EGU General Assembly 2022

Contribution of Gravity Waves to Universal Vertical Wavenumber ($\sim m^{-3}$) Spectra Revealed by a Gravity-wave-permitting General Circulation Model

Haruka Okui[1*], **Kaoru Sato**[1], and **Shingo Watanabe**[2]

Corresponding author(*): Haruka Okui (okui@eps.s.u-tokyo.ac.jp)

[1]Department of Earth and Planetary Science, The University of Tokyo, Tokyo, Japan [2]Japan Agency for Marine–Earth Science and Technology, Yokohama, Japan

Abstract To examine whether universal vertical wavenumber (m) spectra are due to gravity waves (GWs), spectral analysis of GWs in the middle atmosphere was conducted by using a GW-permitting high-top general circulation model. It is shown that GWs are dominant only at high ms, while disturbances other than GWs largely contribute to the spectra at low ms even in the m^{-3} range. We also discuss distributions of the characteristic wavenumbers, slopes, and amplitudes of GW spectra, and effects of vertical shear below the middle atmosphere jets on GW spectral slope and wave saturation.

Reference Okui, H., Sato, K., & Watanabe, S., Contribution of gravity waves to the universal vertical wavenumber ($\sim m^{-3}$) spectra revealed by a gravity-wave permitting general circulation model. *J. Geophys. Res. Atmos.*, **127**, e2021JD036222. https://doi.org/10.1029/2021JD036222

Introduction

Gravity waves (GWs) play fundamental roles in determining the large-scale dynamic and thermal structure of the middle atmosphere by transporting momentum and energy. On the basis of radar (e.g., VanZandt, 1985; Fritts & Chou, 1987; Tsuda et al., 1989, 1990), radiosonde (e.g., VanZandt, 1982; Allen & Vincent, 1995; Sato et al., 2003) observations, it has been shown that **power spectra versus the vertical wavenumber (m)** of horizontal wind (u, v) and temperature (T) fluctuations have **a universal shape with a steep slope, which is proportional to $\sim m^{-3}$**. Several theoretical models explaining this spectral slope were proposed under an assumption of **GW saturation**. However, little evidence has been obtained to show that these universal spectra are fully composed of GWs. Thus, we **confirm the validity of this assumption** by using outputs from a **GW-permitting high-top general circulation model** (GCM).

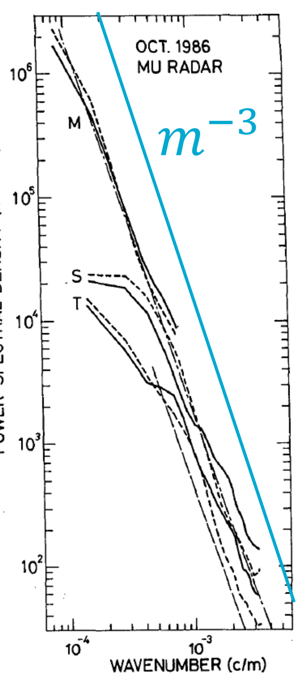


Figure 1 m spectra in the troposphere (T), stratosphere (S), and mesosphere (M) observed by the MU radar at Shigaraki (35°N, 136°E), Japan. Solid (dotted) curves show the spectra of u (v) (Tsuda et al. 1989).

Method

A GW-permitting GCM, **the Japanese Atmospheric GCM for Upper Atmosphere Research (JAGUAR)** (Watanabe & Miyahara, 2009) was used.

GWs Horizontal wavenumber $n \geq 21$

All fluctuations Vertical profiles whose linear trend is removed

Model top	~150 km
Resolution	Horizontal: T639 ($\lambda_h \gtrsim$60km), Vertical: 300 m (340 layers)
Initial values	JAGUAR-DAS analysis data (Koshin et al. 2020, 2021)
Cycle of simulation	3-day spectral nudging & 4-day free-run
Period	5–20 December 2018

GW Contribution to m^{-3} Spectra

Stratospheric m spectra of v (Fig. 2)

- All-fluctuation spectra P_{ALL} have a shape with **a steep slope of $\sim m^{-3}$** at high ms.
- At lower ms, the spectral density of the GW spectra is **smaller** than that of all fluctuations, even **within the $\sim m^{-3}$ range** of the all-fluctuation spectra.

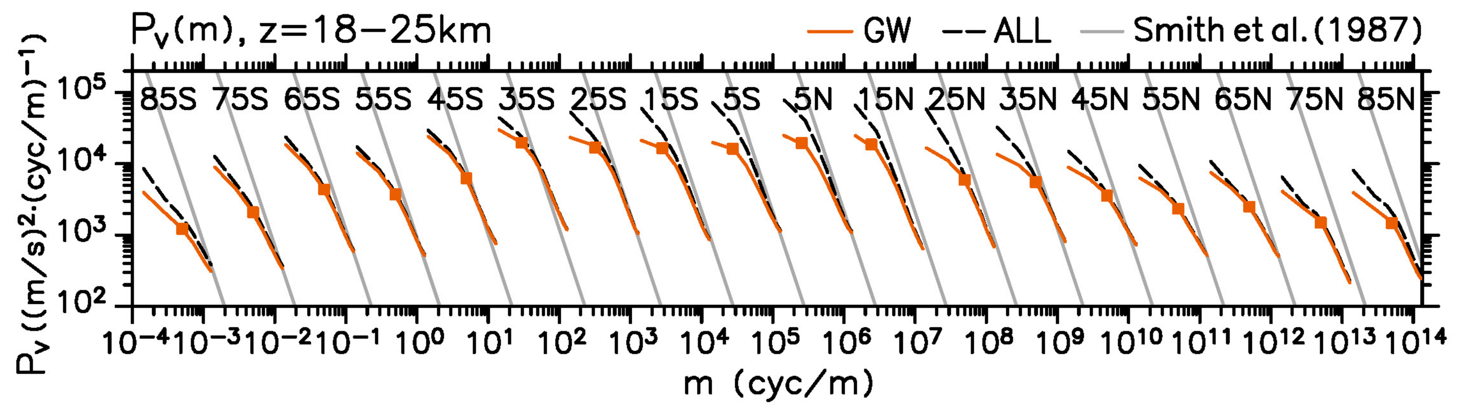


Figure 2 Meridional wind spectra of GWs (orange) and all fluctuations (dashed curves) in the stratosphere averaged zonally and over a latitude region of ±5°.

Characteristics of GW Spectra

GW spectra were fitted to the following equation

$$P_{\mathrm{GW}}(m) = F_0 \frac{m/m_{g*}}{1+(m/m_{g*})^{t+1}} \quad (1)$$

(Allen & Vincent, 1995) to estimate the parameters:

- Characteristic wavenumber: m_{g*}
- Spectral slope of opposite sign: t
- Spectral density at $m = m_{g*}$: $F_0/2$

Latitudinal & vertical variations of m_{g*}, t, & F_0 (Fig. 3)

- m_{g*} (F_0) is **smaller** (**larger**) in higher altitude regions
- **Peaks of t** are observed near the axes of **eastward** (~50°N) and **westward** (~15°S) **jets** in 45–60 km.

