Self-Acceleration and Instability of Gravity Wave Packets: 3. Three-Dimensional Packet Propagation, Secondary Gravity Waves, Momentum Transport, and Transient Mean Forcing in Tidal Winds

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Abstract
Dong et al. (2020, https://doi.org/10.1029/2019JD030691) employed a new compressible model to examine gravity wave (GW) self-acceleration dynamics, instabilities, secondary gravity wave (SGW) generation, and mean forcing for GW packets localized in two dimensions (2D). This paper extends the exploration of self-acceleration dynamics to a GW packet localized in three dimensions (3D) propagating into tidal winds in the mesosphere and thermosphere. As in the 2D packet responses, 3D GW self-acceleration dynamics are found to be significant and include 3D GW phase distortions, stalled GW vertical propagation, local instabilities, and SGW and acoustic wave generation. Additional 3D responses described here include refraction by tidal winds, localized 3D instabilities, asymmetric SGW propagation, reduced SGW and acoustic wave responses at higher altitudes relative to 2D responses, and forcing of transient, large-scale, 3D mean responses that may have implications for chemical and microphysical processes operating on longer time scales.

1. Introduction
As described by Dong et al. (2020, hereafter D20) and elsewhere, gravity waves (GWs) arise from multiple sources in the lower and middle atmosphere and have major impacts throughout the neutral atmosphere and extending well into the thermosphere and ionosphere (TI). The most recognized and significant GW sources in the troposphere and lower stratosphere include convection, airflow over orography, frontal systems, and jet streams (Fritts & Alexander, 2003; Fritts & Nastrom, 1992; Guest et al., 2000; Kim et al., 2003; Luo & Fritts, 1993; Plougonven & Zhang, 2014, and references therein). Additional sources at lower and higher altitudes include secondary GW (SGW) generation by transient body forcing accompanying local GW momentum transport, nonlinear interactions, instability dynamics, and auroral heating (Becker & Vadas, 2018; de Wit et al., 2017; Fritts et al., 2002, 2013; Hocke & Schlegel, 1996; Mayr et al., 1990; Vadas et al., 2003, 2018). Each source yields a spectrum of GW spatial scales and intrinsic frequencies that depend on the source characteristics and the environment in which it occurs. GWs maintaining sufficiently high intrinsic phase speeds and vertical group velocities thereafter may propagate into the mesosphere and lower thermosphere (MLT) or higher (Azeem et al., 2015; Djuth et al., 1997, 2004; Hocke & Schlegel, 1996; Mendillo et al., 1997; Oliver et al., 1997; Vadas & Nicolls, 2009; Yue et al., 2009). In such cases, GW amplitude growth with increasing altitude can be dramatic, yielding amplitudes and momentum fluxes (per unit density) that can be decades larger than near the GW source (Fritts et al., 2018; Fritts & Vadas, 2008; Vadas, 2007). These various dynamics have global implications extending into the TI (Abdu et al., 2009; Fritts et al., 2008; Hysell et al., 2018; Oberheide et al., 2015; Takahashi et al., 2009; Yigit & Medvedev, 2015), but their descriptions via parameterization in global models remain primitive at present (Fritts & Alexander, 2003; Geller et al., 2013; Kim et al., 2003).

Of the recognized GW sources, SGW generation may be the least rigorously studied to date. SGWs are expected to be excited by localized Kelvin-Helmholtz instabilities at horizontal scales dictated by the Kelvin-Helmholtz instability packet extent (Bühler et al., 1999; Chimonas & Grant, 1984; Fritts, 1984). The same expectation applies to local GW packets attaining large amplitudes, breaking, and local momentum deposition in various modeling studies (Horinouchi et al., 2002; Lane & Sharman, 2006; Satomura &
Sato, 1999; Vadas et al., 2018; Vadas & Fritts, 2001, 2002). GW packets having large vertical scales and high intrinsic frequencies necessarily attain larger amplitudes, momentum fluxes, and implied local mean forcing than low-frequency, large-horizontal-scale GW packets. Such packets are susceptible to self-acceleration (SA) dynamics that kink the GW phase in the vertical, stall its vertical propagation, and accelerate the tendency for local momentum deposition (Sutherland, 2006; Fritts et al., 2015, hereafter F15). F15 examined the SA dynamics of GW packets localized only in altitude and identified the 2D and 3D SA instabilities that arise, and the dependence of GW and induced mean responses on initial GW parameters.

More recently, SGW responses have been observed at small horizontal scales in the mesosphere over GW breaking regions in the stratosphere (Bossert et al., 2017) and inferred at intermediate and larger scales downwind of these dynamics in the lee of the major southern Andes terrain in MLT radar observations and global modeling (Becker & Vadas, 2018; de Wit et al., 2017).

The initial SA dynamics study by F15 and the increasing evidence for their roles at higher altitudes were the motivations for more detailed studies of these dynamics and their implications for initial GW packets localized in 2D and 3D. SA dynamics for a GW localized in altitude and along its direction of propagation confined to a 2D plane and allowed to exhibit 3D instabilities so as to realistically constrain GW amplitudes are reported by Dong et al. (2020, hereafter D20).

This paper extends the D20 analysis of SA dynamics and SGW to an initial three-dimensional (3D) GW packet response evolving in 3D tidal winds in the MLT. The model formulation, configuration, and initial and boundary conditions are described in section 2. Section 3 presents the GW event evolution, including primary GW SA dynamics, instabilities, SGW responses to packet stalling and instabilities, and the SGW evolutions and instabilities due to tidal interactions. Local mean responses are described in section 4. Sections 5 and 6 provide a discussion of these results in relation to previous studies and our conclusions.

2. Model Description

The model used for this study is the Complex Geometry Compressible Atmosphere Model (CGCAM) described extensively by D20. Summarizing, CGCAM is a finite-volume model that employs the architecture discussed by Felten and Lund (2006) to discretize the compressible Navier-Stokes equations such that they result in exact numerical conservation of mass, momentum, and kinetic and thermal energies and faithfully represent the underlying conservation laws, apart from specified dissipation. See D20 for additional details.

2.1. CGCAM Configuration and Initial and Boundary Conditions

For our purposes here, a domain extending 2,000 km in the zonal (x) and meridional (y) directions and to 300 km in altitude is specified. A 40-km sponge layer is employed at the upper boundary, and 100-km sponge layers are imposed at each lateral boundary in x and y. Model resolution is as high as 500 m in the central portion of the 3D domain in order to resolve the initial GW SA and breaking instabilities accounting for primary GW dissipation, and the Germano et al. (1991) dynamic large-eddy simulation scheme is employed to account for dissipation at unresolved scales. An exponential mesh stretching allows much coarser resolution of ~13 km at the lateral boundaries where SGW horizontal and vertical wavelengths, $\lambda_x$ and $\lambda_z$, are very large.

