URSI GASS 2023, Sapporo, Japan, 19 – 26 August 2023

Momentum Flux Characteristics and Intermittency of Gravity Waves over Northern Norway using MAARSY

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Abstract

In the present study, we analyzed the wind measurements in the troposphere and lower stratosphere over Andøya in northern Norway (69.30°N, 16.04°E) with the Middle Atmosphere Alomar Radar System (MAARSY) from 2017 to 2020. We calculated the momentum flux and vertical wind power spectra using the fast Fourier transformation (FFT) analysis technique. The spectra are characterized into different regions based on: frequency (lower and higher than $(13\ \mathrm{h})^{-1}$, since the local inertial period over Andøya is 13 h), altitudes (lower troposphere, middle troposphere, tropopause region, and lower stratosphere), and seasons (spring, summer, autumn, and winter). We report for the first time that both the momentum flux spectra and vertical wind power spectra display a seasonal and altitudinal variation with the minimum in summer and the maximum magnitude in the troposphere. We also studied the intermittency of the waves during this period using the Gini coefficient over Northern Norway for the first time, which is used to distinguish the intermittent wave periodicities from the non-intermittent ones. We reveal that the high-frequency (short-period oscillations) gravity waves are more intermittent than the low-frequency (long-period oscillations). Additionally, the most intermittent waves are located in the lower stratospheric altitudes for low-frequency waves, while the high-frequency waves are dominantly intermittent in the whole altitude region with small patches of lower intermittency region.

1 Introduction

The temperature and wind fluctuations, apparent in the weather systems as low- and high-pressure regions in the mid-latitudes, are linked with the baroclinic instability of the mean zonal winds stretching a few thousand kilometers in the horizontal scale and are frequently allocated at synoptic scales [1]. Atmospheric gravity waves (GWs), with periodicities of a few minutes to several hours, are generated through numerous sources like topography, wind shear, convection, etc. The exponential decline of the atmospheric density causes the amplitude of the upward propagating GWs to increase (to conserve energy) and finally break depositing their energy and momentum into the surrounding atmosphere (typically in the mesosphere and at the tropopause altitudes) [2]. It is important to study the momentum flux associated with the breaking of GWs, as it acts as the primary driving mechanism responsible for the summer-to-winter polar circulation along with the thermal structure of the atmosphere [3].

The foremost difference between the waves and the 2-D turbulence is that the wave transport momentum and energy in space, not the 2-D turbulence. Generally, the waves and turbulence are explored in terms of wavenumber (horizontal and vertical) or frequency spectra. The dispersion relation connects the wave frequency to the background atmosphere and the spatial characteristics of the wave (wavenumbers). The vertical wavenumber (m) and frequency (ω) spectra are more appropriate for single-station observations (e.g., radar, lidar, and radiosonde), while the horizontal wavenumber (k and l) spectra are beneficial only for data with global coverage (e.g., model simulations and reanalysis dataset). Not many studies have dealt with the frequency spectra in the troposphere and lower stratosphere [4].

The intermittency of GWs is caused by the sources' activity and their propagation properties eventually filtered by the ambient medium. Consequently, the intermittency of GWs influences global atmospheric circulation [5]. The Gini coefficient is a distinguished parameter to quantify the inequality of income in economics [6]. In more recent years, it was adopted by [7] as a parameter to measure the intermittency of GWs. One of the main advantages of the Gini coefficient is that it comprises integration and thus, it is not too sensitive to the sampling of the dataset along with no requirement of an arbitrary percentile choice. The Gini coefficient ranges between 0 to 1. The Gini coefficient of ‘0’ indicates the less intermittent GWs with a perfectly even distribution, where all wave packets transport an equal amount of momentum flux (MF) and ‘1’ specifies the most intermittent GWs with a seamless uneven one, where a single wave packet transports all the observed MF.