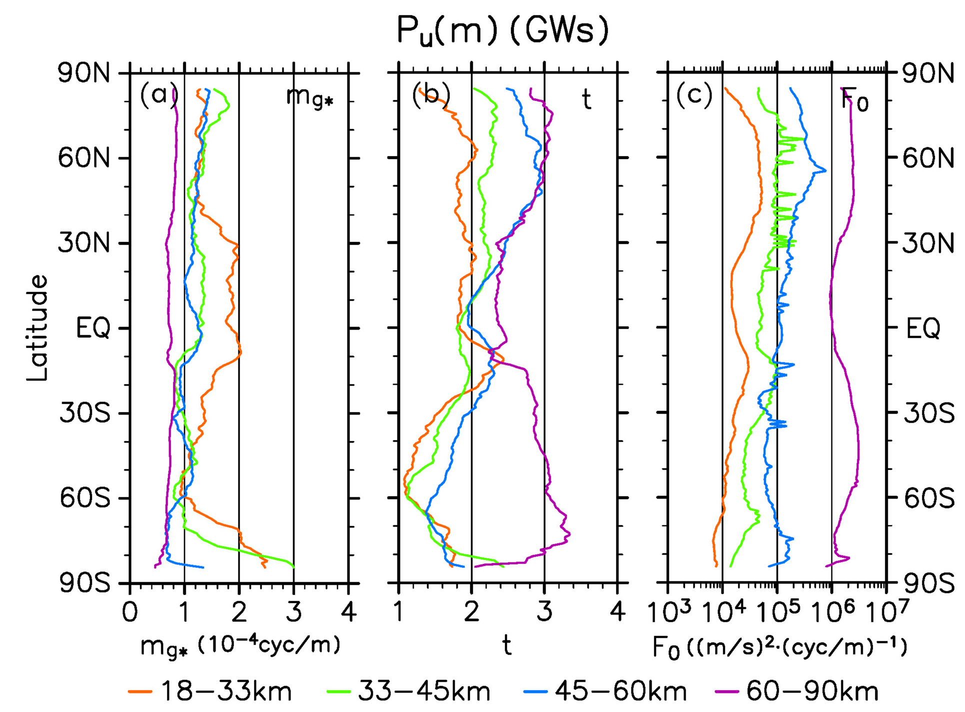


Figure 3 Zonal mean parameters of GW spectra. The color of the curves represents the height region: 18–33 km (orange), 33–45 km (green), 45–60 km (blue), and 60–90 km (purple).

Vertical Shear below the Jets

Integrating the following equations, **the effect of vertical shear** below the middle atmosphere jets on GW spectra was quantitatively examined.

According to the dispersion relation for a hydrostatic and nonrotational internal GW,

$$\frac{\mathrm{d}m(U;z)}{\mathrm{d}z} = \frac{m^2}{N} \frac{U-c}{|U-c|} \frac{\mathrm{d}U}{\mathrm{d}z} \quad (2)$$

Here, U is background wind and N is static stability. We took ground-based phase velocity $c = 0$.

Change in spectral density (Smith et al. 1995):

$$P(m_2) = P(m_1) e^{(z_2 - z_1)/(2H_E/3)} (m_2/m_1), H_E = 18 \text{ km} \quad (3)$$

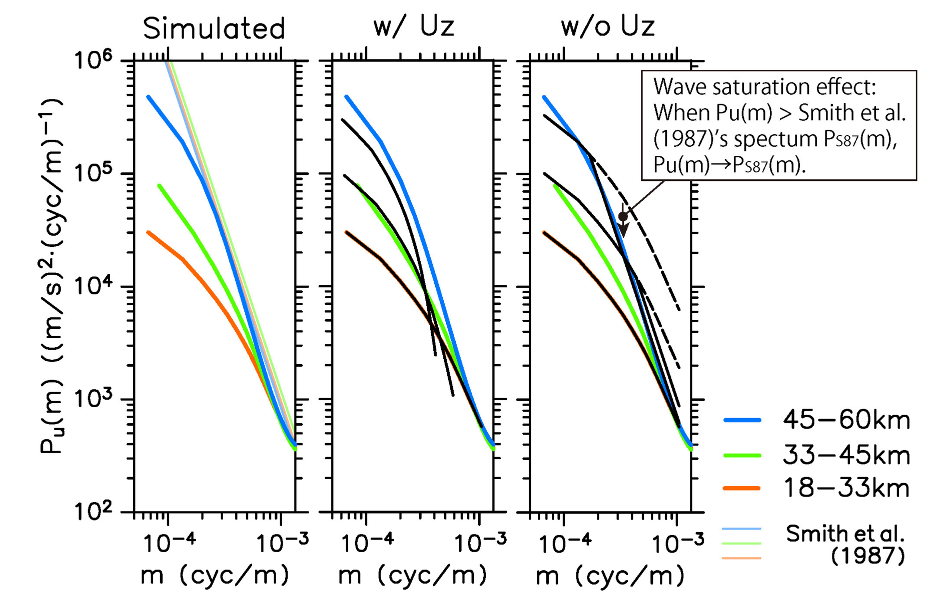


Figure 4 Model-simulated spectra and spectra estimated with and without $\mathrm{d}U/\mathrm{d}z$ for 50°N–60°N.

Shear effect on GW m spectra:

✓ **Steepening** (increase in t)

✓ **Preventing GW saturation**

Contribution of Gravity Waves to Universal Vertical Wavenumber ($\sim m^{-3}$) Spectra Revealed by a Gravity-wave-permitting General Circulation Model

Haruka Okui[1*], **Kaoru Sato**[1], and **Shingo Watanabe**[2]

Corresponding author(*): Haruka Okui (okui@eps.s.u-tokyo.ac.jp)

[1]Department of Earth and Planetary Science, The University of Tokyo, Tokyo, Japan [2]Japan Agency for Marine–Earth Science and Technology, Yokohama, Japan

