Infrasonic observation of microbarom signals in the middle latitude: An investigation of summer and winter season on the upper atmosphere

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Abstract. We report the result of infrasound observation applied to microbaroms between peak winter and summer season of 2018, obtained from ambient noise. For our study several infrasound sensor over Shikoku island was used, which had been installed since 2015. Observation of our microbaroms shows regular pressure variations of a few milliPascals at around 0.2 Hz produced by the incoming of infrasound arrived from the ocean fields. As the result, their amplitudes show prominent greatly in winter time except to depend on the appearance of the atmospheric sound ducts between the surface and the level at certain altitudes. These ducts depend on the wind structure and vertical temperature of the atmosphere. For our station close to the ocean, sound ducting from the oscillation wave of the ocean surface, requires strong contribution westerly winds at certain upper reflection point. With a global reanalysis horizontal wind assimilation, the seasonal wind structure at our geographical study, near 33° N, is shown to distinguish and to account for the observed profiles of microbaroms. Finally, we suggest that use of our network of infrasound sensors would provide a global complementary result to monitor the upper atmosphere conditions in the middle latitude regions.

1. Introduction

It has been known that the waves with frequencies below the human hearing threshold, which is in the sub-audible range, so called infrasound. This waves propagates and can be detected over large distances of hundreds to thousands of kilometers and is subject to only low atmospheric attenuations and because of refraction from the lower-upper atmospheres. Its sources are suitable coming from a wide variety of natural sources e.g. earthquakes, volcanic eruptions, ocean waves like microbaroms, or severe weather, but also from man-made sources such as rocket engine burst, explosions, etc ([1, Ch. 6] for list of infrasonic sources). Many experiments using ground-based microbarometers and infrasonic arrays has been used to investigate the atmospheric structure by infrasound from various man-made and natural sources [2, 3, 4, 5].

It has been reported that the propagation and detectability of infrasound is strongly affected by the upper atmospheric temperature and wind, which the effective sound speed is a function of both atmospheric parameters. Many properties of the atmospheric state such as temperature, pressure, and density are well understood or well modelled in the upper atmosphere. However, a critical property, wind state, is poorly understood because it varies considerably across time
and space and because of a lack of direct measurements. The observed pattern of infrasound signal characteristics are the consequence of the local wind profiles up to the lower thermosphere. Therefore, the monitoring of infrasound arrival signals give advantage information that can be used to understanding the wind structure in the stratosphere and lower thermosphere.

Over the past decades, there have been many advances in evolving to measure winds of upper atmospheric regions directly by a number of measurement campaigns involve sensors on satellites. Instruments that measure wind in the upper atmosphere between approximately 25 and 110 km, include the Thermosphere Ionosphere Mesosphere Energetics and Dynamics-TIMED Doppler Interferometer (TIDI) instrument onboard the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) satellite [6] and the Wind Imaging Interferometer (WINDII) [7] as well as the High Resolution Doppler Imager (HRDI) instrument onboard the Upper Atmosphere Research Satellite (UARS) of NASA [8]. Other ground-based observation such as radar [9, 10], lidar [11], high-level balloons for altitudes below 80 km [12] and the use of meteorological sounding rockets [13] also provide valuable measurements.

In spite of this fact that the actual atmospheric measurement database above the lower atmosphere are still remain sparse and such facilities are require a large expense to build and operate, limited to regions of space and time. Therefore, in order to further understanding this region of the atmosphere, it is need comprehensive observation based on the specifications of the wind structure in the MLT combined with the global empirical atmosphere model such as the second version of Modern-Era Retrospective analysis for Research and Applications (MERRA-2) and all available indirect atmospheric measurements. This empirical model is the current atmospheric reanalysis of NASA that replace the original MERRA reanalysis [14] using an upgraded version of Goddard Earth Observing System-5 (GEOS-5) data assimilation system and includes updates to the model with 3-hourly output extending up to 0.01 hPa [15, 16] and to the Global Statistical Interpolation (GSI) analysis scheme. MERRA-2 can assimilate the upper atmosphere and lower mesosphere (USLM) observations from the newer Microwave Limb Sounder (MLS) onboard the Aura satellite in the scheme of the Three-dimensional Variational (3DVAR, [17]). A detailed description of the MERRA-2 reanalysis was recently reported in [18]. An indirect method for observing wind variations in the atmosphere, which involves recording continuously generated infrasonic waves with short periods, as called microbaroms, which result from the nonlinear interaction of oceanic waves and are almost continuously present at a frequency of 0.2 Hz [19, 20] and become more and more in rich for atmospheric remote sensing [2, 21, 22, 23].

