Secondary Gravity Wave Generation Over New Zealand During the DEEPWAVE Campaign

Katrina Bossert  
*Global Atmospheric Technologies and Science, Inc.*

Christopher G. Kruse  
*Yale University*

Christopher J. Heale  
*Embry-Riddle Aeronautical University, HEALEC@erau.edu*

David C. Fritts  
*Global Atmospheric Technologies and Science, Inc.*

Bifford P. Williams  
*Global Atmospheric Technologies and Science, Inc.*

*See next page for additional authors*

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Secondary gravity wave generation over New Zealand during the DEEPWAVE campaign

Katrina Bossert, Christopher G. Kruse, Christopher J. Heale, David C. Fritts, Bifford P. Williams, Jonathan B. Snively, Pierre-Dominique Pautet, and Michael J. Taylor

Abstract

Multiple events during the DEEP Propagating Gravity Wave Experiment measurement program revealed mountain wave (MW) breaking at multiple altitudes over the Southern Island of New Zealand. These events were measured during several research flights from the National Science Foundation/National Center for Atmospheric Research Gulfstream V aircraft, utilizing a Rayleigh lidar, an Na lidar, and an Advanced Mesospheric Temperature Mapper simultaneously. A flight on 29 June 2014 observed MWs with horizontal wavelengths of ~80–120 km breaking in the stratosphere from ~10 to 50 km altitude. A flight on 13 July 2014 observed a horizontal wavelength of ~200–240 km MW extending from 20 to 90 km in altitude before breaking. Data from these flights show evidence for secondary gravity wave (SGW) generation near the breaking regions. The horizontal wavelengths of these SGWs are smaller than those of the breaking MWs, indicating a nonlinear generation mechanism. These observations reveal some of the complexities associated with MW breaking and the implications this can have on momentum fluxes accompanying SGWs over MW breaking regions.

1. Introduction

Gravity waves (GWs) strongly influence dynamics in the mesosphere and lower thermosphere (MLT), primarily via the transport of energy and momentum from the lower atmosphere to the middle and upper atmosphere. Momentum deposition due to GW breaking and dissipation causes deceleration of zonal mean winds in the MLT, inducing closure of the mesospheric jets, resulting in a residual circulation from the summer to the winter hemisphere near the mesopause [Holton, 1982, 1983; Garcia and Solomon, 1985; Haynes et al., 1991; Fritts and Alexander, 2003; Kim et al., 2003]. An additional consequence of GW breaking is the generation of secondary GWs (SGWs), and this has been shown through several modeling studies [Franke and Robinson, 1999; Holton and Alexander, 1999; Vadas et al., 2003; Satomura and Sato, 1999; Bacmeister and Schoeberl, 1989; Lane and Sharman, 2006; Chun and Kim, 2008; Zhou et al., 2002]. SGWs can be generated in the troposphere and stratosphere [Woods and Smith, 2009; Lane and Sharman, 2006] and in mesosphere and thermosphere [Chun and Kim, 2008; Vadas and Nicolls, 2009; Nicolls et al., 2012; Smith et al., 2013].

Several mechanisms exist for SGW generation. Vadas et al. (2003) suggested a mechanism for linear SGW generation due to the body force resulting from momentum deposition that occurs because of GW breaking. These SGWs have larger resulting scales than the breaking primary wave. However, there also exist modeling studies which demonstrate smaller scale or similar scale SGWs compared to the breaking GW, and these SGWs are generated via nonlinear mechanisms. Bacmeister and Schoeberl (1989) showed downward propagating SGWs on a similar scale to the primary breaking MW. Satomura and Sato (1999) demonstrated the presence of SGWs on much smaller scales than the primary breaking MW. Franke and Robinson (1999) investigated numerically the generation of SGWs that were harmonics of primary GWs, arising due to non-linear wave-self interactions in the vicinity of breaking regions. Snively and Pasko (2003) demonstrated that harmonic small-scale SGWs arising from typical convectively generated primary GWs may be subject to ducting, as proposed by Vadas et al. (2003) in the context of linear SGW forcing.

SGWs transport a portion of the momentum deposited by the breaking primary GW to lower and higher altitudes, but that which is transported upward has more significant effects on the atmosphere due to the exponential reduction in density with height [Lane and Sharman, 2006; Vincent et al., 2013; Chun and Kim, 2008; Vadas and Liu, 2009]. Observations over the Andes suggest the potential for SGWs in the...
Furthermore, observations from over Esrange in Sweden during the GW-LCYCLE 1 campaign demonstrate spectral broadening over regions of orographic wave breaking [Ehard et al., 2016]. Recent observations by Park et al. [2014] show significant correlations between GWs observed near 400 km in altitude with GWs at 90–98 km in altitude and far less correlation with GWs at 82–88 km in altitude, implying that GW activity in the thermosphere region could be driven by what are likely locally generated GWs above 90 km. Additionally, John and Kumar [2012] have shown that the observed GW spectrum in the stratosphere maintains its morphology up to ~80 km and differs in the region from 80 to 100 km. Thus, GWs generated locally near these higher altitudes may be a major contributor to momentum transport above.