Additional Figures

Comparison of Gravity Wave (GW) Amplitudes with Radars

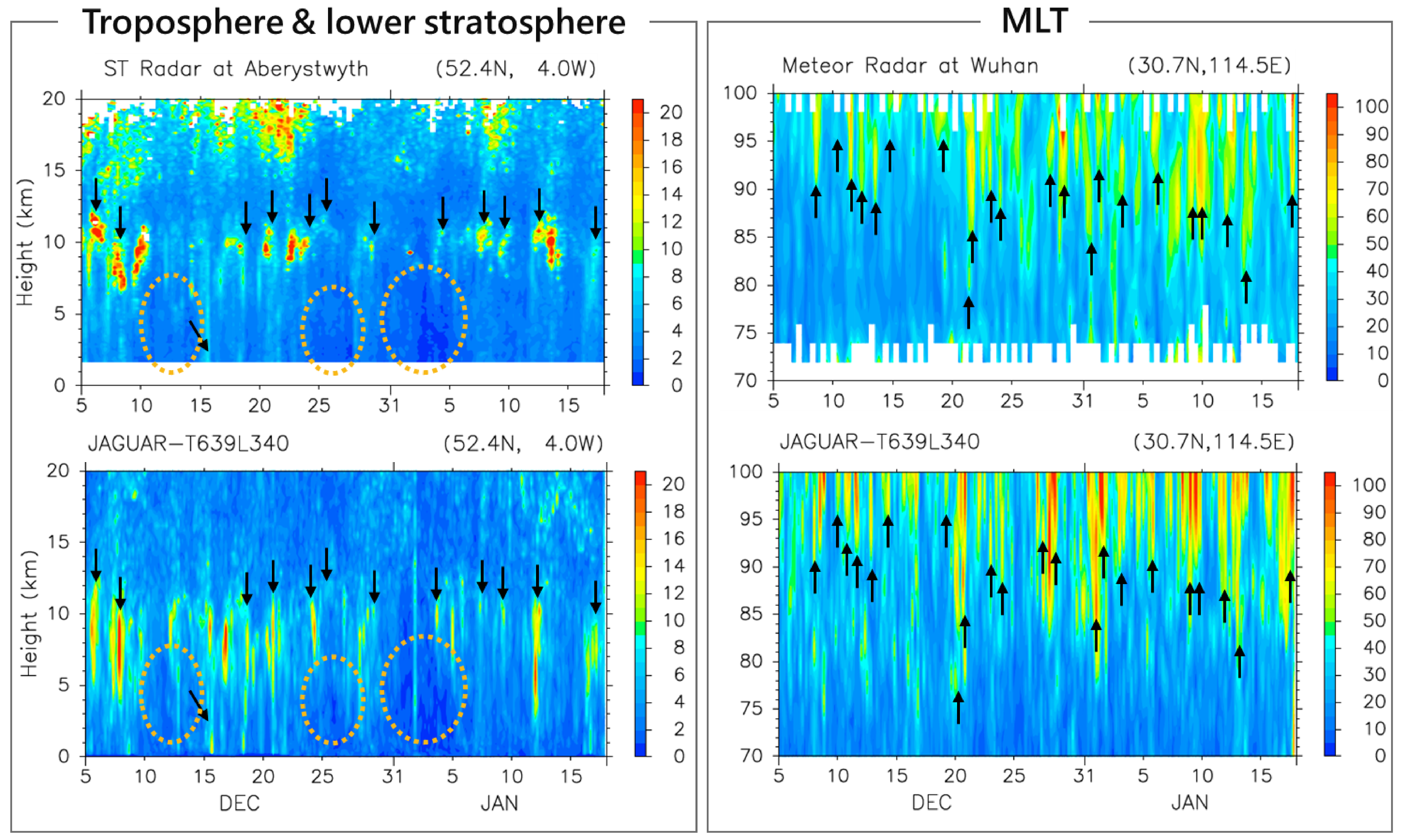


Figure A1 Amplitudes of horizontal wind fluctuations having periods <1 day.
Top: radar observation data
Bottom: JAGUAR results

All-fluctuation & GW Spectra at Shigaraki (35°N, 136°E), Japan

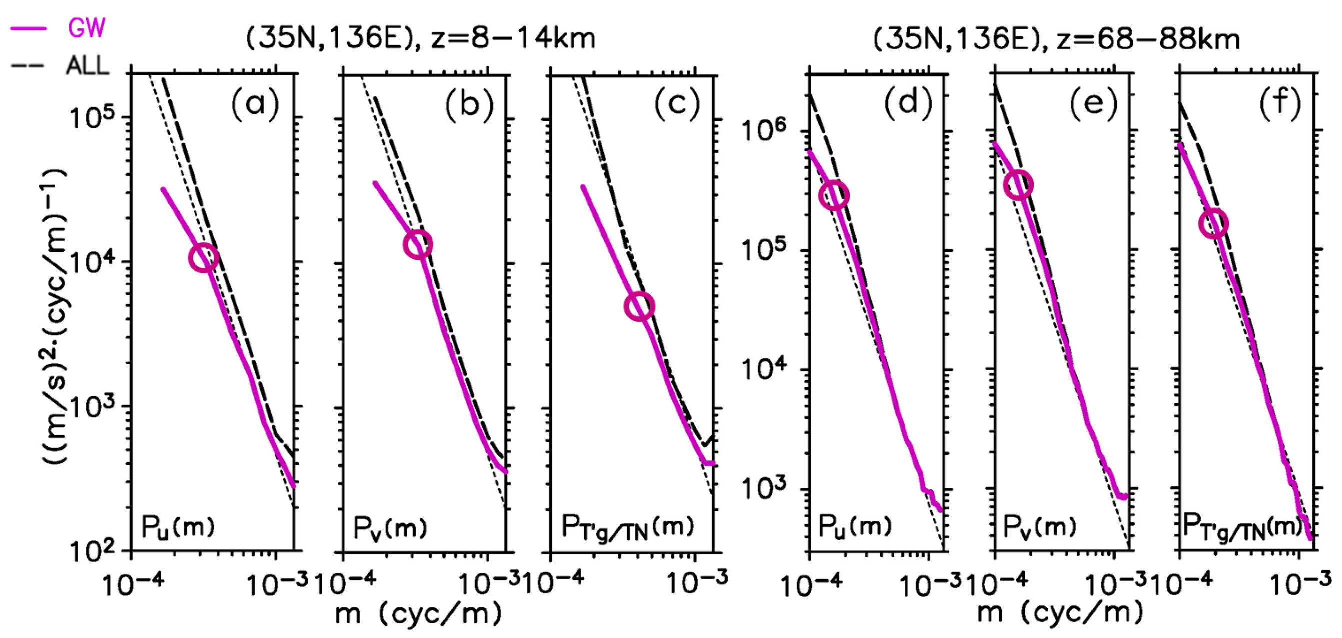
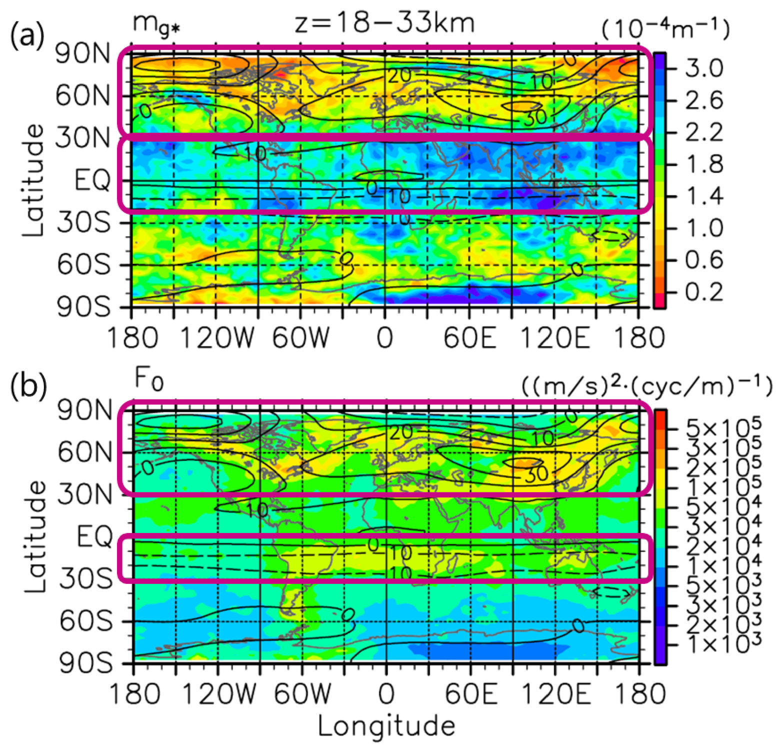


Figure A2 All-fluctuation (dashed curves) and GW (pink curves) spectra of u, v, and T in the lower stratosphere (z=8-14 km) and mesosphere (z=68-88 km).

