Frequency of Mountain Waves Over Kanto Area Revealed by Imaging Observations of OH Airglow

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Frequency of mountain waves over Kanto area revealed by imaging observations of OH airglow

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Abstract

Imaging observations of OH airglow were conducted at Meiji University, Japan (35.613°N, 139.549°E), from May 2018 to December 2019. Mountainous areas, including Mt. Fuji, are located to the west of the imager, and westerly winds are dominant in the lower atmosphere throughout the year. Mountain waves (MWs) are generated on the leeward sides of mountains and occasionally propagate to the upper atmosphere. However, during the observation period (about 1 year and 8 months), only four possible MW events were identified. Based on previous reports, this incidence is considerably lower than expected. There are two possible reasons for the low incidence of MW events: (1) The frequency of MW excitation is small in the lower layers of the atmosphere, and/or (2) MWs do not propagate easily to the upper mesosphere due to background wind conditions. This study verified the likelihood of the former case. Under over-mountain airflow conditions, wavy clouds are often generated on the leeward side. Since over-mountain airflow is essential for the excitation of MWs, the frequency of wavy clouds in the lower atmosphere can be regarded as a measure of the occurrence of MWs. The frequency and spatial distribution of MWs around Japan were
investigated by detecting the wavy clouds from color images taken by the Himawari-8
geostationary meteorological satellite (GSM-8) for one year in 2018. The wavy clouds
were detected on more than 70 days a year around the Tohoku region, but just 20 days a
year around Mt. Fuji. This suggests that few MWs are generated around Mt. Fuji. The
differences between these two regions were examined focusing on the relationship
between the local topography and dominant horizontal wind fields in the lower
atmosphere. Specifically, the findings showed that the angle between the dominant
horizontal wind direction and the orientation of the mountain ridge is a good proxy of
the occurrence of wavy clouds, i.e., excitation of MWs in mountainous areas. We have
also applied this proxy to topography in other areas of the world to investigate areas
where MWs would be occurring frequently. Finally, we discuss the likelihood of "MW
hotspots" at various spatial scales in the world.

**Keywords**
OH airglow, mesosphere, atmospheric gravity waves, mountain waves
1 Introduction

Atmospheric gravity waves (AGWs) propagate horizontally and vertically in the atmosphere. AGWs play an important role in the transportation of energy and momentum from the excitation source to distant places. The most obvious sources include topography, convection, wind shear and jet/front system, although other sources may also be important at certain sites or in association with specific large-scale dynamics (Fritts and Alexander, 2003; Plougonven and Zhang, 2014). In particular, AGWs induced by topography are referred to as mountain waves (MWs). One of the remarkable features of MWs is that they do not have an apparent phase speed if they are observed from the ground. AGWs can propagate vertically in the atmosphere as long as there is no critical level or turning level on the ray-path. The background horizontal wind velocity and apparent horizontal phase velocity (the horizontal phase velocity observed from ground) are equal, and this altitude is referred to as the critical level (Booker and Bretherton, 1967). If there is a critical level in the vertical propagation path of AGWs, then the waves cannot propagate above this altitude. Eventually, MWs are absorbed and dissipate into the background atmosphere at this altitude, and transferring
its momentum and energy to background. AGWs are reflected at the altitude at which

\[ m^2 = 0 \] (\( m \) is vertical wave number). This altitude is called turning level (Fritts and

Alexander, 2003). Tomikawa (2015) shows that AGWs with shorter horizontal

wavelength are more likely to be blocked from propagating vertically due to the turning

level reflection. In addition, since the background atmospheric density decreases with

altitude, the amplitude of the wave increases, and eventually the AGW breaks. In such

cases, momentum and energy are deposited to the background atmosphere. The

momentum that is transferred from the lower to the middle atmospheres drives the

circulation of the middle atmosphere. The excitation source of MWs is fixed on the

ground. Therefore, MWs are one of the important factors that give a certain rhythm to

the middle atmosphere circulation with seasonally varying background winds. It is

important to understand the excitation and propagation process of MWs to quantify the

global atmospheric circulation. Consequently, understanding the excitation and

propagation process of MWs is important for quantitative analyses of global

atmospheric circulation (Fritts and Alexander, 2003).

Several observational studies of MWs have been conducted. It has been shown that
MWs are easily induced by the New Zealand landmass and the Antarctic Peninsula, which act as obstacles to winds in the lower atmosphere blowing over the Antarctic Sea. MWs induced in these areas were frequently detected on the leeward side of the terrain (Espy et al., 2006; Ehard et al., 2017). It has also been reported that MWs generated by the Andes frequently propagate into the upper mesosphere (an altitude of approximately 85 km) (Smith, 2009; Criddle et al., 2011; Hecht et al., 2018). Although, MWs can propagate into the middle atmosphere, there are still numerous unclear points in terms of the relationship between the excitation frequency, propagation process, shape of the source mountain. In particular, the relationship between mountain features and the parameters of MWs are still unclear. At present, the global circulation model (GCM) cannot adequately handle the effects of small-scale AGWs (< 100 km). Consequently, several methods have been proposed for parameterizing the effect of small AGWs in many models, but more observations are required to improve the models (Yiğit et al., 2009, Richter et al., 2010).