In the present study, we illustrate statistically the frequency momentum flux and variance in the vertical wind spectra, covering the troposphere and lower stratosphere region (1.80-18.00 km), using four consecutive years of high-resolution three-dimensional wind measurements observed at a high latitude in the Northern hemisphere. We also inspect the intermittency of the GWs by calculating the Gini coefficient. As we are considering measurements with high temporal resolution over an extensive time window, the Doppler shift due to the background winds is treated as negligible.

2 Data and Methodology

We investigated the wind observations from the Middle Atmosphere Alomar Radar System (MAARSY), situated in Andøya, Norway (69.30°N, 16.04°E). MAARSY is a ‘monostatic radar’ sounding at the frequency of 53.5 MHz with maximum peak power of ~866 kW. It comprises an ‘active phased array’ with 433 individual circularly polarized ‘Yagi antennas’ and an identical number of transceiver modules with individual phase control and a scalable power output of up to 2 kW. MAARSY main antenna array has almost circular layout leading to a ‘symmetric radiation pattern’ with a ‘half-power full beam-width’ of 3.6°(~630 m at the height of 10 km). Comprehensive description of MAARSY is given in [8, 9].

For our analysis, we have utilized the winds for the duration of 2017-2020 (48 months) in the altitude range of 1.80-18.00 km (covering the troposphere and lower stratosphere) with a vertical resolution of 300 m throughout, and a temporal resolution of 15 min. The wind measurements from the first 28 days of each month are divided into four ‘7-day-wide’ windows. The data gaps shorter than 10 hours are filled using a sturdy statistical technique with a moving median. The zonal (meridional) momentum flux (MF) spectra in each of the ‘7-day windows’ are estimated by multiplying the FFT of the zonal (meridional) and vertical wind (as shown in Equation 1). It is performed at every altitude after employing a Hanning window to stop the ‘spectral tails’ of the low-frequency fluctuations from affecting the much weaker high-frequency spectral region. The vertical wind power spectra (VWP) are the squared product of the Fourier components of vertical wind.

$$MF = \mathcal{F}(u) \times \mathcal{F}(w) \tag{1}$$

The MF derived using Equation 1 is averaged across the four ‘7-day windows’ leading to the monthly averaged MF. It is to be noted that the ‘missing data’ fragments lengthier than 10 hours are omitted from the monthly averages. To study the altitudinal variation, the monthly MF is averaged for four altitude ranges, i.e., 1.80-4.20 km (lower troposphere), 4.20-6.00 km (middle troposphere), 7.20-12.00 km (tropopause), and 12.00-18.00 km (lower stratosphere). The intermittency of the GWs is studied using a parameter called ‘Gini coefficient’. It is obtained from the absolute MF data multiplied by the density from the MERRA reanalysis data (later referred as absolute MF), using the formula given in Equation 2 [7], without splitting the monthly winds data. The Gini coefficient is calculated for every month.

$$I_g = \frac{\sum_{n=1}^{N-1}(n\bar{f} - F_n)}{\sum_{n=1}^{N-1} n\bar{f}} \tag{2}$$

where N is number of samples, f ($1<i<N$) is momentum flux sorted in ascending order , F_N is cumulative sum of samples ($F_n = \sum_{i=1}^{n} f_i$), $\bar{f}$ is the mean value (F_N/N).