Comparison of Vertical Wavelength & Spectral Density with Satellite Observations



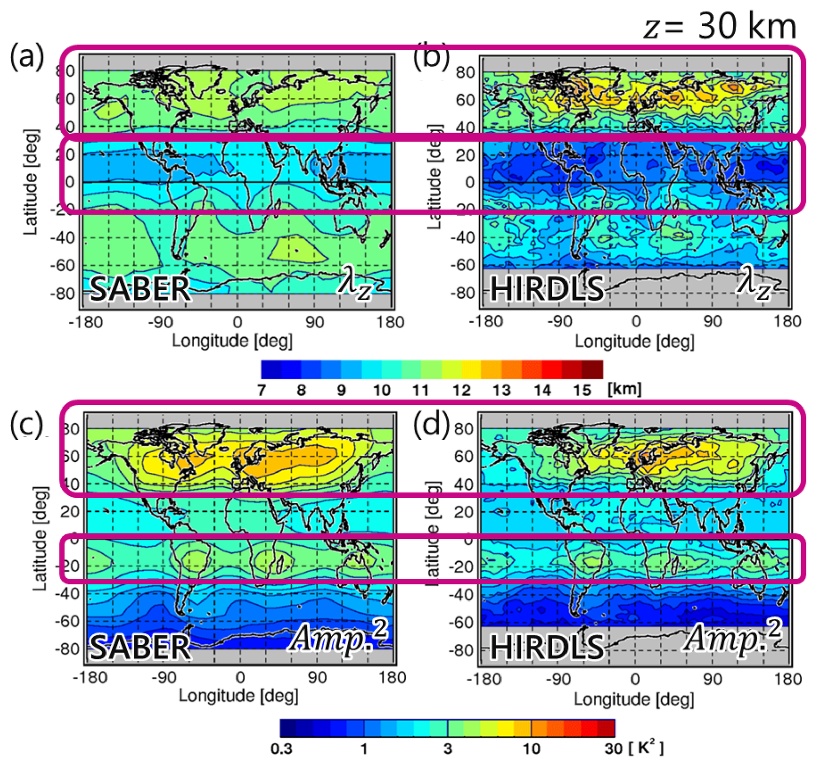
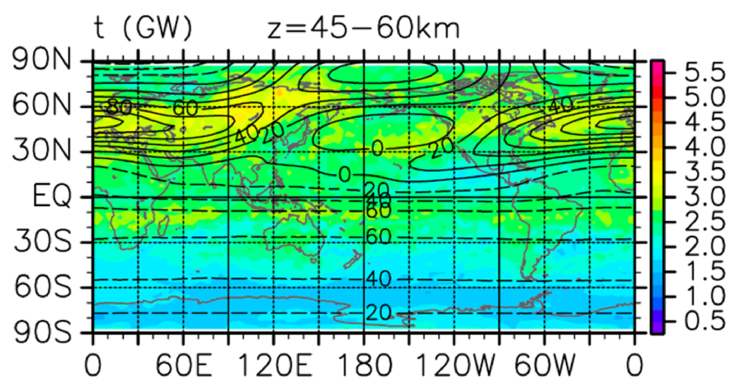


Figure A3 (left) Horizontal distributions of (a) m_{g*} and (b) F_0 in the lower stratosphere (z=18-33 km).

Figure A4 (right) Horizontal distributions of (a, b) vertical wavelength and (c, d) square of the amplitude of GWs having the largest amplitude at z=30 km. (a, c) Data from SABER
(b, d) Data from HIRDLS
(Ern et al. 2018)

Additional Figures

Method of Shear Effect Estimation



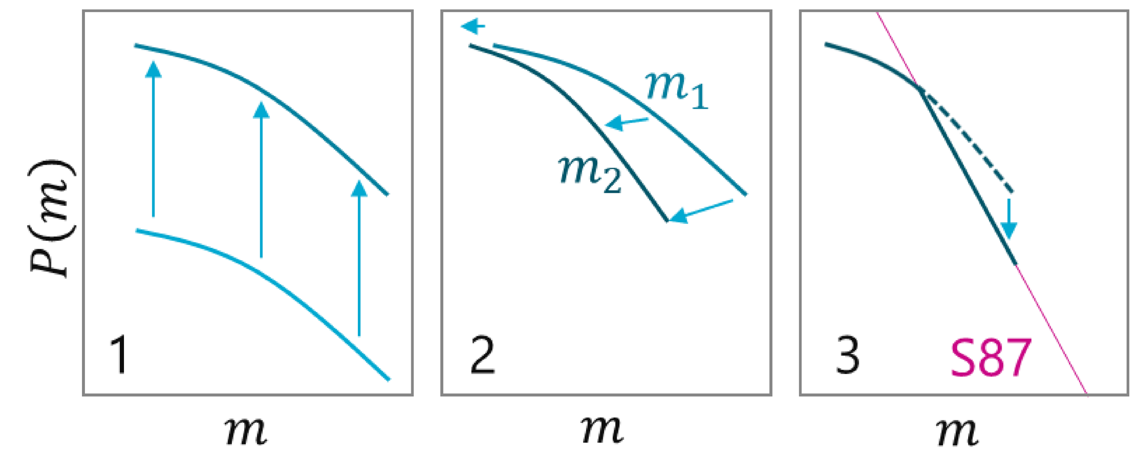


Figure A5 Spectral slope of opposite sign t in z=45-60km. Contours show zonal wind.

Figure A6 Steps of the calculation. 1. Increase spectral density $P(m)$ with height. 2. Integrate m in the vertical direction and multiply $P(m)$ by m_2/m_1. 3. Replace $P(m)$ with Smith et al. (1987)'s spectra P_{S87} when $P(m) > P_{S87}$.

Result of Shear Effect Estimation

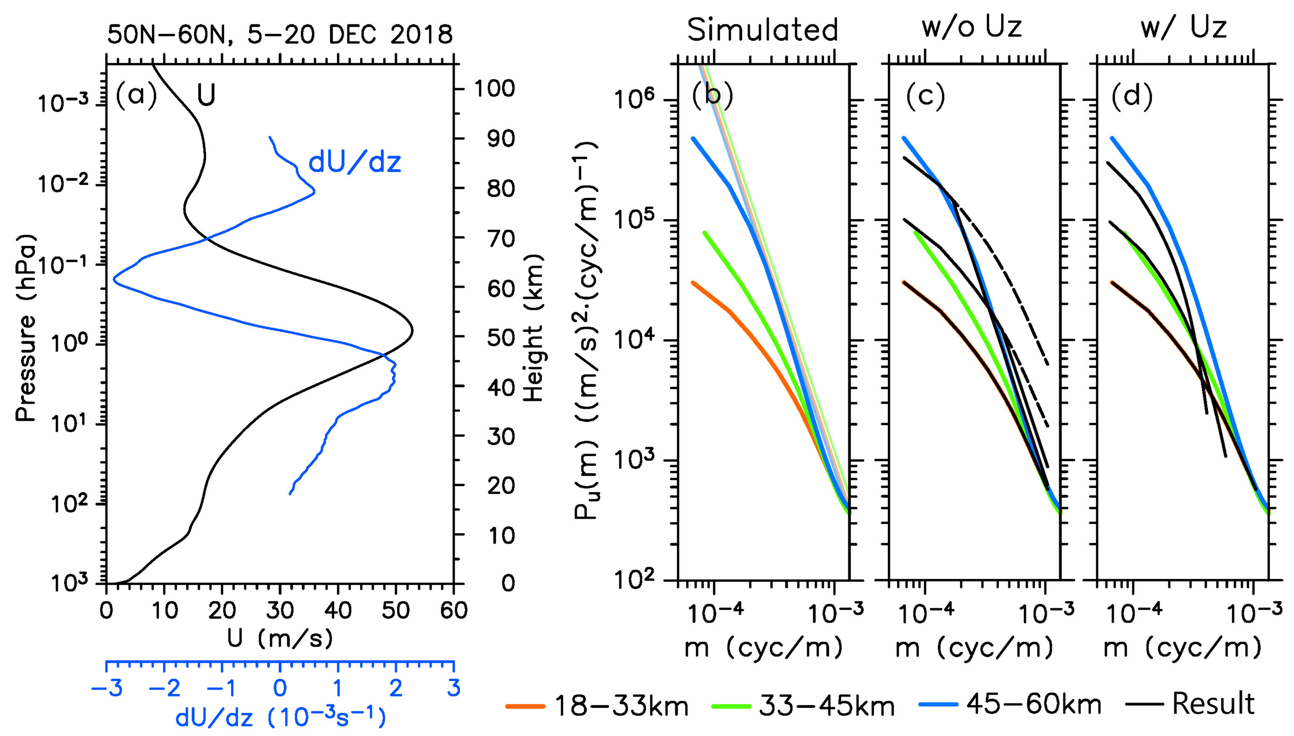


Figure A7 Model-simulated spectra and spectra estimated without and with the effect of dU/dz for 50°N–60°N.