In this study, imaging observations of OH (7-3) airglow at the Kawasaki City campus of Meiji University, Japan (35.613°N, 139.549°E) were conducted from May 2018 to
December 2019 (Figure 1). The objective of the observations was to estimate the frequency of MWs that propagate from the mountainous region into the upper mesosphere over the observation site. The mountainous area located to the west of the observation site includes Mt. Fuji, which is the highest mountain in Japan. Mt. Fuji is an isolated mountain (stratovolcano) with a peak altitude of 3776 m, a horizontal width of approximately 40 km, and a symmetrical bell shape. Since MWs are induced by topography, it is considered that the characteristics of MWs are affected by the underlying topographical features (e.g., mountain shape and direction of mountain ridgeline). The observation data were used to analyze the propagation frequency and the scale parameters of the MWs induced by this bell-shaped mountain.

Details regarding the airglow observation instruments, observation settings, and methods for analyzing the airglow image data are described in Section 2. Results of the airglow imaging observations conducted at Meiji University from May 2018 to December 2019 are presented in Section 3. In Section 4, the occurrence of over-mountain flow in Japan and the frequency of the observed MWs are discussed based on an analysis of cloud images acquired by the Japanese Geostationary Meteorological
Satellite Himawari-8 (GMS-8). A summary of our findings and our conclusions are presented in Section 5.

Figure 1 Location of the observation site (Meiji University, Kawasaki, Japan) (Geospatial Information Authority of Japan, 2020).
2 Observation and analysis

2-1 Instrumentation

In this study, OH airglow imaging observations were conducted at Meiji University, Kawasaki, Japan (35.613°N, 139.549°E) from May 2018 to December 2019. The objective of these observations was to detect MWs that were induced by a lower-atmosphere, westerly wind blowing over the mountainous areas and Mt. Fuji, which are located to the west of the observation site.

A cooled CCD camera (Clara, Andor Technology Ltd., UK) was used for all observations. Table 1 and Figure 2 show the main specifications and components of the camera, respectively. Specifically, the components of the camera consist of a fish-eye lens (objective lens), a mechanical shutter, a collimator lens, an interference filter, a focusing lens, and the detector. The bandpass interference filter, which is 15 nm width and centered at 890 nm, is optimized to detect emissions from the Meinel OH (7-3) band in the near-infrared wavelength. Figure 3 shows a transmittance profile of the interference filter with locations of the major rotational lines belonging to the Meinel OH (7-3) band. This wavelength region was selected because it is less contaminated by
light pollution from surrounding urban areas. The collimator lens is set in front of the filter to suppress the effect of a wavelength-shift in the bandpass filter which depends on an angle of incident light to the filter. The imager was placed in a water-proofed box for field observations; specifically, the box was equipped with a thermostatically controlled heater and intake fan to keep the temperature and humidity inside the box between 5°C and 25°C, and less than 65%, respectively. A mechanical shutter behind the fish-eye lens prevents damage to the CCD due to direct sunlight. This shutter is controlled by a trigger signal sent from the camera.

Table 1 Specifications of the Clara CCD camera.

| Specification                           | Value               |
|----------------------------------------|---------------------|
| Active pixels (W × H)                  | 1392 × 1040         |
| Pixel size (W × H)                     | 6.45 × 6.45 μm      |
| Image area (W × H)                     | 8.98 × 6.71 mm      |
| Thermoelectric cooling                 | -55°C               |
| Quantum efficiency (890 nm)            | 12%                 |
Figure 2 Optical components of the OH airglow imager.

Figure 3 Transparency characteristics of the interference filter. The wavelengths of Q-Branch and P-Branch in the OH (7-3) band are indicated by arrows above the image.
Figure 4 shows the field of view (FOV) of the imager at a typical altitude of the OH airglow layer (85 km). The effective FOV at this altitude has a radius of about 120 km from the observation site, exposure time was 3 min, and the images were taken continuously from sunset to sunrise. To obtain a higher signal to noise ratio (SNR) airglow image, 2 × 2 binning was performed on the CCD. The final image acquired by the observation had dimensions of 696 pixels × 520 pixels. The dark frame used for the dark subtraction method described in section 2-3 was taken every night with the shutter closed at the start of observation. The imager was controlled by a PC installed in the box, and all the acquired image data was saved as TIFF format.
Figure 4 Projection of a georeferenced image acquired at 2:53 JST on January 18, 2019.