The Deep Propagating Gravity Wave Experiment (DEEPWAVE) campaign provided multiple opportunities for studies of MW and SGW generation and responses, and other topics in the stratosphere and MLT via the correlative Gulfstream V (GV) lidars and Advanced Mesospheric Temperature Mapper (AMTM) during 25 research flights. The DEEPWAVE campaign operations took place from Christchurch, NZ, during June and July of 2014 with flights over the South Island of New Zealand, Tasmania, and the surrounding Southern Ocean, a hot spot area for GW activity. An overview and various results from the DEEPWAVE campaign are provided by Fritts et al. [2016a].

LiDAR and AMTM data obtained during two DEEPWAVE South Island cross-mountain research flight legs will be used to investigate two case studies of SGW generation in the stratosphere and in the MLT. Stratospheric observations of SGWs were obtained on 29 June 2014 (RF12), while SGW generation in the MLT was measured on 13 July 2014 (RF22).

2. Instrumentation

Data employed in this study were obtained by instrumentation onboard the GV, which included the Rayleigh lidar, the Sodium resonance lidar, and the AMTM, the latter of which provides overhead OH emission intensity and associated temperatures in an imaging 2-D array. Additionally, two side-viewing OH emission cameras were used during the DEEPWAVE campaign and extended the combined cross-track field of view (FOV) to ~900 km. These instruments are discussed below.

2.1. Rayleigh Lidar

The Rayleigh lidar onboard the GV during the DEEPWAVE campaign used a diode-pumped neodymium-doped yttrium lithium fluoride laser generating 5 W at a 351 nm wavelength and 1 kHz pulse repetition frequency. The return signals were received using a 0.3 m diameter Newtonian telescope. The detector had a 50% quantum efficiency, low-noise, photomultiplier tube. Return signals were recorded at 1 s temporal and 37.5 m resolutions. For the purposes of this analysis, data were grouped into 36 s temporal (~8.6 km spatially) and 600 m altitude bins to improve signal quality. These were then averaged using a sliding average of three bins temporally and four bins in altitude. Background temperatures are calculated using a 20 bin by 4 bin boxcar smoothing or ~160 km horizontal by 1.2 km vertical smoothing, and this is subtracted from the measured temperatures to obtain perturbation quantities. The Rayleigh analysis procedure seed temperatures at 63 km using the European Centre for Medium-Range Weather Forecasts (ECMWF) model temperature at that altitude. Temperature results for these studies are shown from 23.5 km to 51 km.

2.2. Sodium Lidar

The sodium lidar used a narrowband Toptica continuous wave laser that produces 10 W at 589 nm with a 10 MHz linewidth. This output light was locked to the D2a line of the sodium Doppler-free saturation spectrum. An acousto-optic modulator produced 20 μs square pulses repeating at 1 kHz. The pulsed beam had 150 km total range and a 3 km pulse width. The available high-resolution return counts were collected in 1 s temporal (~230 m horizontally) and 300 m range bins which are then averaged with a 15 s (~3.4 km horizontally) and 1.8 km rectangular smoothing during data analysis. To obtain perturbations of small-scale horizontal features, a 100 bin by 8 bin boxcar smoothing was done to obtain the background. For model comparison, the mean sodium density profile used in the model was subtracted from both the model output and the sodium densities. The counts were Rayleigh normalized at altitudes from 30 to 35 km using Mass Spectrometer Incoherent Scatter model outputs. Density errors due to photon noise are $5e7–6e7 \text{m}^{-3}$ between 90 and 100 km near the peak of the layer and less than $4e7 \text{m}^{-3}$ below ~87 km.


2.3. Advanced Mesospheric Temperature Mapper
The Advanced Mesospheric Temperature Mapper (AMTM) allowed for measurements of OH emission intensities and temperatures. For the studies on 13 July 2014, the OH intensities from the AMTM and side-viewing OH cameras were used. The OH emission comes from an ~8 km full width at half maximum layer centered near ~87 km altitude. The AMTM comprises of a 320 × 256 pixel IR sensor, a large-aperture telecentric lens system, and a computer-controlled filter wheel to sequentially image the brightness of the P1(2) and P1(4) lines of the OH(3,1) band. For the studies in this paper, the P1(2) brightness is used. The AMTM provided an overhead OH emission map over ~120 × 80 km area continuously along the GV flight track. During the DEEPWAVE flights, the exposure time for the P1(2) brightness was 4 s. Images were taken every 16 s. The side-viewing cameras offer a wider FOV of several hundred kilometers on either side of the GV. A north-south slice from each image can be used from successive images to generate a keogram map over the extent of the flight, offering a spatial view of the OH emission.

