Frequency Spectra of Wind Velocity Fluctuations between 1 hour and 1 month in the Atmospheric Boundary Layer over Equatorial Indonesia

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(Received December 28, 1994; Revised October 1, 1997; Accepted November 14, 1997)

Frequency power spectra are analyzed from zonal and meridional wind velocities observed continuously in a height range below 2.5 km with the Kyoto University Boundary Layer Radar (BLR) in Serpong, Indonesia (6.4°S, 106.7°E). We find that (i) the spectral slope in a period range from a few hours to a few days is approximately -1; (ii) the power spectral densities in the rainy season are at least about two times larger than those in the dry season; (iii) the diurnal component is dominant both in dry and rainy seasons; (iv) components with periods of about 4 and 10 days are probably associated with mixed Rossby-gravity wavelike cloud clusters and Kelvin wavelike super cloud clusters, respectively; and (v) the power spectral amplitudes increase at least one order of magnitude from the bottom to the top of the equatorial Planetary Boundary Layer (PBL), and the values at the top of the PBL are comparable to those in the upper troposphere over mid-latitudes. The last feature suggests that the equatorial PBL is probably a major source of kinetic energy of the earth’s atmosphere.

1. Introduction

Quantitative information on the energy transport and conversion processes in the atmosphere is given by the power spectra of wind velocity fluctuations, which have become available with the development of radar profiling techniques from the troposphere to the lower thermosphere (see, e.g., Balsley and Carter, 1982; Larsen et al., 1982; Nakamura et al., 1993). These spectra have suggested that kinetic energy is generated in the troposphere and is transported upward mainly by various types of propagating waves. A major source of these waves is anticipated to be in tropical active convections (Tsuda et al., 1994a, b, c). Nevertheless, the bottom of the atmosphere called the planetary boundary layer (PBL), in which tropospheric convections are generated, has not yet been examined closely, for quantitative information on the kinetic energy generation.

However, recent progress in the radar profiling techniques has been extended to the PBL (Ecklund et al., 1988, 1990; May and Wilczak, 1993), and we have also developed an L-band (1357.5 MHz) transportable system called the Kyoto University boundary layer radar (BLR) (Hashiguchi et al., 1995a, b, c). The high temporal and vertical resolutions and the reliability of the three-components of the wind velocity vector observed with the BLR are expected to improve drastically our knowledge and interpretation of the PBL, since many classical techniques such as balloons, aircrafts, and anemometric towers cannot observe the PBL in such detail (see, e.g., Stull, 1988; Garratt, 1992).

In this paper we present a preliminary but quantitative result concerning the horizontal wind velocity spectra for a rather broad frequency band, based on our equatorial PBL observations with the BLR in Indonesia. In the following section, we first give a brief description of the BLR observations. The spectral analysis procedure for the BLR data is described in Section 3. Frequency power spectra of wind velocity fluctuations observed with the BLR are described in Section 4. In Section 5 we discuss kinetic energy generation based on the observational results and summarize the conclusions.
Table 1. Principal specifications of the Kyoto University Boundary Layer Radar (BLR).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating frequency</td>
<td>1357.5 MHz ((L\text{-}band))</td>
</tr>
<tr>
<td>Antenna</td>
<td>three parabolic antennas</td>
</tr>
<tr>
<td>Aperture</td>
<td>3.1 m(^2) (2 m in diameter)</td>
</tr>
<tr>
<td>Gain</td>
<td>25 dBi</td>
</tr>
<tr>
<td>Beamwidth</td>
<td>7.6° (half power)</td>
</tr>
<tr>
<td>Beam directions</td>
<td>fixed into three directions</td>
</tr>
<tr>
<td>Transmitter</td>
<td>three solid state amplifiers</td>
</tr>
<tr>
<td>Peak power</td>
<td>1 kW (maximum)</td>
</tr>
<tr>
<td>Average power</td>
<td>20 W (duty ratio 2%) (maximum)</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>4 MHz</td>
</tr>
<tr>
<td>Pulselength</td>
<td>0.67, 1.0, 2.0 (\mu) s (variable)</td>
</tr>
<tr>
<td>IPP</td>
<td>50, 100, 200 (\mu) s (variable)</td>
</tr>
</tbody>
</table>

2. The Kyoto University Boundary Layer Radar (BLR)

The BLR used in this study was developed by the Radio Atmospheric Science Center (RASC) of Kyoto University in 1991. The basic parameters of the BLR are summarized in Table 1. The BLR is a small and transportable radar operating at a frequency of 1357.5 MHz \((L\text{-}band)\) with a peak transmitter power of 1 kW. The antennas consist of three parabolic antennas with a diameter of 2 m, which are pointed into the vertical and two oblique directions aligned to the east and north at a zenith angle of 15°. The BLR provides vertical profiles of three-components of the wind velocity vector in the lower troposphere, including the PBL, with time and height resolutions of about 1 min and 100 m, respectively.