This is the effective field of view of the OH airglow layer (85 km) in the imager at a typical altitude. The red star indicates the location of the observation site.

2-2 Definition of valid data

Airglow cannot be observed from the ground in cloudy weather. In addition, data with the moon light and the associated scattered light were excluded from the analysis because this light contamination is considerably stronger than the airglow emission. In this study, image data that satisfied the following two conditions were defined as valid data for further analysis:

1) Data was acquired in a clear sky.

2) Data without the moon, its scattered light, and following stray lights causing ghosting and/or flaring.

Figure 5 (a), (b), (c) shows examples of valid data and invalid data.
Figure 5 (a) shows a sample of valid image (clear sky), (b) and (c) show invalid image data with the moon and clouds, respectively.

The acquired image data was visually judged as being valid or not. When valid data were obtained continuously for several hours, then the images were subjected to MW analysis using the method described in Section 2-3.

2-3 Procedure for extracting MW signals from image data

The following analytical method was used for extracting MW signals from airglow image data. Since the apparent horizontal phase speed of MW is zero, MW appears to be almost stationary from the ground observer. In principle, the bright and dark patterns in an airglow image generated by the MWs would become clear by simply integrating the successive images. However, due to the van Rhijn effect, atmospheric extinction effects, and inhomogeneous sensitivity of the optics, simple integration does not
enhance the MW signatures with horizontal wavelengths that have same order as the FOV (see Figure 4). The procedure employed to remove these effects from the integrated airglow image data is described below. First, the elevation and the azimuth angles corresponding to each pixel of the image are determined using star images (Figure 6). The scheme to fit the local horizontal coordinate system to images is described in Suzuki et al. (2017). The azimuth angle, which is the angle from true north, increases counterclockwise in an image. As seen in Fig. 6, data captured at an elevation angle of < 30° cannot be used in further analysis due to FOV obstruction by ground artifacts. The data captured at an elevation angle > 30° was used for analysis in this study. Second, dark counts are removed by subtracting dark frame. Third, point-like structures, such as bright stars, are attenuated by using a 5 pixels × 5 pixels median filter.
Figure 6 Elevation and azimuth angles fitted to an airglow image. Red contour lines show elevation angles, and red dashed lines show azimuth angles. The right and top sides of the image are south and west, respectively. The azimuth is set to 0 degrees northward and increases counterclockwise in an image.

The valid data acquired continuously for 2 hours which corresponds to 40 images were averaged (we call this averaged data $\bar{I}$) (Figure 7(a)). This process smooths the wave with non-zero horizontal phase speed. By this method, stationary AGWs with a horizontal scale below the FOV (horizontal wavelength $< 240$ km) can be detected.

Next, averaged counts at each elevation angle $\Phi$, are calculated from $\bar{I}$ to yield a count
profile, \( \bar{I}(\Phi) \), which is a function of \( \Phi \). \( \bar{I}(\Phi) \) was calculated for the range of \( 30^\circ < \Phi < 90^\circ \) for every 1 degree bin. The red line in figure 7(b) shows an example of \( \bar{I}(\Phi) \), and black plus symbols indicate \( \bar{I} \). By subtracting the corresponding \( \bar{I}(\Phi) \) from the \( \bar{I} \) for all pixels, azimuthally symmetrical effects, such as the van Rhijn effect and atmospheric extinction effects, were removed. Residual counts are axially unsymmetrical components in airglow image data. The amplitude of these residual components to \( \bar{I}(\Phi) \) is then calculated by \( 100 \times \frac{(\bar{I} - \bar{I}(\Phi))/{\bar{I}(\Phi)}}{\%} \) as show in Figure 7(c). We applied this procedure to identify and enhance the stationary and azimuthally non-symmetric structures, i.e., possible MW signatures, in airglow image data.
Figure 7 (a) Example image of ‘2h-averaged count’, $\bar{I}$. Equivalent counts in each pixel are plotted in (b) as a function of an elevation angle with black symbols. The red line shown in (b) is the ‘elevation angle averaged count’, $\bar{I}(\theta)$. (c) shows an amplitude of the residual components ($\bar{I} - \bar{I}(\Phi)$) to the $\bar{I}(\Phi)$.
3 Observation results

The total observation period was approximately 1 year and 8 months from May 2018 to December 2019. The observations were automatically conducted every night. The “observation time” simply means the time that the instruments were operated without system problems, and the “clear sky time” means the time over which the valid data (see 2-2) were obtained. The characteristics of these times over the entire observation period are summarized in Figure 8. If valid data were acquired over two hours, then airglow images were analyzed using the method described in Section 2-3. Table 2 shows the total number of observation days and days with a clear sky in every month.
Figure 8: The summary of observation time and clear sky time.