3. Observations and Modeling
Separate SGW events observed in the stratosphere and the MLT are discussed in detail in the following subsections. These events were observed on flight tracks over the New Zealand South Island on the 29 June 2014 and 13 July 2014.

3.1. Secondary GW Generation in the Stratosphere
The DEEPWAVE research flight on 29 June 2014 (RF12) sampled MW and related dynamics over the New Zealand South Island. The flight extended from 8 to 17 UT with repeated flight segments over both Mount Aspiring (−43.60°, 170.14°E) and Mount Cook (−44.38°, 168.73°) in a rectangular flight track configuration oriented roughly perpendicular to the mountain range. Each flight segment maintained a constant altitude near ~12.5 km (less than 40 m variation per flight leg). Plots of the topography along the two cross-mountain flight tracks are shown in Figure 1. During several of these flight segments, conditions leading to SGW generation and responses at higher altitudes were observed. The data and modeling of these events are further discussed below.

3.1.1. WRF Modeling
The Weather Research and Forecasting (WRF) model was initialized at 00 UTC on 24 May 2014 and run through 00 UTC on 1 August 2014 with outputs provided every 3 h with 6 km horizontal resolution and 111 vertical levels from the surface to 1 hPa (~45 km) with a 10 km sponge layer at the top (35–45 km), with the highest resolution being near the surface (40 levels below z = 10 km). A 2 arcmin digital elevation map was bilinearly interpolated to the WRF grid to produce model terrain. The run was primarily forced by boundary conditions provided by ECMWF (0.125° resolution) operational analyses every 6 h. Adaptive time stepping was used to increase integration efficiency, where the time step was adjusted at every step to approach but not exceed 70% of the maximum stable time step and not allowed out of range 1 s to 30 s. Time steps near 20 s were typical during the mountain wave events. Additional configuration details are given in Kruse and Smith [2015], and this simulation is extensively validated against DEEPWAVE data sets in Kruse et al. [2016].
WRF meridional and zonal winds at 12 UT averaged across both the Mount Aspiring and Mount Cook tracks are shown in Figure 2. Winds along the Mount Cook and Mount Aspiring flight tracks were similar. These model outputs show the winds between 1 and 3 km in altitude, where MW forcing would occur, to be between ~2 and 15 m s\(^{-1}\) zonally and ~−25 m s\(^{-1}\) meridionally, indicating that generated MWs would need to have an intrinsic propagation direction toward the Northwest.

The WRF model spatial outputs at altitudes of 15, 20, and 35 km are shown in Figure 3. Times are offset at each altitude to account for vertical propagation time of the MW. These outputs reveal MW activity oriented ~40° west of north between 10 km and 35 km. The MW activity is also shown to be more notable at higher altitudes above 15 km during earlier times but is not as readily apparent at altitudes near 35 km due to the dissipation experienced between 15 and 25 km. In addition to the ~100 km MW, several smaller-scale features are also observed. There are 20–30 km horizontal wavelength features observed to be oriented along the mountain range of the southern island, and given the orientation and extent of these smaller waves, it is likely that multiple scales of MWs are present. Given the predicted MW orientation and expected propagation toward the Northwest, winds along each flight track were calculated and projected into the plane of MW propagation at 40° west of north for further analysis. The WRF winds projected into the plane of MW propagation are shown in Figure 4. The winds are similar over both Mount Cook and Mount Aspiring, and there is a clear decrease in the wind magnitudes between 10 and 20 km in altitude. WRF winds from 15 UT (not shown) are similar in magnitude to the winds at 12 UT. The WRF projected winds were compared with Hokitika radiosonde measurements taken between 10:53 and 12:17 UT over the range from 171°, −42.7° to 171.7°, −43.5°, and average flight level winds over the Mount Cook and Mount Aspiring tracks. There is good agreement among these measurements, which are plotted with the WRF winds in Figure 5. The winds in the plane of MW propagation decrease to ~10 m s\(^{-1}\) in the Southeast direction near 20 km in altitude. The decrease in the winds in the lower stratosphere has been observed to varying degrees throughout the DEEPWAVE...
campaign and is referred to as a mountain wave valve layer, where the ambient wind speed causes mountain waves to attenuate. The valve layer observation and effects on MW propagation are further described by Kruse et al. [2016].

