Spatial structures and statistics of atmospheric gravity waves derived using a heuristic vertical cross-section extraction from COSMIC GPS radio occultation data

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A number of studies have investigated atmospheric gravity waves (GWs) using temperature profiles from GPS radio occultation (RO). This study is the first to report the horizontal structures of GWs obtained directly by using multiple profiles based on the GPS RO data from the Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC)/FORMOSAT-3 mission. It was found that the horizontal locations of profiles obtained from successive passages of multiple COSMIC satellites were frequently aligned quasi-linearly over distances of around 1500–5000 km. Therefore, almost instantaneous (within 1 h) snapshots of vertical-horizontal cross sections of atmospheric temperature could be obtained. Clear GW features over multiple occultations were identified in many of the cross sections. It was indicated from a statistical analysis that horizontal wavelengths of GWs in the winter (here northern) hemisphere were generally smaller than those in the equatorial region or in the other hemisphere. A positive skewness was found in the probability distribution of the GW amplitude in middle to high latitudes, while the distribution was not skewed in low latitudes. GWs in the northern midlatitudes were studied further. In the zonal direction, both eastward and westward propagations relative to background winds were identified. The GW amplitude had a negative correlation with zonal wind shear. In the meridional direction, northward propagation was dominant, indicating that the dominant source region of meridionally propagating GWs was in the subtropics.

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1. Introduction

Atmospheric gravity waves (GWs) have been studied observationally using a variety of instruments such as radiosondes, radars, and satellites (see Fritts and Alexander [2003] for review). Satellite observations provide better areal coverage than ground-based observations, and the global distribution of GWs and its climatology have been studied extensively by using various instruments on Earth-observing satellites [Wu and Waters, 1996; Preusse et al., 2000]. Also, during the last 10 years, radio occultation (RO) measurements of the Global Positioning System (GPS) signals from Low-Earth-Orbit (LEO) satellites have been used extensively to study GWs [e.g., Tsuda et al., 2000; Ratnam et al., 2004].

Each method for the observation of GWs has its own limitation with respect to vertical resolution and/or averaging along the line of sight (in the case of satellite observation), which is called the “observational filter” [Alexander, 1998]. Satellite observations have coarser vertical resolutions than ground-based instruments in general, but the vertical resolution of GPS RO data can be finer than 1 km [Tsuda et al., 2000; Jensen et al., 2003]. There are still advantages of ground-based instruments. For example, radiosondes and radars can measure horizontal winds, which cannot be obtained by most satellites used to study GWs including GPS RO. A strong advantage of measuring winds is that parameters related to the dispersion relation can be estimated using the hodograph analysis [e.g., Hirota and Niki, 1985] solely based on individual vertical profiles, provided the observed waves have relatively long period and are in the extratropics. Also, wind-profiling radars can be used to observe GWs continuously with high temporal resolution, so one can retrieve the dispersion parameters of GWs without hodographs. On the other hand, some studies have investigated horizontal, as well as vertical, structures of GWs by using satellite instruments such as Cryogenic Infrared Spectrometers and Telescopes for the Atmosphere (CRISTA), a free flier from the Space-Shuttle [Preusse et al., 2002, 2006], the Atmospheric Infrared Sounder (AIRS) onboard the Aqua satellite [Alexander and Teitelbaum, 2007], or a combination of various instruments [Wu et al., 2006].
The first GPS RO measurements were made with the GPS/MET satellite launched in 1995 [Ware et al., 1996]. Since then, a number of LEO satellites have been launched to make GPS RO measurements. So far, however, studies of GWs have been conducted on the basis of individual profiles, from which some parameters can be derived [Liou et al., 2003, 2006] However, the direct derivation of spatial structures of atmospheric waves from multiple RO measurements has been limited to large-scale waves such as the equatorial Kelvin waves [e.g., Tsai et al., 2004; Randel and Wu, 2005] and mixed Rossby-gravity waves [Alexander et al., 2008b].

Table 1. Months at Which the Altitudes of COSMIC LEO Satellites Were Raised From Approximately 500 km to 800 km and the Number of Satellites Sharing the Orbit at 500 km After the Raise

<table>
<thead>
<tr>
<th>Month</th>
<th>Satellite Identification</th>
<th>Satellites Sharing the Orbit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jul 2006</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Sep 2006</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Jan 2007</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>Apr 2007</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Jul 2007</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Oct 2007</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

[4] The first GPS RO measurements were made with the GPS/MET satellite launched in 1995 [Ware et al., 1996]. Since then, a number of LEO satellites have been launched to make GPS RO measurements. So far, however, studies of GWs have been conducted on the basis of individual profiles, from which some parameters can be derived [Liou et al., 2003, 2006] However, the direct derivation of spatial structures of atmospheric waves from multiple RO measurements has been limited to large-scale waves such as the equatorial Kelvin waves [e.g., Tsai et al., 2004; Randel and Wu, 2005] and mixed Rossby-gravity waves [Alexander et al., 2008b].

[5] In April 2006, the six LEO satellites of the Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC)/Formosa Satellite 3 (FORMOSAT-3) mission were launched (hereinafter we use the abbreviation COSMIC, instead of COSMIC/FORMOSAT-3, for brevity). The six satellites have been providing more than 2000 measurements per day [Liou et al., 2007; Anthes et al., 2008], which is nearly an order of magnitude greater than the number of GPS RO measurements per day before they were launched. Therefore, with the COSMIC data one can study space-time structures of atmospheric disturbances with resolutions much higher than those available earlier.

