Nonorographic inertia-gravity waves over New Zealand's Southern Alps: A case study

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Abstract

Wind profiles from radiosondes launched over New Zealand on June 29, 2014 during the Deep Propagating Gravity Wave Experiment (DEEPWAVE; June–July 2014) showed an interesting feature of two sharp peaks in wind speed: one in the upper troposphere and the other in the lower stratosphere. Analysis showed that the lower peak at around 11.5 km was associated with the upper-tropospheric jet. Inertia-gravity waves (IGWs) were found over the South Island from the upper troposphere to the lower stratosphere. The IGWs perturbed the environmental winds, leading to strong and weak wind layers that were tilted in a westerly direction and extended from 10 to 16 km in the IGW zone over the South Island. As a result, the upper wind peak was observed at ~14.5 km and the weak winds immediately below at ~13 km in the IGW zone. These IGWs had vertical wavelengths of ~3 km, horizontal wavelengths of 300–400 km, periods of 9–10 h, and a phase speed of ~11 m s⁻¹.

Numerical experiments showed that airflow over New Zealand's Southern Alps was not the main source for these IGWs. Further analysis suggested that the source of these IGWs in the lower stratosphere was likely due to the spontaneous adjustment of airflow associated with the upper-tropospheric jet streak.

KEYWORDS

DEEPWAVE, gravity waves, inertia-gravity waves, jet-stream, mountain waves

1 INTRODUCTION

Gravity waves frequently occur and significantly affect atmospheric circulations. A major source of gravity waves is airflow passing over mountains, which has been extensively studied (e.g., Lilly et al., 1982; McFarlane, 1987; Smith, 1979; Smith & Kruse, 2017), and can be seen clearly in satellite observations (e.g., Hoffmann et al., 2013). Another source of gravity waves is associated with the jet streak (Guest et al., 2000; Plougonven & Teitelbaum, 2003; Uccellini & Koch, 1987; Zülicke & Peters, 2006), most likely via spontaneous adjustment of an unbalanced flow to a new balanced state (Plougonven & Snyder, 2007; Plougonven & Zhang, 2014; Zhang, 2004). These gravity waves usually have horizontal wavelengths of 50–500 km, vertical wavelengths of 1–5 km, intrinsic periods of 1–10 h, and are therefore called inertia-gravity waves (IGWs). Other potential sources of gravity waves include convection, shear instability, and wave interactions (Fritts & Alexander, 2003).

To study the dynamics of gravity waves from the surface to the upper levels of the atmosphere, the Deep
Propagating Gravity Wave Experiment (DEEPWAVE) was conducted over and around New Zealand from June 4 to July 20, 2014 (Fritts et al., 2016). Analyses of the wind profiles from the radiosondes launched from Hokitika, Haast, and Lauder during DEEPWAVE revealed an interesting feature of two sharp peaks in the zonal wind speed on June 29, 2014: one at ~11.5 km height and the other at ~14.5 km height (Figure 1). A similar two-peaked wind structure was also found in the radiosondes launched on 24 June during DEEPWAVE but had smaller amplitudes.

During DEEPWAVE, the tropopause height fluctuated between 8 and 13 km over New Zealand (Gisinger et al., 2017). On June 29, 2014, based on the radiosonde profiles at Haast, Hokitika, and Lauder (not shown), the tropopause height over New Zealand was 11.5–12 km. According to Winters and Martin (2014), the jet cores of subtropical jet streams (STJ) and polar front jet streams (PFJ) are located in the upper troposphere below the tropopause. The lower wind peak observed on 29 June was likely associated with the upper-tropospheric jet. This hypothesis will be tested in this study. Furthermore, we will investigate how the upper zonal wind maximum at ~14.5 km and the lower minimum at ~12.8 km were generated.

The paper is organized as follows. The model descriptions, synoptic situation, and DEEPWAVE data used in this study are presented in Section 2. Results are presented in Section 3. A short summary is presented in Section 4.

