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Key Points:

- The upward and downward inertia gravity waves (GWs) over Arctic Lidar Observatory for Middle Atmosphere Research are secondary GWs created by the breaking/dissipation of primary GWs from the polar vortex
- The primary GWs are created from imbalance of the polar vortex and are amplified below the wind maximum where the vertical wind shear is large
- The primary and secondary GWs from the polar vortex simulated by the nudged HIAMCM agree well with lidar and Atmospheric InfraRed Sounder observations

Correspondence to:
S. L. Vadas,
vasha@nwra.com

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Secondary Gravity Waves From the Stratospheric Polar Vortex Over ALOMAR Observatory on 12–14 January 2016: Observations and Modeling

Sharon L. Vadas[1], Erich Becker[1], Katrina Bossert[2,3], Gerd Baumgarten[4], Lars Hoffmann[5], and V. Lynn Harvey[6]

[1]Northwest Research Associates, Boulder, CO, USA, [2]School of Earth and Space Exploration, Arizona State University, Tempe, AZ, USA, [3]School of Mathematical and Statistical Sciences, Arizona State University, Tempe, AZ, USA, [4]Leibniz Institute of Atmospheric Physics, University of Rostock, Kühlungsborn, Germany, [5]Jülich Supercomputing Centre, Forschungszentrum Jülich GmbH, Jülich, Germany, [6]Laboratory for Atmospheric and Space Physics, University of Colorado Boulder, Boulder, CO, USA

Abstract We analyze the gravity waves (GWs) observed by a Rayleigh lidar at the Arctic Lidar Observatory for Middle Atmosphere Research (ALOMAR) (16.08°E, 69.38°N) in Norway at $z \sim 20$–85 km on 12–14 January 2016. These GWs propagate upward and downward away from $z_{\text{knee}} = 57$ and 64 km at a horizontally-displaced location with periods $\tau_r \sim 5$–10 hr and vertical wavelengths $\lambda_z \sim 9$–20 km. Because the hodographs are distorted, we introduce an alternative method to determine the GW parameters. We find that these GWs are medium to large-scale, and propagate north/northwestward with intrinsic horizontal phase speeds of ∼35–65 m/s. Since the GW parameters are similar above and below z_{knee}, these are secondary GWs created by local body forces (LBFs) south/southeast of ALOMAR. We use the nudged HIAMCM (HIgh Altitude Mechanistic general Circulation Model) to model these events. Remarkably, the model reproduces similar GW structures over ALOMAR, with $z_{\text{knee}} = 58$ and 66 km. The event #1 GWs are created by a LBF at ∼35°E, ∼60°N, and $z \sim 58$ km. This LBF is created by the breaking and dissipation of primary GWs generated and amplified by the imbalance of the polar night jet below the wind maximum; the primary GWs for this event are created at $z \sim 25$–35 km at 49–53°N. We also find that the HIAMCM GWs agree well with those observed by the Atmospheric InfraRed Sounder (AIRS) satellite, and that those AIRS GWs south and north of ∼50°N over Europe are mainly mountain waves and GWs from the polar vortex, respectively.

Plain Language Summary Atmospheric gravity waves (GWs) are perturbations in the Earth's atmosphere which can be created by wind flow over mountains and breaking GWs. Here, a breaking GW is similar to the breaking of an ocean wave when it overturns. A breaking GW imparts momentum to the atmosphere, which creates secondary GWs. We report on the long-period inertia GWs seen over Arctic Lidar Observatory for Middle Atmosphere Research (ALOMAR) in northern Norway during 12–14 January 2016. We find that the inertia GWs seen over ALOMAR were secondary GWs created by the breaking of primary GWs generated by the imbalance of the polar vortex. We did this via simulating this event with the HIAMCM model and directly comparing these results to lidar and Atmospheric InfraRed Sounder data. After we found that the HIAMCM results agreed very well with these data, we investigated the dynamics which led to the ALOMAR GWs using the HIAMCM model data. This is the first concrete model/data comparison study to show that GWs generated by the polar vortex are important for generating GWs observed in the Earth's mesosphere. This study also highlights the importance of the complicated process dubbed "multi-step vertical coupling," for which secondary, not primary, GWs can explain the wintertime GWs seen in the mesosphere.

1. Introduction

Atmospheric gravity waves (GWs) are created from many processes in the lower atmosphere, including wind flow over topography (M. J. Alexander & Teitelbaum, 2007, 2011; Becker & Vadas, 2020; Fritts et al., 2016, 2021; Hindley et al., 2021; Hoffmann et al., 2013, 2016; Lund et al., 2020; Plougonven et al., 2008; Sato et al., 2012; Smith et al., 2013; Vadas & Becker, 2019; R. Walterscheid et al., 2016; Watanabe et al., 2006), deep convection (M. J. Alexander et al., 1995; Beres et al., 2002; Fovell et al., 1992; Heale et al., 2019; Holton & Alexander, 1999; Holt et al., 2017; Horinouchi et al., 2002; Lane et al., 2001, 2003; Liu et al., 2014; Pandya, 1999; Piani et al., 2000; Song et al., 2003; Stephan & Alexander, 2015; Taylor & Hapgood, 1988; Vadas, Taylor, et al., 2009; Vadas, Yue, et al., 2009; R. L. Walterscheid et al., 2001; Yue et al., 2009), geostrophic adjustment of the tropospheric jet (Fritts & Luo, 1992; Luo & Fritts, 1993; Vadas & Fritts, 2001; Watanabe et al., 2008), and "spontaneous emission" from the polar vortex (S. Alexander et al., 2011; Becker et al., 2022; Chen et al., 2013; Dörnbrack et al., 2018; Gassmann, 2019; O'Sullivan & Dunkerton, 1995; Plougonven & Zhang, 2014; Sato & Yoshiki, 2008; Shibuya et al., 2017; Yoshiki & Sato, 2000; Yoshiki et al., 2004; Zülicke & Peters, 2006, 2008). The amplitude of an upward-propagating GW increases approximately exponentially with height until the GW nears a critical level, breaks, or dissipates directly from molecular viscosity (D. C. Fritts & Alexander, 2003; Hines, 1960; Pitteway & Hines, 1963; Vadas, 2007) (This increase is exactly exponential if the background wind and density scale height $\mathcal{H}$ are constant in altitude.) Upon breaking and dissipating, a GW packet deposits its energy and momentum into the background atmosphere, which creates a local body force (LBF) and heating that excites a new set of GWs called secondary GWs (Becker & Vadas, 2018; Heale et al., 2020; Vadas & Becker, 2018; Vadas & Liu, 2009, 2013; Vadas et al., 2003, 2018). If the primary wave packet is isolated when breaking and/or dissipating, the excited secondary GWs have horizontal wavelengths ranging from $\sim\lambda_H/4$ to several times the horizontal extent of the primary wave packet, where λ_H is the predominant horizontal wavelength of the primary GW packet. If, however, there is significant constructive/destructive interference between several wave packets from different sources at the breaking location, then the horizontal extent of the LBFs and heatings can be significantly smaller than λ_H of the primary GWs (Vadas & Crowley, 2010; Vadas & Becker, 2018, 2019). These smaller-sized forces/heatings excite secondary GWs with significantly smaller horizontal wavelengths than λ_H of the primary GWs.

Gravity wave breaking also excites smaller-scale secondary GWs created by the non-linear interactions of the breaking process (Chun & Kim, 2008; Heale et al., 2020; Lane et al., 2003; Lund et al., 2020; Satomura & Sato, 1999; Snively & Pasko, 2003). Although most of these GWs have small horizontal phase speeds and are reabsorbed near the breaking region (and therefore contribute to the LBFs discussed above), some may propagate out of this region to higher altitudes (D. C. Fritts et al., 2021; Heale et al., 2020).

The temperature perturbations (as a function of z and time) of the secondary GWs excited by a LBF create a striking wave structure for a ground-based observer at a horizontally-displaced location. These structures are dubbed "fishbone structures" (Vadas et al., 2018), and are created because the secondary GW spectrum is rich, with different spectral components propagating at different speeds and ascent angles away from the LBF (A GW's propagation angle with respect to the zenith in an isothermal windless background is $\zeta = \cos^{-1}(\tau_B/\tau_{Ir})$, where τ_{Ir} is the GW intrinsic period and τ_B is the buoyancy period (Vadas, Yue, et al., 2009); thus high (low)-frequency GWs have steep (shallow) ascent angles.) A fishbone structure is asymmetric in z about the "knee" altitude z_{knee}, which is the altitude of the horizontally-displaced LBF. This asymmetry consists of hot and cold GW phases meeting at z_{knee} whereby $T' = 0$. These secondary GWs consist of upward (downward)-propagating GWs having downgoing (upgoing) phases in time above (below) z_{knee}, respectively, in a $z - t$ plot. (In this paper, upgoing/downgoing refers to the movement of a GW's phase in a $z - t$ plot, while upward/downward refers to the group velocity direction (i.e., propagation direction) of a GW.) In an isothermal, constant-wind atmosphere, the secondary GWs at the same distance above and below z_{knee} at a given time have the same horizontal wavelength λ_H, vertical wavelength λ_z, observed period τ_r, propagation direction, and density-scaled amplitude (e.g., $\sqrt{\bar{\rho}}T'$, where T' is the temperature perturbation and $\bar{\rho}$ is the background density). This fishbone structure is visible at any location except perpendicular to the LBF direction (Vadas et al., 2003)

Two fishbone structures containing secondary GWs were identified in wintertime lidar data at McMurdo on 18 June 2014 and 29 June 2011 with $z_{\mathrm{knee}} = 43$ and 52 km, respectively (Vadas et al., 2018). These were inertia GWs with periods of $\tau_r \sim 6$–10 hr and $|\lambda_z| \sim 6$–14 km. Additionally, fishbone structures containing medium to large-scale inertia GWs were identified in simulation data with $z_{\mathrm{knee}} = 35$–60 km at McMurdo (Figure 5 of Vadas & Becker, 2018). These latter GWs had the same density-scaled amplitudes, λ_H, λ_z, τ_r, and propagation direction above and below z_{knee}, and were therefore identified as secondary GWs. The LBF which excited these GWs was created by the breaking of primary GWs from below (Figures 18–22 of Vadas & Becker, 2018).

While the McMurdo study of Vadas et al. (2018) contains the only published cases of secondary GWs in fishbone structures that we are aware of, there have been other high-latitude (HL) lidar studies where upward and downward-propagating inertia GWs have been observed. Baumgarten et al. (2015) and Strelnikova et al. (2020) observed persistent inertia GWs at Arctic Lidar Observatory for Middle Atmosphere Research (ALOMAR) in the stratosphere and mesosphere having upgoing and downgoing phases in time, indicating the possible presence of downward and upward-propagating secondary GWs, respectively. Kaifler et al. (2017) observed upward and downward-propagating inertia GWs at $z \sim 50$ km on 6 December 2015 using a Rayleigh lidar in Finland (Figure 8 of that work). They wrote "Remarkably, upward (upgoing) phase progression waves are found below 50 km and downward (downgoing) phase progression waves above (…) Vertical wavelengths of downward (downgoing) and upward (upgoing) phase progression waves at ∼50 km altitude are in the same range (10–12 km, Figure 8f)." They also found that the wave periods were similar above and below $z \sim 50$ km, $\tau_r \sim 7$–8 hr (Figure 8e of that work), and that the GWs with upgoing phases were downward-propagating GWs. These downward GWs could not have been reflected waves, because reflection occurs when $m \rightarrow 0$ or $|\lambda_z| \rightarrow \infty$ whereby the phase lines become vertical, which was not observed. Here, $m = 2\pi/\lambda_z$. These GWs may have been secondary GWs created by a horizontally-displaced LBF at $z \sim 50$ km.

In fact, inertia GWs are often observed in the wintertime HL stratosphere and mesosphere. These observations have occurred over McMurdo (Chen & Chu, 2017; Chen et al., 2013, 2016; Zhao et al., 2017), Syowa Station (Shibuya et al., 2017), ALOMAR (Baumgarten et al., 2015; Strelnikova et al., 2020), Kühlungsborn Germany (Strelnikova et al., 2021), Alaska (Nicolls et al., 2010; Li et al., 2021), and at the Andes Lidar Observatory (Huang et al., 2017). Such inertia GWs could be secondary or higher-order GWs from orographic forcing (Becker & Vadas, 2018; Vadas & Becker, 2018).

Are there other sources for wintertime inertia GWs? Bossert et al. (2020) analyzed the temperature perturbations in Atmospheric InfraRed Sounder (AIRS) over Europe during January 2016. Although mountain waves (MWs) were visible at midlatitudes (e.g., over the Alps), their study suggested that the HL GWs at $z \sim 30$–45 km may have been created by the stratospheric polar vortex. Dörnbrack (2021) disputed this interpretation, instead arguing that these HL waves were trailing MWs from the Alps due to the blended nature of the phase lines at $z \sim 40$ km. A recent modeling paper using the HIAMCM showed that the polar vortex created inertia GWs during January 2016 (Becker et al., 2022, hereafter B22). That study showed that these GWs were amplified by the transfer of kinetic energy from the large-scale flow to the GWs in a process found to be strongest where the vertical shear of the horizontal wind (hereafter vertical wind shear) was maximum in the middle stratosphere. This amplification process typically occurs at the outer edge of the polar vortex below the altitude where the horizontal wind is the largest. This region allows for the greatest extraction of energy from the mean flow into the generated GWs. B22 also showed that there was a persistent GW hot spot over Europe during January 2016, and that the HIAMCM results agreed well with AIRS data during that month.

In this paper, we investigate the GWs in the fishbone structures observed by a Rayleigh lidar over ALOMAR on 12–14 January 2016. In Section 2, we review the GW dispersion and polarization relations. We analyze the GWs observed by the ALOMAR lidar in Section 3. Since the hodographs are distorted, we develop an alternative method to determine the GW intrinsic parameters using the GW dispersion and polarization relations. In Section 4, we model these events using the nudged HIAMCM, and compare the results with lidar and AIRS data. Because good agreement is obtained, we analyze the HIAMCM results to determine the multi-step vertical coupling that created the GWs over ALOMAR. Section 5 contains our conclusions. Appendix A calculates the fishbone structure for multiple LBFs, and Appendix B compares the GWs in the HIAMCM and AIRS over the Atlantic Ocean during this time period.

2. Parameters and Phase/Amplitude Relationships of a GW

2.1. Gravity Wave Dispersion and Polarization Relations

The general fluid equations are fully compressible, and include GWs and acoustic waves (AWs). Several approximations are commonly employed if $|\lambda_z|$ is not too large, such as the Boussinesq and anelastic approximations. Earth's rotation is included for inertia GWs with intrinsic periods $\tau_{Ir} > 4$ hr at mid and high latitudes by employing the f-plane approximation, where the latitude is assumed fixed. If the background atmosphere is locally-constant and the perturbations are linear, analytic solutions can be obtained. These are the GW dispersion and polarization relations, which govern how the wavenumber, amplitude and phase of a GW changes as it propagates. The general non-dissipative relations were derived by Hines (1960) (dispersion relation) and Vadas (2013) (polarization relations). These expressions are also applicable to a GW in the thermosphere below the altitude where molecular viscosity begins to significantly damp it (Vadas, 2007).

The altitude where molecular viscosity becomes important for significantly damping a GW depends sensitively on λ_z and the intrinsic horizontal phase speed, $c_{IH} = \partial\omega_{Ir}/\partial k_H$, where ω_{Ir} is the intrinsic frequency and $k_H = 2\pi/\lambda_H$ (Vadas, 2007). This damping becomes significant when the following expression is satisfied:

$$\frac{\lambda_z^3 \omega_{Ir}}{8\pi^3 \mathcal{H}\left(1 + \mathrm{Pr}^{-1}\right)} \sim \nu(z) \tag{1}$$

(Equation 9 of Vadas & Liu, 2009), where $\nu(z) = \mu/\overline{\rho}$ is the kinematic viscosity, μ is the molecular viscosity, $\overline{\rho}$ is the background density, Pr is the Prandtl number, and $\mathcal{H}$ is the density scale height. In the thermosphere, $\mathrm{Pr} \simeq 0.62$ (Banks & Kockarts, 1973b; Vadas & Crowley, 2017). Small-λ_z GWs are damped near the turbopause at $z \sim 107$ km. Because ν increases exponentially in z, every GW is eventually damped by viscosity, wherein the changes of its wavenumber, amplitude and phase are described by the viscous dispersion and polarization relations (for example, Vadas & Fritts, 2005; Vadas & Nicolls, 2012).

The compressible, f-plane, non-dissipative dispersion relation for GWs and AWs is

$$\omega_{Ir}^4 - \left[f^2 + c_s^2\left(\mathbf{k}^2 + 1/4\mathcal{H}^2\right)\right]\omega_{Ir}^2 + c_s^2\left[k_H^2 N_B^2 + f^2\left(m^2 + 1/4\mathcal{H}^2\right)\right] = 0 \tag{2}$$

(Hines, 1960). Here, $\omega_{Ir} = 2\pi/\tau_{Ir}$ is the intrinsic frequency:

$$\omega_{Ir} = \omega_r - \left(k\overline{U} + l\overline{V}\right), \tag{3}$$

$\omega_r = 2\pi/\tau_r$ is the ground-based frequency, $\overline{U}$ and $\overline{V}$ are the zonal and meridional components of the background wind, respectively, k, l, and m are the zonal, meridional and vertical wavenumbers, respectively, $k_H = \sqrt{k^2 + l^2} = 2\pi/\lambda_H$, $m = 2\pi/\lambda_z$, $\mathbf{k}^2 = k^2 + l^2 + m^2$, $\mathcal{H} = -\overline{\rho}/\left(d\overline{\rho}/dz\right)$ is the density scale height, $N_B = \sqrt{\gamma - 1}\, g/c_s$ is the buoyancy frequency, $c_s = \sqrt{\gamma g \mathcal{H}}$ is the sound speed, $f = 2\,\Omega \sin\theta$, $\Omega = 2\pi/24$ hr is Earth's rotation rate, θ is the latitude, $g = 9.8(R_\mathrm{E}/(R_\mathrm{E} + z))^2$ is the acceleration due to gravity and $R_\mathrm{E} = 6.371 \times 10^6$ m is Earth's radius. Note that $m < 0$ ($m > 0$) for an upward (downward)-propagating GW, assuming $\omega_{Ir} > 0$ without loss of generality. In addition, $\gamma = 1 + r/C_v = C_p/C_v$, $r = (8{,}308/\mathrm{X_{MW}})$ m^2 s^{-2} K^{-1}, $\mathrm{X_{MW}}$ is the mean molecular weight, and C_v (C_p) is the mean specific heat at constant volume (pressure). If the dominant molecule(s) is diatomic (monatomic), $\gamma = 1.4$ ($\gamma = 1.667$). Simple empirical expressions for $\mathrm{X_{MW}}$ and γ are.

$$\mathrm{X_{MW}} = \frac{1}{2}(\mathrm{X_{MW0}} - \mathrm{X_{MW1}})\left(1 - \tanh\left(\frac{\mathrm{s} - \mathrm{a}}{\Delta_a}\right)\right) + \mathrm{X_{MW1}} \tag{4}$$

$$\gamma = \frac{1}{2}(\gamma_0 - \gamma_1)\left(1 - \tanh\left(\frac{\mathrm{s} - \mathrm{b}}{\Delta_b}\right)\right) + \gamma_1, \tag{5}$$

respectively, where $\mathrm{s} = -\ln\left(\overline{\rho}\right)$ ($\overline{\rho}$ has units of g/m^3), $\mathrm{X_{MW0}} = 28.9$, $\mathrm{X_{MW1}} = 16$, $a = 14.9$, $\Delta_a = 4.2$, $\gamma_0 = 1.4$, $\gamma_1 = 1.667$, $b = 15.1$, and $\Delta_b = 4.0$ (Equations 3 and 4 of Vadas, 2007).