[6] Even with COSMIC, the data density on the average is still too poor to resolve GWs, since 2000 profiles per day would correspond to one profile per day in an area of $2.5 \times 10^5$ km$^2$ (i.e., 500 km $\times$ 500 km). However, since the occultation occurs near the satellites’ orbits, the spatial distribution of data points is not uniform over a short period of time less than a few hours (see section 2). Moreover, we found that the data points obtained from successive passage of the LEO satellites were frequently organized roughly in linear alignments. Therefore, one can obtain “snapshot” vertical cross sections of refractivity or temperature.

[7] By using this feature, we report in this paper for the first time the spatial structures of the atmospheric gravity waves derived directly from GPS RO measurements. In addition, we present case studies and global statistics related to their horizontal wavelengths. Finally, we present the results of our study on the propagation directions and the spatial distribution of wave energy in the northern winter, which extends the study by Alexander et al. [2008a].

[8] Alexander et al. [2008a] conducted a detailed analysis of the potential energy of GWs in December 2006 by using the same COSMIC data as used in this study. They found an enhancement of zonally averaged potential energy at the equatorward flank of the sub-tropical jet extending to the equatorward flank of the stratospheric polar night jet in the Northern Hemisphere. They also found significant longitudinal variability in the energy in northern mid-latitudes, where it was decreased significantly when zonal wind speed approached zero with altitude, indicating that the variation is associated with the critical level filtering. Since they analyzed temperature profiles independently, however, the horizontal structures of the GWs were not studied. Therefore, it would be of interest to study the wave parameters directly from the COSMIC observations in order to elucidate the large variance they found. This was undertaken herein.

[9] The rest of this paper is organized as follows. In section 2, we describe the features of the space-time distribution of the GPS RO measurements by COSMIC. In section 3, we describe our novel algorithm for obtaining “snapshot” vertical cross sections and show their global distribution, which was found to be time-dependent. Results from the analysis on GWs are presented in section 4. Conclusions are drawn in section 5.

2. Data and Satellite Orbits

[10] The data used in this paper were the COSMIC level 2 data produced at the University Corporation for Atmospheric Research (UCAR). In their retrieval, the full spectrum inversion method [Jensen et al., 2003] was used for the lower part of the profiles, and the conventional geometric optical method was used for the upper part of the profiles, whose boundary is not fixed in height, although it is likely in the upper troposphere. The vertical resolution in the lower stratosphere is roughly 1.5 km, and it is finer than 1 km in the troposphere. (It is approximately 0.5 km in the lower troposphere even with the optical method [Kursinski et al., 1997], while it is much finer with the full spectrum method.)

[11] In the following analysis, we used the level 2 “dry temperature,” which is derived from the refractivity by assuming hydrostatic equilibrium and neglecting the existence of water vapor. The dry temperature can be regarded as the actual temperature above an altitude of 10 km. Below the midtroposphere, its deviation from the actual temperature is generally quite large. The level 2 data were interpolated to have an equal vertical spacing of 100 m over the altitude range from 1 km to 38 km. In many cases, the lowest vertical altitude where actual data were obtained was a few km. While data exists above 38 km, it was not used, since retrieval in and above the upper stratosphere depends largely on the atmospheric model used, which gets severer with altitude.

[12] As reference data, we used National Centers for Environmental Prediction (NCEP) Reanalysis 2 data on the standard pressure levels up to 10 hPa. Their horizontal resolution is 2.5°. We used 6-hourly data for temperature and geopotential height, and daily averaged data are used for horizontal winds.

[13] The six COSMIC LEO satellites were launched together by a rocket in April 2006, so they were initially put in a single orbit. The inclination is 72°, and the initial altitude was around 500 km [Liou et al., 2007]. The altitude was elevated to about 800 km on a satellite-by-satellite basis with a time interval of approximately 3 months, as summarized in Table 1 (see Liou et al. [2007] for more details of the maneuvering of satellite altitudes). Raising the altitude of a
satellite changes the rotation speed of its orbital plane in the inertia coordinate system, which is relative to the stars. Thus, the altitude change causes its orbit to shift gradually away from the others. In this way, the six satellites were dispersed so as to eventually form a uniform constellation at about 20 months after their launch. Figure 1 shows the orbits of the 6 satellites in early December of 2006, which was 8 months after the launch. The orbits of satellites 1, 3, 4, and 6 are very close to each other.

[14] Since multiple satellites were sharing a single orbit, GPS RO events were not distributed uniformly in space and time, and the data acquisition rate was quite high in the vicinity of the orbit for about 1 year after the launch. We exploited this feature to elucidate atmospheric disturbances at high resolution by means of the data processing method introduced in section 3.

3. Extraction of Vertical Cross Sections

[15] We consider a swath around the orbit shared by multiple LEO satellites, and we neglect the data from the other LEO satellites. Thus, this analysis is useful only for data within a year after the launch. Possible application to other cases is proposed in section 3.3.