The idealized background environment includes a uniform temperature $T(z) = 246$ K below $z \approx 90$ km, increasing to ~985 K at 260 km (Figure 1a). This yields a scale height $H = 7.2$ km, a buoyancy frequency $N \approx 0.02$ s$^{-1}$, and buoyancy period $T_b = 2\pi/N \approx 318$ s below ~90 km, and corresponding values of $H \approx 29$ km and $N \approx 0.011$ s$^{-1}$ at ~260 km. We also assume an initial mean wind that is zero below ~100 km, asymptotes to a constant $U = 110$ m/s above ~160 km, and approximates a semidiurnal tide in the MLT with $\lambda_z \approx 40$ km, $u' \approx 80$ m/s at $z = 110$ km, and a meridional tidal wind of $v' = 62$ and $-68$ m/s at $z = 104$ and 129 km, asymptoting to a constant $v' = 0$ m/s above ~140 km (Figure 1b). These fields are roughly consistent with MLT winds and tidal fields measured by lidar and radar at 54°S and 69°N under winter conditions (Fritts et al., 2010, Williams et al., 2006). We have ignored tidal temperatures for simplicity, as they have a much weaker influence on GW filtering than the tidal winds.

2.2. Initial GW Packet Specification

As for the 2D GW packet evolutions described by D20, we assume an initial 3D GW packet having $\lambda_x = 45$ km, $\lambda_z = 15$ km, corresponding primary horizontal and vertical wave numbers $k_h = 2\pi/\lambda_x$ and $m_h = 2\pi/\lambda_z$. 
\[ l = 2\pi/\lambda_c \text{ initially, and intrinsic phase speed } c_i = c - U = -44.2 \text{ m/s. Following D20, we also assume a GW packet with Gaussian horizontal velocity amplitude and momentum flux distributions having the forms} \]

\[ u' = u_0 \exp \left[-x^2/2\sigma_x^2 - y^2/2\sigma_y^2 - (z - z_0)^2/2\sigma_z^2\right] \tag{1} \]

and

\[ \rho_0 <u'w'> = \rho_0 <u'w'>_{\text{max}} \exp \left[-x^2/\sigma_x^2 - y^2/\sigma_y^2 - (z - z_0)^2/\sigma_z^2\right] \tag{2} \]

with \( u_0 = 34 \text{ m/s at } 38 \text{ km, } \sigma_x = \sigma_y = \lambda_{c0}, \sigma_z = \lambda_{c0}, z_0 = 40 \text{ km, corresponding 3D GW spanwise and vertical velocities } v', \text{ and } w' - u', \text{ consistent with GW propagation toward negative } x \text{ and the GW polarization relations in D20, and an implied peak initial } \rho_0 <u'w'> \text{ occurring at } -24 \text{ km and initial peak } \Delta U \approx 2.5 \text{ m/s at this altitude at } t = 0. \text{ The parameters were chosen to be representative of a GW packet arising from a strong lower atmosphere source, such as mountain waves over the southern Andes, as described by D20.} \]

The simulation was performed in a domain translating with the initial GW packet \( c_i = -44.2 \text{ m/s in order to show the influences of SA dynamics clearly. Thus, these initial conditions at altitudes above } -50 \text{ km correspond crudely to a high-latitude winter environment with westward propagation of the GW packet with respect to the specified mean } U \text{ and tidal motions, with mean and tidal motions imposing a local minimum effective } U - c = 15 \text{ m/s at } 96 \text{ km and a critical level where } U = c \text{ at } -130 \text{ km. A 2.5D simulation for the same } U(z) \text{ wind, an initial } u' = u_0 \exp[-x^2/2\sigma_x^2 - (z - z_0)^2/2\sigma_z^2], \text{ and highest resolution of } 300 \text{ m was also performed in a 3D domain having a 30-km extent in } y \text{ to allow an assessment of the impacts of 3D packet dispersion on the instability and SGW evolutions.} \]

3. GW Packet Evolutions

3.1. SA Dynamics and Dispersion

GW \( u', w' \), perturbation vorticity magnitude \( |\zeta'| = (\zeta_x'^2 + \zeta_y'^2 + \zeta_z'^2)^{1/2} \), and \( T'/T_0 \) (top to bottom) are shown with \( x-z \) cross sections of the 3D simulation fields at \( y = 0 \) and \( y-z \) cross sections at \( x = 0 \) and \( t = 10, 20, 30, 40, \) and 60 min after initiation in Figures 2 and 3. The fields at these times are shown in subdomains extending 200, 300, 400, 900, and 1,800 km horizontally centered at \( x = y = 0 \), respectively, and extending to 260 km in \( z \). Shown in Figure 4 are \( (x,y) \) cross sections of \( T'/T_0 \) at 30, 40, 50, and 60 min and at altitudes of 80, 120, and 200 km in domains extending over larger regions with increasing altitude and time. \( U(z) \) profiles to 180 km at the evolving packet center at 10, 20, and 30 min are shown in Figure 5.
Referring to Figures 2, 3, and 5, the GW packet is seen to remain largely linear at 10 min, exhibiting only weak departures from uniform phase slopes in $x$, $y$, and $z$, and an induced $|U(z)| \approx 10$ m/s at $\sim 50$ km that is still much smaller than $|U|_{\text{cl}}$. By 20 min, the GW packet has propagated another 0.6 $H$ in altitude, experienced an $\sim 80\%$ further increase in the maximum induced mean wind now peaking at $\sim 72$ km, and expanded horizontally. Amplitude increases and implied accelerations have also led to significant phase distortions and kinking of the 3D GW packet at this time and thereafter, in both the vertical and horizontal planes. See the steeper (shallower) phase slopes at the GW packet upper (lower) edge in Figure 2 and the compressed vertical phases (smaller $\lambda_z$) in the central GW packet at $y = 0$ in Figure 3. Smaller phase compressions are also seen in Figure 3 at the edges of the GW packet in $y$, where the GW amplitude, momentum flux, and induced mean flow are smaller.

By 30 min, the GW packet has increased significantly in amplitude and exhibits $|u'_{\text{z}}| \approx 60$–140 m/s above $\sim 70$ km (see Figures 2, 3, and the discussion of Figure 6 below). The $x$-$z$ cross sections show strong phase kinking in altitude and evidence of initial 2D SA instability dynamics initially described by F15. The $y$-$z$ cross sections show substantially greater GW SA dynamics near $y = 0$, specifically compressed (expanded) GW $\lambda_z$ at the packet lower (upper) edge and an expanded packet extent in $y$. The $x$-$y$ cross sections at 30 min in Figure 4 at 80 and 120 km confirm the GW packet distortion due to initial GW packet localization and implied dispersion in $y$.