The GW dispersion relation is obtained from the smaller root from Equation 2:

$$\omega_{Ir}^2 = \frac{a}{2}\left[1 - \sqrt{1 - 4b/a^2}\right], \tag{6}$$

where

$$a = \left[f^2 + c_s^2\left(\mathbf{k}^2 + 1/4\mathcal{H}^2\right)\right], \tag{7}$$

$$b = c_s^2\left[k_H^2 N_B^2 + f^2\left(m^2 + 1/4\mathcal{H}^2\right)\right] \tag{8}$$

(Equations 31, 33, and 34 of Vadas, 2013). If a GW propagates much slower than c_s $\left(\textit{specifically if}\ \omega_{Ir}/\sqrt{\mathbf{k}^2 + 1/4\mathcal{H}^2} \ll c_s\right)$, Equation 6 reduces to the usual anelastic GW dispersion relation:

$$\omega_{Ir}^2 = \frac{k_H^2 N_B^2 + f^2\left(m^2 + 1/4\mathcal{H}^2\right)}{m^2 + k_H^2 + 1/4\mathcal{H}^2} \tag{9}$$

(Marks & Eckermann, 1995). Then $\lambda_H = 2\pi/k_H$ can be determined via

$$k_H^2 = \frac{\left(\omega_{Ir}^2 - f^2\right)\left(m^2 + 1/4\mathcal{H}^2\right)}{N_B^2 - \omega_{Ir}^2}. \tag{10}$$

Assuming plane wave solutions of the form

$$\left(\mathrm{e}^{-z/2\mathcal{H}}u'\right)(x, y, z, t) = \mathrm{e}^{i\left(\omega_r t - kx - ly - mz\right)}\left(\widetilde{\mathrm{e}^{-z/2\mathcal{H}}u'}\right)(k, l, m), \tag{11}$$

where the widetilde " $\sim$ " denotes taking the Fourier transform of all factors within the parentheses in space and time, the compressible GW polarization relations are

$$\hat{v} = \frac{il\omega_{Ir} - fk}{ik\omega_{Ir} + fl}\,\hat{u} \tag{12}$$

$$\hat{w} = \frac{-\omega_{Ir}\left(m - \frac{i}{2\mathcal{H}} + \frac{i}{\gamma\mathcal{H}}\right)\left(\omega_{Ir}^2 - f^2\right)\left(k\omega_{Ir} + ifl\right)}{\left(N_B^2 - \omega_{Ir}^2\right)\left(k^2\omega_{Ir}^2 + f^2l^2\right)}\,\hat{u}, \tag{13}$$

$$\hat{T} = \frac{N_B^2\left(im - \frac{1}{2\mathcal{H}}\right) - \frac{\omega_{Ir}^2}{\gamma\mathcal{H}}(1-\gamma)}{g\omega_{Ir}\left(m - \frac{i}{2\mathcal{H}} + \frac{i}{\gamma\mathcal{H}}\right)}\,\hat{w}, \tag{14}$$

$$\hat{w} = \frac{-\left(m - \frac{i}{2\mathcal{H}} + \frac{i}{\gamma\mathcal{H}}\right)\left(\omega_{Ir}^2 - f^2\right)}{\left(N_B^2 - \omega_{Ir}^2\right)k_H}\,\hat{u}_H \tag{15}$$

(Equations B3, B8, and B11 of Vadas, 2013 and Equation 42 of Vadas et al., 2018). Here, the "hatted" quantities are the Fourier transforms of the density-scaled perturbations:

$$\hat{u} = \left(\widetilde{\mathrm{e}^{-z/2\mathcal{H}}u'}\right), \qquad \hat{v} = \left(\widetilde{\mathrm{e}^{-z/2\mathcal{H}}v'}\right), \qquad \hat{u}_H = \left(\widetilde{\mathrm{e}^{-z/2\mathcal{H}}u'_H}\right), \tag{16}$$

$$\hat{w} = \left(\widetilde{\mathrm{e}^{-z/2\mathcal{H}}w'}\right), \qquad \hat{T} = \left(\widetilde{\mathrm{e}^{-z/2\mathcal{H}}T'/\overline{T}}\right), \tag{17}$$

where u', v', and w' are the GW zonal, meridional and vertical velocity perturbations, respectively, $u'_H = \sqrt{(u')^2 + (v')^2}$, T' is the temperature perturbation, and $\overline{T}$ is the background temperature. If we assume the sign convection $\mathrm{e}^{i\left(-\omega_r t + kx + ly + mz\right)}$ instead of the RHS of Equation 11, then one must replace i by $-i$ in Equations 12–15 to obtain the corresponding polarization relations. (Note that the chosen sign convention does not affect the physically-observed atmospheric perturbations.) Equations 12–15 yield the phase and amplitude relationships between u', v', w', u'_H, and T'. For example, we can write

$$\hat{T} = (\alpha + i\beta)\hat{w} = A\exp(i\zeta)\hat{w}, \tag{18}$$

where $A = \sqrt{\alpha^2 + \beta^2}$ and $\zeta = \tan^{-1}(\beta/\alpha)$. Then the phase shift between $\hat{T}$ and $\hat{w}$ is ζ and the amplitude ratio is A. If $|\lambda_z| \ll 4\pi\mathcal{H}$, then u', v', w', u'_H, and T' can be substituted in for $\hat{u}$, $\hat{v}$, $\hat{w}$, $\hat{u}_H$ and $\hat{T}$, respectively, in Equations 12–15.

2.2. Hodograph Solutions for a Gravity Wave

Multiplying Equation 12 by its complex conjugate yields

$$\left(l^2\omega_{Ir}^2 + f^2k^2\right)|\hat{u}|^2 - \left(k^2\omega_{Ir}^2 + f^2l^2\right)|\hat{v}|^2 = 0, \tag{19}$$

where "*" denotes the complex conjugate and $|\hat{u}|^2 = \hat{u}\hat{u}^*$, for example, We define the GW propagation direction in the horizontal plane counter-clockwise from east as ψ. Then

$$k = k_H\cos\psi, \qquad l = k_H\sin\psi. \tag{20}$$

Plugging Equation 20 into Equation 19, we get

$$\left[1+\left(\frac{\omega_{Ir}}{f}\right)^2\tan^2\psi\right]|\hat{u}|^2-\left[\left(\frac{\omega_{Ir}}{f}\right)^2+\tan^2\psi\right]|\hat{v}|^2=0. \tag{21}$$

We rotate to a coordinate system parallel to the GW propagation direction so that $\hat{u}_{\parallel}$ and $\hat{u}_{\perp}$ are the parallel (long axis) and perpendicular (short axis) components of the horizontal wind perturbations, respectively. Setting $\psi = 0$ in this system, Equation 21 becomes

$$|\hat{u}_{\parallel}|^2=\left(\frac{\omega_{Ir}}{f}\right)^2|\hat{u}_{\perp}|^2. \tag{22}$$

If $|\lambda_z| \ll 4\pi\mathcal{H}$, $\hat{u}_{\parallel} = u'_{\parallel}$ and $\hat{u}_{\perp} = u'_{\perp}$ so that

$$|u'_{\parallel}|^2=\left(\frac{\omega_{Ir}}{f}\right)^2|u'_{\perp}|^2. \tag{23}$$

Equation 23 shows that the ratio of the parallel to the perpendicular lengths of the ellipse formed by plotting u' versus v' for a GW yields ω_{Ir}/f via the hodograph method, as is well known (for example, Baumgarten et al., 2015; Chen et al., 2013; Cot & Barat, 1986; Sawyer, 1961; Strelnikova et al., 2020; Wang & Geller, 2003; Zhang et al., 2004). Additionally, because the GW propagation direction is parallel to the long axis of the ellipse, ψ is determined from the hodograph except for a 180° ambiguity. This ambiguity is eliminated by using the phase shift between T' and u' (or v') (for example, Baumgarten et al., 2015; Chen et al., 2013). λ_H is then determined from the GW dispersion relation when λ_z is measured.

3. Observations and Analysis of Fishbone Structure GWs at ALOMAR

3.1. RMR Lidar Observations at ALOMAR

We make use of temperature and wind data acquired with the Doppler Rayleigh-Mie-Raman lidar installed at the ALOMAR, located in northern Norway at 69.38°N, 16.08°E. This lidar measures temperatures and winds during daytime and nighttime (for example, Baumgarten et al., 2015; Fiedler et al., 2011; Schöch et al., 2008; von Zahn et al., 2000). Two lasers emit pulses in two different directions with a zenith distance angle of 20°. The azimuths for the north and east viewing telescopes are 0° and 90°, respectively. The backscattered photons are collected by two receiving telescopes. One single detection system is used for recording the backscattered light (among others) at wavelengths of 355 and 532 nm, where the latter is further analyzed with a Doppler Iodine Spectrometer (Baumgarten, 2010). These backscattered signals are used to calculate the temperature profiles (Hauchecorne & Chanin, 1980). The wind is measured in the zonal and meridional directions given by the pointing of the two outgoing beams and the viewing direction of the telescopes. From the measured Doppler-shift, the horizontal wind is calculated assuming negligible contribution from the vertical wind.

The temperature profiles are available up to 90 km during the nighttime and 70 km during the daytime. The (oversampled) data is available with a resolution of 5 min and 150 m. This data allows for the detection of waves down to periods of 1 hr and vertical wavelengths of 1 km. We interpolate over missing data or data that have values which significantly deviate from the mean. We do not use data below 25 km due to uncertainties introduced by the stratospheric aerosol layer and the presence of polar stratospheric clouds (Baumgarten, 2010; Langenbach et al., 2019).

3.2. Extraction of Fishbone Structures From the Lidar Data

Figure 1a shows a time-height cross section of the scaled temperature perturbation, T' exp $(-z/14$ km$)$, and Figure 1b shows the background mean temperature, $\overline{T}$, from the lidar at ALOMAR on 12–14 January 2016. Here, we use Fourier filtering to obtain the perturbations, which have $1 \le \tau_r \le 11$ hr so that the semi-diurnal and diurnal tides are removed and $|\lambda_z| \ge 1$ km. Note that $\tau_r \ge 1$ hr and $|\lambda_z| \ge 1$ km are consistent with the requirement for extracting waves from the lidar data (see Section 3.1). Because exp $(-z/14$ km$)$ is roughly the square root of the background density (since $\mathcal{H} \sim 7$ km), multipying T' by this factor causes the amplitudes of the upward and downward-propagating GWs in the fishbone structures to be the same if $\overline{T}$, $\overline{U}$ and $\overline{V}$ are constant, and therefore enables easier identification of these structures. Figures 1c–1d show the scaled zonal and meridional wind

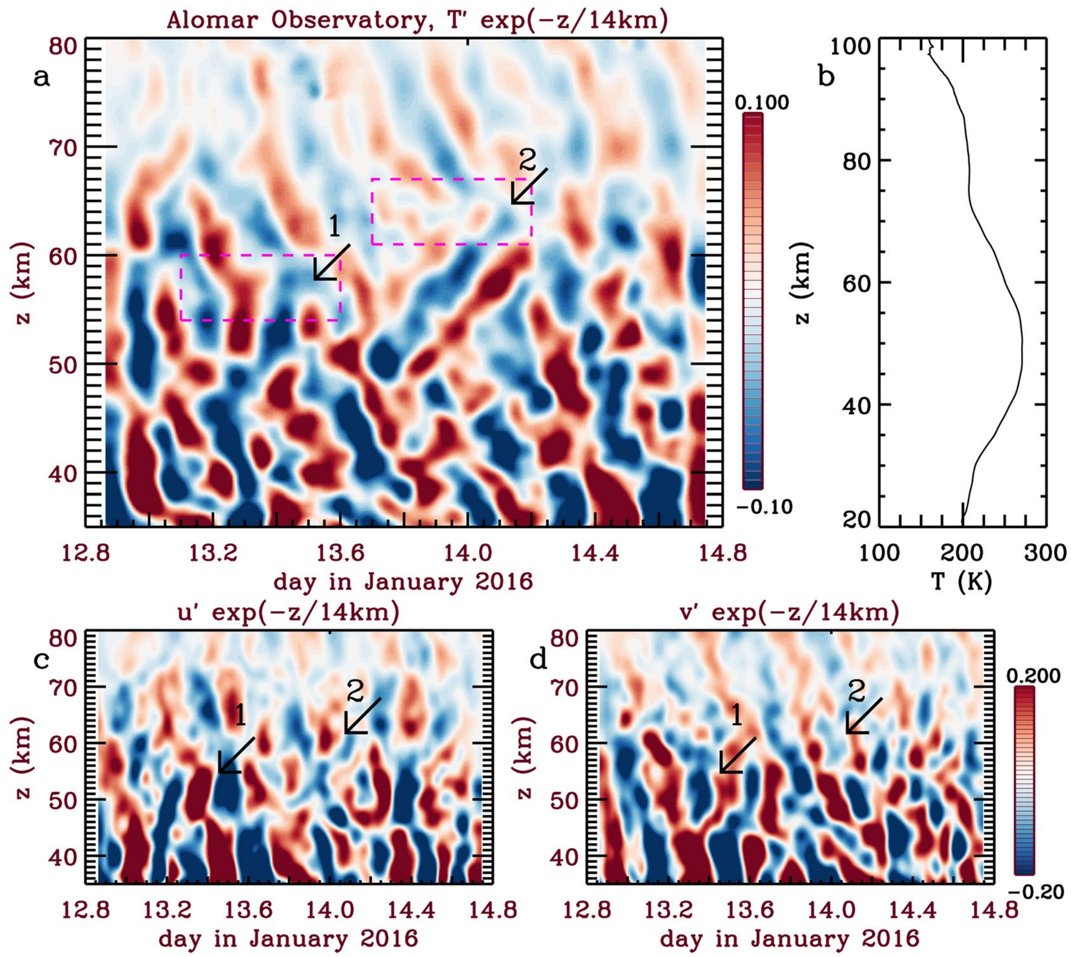

Figure 1. Lidar observations at the Arctic Lidar Observatory for Middle Atmosphere Research on 12–14 January 2016. (a) Scaled temperature perturbations, T' exp $(-z/14$ km) (colors, in K). The pink dash rectangles show the altitude ranges where the downward gravity waves (GWs) (with upgoing phases in time) are generated during events #1 and #2 (see text). (b) Background temperature, $\overline{T}$ (in K). (c) Scaled zonal wind perturbations, u' exp $(-z/14$ km) (colors, in m/s). (d) Scaled meridional wind perturbations, v' exp $(-z/14$ km) (colors, in m/s). The perturbations are filtered to retain GWs with $1 < \tau_r < 11$ hr and $|\lambda_z| \geq 1$ km. The black arrows point at z_{knee} for events #1 and #2. The colors are oversaturated to better see the GWs at $45 < z < 80$ km.

perturbations, u' exp $(-z/14$ km) and v' exp $(-z/14$ km), respectively. Two fishbone structures are observed in Figure 1: events #1 and 2 (black arrows). Note that these structures are not as "clean" as in Vadas et al. (2018) because of constructive/destructive interference of the main fishbone GWs with "contaminant" GWs. (As we find in Section 4 and Appendix A, these contaminant GWs are secondary GWs from neighboring LBFs.)

Figures 2a and 2b show T' exp $(-z/14$ km) for GWs with upgoing and downgoing phases in time, respectively, obtained by taking the Fourier transform of Figure 1a. Upgoing phase lines (suggesting downward-propagating GWs) are only visible below $z \sim 60$ and 66 km during events #1 and #2, respectively. There is a corresponding decrease or dip in amplitude for the downgoing phase lines (suggesting upward-propagating GWs) in Figure 2b at $z \sim 60$ and 66 km during events #1 and #2, respectively. These results suggest that in situ upward and downward-propagating GWs are generated at these altitudes.

We determine z_{knee} as follows. We first locate the altitude range where the amplitudes of the filtered upgoing phase lines (downward GWs) in Figure 2a become quite small at the highest-altitude part of the wave packet. This is the altitude range where the downward secondary GWs are created. During event #1, this altitude range is estimated to be $z \sim 54$–60 km from Figure 2a. We outline this downward-GW generation region with a pink dash rectangle in Figure 2a, and duplicate this rectangle in Figure 1a. We now use the fact that $T' = 0$ for the secondary GWs at z_{knee}, which is the altitude of a (horizontally-displaced) LBF (Vadas et al., 2003, 2018). We then estimate

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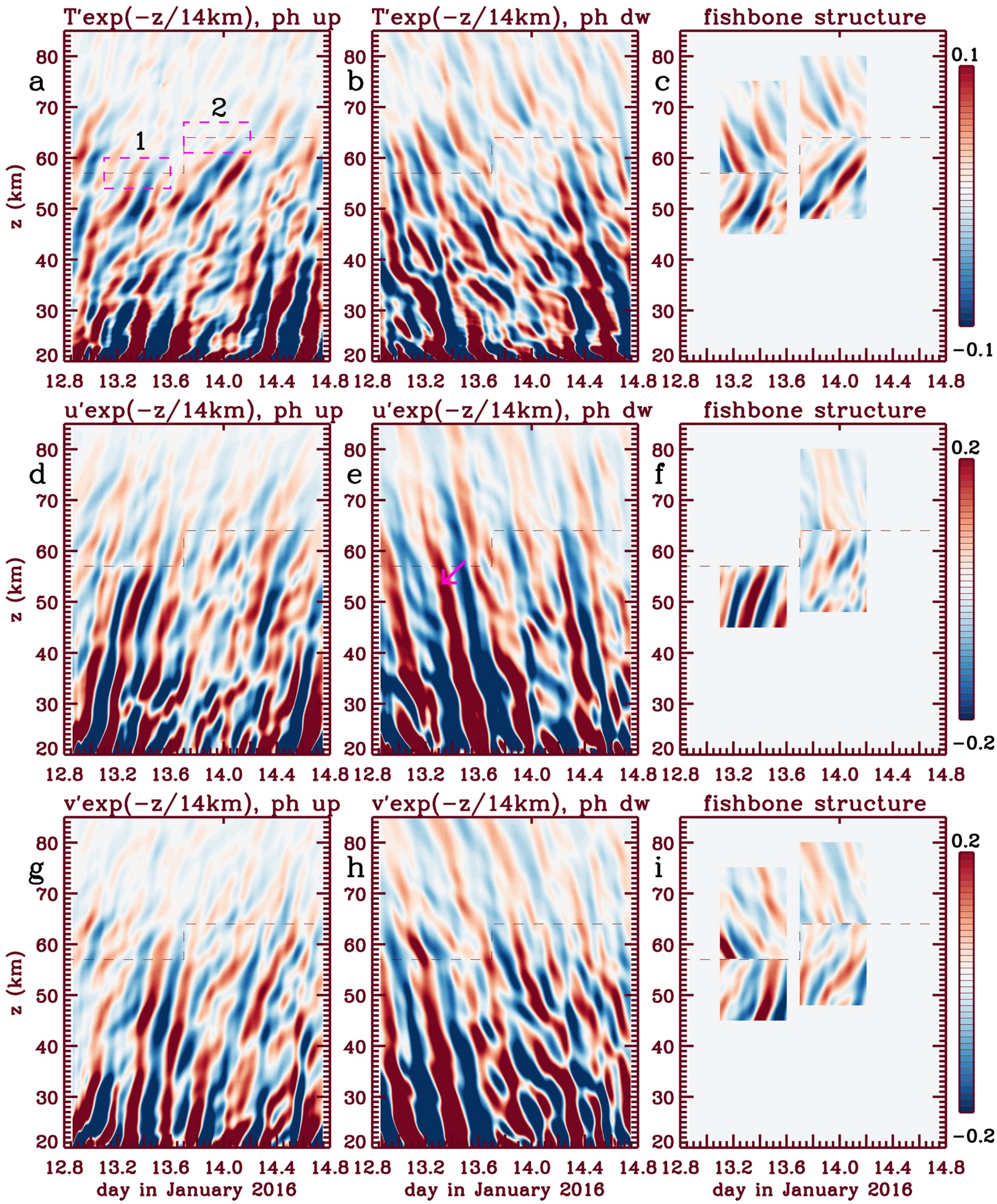

Figure 2. Lidar observations at Arctic Lidar Observatory for Middle Atmosphere Research on 12–14 January 2016. (a) T' exp $(-z/14$ km) (colors, in K) for gravity waves (GWs) with upgoing phases in time. The pink dash rectangles are the same as in Figure 1a. (b) Same as (a) but for GWs with downgoing phases in time. (c) Same as (a–b) but for GWs having upgoing (downgoing) phases below (above) z_{knee} during the time and altitude boundaries for each event (see text). The dashed lines show $z_{\mathrm{knee}} = 57$ km before 13.7 January and $z_{\mathrm{knee}} = 64$ km after 13.7 January. Rows 2–3: Same as the first row but for u' exp $(-z/14$ km) and v' exp $(-z/14$ km), respectively (in m/s). The colors are oversaturated to better see the GWs at $45 < z < 80$ km.

the average altitude within the GW generation region (pink rectangle) where the hot and cold upgoing and downgoing phase lines meet in Figure 1a, and define this altitude to be z_{knee}. Examining the upgoing and downgoing phase lines within the event #1 pink rectangle in Figure 1a, we estimate an average altitude where the hot and cold phase lines meet of $z \sim 57$ km (black arrow); therefore we set $z_{\text{knee}} = 57$ km for event #1.

For event #2, the amplitude of the upgoing phase lines are quite small at $z \sim 60$–65 km (event #2 pink dash rectangle) in Figure 2a. Examining this same altitude range in Figure 1a, we estimate an average altitude where the hot and cold phase lines meet of $z \sim 64$ km (black arrow); therefore we set $z_{\text{knee}} = 64$ km for event #2. Note that the arrows in Figure 1a point directly at z_{knee}. Constructive/destructive interference with secondary GWs from neighboring LBFs makes it more difficult to determine z_{knee} for the main fishbone structures (see Appendix A). Additionally, saturation of the primary GWs smears T' at z_{knee}, thereby making it more difficult to determine z_{knee} of the secondary GWs. We overplot in Figure 2 the knee altitudes $z_{\text{knee}} = 57$ km before 13.7 January and $z_{\text{knee}} = 64$ km after 13.7 January (dashed line). As a consistency check, we note that nearly all of the scaled amplitudes for GWs with downgoing phases decrease near the dashed line in Figure 2b after 13.2 January (Here, 13.2 January refers to ~5 UT on 13 January.)

Note that the event #1 (#2) GWs with downgoing phases (suggesting upward-propagating GWs) in Figure 2b are damped at $z \sim 65$–70 km ($z \sim 72$–78 km); this damping must be caused by wave breaking that is induced by amplitude growth (instead of refraction by the background wind) since λ_z is relatively constant during the damping.

Boundaries that enclose relatively "clean" fishbone structures from Figures 1 and 2 are as follows. Event #1 is chosen to be at $45 < z < 75$ km on 13.1–13.6 January, and event #2 is chosen to be at $48 < z < 80$ km on 13.7–14.2 January. Figure 2c shows those GWs with downgoing (upgoing) phases above (below) the dashed line for the chosen time and altitude boundaries. Fishbone structures are seen during events #1 and 2. Note that the hot-cold phases do not always line up due to the presence of contaminant waves.

The second and third rows of Figure 2 show the corresponding results for u' and v'. Note that large-amplitude GWs not part of the fishbone structure propagate upward from below through event #1 in Figure 2e (purple arrow). Therefore, we do not show the GWs with downgoing phase lines above z_{knee} during event #1 for u' in Figure 2f.

3.3. Estimation of the Intrinsic Parameters of the Lidar GWs From the Hodograph Method

Figures 3a and 3b show the power spectral density (PSD) of T' from Figure 2c, $\left[\tilde{T}'\right]^2$, above and below the knee, respectively, calculated within the time and altitude boundaries for event #1. Here we show the PSD of T' instead of u'_H because we have complete T' data above and below z_{knee} for both events (see the third column of Figure 2). The peak values are $|\tau_r| \sim 5$–8 hr and $|\lambda_z| \sim 10$–20 km. Since $|\tau_r|$ and $|\lambda_z|$ are similar above and below z_{knee}, these GWs are likely secondary GWs from a horizontally-displaced LBF at $z_{\text{knee}} = 57$ km. We fit 2D Gaussian functions to the PSD to obtain best-fit values below z_{knee} for $|\lambda_z|$ and $|\tau_r|$; the results are shown in Table 1.