The BLR was first installed at the MU (Middle and Upper atmosphere) Observatory in Shigaraki, Japan \(34.85°\text{N}, 136.10°\text{E}; 385\text{ m above sea level}\) in December 1991, and continuous observations were conducted during May–August 1992 (Hashiguchi et al., 1995a). After that, it was installed at PUSPISTEK (National Center for Research, Science and Technology) \(6.4°\text{S}, 106.7°\text{E}, 50\text{ m above sea level}\) in Serpong, West Java, which is located in the south-west suburbs of Jakarta, Indonesia and has been continuously operating since 9 November 1992 (Tsuda et al., 1995; Hashiguchi et al., 1995b, c). Observations with the BLR Shigaraki and Serpong have been conducted without any serious problems, except for relatively short stops mainly due to commercial electric power line problems. At the Serpong radar site, surface winds are also monitored with a standard anemometer (OGASAWARA, WS-A54).

3. Spectral Analysis Techniques for the BLR Data

Since the BLR can provide temporally and vertically continuous wind velocity data, spectral analysis can be applied with respect to frequency or vertical wavenumber. In the present work, we have calculated one-dimensional frequency spectra of zonal and meridional wind fluctuations observed with the BLR. Power spectral densities are often calculated from the squared values of Fourier coefficients obtained through the fast Fourier transformation (FFT) of time series. However, if the observed data series has missing samples, FFT cannot be directly applied to the data. Avoiding this difficulty, we applied the method reported by Blackman and Tukey (1959) to the observed data series with some missing data points in order to calculate the power spectral density. We briefly describe the spectrum calculation procedure employed in this work, following the principle of Blackman and Tukey.

From a time series of a certain physical quantity, an auto-correlation function (ACF) is calculated with a maximum lag that must be smaller than the number of the total samples of the series. The chosen maximum lag must be small enough for there to be no missing ACF values. After multiplying the ACF...
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with a lag window (Hanning window), the power spectral density is calculated using a FFT. For computing the frequency spectrum, the data are prewhitened before calculating ACF to make reliable estimates. The original data series \( \{x_i\} \) becomes a prewhitened data series \( \{\tilde{x}_i\} \) with the use of the formula

\[
\tilde{x}_i = x_i - \beta x_{i-1},
\]

where \( \beta \) is the degree of prewhitening, which was taken as 0.95. After the Fourier transformation the spectrum is compensated for prewhitening by recoloring. Finally the spectrum \( \{P_i\} \) is smoothed by the formula

\[
\tilde{P}_i = \frac{P_{i-3} + 6P_{i-2} + 15P_{i-1} + 20P_i + 15P_{i+1} + 6P_{i+2} + P_{i+3}}{64}
\]

as suggested by Endlich et al. (1969).

The BLR detects the mean radial Doppler velocity inside a sampling volume given by the beam width of 7.6° for one beam at a range resolution of 100 m. The vertical velocity determined by using one vertical beam corresponds to the mean value over a volume of roughly 130 m \((=2 \times \tan 3.8° \times 1 \text{ km})\) wide and 100 m thick at 1 km height. Since the zonal and meridional velocities are determined by using one vertical beam and two oblique beams with a zenith angle of 15°, these velocity components are the mean values over a volume of about 400 m \((=(\tan 18.8° + \tan 3.8°) \times 1 \text{ km})\) wide and 100 m thick at 1 km height under an assumption that the wind fields are homogeneous in this volume. The BLR can provide time series of wind velocities with a high time resolution of about 1 min. However, since the noise floor of a frequency spectrum calculated from this time series is raised, probably due to inhomogeneity of the wind fields (particularly in vertical velocities) between vertical and oblique beams, a reliable power spectral density can barely be obtained at frequencies higher than 1 hour\(^{-1}\). Therefore we have calculated frequency spectra from time series of wind velocities averaged every one hour for each range gate (height resolution of 100 m) with a maximum lag of 256 data points (corresponding to a period of \(-11\) days), except for cases when more than 50% of the data were missing in each time series obtained for three months.