3 Results

We divided the zonal and meridional MF spectra into two frequency ranges: high- (<13h) and low- (>13h) frequency ranges based on the local inertial frequency ~(13 h)$^{-1}$ over Andøya. The spectra are additionally characterized into four seasons: summer (JJA: June, July, August), autumn (SON: September, October, November), winter (DJF: December, January, February), and spring (MAM: March, April, May). The height profile of zonal and meridional MF spectra is displayed in Figure 1. The zonal and meridional MFs show maximum variation in the troposphere (1.80-7.20 km). The solid lines demonstrate the median values and the dotted lines on the left and right of the median show the 25th and 75th quartiles (in Figure 1). It is observed that the MF maximizes in the troposphere (around 1.80-8.00 km) and the magnitude decreases as the altitude increases. The variability of the MF decreases with the increasing altitude and the variation of MF is higher for 2 hr to 13 hr than 30 min to 2 hr. Additionally, the MF reduces above 12 km for 2-13 hr, indicating that the GWs could not propagate easily above 10 km altitude. The zonal MF is largely westward (i.e. negative) in the whole altitude range of 1.80-18.00 km. In the lower troposphere (below 7.00 km), the meridional MF is largely northward (i.e. positive) except for the autumn and above 7.00 km, it becomes southward (i.e. negative). Moreover, the MF displays a seasonal variation with the minimum during summer months. It is perceived that the variation is lesser in the lower stratosphere than in the lower troposphere.

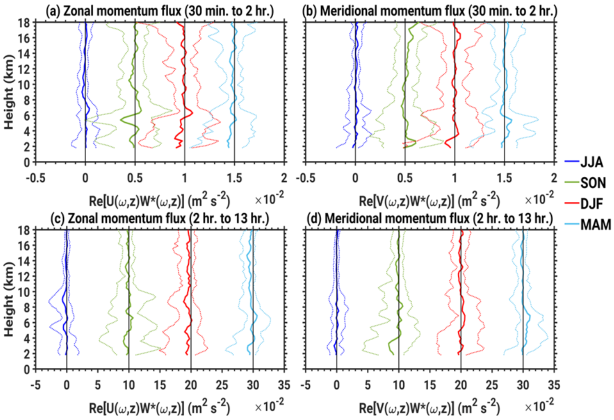

Figure 1. Height profile of zonal (a, c) and meridional (b, d) momentum flux spectra for 30 min to 2 h and 2 h to 13 h. Blue, green, red, and cyan colors indicate summer (June, July, August: JJA), autumn (September, October, November: SON), winter (December, January, February: DJF), and spring (March, April, May: MAM) months. The profiles for SON, DJF, and MAM are shifted by 0.005 (a, b) and 0.1 (c, d) m^{2}s^{-2}.

The height profile of vertical wind power spectra (VWP) is presented in Figure 2, which also demonstrates altitudinal variation like MF spectra with maximum magnitude in the troposphere at the altitudes of ~1.80-10.00 km, the increase of magnitude with the increasing period. The VWP is minimum during the summer (JJA) months than the rest of the seasons. The magnitude of VWP is ~0.001-0.005 $m^{-2}s^{-2}$ for 30 min to 2 hr, ~0.03-0.05 $m^{-2}s^{-2}$ for 2 hr to 13 hr, ~0.20-0.40 $m^{-2}s^{-2}$ for 13 hr to 1 day, and ~0.50- 0.80 $m^{-2}s^{-2}$ for above 1 day oscillations. The peak detected in the height profile of VWP ~2-3 km is not considered for further interpretation as the peak and the values below appear erroneous.

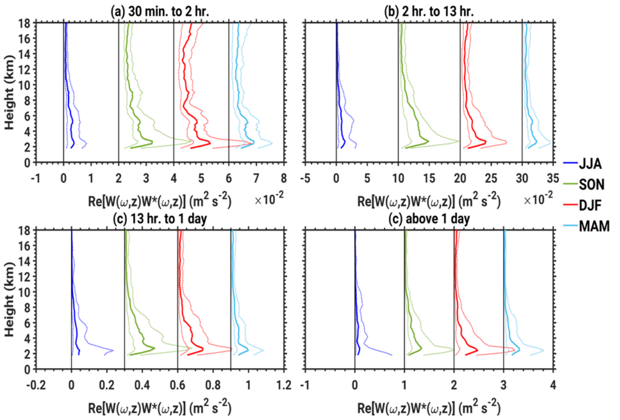

Figure 2. Height profile of vertical wind power spectra for the different periods. The seasons are plotted with different colors as shown in Figure 2. The profiles for SON, DJF, and MAM are shifted by 0.02 m^2s^{-2} (a), 0.1 m^2s^{-2} (b), 0.3 m^2s^{-2} (c), and 1 m^2s^{-2} (d).

