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Gravity wave activity in the upper stratosphere and lower mesosphere observed with the Rayleigh lidar at Tsukuba, Japan

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Abstract. We delineated the climatological characteristics of the potential energy of gravity waves, E_p, using Rayleigh lidar observations made in 1990—1991 at Tsukuba, Japan (36°N, 140°E). Tendency of large and small values of E_p in winter and summer, respectively, was detected in the upper stratosphere (30–45 km), suggesting annual variation with a winter maximum. This annual cycle seemed to be consistent with lidar observations made in France and UK [Wilson et al., 1991; Mitchell et al., 1991]. The obtained E_p values in the upper stratosphere and lower mesosphere (45–60 km) were rather similar to the French data, despite the large scatter of the Tsukuba values.

Introduction

Studies on the climatological characteristics of gravity waves, such as their seasonal and latitudinal variations, were commenced by employing a global data-base of rocketsonde measurements [Hirota, 1984]. Recent ground-based observations with atmospheric radars and lidars have greatly contributed to studies of gravity waves, due to the advantage of continuous monitoring with good time-height resolution, which revealed variations with altitude, latitude and season [e.g., Vincent and Fritts, 1987; Tsuda et al., 1990, 1993; Senft and Gardner, 1991; Wilson et al., 1991].

Using statistical analysis of the monthly MU radar observations over Shigaraki, Japan (35°N, 136°E) for four years, Murayama et al. [1993] revealed annual variation of the gravity wave energy with a winter maximum in the lower stratosphere, while in the upper mesosphere, the semiannual variation with peaks in summer and winter was detected by Tsuda et al. [1990]. Senft and Gardner [1991] also showed the semiannual component of the gravity wave activity in the mesopause region from Na lidar observations at Urbana.

Rayleigh lidar observations also provided density and temperature profiles at about 30–80 km, with good time and height resolutions [e.g., Chanin and Hauchecorne, 1981; Mitchell et al., 1991; Senft et al., 1993], which are useful in complementing MST radar observations, with which one is normally unable to measure the wind fields between 25 and 60 km. The kinetic energy of gravity waves can be derived from the wind velocity variance with MST radar observations, while lidar observations of the density and temperature fluctuations allow the determination of the available potential energy. The Rayleigh lidar observations could interpolate radar studies on gravity wave climatology, resulting in the annual variation of gravity wave potential energy in the upper stratosphere [Wilson et al., 1991; Mitchell et al., 1991]. Wilson et al. [1991] showed that the variation in the lower mesosphere was rather featureless.

In this study we employed a data-base obtained with the Rayleigh lidar at the National Institute for Environmental Studies (NIES) at Tsukuba, Japan (36°N, 140°E) [Sugimoto et al., 1989; Nakane et al., 1992a, b], for studies of the statistical behavior of the potential energy of gravity waves in the stratosphere and mesosphere (30–60 km). We further compare the results with lidar observations made at the Observatoire de Haute Provence (OHP) (44° N, 6° E) and Biscarosse (BIS) (44° N, 1° W) [Wilson et al., 1991], as well as the results at Aberystwyth, UK [Mitchell et al., 1991].

Lidar Observations and Data Processing

Lidar observations at NIES were started in 1988, the details of the lidar system and basic experimental procedures being described elsewhere [Sugimoto et al., 1989; Nakane et al., 1992b]. The atmospheric density was derived from the Rayleigh scattering intensity with a 351 nm laser with height and time resolutions of 0.15 km and 10 min, respectively, and the temperature profile was further inferred with the hydrostatic assumption of an ideal gas.

The observation periods are illustrated in Figure 1, the observations being conducted only at night, with intervals ranging from a few to 10 hours. Note that the observations were more frequently conducted in winter months due to the better weather conditions than in summer.

The upper limit of the height range for each profile was determined by investigating the statistical behavior of the received signal. Note that we did not include a profile which showed great variation near the stratopause, which seemed to include the effect of the enhanced activity of planetary waves [Wilson, private communication].