4. Frequency Power Spectra of Wind Velocity Fluctuations

Since the climatology of the Java Island is characterized by an annual cycle of rainy and dry seasons, we compared frequency power spectra between the dry and rainy seasons. Figure 1 shows frequency power spectral densities calculated for zonal and meridional wind velocities observed with the BLR at the height range of 0.4–2.4 km and with a standard anemometer at 10 m height above the ground during August–October 1993 (dry season) and December 1993–February 1994 (rainy season). The spectra were averaged over height regions 0.6 km thick. The height of the PBL has a diurnal variation and often reaches 3–5 km in the afternoon on clear days (Hashiguchi et al., 1995b).

The spectral slope obtained from the BLR data is fairly similar between the zonal and meridional components, and the dry and rainy seasons, showing a logarithmic slope of \(-1\) at frequencies at least higher than 1 day\(^{-1}\). A slope of \(-5/3\) has been reported in observations in the extra-tropical lower and middle atmosphere in earlier studies however (e.g., Balsley and Carter, 1982; Larsen et al., 1982; Gage et al., 1986; Tsuda et al., 1994b). The slope for the meridional component in the dry season is gentler than \(-1\) at frequencies less than 1 day\(^{-1}\). On the other hand, the slopes obtained from the anemometer data for all the cases are close to \(-5/3\) at the higher frequency range (approximately higher than the semidiurnal component). As shown in Fig. 2, the spectral slope obtained by the BLR observations in Shigaraki, Japan was closer to \(-5/3\) rather than \(-1\), which is consistent with results obtained from the MU radar data for a 2.5–3.4 km height range at the same place for about 100 hours during 15–19 June 1992. Therefore, we do not consider that the differences in slope between the anemometer and radar spectra at the equator are due
Fig. 1. Frequency power spectral densities for (left panels) zonal and (right panels) meridional wind velocities observed with the BLR (0.4–2.4 km) and a standard anemometer (10 m) in Serpong, Indonesia during (upper panels) August–October 1993 and (lower panels) December 1993–February 1994. Spectra at 1.1–1.7 km and 1.8–2.4 km heights are multiplied by a factor of 10 and $10^2$, respectively, to separate them on the graph. The axes are correct for the spectra at 10 m and 0.4–1.0 km heights. Slant solid and dashed lines indicate the logarithmic spectral slopes of $-1$ and $-5/3$, respectively. Vertical dotted-dashed lines indicate the period of one day.
A common feature in all cases in Fig. 1 is that the spectral amplitudes above 0.4 km are about 10 times as large as those at the ground an increase slightly with height (recall that the values at 1.1–1.7 km and 1.8–2.4 km heights are multiplied by a factor of 10 and 10^2, respectively). In order to examine the relative dominance of various components, we present energy-content contour plots of the spectral amplitudes obtained for each sampled height (see Fig. 3). We found the following features concerning vertical and seasonal variabilities of these spectral amplitudes:

i) The spectral amplitudes in the rainy season are about two or more times larger than those in the dry season in the almost entire observed height and frequency ranges.

ii) In all height ranges the diurnal component is a dominant feature. Near the ground and at heights above about 2 km, this component is strongest in the meridional wind in the dry season. This result is consistent with features noted in earlier studies (Hashiguchi et al., 1995b): striking diurnal variations of the top of the PBL which extend up to 3 km or higher on clear days. The predominance for the meridional wind may be explained by a sea-land breeze circulation near the coastline which runs in the west-east direction. We have confirmed that the meridional winds have a reversal at an altitude of around 1.5 km between the sea-land breeze near the surface and its counterbalancing flow in the upper levels. A semidiurnal component is also seen clearly in the dry season. The diurnal and semidiurnal peaks are both weak in the data obtained in Shigaraki (Fig. 2), although we have found similar PBL-top diurnal variations on a few clear days. In Serpong these peaks are found even in the rainy season, and are correlated with severe rainfalls concentrated in afternoons (12–24 LT).