The monthly height profile absolute MF for various periods during 2017 shows that the absolute MF is larger during January-May and August-December for all the periods, although the magnitude is larger for 30 min to 1 day (Figure 3). The maximum MF is observed during January-March and September-December at altitudes of 1.80-10.00 km. The absolute MF is comparatively lesser in the summer months. Furthermore, it is seen that the absolute MF shows a peak around 5.00-9.00 km altitude.

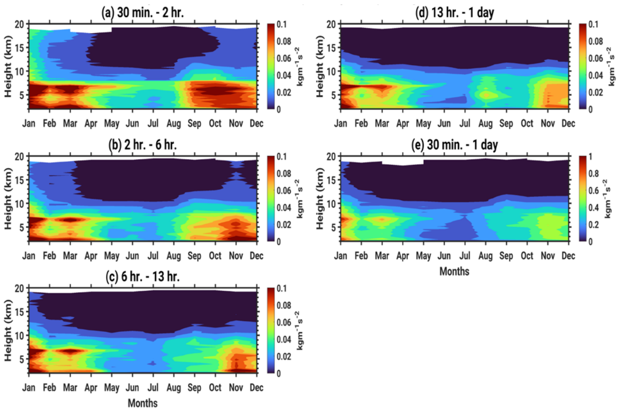

Figure 3. Height versus profile of absolute momentum flux multiplied with density for different periods (a) 30 min to 2 hr, (b) 2 hr to 6 hr, (c) 6 hr to 13 hr, (d) 13 hr to 1 day, and (e) 30 min to 1 day during 2017 over Andøya.

Figure 4 depicts the height profile of the Gini coefficient of absolute MF data for different periods during 2017. It is observed that the Gini coefficient for all the periods ranges between 0.30-0.50. The Gini coefficient values are higher for 30 min to 2 hr and 2 hr to 6 hr, where the values are mostly around 0.45-0.50 at the lower tropospheric and lower stratospheric altitudes. It is also perceived that the maximum Gini coefficient values are in the lower tropospheric altitudes of 5.00-9.00 km. The Gini coefficient comparatively decreases in the lower troposphere for the periods of 6 hr to 13 hr and 13 hr 1 day and it ranges between 0.30-0.40, while the values are around 0.45-0.50 in the lower stratosphere. In the case of 30 min to 1 day, covering all the other periods, it is visible that the magnitudes of the Gini coefficient are comparatively smaller in the middle troposphere (around 0.30-0.35) than in the lower troposphere and stratosphere.

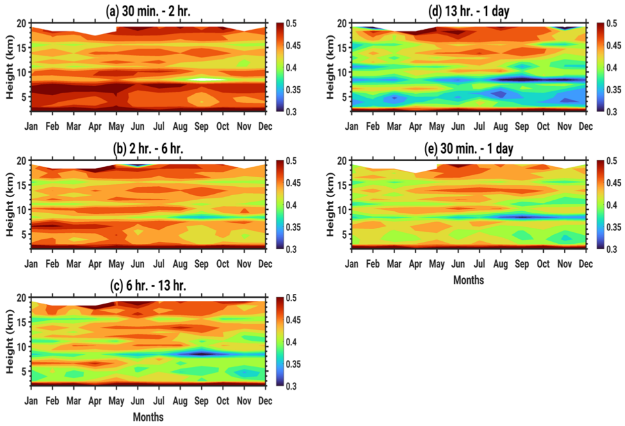

Figure 4. Height versus profile of Gini coefficient calculated for absolute momentum flux multiplied with density for different periods (a) 30 min to 2 hr, (b) 2 hr to 6 hr, (c) 6 hr to 13 hr, (d) 13 hr to 1 day, and (e) 30 min to 1 day during 2017 over Andøya.