2 DESCRIPTIONS OF MODEL, OBSERVATIONS, AND SYNOPTIC SITUATION

The Numerical Weather Prediction (NWP) model used in this study is a regional configuration of the UK Met
Office Unified Model (UM) with the ENDGame dynamical core (Walters et al., 2017; Wood et al., 2014). The regional model has 70 terrains following vertical levels, with the top-level 80 km above the mean sea level. In this study, three regional model configurations were used with resolutions: 0.11° (~12 km, Figure 2a) with a domain size of 324 × 324 grid points (Yang et al., 2012); 0.036° (~4 km) with a domain size of 972 × 972 grid points; and 0.0135° (~1.5 km) with a domain size of 1350 × 1200 grid points. The 4 km domain is similar in extent to the 12 km domain, extending from 52.7°S, 137.26°E at the lower-left corner to 18.22°S, 183.76°E at the upper right, while the 1.5 km domain is smaller (depicted in Figure 2b by the solid black outline) and extends from 49.0°S, 161.5°E at the lower-left corner to 31.0°S, 182.0°E at the upper right. None of these configurations used data assimilation and the initial conditions (at 0000 NZST June 29, 2014) and lateral boundary conditions for the 12 and 4 km simulations were provided by the operational Global UM run at the Met Office. Initial and lateral boundary conditions for the 1.5-km run were derived from the outputs of the 12-km run. No DEEPWAVE observations were assimilated in the Global UM model runs.

For each resolution, two simulations were conducted to isolate the effect of orographic gravity waves: one with New Zealand’s terrain included and the other with it removed. For the latter, the mountain heights (including...
subgrid mountain heights) of New Zealand were set to 0. In the following, if not stated specifically, the diagrams shown are from the 12-km resolution simulations.

During DEEPWAVE, radiosondes (Vaisala RS92-SGPD instruments attached to Totex TA600 balloons) were launched at Hokitika, Haast, and Lauder (Figure 2d). These radiosondes had a much higher temporal resolution (1 s) and vertical resolution (1–6 m) for observations than the routine radiosondes launched from Invercargill, at the southern end of the South Island (Tradowsky et al., 2018). In the interpolation of model-level data to the balloon tracks, both the time and location of the balloons were considered so that observation and simulation profiles match in both time and locations along the balloon track. Hourly NWP model outputs were used for this interpolation. The radiosondes chosen for this study were launched at Hokitika at 1432 NZST, Haast at 1500 NZST, and Lauder at 1728 NZST on the June 29, 2014 (Figure 1a–c). Each sonde took about 1 h to reach the lower stratosphere. The model simulation was initialized at 0000 NZST June 29, 2014 and outputs at 1600 NZST were used to describe the synoptic situations. At 1600 NZST, a low-pressure center lay over the Tasman Sea to the west of New Zealand (Figure 2a). A region of high pressure with a north-to-south orientation lay to the east of New Zealand. Between 900 and 200 hPa, the winds over the South Island were mainly north-westerly, indicating that the balloons traveled from the northwest to the southeast. At 200 hPa (Figure 2b), a meandering upper-tropospheric jet streak was found extending from ~30°S east of Australia to ~40°S over New Zealand. Over the South Island, the maximum wind speed was 40–45 m s⁻¹ at a height of ~11.5 km, associated with the upper-tropospheric jet (Figure S1a,b) and located immediately below the tropopause at ~11.5–12 km, inferred from the three radiosondes (not shown).

Although smoother, the wind profiles at the three sites were well simulated by the model on June 29, 2014 (Figure 1). The altitudes of the two wind peaks were also well simulated, except that the simulated wind maxima were smaller than observed. Some of the errors in the simulated zonal wind speed maxima may be due to the relatively coarse model vertical resolution (~600 m) in the upper troposphere to the lower stratosphere.

### RESULTS

#### 3.1 Wave parameters

Mountain waves were the dominant waves over the South Island of New Zealand during DEEPWAVE (Smith & Kruse, 2017). The observed two wind peaks from the upper troposphere to the lower stratosphere are likely associated with gravity waves. To isolate these gravity waves in the lower stratosphere, a Lanczos band-pass filter (Claude, 1979) with vertical wavelength cut-off from 1.5 to 10 km (hereafter referred to as VBF, for vertical band-pass filter) was applied to the radiosonde observations and the corresponding simulations. This is to isolate the gravity waves with a vertical wavelength of 2–5 km that were often found in the lower stratosphere (e.g., Chun et al., 2006; Karoly et al., 1996; Scavuzzo et al., 1998; Vincent & Alexander, 2000). For the zonal and meridional winds, filtered using VBF, (Figure 1d–f), waves with the largest amplitudes were found at altitudes between 12 and 16 km.