Table 2: Number of total observation days and days with clear sky (more than 2 hours) in each month.

| Month | 2018 | 2019 |
|-------|------|------|
| Jan   | 11   | 31   |
| Feb   | 28   | 2     |
| Mar   | 31   | 22   |
| Apr   | 23   | 11   |
| May   | 30   | 31   |
| Jun   | 31   | 30   |
| Jul   | 30   | 25   |
| Aug   | 31   | 25   |
| Sep   | 0    | 30   |
| Oct   | 7    | 31   |
| Nov   | 5    | 25   |
| Dec   | 8    | 30   |
| Total | 215  | 335  |

| Month        | 2018 | 2019 |
|--------------|------|------|
| Observation days |      |      |
| Clear sky days (more than 2 hr) |      |      |

We carefully analyzed all image data by applying the procedure outlined in Section 2-3.
and counted the number of events with a stationary wavy pattern (i.e., possible MW signatures). Figure 9 shows examples of the stationary wave events that continued for more than 2 hours. The stationary structures were detected only on the four days shown in the figure. This number of possible MW events is considered to be unexpectedly low despite the observation site being located in a region that appears to be well suited for observing MWs (i.e., on the leeward side of mountains that would be expected to propagate MWs into upper atmosphere).
Figure 9 Possible MW events detected by the OH airglow imager during the observation period.

In section 4, we consider the reasons for the low number of possible MW events detected by the airglow observations. Specifically, we focused on the relationship between wind conditions in the lower atmosphere and features of the local orography to explain the results.
4 Discussion

4-1 The frequency of MW events revealed by the airglow imaging observations

We used to expect that numerous MWs would be induced by the mountainous area located to the west of the observation site, and that these MWs would propagate to the upper mesosphere. However, only four possible MW events were identified from the airglow observations over a period of approximately 1 year and 8 months (from May 2018 to December 2019). Criddle et al. (2011) identified a total of 68 MW events (AGW with an apparent horizontal phase speed <5 m/s) by OH airglow imaging observations conducted at Cerro Pachon, Chile (30.2°S, 70.7°W), from August 2009 to August 2010. In that study, the MWs were detected mainly in July and it is considered that the MWs were induced by the westerly winds blowing over the Andes. Despite similarities in the observation sites, the detection frequency of MWs in their study (68 events / year) far outnumbered that in this study (4 events / 1 year and 8 months).

We consider that there are two possible reasons for the relatively low number of MWs observed in our study. First, fewer MWs are induced by the mountainous area around Mt. Fuji. Second, MWs may be induced by the mountainous area around Mt. Fuji, but
their propagation is impeded and they fail to reach the airglow layer due to the presence of a critical level and/or a turning level on ray-path. We focused on the former hypothesis as a possible explanation for our results in this issue. We therefore employed a simple proxy to explain the generation frequency of MWs in the mountainous area around Mt. Fuji in the next section.

4-2 Simple proxy to assess the frequency of MW excitation

When MWs are induced, wavy clouds such as those shown in Figure 10 are frequently generated on the leeward side of the mountainous area. Such clouds form when the winds in the lower atmosphere that are moving towards the orographic source contain sufficient water vapor to be saturated. These clouds have been frequently observed over Japan by the GMS-8 satellite (Bessho et al., 2016). However, if the atmosphere is dry, then there is a high possibility that wavy clouds will not appear, even if MWs are induced. Therefore, the absence of wavy clouds does not mean that MWs are not being induced. The formation of wavy clouds indicates that mountain-crossing airflow has occurred. Therefore, in this study, we assumed that MWs are induced whenever wavy
clouds were formed on the leeward side of the mountains (for example, see Figure 10).

In other words, we used the formation of wavy clouds as a proxy for the induction of MWs.

Figure 10 Wavy clouds detected over the Tohoku area, Japan at 3:00 UT on June 22, 2018 by GMS-8.

In this study, ‘wavy clouds’ are defined as a set of three or more clouds oriented in parallel rows that are generated in the vicinity of mountainous areas. We examined the generation frequency and the spatial distribution of these wavy clouds over Japan by
analyzing color images acquired by GMS-8 in 2018. In addition, the direction of the wave front and the distance between two adjacent clouds that make up a wavy cloud were calculated using the following procedure:

i) Divide image data for Japan (3301 pixels × 2701 pixels) into smaller images (300 pixels × 300 pixels, i.e., 300 km × 300 km) and check if there are wavy clouds in this area. When wavy clouds exist in a sub-image, further subdivide the image (100 pixels × 100 pixels, i.e., 100 km × 100 km) (Figure 11) and move to the next step.