3.1. Coordinate Transformation

[16] We assume a coordinate system suitable to represent the satellite swath. As illustrated in Figure 2, we take a coordinate \( p \) along the satellite track and a coordinate \( q \) across it, which are analytically defined as follows:

\[
\begin{align*}
\sin q &= \sin \phi \cos \theta - \sin \lambda' \cos \phi \sin \theta, \quad (1) \\
\cos p &= \cos \lambda' \cos \phi \cos^{-1} q, \quad (2) \\
\sin p &= (\sin \lambda' \cos \phi + \sin \phi \sin \theta) \cos^{-1} q, \quad (3)
\end{align*}
\]

Here \( \phi \) is latitude, \( \theta \) (a positive constant) is the orbit inclination ((72/180) \( \pi \) for COSMIC), and \( \lambda' \) is the longitude relative to the orbital plane defined below. Equations (1)–(3) are obtained by considering the “longitude” \( p \) and “latitude” \( q \) in a spherical coordinate system whose “equator” intersects the Earth’s equator at the angle of \( \theta \) (a derivation can be made using the following equations: \( x \equiv \cos \lambda' \cos \phi, y \equiv \sin \lambda' \cos \phi, z \equiv \sin \phi, X \equiv \cos \phi \cos q, Y \equiv \sin p \cos q, Z \equiv \sin q, X = x, Y = y \cos \theta + z \sin \theta, \) and \( Z = -y \sin \theta + z \cos \theta. \)"

[17] The longitude relative to the orbital plane \( \lambda' \) is defined as

\[
\lambda' \equiv \lambda - \lambda_0 - \alpha \tau, \quad (4)
\]

\[
\tau \equiv \omega^{-1} p, \quad (5)
\]

where \( \lambda \) is longitude, \( \lambda_0 \) is a constant to be determined by an iterative method (see below), \( \alpha \) is the angular speed of the rotation of the orbital plane, which is relative to the rotating Earth, and \( \omega \) is the angular speed of the satellite movement around the Earth.

[18] While the domain of \( q \) is taken to be \([-\pi/2, \pi/2]\), the ambiguity of \( p \) with a multiple of \( 2\pi \) is determined so that \( p \) increases monotonically with time as the receiving LEO satellites circle the Earth. Therefore, \( \tau \) is approximately equivalent to the time. Since \( \theta \) is positive, the origin of \( p \) (where \( p = 0 \)) is always set to a point at which one of the satellites, i.e., the reference satellite, crosses the equator from south to north.

[19] When only one LEO satellite is considered, \( \lambda_0 \) can be set to the longitude at which the satellite passes the equator.

[20] Figure 2. Relationship between the two coordinate systems \( \lambda' - \phi \) and \( p-q \), which share the origin \( O \). Here \( \lambda' \) is the longitude relative to the orbital plane (equation (4)). The thick solid line represents the equator. The thick dashed line represents a line at which \( q = 0 \), which represents a mean orbit of the LEO satellites. Thin dash-dotted lines are contours with respect to \( \phi \), and thin dotted lines are contours with respect to \( q \).
northward at around a reference time. When multiple LEO satellites are considered, as in this study, however, the longitudes are not unique. In this case, we can set \( l_0 \) so that the line at which \( q = 0 \) in the \( p-q \) coordinate system represents some kind of mean of the satellite orbits. The actual algorithm we used is to make the ensemble average of \( q \cos p \) approach zero by using an iteration. Here the initial values of \( l_0 \) were changed until the iteration converged. This procedure is referred to as the iteration 1 in what follows.

\[ \text{[21]} \]

Iteration 1 can be explained as follows. The COSMIC LEO satellites have GPS antennas on both sides with respect to the direction of satellite movement. Therefore, rather than explicitly considering the orbits of the multiple satellites, we chose to set \( l_0 \) so that the data points distribute evenly with respect to \( q = 0 \). The iteration was performed to make the ensemble average of \( q \cos p \) approach zero, since, for a given increment of \( \lambda_0 \), the sign of the increment of \( q \) depends on whether \( \pi/2 < p - 2n\pi < \pi/2 \) (i.e., the observation is made when the satellite is heading north) or \( \pi/2 < p - 2n\pi < 3\pi/2 \), where \( n \) is an arbitrary integer.

\[ \text{[22]} \]

Since \( \lambda_0 \) depends on \( p \) as in equations (4)–(5), the lhs and rhs of equations (1)–(3) are recurrent with respect to \( p \). Therefore, it is not straightforward to derive \( p \) and \( q \) from \( \lambda_0 \) and \( \phi \) even if \( \lambda_0 \) is fixed. This recurrence can be numerically solved by iteration, which is referred to as the iteration 2. The initial value of \( p \) can be derived by substituting \( \tau \) with the observation time relative to the reference time. In this study, the iterations 1 and 2 were repeated alternately twice to numerically derive \( p, q, \lambda_0 \).

\[ \text{[23]} \]

Figure 3 shows an example of the distribution of data points in the swath, which are defined with the tangent points of the GPS RO at the altitude of 10 km. Since Figure 3 is for 1 December 2006, data from the four satellites on the orbit were used (see Table 1). Each plot shows data points corresponding to one circle of the satellites around the Earth. Since the satellite rotation period is about 90 min, the data points having \( p \) values close to each other are observed with time differences of less than 1 h, and a plot consists of data obtained roughly within 2 h. Most data points obtained by the four satellites are within a swath with

Figure 3. Distribution of the tangent points at the altitude of 10 km in the \( p-q \) coordinate obtained on 1 December 2006. Different marks are used for different receiving satellites (four kinds are used for the four satellites). The axes are normalized by \( 2\pi \), and each of the plots corresponds to a satellite circulation around the Earth. The left (right) half of the plots represents the Northern (Southern) Hemisphere, and the two sides and the center of the plots (i.e., where the remainder of \( p \) by the division by 1 is 0 or 0.5) correspond to where the satellites pass the equator.
a 5000-km width (0.125 with respect to $q/2\pi$, in which Figure 3 is scaled).