$\Delta U(z)$ at 30 min (Figure 5) reveals a peak of $\sim 30$ m/s toward negative $x$ from $\sim 68$ to 76 km approaching the initial phase speed of the GW packet. This confirms the expectation of strong SA dynamics beginning at this time.

Beyond 30 min, the 3D GW packet continues to propagate to higher altitudes, increases further in amplitude, and exhibits onset of 3D instabilities at the packet leading edge where initial instabilities are 2D, and at the

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**Figure 2.** (from top) 3D GW $u'$, $w'$, $|\zeta'|$, and $T'/T_0$ $x$-$z$ cross sections at 10, 20, 30, 40, and 60 min (clockwise from upper left, all centered at $x = y = 0$). Color scales are shown at right for each panel.
trailing edge where initial instabilities are 3D (F15). The instabilities intensify to ~40 min and result in strong dissipation of the initial GW packet thereafter (see section 3.2).

3.2. Implications of 3D and 2.5D Packet Dispersion

Corresponding 2.5D results largely mirror those for the 3D simulation and also illustrate some important differences. The 2.5D x-z cross sections corresponding to Figure 2 are not shown because they are virtually identical in form to the 3D fields at the GW scales, except that the 2.5D fields are larger by ~2–3 times at later times and higher altitudes. This is because spanwise 3D packet dispersion necessarily results in substantially weaker GWs at higher altitudes. These differences can only arise due to the Gaussian distribution of the initial GW packet momentum flux in y, and imply that an assumption of a 2D GW packet will badly overestimate responses at higher altitudes.

The 3D GW packet dispersion and phase distortions are driven by two factors. Localization in x and z implies a spectrum of initial GW k and m yielding dispersion in x and z that would not otherwise occur in the initial uniform environment below the tidal winds. Of greater importance here, GWs comprising the 3D packet experience zonal accelerations in the direction of packet propagation given by

\[
dU/dt \sim -(1/\rho_0) d[\rho_0 <u'w'>]/dz \sim \exp(-y^2/\sigma_y^2)\]

from equation 2 and imply the largest initial spanwise gradients in dU/dz at \( y = \pm 0.71\sigma_x \). The evolving U(x,y,z) thus acquires lateral mean shear that varies as \(-\exp(-y^2/\sigma_y^2)\), differentially rotates GW propagation directions increasingly away from negative x as d\Delta U/dy with maxima at \( x = \pm 0.71\sigma_y \), and yields a bow-wave form in the x-y plane at the leading edge of the GW packet (see the left panels of Figure 4 at 30 min).

Differential advection of the GW phase structure in x is also largest initially at \( x = \pm 0.71\sigma_x \) for the same reasons and accounts for the smaller (larger) \( \lambda_x \) at the leading (trailing) packet edge seen at 30 min in Figure 4. Similar responses occur in altitude but are complicated by density variations in z (see equation

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**Figure 3.** As in Figure 2 but for y-z cross sections (all centered at \( x = y = 0 \)). Note the asymmetric fields due to refracted GW propagation in variable tidal meridional winds.
These influences are common to both the 3D and 2.5D packets and do not contribute significantly to their different responses.

To explore the differences between the 3D and 2.5D GW packet fields prior to 3D instabilities and strong SGW responses more quantitatively, we show in Figure 6 profiles of $u'$, $T'$, $\rho_0 <u'w'>$, $\rho_0 <w'T'>$, $\Delta U$, and $\Delta T$ at 10, 20, and 30 min obtained at the packet centers. Mean fields and GW fluxes are averaged horizontally over the GW phase in each packet. As noted above, differences at these early times are due entirely to spanwise dispersion of the 3D packet over this interval as no GW dissipation has yet occurred. For reference, the peak initial $u'$ and $\rho_0 <u'w'>$ occurred at 38 and 24 km, respectively.

GW $\rho_0 <u'w'>$ from 10 to 30 min shown in Figure 6a reveals several interesting features. The 3D peak flux is smaller and at a comparable altitude at 10 min but occurs at incrementally lower relative altitudes at 20 and 30 min. Additionally, the majority of the vertically integrated flux in each case shifts increasingly with time to altitudes above the respective peaks. The causes of these differing responses are the differing feedbacks of the evolving $\Delta U(z,t)$ on the vertical GW structure in altitude. Emerging $\Delta U$ (Figure 6c) imposes increasing negative GW phase speeds from the peak $\rho_0 <u'w'>$ to ~50–60 km that dictate the kinking of the GW phase structures in altitude seen in the vertical cross sections discussed above. The evolving $\Delta U$ also impose environments having $\text{d}c/\text{d}z > 0 > 0$ and decreasing (increasing) GW $\lambda_z$ below (above) the GW $\rho_0 <u'w'>$ peaks. These influences compress (expand) the trailing (leading) edges of both GW packets, increase in time, and comprise the SA dynamics driving these evolutions. They also act less strongly for the 3D GW packet due to spanwise dispersion.
The differing mean-flow interactions in the 3D and 2.5D cases also impose differing GW evolutions with increasing time and altitude. Specifically, $u'$ and $T'$ profiles (Figures 6b and 6e) are nearly indistinguishable throughout the domain at 10 min because the cumulative $\Delta U$ evolved slowly and the GW packets propagated only ~9 km ($\sim$0.6$\lambda_z$) over this time. Larger differences arose thereafter due to spanwise dispersion impacting amplitudes at lower altitudes and differing propagation environments encountered by the packet leading edges as $\Delta U$ became significant. Throughout these times, however, GW $\rho_0 < w' T'>$ and $\Delta T$ remained small. The oscillatory $\Delta T$ seen above ~70 km, especially at 30 min, is almost certainly a consequence of incomplete GW phase averaging along $x$ due to $\lambda_x$ variations in $x$ resulting from the streamwise packet divergence/convergence discussed above.

### 3.3. Instability Dynamics

As noted above, 3D and 2.5D SA dynamics lead to initial 2D SA instabilities at the upper edge of the GW packet by 30 min (see the cross sections in Figure 2), but the initial 3D instabilities at the trailing edge of
each packet described by F15 and D20 have yet to form. Thereafter, the progression of instability dynamics in both cases is rapid and has significant implications for evolutions of the GW fields, and, importantly, their differences accompanying the presence (absence) of spanwise GW packet dispersion and the influences of tidal winds at higher altitudes.

Zoomed $x$-$z$ cross sections of the instability dynamics in the 3D and 2.5D packet fields are shown from 30 to 60 min at left and right, respectively, in Figure 7. The 3D $y$-$z$ cross sections at $x = -60$ and 0 km are shown at the same times at left and right in Figure 8 to illustrate the influences of 3D GW dispersion on instability responses due to increasing $|dU/dx|$ and $|dU/dy| \neq 0$ for $y \neq 0$.