Figure 11 Subdividing the original GMS-8 image into sub-images to isolate wavy clouds for deriving wavelength and wave front.
ii) Select two adjacent rows of clouds form a wavy cloud in a 100 pixels × 100 pixels image. Mark two points on along the centerline of each cloud and acquire the position of each point on the image (Figure 12(a)). The positive values of the \((x, y)\) coordinates in Figure 12 corresponds to the (east, north) directions, respectively.

iii) The equations for the two straight lines are derived from the position acquired in ii). The gradients of each line are defined as \(a_1\) and \(a_2\), and the mean value, \(\bar{a}\), of \(a_1\) and \(a_2\) is defined as the mean gradient of the two lines (Figure 12(b)).

iv) The equations of the two straight lines with gradients \(\bar{a}\) passing through the midpoint of the two points are derived for each cloud selected in iii). The midpoints are point \(M_1\) and point \(M_2\) in figure 12(b). Let the coordinates of point \(M_1\) and point \(M_2\) be \((x_1, y_1)\) and \((x_2, y_2)\), respectively. The Y-axis intercept \(b'_1\) of an equation is calculated by \(b'_1 = y_1 - \bar{a}x_1\). Similarly, \(b'_2\) is calculated. The distance between two cloud rows, i.e., the wavelength, \(\lambda\), and the direction of the wave front, \(\theta\), are obtained as shown in Figure 12(c). The difference between the Y-axis intercepts \(b'_1\) and \(b'_2\) of
the two straight lines is defined as $\Delta y$, and $\lambda$ is calculated by $\Delta y \cos \theta$. We assumed $\theta$ to be $0^\circ$ in the eastward direction and that it increases counterclockwise.

Figure 12. (a) and (b) show the calculation method of wavy cloud wavelength, $\lambda$, and wave front, $\theta$. (c) shows the definition of wavy cloud wavelength, $\lambda$, and wave front, $\theta$. 

$\bar{a} = \frac{a_1 + a_2}{2}$
Wavy clouds were typically stable and were continuously observed at the same location for several hours. Although the GMS-8 color image is acquired over 2.5 min, we analyzed the image data acquired every hour (taken at 9:00, 10:00, 11:00 …) to simplify the analysis. When wavy clouds were detected in the same area in successive images, it was considered that the image represented the same event. The number of days when wavy clouds were observed was counted for each sub-image (100 km × 100 km).

4-3 Frequency of wavy clouds over Japan

We analyzed GMS-8 color images acquired from January 2018 to December 2018 to detect wavy clouds over Japan. Figure 13(a) shows the occurrence frequency and spatial distribution of wavy clouds over Japan in this period. The color scale represents the number of days on which wavy clouds were observed. Wavy clouds were frequently observed over Hokkaido and the Tohoku region. Focusing on Tohoku region, the area with highest frequency of wavy clouds was 79 days/year (Figure 13(b)). In contrast, even over the highest area of the Kanto region, which is also within the FOV of our airglow imager, wavy clouds were detected only on 21 days/year. Furthermore, in most
areas around the Kanto region, wavy clouds were detected only on approximately 10 days/year (Figure 13(c)). The relatively low frequency of wavy clouds observed over the Kanto region is consistent with the low frequency of MWs revealed by our airglow observations. From these results, it is found that the occurrence frequency of wavy clouds differs markedly among regions, even though there are numerous mountainous areas throughout Japan.
Figure 13 Numbers of days with wavy clouds in 2018 (a) over Japan and surrounding area, (b) Tohoku region, and (c) Kanto region.

The MERRA-2 (MERRA-2 tavg3_3d_asm_Nv: 3d, 3-Hourly, Time-Averaged, Model-Level, Assimilation, Assimilated Meteorological Fields V5.12.4) reanalysis data (Gelaro et al., 2017), was used to calculate the wind velocity at an altitude of 1000 m at the center of each area and used as the background wind. The spatial resolution of the meteorological fields is 0.5° × 0.625°, and the time interval is 3 hours. We examined the
angle between the wave front direction and the background horizontal wind direction using this data set. Figure 14 shows the total occurrence frequency of the number of events with wavy clouds that was enumerated using this angle. The findings showed that more than 75% of wavy clouds had an angle $\geq 60^\circ$. The direction of the phase line of the wavy clouds was considered to reflect the orientation of the mountain ridgeline. Therefore, it was expected that MWs are frequently induced in regions where the angle between the direction of the background horizontal wind and the mountain ridgeline are $\geq 60^\circ$.

Figure 14 Distribution of the occurrence frequency of wavy cloud events enumerated based on the angle between the direction of the phase line of the wavy clouds and the background wind direction.
4-4 Relationship between topography and background wind in the lower atmosphere

The difference in the number of MWs generated each region is considered to be the result of the interaction between topography and the synoptic horizontal wind field in the lower layers of the atmosphere. We examined the relationship between topographical features and the horizontal wind field by using geographical elevation data and a meteorological reanalysis data. The details of each data type are described in this section.