The detection of microbaroms arrival signals by an infrasound array will be dependent on wind structure in the upper atmosphere and thermospheric refraction [22, 24]. With refer to the infrasound propagation, the lower thermosphere forms the upper region of an acoustic duct because of its steep thermal gradient. The stratosphere becomes a suitable duct for ground-to-ground propagation, if the jet stream of this region is strong enough. In the study reported by [2, 25], the fluctuations of wind due to solar migrating tides cause sound refraction and ducting in the thermosphere to change along with tides. This reflects that observations of thermospheric infrasound arrival are affected to the atmospheric tides. In this paper, the detection of infrasound by means of microbaroms variation in relation to fluctuation of thermospheric horizontal wind is discussed.

The structure of the paper is as follows: in section 2 we describe measurement with an approaching method for this study by using the infrasonic signals recorded over Shikoku island, Japan. The microbarom arrivals retrieved from the recorded infrasound signals in different season, summer and winter are analyzed and discussed in section 3. The last section summarizes for our findings.
2. Measurements
Since 2005, KUT collaborated with several local institutions to take the initiative to build an infrasound sensor that is integrated with several MEMS (Micro-Electro-Mechanic System) sensors in order to measure 3-axis acceleration in seismic waves, atmosphere temperature, atmospheric pressure and the level of audible noise sound. Apart from that, the sensor system is also equipped with a signal processing unit for continuous processing in real time and network connecting ports for data acquisition [26].

Currently, a total of 20 infrasound sensors are distributed uniformly over the Japanese islands and continuously operated. The Japanese infrasound station network is shown in Figure 1, where the network is denser on Shikoku Island Figure 1(b) for the detection of natural disasters, such as tsunamis and volcanic eruptions.

![Figure 1. The locations of infrasound sensors (type: ADXII-INF01) in Japan. (a) Distribution of sensor location over Japan; (b) Infrasound sensor location over Shikoku island, Japan.](image)

All data recorded by the sensors are sent via the File Transfer Protocol (FTP) to the database server where they are archived, and are also displayed online at [http://infrasound.mydns.jp/](http://infrasound.mydns.jp/). Routine analysis of the combined data from several stations/sensors provides an advantage in determining the sources of infrasonic waves.

In order to investigate any systematic variations of microbaroms, measurements were made to determine their periodically amplitude variations for several time of recordings. We select the month of February for cold condition and the month of August for the warm condition as reported by the Japan Meteorological Agency (JMA) shown in table 1.

In the first step of processing, All the day during the target of the observation month are investigated for microbarom arrival signals recorded over infrasound stations in Shikoku island. Next, the evaluated data were then band-pass filtered in order to ensure an accurate and nonaliased slowness estimate and to eliminate pressure fluctuations affected by the wind and other sources with frequencies outrange of the microbarom band. The filter is used a second-order Butterworth with frequency range between 0.1 and 0.5 Hz. For the initial identification of strato-thermosphere reflection, the output of filtered data are then plotted in each 24-h recording partially a few minute of each 30 min separation in order to examine the typical semi-diurnal amplitude variations. For our analysis, we used our scheme in order to estimate the wind in the atmosphere using celerity and azimuth estimated from our beam-forming algorithm. The basic idea of our approach was to use the set of delays between signals to steer the array to different
Table 1. Statistic of monthly mean temperatures over Shikoku island, Japan in 2018 (source: www.data.jma.go.jp).

**KOCHI WMO Station ID: 47893 Lat 33°34.0′N Lon 133°32.9′E**

**Monthly mean air temperature (°C)**

| Year | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Annual |
|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|--------|
| 2018 | 5.4 | 5.8 | 12.9| 17.3| 20.1| 23.4| 28  | 28.6| 24.5| 19.2| 14.1| 9.9 | 17.4   |

**Monthly mean daily maximum temperature (°C)**

| Year | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Annual |
|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|--------|
| 2018 | 10.9| 11.2| 18  | 22.4| 24.4| 27.8| 31.7| 32.8| 28.6| 24.4| 19.8| 14.4| 22.2   |

**Monthly mean daily minimum temperature (°C)**

| Year | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Annual |
|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|--------|
| 2018 | 0.9 | 1.2 | 7.5 | 12.2| 16  | 19.9| 25.1| 25.2| 21.5| 14.9| 9.3 | 6.1 | 13.3   |

areas or points in a scanning region. When the steering direction coincides with a source, the maximum output power will be observed.

**Figure 2.** Schematic illustrating the steps in our approach to determine the arrival direction and propagation speed of the incoming signal’s source.
In more detail, each signal was filtered individually using different frequency bands based on the results of the previously estimated Power Spectral Density (PSD). Then, as shown in Figure 2, further processing of each group of signals was performed via several operations. First, to examine signal coherency and further minimize the effects of discontinuity between the end and the starting point of the time series, a set of time shifts between sensors and a cosine taper were applied. Second, we directed the rotation scanning to a specific point by using a set of time shifts. Finally, the peak coherence was calculated to identify the signal source. In this step, we applied cosine-tapered windows of 120 s duration with 90% overlap in the spectral processing of each sensor, and determined the covariance of the signals at different stations. The window length was chosen to be proportional to the envelope width of the signals.