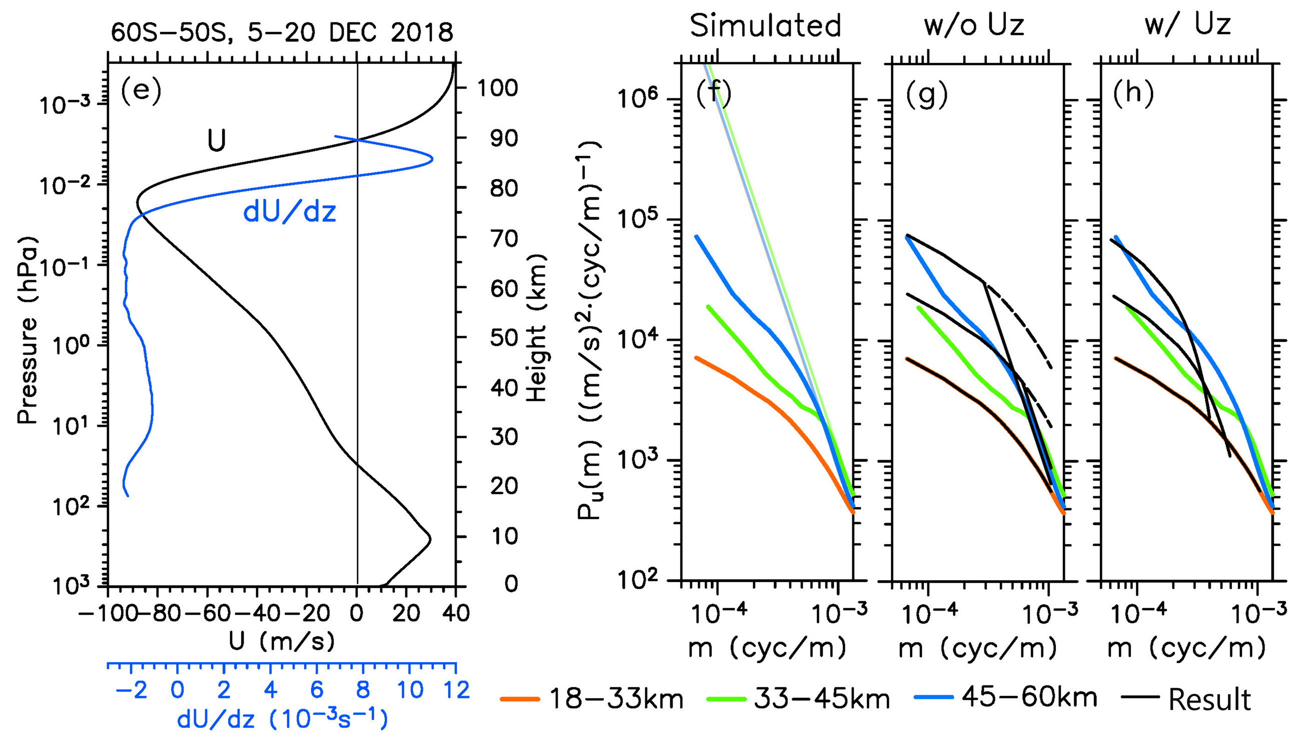


Figure A8 Model-simulated spectra and spectra estimated without and with the effect of dU/dz for 50°S–60°S.

Reference Okui, H., Sato, K., & Watanabe, S., Contribution of gravity waves to the universal vertical wavenumber ($\sim m^{-3}$) spectra revealed by a gravity-wave permitting general circulation model. *J. Geophys. Res. Atmos.*, **127**, e2021JD036222. https://doi.org/10.1029/2021JD036222

EGU General Assembly 2022

EGU General Assembly 2022

Contribution of gravity waves to the universal vertical wavenumber (m^{-3}) spectra revealed by a gravity-wave permitting general circulation model

Haruka Okui*[1], Kaoru Sato*[1], & Shingo Watanabe*[2]

*1 Department of Earth and Planetary Science, The University of Tokyo

*2 Japan Agency for Marine–Earth Science and Technology

Okui, H., Sato, K., & Watanabe, S. (2022). Contribution of gravity waves to universal vertical wavenumber (~m^{-3}) spectra revealed by a gravity-wave-permitting general circulation model. *Journal of Geophysical Research: Atmospheres*, **127**, e2021JD036222. https://doi.org/10.1029/2021JD036222

Gravity Waves & Vertical Wavenumber (m) Spectra

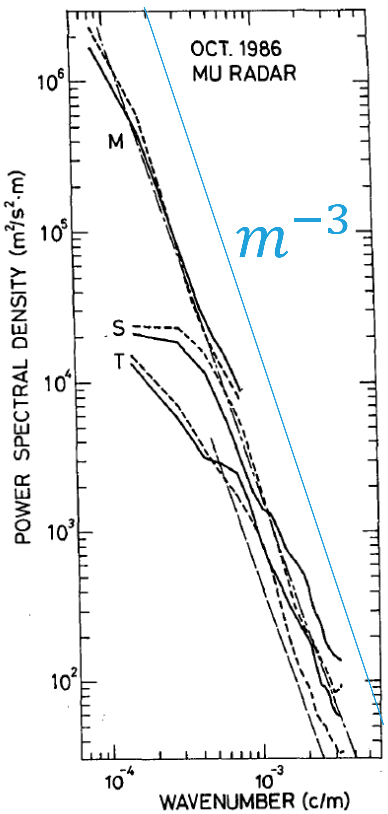


Figure 1 m spectra in the troposphere (T), stratosphere (S), and mesosphere (M) observed by the MU radar at Shigaraki (35°N, 136°E), Japan. Solid (dotted) curves show the spectra of u (v) (Tsuda et al. 1989).

Observations with high vertical resolutions (Radars, lidars, radiosondes, …)

Universal m spectra with **a steep slope** $\propto m^{-3}$

Theoretical studies
(e.g., Smith et al. 1987; Sato & Yamada 1994)

$$P_u(m) \approx \frac{N^2}{6m^3}, \quad P_{\theta g/\theta_0 N}(m) \approx \frac{N^2}{10m^3}$$

Assumption of **gravity wave saturation**

Are observed m spectra totally attributable to saturated gravity waves?

Model & Methods

Japanese Atmospheric General circulation model for Upper Atmosphere Research (JAGUAR) (Watanabe & Miyahara 2009)

Vertical domain	0–150 km
Resolution	Horizontal resolution: T639 ($\lambda_h \gtrsim$60km) Vertical resolution: 300m (340 layers)
GW parameterization	Not be used
Initial values	Reanalysis data carried out by JAGUAR-DAS (Koshin et al. 2020, 2022) ◂ PREPBUFR, MLS, SABER & SSMIS
Cycle of simulation	3-day spectral nudging & 4-day free-run ◂ Analyzed
Period	5–20 December 2018 (4-day free-run x 4)