3.1.2. Primary MW Observations
Rayleigh lidar temperature perturbations for three passes over Mount Aspiring are shown in Figure 6. Those for two consecutive passes across Mount Cook are shown in Figure 7. In all of the passes except for the early
pass over Mount Aspiring there appears to be breaking at and below altitudes observed by the Rayleigh lidar as the MWs are not fully apparent at all altitudes, and the phases are distorted in altitude and along the flight path. The MW phases are highlighted with dotted lines in Figures 6 and 7. GWs with different phase orientations are observed at higher altitudes above the MWs in the latter two passes of Figure 6 and in the first pass of Figure 7, and these become especially apparent near ~30 km and above. Since the MWs have an intrinsic phase speed toward the northwest against the mean wind, the observed GWs with different phase orientations above ~30 km cannot be MWs forced under the same conditions as the dominate MW scales at lower altitudes, as their phase orientations do not match those of MWs. The early pass over Mount Aspiring shows that the MW is visible at all ranges and altitudes along the flight track, indicating that less breaking has taken place with the MW up to observed altitudes during this time. Additionally, no secondary GW features are apparent above 30 km for this first pass. Vertical cross sections from the Mount Cook and Mount Aspiring flight tracks in the WRF model near similar times to the observations are shown in Figure 8. These outputs demonstrate the presence of the ~100 km MW and also ~20–30 km horizontal wavelength features that are also aligned with a westward phase tilt. As previously mentioned, these specific features may be smaller-scale MWs. There are no clearly visible features that have different phase orientations from the primary MWs.

The WRF model predicts strongly reduced winds in the plane of MW propagation between ~15 and 25 km. The reduced winds limit the MW amplitude and induce MW breaking, dissipation, and nonlinear effects [Fritts, 1984; Lindzen, 1981]. The condition for GW stability in terms of GW perturbation amplitude with respect to the background wind is given by equation (1) [Fritts, 1984],

$$|u_0| < c_H - \bar{U}_H$$  (1)

where $c_H$ is the ground relative phase speed and $\bar{U}_H$ is the mean background wind in the direction of MW propagation. Relevant parameters for equation (1) and other equations used in this section are defined in Table 1.

During formation or in temporally varying mean winds, MWs may have variable phase speeds, but a general
assumption for MWs is that the ground relative phase speed is close to zero. In this typical case of MWs, $c_H = 0$, so their amplitude is limited by the magnitude of $U_H$. The $U_H$ value can be estimated from the WRF model output. For the passes over Mount Cook and Mount Aspiring in Figures 6 and 7, the MW is coherent at lower altitudes, and vertical and horizontal wavelengths can be estimated, also allowing for estimates of $U_H$. $U_H$ is also related to the vertical wavelength using the dispersion relation given in equation (2),

$$ m^2 = \frac{N^2}{(c_H - U_H)^2} - \frac{k_H^2}{4H^2} $$

where $N$ is the buoyancy frequency in $s^{-1}$, $k_H$ is the horizontal wave number, $H$ is the scale height, and $m$ is the vertical wave number. $N^2$ was calculated from equation (3), where $g$ is the gravitational acceleration, $T$ is the background temperature, and $\Gamma$ is the adiabatic lapse rate.

$$ N^2 = \frac{g}{T} \left( \frac{dT}{dz} + \Gamma \right) $$

Using the averaged Rayleigh temperatures along the flight passes, the mean $N^2$ was calculated to be between $3.5e-4$ $s^{-2}$ and $4e-4$ $s^{-2}$. The horizontal and vertical wavelengths $\lambda_H$ and $\lambda_z$ were approximated for both cases as well between 25 km and 40 km. Measurements along the flight track, which was nearly perpendicular to the MW, showed $\lambda_H \sim 100$ km for the MW (values ranged between 80 and 120 km). Below 32 km, the MW appeared to have a $\lambda_z \sim 4$–5 km. Between 30 and 40 km, MW perturbations appeared to have a $\lambda_z \sim 7$–8 km. Using these $\lambda_H$ and $\lambda_z$ estimates and $N^2 = 3.75e-4$ $s^{-2}$, equation (2) yields a wind $U_H \sim 12$–15 m s$^{-1}$ between 25 and 30 km and $\sim 20$–25 m s$^{-1}$ between 30 and 40 km for flight times shown in Figures 6 and 7. Wind estimates using the MW $\lambda_z$ observed in the lidar data are similar to those predicted by WRF.

\[ \text{Figure 6. Rayleigh lidar temperatures for three passes over Mount Aspiring. Distance from Mount Aspiring is positive toward the Southeast and negative toward the Northwest. The dotted lines demonstrate the MW phase lines. The black arrows demonstrate secondary wave features above the MW region.} \]