Comparing the 3D and 2.5D packet cross sections in Figure 7, we see both strong similarities and significant differences. The forms of their responses are similar, given that they are dictated by the character of the underlying GW fields in evolving winds. However, they differ in their intensities, extents, and the degrees of SA and 3D dynamics that have occurred at each time. GW amplitudes are nearly identical at the lowest altitudes at $y = 0$ up to 30 min, but only 2D SA dynamics have occurred by this time, as noted above. Increasing differences in time and altitude arise due to the strong spanwise packet divergence following 3D packet phase distortions and increasing outward GW propagation (away from negative $x$ and $y = 0$) discussed above.

The 2.5D packet exhibits 3D instabilities that persist at lower altitudes due to continued upward propagation of the trailing GW packet and become more intense with increasing altitude. Such dynamics are expected for 3D GW packets that have a larger extent across than along the plane of GW propagation, hence weaker induced $dU/dy$. This includes partial penetration of the ~80-m/s zonal wind maximum at ~110 km, and confinement of instabilities to lower and higher altitudes, in contrast to the continuous instabilities in altitude for no initial mean wind in D20.

The 3D packet also exhibits strong 2D and 3D instabilities that extend from ~70 to 140 km at 40 min and to somewhat lower and higher altitudes and larger $|x|$ thereafter, due to continuing amplitude growth at the leading and trailing edges of the GW packet. However, the instabilities are markedly less intense and extensive than in the 2.5D packet because of the strong spanwise dispersion accompanying spanwise localization of the initial 3D GW packet. As a result, 3D packet instabilities intrude to a much smaller degree into the

Figure 7. As in Figure 2 but for $x$-$z$ subdomain cross sections of $|\zeta'|$ for the (left and right) 3D and 2.5D GW packets encountering tidal winds above ~70 km at (top to bottom) 30, 35, 40, and 60 min. Note the absence of instabilities at ~110 km where eastward tidal winds cause large GW $\lambda_z$.
strong and variable tidal winds than seen in the 2.5D packet (see Figure 7). The reason is that the local GW field is more likely to exhibit instabilities where its $|c|$ and $\lambda_z$ become smaller due to stronger mean winds and shears (Figure 1b).

This argument also explains the different instability altitudes at the spanwise edges of the 3D packet $y$-$z$ cross sections in Figure 8 at 35 min and after (see the GW phase orientations at early times in Figure 8 with the tidal winds in Figure 1). In these cases, GWs propagating toward negative $x$ and positive (negative) $y$ experience decreasing (increasing) $c_i$ and $\lambda_z$ and instabilities displaced downward (upward) with respect to the GWs at $y\sim0$ due to the meridional tidal wind maximum at $\sim105$ km, with negative maxima at $\sim88$ and $128$ km.

Comparing the 3D packet instability features at 40 and 60 min in Figures 2, 3, 7, and 8, it is apparent that instability scales and intensities have decreased at the later times in all regions. At the lowest altitudes, the trailing portion of the GW packet has expanded significantly in $y$ due to earlier spanwise dispersion, decreased in amplitude and $\lambda_z$, and yielded weaker instabilities as a result. The same is true at $\sim70$–$140$ km altitudes, where the instabilities are also weaker and confined to lower altitudes and thinner layers. The 2.5D packet evolution is more representative of GW packets having $\sigma_y >> \sigma_x$. In such cases, GW packet instabilities are stronger and more sustained throughout the atmospheric column. The implications of the 3D and 2.5D GW packet dynamics for SGW generation, GW spectral evolution, and mean forcing are explored below.

### 3.4. SGW and AW Generation and Propagation

As discussed by D20, SGWs readily arise from 2D GW packets undergoing localized SA dynamics and 2D and/or 3D instabilities. D20 also showed that 2D GW packets having amplitudes constrained by realistic 3D instabilities are somewhat less efficient sources of SGWs than their 2D counterparts. This is because 3D instabilities, where they occur, more efficiently reduce GW amplitudes at lower altitudes, hence also reduce momentum transport to, and deposition at, higher altitudes. Here we examine SGW generation...
and propagation for a 3D GW packet exhibiting realistic 3D dispersion and instabilities in 3D tidal winds shown in Figures 2–4. Corresponding 2.5D cross sections are not shown because they are virtually identical in form to the 3D fields at the GW scales, except that the 2.5D fields exhibit SGW amplitudes larger than the 3D amplitudes by ~2–3 times at later times and higher altitudes.

Despite the early stages of 2D SA instabilities and the absence of 3D instabilities and dissipation in the 3D GW packet at 30 min (see Figures 2 and 3), SGWs having \( \lambda_x \sim 100 \) km accompany the leading edges of the GW packet and extend to ~250 km with weak amplitudes. These are necessarily generated at earlier phases of SA instabilities when the responses are 2D and most confined in the zonal direction (see section 3.1). SGW responses and scales increase strongly from 30 to 60 min, even as 3D instabilities are decaying strongly at lower altitudes. SGW responses extend ~800 and 1,600 km in \( x \) at the latter times.

Responses in the \( y-z \) plane are similar, and include the same \( \lambda_y \), but are not as strong near \( x = 0 \) because these fields are near the node between the eastward and westward responses, and the SA responses do not project as efficiently into the \( y-z \) plane (compare the \( x-z \) and \( y-z \) cross sections at 60 min in Figures 2 and 3). In each plane, the SGW \( \lambda_h \) increases at increasing distances, exhibiting \( \lambda_h \sim 100 \) km at ~200 km over the primary instabilities and achieving \( \lambda_h \sim 200–300 \) km at the outer edges of the domain at altitudes above ~130 km.

Figure 4 shows most clearly the outward SGW radiation from the site of the localized initial GW packet. At the lower altitudes, these are seen initially at 120 km beginning at ~40 min and propagate primarily toward negative \( x \) because of the orientation of the initial GW packet. As the GW packet undergoes SA dynamics and stalls (from ~30 to 40 min), however, SGW generation becomes more isotropic and yields more circular responses at larger \( \lambda_h \) at 120 km and above. The dominant direction of propagation at 120 km is toward negative \( x \) because of the strong positive tidal winds at and below 120 km. At 200 km and above, the dominant SGW propagation direction varies strongly with \( \lambda_h \). SGWs having intermediate and larger \( \lambda_h \) and high phase speeds propagating toward negative \( x \) outrun the tidal winds and refract to smaller \( \lambda_x \). Those propagating toward positive \( x \) having larger \( \lambda_h \) refract to larger \( \lambda_x \) and continue to propagate vertically, but those having smaller \( \lambda_h \) become evanescent and do not reach higher altitudes.