4 Discussion and Summary

We studied the statistical characteristics of momentum flux (MF) and variance in the vertical wind power spectra (VWP) in the altitude region of 1.80-18.00 km (covering the troposphere and lower stratosphere) using MAARSY. The MF spectra spread over a wide range of $(1h)^{-1}$ to $(3.5d)^{-1}$, which are mainly categorized into high-frequency ($<(13h)^{-1}$) and low-frequency ($>(13h)^{-1}$) components. The frequency MF and VWP are further classified for altitude and seasons to probe the troposphere and lower stratospheric region in detail. To understand the intermittent nature of the waves over Andøya, we also studied the absolute MFs and calculated their Gini coefficients. The important results obtained from the present study are as follows:

a. *Frequency-based distinction:* The MF and VWP depict frequency dependence, where the magnitude increases from the high-frequency to the low-frequency oscillations. The absolute MF depicts higher magnitude for the high-frequency (30 min to 2 hr > 2 hr to 6 hr >

6 hr to 13 hr) oscillations than the low-frequency ones (13 hr to 1 day). The Gini coefficient also shows a dependence on frequency, where maximum Gini coefficient values of 0.45-0.50 are observed for 30 min to 2 hr and 2 hr to 6 hr throughout 1.80-18.00 km, while the Gini coefficient values are around 0.30-0.40 for 6 hr to 13 hr, 13 hr to 1 day and 30 min to 1 day. Hence, it can be said that the most intermittent GWs have periodicities below 6 hr over Andøya.

b. *Altitudinal variation*: The altitudinal variation is also visible in the MF and VWP spectra with a maximum variation of magnitude in the troposphere at the altitudes of 1.80-10.00 km. Above ~10.00 km, the variation of magnitude drastically decreases, which could be due to the presence of the tropopause at that altitude region in Andøya. The presence of tropopause is marked by the baroclinic instability region [10] leading to the breaking of most of the tropospheric GWs. The absolute MF is higher in the lower troposphere (~1.80-10.00 km) than in the lower stratosphere. The corresponding Gini coefficient shows more magnitude (more intermittent) in both the troposphere and lower stratosphere for the high-frequency oscillations, whereas the magnitude in the middle troposphere decreases for the low-frequency oscillations (less intermittent).

c. *Seasonal variation*: The MF and VWP demonstrate, for the first time, clear seasonal variation with a steeper slope during summer than during the other seasons. This variation is attributed to the seasonal variation of background horizontal wind intensity. The study by [9] reveals that the zonal wind is around 15–20 ms^{-1} above ∼4 km, while the eastward zonal winds are around 0-5 ms^{-1} during summer. The meridional wind at the MAARSY site is typically southward above ∼7 km during January–June (∼8–10 ms^{-1}) and October–December (∼5 ms^{-1}), while it becomes weaker (∼0–8 ms^{-1}) during the months of June–September [10]. Therefore, it can be presumed that the weak horizontal winds affect the seasonal variation during summer [10]. The absolute MF depicts seasonal variation with the minimum magnitude during the summer months typically starting around May and continuing until mid-August. Although the Gini coefficient of absolute MF does not demonstrate a clear seasonal variation, it can be seen that the Gini values have more magnitude (more intermittent) during summer at the lower altitudes (1.80-3.00 km).

Overall, the present study provides in-depth statistical characteristics of the frequency MF and VWP spectra for both the horizontal and vertical winds in the troposphere and lower stratosphere region during 2017-2020 using MAARSY located at Andøya, Norway (69.30°N, 16.04°E). Additionally, this is the first study to characterize the intermittent nature of waves over Andøya.

Acknowledgements

P.G. would like to thank the scientists and technicians of IAP for successful operation and maintenance of MAARSY. P.G. duly acknowledges the MERRA team for providing reanalysis data accessed at doi:10.5067/HO9OVZWF3KW2.

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