3.2. Heuristic Clustering

[24] We found that the data point distribution is not random within the swath, as can be easily seen in Figure 3. There are many data points distributed nearby to form roughly line-shaped structures. In this study, we exploit this feature by clustering quasi-linearly aligned data points with the method shown below in the $p-q$ coordinate system, as illustrated in Figure 4. In this algorithm, we used the location of tangent points at 10 km. The tangent points vary with altitude for each profile, but the distance at which the tangent point shifts from 10 km to 30 km is typically about 1° or less as shown later, so it is neglected in this study. The algorithm is as follows:

[25] 1. As initial clusters, all pairs having distances ($d$) shorter than a constant $dr$ are chosen. (In practice, a small minimum distance $ds$ is also introduced for efficiency, so only pairs with $ds < d < dr$ are used, which does not essentially affect the result.) For each of the initial pairs, the following processes are applied.

[26] 2. A line segment is assumed between the points making up each pair and is extended by the distance of $dr$ at both ends. Then a rectangle with a width of $dw$ and the line running through its center is assumed (second step in Figure 4). Then, all data points inside the rectangle are added to the cluster.

[27] 3. The data points in the cluster are projected onto the center line, and the end points are replaced with respect to the positions along the line. If one or two of the end points are actually replaced, return to the previous process to find more data points (third and fourth steps in Figure 4).

[28] 4. After the iteration, clusters that have fewer than a threshold value, $N$, of data points are excluded. Also, clusters having the same combination of data points are unified.

[29] Clusters formed in this way are not necessarily independent, which will be considered in statistical analyses in what follows. Two clusters can share some of the data points. Occasionally, significant overlaps occur such that, for example, one cluster consists of data points $P_1$, $P_2$, $P_3$, $P_4$, $P_5$, and $P_6$, while another consists of data points $P_1$, $P_2$, $P_3$, $P_4$, $P_5$, and $P_6$. However, this feature is rather suitable for examining the sensitivity to subtle changes in data point selection. Note that line clusters that cross each other can be identified separately with this method. The values of the parameters chosen in this study are as follows: $N = 6$, $dw = 600$ km, $ds = 300$ km, and $dr$ is either 600 km or 1000 km. Hereinafter, the clusters are called as “lines”.

[30] In this study, the clustering was conducted in the $p-q$ coordinate system. Since the width of the swath was only about 5000 km, we neglected the spherical geometry in this coordinate system.

[31] Figure 5 shows the global distribution of the lines obtained from the data over December of 2006 and January and February of 2007, when $dr = 1000$ km. The number of lines obtained in this 3-month period is over 800. As stated above, not all of them are independent. For each of approximately 15% of the lines, we found another line that has significant overlapping of data points. In addition, for each of a few percent of the lines, another line was found nearby in space and time and almost in parallel, so even though data points are not shared, the lines may not be independent in terms of gravity wave analysis. When $dr = 600$ km, the number of the lines obtained for the same period of time is 186, in which we found 173 independent lines.

[32] As seen in Figure 5, the distribution of the lines is quite sparse in the equatorial region, while it is especially high between 40 and 60° in both hemispheres. The latitudinal distribution is basically explained by those of the RO events. In addition, there are longitudinal ranges in which relatively large number of lines are obtained for a given month, and these ranges move eastward gradually. The enhancement is roughly hemispheric so that there are two (occasionally four) ranges along zonal circles. We did not investigate the reason for this longitudinal nonuniformity, but it should be associated with relations between the LEO orbits and GPS satellite orbits. The data density is not particularly low in the longitudinal ranges in which lines are relatively sparse, so the longitudinal contrast should be related to whether the data points tend to be aligned linearly or not.

3.3. Possible Application to Spherical Geometry

[33] Although we performed clustering in the $p-q$ coordinate system, it can also be performed using the conventional spherical geometry. In such a case, another threshold should be introduced to limit amount of time over which data points are considered. Also, spherical geometry should be explicitly considered. The 5000-km-wide swaths in which RO events occur overlap in the polar region. Therefore, using the spherical coordinate system would increase the spatial resolution in that region.

4. Study of Gravity Waves

[34] Observations consisting of each of the lines obtained by the method introduced in section 3 are made within approxi-
approximately 1 h. Here we examine whether or not the sampling of the lines can be regarded as roughly “instantaneous”, when dealing with gravity waves (GWs).