Also seen above ~140 km in Figures 2 and 3 are clear AWs, especially in \( w' \), and also in \( u' \) and \( T'/T \). Weak initial responses at 30 min are necessarily generated at lower altitudes prior to the occurrence of 3D instabilities. AWs achieve much larger amplitudes prior to 40 min, and somewhat thereafter, have phase speeds of ~500–600 m/s at the highest altitudes, and exhibit asymmetries in their responses due to the tidal winds, especially in the \( x-z \) plane (see Movies S1 and S2 in the supporting information). They appear to arise largely due to strong, local, transient dynamics, and especially 3D instabilities, at lower altitudes, because they disappear rapidly following cessation of these instabilities.

The major SGWs and AWs are significantly weaker in the 3D case than in the 2.5D case (not shown). At 30 min and later the primary 2D SA dynamics have largely abated and the 3D instabilities are significantly weaker in the 3D than in the 2.5D fields (see Figure 7). This causes the 3D AW and SGW amplitudes to be ~30% smaller in the 3D than in the 2.5D case at 30 min. The discrepancy for both SGWs and AWs is larger at 40 min, with ~60% smaller amplitudes, while at 60 min the dominant SGWs at the larger scales are smaller by ~80%. At each time, these differences can largely be attributed to 3D GW packet dispersion and the weaker induced mean flows and transience that result.

Based on previous modeling studies cited above, we expect that SGWs and AWs can also arise from GW breaking dynamics at smaller scales. Such smaller scales are seen to arise in both the 3D fields in Figures 2 and 3 and in the 3D \( \lambda^* \) fields in Figures 7 and 8 following 3D instability onset. Apparent GW \( \lambda_h \) less than the \( \lambda_i \sim 40–60 \) km initial GW scales are seen initially at 35 and 40 min in Figure 7 at left above ~80 km, and at 60 min above ~60 km, especially in Figure 7. Importantly, however, very small-scale SGWs excited at low altitudes likely have little potential to survive continuing instabilities and reach higher altitudes due to their small phase speeds, tidal wind shears, and increasing viscosity. Larger-scale sources nevertheless appear able to generate SGWs that can propagate to higher altitudes and to larger \( |x| \) and \( |y| \) at late stages in the simulation (see Figures 7 and 8 at lower left). In contrast, we expect AWs arising from GW breaking dynamics at lower altitudes to readily reach high altitudes due to their very high phase speed throughout the atmosphere. Quantifying AW sources and magnitudes may prove to be important, given their potential to achieve large energy fluxes from lower altitudes into the MLT.
3.5. Tidal Influences on GW SA Dynamics

The 3D GW packet responses shown in Figures 2–4, 7, and 8 all exhibit influences of the assumed tidal winds, a number of which were discussed above. Specific features include (1) an increase in the initial GW $\lambda_c$ centered at ~110 km, (2) modulation of the SGWs propagating largely in the x-z plane spanning tidal altitudes, (3) an absence of GW instabilities at altitudes near 110 km, and (4) systematic variable $\Delta U$ in altitude having negative maxima at ~90 and 120 km and a weak positive maximum at ~105 km. A comparison of the altitudes of these responses with the zonal tidal wind yields a plausible explanation for all of these features. The linear GW polarization relations show that $\lambda_c$ decreases with decreasing $|c|/(a$ and vice versa), as occurs for GWs propagating toward negative x where $dU/dz < 0$, as at ~90 and 120 km. Decreasing $\lambda_c$ also increases the tendency for instabilities as it increases $|u'|$ relative to decreasing $|c|$, such that the nondimensional GW amplitude $a = |u'|/|c|$ eventually approaches or exceeds the nominal threshold for instability, $a \sim 1$. The consequences are GW dissipation and momentum deposition in these locations, the opposite response, increasing $\lambda_c$ and suppression of GW dissipation, and momentum deposition, where GW $|c|$ increases, as at ~105 km for GW propagation toward negative x. These dynamics imply filtering of the GW spectrum that encourages vertical propagation of GW propagating horizontally opposite to the tidal wind maxima. This simple explanation accounts qualitatively for the first three features noted above. These GW dissipation and filtering processes are expected to yield large zonal accelerations where the dominant GWs are undergoing strong dissipation and momentum deposition. For predominant propagation of the GW packet toward negative x, these altitudes are ~90 and 120 km, and the $\Delta U(z)$ profiles at 30, 40, and 50 min in Figure 5 confirm this response. The implication of these results is that, while SA dynamics are strong, they are also necessarily modulated by background winds (see Movie S3 in the supporting information).

3.6. Cospectra of $u'$

The 3D simulation $u'$ spectra along x and y, denoted $<u'^2>$ for $|x|$ and $|y|$ ≤ 200 km, are shown at left and center in Figure 9. Corresponding 2.5D spectra along x are shown at right in Figure 9. The spectra are averaged over $|y|$ ≤ 15 km and $|x|$ ≤ 200 km, respectively, and also averaged over 10 km in altitude in four ranges from 30 to 100 km.

Considering first the 3D simulation spectra at 15-min (black lines), we see that $<u'^2(k)>$ is largest below 60 km, largely reflects the initial GW packet wave number dependence in k (the major peak at the GW $\lambda_c = 2\pi/k_0 = 45$ km), and that $<u'^2(l)>$ occurs at smaller l, as expected from inspection of the spanwise fields in Figures 3 and 8. Peak spectral densities in k and l are ~3–10 times smaller at 70–80 km, and much smaller in both spectra above 90 km. These features are consistent with the initial stages of SA dynamics and the apparent absence of initial SGWs and instability dynamics revealed in previous figures.

At 30 min, the 3D GW packet has broadened in x and y and propagated ~15-km higher, initial 2D SA instabilities achieve large amplitudes, and initial SGWs and AWs appear above ~120 km. In response, the spectra (blue lines) show the GW and its harmonics to continue to decrease with increasing k at 30–40 km but to exhibit similar amplitudes at $\lambda_c$ and $\lambda_y < 30$ km (k and l > 0.2 km$^{-1}$) from 30–60 km. Spectral amplitudes at $k = l = 1$ km$^{-1}$ ($\lambda_c = \lambda_y = 2\pi$ km) and ~70–100 km remain very disparate, however, with $<u'^2(k)> ~10^{-8}$ larger than $<u'^2(l)>$, as 3D dynamics have yet to occur.