\[ \text{Figure 7. Rayleigh lidar temperatures for two passes over Mount Cook. Distance from Mount Cook is positive toward the Southeast and negative toward the Northwest. The dotted lines in the right figure indicate MW phase lines. The black arrows demonstrate secondary wave features above the MW region, and the gray arrows demonstrate small-scale features associated with MW breaking.} \]
Given the noted decrease in $U_H$ in WRF above 10 km, the observed small $\lambda_z$ in the lidar measurements between 25 and 30 km indicative of small $U_H$ and the low temperature perturbation of the MWs at these altitudes, the evidence supports that these MWs propagating through the valve layer are experiencing effects of saturation due to the decreasing $U_H$ between 10 and 20 km, and associated dissipation. This is also indicated by the WRF model outputs shown in Figure 8, especially over Mount Cook. The temperature perturbations over Mount Cook decrease with altitude, and those over Mount Aspiring appear to stay relatively constant with altitude. It is expected for a nondissipating GW that amplitude will grow with altitude by $\sim e^{(x-x_0)/2H}$ [Fritts and Alexander, 2003]. As discussed in Fritts [1984], saturation occurs when the GW amplitude is limited by the background wind, which can happen when a GW approaches a decrease in background winds or when the amplitude and growth with altitude are limited due to the background winds. Thus, a decreasing or constant amplitude with altitude and time indicates a dissipating GW. As previously shown by equation (1), $u_H$ can be used to indicate saturation. One would expect more dissipation to occur as $u_H/U_H$ approaches 1. WRF $u_H$ values over the Mount Cook and Mount Aspiring tracks are given in Figure 9. The Mount Cook track shows $u_H$ perturbations near 10 m s$^{-1}$, which results in saturation. The $u_H$ minimum for both flight tracks is found near 20 km, close to the $U_H$ minimum, and perturbations above this region begin to increase again, though not necessarily exponentially.

It should also be noted that there may be regions of higher and lower $U_H$ not captured by WRF. This variability in winds can have influences on MW propagation and dissipation at all altitudes. The lidar observations at higher altitudes show that there is variability in the MW vertical structure over both Mount Cook and Mount Aspiring, indicating the transience and turbulence associated with the breakdown of the MWs. It is clear that there is a strong trend of decreased winds at lower altitudes contributing to this.

### 3.1.3. Secondary GW Observations

The Rayleigh lidar measurements show GW features seen initially near ~30–35 km arising above regions of MW breaking. The location of these observed features indicate the possibility that these GWs are SGWs arising from MW breaking and dissipation. These features are indicated by black arrows in Figures 6 and 7. The later pass over Mount Cook in Figure 7 observed multiple small-scale features that appear to be associated with the MW dissipation, but these did not have a distinct phase structure. These features are indicated by gray arrows. The first pass over

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**Table 1.** Gravity Wave and Background Parameters Used in This Paper

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U = (U, V, W)$</td>
<td>background wind vector</td>
</tr>
<tr>
<td>$(u', v', w')$</td>
<td>GW wind perturbation (zonal, meridional, vertical)</td>
</tr>
<tr>
<td>$\bar{U} = \frac{(kU + lV)}{kH}$</td>
<td>horizontal background wind in direction of wave propagation</td>
</tr>
<tr>
<td>$H = RT/g$</td>
<td>atmospheric scale height</td>
</tr>
<tr>
<td>$\lambda_x, \lambda_y, \lambda_z$</td>
<td>wavelengths (zonal, meridional, vertical)</td>
</tr>
<tr>
<td>$k = (k_x, k_y, k_m)$</td>
<td>wavenumbers (zonal, meridional, vertical)</td>
</tr>
<tr>
<td>$\lambda_H = \frac{2\pi}{k_H}$</td>
<td>horizontal wavelength</td>
</tr>
<tr>
<td>$k_H = \sqrt{k_x^2 + k_y^2}$</td>
<td>horizontal wave number</td>
</tr>
<tr>
<td>$m = 2\pi/\lambda_z$</td>
<td>vertical wave number</td>
</tr>
<tr>
<td>$u_H = \sqrt{u'^2 + v'^2}$</td>
<td>horizontal wind perturbation</td>
</tr>
<tr>
<td>$c_H$</td>
<td>horizontal phase speed</td>
</tr>
</tbody>
</table>
Mount Aspiring shows the MW clearly up to 50 km, but no additional GW features appear to be present at higher altitudes. A Morlet Wavelet analysis was performed on the Rayleigh lidar temperature perturbations at 33 km and 45 km for each of the five cross mountain passes. These results are shown in Figures 10 and 11 for the Mount Aspiring and Mount Cook passes, respectively. For these analyses, temperature perturbations at 45 km were normalized to account for growth in altitude expected for GWs and MWs over the range between 33 and 45 km. A scale height of 6.3 km was used for this normalization. For the five passes, waves are present with a $\lambda_H$ between ~80 and 130 km near 33 km in altitude. The wavelet analyses for Mount Aspiring at 33 km are shown in Figures 10a, 10c, and 10e, and the corresponding wavelet analyses at 33 km for the Mount Cook passes are shown in Figures 11a and 11c. The horizontal wave scales change significantly at 45 km in altitude for all passes except for the earliest pass over Mount Aspiring, shown in Figure 10b, where the dominant $\lambda_H$ is still ~130 km, and no notable spectral power for $\lambda_H$ below 50 km. The dominant $\lambda_H$ at this higher altitude vary between 30 and 50 km for the four later passes shown in Figures 10d and 10f and 11b and 11d, and the spectra associated with the primary MW have largely dissipated, indicating continued MW dissipation between 33 and 45 km. While clear indications of SGW phases were not apparent in the temperature perturbations during the second pass over Mount Cook, the wavelet analysis shows a decreased power associated with the primary MW spectra, and an increase in smaller-scale features, which may be associated with the MW breaking. This change in dominant wave scales shifting from the wavelength of the primary MW to smaller scales at higher altitudes is indicative of SGW generation associated with the primary MW dissipation. It should be noted that in the first pass where the MW has maintained structure up to 50 km, there were no observable smaller-scale GW features. This provides further evidence that the dissipating MWs at lower altitudes are associated with the smaller $\lambda_H$ GW features observed at higher altitudes.