Typical lengths of the lines are 1500 to 5000 km. Let \( c \) be the ground-based horizontal phase speed of a gravity wave to be observed and \( \lambda \) be the horizontal wavelength along the line. The time scale that one can regard as instantaneous (\( T \)) can be defined as \( 1/(2\pi c) \) of the period of the wave, so \( T = \lambda/(2\pi c) \). If we assume that the maximum of \( c \) is 100 m/s and the minimum of \( \lambda \) is 1500 km, the minimum of \( T \) is estimated to be 0.7 h, which is comparable to the time difference of the observations within a line. Therefore, for a wave that is resolved in the current analysis without aliasing, we can assume that sampling is made roughly instantaneously. The horizontal wave number spectra of atmospheric GWs are red, having an spectral exponent around \(-2\) (or \(-5/3\)) [Fritts and VanZandt, 1993]. Therefore, statistically speaking, aliasing of smaller-scale GWs is expected to be significant, although in some cases there could be significant aliasing, such as that due to mountain waves.

Studies on atmospheric GWs are presented in what follows. Results with \( dr = 1000 \) km are used unless explicitly stated.

4.1. Case Studies and Global Statistics

Figures 6 and 7 show examples of extracted vertical cross sections. The seven digit numbers in Figures 6 and 7 label occultations, with the first digits expressing the receiving satellites and the remaining digits being arbitrary identifiers. The times of occultations are shown in the right margin of Figures 6c and 7c. From a comparison between Figures 6a and 7a and Figures 6b and 7b, it is obvious without any kind of filtering that the GPS data have richer vertical structures than the NCEP reanalysis 2 data sampled at the standard pressure levels.

Figures 6d, 6e, 7d, and 7e were obtained by applying high-pass filters using the Fourier transform for each vertical profile. In order to avoid artifacts due to imposition of the
cyclic boundary condition, the upper boundary of the data are extended from 38 km to 80 km, and a linear interpolation is made between the temperature value at 38 km and that at the lowermost altitude. Note that the detrending and cosine tapering, which are frequently used to obtain spectra, were not very efficient for the purpose of filtering, since the tapering introduces artificial "wave" components near the boundary. Figures 6f and 7f show the root-mean-square amplitude of the filtered disturbances, obtained by applying a running mean over the distance of the cutoff wavelength $\lambda_{zc}$ = 10 or 5 km to the root mean square.

Figure 6. (a) Vertical cross section of the dry temperature along a line obtained on 1 December 2006. (b) The temperature from the NCEP reanalysis 2 data sampled at the same data points after linear interpolation. (c) The locations of the data points, where the tangent points at the altitude of 10 km are shown in red and those on top of the tangent points at 30 km, which are almost hidden, are shown in green. The times of occultations are shown in the right margin of Figure 6c. The blue contours show the sea level pressure from the NCEP data. Horizontal axes of Figures 6a, 6b, 6d, and 6e are the locations of the tangent points at 10 km projected onto the line segment between the two ends of the line with the westernmost point on the left-hand side. Figure 6c shows the temperature from the NCEP reanalysis 2 data interpolated horizontally to the data points. COSMIC dry temperature disturbances obtained by the high-pass filtering with (d) $\lambda_{zc}$ = 10 and (e) $\lambda_{zc}$ = 5 km. (f) The root-mean-square amplitudes with running means for $\lambda_{zc}$ = 10 and 5 km in blue and black, respectively, and without and with the subtraction of horizontal averages (see section 4.1) with thick and thin lines, respectively.

GWs if their group propagation is upward. Since the pattern is coherent across multiple independent RO profiles, it should be a real, not spurious, feature. GW-like features are seen in the lower stratosphere of most vertical cross sections, although the patterns and propagation directions are not always clear.

[40] Gubenko et al. [2008] proposed a method to identify fluctuations in observed temperature profiles as wave induced, assuming gravity wave shear saturation. They introduced a parameter $a_e$ expressed as

$$a_e = \frac{g |m|}{N^2} \frac{|T|}{T},$$

where $g$ is gravity, $m$ is vertical wave number, $N$ is buoyancy frequency, $|T|$ is the amplitude of the fluctuation, and $T$ is the background temperature. The value of $a_e$ is smaller than...
if the fluctuation is due to saturated (or subsaturated) monochromatic inertia gravity wave with respect to the shear instability. They further derived the horizontal wavelength $l_H$ assuming the saturation as

$$l_H = \frac{2 l_z N}{f} \left(1 - \frac{a_e}{a_c}\right)^{1/2},$$  \quad (7)$$

where $l_z$ is the vertical wavelength, and $f$ is the Coriolis parameter. As for a subsaturated inertia GW, $l_H$ gives the upper bound of its horizontal wavelength. Gubenko et al. [2008] not only derived these parameters from observed GPS RO profiles but also estimated their uncertainties. As for the two cases they examined, the uncertainty of $l_H$ was 40–50%.

We applied this analysis to the cases we obtained. From the GW-like feature with $l_z \approx 8–9$ km at altitudes 20–33 km in Figure 6d, $a_e$ was estimated to be 0.2, which is less than 1, and $l_H$ was derived to be $1.1 \times 10^3$ km. We did not estimate its uncertainty, but it is expected to be large as in the work by Gubenko et al. [2008]. On the other hand, the horizontal wavelength along the direction of the cross section, $l_C$, was estimated to be about $8 \times 10^3$ km by visually extrapolating patterns in Figure 6d (these estimates may have large errors). If the propagation direction was not along the cross section, the actual horizontal wavelength was less than $l_C$, which is in any case smaller than the estimated $l_H$. This result indicates that the GW-like feature may be explained by a subsaturated (or possibly saturated, given the large uncertainty) inertia GW.

