated near the peak of the PNJ have phase fronts aligned parallel with the wind vector in this region. This is consistent with the results of Sato and Yoshiki (2008) for GWs being generated by the PNJ due to spontaneous emission. The phase fronts of the GWs are also aligned southwest to northeast, which implies that they are propagating either southeastward or northwestward. Either wave could be generated from a southeastward or northwestward body force. This generation mechanism resulting from a body force has previously been discussed in Vadas et al. (2003, 2018). In the context of Event 2, the body force assumed in that theory would correspond to a self-induced perturbation of quasi-geostrophic imbalance of the polar vortex, leading to the vortex-generated GWs. The amplitude of these observed GWs is about one fifth of those MWs propagating to the stratosphere shown in Event 1 despite similar λ_{τ} between



Figure 11. Panel (a) shows zonal (solid lines) and meridional (dashed lines) wind profiles from MERRA-2 at 48°N (red) and 54°N (black) averaged longitudinally over 8–33°E. Panels (b) and (c) show latitude-altitude sections of zonal and meridional winds along the same path as Figure 10c. White dotted lines indicate the same region as those shown in Figure 10c.





Figure 12. MERRA-2 wind magnitude and wind vectors at z = 42 km and 12UT.

30 and 40 km, and hence similar AIRS vertical averaging. Such an amplitude difference is expected for localized stratospheric generation of GWs versus those GWs which have grown over several scale heights, in analogy to the amplitude difference of secondary versus primary GWs (Vadas et al., 2003, 2018).

Finally, those GWs which are generated locally by the PNJ due to acceleration/deceleration from nonlinear dynamics of the PNJ would be expected to have upward and downward propagating components (Sato et al., 1999). While downward versus upward propagation cannot be unequivocally determined from the AIRS data, it is proposed here that the observed GWs may be generated near the 42 km level and may



Figure 13. MERRA-2 wind vectors at 42 km on 12 January 2016 at 12UT plotted over AIRS T' at 36 km at 11.5–11.6UT.



propagate upward above and downward below this level, similar to in situ generation from the PNJ discussed in Sato et al. (1999). This would result in upward and downward propagating GWs generated with the same propagation direction and horizontal wavelengths. The orientation of the GW phase lines in Figure 10 indicates that if the GWs are downward propagating below 42 km, then they are propagating toward the southeast, and above 42 km if the GWs are propagating upward then they are also propagating toward the southeast. GWs generated from a body force near 42 km have equal amplitudes for the same intrinsic horizontal phase speeds (in the frame of reference of the background winds) (Vadas et al., 2018). From Figure 11, the wind is northeastward at 42 km. Above this altitude, the wind is strongly eastward (increasing eastward as *z* increases), and below, the wind is more strongly northward (increasing northward as *z* decreases). Therefore, upward and downward southward propagating GWs would be propagating into very different wind environments.

3. Discussion and Conclusions

AIRS measurements on 12 January 2016 showed significant T' associated with GWs over Europe. The sources of these observed GWs contributing to the T' were investigated over the region of western Europe and Scandinavia. Different sources of GWs were found to contribute to T' variances during this period. The strongest of these stratospheric GWs were MWs arising due to flow over the Alps. MWs are especially sensitive to stratospheric winds associated with the PNJ in addition to tropospheric wind forcing over the mountainous region. In the case of MWs observed on this day, peak amplitudes near 50 km in altitude reached ~25–30 K when the PNJ winds were strong and persistent 30–60 km. Weaker MWs were also observed ~1,000 km to the east over the Carpathian Mountains. These MWs encountered weaker winds in the stratosphere and had lower amplitudes. It is also likely that trailing waves are present between this region. However, the largest amplitude GWs detected in AIRS originate from sources near or below the observation. MWs were not clearly observed at later times near 13UT, and we show that this is due to a change in surface forcing conditions over the mountains.

Another source of GWs observed by AIRS on this day is the PNJ itself. GWs generated in the stratosphere have lower amplitudes, ~1/5 the amplitude of those MWs generated in the troposphere, which grow in amplitude as they propagate up to stratosphere. Additionally, AIRS vertical temperature measurements provide a unique look at the GW phase changes that occur as a function of altitude for GWs generated near the peak of the PNJ. GWs generated near the PNJ appear to have upward and downward propagation directions similar to secondary GWs generated in this region (e.g., as shown in observations presented by Vadas et al., 2018). In the case observed by AIRS, vertical wavelengths were long enough to be within the threshold of detection of AIRS. However, it should be noted that smaller vertical wavelengths that would not be observed by AIRS may also be generated by the PNJ (Yoshiki & Sato, 2000). It is also emphasized here that there are several regions of increased shear at multiple altitudes within the PNJ during this time period. These also have the potential to generate GWs at different scales and over different regions. Such jet-generated GWs may be present as well, and may cause constructive and destructive interference among existing waves. Unfortunately, AIRS does not have the vertical resolution to detect all of these smaller vertical scales that may also be present.

In the case study shown here, the PNJ plays a significant role in the propagation and generation of the GWs observed by AIRS. Orographic GWs generated in the troposphere with a favorable propagation orientation experience amplitude growth in the region of the PNJ due to the absence of instability and breaking in regions of increasing winds. The PNJ also has the potential to generate GWs similar to tropospheric jet-generated GWs. AIRS observed significant GW activity on this day over the region of overlap between the Alps, the tropospheric jet, and the PNJ. These observations demonstrate that there can be multiple sources of GWs active in the same region, all of which play a role in momentum transport in the stratosphere and at altitudes above this region.

Data Availability Statement

AIRS data are publicly available at https://airs.jpl.nasa.gov/data/get_data. The AIRS gravity wave data sets used in this study can be obtained from this site (https://datapub.fz-juelich.de/slcs/airs/gravity_waves/ index.html). MERRA-2 data are available at MDISC, managed by the NASA Goddard Earth Sciences



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