It is unlikely that these SGW features are propagating downward, assuming that SGWs would have a small initial amplitude, as any downward propagation would reduce the amplitude exponentially with decreasing altitude. However, SGWs generated in the region of strongest MW dissipation between 10 and 20 km would have 2–3 scale heights to grow in amplitude, reaching the more visible perturbations seen above 30 km. We note that these features are not observed in the lower altitudes of the lidar data. There are several potential reasons for this. The SGW packets being generated are intermittent; thus, the packets will not be seen at all altitudes. Additionally, the SGW packets do not propagate vertically but propagate along slanted paths dictated by their group velocities from nearby MW breaking regions that may occur at multiple sites over the South Island. Also, the amplitude of initially generated SGWs may be quite small, thus undetectable by the lidar at lower altitudes.

It should also be noted that it is possible that these SGW features at higher altitudes may come from other sources, and it is even likely that there are waves from other sources superimposed on the MWs. However, the SGW features are most strongly observed during the middle passes over Mount Cook and Mount Aspiring where the MW has become much less coherent and not observed everywhere along the pass. Small-scale features are not observed until over 40 km in altitude during the last pass over Mount Cook, where the MW is visible at least up to 40 km and across the whole flight leg. These SGWs are also not
observed during the first pass over Mount Aspiring when the MW is visible up to higher altitudes, thus experiencing less dissipation. Given this, it appears that these small horizontal scale features are associated in time with the MW breaking at lower altitudes. These secondary features vary between the passes when present, but all demonstrate $\lambda_H$ that are shorter than the initial MW, and phase slopes with altitude that are opposite to the MWs below. These secondary features likely have varying phase speeds, which could cause measured $\lambda_H$ to be longer or shorter than the actual $\lambda_H$ depending on the phase and orientation of the SGWs, but the actual $\lambda_H$ would still be less than the initial MW $\lambda_H$. Given the shorter $\lambda_H$, it appears that these SGWs are generated through nonlinear dynamics accompanying the MW breaking in the valve layer as opposed to the linear SGW generation mechanism proposed by Vadas et al. [2003].

Figure 10. Morlet Wavelet analysis of the Rayleigh temperature perturbations for the three flight cross sections over Mount Aspiring. (a, c, and e) Analyses done at 33 km in altitude. (b, d, and f) Analyses done at 45 km in altitude. Figures 10d and 10f demonstrate the emergence of smaller scale features at higher altitudes and a shift in spectral power from the primary MW to the smaller scale features at 45 km.
Throughout the above discussion, we have assumed that MW breaking and SGW generation accompany the approach of the MW amplitude to the overturning condition $u_H = \frac{1}{H}$, implying a Richardson number $R_i = 0$. The Richardson number is not a perfect guide to MW, or more general GW breaking, however, as theory and modeling reveal that a GW can become unstable and initiate 3-D instabilities and turbulence for $R_i$ below and above $\frac{1}{4}$ [Lombard and Riley, 1996; Sonmor and Klassen, 1997; Fritts et al., 2009a, 2009b]. As a result, it is useful if an estimate yields $R_i \approx 0$, but this is not a necessary condition for instability in multiscale flows in which $R_i$ is highly variable and there are multiple sources of instabilities [Fritts et al., 2016b]. In the case of the MW observations for 29 June 2014, the associated WRF modeling demonstrates amplitude decay of the MWs within the region of the valve layer as previously shown in Figures 8 and 9, indicating dissipation associated with instabilities.

### 3.2. Secondary GW Generation in the MLT

During the DEEPWAVE flight on 13 July 2014 (RF 22), there were four flight segments over South Island that occurred between 6 UT and 9.5 UT. Figure 12b shows the mountainous terrain along these passes, all of which went over Mount Cook.

#### 3.2.1. Propagation Environment

Throughout the 13 July 2014 flight, a notable ~200–240 km MW was observed during the entire flight in the Rayleigh lidar, sodium lidar, and AMTM. Additionally, several smaller scale GWs were observed by the AMTM and sodium lidar. The momentum fluxes of these waves were discussed previously by Bossert et al. [2015]. Figure 12a shows the Rayleigh measurements of the ~200–240 km MW that was discussed in Bossert et al. [2015]. Figure 13a shows the OH airglow emission along the first pass,
highlighting the ~200–240 km MW and some features at smaller scales. This AMTM measurement revealed multiple smaller-scale features within the larger-scale MW. As described by Bossert et al. [2015], there was a critical level for MWs near ~90 km where zonal winds approached zero, which prevented the ~200–240 km MW from propagating to higher altitudes, and strongly constrained the MW amplitude approaching this altitude (as is expected from equation (1)).