The 3D packet instability dynamics become very strong at altitudes of ~50–140 km by 45 min, and the k and l spectra reflect their impacts. The k spectra near $k_0$ all decrease by this time due to conversion of GW energy into 3D turbulence, SGWs, and AWs. As a result, spectral amplitudes increase at higher k and l, and lower k, especially at ~50–100 km altitudes. These yield spectral slopes approaching ~5/3 at k and l corresponding to $\lambda_c$ and $\lambda_y < 5–20$ km where Figures 7 and 8 show instabilities begin to constrain GW amplitudes at these altitudes. Importantly, the k and l spectral amplitudes are also now consistent, suggesting a relatively isotropic spectrum above ~70 km as a result of strong instability dynamics spanning a broad region at lower altitudes. Further, these slopes are consistent with that predicted for GWs extending to small scales, assuming spectral forms consistent with early atmospheric observations (VanZandt, 1982).

As discussed above, the 3D packet instability intensities decrease significantly at all altitudes from 40 to 60 min (see Figures 7 and 8). This leads to reduced primary GW amplitudes and much decreased, or cessation of, SGW and AW excitation over this interval. The 3D spectra reflect these dynamics, where spectral
amplitudes below 80 km at $\lambda_x$ and $\lambda_y \sim 20$ km and less are smaller by factors of ~2–10 times or more at 60 min relative to those at 45 min. Spectral amplitudes at 60 min above 90 km decrease by a smaller factor due to sustained energy inputs at the higher altitudes at the later times.

Comparing the 3D and 2.5D $k$ spectra in columns 1 and 3 of Figure 9, we see quite close agreement at 15 min at altitudes below 80 km, apart from increased harmonic excitation in the 2.5D case having no lateral packet dispersion. This is because the initial GW packets have propagated only ~15 km above their initial position, SA dynamics are only beginning to occur, and there has been only weak refraction of the 3D GW packet away from the $x-z$ plane by this time. Even the 2.5D spectral amplitude at 90–100 km is only ~3 times larger due to weak 3D dispersion over ~6 scale heights at earlier times.

By 30 min, however, increasing differences are seen at all altitudes. Referring to Figure 7, we note a tendency for lower and stronger SA dynamics accompanying the 2.5D packet evolution due to its lack of divergence in $y$. The lack of spanwise dispersion results in elevated spectral energies of the primary GW and its higher
harmonics below 60 km at this time. The stronger 2.5D GW and instability dynamics also drive larger spectral amplitudes at larger $k$ than seen in the 3D case that are more pronounced at 50–60 km and decrease above.

More dramatic differences are seen at 45 and 60 min. Here lack of spanwise dispersion yields comparable or larger initial GW amplitudes below 80 km, despite stronger tendencies for 2D and 3D instabilities for the 2.5D simulation. At all altitudes, however, higher $k$ spectra are more energetic in the 2.5D case due to its stronger instability dynamics at these times. Specifically, the 3D GW case exhibits an approximate $-5/3$ slope above 70 km at scales of ~6–30 km at these times, but the 2.5D case exhibits larger spectral amplitudes and slopes nearer $-5/3$ above 50 km extending to smaller scales at these later times.

### 3.7. Cross Spectra

Momentum and heat flux cross-spectra $<u'w'>$, $<v'w'>$, and $<w'T'>$ along $x$ and $y$ for the 3D and 2.5D simulations averaged as above are shown in Figure 10. Considering first the 3D simulation spectra along $x$ at 15 min (black lines), we see that the major fluxes are confined to altitudes below 80 km and

![Figure 10](image-url). As in Figure 9 for the $<u'w'>$, $<v'w'>$, and $<w'T'>$ cross spectra (solid, dashed, and dotted lines, respectively) along $x$ and $y$. Units for the three cross spectra are m$^3$/s$^2$ and K m$^2$/s.
accompany the initial GW and its harmonics in $k$ ($\lambda_k = 45/n$ km, for $n = 2, 3, ...$). Of these, the first harmonic makes the major contributions at all altitudes to $<u'w'>$ because of its larger vertical group velocity, $c_{g0}$, and to $<w'T'>$ because the primary GW ($\lambda_k = 45$ km) has $w'$ and $T'$ in approximate quadrature. The $<u'w'>$ spectra along $x$ are very weak because differential SA dynamics have only begun to influence the initial GW orientation at this time. Spanwise ($y$) flux spectral power at 15 min is confined to smaller $l$ in all cases due to the weak SA influences.

The flux spectra evolve rapidly and reflect the vertical propagation and changing character of the GW responses at 30 min. Spectral amplitudes along $x$ decrease somewhat at the initial GW and larger scales from 30–60 km, but increase at smaller scales below 60 km and increase strongly and extend to lower and much higher $k$ above 70 km. All flux spectra also approach a $-5/3$ slope at scales of 3-20 km above 70 km. Similar responses are seen in the spectra along $y$, and with similar amplitudes and slopes where amplitudes are large.

At 45 min, flux spectral amplitudes exhibit significant variability, with both increases and decreases at larger scales relative to those at 30 min, but consistent, and sometimes dramatic, increases at smaller scales relative to those at 30 min. Amplitudes also increase and extend to higher $k$ and higher $l$ at 50–100 km, and achieve roughly isotropic shapes and amplitudes at the higher $k$ and $l$. However, all flux spectral amplitudes in $k$ and $l$ decrease strongly above 50 km by 60 min at most $k$ and $l$, but with slower decreases at the highest altitudes.

Turning to a comparison of the 3D and 2.5D momentum and heat flux $k$ spectra in columns one and three of Figure 10, we see quite close agreement at 15 min at all altitudes, as seen in the $u'$ spectra in Figure 9. As seen there, this is because the initial GW packets have propagated only ~15 km in altitude, SA dynamics are only beginning, no significant refraction of the 3D GW packet away from the $x$-$z$ plane has occurred by this time, and the spectral shapes and amplitudes are thus nearly identical.

Increasing differences occur at all altitudes by 30 min, however, due to the tendency for lower and stronger SA dynamics accompanying the 2.5D packet evolution because of its lack of dispersion in $y$, causing more rapid initial SA instabilities and stronger driving of 3D instabilities thereafter. The stronger 2.5D GW and instability dynamics drive larger flux spectral amplitudes extending to larger $k$ and approaching a $-5/3$ slope at $\lambda_k \sim 3$-20-km scales at altitudes above 50 km at this time. By comparison, the full 3D results enable instabilities consistent with the 3D dispersion of the GW packet, hence weaker instabilities and smaller flux spectral amplitudes that only yield strong interactions and turbulence above 70 km at this time.