We also applied this analysis to the GW-like feature with $l_z \approx 3.5$ km at around the altitude of 20 km in Figure 6e. The values of $a_e$, $l_H$, and $l_C$ were estimated to be 0.2, $6 \times 10^3$ km, and $2 \times 10^3$ km, respectively. Therefore, the feature may be explained by a subsaturated inertia GW. We further applied this analysis to GW-like features (i.e., cases in which slantwise phase structures are seen) in the cross sections shown in Figures 6 and 7, and in all cases, the values of $a_e$ were smaller than 1, and the values of $l_H$ were greater than or comparable to those of $l_C$.

Figure 7 shows an example for low latitudes. The cold tropical tropopause is around 17 km. Thus the signal around the tropopause altitude in Figure 7d is predominantly due to the sharp minima in temperature profiles. However, there are actual wave-like features in the lower stratosphere, as seen in the fluctuating contour line intervals in the raw temperature plot (Figure 7a). Moreover, the temperature disturbances around the tropopause altitude have significant wave-like features with vertical wavelengths less than 2 km, with coherent structures across the three RO profiles observed equatorward of $10^\circ$N (Figure 7d). A significant wave packet having a vertical wavelength of about 4 km with a northward phase tilt is seen between 24 and 30 km (Figure 7e; southern (left-hand) half of the plot; note that most of the data points are situated in the southern half of the line).

The high-pass filtering is also applied after subtracting averages for each altitude over the profiles consisting of a line. By this subtraction, one can roughly eliminate structures
that have horizontal scales larger than the line length. Therefore, the results predominantly consist of contributions from smaller-scale disturbances along the direction of the line. Figures 6f and 7f show the amplitudes obtained without and with the subtraction.

Figure 8 shows the amplitudes at 28 km for the four filters ($\lambda_{zc} =$ 10 and 5 km; without and with the prior subtraction of horizontal means) as a function of the mean latitudes of data points in the lines. Here we used only the lines whose both ends are separated over distances between 1500 and 3000 km. Comparison between Figures 8a and 8b shows that the difference in the amplitudes without and with the horizontal mean subtraction is relatively large in low latitudes, suggesting there are greater contributions from waves having horizontal wavelengths larger than the line lengths than in the middle to high latitudes. This result can be explained by the latitudinal variation of the Coriolis parameter; the wavelengths of GWs in low latitudes can generally be larger than those in middle to high latitudes for given vertical wavelengths because of the smaller Coriolis parameter, which allows GWs with longer periods, and thus with longer horizontal wavelengths, to exist. See Sato et al. [1999] for the meridional distribution of GW periods deduced from an atmospheric general circulation model.

The mean latitudinal distribution of the amplitude, indicated by the curved line in Figure 8a, agrees qualitatively with past studies that showed an enhancement in low latitudes (Ogino et al. [1995], with radiosondes, and Tsuda et al. [2000], with GPS RO) along with an enhancement in the winter hemisphere [Ratnam et al., 2004]. However, the
contrast between the low latitudes and middle to high latitudes is smaller in Figure 8b than in Figure 8a, especially in the Northern Hemisphere. This indicates that there are greater contributions from waves whose wavelengths are shorter than 3000 km in northern middle to high latitudes than in the low latitudes or in southern middle to high latitudes. It further suggests that horizontal wavelengths are generally smaller in the former than in the latter. Preusse et al. [2006] estimated the latitudinal distribution of horizontal wavelengths of GWs from measurements by the CRISTA instrument. The estimated horizontal wavelengths for waves with vertical wavelengths shorter than 14 km had a maximum in the equatorial region, and they were larger in the Southern Hemisphere than in the Northern Hemisphere. Therefore, the latitudinal distribution shown above appears consistent with their study. However, their observations were made in August (in 1997 and 2003). Thus, in terms of the contrast between the winter and summer hemispheres, their findings are the opposite of ours. The difference between the results without and with the horizontal mean subtraction is small for $\lambda_c = 5$ km (Figures 8c and 8d).

[47] It is noteworthy in both Figures 8a and 8b that the distribution of amplitudes in middle to high latitudes is positively skewed so that a small number of profiles show significantly large amplitudes. That is, GWs with significantly large amplitudes are occasionally observed. The skewness values derived from the amplitudes at latitudes poleward of 40°NS are 1.1 and 0.9 for Figures 8a and 8b, respectively. On the other hand, the amplitudes of the profiles equatorward of 30°NS are not significantly skewed; the skewness values derived from amplitudes equatorward of 35°NS are –0.2 and 0.2 for Figures 8a and 8b, respectively. These results are summarized in Figure 9.

4.2. Analysis of Stratospheric Gravity Waves in Northern Winter

[48] In this section, we investigate the spatial structures of the GWs in the northern midlatitudes and perform statistical analyses to elucidate the formation of the large variability in the GW energy studied by Alexander et al. [2008a] (hereinafter referred to as A08).