Figure 3c shows the lidar perturbations u', v' and $(g/N_B)T'/\overline{T}$ as functions of time at $z = 54$ km via setting $N_B = 0.02$ rad/s and $g = 9.8(R_{\text{E}}/(R_{\text{E}} + z))^2 = 9.6\ \ \text{m/s}^2$. Figures 3d and 3e show temporal and altitudinal hodographs, respectively. The hodographs rotate counter-clockwise in time and altitude, thereby implying that the GWs below z_{knee} propagate downward in time. These hodographs are distorted ellipses due to the presence of contaminant GWs which create "branched" and "checkerboard" patterns in T' at $45 < z < 57$ km and at 13.1–13.6 January in Figures 2c, 2f, and 2i. These contaminant GWs are likely secondary GWs from neighboring LBFs (see Section 4).

We roughly estimate $u'_{\parallel} \sim 21\ \ \text{m/s}$, $u'_{\perp} \sim 4\ \ \text{m/s}$, and $u' \sim 17$ m/s from Figure 3d, where u' is the total zonal velocity perturbation (i.e., the projection of the hodograph onto the u' axis). Using Equations 10 and 23 and Table 1, $|\lambda_z| = 15$ km and $2\pi/f = 12.8$ hr, we estimate $\tau_{Ir} = 2\pi/\omega_{Ir} \sim 2.4$ hr and $\lambda_H = 421$ km. Using Equation 20, $\psi = \cos^{-1}\left(u'/u'_{\parallel}\right)$, which yields northwest or southeast propagation directions of $\psi \sim 144°$ or $-36°$.

Figure 4a shows the wind from NASA's Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) reanalysis data (Gelaro et al., 2017) on 13.0 January at $z = 48$ km, which is the height where the polar night jet has a maximum speed of $U_{\text{tot}} = 133$ m/s, where $\text{U}_{\text{tot}} = \sqrt{\overline{U}^2 + \overline{V}^2}$. The jet is strong over the Atlantic Ocean and northern Europe. We overplot the vortex edge (white line) using the streamfunction method of Harvey et al. (2002). The vortex edge roughly follows the poleward flank of the wind maximum.

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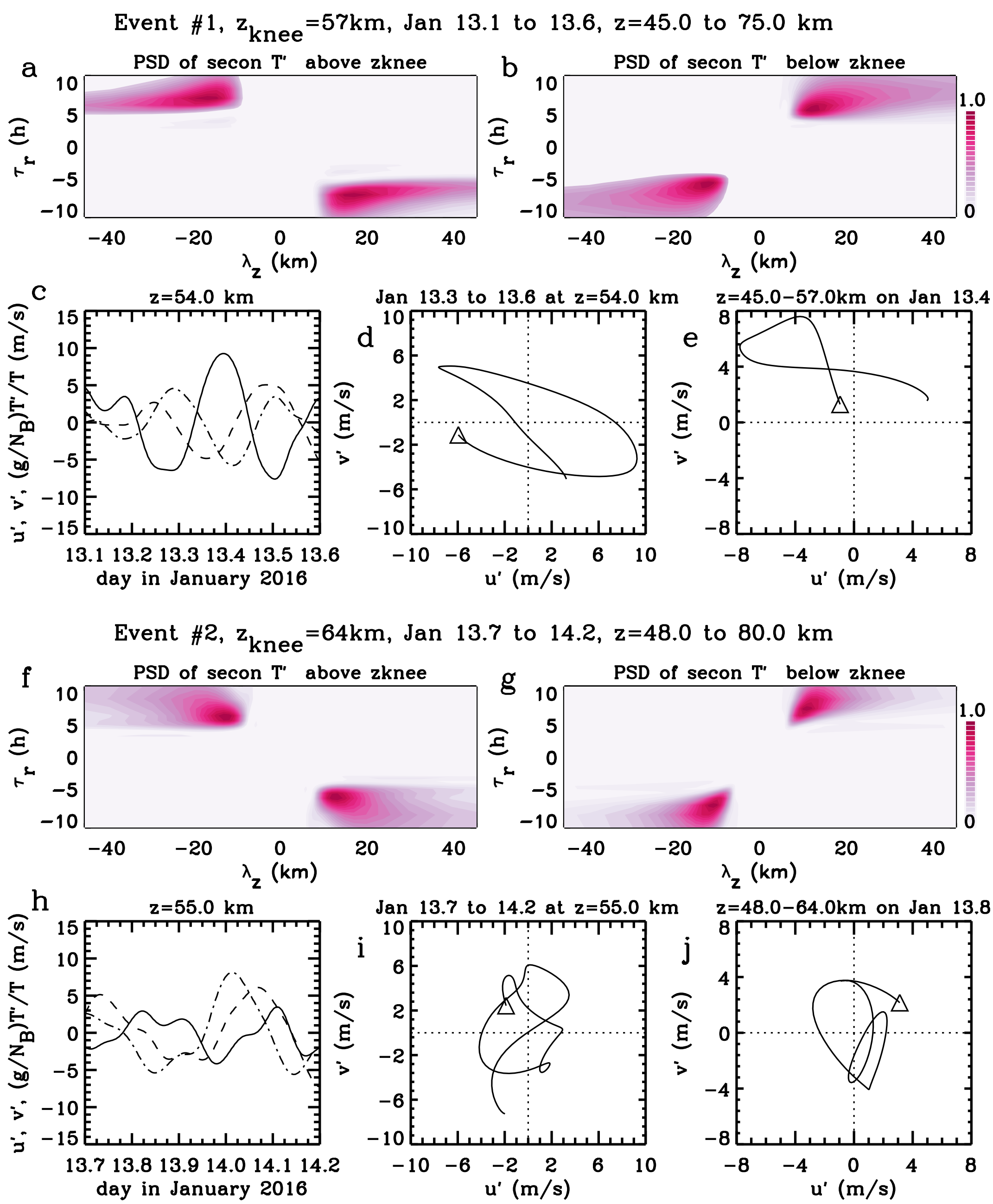

Figure 3. Lidar observations at Arctic Lidar Observatory for Middle Atmosphere Research on 13 and 14 January 2016. (a–e): Event # 1. (a, b) power spectral density of T' from Figure 2c, $\left[\widetilde{T'}\right]^2$, above and below $z_{\mathrm{knee}} = 57$ km, respectively, within the event boundaries (colors). (c) u' (solid), v' (dashed), and $(g/N_B)T'/\overline{T}$ (dashed-dotted) (in m/s) at $z = 54$ km. (d) u' versus v' for 13.3–13.6 January (triangle at 13.3 January) at $z = 54$ km. (e) u' versus v' for $z = 45$–57 km on January 13.4 (triangle at $z = 45$ km). (f–j): Same as (a–e) but for event # 2 with $z_{\mathrm{knee}} = 64$ km with the following changes: (h): $z = 55$ km. (i): u' versus v' for 13.7–14.2 January (triangle at 13.7 January) at $z = 55$ km. (j): u' versus v' for $z = 48$–64 km on January 13.8 (triangle at $z = 48$ km).

Figures 4b and 4c show the horizontal wind at $z = 54$ and 58 km. Below z_{knee} during event #1, the wind is mainly eastward at ALOMAR (asterisk). If the event #1 GWs propagated northwestward (southeastward), they would have propagated mainly against (with) the wind, which would have resulted in $\tau_{Ir} < |\tau_r|$ ($\tau_{Ir} > |\tau_r|$) from the Doppler shift. Since $\tau_{Ir} < |\tau_r|$, the event #1 GWs must have propagated northwestward.

Figures 3f–3j and Table 1 show the corresponding results for event #2. Since $|\tau_r|$ and $|\lambda_z|$ are similar above and below z_{knee} in Figures 3f and 3g, these GWs are likely secondary GWs. While the hodograph in Figure 3j rotates

Table 1
Alternative Method: Intrinsic Parameters of Secondary Gravity Waves Over Arctic Lidar Observatory for Middle Atmosphere Research

	PSD of T'		Parameters using GW dispersion and polarization relations				
Event	$\lvert\lambda_z\rvert$ (km)	$\lvert\tau_r\rvert$ (h)	λ_H (km)	τ_{Ir} (h)	c_H (m/s)	c_{IH} (m/s)	ψ (deg)
# 1	15.3 ± 4.7	6.7 ± 1.7	477.2 ± 279.5	2.8 ± 0.9	20.0 ± 9.5	48.2 ± 9.4	134.7 ± 8.1
# 2	12.3 ± 3.5	8.3 ± 2.0	1,471.5 ± 227.7	7.6 ± 0.6	57.9 ± 16.6	52.1 ± 10.3	90.9 ± 7.9

counter-clockwise in z, the hodograph in Figure 3i rotates both clockwise and counter-clockwise in time due to the presence of contaminant GWs (see Figure 3h and Figures 2c, 2f, and 2i), thereby yielding an ambiguous result. We roughly estimate $u'_{\parallel} \sim 7\,\mathrm{m/s}$, $u'_{\perp} \sim 4\ \mathrm{m/s}$, and $u' \sim 3$ m/s. Using Equation 23, we estimate $\tau_{Ir} = 2\pi/\omega_{Ir} \sim 7.3$ hr and $\psi = 115°$ or $-65°$.

Figure 4d shows the wind on 13.5 January at $z = 48$ km, the height where the polar vortex has a maximum speed of $U_{\rm tot} = 156$ m/s, and Figures 4e and 4f show the wind at $z = 54$ and 64 km. Below $z_{\rm knee}$ during event #2, the wind is mainly eastward at ALOMAR. If the event #2 GWs propagated northward or southward, they would have propagated approximately perpendicular to the wind direction, so that $\tau_{Ir} \simeq \tau_r$. Because T' peaks before u' in Figure 3h, we show in Section 3.4 that these GWs propagated northward.

3.4. Alternative Method to Determine the Intrinsic Parameters of Lidar GWs

The hodograph method used in Section 3.3 is the usual way to determine the intrinsic parameters of inertia GWs from lidar data. However, because of contamination from other GWs, we were only able to obtain rough estimates of these parameters. We now present an alternative method to obtain the best-fit intrinsic GW parameters and $1-$ sigma errors using the GW polarization and dispersion relations.

To motivate this method, Figure 5a shows u', v', $(g/N_B)T'/\overline{T}$ as functions of time at a fixed altitude for a possible event #1 GW that is downward and northwestward-propagating with $u'_H = 7\ \ \mathrm{m/s}$, $\lambda_H = 310$ km, $\tau_{Ir} = 2$ hr and $\psi = 150°$, and Figure 5b shows the corresponding hodograph in time. Here we use the GW polarization relations given by Equations 12–14 with $\gamma = 1.4$, $N_B = 0.02$ rad/s, $\mathcal{H} = 7$ km, $g = 9.8(R_{\rm E}/(R_{\rm E}+z))^2 = 9.6\ \ \mathrm{m/s^2}$, and $m > 0$ (because the GW is downward-propagating). We calculate ω_{Ir} from Equation 3 using k and l from Equation 20 and $\overline{U}$ and $\overline{V}$ from MERRA-2 at $z = 54$ km, and ensured that it equaled ω_{Ir} from Equation 6. (Note that $\overline{U}$ and $\overline{V}$ from MERRA-2 are similar to the mean wind measured by the lidar at this altitude.) In Figure 5a, u' and v' are approximately $\sim$180° out of phase because the GW propagates northward ($l > 0$) and westward ($k < 0$). Additionally, the T' peak precedes the u' peak by $\sim$90°.

We employ the mid-frequency approximation for GWs whereby $N_B \gg \omega_{Ir} \gg f$, and assume that $|\lambda_z| \ll 4\pi\mathcal{H}$. Then Equations 13 and 14 become

$$\frac{T'}{\overline{T}} \simeq \frac{-im\omega_{Ir}}{gk}u'. \tag{24}$$

If a GW propagates downward and eastward, then $m>0$ and $k>0$ so that $T'/\overline{T} \propto -iu'$. Since x, y, and z are constants, $u' \propto u'_0 \exp(i\omega_r t)$ from Equation 11, where u'_0 is the amplitude of u'. Then, $T'/\overline{T} \propto u'_0\exp(i\,\omega_r(t-\pi/(2\omega_r)))$, since $i = \exp\,(i\pi/2)$. Therefore T' peaks 90° after u' for a downward and eastward-propagating GW in this background wind. But if the GW propagates downward and westward, then $T'/\overline{T} \propto u'_0\exp(i\,\omega_r(t+\pi/(2\omega_r))$ causing T' to peak 90° before u', as seen in Figure 5a.

Figures 5c and 5d shows the analogous results for a possible event #2 GW that propagates downward and northwestward with $\lambda_H = 1{,}360$ km, $\tau_{Ir} = 7$ hr, and $\psi = 110°$. As for the previous case, T' peaks $\sim$90° before u'. Note that the hodograph in Figure 5d is rounder than in Figure 5b because τ_{Ir} is larger.

While the hodograph of a monochromatic GW is a "perfect" ellipse (e.g., Figures 5b and 5d), the hodographs of the lidar GWs are distorted ellipses due to contaminant GWs having similar τ_r and λ_z (see Figures 3d, 3e, 3i, and 3j). We now determine the best-fit intrinsic GW parameters, τ_{Ir}, λ_H, and ψ, and corresponding 1-sigma errors from $u'(t)$, $v'(t)$, and $T'(t)$ at a given altitude and location via searching parameter space for GWs consistent with the data and with the GW f-plane compressible dispersion and polarization relations for specified values of $\overline{U}$, $\overline{V}$, $\overline{T}$, γ, $\mathcal{H}$, N_B, g, and f.

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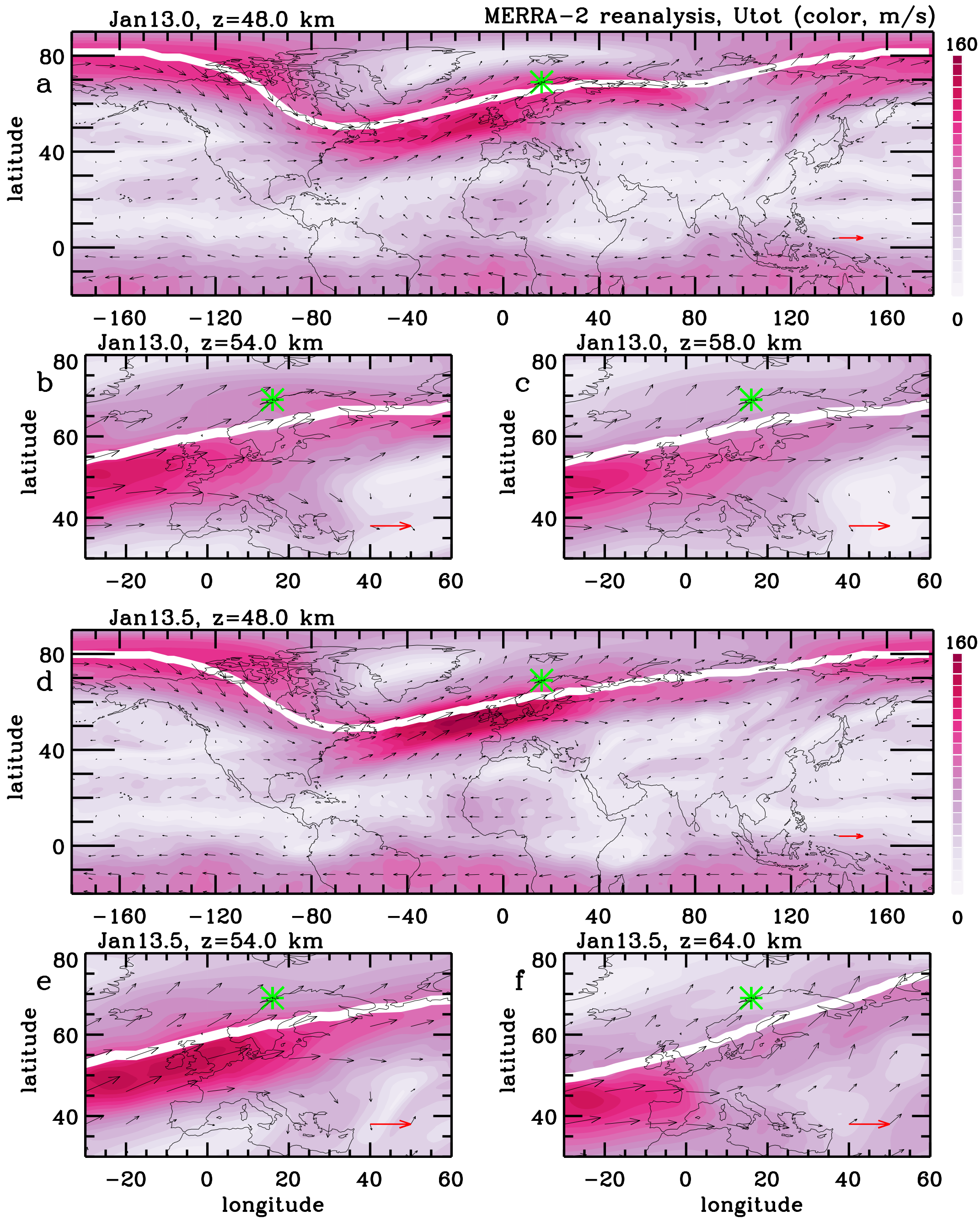

Figure 4. Horizontal wind from MERRA-2 reanalysis (vectors, in m/s). The colors show the magnitude of the horizontal wind, U_{tot} (in m/s) (a–c): 13.0 January 2016. (a) $z = 48$ km. (b) $z = 54$ km. (c) $z = 58$ km. (d–f): 13. 5 January 2016. (d) $z = 48$ km. (e) $z = 54$ km. (f) $z = 64$ km. The red arrows show an eastward wind vector with $U_{tot} = 100$ m/s. The green asterisks show Arctic Lidar Observatory for Middle Atmosphere Research. The white lines show the vortex edge.

We perform four nested loops through specified ranges of values for λ_H, λ_z, τ_r, and ψ. Here, λ_H ranges from $\lambda_H = 100$–3,000 km and ψ ranges from $-180°$ to $180°$. Additionally, $|\lambda_z|$ ranges from $\overline{\lambda_z} - \sigma_{\lambda_z}$ to $\overline{\lambda_z} + \sigma_{\lambda_z}$ and $|\tau_r|$ ranges from $\overline{\tau_r} - \sigma_{\tau_r}$ to $\overline{\tau_r} + \sigma_{\tau_r}$ where $\overline{\lambda_z}$ and $\overline{\tau_r}$ are the best-fit values of λ_z and τ_r and σ_{λ_z} and σ_{τ_r} are the errors in these values from the PSD (see Table 1). In addition, τ_r ranges over negative and positive values, and $m = 2\pi/\lambda_z$ is negative (positive) for an upward (downward)-propagating GW. Within these loops, we set $\omega_r = 2\pi/\tau_r$ and $k_H = 2\pi/\lambda_H$, determine k and l from Equation 20, and calculate ω_{Ir} from Equation 3. We then calculate ω_{Ir} independently from Equation 6 (or Equation 9 if $|\lambda_z| \ll 4\pi\mathcal{H}$); if these ω_{Ir} values agree to within a

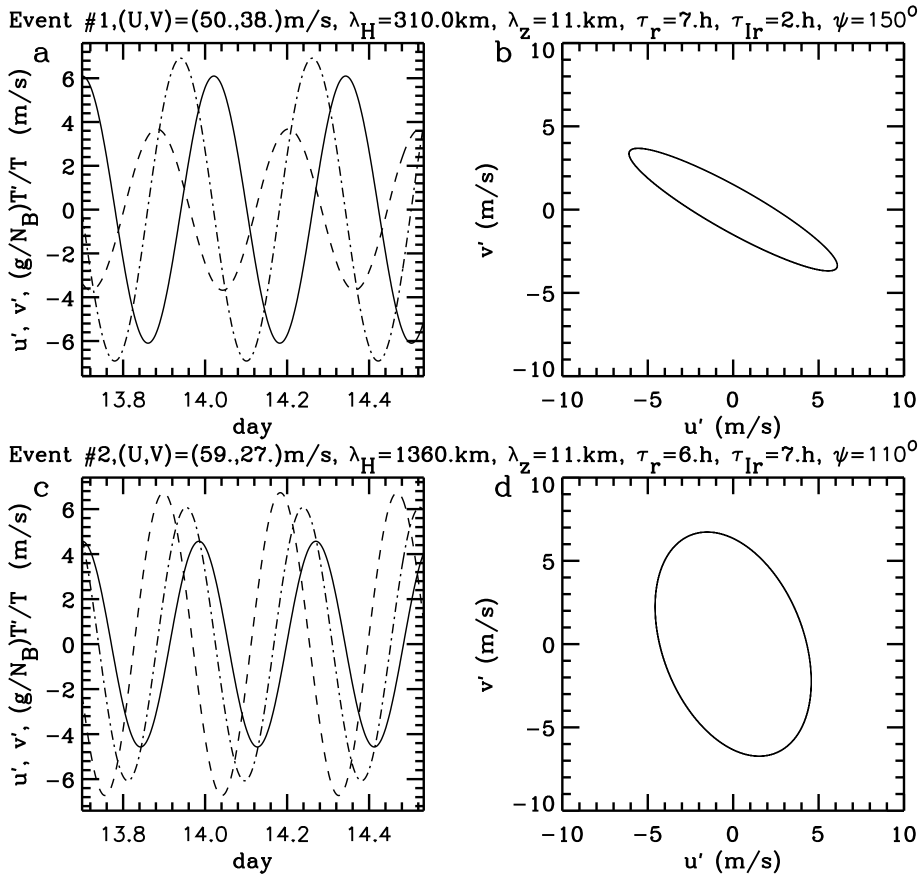

Figure 5. Theoretical solutions to the gravity wave (GW) polarization and dispersion relations for monochromatic GWs. (a) u' (solid line), v' (dashed line), and $(g/N_B)T'/\overline{T}$ (dashed-dotted line) (in m/s) for a possible event #1 GW with $\lambda_H = 310$ km, $\lambda_z = 11$ km, $\tau_r = 7$ hr, $\tau_{Ir} = 2$ hr, and $\psi = 150°$. (b) Hodograph of u' versus v' in time. (c–d): Same as (a–b), but for a possible event #2 GW with $\lambda_H = 1{,}360$ km, $\lambda_z = 11$ km, $\tau_r = 6$ hr, $\tau_{Ir} = 7$ hr, and $\psi = 110°$. The background wind is obtained from MERRA-2 reanalysis at the location of Arctic Lidar Observatory for Middle Atmosphere Research. Row 1: $(U, V) = (50, 38)$ m/s at $z = 54$ km at 6 UT on 13 January 2016. Row 2: $(U, V) = (59, 27)$ m/s at $z = 55$ km at 0 UT on 14 January 2016.

small prescribed tolerance, we know this GW could have propagated in this direction in this atmosphere. We then check if the theoretical ratio of the maximum value of u' to the maximum value of v' (and/or the maximum values of $(g/N_B)T'/\overline{T}$ and w') from Equations 12–14 is within the specified tolerance range for the observed ratio of these maximum values (e.g., from Figures 3c and 3h). We calculate the former ratio by setting $u'(t)$ at a given altitude and location to be $u'(t) = u'_0\exp(i\omega_r t)$, calculate $v'(t)$ from Equation 12 then calculate max (u')/max (v'), where max () denotes the maximum value. Several amplitude ratios can be used to better-constrain the resulting GW parameters if the contaminant GWs have relatively small amplitudes. We also calculate the phase of T' minus that of u', divide by $|\omega_r|$, and require this angle to be within a specified tolerance range from the observations. If the ratio(s) and phase shift(s) are within the specified tolerances, then this solution agrees with the observations and is saved as a viable solution.