As for the $u'$ spectra shown in Figure 9, more dramatic differences between the 3D and 2.5D simulation flux spectra are seen at 45 and 60 min. The lack of spanwise dispersion was seen above to enable instability dynamics extending from ~30 to 130 km beginning near 30 min and persisting to 60 min and presumably beyond (see Figure 7, right). The larger GW amplitudes and stronger instabilities in the 2.5D simulation yield larger flux spectral amplitudes at larger $k$ than seen in the 3D spectra at all altitudes at these times. At 30–60 km altitudes, spectral amplitudes at larger $k$ exceed those at earlier times, despite the more rapid decay of initial GW contributions in the 2.5D case. At the higher altitudes and smaller scales, flux spectral amplitudes are significantly larger in the 2.5D case and also decay more slowly between 45 and 60 min than in the 3D case.

3.8. Large-Scale Fluxes and Flow Responses

Perturbation fields shown in Figures 2–4 reveal the expansion of the 3D GW packet due to dispersion and refraction accompanying varying SA dynamics along $x$ and $y$ at early times. Additional refraction in $x$ and $y$ arises due to propagation in the varying tidal winds imposed above ~70 km. This acts to dissipate GWs experiencing decreasing $|\zeta|$ and $\lambda_z$, hence decreasing $|<u'w'>|$ and $|<v'w'>|$, and to enable GWs having increasing $|\zeta|$ to have increasing $|<u'w'>|$ and $|<v'w'>|$. The $\rho_0 <u'w'>$ and $\rho_0 <v'w'>$ divergence is thus highly structured in the tidal fields, has different influences in different portions of the GW fields, and leads to large-scale flow responses in $U$, $V$, and $T$.

The $<u'w'>$ and $\Delta U$ fields shown at 30 min in Figures 11a and 11c reveal these dynamics clearly. SA dynamics are strong, but SGWs are weak at this stage (see Figure 2). Hence, GW propagation below ~120 km is largely toward negative $x$, $<u'w'> < 0$, and the maxima occur at ~90 and 110 km, thus coincident with, or just above, maxima in positive $U$ and $|\zeta|$.
Implications for $\Delta U$ are shown at 30 min at upper left in Figure 11c. These reveal a symmetric response about the packet center in $\Delta U$ having a large negative maximum at ~95 km, a weak positive maximum in the opposite tidal shear at ~105 km, and a weaker negative maximum at ~113 km. Responses to the largely zonal $\Delta T$ are asymmetric along $x$ because induced $\partial U/\partial x < 0$ ($>0$) at negative (positive) $x$ with respect to the central GW packet implies $\partial w/\partial z > 0$ ($<0$) and $\partial T/\partial z < 0$ ($>0$) at these locations.

Similar responses are seen accompanying the primary GW packet at 45 min at upper right in Figures 11a, 11c, and 11d. At this time, the major $\langle u'w' \rangle$ has shifted toward negative $x$ because of the increasing negative $c$ due to SA dynamics and expanded somewhat along $x$ due to the continuing dispersion of the GW packet as it propagates to higher altitudes. The cumulative $\Delta U$ is stronger and retains the influences of tidal modulation of the GW $\langle u'w' \rangle$ and also exhibits increasing negative $\Delta U$ due to sustained negative $\langle u'w' \rangle$ and the associated flux divergence as the packet increasingly advects toward negative $x$ and extends to higher altitudes. The evolution of $\Delta T$ likewise retains elements of its initial character, including its anti-symmetric responses to GW forcing and induced mean winds that become increasingly structured in altitude at later times. Importantly, the maximum responses in $\Delta T$ at 45 min occur at ~96 and 113 km at the eastern and western flanks of the peak $\Delta U$, and between the alternating $\Delta U$ maxima in altitude for the reasons discussed above. Also seen more clearly in $\Delta T$ than in $\Delta U$, due to the induced large-scale motions in the $x$-$z$ plane, is a large-scale cooling (weaker warming) toward negative (positive) $x$ extending from ~140 to 260 km.

By 60 min, the primary GW packet disperses further in $x$ and $y$ and largely dissipates, but SGWs are still prevalent and extend to high altitudes and large horizontal distances from the initial packet location. SGWs propagating toward negative $x$ are refracted to smaller $c_y$ and $\lambda_z$ (see Figure 2) due to the assumed $-100$ m/s zonal tide amplitude and the implied smaller SGW negative $c_y$. In contrast, SGWs

Figure 11. (a and b) Streamwise and spanwise cross sections of $\langle u'w' \rangle$ and $\langle v'w' \rangle$, respectively, and (c and d) streamwise cross sections of $\Delta U$ and $\Delta T$, respectively, all at 30, 45, and 60 min (clockwise from top left).
propagating toward positive \( x \) are refracted to larger \( c_{g \omega} \) and \( \lambda_z \) due to much larger positive \( c_i \) (compare the eastward propagating and westward propagating SGW \( \lambda_z \) at high altitudes and 60 min in Figure 2). The responses in \( \Delta U \) and \( \Delta T \) at 60 min are similar to those at 45 min, likewise further extended in \( x \), but are weaker at higher altitudes and larger \( |x| \) due to the much smaller large-scale horizontal divergence forcing these responses.

Similar dynamics occur in the meridional plane, but the responses are neither symmetric nor antisymmetric because the GW packet components having nonzonal propagation are influenced by zonal and meridional large-scale motions. The combined zonal and meridional wind influences on the GW packet evolution account for the strongly asymmetric \( \langle v'w' \rangle \) at the later times shown in Figure 11b. Nevertheless, the major response in the meridional plane at 30 min is the strong negative \( \langle v'w' \rangle \) at \( \sim 105-110 \) km. This occurs immediately above the maximum tidal \( V \) (see Figure 1) and is consistent with the negative correlations of \( \langle u'v' \rangle \) and \( U \) discussed above. A similar anticorrelation is seen at 45 min, where positive \( \langle v'w' \rangle \) centered at \( \sim 130 \) km occurs at and immediately above a maximum negative meridional tidal wind. This anticorrelation persists to 60 min, at which time both positive and negative \( \langle v'w' \rangle \) are seen at higher altitudes in the absence of tidal meridional winds above \( \sim 140 \) km.

To explore the structures of these layered responses in greater detail, we show horizontal cross sections of \( \Delta U \) at adjacent maxima at 100- and 120-km altitudes and 30, 45, and 60 min in Figure 12. At each altitude, the full \( u \) and \( v \) fields were averaged over 600 km in the central domain, with increasing averaging approaching the domain boundaries to account for increasing GW \( \lambda_h \) at larger distances from the primary SA dynamics over the initial GW packet. Spatial averaging largely removed the GWs at increasing radii and also suppressed the smaller-scale mean responses near their maxima. Finally, we note that another large-scale response having a comparable vertical scale, orientation, and \( \Delta U \) to that at 120 km is present at \( \sim 85 \) km where SA dynamics first encounter increasing zonal tidal winds.