Gravity waves (GWs) — Horizontal wavenumber $n \geq 21$

All fluctuations — Vertical profiles whose linear trend is removed

Comparison Between GW & All-fluctuation Spectra

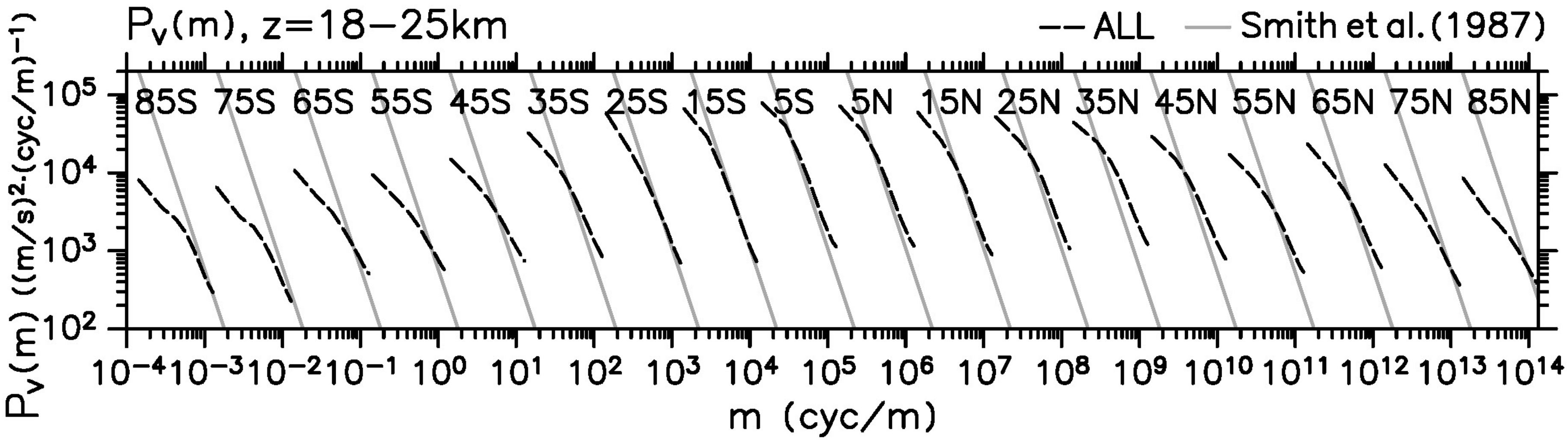


Figure 2 Meridional wind spectra of GWs (orange) and all fluctuations (dashed curves) in the stratosphere averaged zonally and over a latitude region of $\pm 5°$.

✓ Good agreement with theoretical spectra (Smith et al. 1987)

Comparison Between GW & All-fluctuation Spectra

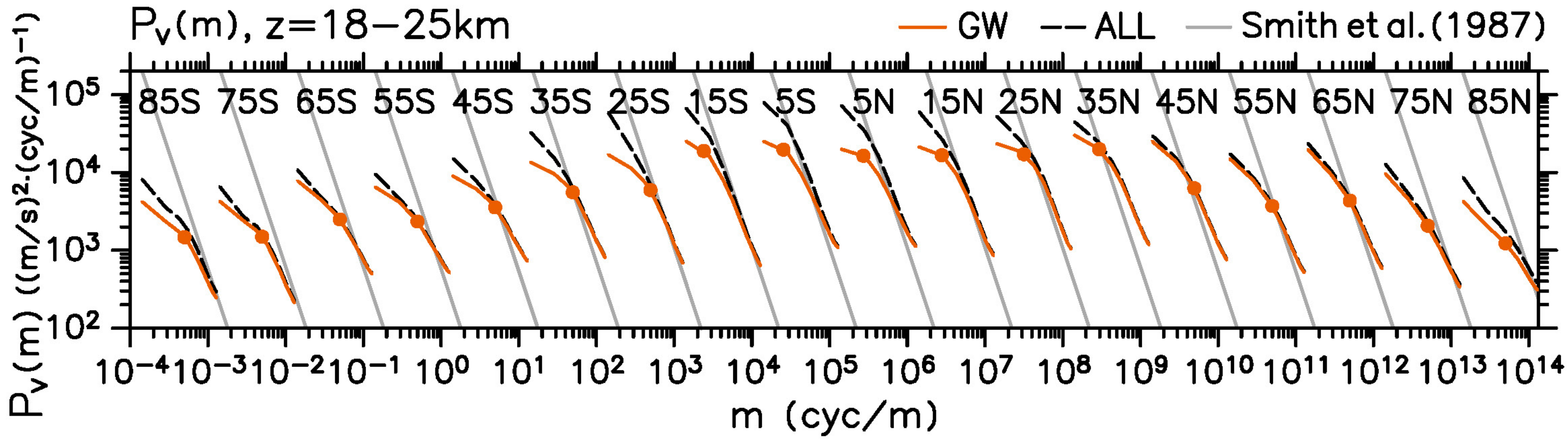
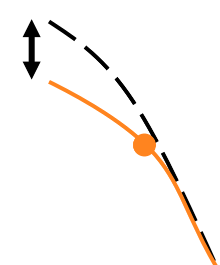


Figure 2 Meridional wind spectra of GWs (orange) and all fluctuations (dashed curves) in the stratosphere averaged zonally and over a latitude region of ±5°.

✓ Good agreement with theoretical spectra (Smith et al. 1987)

✓ Remarkable gaps between GW & all-fluctuation spectra in a lower m range than the folding point of GW spectra (●)

→ Contribution of fluctuations other than GWs to the lower m part of the steep spectral slope



GW Characteristics – Three Parameters: (m_{g*}, F_0, t)

GW spectra were fitted to the equation (Allen & Vincent, 1995)

$$P_{GW}(m) = F_0 \frac{m/m_{g*}}{1 + (m/m_{g*})^{t+1}}$$

to estimate the parameters:

- Characteristic wavenumber: m_{g*}
- Spectral density at $m = m_{g*}$: $F_0/2$
- Spectral slope of opposite sign: t

t increases with increasing altitude in the winter jet region

Due to the strong shear below the jet?

t increases with increasing altitude

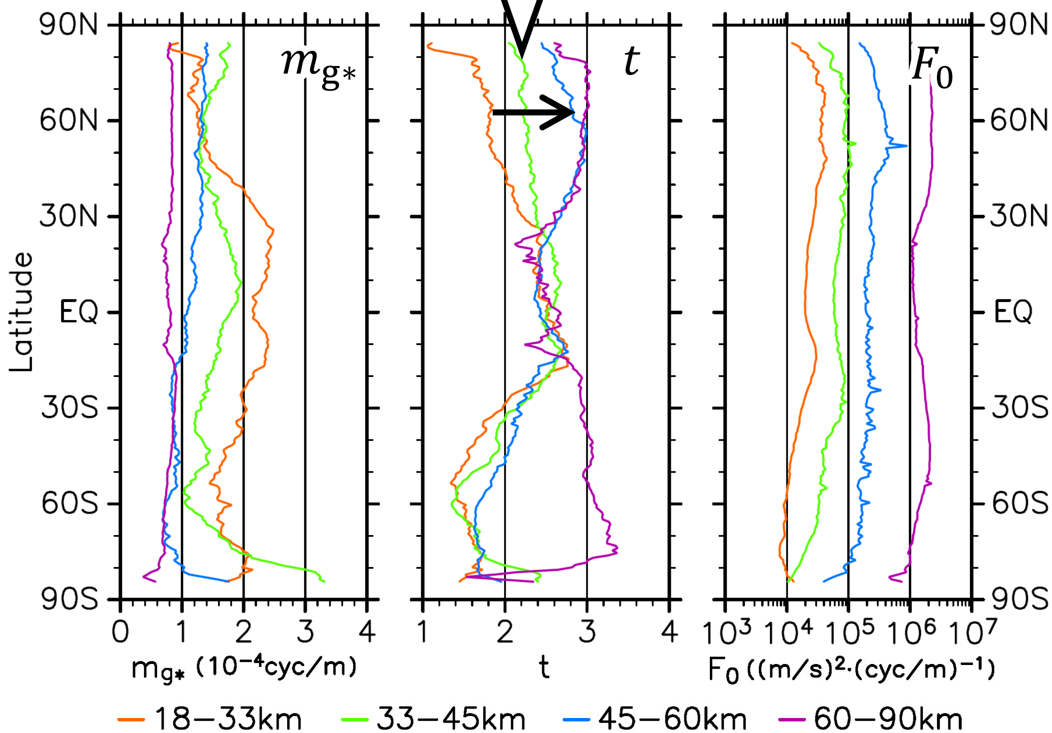


Figure 3 Zonal mean parameters of GW zonal wind spectra. The color of the curves represents the height region: 18–33 km (orange), 33–45 km (green), 45–60 km (blue), and 60–90 km (purple).