3. Approaching Technique for the Vertical Profiles of Wind Velocity
This section will show how the infrasound propagate in our atmosphere. It has been known that the detectability of infrasound strongly depends on the stratospheric winds and temperature. As infrasonic signals where less attenuation are typically refracted upwards as they propagate away from the source, due to decreasing temperature in the atmosphere. And, partially refracted back down to the ground from altitudes at which the sound speed is at least the sound speed on the ground. At most latitudes, the temperature at the stratopause, and thus the sound speed, is less than the sound speed on the ground so that the temperature increase in the upper stratosphere is not sufficient to return back the sound to the ground. However, there is generally a strong wind at the height of the atmosphere. An acoustic signal at some distance located at a position R1, $\theta_0$ is the angle of reflection and the angle of incidence of a sound ray on the lower level of the atmosphere layer $z_0$, as a function of vertical profile of the effective refractive index (see figure 3). The effective refractive index fluctuates in the atmosphere at altitude between $z = z_0$ and $z = z_H$.

![Figure 3. Schematic of wave reflection from the atmospheric layer (h = $[Z_0, Z_H]$). R1 and R2 are the location point of infrasound source and sensor, respectively, and $\theta^o$ is the angle for both reflection and incident wave.](image)

4. Mid-Latitude Winds structure in the upper atmosphere
The wind in the altitude of the upper atmosphere is eventually modulated by variation of tidal components. Higher altitude, nonlinear contribution influences from long waves also become
another important role of the variations. These structure should be known in order to understand their contribution to the sound reflections.

4.1. Seasonal Wind
The monthly variation of the zonal wind in middle latitudes shown in figure 4. The seasonal reversal changing of the zonal wind in the atmosphere is the most obvious behavior, appear between 10 and 30 km. As a consequence of the stratospheric cold phase at high latitude atmosphere during winter time cause the strong west jet stream of the stratosphere. At higher altitude, between 40 and 80 km, easterly winds are most dominant in the second to third quarter of the year, mostly high in summer. This behavior view of the wind in the atmosphere will be used later in this study for our analysis.

![Figure 4. Monthly variation of the zonal wind speed in middle latitudes.](image)

4.2. Diurnal Wind
Diurnal (daily) variation of wind is largely a thermally-induced oscillation caused by continuously heating and cooling of surface in the lower levels (e.g. troposphere) from direct absorption of insolation and by ozone absorption in the stratosphere and lower mesosphere. These major features observed at these levels as a response to absorption solar energy by water vapor and ozone become important. At middle latitudes, the absorption of ozone becomes important and leads to trapped modes that decay exponentially with increasing height.

Figure 5 and 6 show diurnal zonal wind at infrasound station KCZ07 (33° N) during a particular sample observation 20-21 February 2018 and 27-27 August 2018. The level layer in figure 6 express the altitude in the range between 150 m to 76 km. The vector represent direction toward which horizontal wind in moving. Strongest westerly winds can be seen in the altitude of isotherm layer around 12 km after consistently increase with smooth gradient from the surface during the period of 20-21 February 2018 (see figure 5(a)- 5(b) and 6(a)- 6(b)). Oppositely season, the summer, strongest wind flows appear in the altitude of 45 km during the period of 27-28 August 2018 (see figure 5(c)- 5(d) and 6(c)- 6(d)), with reversing flow and not as strong as in the winter. In the altitude below 10 km, the flow pattern does not show extreme
variation. At altitudes above 40 km in both seasons, the pattern is seen widely variate. The absorption of solar heat radiation by ozone and water evaporation due to surface heating shows a role contributing to variations in the vertical structure of the atmosphere.

![Diurnal variation of amplitude of zonal wind component at 33° N.](a)

![Diurnal variation of amplitude of zonal wind component at 33° N.](b)

![Diurnal variation of amplitude of zonal wind component at 33° N.](c)

![Diurnal variation of amplitude of zonal wind component at 33° N.](d)

**Figure 5.** Diurnal variation of amplitude of zonal wind component at 33° N.
Although, recently, less number observations of upper atmospheric wind are available, the wind model of MERRA-2 compiled from advances observations with theoretical and empirical sources could be used to evaluated the wind structure to the sound propagation. The variability of the microbaroms maximum may thus be related to the variability of winds in the atmosphere.