Wave parameters were calculated for the waves with large amplitudes at heights between 12 and 16 km. At
the three sites (Figure 1d–f), vertical wavelengths ($L_z$) were $\sim 3$ km (Tables S1–S3). $L_z$ was determined as twice the vertical distance between the closest amplitude maximum and minimum within heights of 12–16 km. Based on linear IGW theory, the ellipticity of the hodograph indicated that the waves were IGWs (Figure 3). The perturbed wind directions associated with the waves changed anticyclonically with altitude (Figure 3), indicating upward wave energy propagation. The horizontal propagation of the IGWs is shown by the orientation of the ellipses of the hodograph. It was northwest to southeast (Figure 3), following the north-westerly environmental airflow in the lower stratosphere (Figure 2b).

Using linear theory (Sawyer, 1961), other wave parameters can be obtained. The ratio between the major and minor axes of the ellipse of the wind profile is used to determine the intrinsic frequency, $\omega$. Since $\omega = \sqrt{f^2 + \frac{g N^2}{m^2}}$, where $f$ is the Coriolis parameter, $N$ is the Brunt Vaisala frequency (taken as $0.02 \text{s}^{-1}$ in the lower stratosphere), and $m$ is vertical wave number, the horizontal wave number $k$ can be calculated. The horizontal intrinsic phase speed is given by $c_i = \frac{\omega}{k}$. Following Gong and Geller (2010), the wave horizontal kinetic energy ($KE$) was calculated (Tables S1–S3).

For the radiosonde observations and the corresponding simulations with and without terrain, the horizontal wavelengths were 300–400 km; wave periods were 9–10 h; and the horizontal phase speed was $\sim 11 \text{ m s}^{-1}$ at the three sites (Tables S1–S3). The northwest to southeast wave propagation and the upward wave propagation were well simulated by the model. These facts indicate that the gravity wave structure was well simulated by the model with 12-km horizontal resolution.

3.2 | Structure of the IGWs

Figure 4a,b shows the cross-sections of potential temperature and vertical velocity along transects chosen so as to be approximately parallel to the balloon tracks. Significant mountain wave activity was found in the troposphere and lower stratosphere due to airflow over mountains. In the simulation without mountains, only smaller wave-like structures were identified from the weak vertical velocity perturbations in the lower stratosphere (Figure 4c,d).

To see the wave patterns in the lower stratosphere clearly, a band-pass filter developed by Kruse and Smith (2015) was applied to the vertical velocity at a height of 14 km. As the simulated horizontal wavelength of the IGWs was 300–400 km (Tables S1–S3), the filter was designed to keep waves with a wavelength of 250–450 km (hereafter referred to as HBF1, for horizontal band-pass filter). Waves were clearly shown by the shape and magnitude of the perturbed vertical velocity and
were found not only around and over New Zealand but also upstream (Figure S2). In time–distance diagrams (Figure S2), the waves are identifiable by the perturbed vertical velocity and the potential temperature gradually moving south-eastward throughout the simulation, arriving over the South Island around 1200 NZST. This is further confirmed from the simulated wind profiles (Figure S3) which show that the two-peaked wind structure from 10 to 16 km height over the South Island did not occur before 1200 NZST.

Figure 5a,b shows the cross-section of the waves in the lower stratosphere. The lines of the constant phase of the waves indicated by the filtered vertical velocity and potential temperature fields using HBF1 were tilted westward with increasing height. The tilted relatively warm and cold regions lay between the tilted upward and downward motion regions, corresponding to a roughly π/2 phase shift. The tilted perturbed winds perpendicular to the cross-section plane were almost in phase with the perturbed thermal fields (not shown), supporting the idea that the simulated waves were IGWs based on linear theory. Their vertical and horizontal wavelengths were ~3 and ~380 km, respectively, very close to those derived from the simulated sounding data (Tables S1–S3).