Evaluation of Vertical Shear Effect on GW m Spectra

Integrating

$$\frac{\mathrm{d}m(U;z)}{\mathrm{d}z} = \frac{m^2}{N}\frac{U-c}{|U-c|}\frac{\mathrm{d}U}{\mathrm{d}z}$$

Without shear effect
(amplitude growth only)

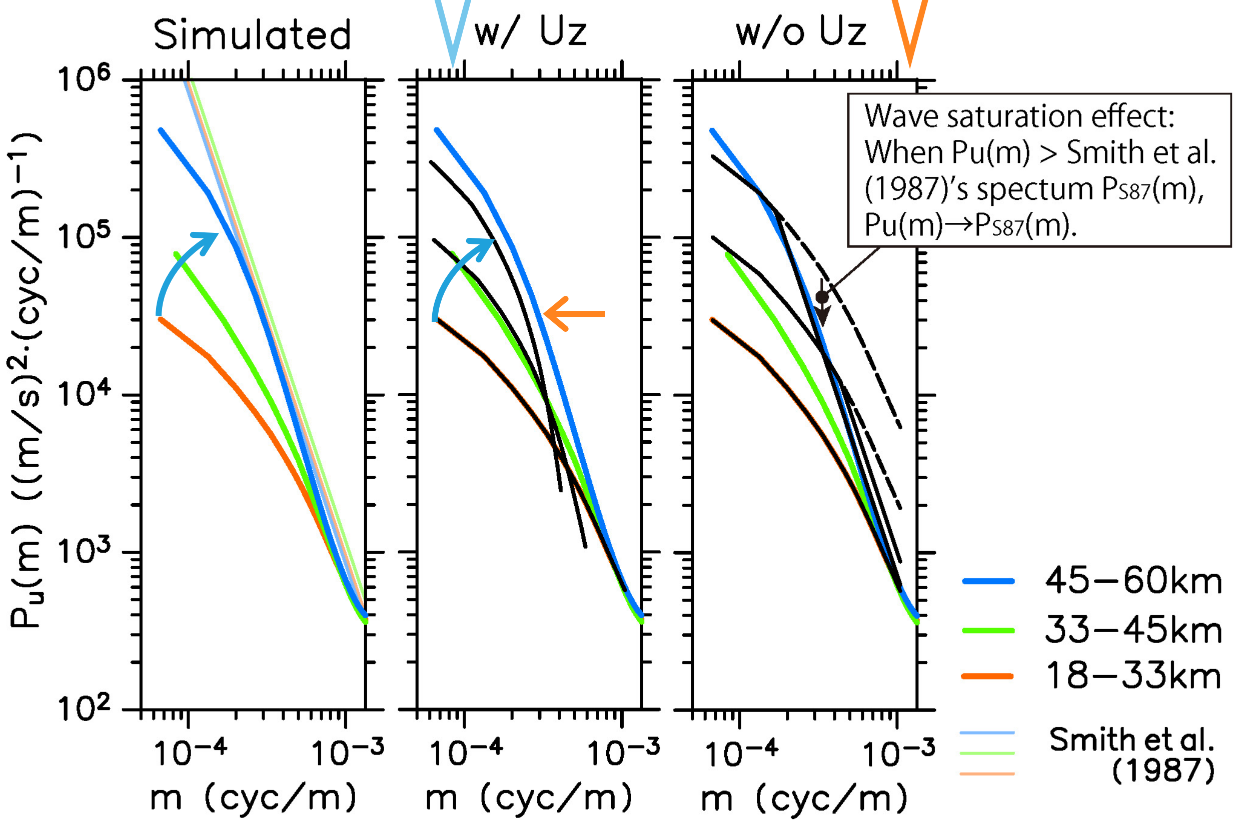


Figure 4 Model-simulated spectra (color) and spectra whose vertical changes are estimated with and without $\mathrm{d}U/\mathrm{d}z$ (black) for 50–60°N.

Vertical shear ($\mathrm{d}U/\mathrm{d}z$) effect : Steepening + Preventing wave saturation

Summary

To examine whether universal vertical wavenumber (m) spectra are due to gravity waves (GWs), spectral analysis of GWs in the middle atmosphere was conducted by using a GW-permitting high-top general circulation model.

Key Points

- GWs are dominant only at high ms of the universal m spectra
- Disturbances other than GWs significantly contribute to the spectra at low ms

- Distributions of the characteristic wavenumbers, slopes, and amplitudes of GW spectra were shown

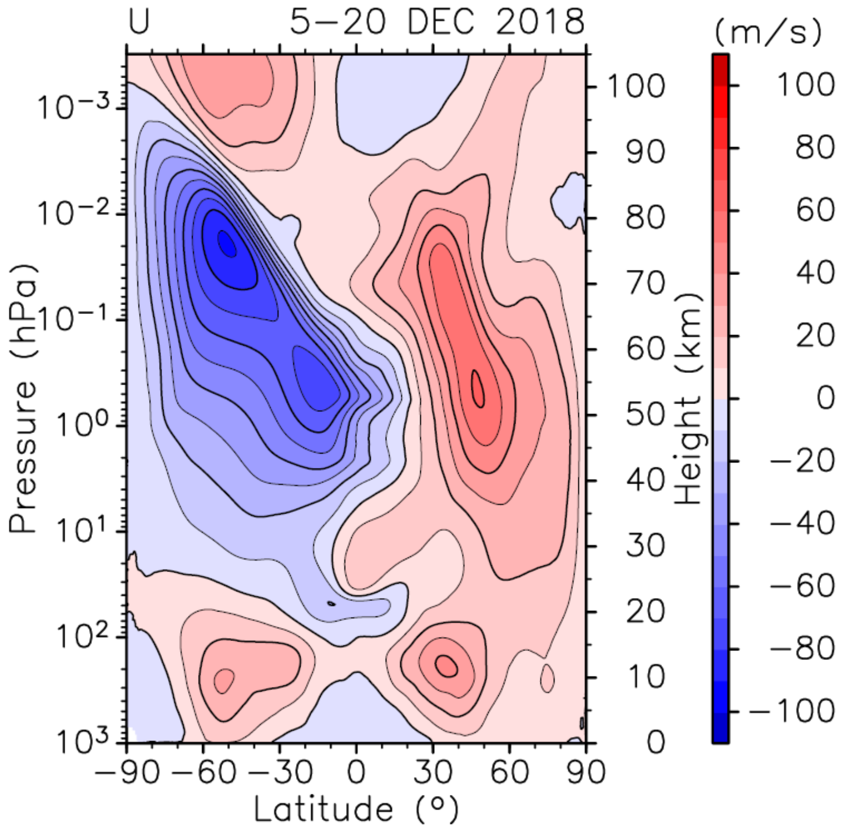
- Effects of vertical shear below the middle atmosphere jets steepen GW spectra and prevent GW saturation