We first averaged the profiles for one hour, and defined a background profile $\overline{\rho(z)}$ by using the least-squares fit of

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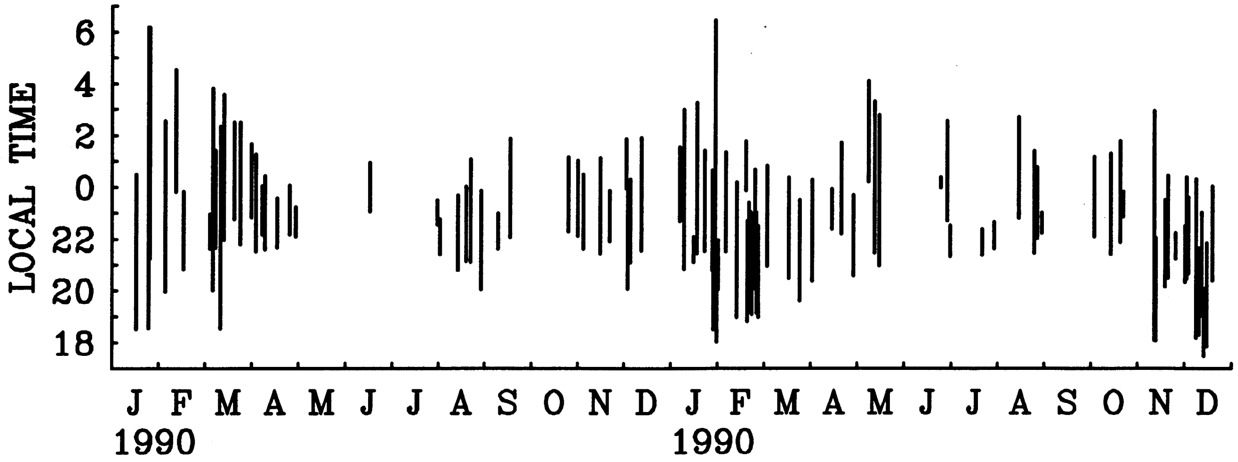

Fig. 1. Observation periods with the NIES Rayleigh lidar in 1990–1991. The vertical scale represents the local time at night.

$\rho_0 \exp[az^2 + bz + c]$ to extract the relative density fluctuations $\rho'/\overline{\rho} = \rho/\overline{\rho} - 1$. We obtained vertical wavenumber spectra of $\rho'/\overline{\rho}$ at 30–45 km and 45–60 km altitude, and then determined the mean spectrum for each day. We integrated the spectrum in the wavenumber range of 6.7×10^{-5}–1×10^{-3} cyc/m (1–15 km in wavelength), and then subtracted the noise power, which was inferred from the noise floor of the corresponding spectrum.

From the integrated power, $\overline{(\rho'/\overline{\rho})^2}$, the potential energy density of gravity waves can be inferred. Note that we disregarded the energy values when the noise power was too great (larger than 2/3 of the signal power, or larger than 10 and 200 Jkg^{-1} at 30–45 and 45–60 km, respectively).

The available potential energy density per unit mass of gravity waves, E_p, can be inferred from $\rho'/\overline{\rho}$ and the Brunt-Väisälä frequency, N, as:

$$E_p = \frac{1}{2}N^2\overline{\zeta^2} = \frac{1}{2}\left(\frac{g}{N}\right)^2\overline{\left(\frac{\rho'}{\overline{\rho}}\right)^2} \qquad (1)$$

where ζ is the vertical displacement of an air parcel and g the gravitational acceleration [e.g., Wilson et al., 1991]. The value of N is the Brunt-Väisälä frequency averaged over a height range, 30–45 or 45–60 km, which was calculated from the vertical derivative of observed hourly mean temperature.

Seasonal Variation of Gravity Wave Energy

The daily and monthly mean values of E_p in the upper stratosphere (30–45 km) are shown in Figure 2 in comparison with the results of Wilson et al. [1991] in the same height range obtained at OHP and BIS. The monthly mean value observed over Tsukuba was as large as 7-12 Jkg^{-1} in January, February and April, while it was only 3–5 Jkg^{-1} in May–August, and it was enhanced to about 10 Jkg^{-1} in October–December.

The monthly values in January–August at Tsukuba reasonably agreed with the results at BIS, showing a decrease of E_p from January to June. The E_p values at OHP agreed with the Tsukuba data in June and August, while they tended to be larger than at Tsukuba in January and February. On the other hand, the values in October–December at Tsukuba were significantly larger than those at OHP and BIS.

Although the observation over Tsukuba showed the smaller number of measurements especially in summer and the large scatter in the E_p values, there seemed the tendency of larger and smaller values in winter and summer, respectively, implying an annual variation with a maximum in winter. This annual cycle of E_p at 30–45 km is consistent with the results in France, especially in the period from January to June, although the latitudes of the observation sites are different.

The significant enhancement was found in October–December at Tsukuba, which may be attributed to the fewer values in these months but may be related to some physical process such as interaction between gravity waves and planetary waves enhanced in winter.