iii) The zonal wind amplitudes are significantly larger than the meridional wind amplitudes at periods of around 10 days (particularly in the rainy season). They are consistent with the activity of eastward moving super cloud clusters (Hashiguchi et al., 1995c) which have Kelvin-wavelike structures and behavior (particularly near the tropopause; cf. Tsuda et al., 1994b, 1995).
iv) Above 2 km height the meridional wind amplitudes in the rainy season are larger than the zonal wind amplitudes at periods of around 4 days. We have noted in earlier studies (Hashiguchi et al., 1995c) that rainy season cloud activity and rainfall have a periodicity of 3–5 days. It seems that the 4 day component is associated with such active convective clouds which several studies have reported as possibly having mixed Rossby-gravity wavelike structures and westward moving behavior (e.g., Takayabu and Nitta, 1993).
5. Discussion and Concluding Remarks

We have been successfully conducting observations with the BLR in Serpong, Indonesia since November 1992. Frequency power spectra of horizontal wind velocities in a broad frequency band of approximately 1 hour–1 month have been presented in this paper. We have found that above ground level the spectral slope is approximately $-1$ in a period band from a few hours to a few days, and that there exists striking diurnal oscillations corresponding to PBL-top variations, sea-land breeze circulations (both on clear days in the dry season), or frequent appearance of rainfalls and cloud convections in the afternoon (particularly in the rainy season). The slope $-1$ is quite different from values $-5/3$ so far observed mainly in the extra-tropical lower and middle atmosphere. The components with periods longer than one day consist of Kelvin-wavelike super cloud cluster (period ~10 days) and possibly mixed Rossby-gravity wavelike cloud clusters (~4 days).

The spectral amplitudes in the PBL increase more than one order of magnitude from the bottom to the top of the PBL, and the latter values are comparable to values in the mid-latitude upper troposphere and $1/100-1/30$ those in the mid-latitude upper mesosphere (e.g., Balsley and Carter, 1982; Larsen et al., 1982; Nakamura et al., 1993), as shown in Fig. 4. Considering the upward exponential decrease (only 20% inside the PBL and about one order of magnitude in the free troposphere) of atmospheric density, we consider that the kinetic energy increases at least about 8 times from the bottom to the top of the PBL, decreases about one order from the PBL to the upper troposphere, and again decreases two or three orders from the tropopause to the mesopause. Although the upward decrease of wave energy in the extra-tropical middle atmosphere has been previously reported (e.g., Tsuda et al., 1994a; Yamanaka and Fukao, 1994),

![Fig. 4. Comparison between the horizontal wind frequency spectra obtained in this study (thick curves) and earlier (extra-tropical lower- and middle-atmospheric) studies (thin curves) (Balsley and Carter, 1982; Larsen et al., 1982; Nakamura et al., 1993).](image-url)
the upward decrease in the free troposphere and the upward increase in the equatorial PBL are new results obtained in this study. These features suggest that the equatorial PBL is probably the major source region of kinetic energy of the earth’s atmosphere. Since we have found also that the power spectral densities in the rainy season are stronger than those in the dry season, we consider that such kinetic energy is generated probably through cloud convection from sensible and latent heat inputs by the strong solar radiation and the warm equatorial ocean.

The BLR can directly observe vertical atmospheric motion in clear atmosphere. During precipitation, however, the motion of precipitation particles is obtained since the L-band radio wave BLR is very sensitive to the precipitation. It is noted that even in such rainy weather the horizontal winds can be observed correctly with the BLR because the horizontal motion of precipitation particles follows almost perfectly the motion of the surrounding atmosphere. In subsequent papers we will calculated spectra also for vertical atmospheric motion by selecting carefully for data collected only during periods of no precipitation.

We acknowledge the ceaseless encouragement of Prof. S. Kato of the Japan-Indonesia Science and Technology Forum (JIF) during this observation campaign. We are grateful to Drs. M. Yamamoto and T. Nakamura of RASC, Kyoto University, and Dr. T. Adachi of Communications Research Laboratory for their useful suggestions and comments. We thank Dr. W. O. J. Brown of McGill University for his careful reading of the original manuscript. We thank Ir. S. W. B. Harijono of BPPT (Agency for the Assessment and Application of Technology), Prof. H. Wiryoasumarto of LAPAN (National Institute of Aeronautics and Space), all the operators who maintain the Serpong radar observatory, and colleagues of BPPT, LAPAN and RASC for their collaborations. The first author (Hashiguchi) is supported by a grant (1289) of the Japan Society for the Promotion of Science (JSPS) under the Fellowships for Japanese Junior Scientists. The present study was financially supported also by Grants-in-Aids (02554012, 04NP0201, 05NP0201) of the Japanese Ministry of Education, Science and Culture.

REFERENCES