### 3.2.2. Secondary GW Observations

High-resolution sodium densities and perturbations were computed for some portions of the flight, including the first pass. Figure 13b shows the sodium densities along the flight track for pass 1. These reveal larger-scale features associated with the MW as low as ~70 km that disappear near the critical level, and many smaller-scale features beginning ~15 km below the critical level to ~15 km above. Figure 14 shows density perturbations over a portion of the pass shown in Figure 13b starting just over Mount Cook to 200 km east of Mount Cook. These perturbations were found by subtracting a running background mean of 100 bins temporally and 2.4 km vertically in order to emphasize smaller features with \( \lambda_H < 30 \) km within larger-scale features. These perturbations emphasize the presence of small-scale features on the order of ~10–30 km horizontally having varying phase orientations at different altitudes. At lower altitudes, these appear to accompany the lowest excursions of the Na layer due to the primary ~200–240 km MW discussed by Bossert et al. [2015]. Near and above ~85 km, however, there are multiple regions in which the phases having maximum Na densities exhibit primarily upstream (up and to the west) or downstream (up and to the east) orientations. Referring to Figure 14, the larger scales ~20–30 km horizontally, indicated with red arrows, have phase structures that are nearly vertical, but with suggestions of upstream phase tilts at ~75 km and at ~95 km. Phase tilts are more conspicuous for the ~10 km Na perturbations, with both upstream and downstream tilts where indicated by white arrows. Morlet Wavelet analyses at 75 km, 86.5 km, and 94 km further demonstrate the presence of these wave scales, and the resulting analyses are shown in Figure 15. At 75 km and 86.5 km, there is a notable presence of waves in the 10–20 km range. At 86.5 km and 94 km, there is evidence of 40 km horizontal wavelength GWs. Near 94 km, the 20–30 km GWs are clearly seen in the wavelet analysis. These confirm a variable spectra of small horizontal scale GWs near the region of MW breaking. It should also be noted that these observed GWs may also have a wide range of phase speeds which we cannot detect from the sodium densities alone. These phase speeds have the potential to make observed GWs appear to have longer or shorter horizontal wavelengths depending on the direction of propagation relative to the flight.
path. Assuming a flight speed of 240 m s\(^{-1}\), \(\lambda_H\) ranging from 20 to 30 km as measured by Bossert et al. [2015], and phase speeds ranging from \(-100\) m s\(^{-1}\) to 100 m s\(^{-1}\), resulting \(\lambda_H\) measurements from the sodium lidar would range between 15 km and 50 km in the extremes of these cases. Thus, the spectra of observed waves may have horizontal wavelengths slightly outside of, or smaller than, the range of 10–40 km.

It is important to note that the ability to detect smaller-scale GWs in the sodium densities is dependent on the layer structure itself [Swenson and Gardener, 1998; Shelton et al., 1980; Bossert et al., 2014]. However, due to the larger sodium density gradient on the bottomside of the layer than near the center of the layer, GWs in this lower region are more readily detected in the density perturbations. Given the different alignment of these structures, and the background MW in the presence of a critical level, these wavelike features appear to have arisen accompanying MW breaking below \(-90\) km, and perhaps extending as low as \(-72\) km. The periodic phase structures, their various phase slopes with altitude, and the occurrence of these features immediately above a region of strong MW breaking suggest that these are features associated with MW breaking and SGWs being generated below. While a critical level exists for MWs, SGWs generated from such a region would have a range of phase speeds and propagation directions, meaning that a critical level for MWs would not hinder SGW propagation when the intrinsic phase speed is significantly different from zero. Heale et al. [2017] found through simulation of the 200 km MW from this day that there was evidence for SGWs at these altitudes with varying wavelengths. A comparison of modeling results and lidar data is discussed in the following section.

Figure 13. (a) The OH airglow emission along the first pass, which highlights the \(-200\) km MW as well as multiple smaller-scale features within the larger scale MW. (b) The corresponding sodium density measurements.
3.2.3. Secondary GW Instabilities and Model Comparisons

Heale et al. [2017] also found evidence for SGWs and wavelike features in two-dimensional nonlinear simulations of this ∼200 km MW event, which were identifiable throughout the upper mesosphere, including above and below the critical level. In simulated mesospheric OH(3,1) airglow temperature data, which in part overlaps the depth of the sodium layer, secondary wavelike features were identified with horizontal scales ∼10–20 km, in addition to quasi-stationary and nonstationary SGWs with dominant wavelengths of ∼100, ∼60–80, and ∼20–30 km [see Heale et al., 2017, Figure 7]. Detailed analyses found that these features emerged within the warm phase fronts of the primary medium scale ∼200 km wave and indicate nonlinearly generated secondary waves and, at smaller scales, two-dimensional instability structures.