[49] Figure 10 shows examples of the vertical cross sections in the longitudinal ranges in which GWs were shown by A08 to have had large potential energy in northern midlatitudes in December 2006 (note that they...
used a high-pass filter to pass wavelengths smaller than 7 km). Figures 10a–10d show lines aligned predominantly in the zonal direction. In Figure 10b, disturbances between 20 km and 30 km are tilted to indicate an eastward propagation relative to background winds, if we assume that the GWs are propagating upward; such an assumption is also made in the following. In Figure 10d, however, the disturbances between 20 and 30 km are almost horizontally aligned, so the propagation direction is not clear (the propagation direction might be predominantly meridional in this case, or it may be due to wave). Figure 6, on the other hand, shows an example of westward propagation. We have examined many cases in which lines are obtained in the zonal direction in the regions where GWs are enhanced. As a result, both eastward and westward propagating cases were found, as well as the cases that appeared to suggest superposition of the two directions. Westward propagation was slightly more frequent than eastward propagation. We also found cases like that in Figure 10d, where the phase lines were horizontally aligned.

Figure 11. Scatter diagrams showing the wave amplitude at the altitude of 25 km (in K) versus (a–d) the zonal wind shear defined by the difference between 10 and 70 hPa, (e–h) zonal wind at 30 hPa, (i–l) meridional wind shear between 10 and 70 hPa, or (m–p) meridional wind at 30 hPa. Here we used the daily averaged NCEP winds at the grid point nearest to the center of each line. The four plots in each row show the results from the four filters as in Figure 8. Lines show linear regressions.
Figures 10f and 10h indicate poleward propagation. We examined many cases where lines are obtained roughly in the meridional direction. The propagation direction indicated was predominantly northward relative to background winds. However, it is difficult to further estimate the partitioning of the propagation directions quantitatively, since in cases in which the propagation direction was unclear, the lack of clarity may have been because the data point alignment was not purely linear, or because of errors in RO retrieval for one or more of the profiles in the lines.

As described in section 1, A08 showed enhancement of the zonal mean GW energy, whose distribution is tilted poleward with increasing altitude. The tilt may be (1) due to the dominance of poleward propagation or (2) due to the critical level filtering associated with the zonal wind distribution whose contour lines are tilted poleward. The results shown above (the meridional propagation is predominantly northward) are consistent with speculation 1, although speculation 2 may also be relevant.

In order to further elucidate the relationship between the GW amplitude and horizontal winds, scatter diagrams were made along with correlation analyses. In Figure 11, we show the results with \( dv = 600 \text{ km} \) at \( 25 \text{ km} \), since we obtained a large number of cross sections in middle to high latitudes even with this parameter value, which is stricter than \( dv = 1000 \text{ km} \). Similar results were obtained for both parameter values. Again, we used only the lines whose both ends are separated by distances between 1500 and 3000 km. Among the 173 independent lines (see section 3.3), we used 56 lines that satisfy this distance criterion and have the center of the both ends between 40°N and 65°N. Figures 11a–11d show the relationship between wave amplitude and zonal wind shear in the lower stratosphere defined as the difference between 10 and 70 hPa. For the sample number of 56, the 95% and 99% significance levels are 0.26 and 0.34, respectively. The correlation coefficients are summarized in Table 2.

Table 2. Correlation Coefficients \( r_{xy} \)

<table>
<thead>
<tr>
<th>( \lambda_v = 10 \text{ km} )</th>
<th>( \lambda_v = 5 \text{ km} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( x )</td>
<td>dev</td>
</tr>
<tr>
<td>( y )</td>
<td>dev</td>
</tr>
<tr>
<td>( u(10)−u(70) )</td>
<td>(-0.31)</td>
</tr>
<tr>
<td>( u(30) )</td>
<td>(0.05)</td>
</tr>
<tr>
<td>( v(10)−v(70) )</td>
<td>(0.28)</td>
</tr>
<tr>
<td>( v(30) )</td>
<td>(0.41)</td>
</tr>
</tbody>
</table>

*Horizontal winds or their shear are represented by \( x \) (rows), and \( y \) represents the amplitude of the temperature perturbation at \( z = 25 \text{ km} \) obtained after applying various filters (columns) as shown in Figure 11. Here “nodev” and “dev” mean without and with the prior subtraction of the mean along the lines, respectively. Values greater than 0.34, which is the 99% significant level, are shown in bold.

[54] Figures 11i–11l and 11m–11p show the correlation of the amplitudes of temperature disturbances to meridional wind shear and meridional winds, respectively. The correlation was positive for all cases, and the correlation to meridional winds was more significant than the correlation to meridional wind shear, in contrast to the zonal wind cases.