5. Mid-Latitude Temperature Profiles in the upper atmosphere

The reanalysis of MERRA-2 provide meteorological information on atmospheric structure by seasons with diurnal variation. Figure 7 shows winter and summer mid-latitude (at near 33° N) vertical temperature below 80 km, are generated from the model. The profiles in winter and summer begin with surface temperature of around 275 K and 300 K, respectively, and contain isothermal layers: in winter, 205 to 230 K at 15 to 20 km and 270 to 275 K at 47 to 50 km; in summer, the temperatures, 190 to 200 K at 15 to 20 km and around 260 K at 47 to 50 km. This typical of a particular mid-latitude and season atmospheric temperature structure, the relative humidity has a contribution for the winter and summer. In the low altitude, below 10 km, a change with height larger than that in winter is depicted, reflecting the warm summer surface temperature with resulting lower relative humidity.

Referring to Figures 4 - 6, the zonal wind structure components in the atmosphere play a role in the infrasound wave propagation, specifically the microbarom. The vertical profile of atmospheric temperature has two vertical temperature gradient types, where generally the negative gradient allows the sound waves easier to propagate vertically until they reach a height where the wave strength is lost due to absorption by characteristic composer of the layer and deflected at the refraction point by the horizontal wind components is at least is still enough in ducting layers.

As the horizontal wind component profile shown in figures 5 and 6, strong wind flow can tend to form a ducting layer in the atmosphere. In winter, the ducting layer is formed at an altitude between 15 to 20 km with characteristics that are denser than summer where the ducting is formed at higher altitude and seems less dense.

6. Result on variation of microbaroms

The characteristic variations of microbaroms in the winter and summer session is a semidiurnal variation in pressure as represented by 24-h dayplot of 30 min one full line and their unfiltered spectral of raw data are shown in figure 8. The PSDs for ambient noise in a sample day of winter and summer seasons are shown in figure 8(b) and 8(d). All spectra calculated for each season is plotted as blue lines, the median for each interval as a red line, and the 5th and 95th percentiles of the distribution as black and yellow lines, respectively. At any season and frequency the PSD varies by 20 to 40 dB of magnitude. The peak of these PSD around 0.2 Hz is caused by microbaroms where its peak in the summer is lower than in the winter.

Having plotted the spectral profile of the ambient noise pressure recorded by the sensor, we can now apply the information of the changing vertical structure of wind in the atmosphere to an interpretation of observed variations of microbaroms. The characteristic pressure variations of microbaroms in the summer is a semidiurnal fluctuation which represented by the dayplot of band-pass filtered shown in figure 8(a). At time this common profile is altered through less occurrence of the horizontal wind in the atmosphere and cause small account of arrival signals that totally reflected downward to the ground.

A sample of strong typical winter-type record is shown in figure 8(c) and 8(d). The signal is clearly stronger than other recorded in the summer season. The amplitude variations of recorded microbaroms is considerably broader. This peak is revealed as a prolongation of the propagation factors, known as the horizontal wind structure of the atmosphere. The strong wind at a certain altitude of the atmosphere allows this level to generate the sound channel for the infrasound incoming from above to the ground.
Figure 6. Reanalyzed zonal wind at infrasound station KCZ07 (33N), for 20-21 February 2018, a and b, 27-28 August 2018 c and d. The vector represent direction toward which horizontal wind in moving.
7. Conclusion
In this study, infrasound propagation through two different seasons was analyzed for midlatitude in the southern part of Japan. A case study reported on the signal arrival of microbaroms...
Figure 8. Dayplot of microbarom records for a sample day in summer and winter of 2018. In each figure b and d, PSDs of unfiltered signals recorded at station KCZ07 during period 27-28 August 2018 and 20-21 February 2018. Figure a and c are band-pass filtered of signals in b and d where one full line represents 30 minutes with an amplitude height between line about 0.6 Pa.
observed with infrasonic sensors on Shikoku Island, Japan. The latest analysis of MERRA-2’s global atmospheric specifications has been used to evaluate atmospheric conditions during the observation period. The strongest horizontal wind component is seen to form in both seasons so that ducting layers are formed. In winter, the ducting layer is formed more dense in the lower atmosphere than in the summer, when the ducting layer is formed slightly soft at the higher altitude of the atmosphere. This leads to a maximum refraction downward to the surface in winter than in summer. Although monitoring of our microbaroms has been noted only in the winter and warm periods, the use of infrasound makes it possible to understand the characteristics of infrasound waves, specifically their propagation due to the influence of the variability of atmospheric vertical structures. In general, the results of observations and modeling are in agreement.

Author's Contributions
Conceptualization, M.B. and M.-y.Y.; methodology, M.B.; software, M.B.; validation, M.B. and M.-y.Y.; formal analysis, M.B.; investigation, M.B.; resources, M.B.; data curation, M.B.; writing—original draft preparation, M.B.; writing—review and editing, M.B. and M.-y.Y.; visualization, M.B.; supervision, M.-y.Y.; project administration, M.-y.Y.; funding acquisition, M.-y.Y. All authors have read and agreed to the published version of the manuscript.

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