Although Heale et al. [2017] did not report the sodium layer density perturbations associated with the event, they are here shown in Figure 16 for comparison of their dominant primary and secondary scales, finding significant agreement as discussed next. Note that the enhanced sodium density at 70–80 km in the observed data, not apparent in the model data, appears due to the initialization of the model sodium layer. The model does not account for self-consistent sodium chemistry, nor the inhomogeneous initial state of the layer, so it is initialized with the average sodium density of the measured layer over this region and advected thereafter at the fluid velocity in the same manner as species in the airglow model [Snively et al., 2010]. The assumption that the layer may be modeled as a tracer of dynamics is consistent with conclusions of Hickey and Plane [1995], although chemistry becomes important especially at lower altitudes, where we also find disagreement in relative densities.

Figure 16a depicts the measured sodium density perturbations with a background subtraction that was averaged over the entire flight section as was similarly done for perturbations in the model output (note that this background subtraction method includes larger horizontal scales than in Figure 14). The data in Figure 16a were also low-pass filtered to remove scales smaller than 5 km as the model will dampen smaller horizontal scales. Figure 16b shows the modeled sodium density for the simulation of Heale et al. [2017] plotted for the same region (at a simulation time of ∼10 h). Identified clearly within both are (1a and 1b) overturning features within an apparent ∼60–80 km secondary wave feature, exhibiting 25 km scale sizes; these are also apparent...
again with ~200 km periodic spacing (4a and 4b). Embedded within the phase fronts of the 200 km wave, modulated also by intermediate-scale secondary waves, are 10–20 km secondary wavelike features (2a and 2b, in a lower phase front of the MW, and 3a and 3b above). These features, captured in both data and model, appear to arise naturally within the 200 km wavefield and, furthermore, appear at similar amplitudes in each. Nevertheless, the scales and amplitudes of density perturbation structures of primary and secondary waves and features agree remarkably well, providing further validation for the model results of Heale et al. [2017] and support for the interpretations of data presented here and by Bossert et al. [2015].

4. Discussion and Conclusions

Measurements obtained during the DEEPWAVE campaign revealed numerous MW events and rich atmospheric dynamics over New Zealand. On two separate days, breaking MWs were observed at different altitudes over the Southern Alps. These breaking regions arose due to decreasing winds, resulting in saturation and subsequent MW dissipation. Both instances showed evidence of SGW generation. The lidar measurements performed from the GV aircraft provided horizontal cross sections of temperatures and Na densities. Unlike ground-based data, these measurements were able to define the horizontal and vertical phase structures of stationary MWs and the propagating SGWs arising at higher altitudes. These measurements also show SGWs with differing phase orientation from the MWs that would otherwise be challenging to infer from ground-based instruments.

The SGWs were observed above regions of MW breaking and had smaller horizontal scales than the breaking MWs. The smaller-scale SGWs also had differing phase orientations from the MWs along the flight tracks, which demonstrates that they cannot be generated in the same way that the MWs were, and must be generated from a different source. While there is the potential for GWs to be generated from multiple sources in the lower atmosphere, in these cases, the most likely source is generation from the breaking and dissipation of MWs. In the 29 June stratospheric MW breaking case, downward propagating GWs, especially GWs that would be propagating from regions above 50 km, would quickly decay in amplitude, making them nearly undetectable at altitudes near 35 km. The observed GWs during this flight above 35 km had notable amplitudes of several K. Given the environment conducive to MW breaking in the midstratosphere, and the location of the observed GWs above this region, the most probable source is via SGW generation in the midstratosphere. This situation is similar for the SGWs observed in the MLT region, which were also observed near a region of MW breaking. Given the smaller horizontal scales of these SGWs compared to the primary breaking MW in both scenarios, the generation mechanism appears to be nonlinear.

The observed SGWs in regions of MW breaking indicate the complexity of MW breaking events. Their presence demonstrates the implications of GW and MW breaking on momentum transfer within the atmosphere. Regions of strong MW activity may have influences higher up in the atmosphere beyond the stratosphere and mesosphere. While the observed SGWs in this region are small scale (<50 km

Figure 16. Comparison of perturbed sodium densities below the layer peak for (a) filtered data and (b) the numerical model simulation results of Heale et al. [2017], initialized with an average measured profile. The highlighted and labeled in boxes are secondary features apparent in both data and model.
horizontally), there should also be larger scales of SGWs present based on theory, but at scales potentially not resolved in the limited streamwise extent of the lidar measurements on each cross-mountain flight segment. Additionally, there are still influences of these smaller-scale SGWs and associated breaking that are unknown. These recent observations demonstrate the importance of GW and MW hot spots and their potential to influence the atmosphere through SGW generation.

References