[55] The correlations of GW amplitude to zonal wind shear, meridional winds, and meridional wind shear were not independent. There was a strong positive correlation between meridional winds at 30 hPa and meridional wind shear between 10 and 70 hPa, with a coefficient of 0.57, when the data were sampled at the same location and time as in Figure 11. Thus, the correlation of the amplitude to the meridional wind shear may be controlled by its correlation to the meridional winds. Also, zonal wind shear between 10 and 70 hPa and meridional winds at 30 hPa had a negative though weaker correlation, with the coefficient, calculated in the same way, being \(-0.26\). On the other hand, the correlation between meridional and zonal winds at 30 hPa was much weaker (0.15). Therefore, it appeared that the negative correlation shown in Figures 11a–11d may be controlled by the correlation to meridional winds. Therefore, we examined partial correlations to elucidate possible contamination through correlations among horizontal wind properties. The partial correlation between \( x \) and \( y \) given a control variable \( z \) is expressed as follows:

\[
r_{xy|z} = \frac{r_{xy} - r_{xz}r_{yz}}{\sqrt{1 - r_{xz}^2} \sqrt{1 - r_{yz}^2}}
\]

where \( r_{xy} \) is the correlation coefficient between \( x \) and \( y \), and so on. Table 3 shows the partial correlation coefficients. The values shown in Table 3 are weaker than those shown in Table 2. However, the difference is not large, so the contamination through the hidden correlations between zonal wind shear and meridional wind velocity is not severe.

[56] The negative correlation between the GW amplitude in temperature and zonal wind shear can be explained if we assume an amplification of westward propagating GWs in the negative shear, as has been shown for the amplification of the Kelvin waves in the positive shear [Shiotani and Horinouchi, 1993]. However, this hypothesis is not supported by close examination of the actual cases obtained in this study. Here we examined the horizontal structures of temperature disturbances in the lines predominantly aligned in the zonal direction under negative zonal wind shear, but the apparent propagation directions varied as mentioned earlier. A simpler explanation by A08 based on the filtering

Table 3. Similar to Table 2 but for the Partial Correlation \( r_{xy|z} \)

<table>
<thead>
<tr>
<th>( x )</th>
<th>( z )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \lambda_v = 10 \text{ km} )</td>
<td>( \lambda_v = 5 \text{ km} )</td>
</tr>
<tr>
<td>( u(10)−u(70) )</td>
<td>( v(30) )</td>
</tr>
<tr>
<td>( v(30) )</td>
<td>( u(10)−u(70) )</td>
</tr>
</tbody>
</table>

*The first and second columns are \( x \) and \( z \), respectively, and \( y \) is the amplitude with various filters (third through sixth columns).
of GWs whose phase speed is close to zero (see section 1) may rather be relevant. However, it is difficult to confirm this from the current data, so we leave it as an open question.

As for the meridional direction, northward propagation is dominant. Therefore, the positive correlation between the amplitude and the meridional wind shear cannot be explained by critical level filtering. Also, the correlation to meridional winds was rather stronger than that to the meridional wind shear. This result can be explained if the dominant source region in the troposphere is in lower latitudes and northward winds help GWs reach higher latitudes, as illustrated in Figure 12. This interpretation appears consistent with A08, in which the GW energy is enhanced in the subtropics in the upper troposphere and the enhancement extends upward and poleward.

5. Conclusions

To investigate GWs in the lower stratosphere, we used the GPS RO data derived at UCAR by using the LEO satellites of the COSMIC/FORMOSAT-3 mission. The satellites were launched by a single rocket, and there were more than 3 satellites on the initial orbit at the altitude of 500 km over a year after the launch. The RO events were thus distributed heavily around the orbit, while observation was sparse elsewhere.

It was found that the tangent points of the RO events obtained with successive passages of the LEOs on the orbit within about 1 h were frequently aligned in more or less linear shapes. We exploited this feature by introducing an algorithm to extract the “lines” heuristically. This processing was applied to the COSMIC level 2 dry temperature data over the period from December 2006 through February 2007, during which three or four satellites were on the orbit. We obtained many lines, and from these we derived snapshot horizontal-vertical cross sections, suggesting the usefulness of the analysis. A statistical analysis was performed for high-pass filtered temperature disturbances. Its latitudinal distribution, with peaks in the equatorial region and in the middle to high latitudes of the winter (here northern) hemisphere, was consistent with past studies. If we exclude large-scale disturbances by subtracting horizontal averages for each vertical cross section, the peak in the Northern Hemisphere is more pronounced, indicating that the horizontal wavelengths of GWs in the northern middle to high latitudes are generally smaller than those in the equatorial region. We also examined the probability distribution of the amplitudes of temperature disturbances. The distribution was positively skewed in the middle to high latitudes so that GWs with significantly large amplitudes were observed occasionally, while no such skewness was found equatorward of 30°N.

Finally we investigated the large variation in the potential energy of GWs found by Alexander et al. [2008a] from the COSMIC data for December 2006. While GWs propagated both eastward and westward in the zonal direction, the meridional propagation was predominantly northward. The GW amplitudes were negatively correlated with zonal wind shear in the lower stratosphere, although the mechanism of the association was not identified in the current analysis. The GW amplitude was positively correlated with the meridional winds, which could be explained by assuming that the ray paths changed according to the change in meridional winds, and northward winds help GWs to reach midlatitudes.

In this paper, we focused on atmospheric GWs. However, the cross-sectional analysis shown here should be useful to study many other kinds of atmospheric disturbances as well.

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References


Figure 12. Schematic illustration of the relationship between the background meridional wind and the GW propagation into the northern (winter) midlatitude lower stratosphere based on the analysis of propagation directions and correlations. The vertical range covered is from approximately 10 km to 30 km. The thin lines indicate background winds, and the thick arrows indicate representative GW rays.


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