A zonal wind speed maximum of ~40 m s⁻¹ was found at ~11.5 km altitude (Figure 5a). Another relatively strong (30–35 m s⁻¹) zonal wind band was tilted from east to west, extending from ~12 to ~16 km, and was almost parallel to the constant phase lines of the waves. These tilted strong zonal winds were due to the westerly perturbed winds associated with the IGWs (Figure 5a,b) that enhanced the environmental winds in the IGW zone. A corresponding band of weak zonal winds, similarly tilted, was immediately below the strong wind band. This was due to the easterly perturbed winds associated with the IGWs that weakened the environmental winds in the IGW zone (Figure 5a,b). In other words, the IGWs perturbed the environmental flow in the IGW zone, leading to strong and weak tilted wind layers increasing in altitude from ~12 to ~16 km in a westerly direction.

When a balloon was launched at Hokitika in the afternoon on June 29, 2014, it traveled eastward, approximately along the cross-section of Figure 5a while ascending. The lower wind peak (Figure 1a) was observed when it reached ~11.5 km, where the wind speed maximum associated with the upper-tropospheric jet was found. The upper wind speed peak was observed when it reached ~14.5 km (Figure 5a), the height of the strong wind layer.
due to the IGW activity. Between the two wind peaks, a minimum at ~12.8 km was observed due to the activity of the IGWs described earlier. The same scenario was also found for the balloons launched at Haast and Lauder in the afternoon on June 29, 2014 (Figure 5b).

The IGWs had vertical and horizontal wavelengths of ~3 and ~400 km, respectively. To further support our hypothesis that the lower wind peak was associated with the upper-tropospheric jet, the wind speed was averaged over a horizontal wavelength of 400 km (Figure S1c) and vertical wavelength of 3 km (Figure S1d). The weak and strong, tilted wind layers disappeared for the averaged wind field, leaving only the upper-tropospheric jet at a height of ~11.5 km (Figures S1 b vs. S1c and S1d).

### 3.3 | Source of the IGWs

Uccellini and Koch (1987) suggested that the exit region of the jet streak is a flow configuration conducive to intense mesoscale gravity waves. This was confirmed in later studies (e.g., Guest et al., 2000; Plougonven & Teitelbaum, 2003; Wu and Zhang, 2004; Zülicke & Peters, 2006). The North Island was very close to the exit region of the jet streak (Figure 2b), within the area suggested by Uccellini and Koch (1987). The IGWs in the lower stratosphere could therefore be generated by spontaneous adjustment of the airflow in the exit regions of the jet streak. However, the dominant mountain waves over the South Island during DEEPWAVE (Smith & Kruse, 2017) could be the source of the IGWs. To test which was more important, simulations that removed New Zealand’s terrain were conducted.

Generally, mountain wave activity disappeared when the mountains were removed from the model simulations (Figure 4). However, the IGW patterns with wavelength 300–400 km (Figure 2c,d) persisted in simulations with and without mountains. This is because the mountain waves mainly possessed horizontal wavelengths of 50–250 km (Figure S4). These mountain waves were relatively stationary and had much slower phase speed and stronger vertical velocity than those of the nonorographic IGWs (Figure S5).

In the cross-sections (Figure 5), the vertical structure of the IGWs was almost the same for the simulations with and without mountains in terms of the orientation and magnitude of the perturbed vertical velocity, potential temperature, and perturbed horizontal winds due to the IGW activity. The vertical and horizontal wavelengths were also almost the same for simulations with and without mountains. Similar features were also found in simulations performed at 4- and 1.5-km resolutions (Figures S6 and S7).

Figure S8 shows the observed and simulated zonal wind profiles with and without mountains at three model resolutions: 12, 4, and 1.5 km. Pronounced differences in zonal wind speed were found at lower levels. At Hokitika and Lauder, the wind maximum at ~2.5 km due to the mountains was not present in the simulations without mountains. At Haast, the near-surface strong easterly winds due to mountain blocking were much better simulated by the simulations with mountains. Some differences were also found at heights above ~15 km at Haast and Lauder, especially for the 1.5-km resolution simulations. However, in the 10–15 km layer where the two wind peaks were found, similar zonal winds were found for simulations with and without mountains for each of the three resolutions (Figure S8).