Finally, we create histograms of the number of viable GW solutions as functions of λ_H, τ_{Ir}, c_H, c_{IH}, and ψ. Gaussian functions are then fitted to these histograms to obtain best-fit values with 1 − sigma errors. Here, the intrinsic horizontal phase speed is

$$c_{IH} = \omega_{Ir}/k_H = c_H - U_H, \tag{25}$$

where $U_H = \left(k\overline{U} + l\overline{V}\right)/k_H$. By definition, $c_{IH} \geq 0$ because the GW would have been absorbed by a critical level if it had reached zero from a positive value.

We now perform this analysis for events #1 and #2. From Figures 3c and 3h, we estimate $u'_0/v'_0 = 1.5$ to 2.2 for event #1 and $u'_0/v'_0 = 0.5$ to 0.7 for event #2, where u'_0 $\left(v'_0\right)$ is the amplitude of u' (v'). For both, we require T'

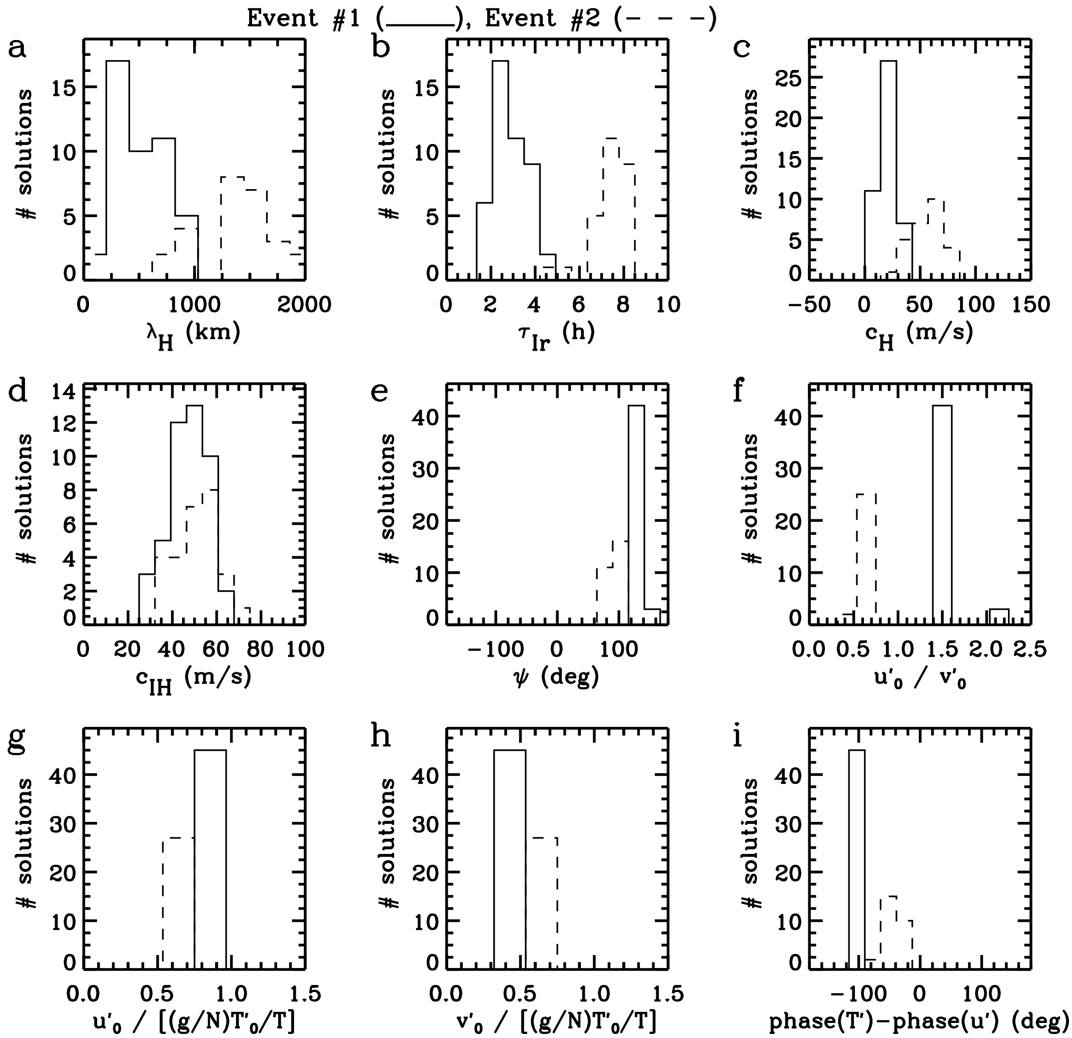

Figure 6. Number of viable gravity wave solutions to the f-plane compressible polarization and dispersion relations for Arctic Lidar Observatory for Middle Atmosphere Research lidar events #1 (solid line) and #2 (dashed line) as functions of (a) λ_H, (b) τ_{Ir}, (c) c_H, (d) c_{IH}, (e) ψ, (f) u'_0/v'_0, (g) $u'_0/\left[(g/N_B)T'_0/\overline{T}\right)$, (h) $v'_0/\left[(g/N_B)T'_0/\overline{T}\right)$, (i) phase (T') − phase (u').

to lead u' by 20° to 160° from Figures 3c and 3h. We set $m > 0$ since these GWs are downward-propagating. We allow τ_r to range over positive and negative values to allow for the possibility that upward-propagating GWs have upgoing phase lines in time (see below). The background wind $\left(\overline{U}, \overline{V}\right)$ and temperature $\overline{T}$ are obtained from MERRA-2 at ALOMAR on 13.25 January at $z = 54$ km and on 14.0 January at $z = 55$ km for events #1 and #2, respectively. In addition, we set $\gamma = 1.4$, $\mathcal{H} = 7$ km, $g = 9.8(R_E/(R_E + z))^2$, $N_B = 0.02$ rad/s, $c_s = \sqrt{\gamma g \mathcal{H}}$, $f = 2\,\Omega \sin\theta$, $\Omega = 2\pi/(24$ hr), and $\theta = 69.38°$.

Figure 6 shows the number of (viable) GW solutions for events #1 and #2 as functions of λ_H, τ_{Ir}, c_H, c_{IH}, ψ, u'_0/v'_0, $u'_0/\left[(g/N_B)T'_0/\overline{T}\right)$, $v'_0/\left[(g/N_B)T'_0/\overline{T}\right)$, and the angular phase shift between T' and u', where T'_0 is the amplitude of T'. Both events contain medium to large-scale GWs, although the GWs in event #1 are mainly medium-scale, medium-frequency GWs with λ_H = 250–800 km and τ_{Ir} = 2–4 hr, while the GWs in event #2 are mainly large-scale, medium to low-frequency GWs with λ_H = 800–1,700 km and τ_{Ir} = 6.5–8 hr. The GWs propagate northwestward during event #1, and northward during event #2. Note that the GWs in both events have c_{IH} = 35–65 m/s. We fit 1D Gaussian functions to these histograms. The best-fit parameters with 1-sigma errors are given in columns 4–8 in Table 1.

We now check that the upgoing phase lines (in time) below z_{knee} correspond to downward-propagating GWs. If an upward-propagating GW propagates against the background wind (i.e., $U_H < 0$), then its phase lines can be

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upgoing (not downgoing) in time in a $z - t$ plot if the GW is swept downstream in the same direction as the wind; this occurs if $c_H < 0$ (and $\tau_r < 0$) (see text surrounding Equation 60 in Vadas et al., 2018), which can only occur if $U_H < 0$ and $|U_H| > c_{IH}$ from Equation 25. From Figure 6c, $c_H > 0$ for all of the viable GW solutions. Therefore, the upgoing phase lines below z_{knee} correspond to downward-propagating GWs during both events. We conclude that events #1 and #2 were secondary GWs created from LBFs located southeast/south of ALOMAR at $z \sim 57$ and 64 km prior to 13.0 and 13.7 January, respectively.

4. Modeling the Primary and Higher-Order Gravity Waves Over Europe on 12–14 January 2016

4.1. Description of the HIgh Altitude Mechanistic General Circulation Model With Specified Dynamics

The HIAMCM is a high-resolution, GW-resolving, global circulation model (Becker & Vadas, 2020, hereafter BV20). It is based on a standard spectral dynamical core with a terrain-following hybrid vertical coordinate, and a correction for non-hydrostatic dynamics. Molecular viscosity, thermal diffusivity, and ion drag are included in the thermosphere so that a sponge layer is not needed or used there. The HIAMCM explicitly simulates momentum and energy deposition from GWs, including their spatial and temporal intermittency. This momentum and energy deposition occurs because resolved GW packets that become dynamically unstable are damped by the subgrid-scale turbulent diffusion (vertical and horizontal). Note that subgrid-scale diffusion is necessary for creating the wave-mean flow interactions, as is evident from the Wentzel-Kramers-Brillouin (WKB) solution for GWs damped by diffusion (for example, Becker, 2012; Lindzen, 1981). Further information is available in BV20.

In this study, we employ a model version similar to BV20, except we nudge the large-scale winds and temperatures from MERRA-2 reanalysis data (global down to $\lambda_H = 2{,}000$ km) into the HIAMCM at $z = 0$–70 km in spectral space (B22). The data used in this study is identical to that from B22. Because the MERRA-2 data is 3-hourly, we linearly-extrapolate the nudging for each model time step. We do not nudge scales having $\lambda_H < 2{,}000$ km; hence, GWs are generated self-consistently in the HIAMCM (e.g., by wind flow over orography, imbalance of the polar night jet, etc.). The horizontal grid spacing is ∼52 km, and the effective horizontal resolution corresponds to $\lambda_H = 156$ km. The vertical grid spacing varies from ∼500 m below 70 km to ∼10 km at the highest altitudes, thereby allowing for the simulation of GWs with $\lambda_z \geq 1$ km below 70 km. GW perturbations with $\lambda_H \leq 2{,}000$ km are extracted from the model output by interpolating the model data to constant height surfaces, then applying a spectral decomposition which only retains horizontal wavenumbers larger than 20 (corresponding to $\lambda_H \leq 2{,}000$ km).

4.2. Modeled Secondary Gravity Waves Over ALOMAR, and Comparison With Lidar Observations

Figure 7a shows $T' \exp(-z/14 \text{ km})$ as a function of time on 12–14 January 2016 at ALOMAR from the HIAMCM. Figure 7b shows the same perturbations, but filtered (via Fourier transform) to retain GWs with $\tau_r \leq 11$ hr and $|\lambda_z| \geq 1$ km in order to remove the semi-diurnal and diurnal tides and to compare directly with the lidar observations. We see two GW fishbone structures with $z_{\text{knee}} \sim 56$–58 km on 13–13.6 January and $z_{\text{knee}} \sim 65$–67 km on 13.7–14.3 January. Boundaries that enclose relatively "clean" structures are chosen as follows. Event #1 occurs at $45 < z < 68$ km on 12.9–13.7 January, and event #2 occurs at $40 < z < 85$ km on 13.7–14.3 January. Using the method described in Section 3.2, we estimate average knee altitudes of $z_{\text{knee}} = 58$ and 66 km for events #1 and #2, respectively. The fishbone structures in Figure 7b are contaminated with other GWs having upgoing and downgoing phases in time that appear to emanate from similar altitudes. As we show below, these are secondary GWs from neighboring LBFs which causes some of the GWs to have upgoing (downgoing) phase lines a few km above (below) the dashed line. (Appendix A shows how multiple body forces affect the fishbone structure.) Figures 7c and 7d shows the GWs from Figure 7b with upgoing and downgoing phases in time, respectively. Note that the GWs with upgoing phases are mainly concentrated below the dashed lines, indicating that downward propagating GWs are generated in the region of the dashed line.

Figure 8a shows a blow up of Figure 7b. The GWs in the fishbone structures have $\tau_r \sim 4$–9 hr and $|\lambda_z| \sim 10$–25 km. Figure 8c shows the HIAMCM GWs with downgoing (upgoing) phases in time above (below) the dashed line in Figure 7b. As for the lidar data, the hot-cold phases do not always line up because of constructive/destructive interference of the secondary GWs with contaminant GWs. We now compare the HIAMCM GWs with the ALOMAR lidar GWs. Figure 8b shows $T' \exp(-z/14 \text{ km})$ for the ALOMAR lidar GWs from Figure 1a. Remarkably, the amplitudes, location and times of the GWs are quite similar to the HIAMCM GWs in Figure 8a during

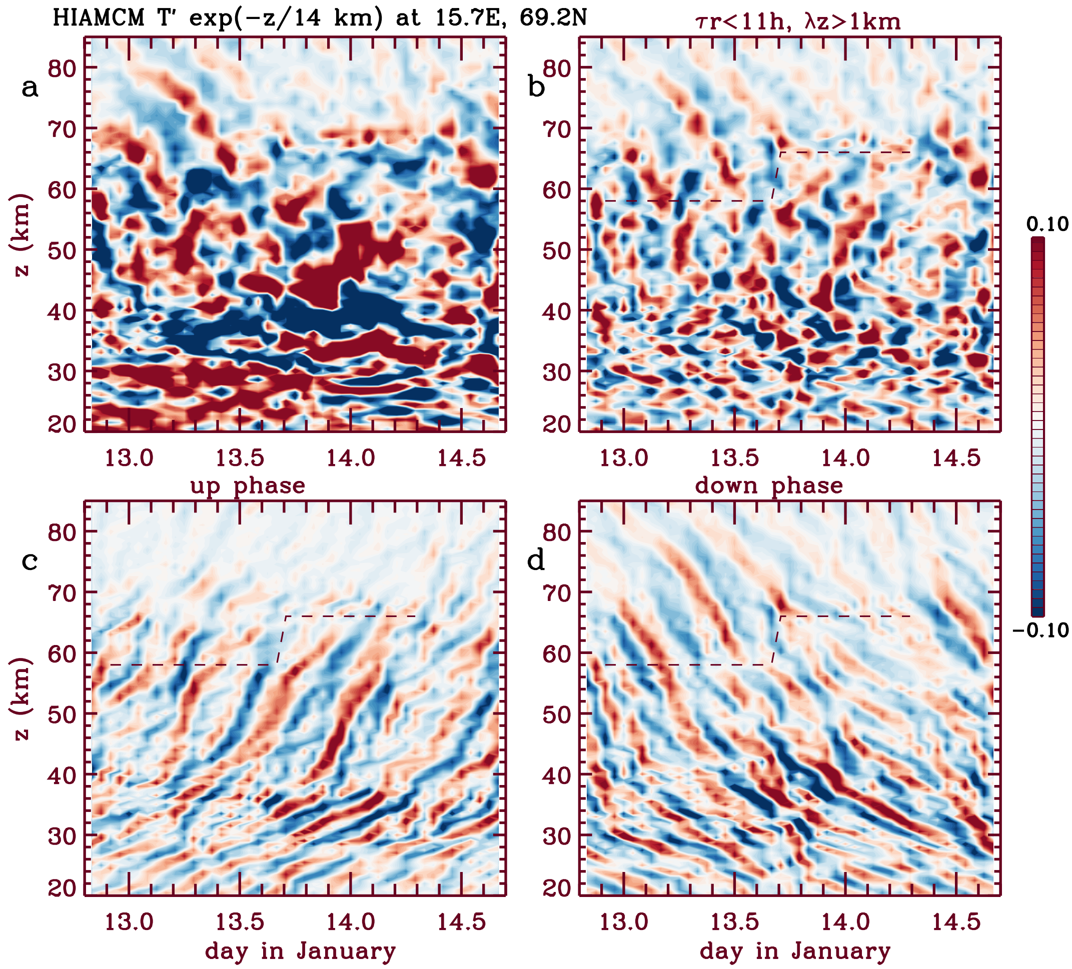

Figure 7. (a) Scaled temperature perturbations, T' exp $(-z/14$ km) (colors, in K), from the nudged HIAMCM on 12–14 January 2016 over Arctic Lidar Observatory for Middle Atmosphere Research. (b) Same as (a) but filtered to retain gravity waves (GWs) with $\tau_r \leq 11$ hr and $|\lambda_z| \geq 1$ km. (c) GWs from (b) with upgoing phases in time. (d) GWs from (b) with downgoing phases in time. The dashed lines show z_{knee} during the time and altitude boundaries for events #1 and #2 (see text). The colors are oversaturated in (a) to better see the GWs at $45 < z < 80$ km.

both events. Figure 8d shows the ALOMAR lidar GWs with downgoing (upgoing) phases in time above (below) the dashed line in Figure 2. The altitudes and parameters of the upward and downward-propagating secondary GWs are quite similar to the HIAMCM GWs from Figure 8c. Note that the upward-propagating event #2 GWs are weaker in the HIAMCM than in the lidar data. This weakening may be due to the fact that the large-scale wind in the HIAMCM is only weakly nudged above 40 km and is not nudged above 70 km (see Figure 1 in B22), and may therefore diverge from the actual atmospheric wind at these altitudes.

4.3. Comparison of the HIAMCM GWs With AIRS Observations

We now compare the GWs in the HIAMCM with those extracted from the AIRS data (Eckermann et al., 2019; Gong et al., 2012; Hoffmann & Alexander, 2009). Temperature perturbations are retrieved from AIRS using a fourth order polynomial detrending zonally at each altitude, and are interpolated onto a 0.5° grid in latitude and longitude. The left column of Figure 9 shows horizontal slices of T' from the HIAMCM at various altitudes of $z = 36$–48 km and at various times during 12–14 January. Medium-scale MWs with $\lambda_H \simeq 250$ km are seen around ∼40°–50°N over the Alps and Carpathian Mountains at $z = 36$–48 km at ∼4°–20°E and ∼25°–35°E, respectively. Due to the orientation of the phase lines, these MWs mainly propagate zonally. In addition, HL, larger-λ_H GWs are seen at ∼− 10°–50°E and ∼50–70°N which propagate northwestward or southeastward. These HL GWs are quite prevalent over Scandinavia, northern Europe, UK, and northwestern Russia. It was speculated by Bossert

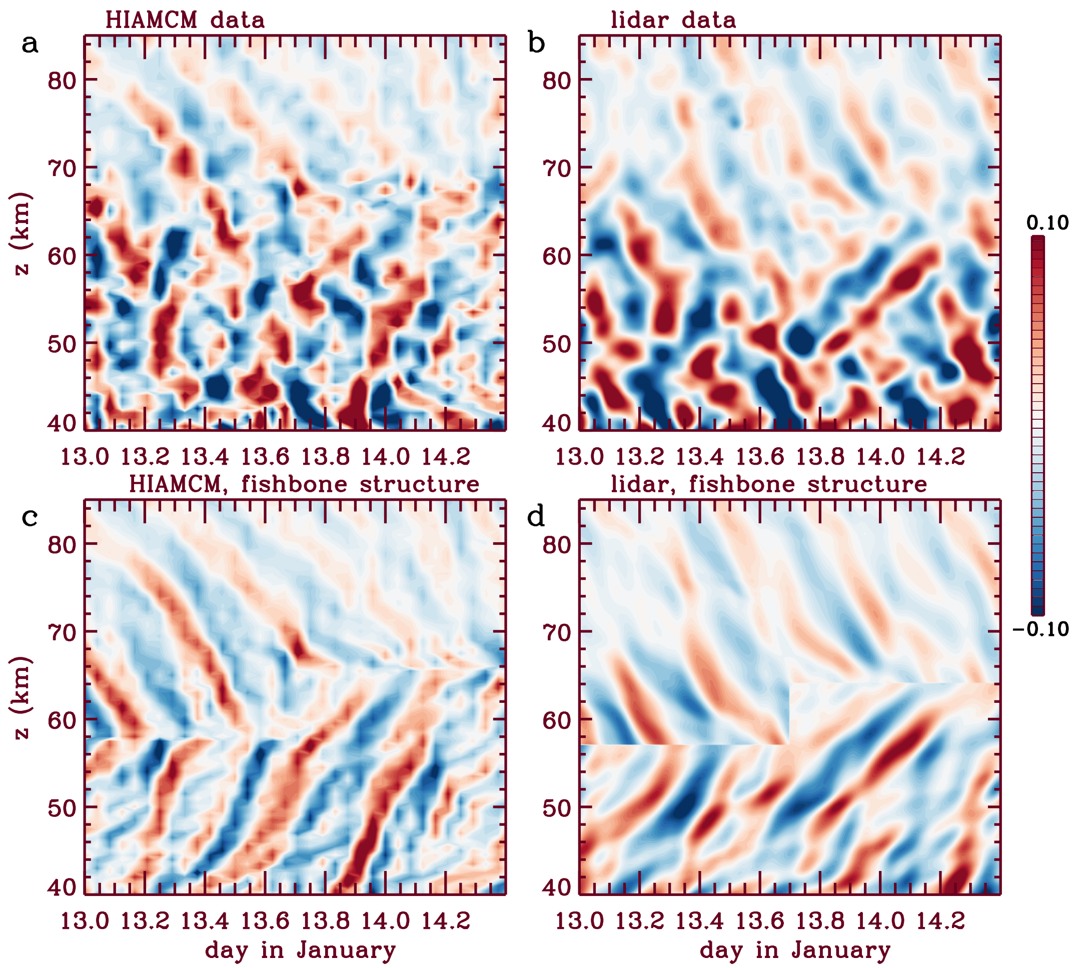

Figure 8. Scaled temperature perturbations, T' exp $(-z/14$ km) (colors, in K) on 12–14 January 2016. The left column shows the HIAMCM data, while the right column shows the Arctic Lidar Observatory for Middle Atmosphere Research lidar data. Row 1: All gravity waves (GWs). Row 2: GWs with downgoing (upgoing) phases in time above (below) z_{knee} during events #1 and #2.

et al. (2020) that similar HL GWs on 12 January 2016 were generated by the polar vortex; this hypothesis was confirmed for an event on 11 January 2016 (B22).