Mitchell et al. [1991] also conducted Rayleigh lidar observations in the stratosphere over Aberystwyth (52°N, 4°W), and analyzed the wave components with vertical scales smaller than 15 km as well. They showed that seasonal variation of E_p was fairly annual with a maximum in January at the stratospheric heights above 30 km, which was consistent with the results here. The MU radar experiments revealed that the gravity wave activity deduced from wind velocity fluctuations with wave periods of 5 min–21hr showed the evident annual variation with a winter maximum at the height range of 15.5–17 km [Murayama et al., 1993].

These observational studies imply that the annual variation in gravity wave activity in the stratosphere was widely seen at least at mid-latitude.

In Figure 3, we present the results obtained in the lower mesosphere (45–60 km), although it is rather difficult to discuss the seasonal variation of E_p because results were not available in June, July, September or October. However, the monthly mean values in January–May, August, November and December were comparable to the results at OHP and BIS. Despite large scatter of the values at Tsukuba, the monthly means of E_p of 20–50 Jkg^{-1} were not very different from those at OHP and BIS, although the former was larger by factors within 2.5. The seasonal

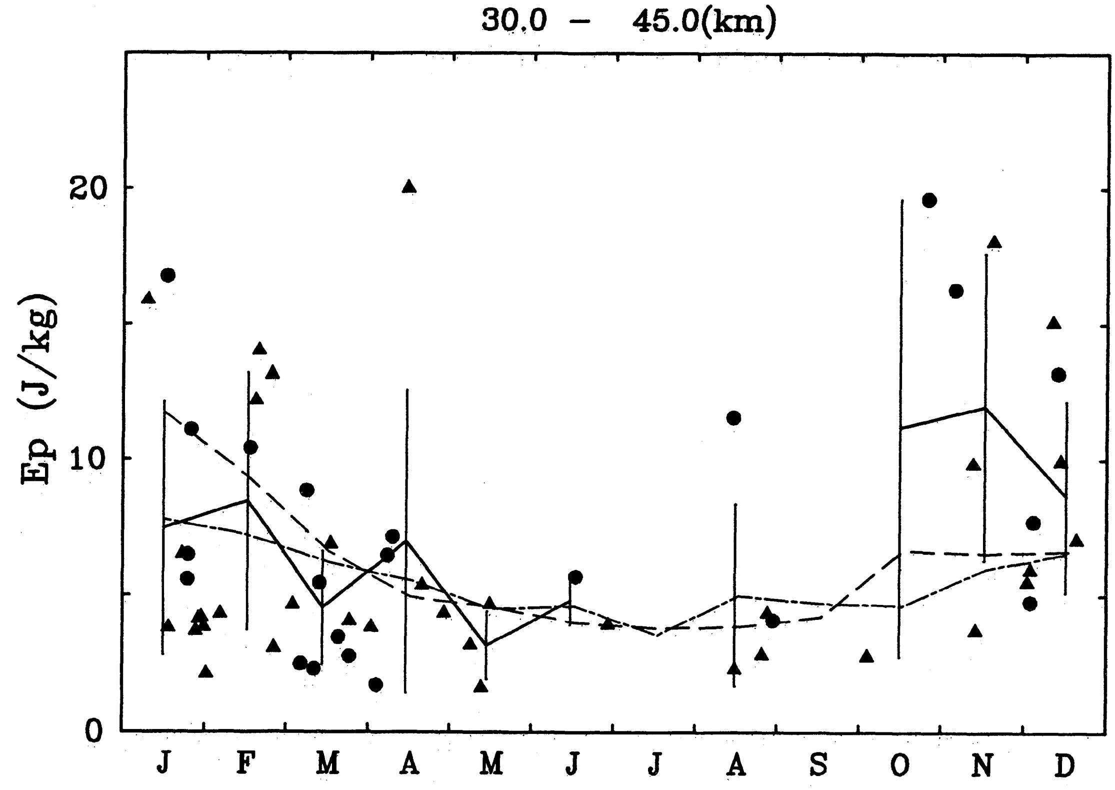

Fig. 2. Daily mean potential energy in the height range of 30–45 km observed with the Rayleigh lidar of NIES, in 1990 (circles) and 1991 (triangles), solid lines and vertical bars indicating the monthly means and standard deviations, respectively. Dashed and dot-dashed lines represent the monthly means of E_p observed at OHP (44°N, 6°E) and BIS (44°N, 1°W) in 1986–1989, respectively [after Wilson et al., 1991].