As described earlier, the mountain waves mainly occurred in horizontal wavelengths of 50–250 km (Figures S4 and S5). This is further supported by the wave KE spectrum over the South Island (Figure S9) where significant differences in KE between simulations with and without mountains were found for wavelengths lower than 250 km, and especially for a wavelength of 100–150 km. The KE was ~14,000 J·kg⁻¹ for the waves with a horizontal wavelength of 400 km, while the maximum difference in KE between simulations with and without mountains is only 1500 J·kg⁻¹ at a horizontal wavelength of 100–150 km (Figure S9). This indicated that the total KE for these mountain waves in the 12- to 16-km layer over the South Island was much smaller than that of waves with a horizontal wavelength larger than 350 km. This is further supported from the calculated KE using the simulated radiosonde data for a vertical wavelength in the 12- to 16-km layer at Hokitika, Haast, and Lauder (Tables S1–S3). At the three sites, the KE for the wavelength range of 50–250 km was less than half of that for the 250–450 km wavelength range. In other words, mountain waves had little effect on the wind profiles in the lower stratosphere over the South Island. These results indicate that airflow over the mountains was not the main source of these IGWs in the lower stratosphere. It is, therefore, suggested that the main source was the spontaneous adjustment of airflow associated with the upper-tropospheric jet streak. However, a study to confirm this hypothesis is out of the scope of this paper and will be investigated following Zülicke and Peters (2006) in the future.

### 3.4 | Jet splitting

A double-jet structure with the peak wind speeds at ~11.5 and 14.5 km height was described by Portele et al. (2018) over the windward side of the South Island. They
suggested that the two jets “belong to the split branch of the STJ and the STJ itself.” However, how the splitting occurred was not clear.

Figure S10 shows cross-sections along the southern transect of Figure 2c. Similar to Figure 5, pronounced IGWs with horizontal wavelengths of 350–400 km were identified from the perturbed vertical velocity and potential temperature layers that were tilted in a westerly direction (Figure S10c–e). For the horizontal wind speed, in addition to the maximum at ~11.5 km associated with the upper-tropospheric jet (Figure S10b), another strong wind zone was found at ~15 km height to the northwest of the South Island. This observed vertical wind structure was called double-jets in Portele et al. (2018). As shown in Figure S10b, the upper strong wind zone (the weak wind zone immediately below) was tilted westward and extended from 11.5 km level. The orientation of the upper strong wind zone (the weak wind zone) was parallel to the phase line of the IGWs and corresponded well to the perturbed northwesterly (southeasterly) winds associated with the IGWs (Figure S10c,e). These perturbed winds enhanced (weakened) the northwesterly environmental winds to generate the tilted upper jet and the weak wind between the two jets. Therefore, it is mainly the activity of IGWs that split the environmental winds into the double-jet structure, the same process that generated the two peaks in zonal wind speed described earlier.

4 | SUMMARY

Two sharp peaks in the zonal wind between 11 and 15 km altitude were found in radiosonde profiles from June 29, 2014 during DEEPWAVE. Numerical experiments and subsequent analyses showed that the lower wind peak was mainly associated with the upper-tropospheric jet at ~11.5 km. The upper wind speed peak at ~14.5 (and wind minimum at ~12.8 km) was mainly due to the zonal winds enhanced (weakened) by perturbations associated with IGWs in the IGW zone. The double-jet structure in the lower stratosphere, considered as the splitting of STJ and the STJ itself by Portele et al. (2018), was generated due to the activity of the IGWs.

These IGWs had a vertical wavelength of ~3 km, a horizontal wavelength of 300–400 km, periods of 9–10 h, and a wave phase speed of ~11 m s⁻¹. Most of the simulated wave parameters and the propagation of the IGW were close to observed values.

Numerical experiments with and without New Zealand’s terrain showed that airflow passing over the South Island’s mountains was not the main source of these IGWs. It is suggested the source of the IGWs in the lower stratosphere was likely associated with the upper-tropospheric jet streak. Small mountains well resolved by higher model horizontal resolutions (e.g., 4 and 1.5 km) had little effect on the two-peaked wind structure. However, the model vertical resolution may be important for the wind profile simulation and will be addressed in a separate paper.

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AUTHOR CONTRIBUTIONS

Yang Yang: Formal analysis; investigation; methodology; writing – original draft; writing – review and editing. Trevor Carey-Smith: Project administration; resources; visualization; writing – review and editing. Stuart Moore: Data curation; formal analysis; software; writing – review and editing. Mike Revell: Conceptualization; supervision; writing – review and editing. Michael Uddstrom: Resources; supervision; writing – review and editing.

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