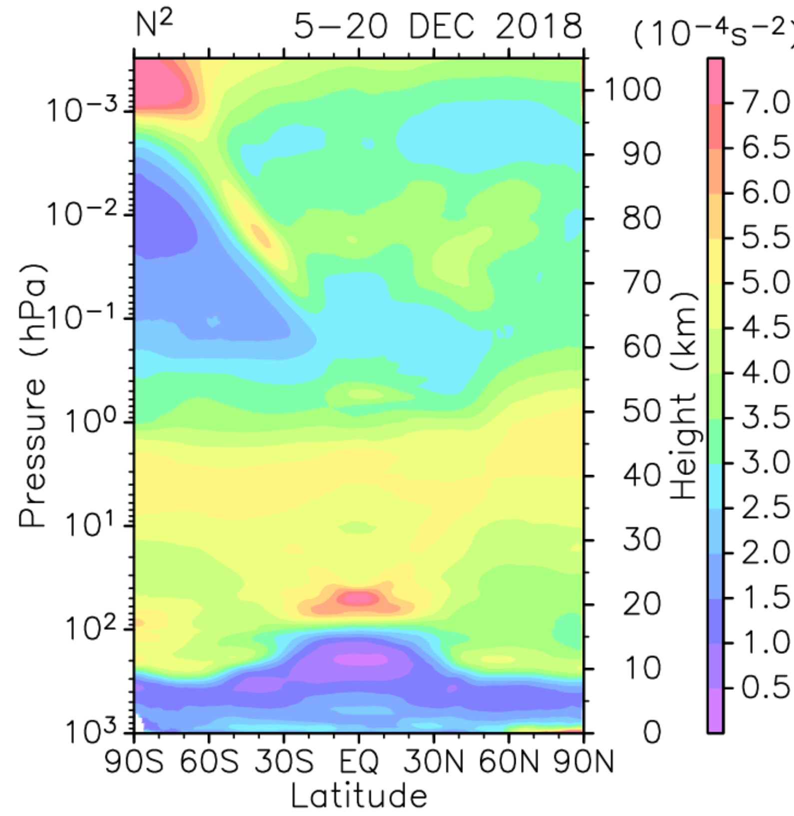
→ Possible impact on GW momentum deposit

Okui, H., Sato, K., & Watanabe, S. (2022). Contribution of gravity waves to universal vertical wavenumber (~m^{-3}) spectra revealed by a gravity-wave-permitting general circulation model. *Journal of Geophysical Research: Atmospheres*, **127**, e2021JD036222.
https://doi.org/10.1029/2021JD036222

EGU General Assembly 2022

Appendix: Zonal Mean Field – $\bar{u}$ & $\overline{N^2}$





Appendix: Candidates for Disturbances in Universal Spectra

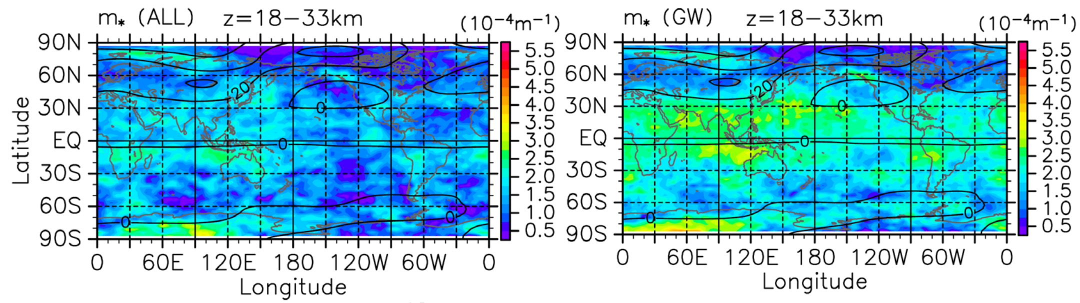
- Equatorially-trapped waves
  - Rossby-gravity waves
  - Inertia-gravity waves
- Rossby waves

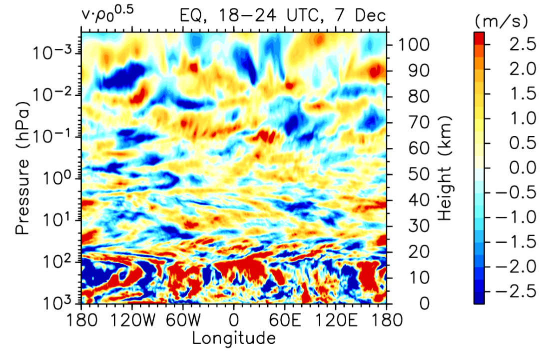
→ △ In the SH where $\bar{u} < 0$

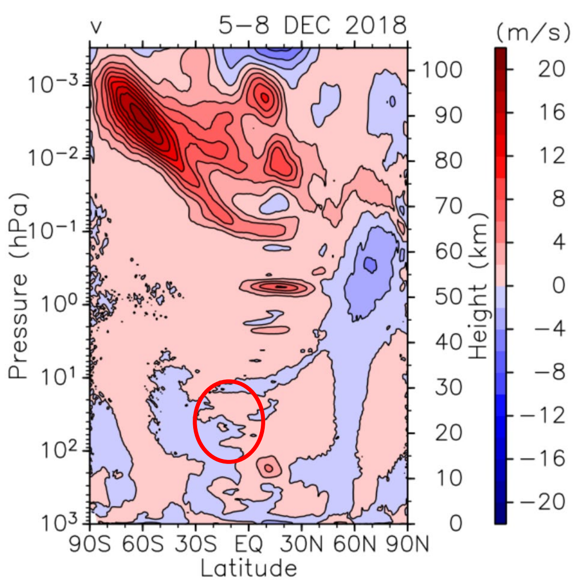
- Inertial instability

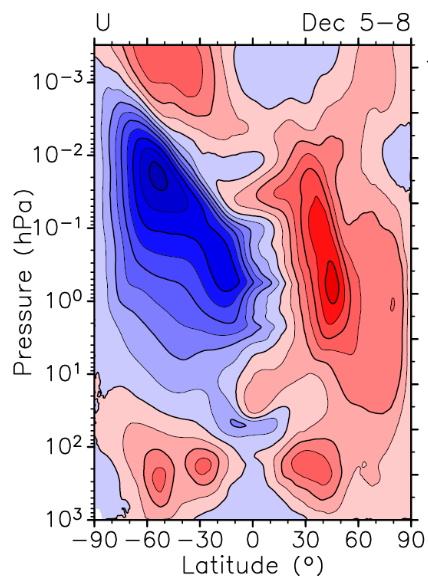
→ △ Anomalous PV was hardly observed

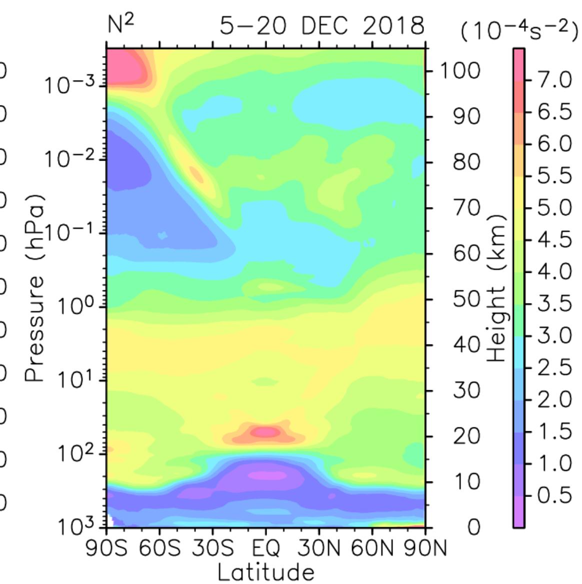
- Secondary circulation associated with QBO











Appendix: Candidates for Disturbances in Universal Spectra

- Equatorially-trapped waves
  - Rossby-gravity waves
  - Inertia-gravity waves
- Rossby waves

→ △ In the SH where $\bar{u} < 0$

- Inertial instability

→ △ Anomalous PV was hardly observed

- Secondary circulation associated with QBO