First, we derived the elevation data by using PNG Elevation tile provided by Geospatial Information Authority of Japan (Figure 15(a)) (Nishioka and Nagatsu, 2015). The elevation value of each pixel is calculated from the pixel value using equations (1) as follows:

\[
X = 2^{16}R + 2^{8}G + B
\]

\[
\begin{align*}
H &= Xh_{\text{res}} & (X < 2^{23}) \\
H &= 0 & (X = 2^{23}) \\
H &= (X - 2^{24})h_{\text{res}} & (X > 2^{23})
\end{align*}
\]

where, \(R\), \(G\), and \(B\) are the color components of the pixel value of the elevation tile, 

\(h_{\text{res}}\) (\(= 0.01\) m) is the elevation resolution, and \(H\) is the elevation value. Figure 15(b)
shows the elevation converted from Figure 15(a). Then, mountain ridgelines were extracted from each tile using a median filter as described by Iwahashi (1994) to deduce the topographic features. The median filter is applied to the elevation data, and this is defined as $M$. The position where $H(x, y)$ is larger than the median $M(x, y)$ of the 3×3 surrounding pixels is the mountain ridge ( $(x, y)$ are the pixel coordinates of the image). Figure 15(c) shows the mountain ridgelines deduced from Figure 15(b). After smoothing fine structures less than 40 km, the elevation map of extracted ridgelines was divided into squares of 40 km × 40 km, referred to here as “square blocks”. If a mountain ridgeline exists in a square block, then the orientation of the mountain ridgeline, $\theta'$, was calculated as follows. Rotate the image counterclockwise by 1° increments from 0° to 180° and calculate the standard deviation of elevation values vertically in the square block, and then add the horizontal direction obtained for each 1° increment. Then, find the rotation angle (RA) which minimizes that value. When the RA of the image is $\leq 90°$, the orientation of mountain ridgeline, $\theta'$, can be calculated as $\theta' = 90° - RA$, and when RA is $> 90°$, $\theta' = 270° - RA$. The orientation of the mountain ridgeline is expressed as $0° \leq \theta' \leq 90°$ (Figure 15(d)).
Figure 15 Method for estimating elevation data. (a) ‘Elevation tile’ provided by Geospatial Information Authority of Japan, (b) elevation data calculated from the ‘elevation tile’, (c) mountain ridgeline extracted from (b) using the method of Iwahashi (1994), (d) enlarged view of the yellow inset in (c) and definition of the direction of the mountain ridgeline $\theta'$. We used MERRA-2 reanalysis data to examine the horizontal wind directions in the lower layer of the atmosphere. We adopted this wind field as a synoptic wind field. The wind velocity at an altitude of 1000 m at the center of each elevation tile was calculated
using this data. We defined the wind direction as 0° in the east and the angle increases counterclockwise.

The angles between the horizontal wind directions and the directions of the mountain ridgelines ($\theta'$) that were deduced using the above method were calculated for the entire world; we defined this angle as $\alpha$. As mentioned in Section 4-3, $60^\circ \leq \alpha \leq 90^\circ$ is considered to be favorable for inducing wavy clouds, i.e., over-mountain airflow, which is the primary source of MWs. Figure 16 shows the annual ratio, $P$ which satisfies the condition, $60^\circ \leq \alpha \leq 90^\circ$ around Japan. Wind data on 9:00, 12:00 and 15:00 were used on this calculation because we would like to compare with wave cloud occurrence frequency which is derived from GMS-8 color images acquired during day. The isolated data points surrounded by zero are omitted from this plot. These areas were highly consistent with the observed wavy cloud counts shown in Figure 13. High values were clearly observed in the Tohoku and Hokkaido regions, and low numbers were clearly observed around Kanto region.
Figure 16 Annual occurrence of the condition satisfying $60^\circ \leq \alpha \leq 90^\circ$. The annual occurrence ratio of the condition is represented out of 2920 wind data. This number indicates the ratio at which favorable conditions occur for the induction of wavy clouds.

Figure 16 is well consistent with the distribution of the occurrence frequency of wavy clouds. The simple proxy, $\alpha$ is considered to be a good measure for predicting MW hotspots around the world. We estimated the global distribution of $\alpha$ in the same
manner used to produce Figure 16 and present the results in Figure 17. Its range is between 70.6 °S and 70.6 °N and 180.0 °W and 180.0 °E. Importantly, it is noted that all 3-hour average wind data (8 wind data a day) are used in this calculation.

Colored plots were observed around the major mountainous areas around the world. For example, in the Andes and Antarctic Peninsula regions (surrounded by red circles in Figure 17), which are well known sources of MWs, numerous colored plots were shown. However, the findings showed that major mountain area are not ‘permanent’ hot spots of wavy clouds. The annual ratio of $60^\circ \leq \alpha \leq 90^\circ$ in those areas is about 25~50%.

In the high latitude and mid-latitude of the Northern Hemisphere, there are many spots with the ratio over 25 %. The 25% means that wavy clouds (MWs) will occur in these areas more than a season. In low latitude regions such as Mexico, the northern African, southern India and Southeast Asia, there are some hotspots with the ratio over 50%.