We apply an AIRS observational filter to the HIAMCM data. Ern et al. (2017) found that for medium-scale GWs with $\lambda_H \leq 600$ km and $\lambda_z \geq 24$ km, the sensitivity function is ≥ 0.8 (their Figure S3 in Supporting Information). Therefore, we remove HIAMCM GWs with $|\lambda_z| < 24$ km via Fourier filtering. The middle column of Figure 9 shows the result. As expected, many of the GWs seen in the left column are absent here. The right column shows the AIRS T' at the same altitudes and times. In general, the parameters of the GWs (λ_H, orientation of the phase lines, location and amplitudes) in the observationally-filtered HIAMCM data agree very well with those in the AIRS data.

Figure 9 provides an excellent validation of the horizontal structure of the GWs simulated by the HIAMCM at $z = 36$–48 km over Europe on 12–14 January 2016. In Appendix B we show that the HIAMCM GWs also compare well with those from AIRS over the Atlantic Ocean during this time period. The validation of the HIAMCM GWs with those from the ALOMAR lidar and AIRS provides the necessary justification to use this model to determine the source of the secondary GWs observed over ALOMAR.

4.4. X-Structure of the Secondary GWs During Event #1

Figure 10a shows $T'\sqrt{\bar{\rho}/\rho_0}$ as a function of latitude and z at 15.7°E at 07 UT on 13 January from the HIAMCM. The colors are over-saturated to better-illuminate the secondary GWs. The upward and downward-propagating

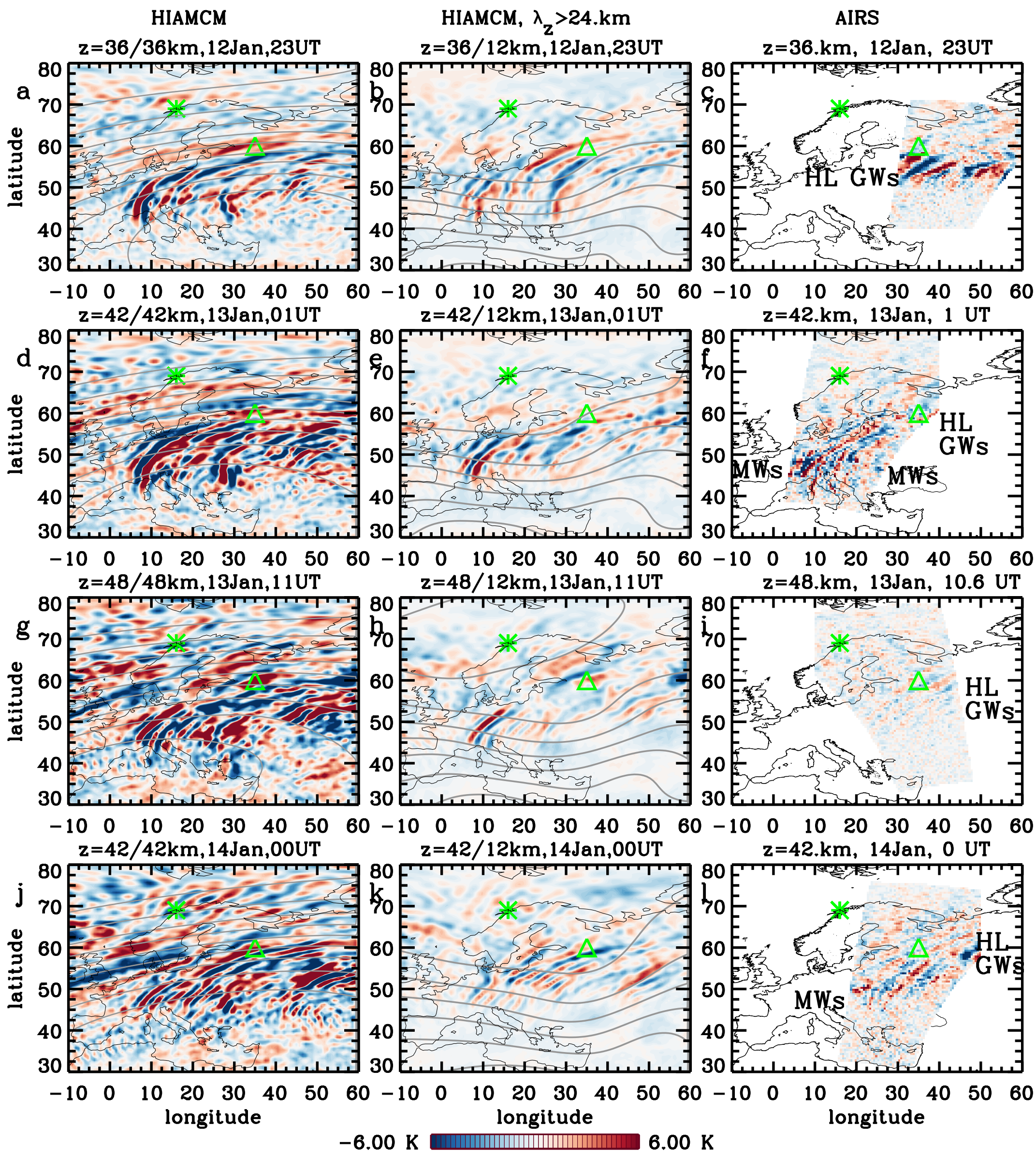

Figure 9. T' (colors, in K) in 2016. Row 1: 23 UT on 12 January at $z = 36$ km. Row 2: 1 UT on 13 January at $z = 42$ km. Row 3: 11 UT on 13 January at $z = 48$ km. Row 4: 0 UT on 14 January at $z = 42$ km. The left column shows the HIAMCM gravity waves (GWs) and large-scale horizontal streamfunction (gray lines) at the same times and altitudes. The middle column is the same as the left column except 1) filtered to remove GWs with $|\lambda_z| < 24$ km, and 2) the stream function is shown at $z = 12$ km. The right column shows the Atmospheric InfraRed Sounder GWs. Labels show the mountain waves and high-latitude ("HL") GWs. The green asterisks and triangles show Arctic Lidar Observatory for Middle Atmosphere Research and the event #1 local body force. The colors are oversaturated in column 1 to better see the GWs in column 2.

secondary GWs over ALOMAR at 69.2°N (turquoise line) are part of a faint secondary GW "X"-structure centered at $z = 55$–60 km and 58°–62°N. These phase lines have a checkerboard appearance due to the constructive/destructive interference of the secondary GWs with other GWs. The dominant positive phase lines of the X-structure GWs are outlined with dashed lines, as we confirm in Figure 11d. Importantly, primary GWs from below dissipate where the secondary GWs are generated, at $z \sim 50$–55 km at 55°–62°N near the edge of the vortex (white line). The amplitudes of the secondary GWs are much smaller than those of the primary GWs, as is typical for secondary GWs generated by a LBF created by the breaking/dissipation of primary GWs (Vadas et al., 2018). Figure 10b shows a blow-up of the primary GWs at 22 UT on 12 January, just prior to event #1. These primary GWs are part of a different X-structure centered at $z = 25$–35 km and 49°–53°N (dash-dot lines). The upward

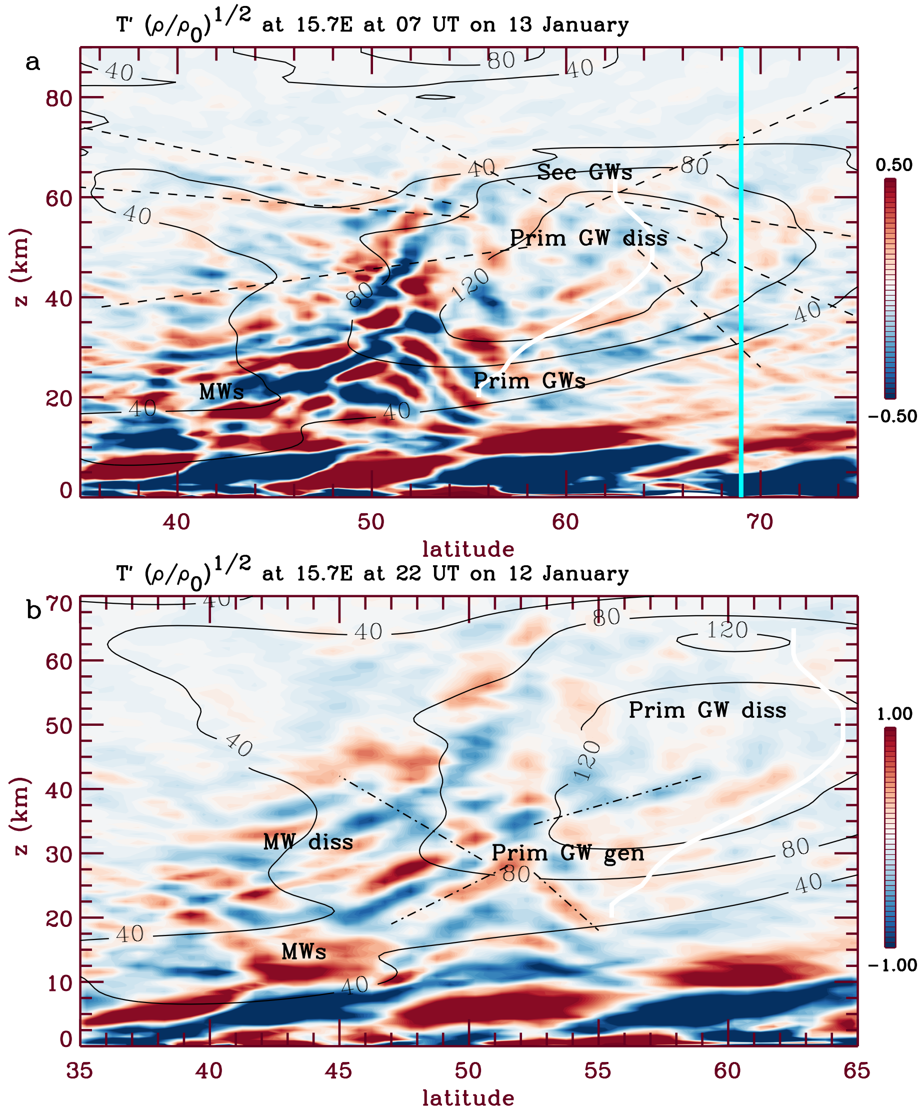

Figure 10. (a) $T'\sqrt{\bar{\rho}/\rho_0}$ (colors, in K) as a function of latitude at 15.7°E at 07 UT on 13 January 2016 from the HIAMCM during event #1, where $\rho_0 = 1{,}241$ g/m^3. The dash lines highlight secondary gravity wave (GW) phase lines. The solid black lines show U_{tot} (in m/s). (b) Same as in (a) but at 22 UT on 12 January with a larger color scale and for different latitude and altitude ranges to better see the primary GWs. The dash-dot lines highlight primary GW phase lines. Labels show mountain waves, primary and secondary GWs, as well as generation ("gen") and dissipation ("diss") regions. The turquoise line shows Arctic Lidar Observatory for Middle Atmosphere Research, and the white lines show the edge of the polar vortex. The colors are oversaturated to better see the GWs.

primary GWs break/dissipate at $z \sim 50$–55 km and 55°–62°N, which creates the LBF that generates the event #1 secondary GWs.

We now extract the X-structure of the secondary GWs. Figure 11a is the same as Figure 10a, but with different altitude ranges and color scales to emphasize the secondary GWs. Figure 11b shows the northward/upward and southward/downward-propagating GWs from Figure 11a. The primary GWs that dissipate at $z \sim 50$–55 km and at 55°–62°N propagate upward/northward from $z \sim 25$–35 km and ~50°N. Note that in the HIAMCM, wave damping is caused by the diffusion scheme. For the primary GWs in Figure 11b, enhanced diffusion coefficients are triggered by the amplitude growth and reduced static stability due to $d\bar{T}/dz < 0$ in the mesosphere (since $|\lambda_z|$ is virtually unchanged where the GWs dissipate).

Figure 11c shows the southward/upward and northward/downward-propagating GWs obtained from Figure 11a. Figure 11d shows the extracted X-structure of the secondary GWs, which is obtained by retaining

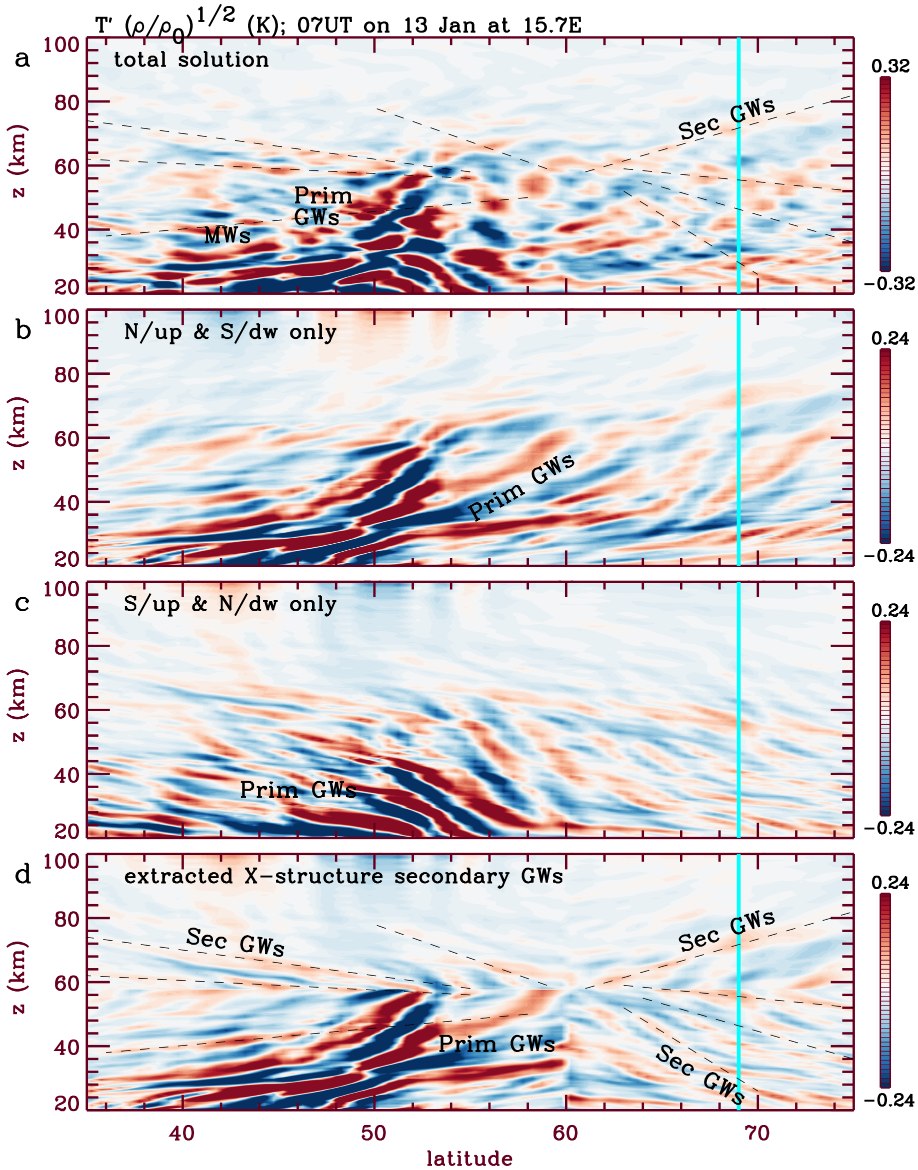

Figure 11. $T'\sqrt{\rho/\rho_0}$ from the HIAMCM (colors, in K) as a function of latitude at 07 UT on 13 January 2016 at 15.7°E during event #1, where $\rho_0 = 1{,}241$ g/m^3. (a) Total solution. (b) Northward/upward and southward/downward gravity waves (GWs). (c) Southward/upward and northward/downward GWs. (d) Extracted X-structure of the secondary GWs in event #1. The center of the structure is at $z_{\text{knee}} = 58$ km and $\theta_{\text{cen}} = 60$°N. Upward/northward primary GWs contaminate the structure at 40°–60°N and $z = 20$–60 km in (d). Dash lines show the secondary GW phase lines, and are the same as in Figure 10a. The turquoise lines show Arctic Lidar Observatory for Middle Atmosphere Research. The colors are oversaturated to better see the secondary GWs.

southward/upward and northward/downward propagating GWs for $z > z_{\text{knee}}$ south of θ_{cen} and for $z < z_{\text{knee}}$ north of θ_{cen}, and by retaining northward/upward and southward/downward propagating GWs for $z > z_{\text{knee}}$ north of θ_{cen} and for $z < z_{\text{knee}}$ south of θ_{cen}. Here, $z_{\text{knee}} = 58$ km and $\theta_{\text{cen}} = 60$°N. The dashed lines (which are the same as in Figure 10a) overlay well with the X-structure of the secondary GWs. These secondary GWs have much smaller amplitudes than the primary GWs, as expected. Note that the upward/northward primary GWs contaminate the extracted X-structure of the secondary GWs (saturated colors in the lower left corner of Figure 11d). Comparing Figures 11b and 11c with Figure 9, the GWs in the HIAMCM and in AIRS at 50°–60°N are mainly upward/northward primary GWs, because the downward/southward secondary GWs in this region have much smaller amplitudes.

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4.5. Verification and Parameters of the Secondary GWs

We now verify that the HIAMCM fishbone structure GWs in Figure 8c are secondary GWs (i.e., that they have the same parameters and propagation directions above and below z_{knee}). We transform T' onto a 2D Cartesian grid that is perpendicular to a line from the center of Earth to its surface at 24.7°E and 53.2°N (Vadas & Becker, 2018, their Appendix B). The coordinates on this 2D plane are (x'', y''). Figures 12a and 12b shows horizontal slices of T' for GWs with $450 < \lambda_H < 2{,}000$ km at $z = 54$ km (below z_{knee}) and at $z = 62$ km (above z_{knee}) at 2 UT on 13 January during event #1. GWs with $\lambda_H \sim 500$–1,500 km are seen above and below z_{knee} near ALOMAR (asterisk). The orientation of their phase lines indicate that they propagate northwest or southeastward. These are the secondary GWs in the fishbone structure. We draw a line perpendicular to these phase fronts that passes through ALOMAR, and place a triangle at $\theta_{\text{cen}} = 60$°N in Figures 12a and 12b. This triangle is the estimated location of the LBF which generated these event #1 GWs. Since secondary GWs generated by a LBF primarily radiate upward and downward, in and against the direction of the LBF, they constitute four distinct "headlights" of GWs (if the background wind is negligible) (Vadas et al., 2003). Therefore, the northwestward or southeastward propagation directions of the secondary GWs is consistent with either a northwestward or a southeastward LBF.

Figures 12d and 12e show keograms of T' as functions of x'' and time below and above z_{knee} at $y'' = 1{,}500$ km, and Figures 12g and 12h show keograms as functions of y'' and time below and above z_{knee} at $x'' = -500$ km. This location $(x'', y'') = (-500, 1{,}500)$ km, is somewhat south of ALOMAR. The GWs propagate northwestward over ALOMAR during event #1 (dashed lines), with similar x'' and y'' phase speeds below and above z_{knee} of $c_x \sim -40.5$ m/s and $c_y \sim 23.1$ m/s. Here, $c_x = \omega_r/k = \lambda_x/\tau_r$ and $c_y = \omega_r/l = \lambda_y/\tau_r$ are the phase speeds in the x" and y'' directions, respectively. From Equation 20,

$$\tan\psi = l/k = c_x/c_y. \tag{26}$$

Therefore, the estimated propagation direction of these GWs is $\psi \sim 150°$ (counter-clockwise from east). The horizontal phase speed of a GW is (for example, Equations 13 and 14 of Vadas & Becker, 2018)

$$c_H = \frac{\omega_r}{k_H} = \frac{1}{\sqrt{(k/\omega_r)^2 + (l/\omega_r)^2}} = \frac{1}{\sqrt{1/c_x^2 + 1/c_y^2}}. \tag{27}$$

Therefore, $c_H \sim 20$ m/s. From Figures 12d and 12e and 12g and 12h, $\tau_r \sim 8$ hr above and below z_{knee}, which yields $\lambda_H = c_H/\tau_r \sim 580$ km. These event #1 parameters, $\lambda_H \sim 580$ km, $\tau_r \sim 8$ hr, $c_H \sim 20$ m/s, and $\psi \sim 150°$, agree very well with the values deduced from the lidar observations (see Table 1). Therefore, we conclude that the HIAMCM is able to simulate the event #1 GWs very well. Because the GW parameters are similar above and below z_{knee}, we conclude that the event #1 GWs are secondary GWs, and that they are created by a northwestward or a southeastward LBF that is located southeast of ALOMAR at ~35°E and ~60°N. The turquoise arrow in Figures 12a and 12b shows the approximate propagation direction of the secondary GWs.