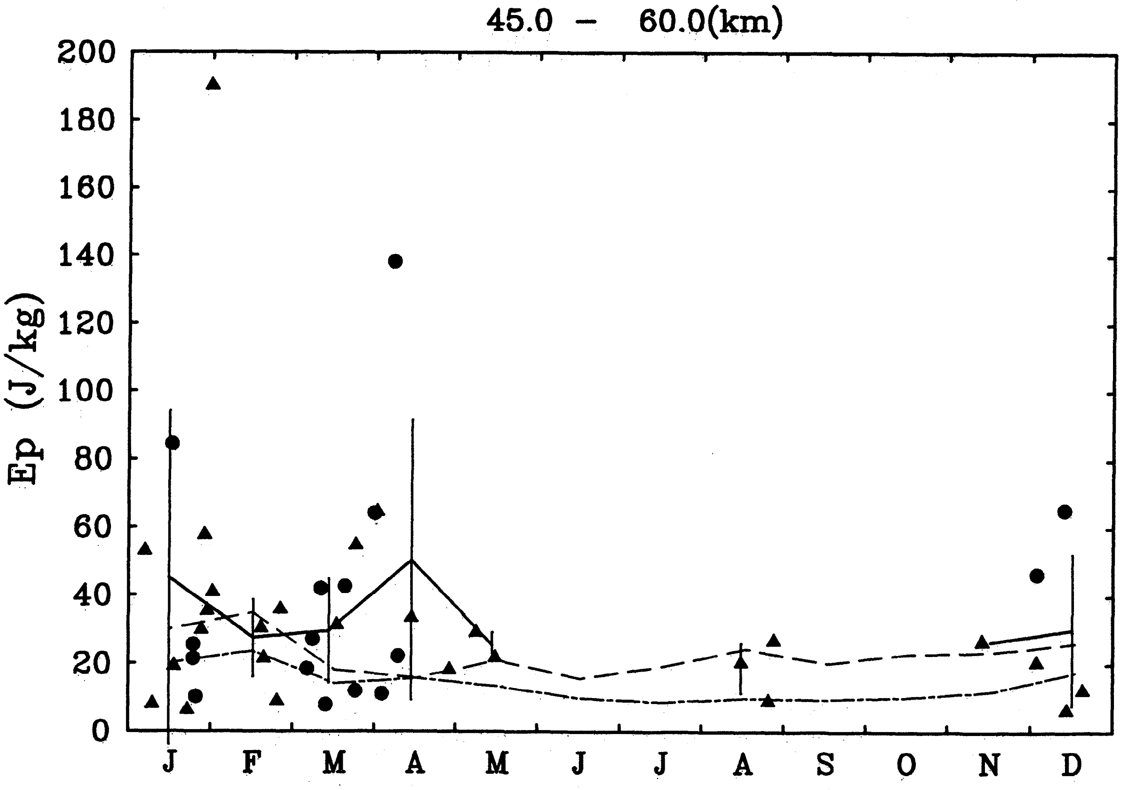

Fig. 3. The same as in Fig. 2 except that the results are for the lower mesosphere (height range, 45–60 km).

variation of E_p in France was rather featureless, with which the Tsukuba results were consistent.

On the basis of the rocketsonde observations, Hirota [1984] reported that the annual mean value of the intensity of the temperature fluctuations induced by gravity waves was larger at middle latitudes centered at 25°N than those at higher latitudes, which showed that the annual mean at 35°N was larger than at 44°N by a factor of about 1.3. From radar observations, Nakamura et al. [1993] detected the latitudinal distribution, including a hemispheric difference, of the gravity wave activity in the mesosphere. The results at Tsukuba, OHP and BIS in the upper stratosphere and lower mesosphere seem to be consistent with those of Hirota [1984] as to the general tendency of latitudinal variation, despite Hirota's analysis of a different component of gravity waves.

Concluding Remarks

From the NIES Rayleigh lidar observations made in 1990–1991, we obtained the potential energy density of gravity waves in the upper stratosphere (30–45 km) and lower mesosphere (45–60 km). We can summarize the main results as follows.

1. From the NIES Rayleigh lidar observations over Tsukuba in 1990–91, the monthly mean values of E_p were determined in the 30–45 km and 45–60 km regions.

2. At 30–45 km the E_p values were not very different from those at OHP and BIS [Wilson et al., 1991], further implying an annual variation with a maximum in winter, which was consistent with those at OHP and BIS especially in January–June, despite the large scatter of the Tsukuba data. Although the values were slightly larger at Tsukuba than in France, the values at Tsukuba in October–December were significantly enhanced compared to those in France. The stratospheric annual cycle also agreed with the lidar results at Aberystwyth [Mitchell et al., 1991].

3. In the lower mesosphere (45–60 km), the monthly mean values were not very different from those at OHP and BIS, although data at Tsukuba in June, July, September and October were not available. The Tsukuba results were consistent with the featureless seasonal variations in France.

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