Importantly, this plot merely shows the distribution of potential wavy cloud hot spots, i.e., the locations at which the active induction of MWs by over-mountain airflow may occur. Thus, it will be important to confirm the actual frequency of MWs being propagated into the upper atmosphere in these areas by further observations.
Figure 17 Same as Figure 16, except that it shows the distribution of $\alpha$ at a global scale. The Andes Mountains and the Antarctic Peninsula are indicated by red circles.

The red star symbol in the Andes area shows the observation site of Criddle et al. (2011).

### 4-5 Comparison with model results

Sato et al. (2009) examined the origins of mesospheric gravity waves and the associated vertical flux of zonal momentum using a high-resolution global spectral climate model (KANTO model). Their model resolution was T213 (triangular truncation at wavenumber 213 corresponding to about 60 km) in the horizontal direction and 300 m
in the vertical direction. The horizontal wavelength resolved in this model is 188 km or 
more (Watanabe et al., 2008). The momentum flux is a good diagnostic tool for 
estimating the effects of gravity waves because it is conserved, unless wave generation 
and/or dissipation occur (Eliassen and Palm, 1961).

Comparing their results with our Figure 17 shows that the findings of the two studies 
are in good agreement in the Andes and the Antarctic Peninsula (red circles) where the 
effects of topographic gravity waves are dominant. On the other hand, Figure 17 also 
shows that there are numerous small-scale (~80 km) hot spots in the mid-latitude 
regions of the Northern Hemisphere. The effect of such small areas on the atmospheric 
circulation is difficult to estimate in model calculations due to the limitations imposed 
by the spatial resolution of most models. Although it has the characteristic that AGWs 
with short wavelengths are easily reflected (Tomikawa, 2015), we consider that the total 
effects from these small areas is likely larger than that estimated in the study of Sato et 
al. (2009). Therefore, it is considered that if the MWs that are induced in these small 
areas can propagate to the upper mesosphere, then the total contribution of small 
excitation sources on circulation in the middle atmosphere cannot be ignored. It is
therefore considered necessary to conduct observations in order to verify whether or not MWs excited by such small area can propagate to the upper mesosphere.
Summary and conclusion

Imaging observations of OH airglow were conducted at Meiji University, Japan (35.613 °N, 139.549 °E) from May 2018 to Dec 2019 to reveal the occurrence frequency of MWs induced by the mountainous areas around Mt. Fuji which are located to the west of the imager. Careful analysis was applied to deduce large stationary structures in the airglow images. However, unexpectedly, the detection frequency of MWs in our observations (4 events/1 year and 8 months) was surprisingly low relative to previous observations conducted near mountainous areas. To clarify this disparity, we examined the relationship between topography and horizontal wind fields using geographical elevation data and a model of meteorological fields.

First, we examined the occurrence frequency of wavy clouds that formed in the lower atmosphere around and over Japan by analyzing color image data obtained by the GMS-8 satellite. The results showed that wavy clouds formed in the leeward sides of mountain ridges and that the occurrence frequency of these clouds was high in northern regions of Japan and low in southern regions (including our observation site). Since this difference was considered to reflect the occurrence of over-mountain flow, which is a
prerequisite for MW induction in mountainous areas, we then attempted to elucidate the
underlying reasons for this spatial disparity. As a result, we developed a simple index,
\( \alpha \), which is the angle between the orientation of mountain ridgeline and the background
wind. This measure can be used as a measure of the occurrence frequency of MW in
each region and it was confirmed to be a good proxy for explaining the occurrence
frequency of wavy clouds. The condition \( \alpha > 60^\circ \) was found to be favorable for
induction of the wavy clouds near mountainous areas, and we also mapped the global
distribution of \( \alpha \). The results showed that areas with \( \alpha > 60^\circ \) were highly consistent with
areas with high momentum flux to the upper atmosphere, as suggested by both previous
observations and the GCM. In addition, it was also found that there are many small
areas that satisfy the condition \( \alpha > 60^\circ \) for more than a season in high latitude and mid-
latitude of the Northern Hemisphere. Even though each size of these areas was small,
integrated effect of waves generated in each of these small areas could possibly affect
circulation in the middle atmosphere. It is therefore considered necessary to verify
whether the MWs induced in these small areas can propagate to the middle atmosphere
or not.
As a next step, we are planning to expand the OH airglow imaging observations to the Tohoku region and/or Hokkaido where the high occurrence rate of excitation of MWs is expected to clarify the effects of small-scale topography on circulation in the middle atmosphere.
Figure 1 Location of the observation site (Meiji University, Kawasaki, Japan) (Geospatial Information Authority of Japan, 2020).

Figure 2 Optical components of the OH airglow imager.