Figure 12c shows a horizontal slice of T' at 22 UT on 13 January for the event #2 GWs with $450 < \lambda_H < 2{,}000$ km at $z = 71$ km (above z_{knee}). The map has a disorganized checkerboard appearance, which occurs when there is significant constructive/destructive interference between multiple wave packets. There is a small wave packet south of ALOMAR with $\lambda_H \sim 800$–1,000 km. Corresponding keograms as functions of x'' and y'' are shown in Figures 12f and 12i above z_{knee}. Although it is difficult to locate this packet in the noisy keograms, the event #2 GWs may propagate northward with $c_x \sim -2.67$ m/s and $c_y \sim 31.8$ m/s (dashed-dotted lines), which yield $\psi \sim 95°$ and $c_H \sim 2.7$ m/s. Although ψ and λ_H agree well with the values in Table 1, c_H is too small. This discrepancy is likely due to the difficulty of locating the GW packet without additional filtering, which is beyond the scope of this paper. For the rest of this paper, we focus on the event #1 GWs.

4.6. Parameters of the Primary GWs That Created Event #1

We now determine the parameters of the primary GWs that created event #1. Figures 13a and 13b show horizontal slices of T' for GWs with $200 < \lambda_H < 400$ km at 22 UT on 12 January at $z = 45$ and 55 km. A GW packet with $\lambda_H \sim 400$ km propagates northwest or southeastward at the approximate location of the LBF (triangle). This packet is not seen northwest of the LBF because the primary GWs break and dissipate there, near the edge of

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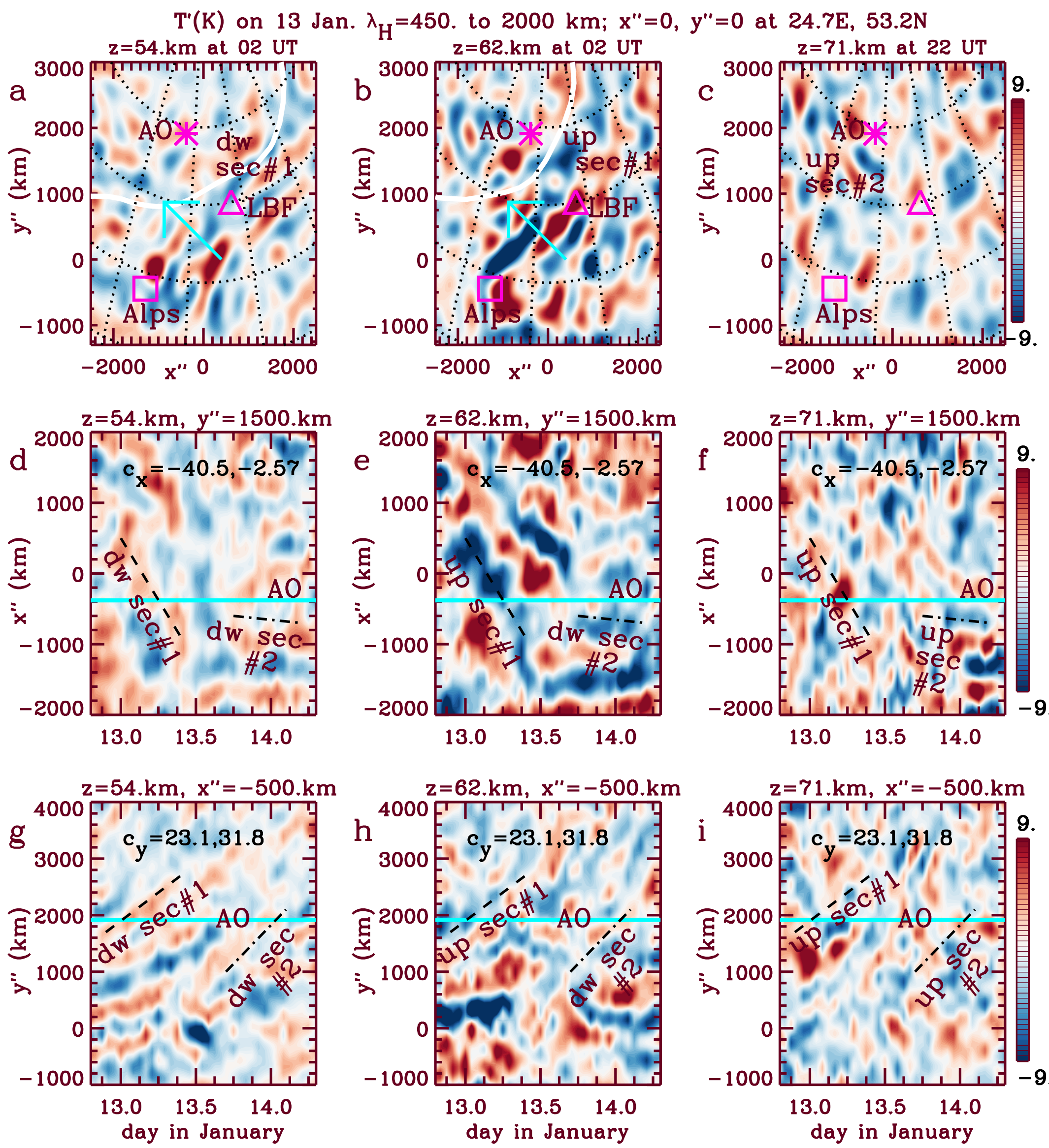

Figure 12. T' (colors, in K) from the HIAMCM for $450 < \lambda_H < 2{,}000$ km on a 2D Cartesian grid with coordinates (x'', y'') parallel to the Earth's surface at 24.7°E and 53.2°N ($x'' = y'' = 0$) in 2016. Left to right columns show $z = 54$, 62 and 71 km, respectively. (a–c) Horizontal slices at 2, 2 and 22 UT on 13 January 2016, respectively. Arctic Lidar Observatory for Middle Atmosphere Research (ALOMAR) ("AO," asterisks), the northern edge of the Alps at 8°E, 48°N (squares), and the event #1 local body force at 35°E, 60°N ("LBF", triangles) are shown. Turquoise arrows show the approximate propagation direction of the downward ("dw") and upward ("up") event #1 gravity waves (GWs) and white lines show the vortex edge in (a–b). Dotted lines show 0°–60°E in 20° increments and 50°–70°N in 10° increments. (d–f) Keograms of x'' versus time at $y'' = 1{,}500$ km. (g–i): Keograms of y'' versus time at $x'' = -500$ km. Dash (dash-dot) lines indicate event #1 (#2) GWs. ALOMAR is shown by the turquoise lines. c_x and c_y are listed in (d–i) (in m/s). The colors are over-saturated to see the secondary GWs.

the polar vortex (white line). Note that the lines of constant phase are roughly parallel to the edge of the polar vortex. Figures 13c and 13d shows keograms of the primary GWs just southeast of the LBF (turquoise lines). These GWs propagate slowly southeastward on 12 January and slowly northwestward on 13–13.5 January. We estimate $\psi \sim -60°$ and $c_H \sim 1.2$ m/s on 12.0–13.0 January, and $\psi \sim 148°$ and $c_H \sim 5.5$ m/s on 13.0–13.5 January. If the GWs on 12 January dissipate, a southeastward LBF is created with $\psi \sim -60°$, which would excite southeastward and northwestward propagating secondary GWs. Therefore, the propagation direction of

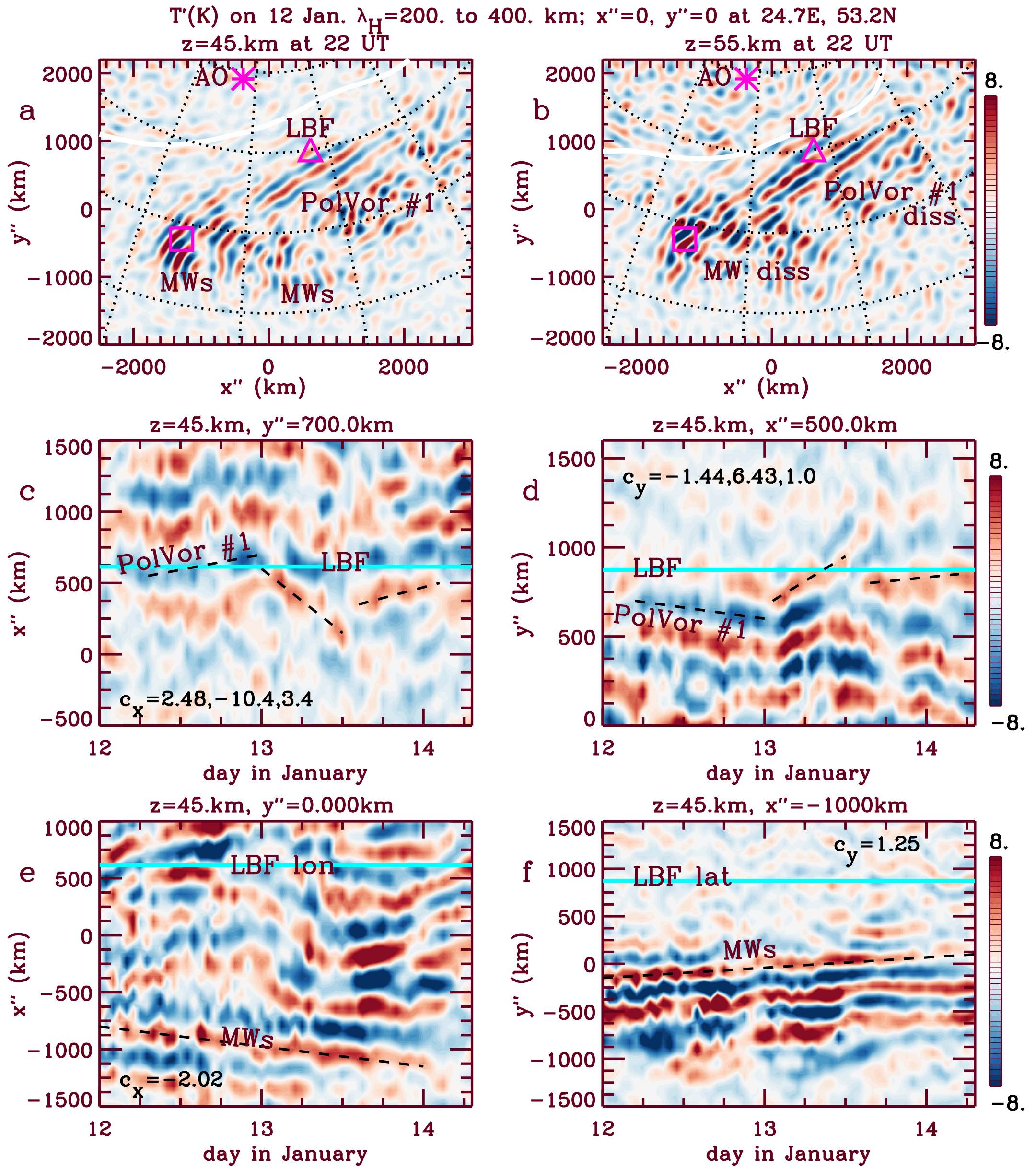

Figure 13. T' (colors, in K) from the HIAMCM for $200 < \lambda_H < 400$ km on a 2D Cartesian grid (with coordinates (x'', y'') parallel to Earth's surface at 24.7°E and 53.2°N ($x'' = y'' = 0$) in 2016. Horizontal slices at (a) $z = 45$ km and (b) $z = 55$ km at 22 UT on 12 January. The asterisks, squares, triangles, dotted lines, and white lines are the same as in Figures 12a and 12b. The propagating and dissipating ("diss") mountain waves and gravity waves (GWs) from the polar vortex ("PolVor") are labeled. (c) x'' vs. time at $y'' = 700$ km. (d): y'' vs. time at $x'' = 500$ km. (e) x'' vs. time at $y'' = 0$ km. (f): y'' versus time at $x'' = -1{,}000$ km. Dashed lines indicate the phase lines of the GWs of interest. c_x and c_y are listed (in m/s). The local body force (LBF) is shown in (c–d) (turquoise lines). The longitude and latitude of the LBF are shown in (e–f), respectively (turquoise lines).

this primary GW is consistent with the propagation direction of the observed event #1 secondary GWs (i.e., $\psi = 150°$).

Figures 13e and 13f show keograms of the northern edge of the MWs generated by the Alps. The MWs propagate very slowly, and do not propagate north of $y'' = 0$ (i.e., 53°N) on 12 January. Therefore, these MWs could not have created the event #1 LBF.

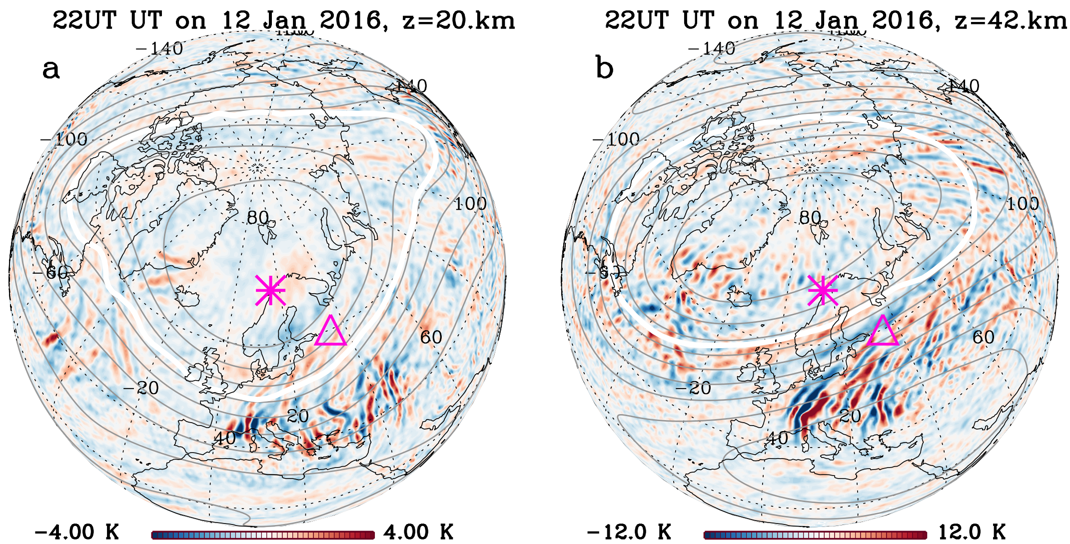

Figure 14. Global view of T' (colors, in K) and the large-scale horizontal streamfunction (gray lines) from the HIAMCM at 22 UT on 12 January 2016. (a) $z = 20$ km. (b) $z = 42$ km. The purple asterisks and triangles show Arctic Lidar Observatory for Middle Atmosphere Research and the event #1 local body force at 35°E and 60°N, respectively. The white lines show the vortex edge.

4.7. Source of the Primary GWs That Created Event #1

Figure 14a shows a global view of T' at 22 UT on 12 January at $z = 20$ km. MWs are seen over Europe and Greenland, and HL GWs are seen over northern Europe and Siberia. We also see GWs in the jet exit region in the lower stratosphere east of Newfoundland over the western Atlantic Ocean. Figure 14b shows T' at $z = 42$ km. The HL GWs over Norway, Sweden, northern Scotland and west of Ireland are aligned with the streamfunction and are located near the edge of the polar vortex.

Figure 15 shows horizontal slices of T' from $z = 15$–70 km at 2 UT on 13 January. At $z = 15$ and 20 km, MWs are present south of 50°N (e.g., over the Alps). Their phase lines are roughly perpendicular to the background wind, as indicated by the streamfunction. At $z = 26$ km, HL GWs appear north of 50°N. These GWs are separated latitudinally from the MWs to the south, and are also observed north and east of the Alps over Norway and Scotland. At $z = 42$ km, the phase lines of the HL GWs and the MWs appear to blend together at 52°–55°N, thereby incorrectly implying that these HL GWs (near the LBF) might be trailing MWs (Dörnbrack, 2021). These HL GWs also occur over Norway and Scotland, thereby countering the idea that these HL GWs are trailing MWs. At $z = 53$ km, the HL GWs and MWs are dissipating, as indicated by the relatively weak increase in their amplitudes from $z = 42$ to 53 km (since the amplitude of a non-dissipating GW would have increased by $\exp(\Delta z/2\mathcal{H}) = \exp(11/14) = 2.2$ in an isothermal, constant wind atmosphere). At $z = 70$ km, the HL GWs and MWs have dissipated.

Figure 16 shows longitude-height slices of $T'\sqrt{\bar{\rho}/\rho_0}$ at 22 UT on 12 January. At 45°N, MWs occur over the Alps and Carpathian Mountains. At 51°N, the MWs are mostly absent. Instead, GWs within X-structures are generated at $z \sim 25$–35 km at 10–50°E. X-structure GWs are also generated at $z \sim 25$–35 km at 59°N, although the generation region is further east. At 69°N, GW generation is small.

Figure 17 shows latitude-height slices of $T'\sqrt{\bar{\rho}/\rho_0}$ at 22 UT on 12 January. GWs within X-structures are generated at $z \sim 25$–45 km and 50°–60°N for 40°W–50°E, including at 25°W and 40°W over the Atlantic Ocean. The generation regions are close to the edge of the stratospheric polar vortex, ~5–10 km below the wind maximum where the vertical wind shear is large. Note that there is minimal GW generation near the edge of the polar vortex at 100°E because the vortex is weak there, although MWs are generated over the Plateau of Tibet at ~40°N. Therefore, we conjecture that the X-structure GWs at 40°–50°E are generated by imbalance of the stratospheric polar night jet; we verify this conjecture in Section 4.8. In general, the X-structure GWs dissipate at $z \sim 50$–65 km, which is a few to ~20 km above the altitude where the wind speed in the polar night jet is maximum.

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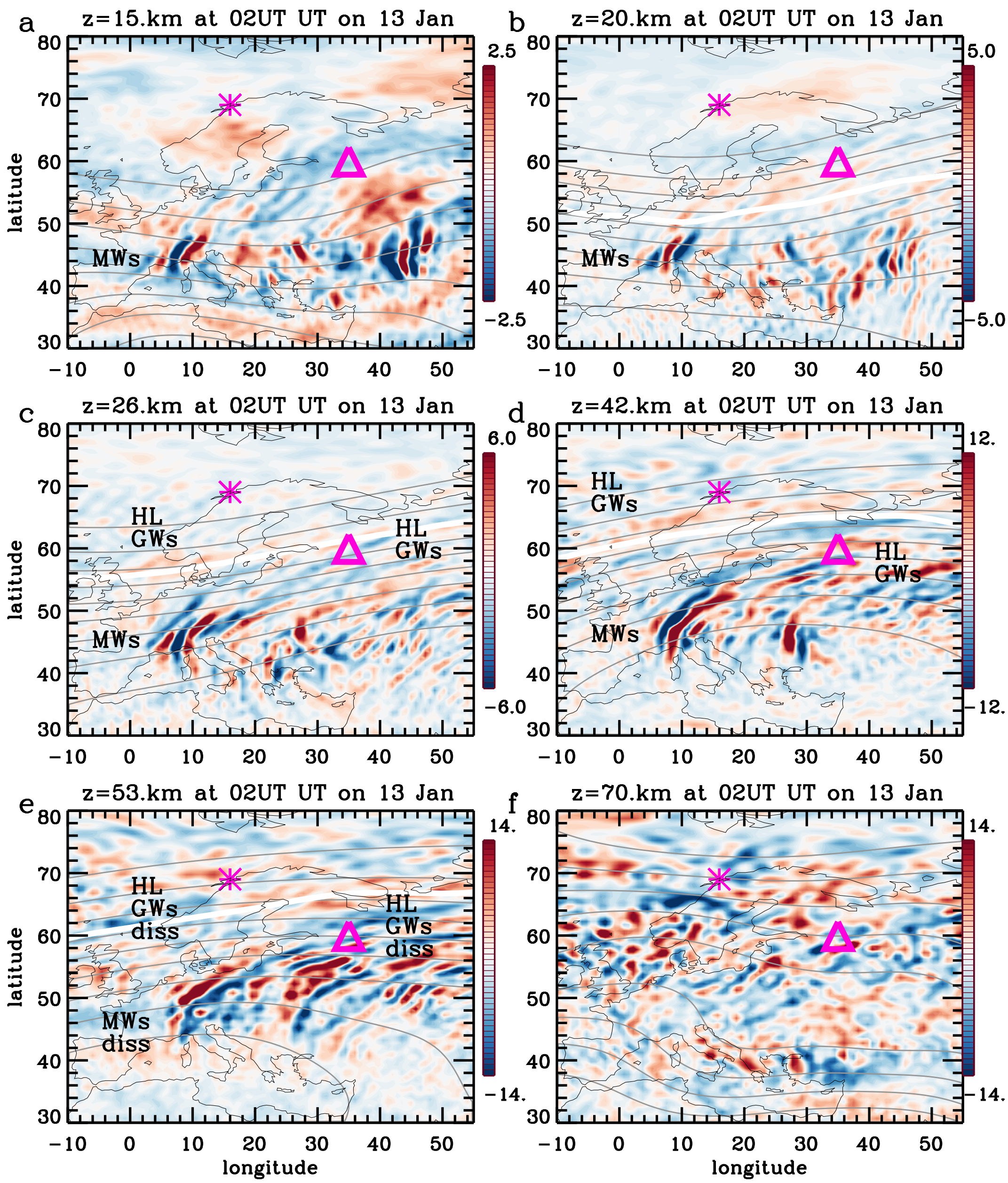

Figure 15. T' (colors, in K) and the large-scale horizontal streamfunction (gray lines) from the HIAMCM at 2 UT on 13 January 2016. (a) $z = 15$ km. (b) $z = 20$ km. (c) $z = 26$ km. (d) $z = 42$ km. (e) $z = 53$ km. (f) $z = 70$ km. The asterisks show Arctic Lidar Observatory for Middle Atmosphere Research and the triangles show the event #1 local body force at 35°E and 60°N. Labels show propagating and dissipating ("diss") mountain waves and high-latitude ("HL") gravity waves. The vortex edge is shown as white lines in (a–e).