Collectively, SA dynamics and tidal filtering of the primary GWs and SGWs, and the associated momentum flux divergence and body forcing, lead to layering of local zonal and meridional mean winds and temperatures that extend over a large region. Ultimately, these yield local mean flows comprising horizontal vortex pairs and additional SGWs having large horizontal scales and small \( c_{g \omega} \) and \( \omega_i \). The horizontal vortex pairs self-advekt along their axes, while the SGWs propagate to higher and lower altitudes, and likely also interact with tidal shears where these are significant.

Figure 12. (a and b) Horizontal cross sections of \( \Delta U \) at 100 and 120 km in increasing horizontal domain sizes at (left to right) 30, 45, and 60 min, respectively. Vectors in each panel show the total horizontal wind, \( \Delta U \) and \( \Delta V \), with the peak vector magnitude equal to the maximum of the respective color scale in that panel.
4. Discussion

Results presented here illustrate the evolutions and dynamics of initially linear 2.5D and 3D GW packets as they propagate to higher altitudes, exhibit nonlinear responses due to amplitude growth with altitude, and interact with tidal winds. These results extend those for a 1D GW packet localized only in altitude by F15, and for 2D and 2.5D GW packets described in D20 in several ways. D20 demonstrated that (1) SA dynamics identified initially in 1D GW packets are operative in 2D packets, (2) SA responses exhibit spatial variability across 2D packets, and (3) SA dynamics lead to strong generation of SGWs and AWs prior to and accompanying GW dissipation that readily propagate to much higher altitudes. D20 also showed that 3D instabilities subsequent to initial 2D SA dynamics cause strong initial GW and SGW dissipation and significantly reduce SGW and AW responses at higher altitudes.

Implications of 3D GW packet localization include (1) 3D dispersion of the GW packet due to SA dynamics that differentially rotate the GW propagation direction away from \( y = 0 \) for increasing \(|y|\) and time, and (2) additional reductions of GW amplitudes, SA dynamics, and SGW and AW generation at higher altitudes due to 3D packet dispersion at lower altitudes. Inclusion of representative 2D tidal winds above \( \sim 70 \) km also enabled an assessment of the influences of tidal shears on primary GW and SGW instability dynamics, momentum transport and deposition, induced transient mean flows, and additional SGWs accompanying these dynamics. Tidal shears were found to constrain GW amplitudes and cause GW dissipation, momentum deposition, and local body forces accompanying decreasing \( c_t \). These dynamics yielded layering of induced mean responses extending horizontally \( \sim 400–600 \) km or larger as GW activity subsided.

Comparing these results with previous studies of SGW generation by local body forces, we note some similarities and also a revision of previous assumptions. Vadas and Fritts (2001, 2002) and Vadas et al. (2003, 2018) argued that SGW forcing and scales are dictated by the spatial and temporal scales of a region undergoing strong GW breaking, and that dissipation yielding momentum deposition is the cause of SGW generation. An analogous mechanism was proposed by Luo and Fritts (1993) but employed a different assumed source for an initial, unbalanced flow that did not require dissipation. By comparison, our results demonstrate unequivocally that initial large-scale SGW generation accompanies body forcing by a GW approaching the amplitude leading to SA dynamics, which cause stalling, cessation of GW vertical propagation, and effective transient GW momentum deposition prior to turbulence and GW dissipation. Thus, large-scale SGW generation precedes, and thereafter may accompany, 3D instability dynamics and turbulence due to GW breaking. In a general and/or complex flow, such as the assumed tidal winds at higher altitudes, continuing interactions among GWs and their varying environments surely imply that SGW generation is a continuous process where these dynamics are active.

We are not aware of any published data exhibiting SA dynamics and its generation of SGWs. However, we are aware of presently unpublished data that reveal such dynamics in ground-based OH airglow imaging (M. Taylor data at the Arctic Lidar Observatory for Middle Atmosphere Research and Bear Lake Observatory) and polar mesospheric cloud imaging aboard the 2018 PMC Turbo stratospheric balloon experiment (Fritts et al., 2019).

5. Summary and Conclusions

GWs transport momentum that resides in the local mean flow. For small-amplitude GWs, this momentum increment is small and leads to slow and systematic GW/mean-flow interactions and influences on the GW that are described well by weakly nonlinear theory (Dosser & Sutherland, 2011; Bühler, 2014). As GW amplitudes increase, however, mean-flow variations become large and cause strong distortions of the GW phase structure referred to here as self-acceleration (SA). This is because mean-flow accelerations arising from GW momentum flux divergence accelerate the GW phase speed. These SA dynamics can occur at all GW scales, and they likely have profound effects on GW propagation, evolution, and dissipation throughout the atmosphere. Yet their implications for GW parameterization and weather forecasting are only beginning to be explored (see Scinocca & Sutherland, 2010, addressing mountain wave SA dynamics).

The SA dynamics addressed here accompany GW packets localized in three dimensions and exhibiting strong nonlinear dynamics. They progress especially rapidly for GWs having higher intrinsic frequencies due to their larger vertical group velocities and steeper phase slopes. Initial 3D GW SA dynamics involve
phase distortions that vary in the streamwise and spanwise planes due to initially streamwise momentum flux divergence that varies in 3D. This results in a GW packet having divergent phase and group velocities in a horizontal plane. Horizontal divergence can significantly offset the rapid evolution of phase distortions with increasing altitude seen for 1D and 2D packets for sufficiently small GW packet extents in the horizontal. However, it does not prevent local, quasi-2D SA dynamics that tilt phases toward vertical at the packet leading edge and stall the 3D packet vertical propagation. Subsequent 2D and 3D SA dynamics at the leading edge and 3D breaking dynamics in increasing shears at the trailing edge contribute to rapid dissipation of the initial GW packet thereafter.

Induced 3D winds driven by SA dynamics of localized 3D GW packets project, in part, onto SGWs having scales dictated by the forcing geometry and temporal evolution. AWs are also excited by these dynamics and readily propagate to much higher altitudes but have no apparent influence on the GW dynamics. As all GW packets are localized in space and time, and GWs exhibit large amplitudes implying strong local mean-flow interactions throughout the atmosphere, SGW generation must occur virtually continuously on horizontal scales from tens of meters to thousands of kilometers from the stable boundary layer into the thermosphere. Nevertheless, we expect the major contributions to occur for those GW packets accounting for the largest local energy and momentum fluxes from sources at lower altitudes.

Recent inferences of statistical or specific local SGW responses accompanying expected GW breaking and momentum deposition in several observational and modeling studies provide evidence of the broad importance of these dynamics throughout the atmosphere (de Wit et al., 2017; Becker et al., 2018; Vadas et al., 2018). Specifically, our modeling results presented here demonstrate that SGW generation is an inherent consequence of GW propagation and momentum transport for localized GW packets.

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