Figure 3 Transparency characteristics of the interference filter. The wavelengths of Q-Branch and P-Branch in the OH (7-3) band are indicated by arrows above the image.

Figure 4 Projection of a georeferenced image acquired at 2:53 JST on January 18, 2019. This is the effective field of view of the OH airglow layer (85 km) in the imager at a typical altitude. The red star indicates the location of the observation site.

Figure 5 (a) shows a sample of valid image (clear sky), (b) and (c) show invalid image data with the moon and clouds, respectively.

Figure 6 Elevation and azimuth angles fitted to an airglow image. Red contour lines show elevation angles, and red dashed lines show azimuth angles. The right and top sides of the image are south and west, respectively. The azimuth is set to 0 degrees northward and increases counterclockwise in an image.

Figure 7 (a) Example image of ‘2h-averaged count’, $\bar{I}$. Equivalent counts in each pixel are plotted in (b) as a function of an elevation angle with black symbols. The red line
shown in (b) is the ‘elevation angle averaged count’, \( \bar{I}(\Phi) \). (c) shows an amplitude of the residual components \( \bar{I} - \bar{I}(\Phi) \) to the \( \bar{I}(\Phi) \).

Figure 8 The summary of observation time and clear sky time.

Figure 9 Possible MW events detected by the OH airglow imager during the observation period.

Figure 10 Wavy clouds detected over the Tohoku area, Japan at 3:00 UT on June 22, 2018 by GMS-8.

Figure 11 Subdividing the original GMS-8 image into sub-images to isolate wavy clouds for deriving wavelength and wave front.

Figure 12 (a) and (b) show the calculation method of wavy cloud wavelength, \( \lambda \), and wave front, \( \theta \). (c) shows the definition of wavy cloud wavelength, \( \lambda \), and wave front, \( \theta \).

Figure 13 Numbers of days with wavy clouds in 2018 (a) over Japan and surrounding area, (b) Tohoku region, and (c) Kanto region.

Figure 14 Distribution of the occurrence frequency of wavy cloud events enumerated.

Figure 15 Method for estimating elevation data. (a) ‘Elevation tile’ provided by Geospatial Information Authority of Japan, (b) elevation data calculated from the
‘elevation tile’, (c) mountain ridgeline extracted from (b) using the method of Iwahashi (1994), (d) enlarged view of the yellow inset in (c) and definition of the direction of the mountain ridgeline $\theta'$. 

Figure 16 Annual occurrence of the condition satisfying $60^\circ \leq \alpha \leq 90^\circ$. The annual occurrence ratio of the condition is represented out of 2920 wind data. This number indicates the ratio at which favorable conditions occur for the induction of wavy clouds. 

Figure 17 Same as Figure 16, except that it shows the distribution of $\alpha$ at a global scale. The Andes Mountains and the Antarctic Peninsula are indicated by red circles.

The red star symbol in the Andes area shows the observation site of Criddle et al. (2011).

Table 1 Specifications of the Clara CCD camera.

Table 2 Number of total observation days and days with clear sky (more than 2 hours) in each month.
580  **List of abbreviations**

581  AGW: Atmospheric gravity wave

582  FOV: Field of view

583  GCM: Global circulation model

584  GSM-8: The Himawari-8 geostationary meteorological satellite

585  MW: Mountain wave

586  SNR: Signal to noise ratio

587  **Ethics approval and consent to participate**

588  Not applicable.

589

590  **Consent for publication**

591  Not applicable.

592

593  **Availability of data and materials**

594  Please contact H. Suzuki (suzuhide@meiji.ac.jp) if you would like to use the OH

595  airglow image data of Meiji University (35.613 °N, 139.549 °E) from May 2018 to
December 2019. Himawari-8 meteorological satellite visible light observation data are from “https://sc-nc-web.nict.go.jp/wsdb_osndisk/shareDirDownload/03ZzRnKS”.

Reanalysis data MERRA-2 can be accessed at https://disc.sci.gsfc.nasa.gov/datasets/M2T3NVASM_5.12.4/summary?keywords=%22MERRA-2%22 (10.5067/SUOQESM06LPK). The PNG format elevation data are from “https://cyberjapandata.gsi.go.jp/xyz/demgm_png/{z}/{x}/{y}.png”. In this URL, z is zoom level, x and y are tile coordinate, and they are defined by Geospatial Information Authority of Japan.

Competing interests

We have no competing interests.

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Authors' contributions

SI operated OH airglow imager at Ikuta on site and, led data analysis, and wrote the first draft of manuscript. MO designed and installed the OH airglow imager. SI, MO and HS (corr-auth) discussed analysis method of OH airglow image data. SI, HS and YT discussed the method of the estimation of mountain wave hotspots. All authors contributed improving the manuscript. All authors have read and approved the final manuscript.

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The present affiliation of MO is NTT FACILITIES, INC., Tokyo, Japan.
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