4.8. MKS and MPC Formalism: Primary and Secondary GWs From the Polar Vortex

B22 derived the mesoscale kinetic energy source (MKS), which describes the rate at which GWs extract kinetic energy from the geostrophic flow. They found that the MKS is positive in regions where GWs are generated or amplified, which can occur when GWs are generated by an imbalance of the polar night jet, or when GWs from another source propagate from below into a shear region. They also derived the mesoscale potential energy flux convergence (MPC), which is a 3D generalization (in spherical geometry) of the usual vertical potential energy flux convergence. This energy flux convergence is the main contributor to the energy deposition of GWs in the single column picture (for example, Becker, 2017). B22 found that GWs are generated by imbalance of the

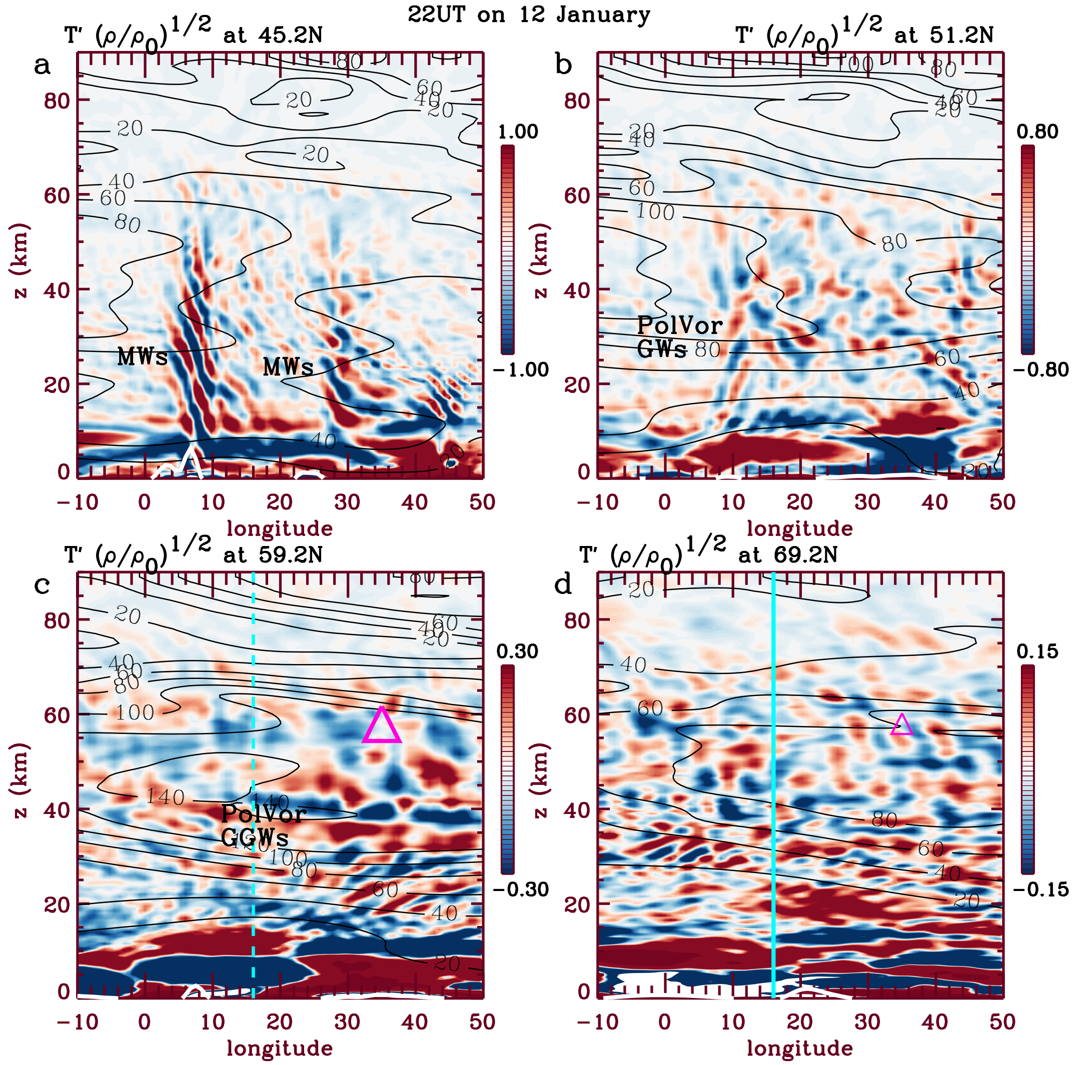

Figure 16. $T'\sqrt{\rho/\rho_0}$ (colors, in K) at 22 UT on 12 January 2016 from the HIAMCM, where $\rho_0 = 1{,}241$ g/m^3. (a) 45.2°N. (b) 51.2°N. (c) 59.2°N. The purple triangle shows the event #1 local body force (LBF) and the dashed turquoise line shows the longitude of Arctic Lidar Observatory for Middle Atmosphere Research (ALOMAR). (d) 69.2°N. The turquoise line shows ALOMAR and the small purple triangle shows the longitude of the event #1 LBF. Black lines show U_{tot} (in m/s). White lines at the lower boundary show the height of the Earth's surface (in km) times 5. Labels show mountain waves and gravity waves (GWs) generated by the polar vortex ("PolVor"). The colors are oversaturated to better see the GWs at $z > 15$ km.

stratospheric polar night jet, and that these GWs are amplified by the jet in regions where MKS > 0 and MPC < 0, as long as the region is free of dissipating GWs that propagated upward from below. In the case of energy deposition by dissipating GWs from below, MKS < 0 and MPC > 0.

Figures 18a and 18b shows the MKS and MPC in the stratosphere averaged from z = 30–50 km and 21–24 UT on 12 January. South of 50°N, MWs are partly reamplified by the polar night jet. The alternating pattern of MPC south of ~50°N is indicative of individual MW packets with finite horizontal extent, thereby causing minus/plus-patterns of horizontal potential energy flux convergence in the direction these waves propagate intrinsically (i.e., westward). The reamplification of the MWs extends as far north as ~52°N at 0°–20°E. North of 50°, primary HL GWs are generated by the polar night jet where MKS > 0 and MPC < 0; this occurs over a broad region at 20°–40°E and 50°–55°N.

The generation region for the HL GWs can also be seen in Figures 19c and 19d, which shows the density-weighted MKS and MPC averaged at 52°–60°N and 21–24 UT. This generation region occurs at z = 25–50 km at 15°–50°E.

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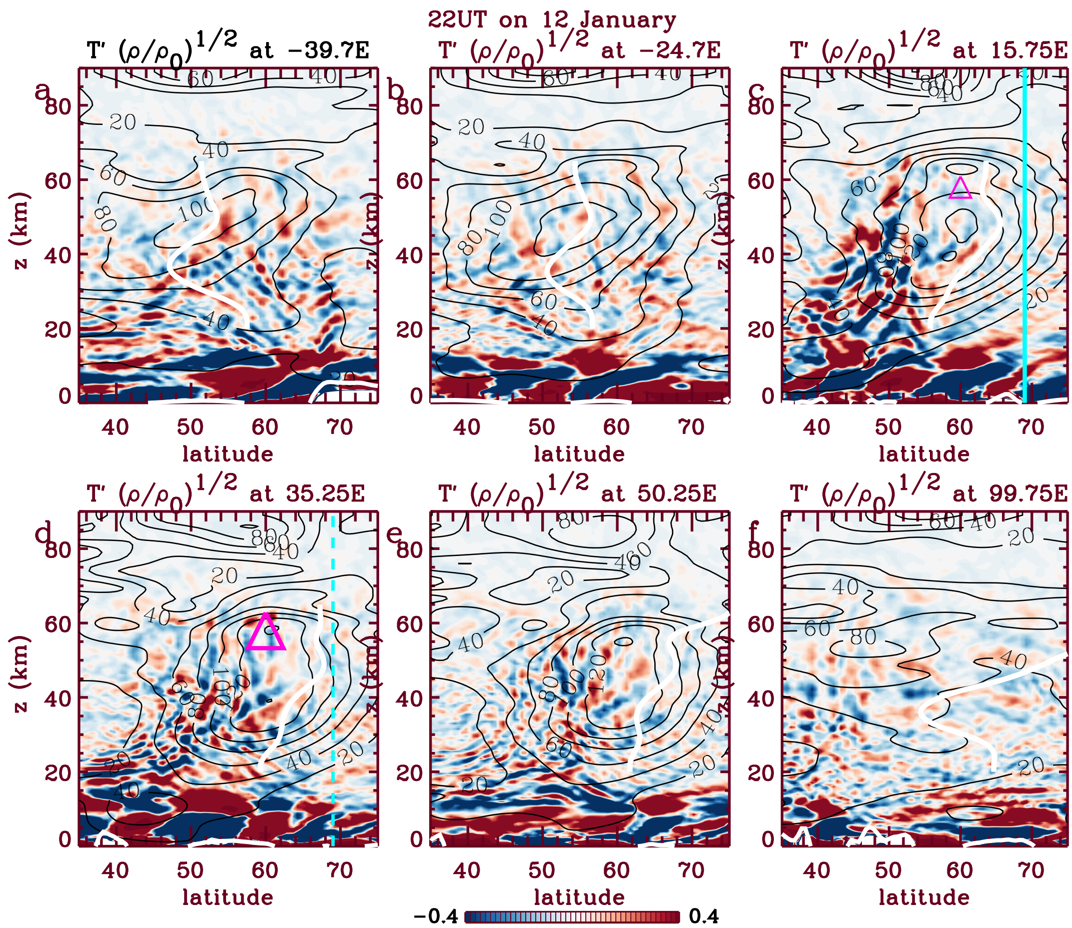

Figure 17. $T'\sqrt{\bar{\rho}/\rho_0}$ (colors, in K) at 22 UT on 12 January 2016 from the HIAMCM, where $\rho_0 = 1{,}241$ g/m^3. (a) 39.7°W. (b) 24.7°W. (c) 15.8°E The turquoise line shows Arctic Lidar Observatory for Middle Atmosphere Research (ALOMAR) and the small purple triangle shows the latitude of the event #1 local body force (LBF). (d) 35.3°E. The dashed turquoise line shows the latitude of ALOMAR and the purple triangle shows the event #1 LBF. (e) 50.3°E (f) 100°E. Black lines show U_{tot} (in m/s). White lines at the lower boundary show the height of the Earth's surface (in km) times 5. White lines show the vortex edge. The colors are over-saturated to better see the gravity waves at $z > 15$ km.

We also show the mesoscale vertical potential energy flux density (PEFD) in Figure 19, which is positive (negative) for upward (downward)-propagating GWs (for example, BV18). The PEFD in Figures 19c and 19d is positive at $z = 25$–50 km at 10°–50°E, and increases from 0.1 to 0.5–0.7 at $z = 20$–45 km at 15°–50°E. This behavior confirms that the HL GWs are generated at $z > 20$ km. Above $z \sim 50$ km, however, MKS < 0, MPC > 0 and the PEFD decreases in altitude, thereby indicating that these HL GWs are dissipating and are depositing momentum and energy into the atmosphere. Importantly, there is a small GW generation region at $z \sim 58$–60 km and 32–38°E where MKS > 0 and MPC < 0 in Figures 19c and 19d; this generation region is co-located with the event #1 LBF (labeled "B").

Figures 18c and 18d shows the MKS and MPC in the lower mesosphere averaged from $z = 55$–60 km and 21–24 UT on 12 January. Negative MKS and positive MPC over the Alps and Carpathian Mountains indicate strong MW dissipation. North of 52°N, GW generation occurs over southern Sweden and at 32°–38°E and 54°–60°N. This latter region overlaps with the event #1 LBF ("B"). We also show in Figures 18c and 18d the horizontal body forces vectors at $z = 57$ km and 57.75°N at 24°, 30°, and 36°E averaged from 22 to 23 UT. The forces at these locations are southeastward with average amplitudes of ~150–250 m/s/day. Thus the primary GWs created by the polar vortex were propagating southeastward when they dissipated, which agrees with the keograms in Figures 13c and 13d.

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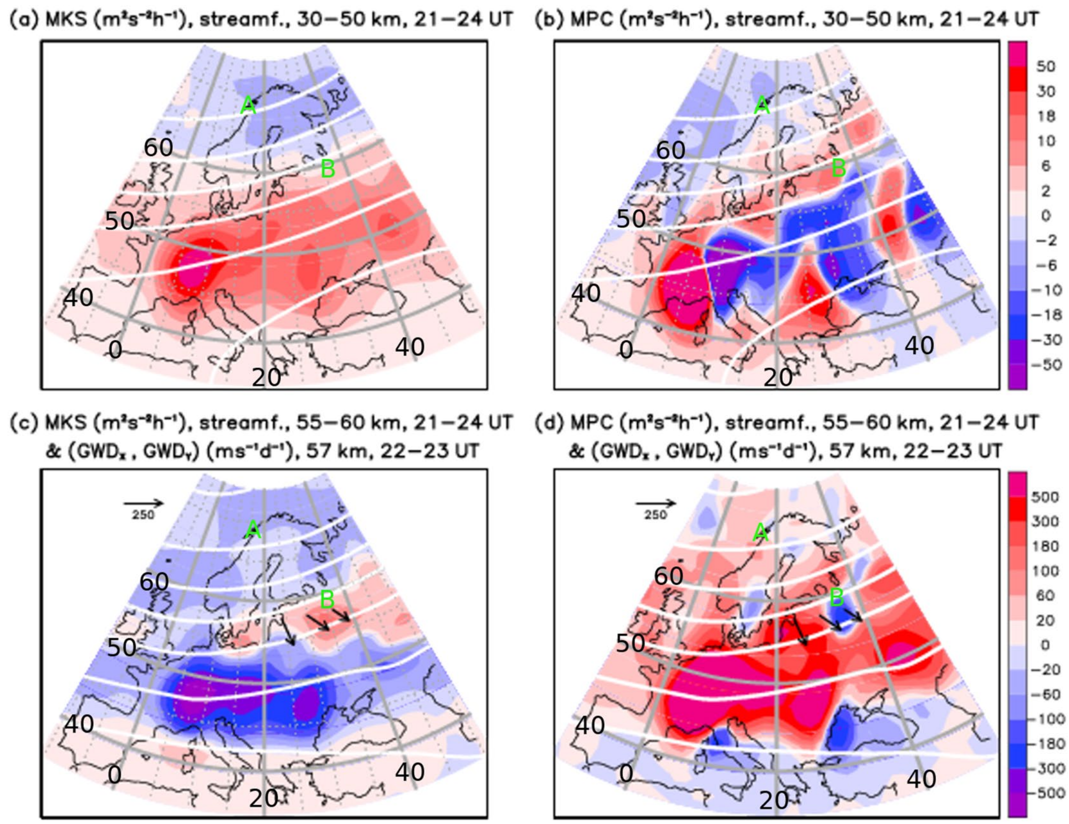

Figure 18. (a) Horizontal plot of the mesoscale kinetic energy source (MKS, colors, in m^2/s^2/h) averaged from z = 30–50 km and 21–24 UT on 12 January 2016 for gravity wave perturbations with λ_H < 1,350 km. White contours show the correspondingly averaged horizontal streamfunction with intervals of 5 × 10^7 m^2/s. Gray lines show 0°, 20°, and 40°E and 40°, 50°, and 60°N, as labeled. (b) Same as (a), but for the mesoscale potential energy flux convergence (colors, in m^2/s^2/h). (c, d) Same as (a, b), but averaged from z = 55–60 km. Black arrows show the horizontal body force (momentum deposition) vectors averaged from 22 to 23 UT at z = 57 km and 57.75°N for 24°, 30°, and 36°E. Arctic Lidar Observatory for Middle Atmosphere Research and the event #1 local body force are labeled in green as "A" and "B," respectively. The black arrows in the upper left of panels (c–d) show 250 m/s/day vectors.

Figures 20a and 20b shows the zonal and meridional components of the GW drag (GWD) averaged over z = 30–50 km and 22–23 UT on 12 January. South of 50°N, dissipating MWs create a westward drag with a weak northward component. North of 50°, however, the drag is southward with a weak eastward component. Figures 20c and 20d shows the zonal and meridional components of the GWD averaged from z = 55–60 km and 22–23 UT. The drag is southeastward at 20°–40°E and 55°–60°N (see Figures 18c and 18d and 19c and 19d), which agrees well with the location of the event # 1 LBF ("B").

We thus conclude that the primary HL GWs which led to event #1 were created and amplified by the polar night jet. Upon dissipation, they created multiple southeastward LBFs at 20°–40°E and 55°–60°N, one of which excited the event #1 secondary GWs observed over ALOMAR.

4.9. MKS and MPC Formalism: Mountain Waves at Mid-Latitudes

Figure 19a shows the density weighted MKS averaged from 44°–50°N and 21–24 UT on 12 January. MW signatures are seen at 0°–15°E (Alps), 23°–32°E (Carpathian Mountains) and 36°–50°E (Caucasus Mountains). The positive to negative MPC seen for each MW signal in Figure 19b results as follows. There is a westward potential energy flux upstream of the mountainous region because the intrinsic group velocity of the MWs is predominantly westward, which causes the energy flux to emerge eastward of the mountain range and to converge

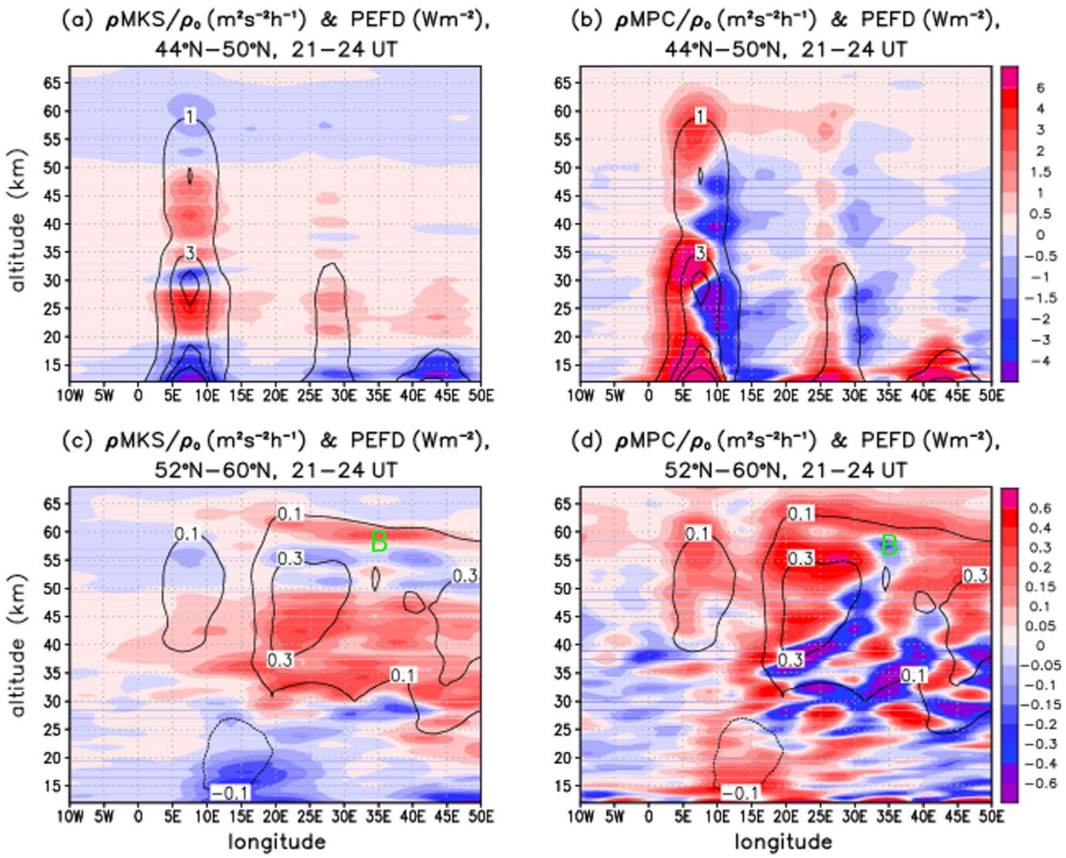

Figure 19. (a) Density weighted mesoscale kinetic energy source (MKS) ($\overline{\rho}$ MKS/ρ_0, colors, in $m^2\ s^{-2}\ h^{-1}$) and mesoscale vertical potential energy flux density (PEFD, black contours in W m^{-2}) as functions of longitude and altitude for perturbations with $\lambda_H < 1{,}350$ km. Fields are averaged from 44°–50°N and 21–24 UT on 12 January 2016. PEFD corresponds to $\overline{p'w'}$, where p' and w' are the pressure and vertical velocity perturbations in the $z-$ coordinate system. ρ_0 is the average density at $z = 12$ km. (b) Same as (a), but for the mesoscale potential energy flux convergence (MPC) ($\overline{\rho}$ MPC/ρ_0, colors, in $m^2/s^2/h$). (c and d) Same as (a and b), but averaged from 52°–60°N. The event #1 local body force is labeled in green as "B" in (c and d).

further westward. These MWs dissipate at $z \sim 40$–50 km. Additionally, there is a region of negative PEFD at 5°–15°E farther to the north in Figures 19c and 19d, which indicates downward-propagating GWs. These are likely downward-propagating secondary GWs from MW breaking.

5. Conclusions

In this paper, we analyzed the GWs within two fishbone structures observed by a Rayleigh lidar in the stratosphere and lower mesosphere above ALOMAR in northern Norway during 12–14 January 2016. These structures were located at $z \sim 40$–85 km on ∼13.1–13.6 January and 13.7–14.2 January with $z_{knee} = 57$ and 64 km, respectively. Because the hodographs were significantly distorted due to contamination from secondary GWs from neighboring LBFs, we introduced an alternative method to extract the predominant GW parameters from the data. This method involves solving the GW polarization and dispersion relations for the observed vertical wavelengths and wave periods, and constraining the results with the observed amplitude ratios and phase shifts. We found that the event #1 GWs propagated northwestward, were medium-scale and medium-frequency, and had $\psi = (135 \pm 8)°$, $\lambda_H = 477 \pm 280$ km, $\tau_{Ir} = 2.8 \pm 0.9$ hr, $\tau_r = 6.7 \pm 1.7$ hr, $c_H = 20.0 \pm 9.5$ m/s, and $c_{IH} = 48.2 \pm 9.4$ m/s. We found that the event #2 GWs propagated northward, were large-scale inertia GWs, and had $\psi = (91 \pm 8)°$, $\lambda_H = 1{,}472 \pm 228$ km, $\tau_{Ir} = 7.6 \pm 0.6$ hr, $\tau_r = 8.3 \pm 2.0$ hr, $c_H = 57.9 \pm 16.6$ m/s, and $c_{IH} = 52.1 \pm 10.3$ m/s. Because the GW parameters and propagation directions were similar above and below z_{knee}, and because we found

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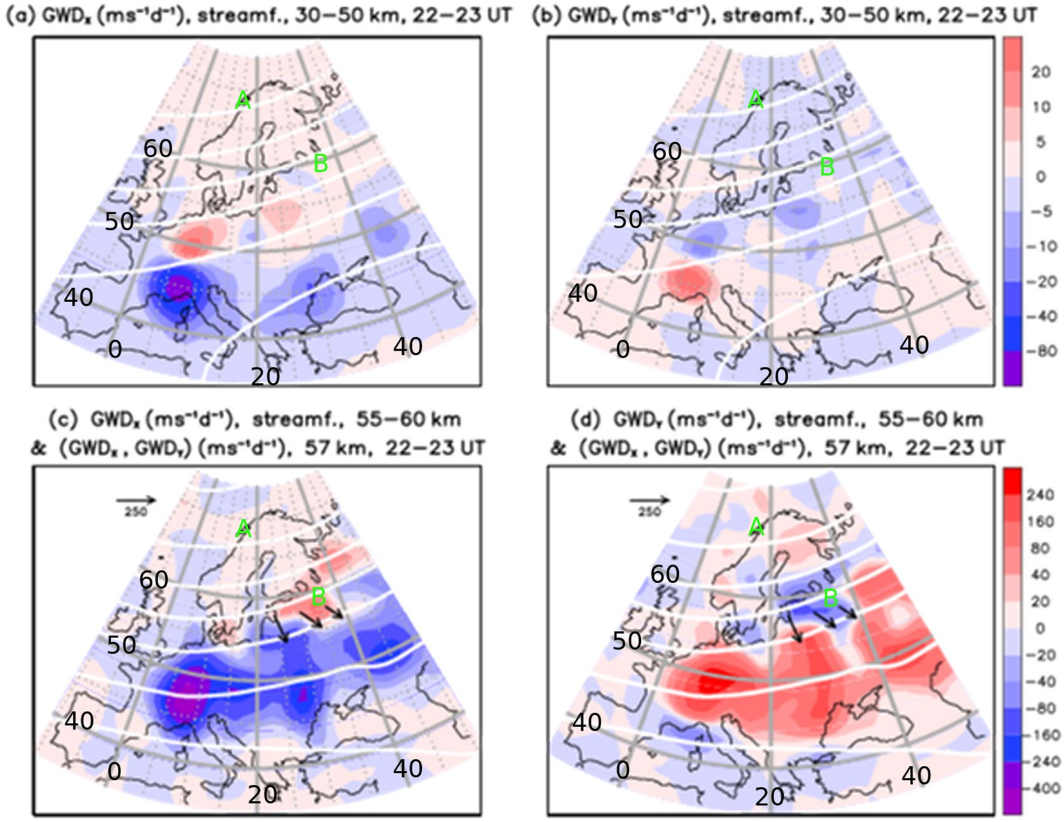

Figure 20. (a) Zonal GW drag (GWD_x) and (b) meridional (GWD_y) (colors, in m/s/d) averaged from z = 30–50 km and 22–23 UT on 12 January 2016 for perturbations with λ_H < 1,350 km. White contours show the correspondingly averaged horizontal streamfunction with interval of 5×10^7 m^2/s. Gray lines show 0°, 20°, and 40°E and 40°, 50°, and 60°N, as labeled. (c and d) Same as (a and b), but averaged from z = 55–60 km. Black arrows are the same as in Figure 18. Arctic Lidar Observatory for Middle Atmosphere Research and the event #1 local body force are labeled in green as "A" and "B," respectively.

that the GWs with upgoing phases in time below z_{knee} were downward-propagating, we concluded that these GWs were secondary GWs created by LBFs southeast and south of ALOMAR at z = 57 and 64 km, respectively.

To determine the source of the primary GWs which created the LBFs, we modeled these events using the high-resolution, GW-resolving HIAMCM with the large-scale wind and temperature nudged to MERRA-2 reanalysis in spectral space. Remarkably, we found that the HIAMCM simulated similar fishbone structures at similar times and altitudes, with z_{knee} = 58 and 66 km for events #1 and #2, respectively. To further validate the model, we compared the HIAMCM GWs with those observed by the AIRS satellite over Europe and the Atlantic Ocean during these events, and found that they agreed quite well. This agreement justified our use of the HIAMCM to determine the cause of the observed events over ALOMAR.

We found that the event #1 GWs (modeled by the HIAMCM) were part of an "X" structure in latitude and altitude at 15.7°E, with a center at z = 58 km and 60°N. Using keograms, we found that the GW parameters and propagation directions above and below z_{knee} were nearly the same. Therefore, we concluded that these GWs were secondary GWs created by a LBF, and that the LBF was located at z = 58 km, 35°E and 60°N. We found that these secondary GWs had $\lambda_H \sim$ 580 km, $\tau_r \sim$ 8 hr, $c_H \sim$ 20 m/s, and $\psi \sim$ 150°, which agreed very well with the values deduced from the lidar observations.

We then investigated the wave dynamics which led to the event #1 LBF. We found that primary GWs propagated upward from below and dissipated at $z \sim$ 50–55 km and 55–62°N, thereby creating this LBF. These primary GWs were part of a different X-structure generated/amplified at $z \sim$ 25–35 km at 49°–53°N. Because this source

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region was located near the edge of the polar vortex where the vertical wind shear was large (below the altitude of the wind maximum), and because this region was separate from the MWs at midlatitudes, we postulated that these GWs were created by the imbalance of the stratospheric polar night jet and were amplified by the jet in regions where the vertical wind shear was large. To test this conjecture, we examined the MKS, which describes the rate at which GWs extract kinetic energy from the geostrophic mean flow, as well as the MPC, because GWs are amplified by the jet in regions where the vertical wind shear is large such that MKS > 0 and MPC < 0. We found that north of ~50°N at 15°–50°E, primary GWs were generated at $z = 25$–50 km by the polar night jet, and then dissipated above $z \sim 50$ km. We also found a small GW generation region above this dissipation region at $z \sim 58$–60 km and 30–40°E which contained LBFs (including the event #1 LBF). We therefore concluded that these LBFs generated the secondary inertia GWs observed over ALOMAR, and that these LBFs were generated by the breaking and dissipation of primary GWs. In turn, these primary GWs were generated by the imbalance of the polar night jet and were amplified by the vertical wind shear in the jet below the wind maximum near the vortex edge.

Because the secondary GWs in events #1 and 2 have relatively small horizontal phase speeds, they are not expected to survive the large background winds in the mesosphere-lower-thermosphere (MLT) region and propagate into the thermosphere. Indeed, the secondary GWs observed over ALOMAR are seen to dissipate at $z \sim 65$–70 km ($z \sim 70$–80 km) during events #1 (#2) (see middle column of Figure 2). These GWs likely undergo wave breaking, since λ_z does not decrease significantly during dissipation. These processes likely generate tertiary GWs. A companion paper explores these higher-order GWs to $z \sim 400$ km on 12–14 January by analyzing the HIAMCM data and comparing with data. That study will enable a more-complete and accurate picture of how momentum and energy are transferred via multi-step vertical coupling from the polar vortex and other lower atmosphere sources into GWs and variability in the rarefied thermosphere.

Appendix A: Secondary Gravity Waves Excited by Local Body Forces

In Section 4.6, we found that although the primary gravity waves (GW) packet which created event #1 was fairly coherent near its breaking level, its amplitude and propagation direction varied somewhat at 50°–60°N (see Figures 13a and 13b), thereby resulting in body force vectors having different amplitudes and directions (black arrows in Figures 20c and 20d). Therefore, instead of a single large LBF being created where the primary GW packet broke, many neighboring local body forces (LBFs) having different amplitudes and directions at somewhat different altitudes, locations and times were created. Previous studies found that many adjacent LBFs are common in the wintertime stratosphere and mesosphere in regions of GW breaking (Vadas & Becker, 2018, their Figures 21 and 22) (Vadas & Becker, 2019, their Figures 8 and 9).

In this appendix, we model the secondary GWs excited by multiple idealized neighboring LBFs. We solve the linear, f-plane compressible fluid equations for an idealized Gaussian LBF that begins at 12.7 January, is located at 35°E, 60°N, and $z_{\mathrm{knee}} = 57$ km, and has a full width of $\mathcal{D}_H = 4.5\sigma_x = 4.5\sigma_y = 500$ km, a full depth of $\mathcal{D}_z = 4.5\sigma_z = 12$ km, a full duration of $\chi = 2.6$ hr, and a direction of $\psi = 315°$. We assume that the background atmosphere has $\overline{T} = T_0 = 231$ K, $N_B = 0.02$ rad/s and $\overline{\rho} = \overline{\rho}_0 \exp(-z/\mathcal{H})$ with $\mathcal{H} = 6.9$ km. The total horizontal force is $\mathbf{F}\mathcal{F}$ (RHS of Equation 1 in Vadas, 2013), where $\mathbf{F}$ depends on space and $\mathcal{F}$ depends on time. The solutions were calculated in that work for $\mathcal{F} = [1 - \cos(2\pi n t/\chi))/\chi$ for $0 \leq t \leq \chi$ and $\mathcal{F} = 0$ otherwise, where n is an integer [Equation 38 of Vadas, 2013). Here we choose $n = 1$, and assume a Gaussian for the LBF of

$$\mathbf{F} = F_x\hat{\mathbf{i}} + F_y\hat{\mathbf{j}} = A\left(\cos\psi\hat{\mathbf{i}} + \sin\psi\hat{\mathbf{j}}\right)\exp\left[-\frac{(x-x_0)^2}{2\sigma_x^2} - \frac{(y-y_0)^2}{2\sigma_y^2} - \frac{(z-z_0)^2}{2\sigma_z^2}\right]. \tag{A1}$$

Here A is the amplitude of $\mathbf{F}$ (in m/s), and the center of the force is at (x_0, y_0, z_0). We choose (x_0, y_0) to be the estimated event #1 LBF location of 35°E and 60°N, and evaluate the solutions at ALOMAR (i.e., at $x = -888$ km and $y = 1{,}000$ km in this coordinate system). In order that the secondary GWs have similar amplitudes as those observed by the lidar (i.e., Figure 8), we choose $A = 2{,}000$ m/s, which yields an average instantaneous acceleration in the vicinity of the LBF of $A/(4\chi) \sim 0.053$ m/s^2 or ~192 m/s/h. This acceleration is significantly larger than the hourly-averaged accelerations there (black arrows in Figures 20c and 20d).

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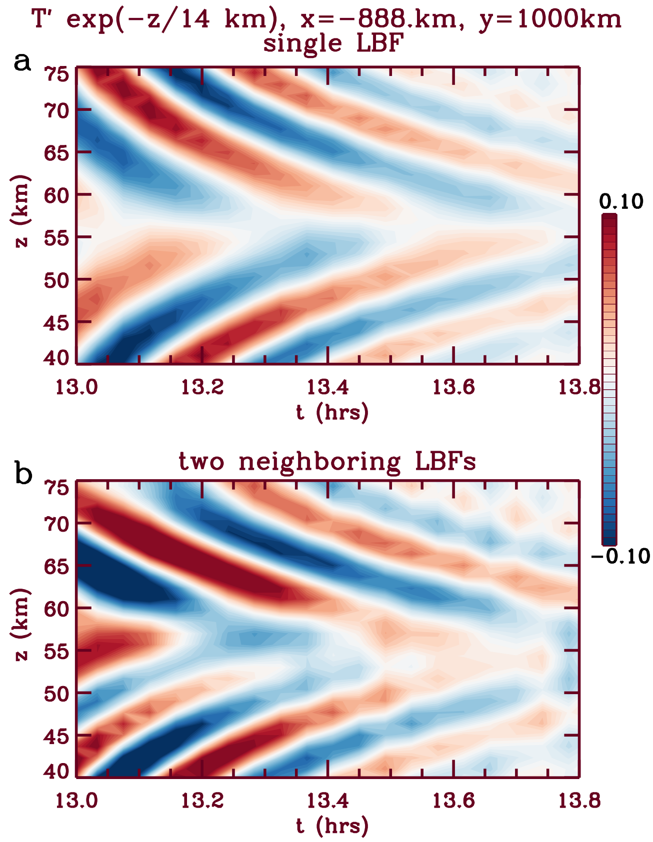

Figure A1. Theoretical fully compressible *f*-plane solutions of the secondary gravity waves excited by local body forces (LBFs) in an isothermal, windless atmosphere (see text). (a) Height-time cross-section of T' exp $(-z/14$ km) (colors, in K) at Arctic Lidar Observatory for Middle Atmosphere Research (i.e., at $x = -888$ km and $y = 1{,}000$ km) created from a local body force (LBF) centered at $z_{\rm knee} = 57$ km, 35°E and 60°N (b) Same as (a), but for two neighboring LBFs (x_0, y_0) is at the estimated event #1 LBF location of 35°E and 60°N. Note that the color scale is the same as in Figure 8.

Figure A1a shows T' exp $(-z/14$ km) as a function of altitude and time at the location of ALOMAR for a single LBF. A fishbone structure is apparent, which contains upward and downward-propagating secondary GWs. Figure A1b shows the corresponding result for two neighboring LBFs; the first LBF is the same as in Figure A1a, while a second LBF has the same amplitude, but occurs 1 hr earlier, and is 500 km west, 200 km north, and 4 km higher than the first LBF. Although the main fishbone structure is still apparent, a weak checkerboard appearance occurs from constructive/destructive interference of the secondary GWs from both LBFs. This appearance makes it more difficult to determine $z_{\rm knee}$ and to identify the GW parameters from the corresponding hodographs.

Appendix B: Comparison of HIAMCM GWs With AIRS GWs Over the Atlantic Ocean

In order to further validate the HIAMCM, we compare the gravity waves (GWs) in the HIAMCM with those from AIRS over the Atlantic Ocean during this time period. The left column in Figure B1 shows T' for the HIAMCM GWs at $z = 36$ km and at various times from 15 UT on 12 January to 3 UT on 14 January. MWs over southern Greenland and GWs generated by the polar vortex with phase lines aligned with the streamfunction (gray lines in left column) are seen. Additionally, GWs generated by the imbalance of the tropospheric jet in the jet exit region east of Newfoundland are seen. This latter source occurs where the streamfunction at $z = 12$ km expands (gray lines in middle column).

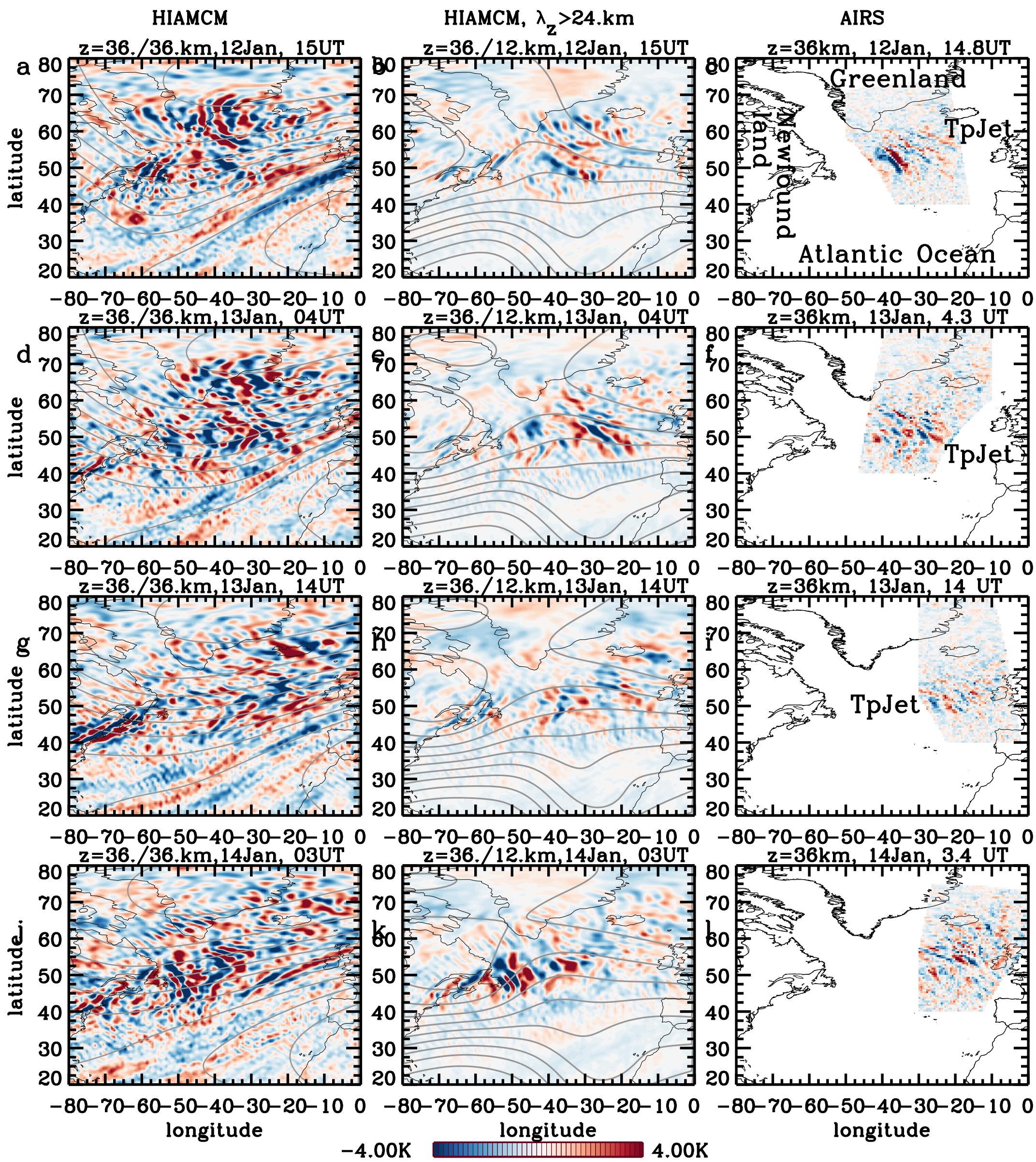

Figure B1. T' (colors, in K) at $z = 36$ km over the Atlantic Ocean in 2016. Row 1: 15 UT on 12 January. Row 2: 4 UT on 13 January. Row 3: 14 UT on 13 January. Row 4: 3 UT on 14 January. The left column shows the HIAMCM gravity waves (GWs) and large-scale horizontal streamfunction at the same times and altitude (gray lines). The middle column is the same as the left column except (1) filtered to remove GWs with $|\lambda_z| < 24$ km, and (2) the stream function is shown at $z = 12$ km. The right column shows the Atmospheric InfraRed Sounder GWs. Labels show the GWs generated by the tropospheric jet east of Newfoundland ("TpJet").

The middle column of Figure B1 shows the observationally-filtered HIAMCM T' for GWs with $|\lambda_z| \geq 24$ km. In general, the large-λ_z MWs and GWs from the polar vortex have small amplitudes. For the MWs over Greenland, this is likely because the polar night jet is displaced south of Greenland (see Figure 4a), which limits the growth of $|\lambda_z|$. For the GWs excited by the polar vortex, this is likely because (a) the wind in the polar vortex is weaker over the Atlantic Ocean than over northern Europe, thereby limiting the growth of $|\lambda_z|$, and (b) the vertical wind shear is smaller over the Atlantic Ocean, which limits the amplification of the polar vortex-generated GWs (see Figures 17a and 17b). The right column of Figure B1 shows the AIRS T'. In general, very good agreement is seen between the observationally-filtered HIAMCM GWs and the AIRS GWs.

Data Availability Statement

MERRA-2 reanalysis data was used to nudge the HIAMCM, and is available in English for download at https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/data_access/. The model data shown in this paper will be available at the time of publication in English at https://www.cora.nwra.com/vadas/Vadas-etal-JGR-2022-SecGWs-files/.

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