Examination of 3–6 day Disturbances over Equatorial Indonesia Based on Boundary Layer Radar Observations during 1996–1999 at Bukittinggi, Serpong and Biak

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(Manuscript received 1 February 2000, in revised form 28 October 2000)

Abstract

Spectral features of lower tropospheric horizontal wind observed during 1996–1999 by Bukittinggi, Serpong and Biak boundary layer radars show 3–6 day periodicities in zonal and meridional components and longer period zonal wind oscillations. Using bandpass filtering analysis the 3–6 day modes show a westward phase speed of about 700 km day⁻¹ and a zonal wavelength of about 3500 km, and propagate through the Indonesian maritime continent when the westerly wind is prevailing at Biak.
1. Introduction

Westward moving disturbances with a temporal scale of around four days have been frequently observed in the tropics over the equatorial Pacific. Yanai et al. (1968) made a spectral analysis of time series of rawinsonde data over the tropical Pacific from surface to the lower stratosphere, and described 4–5 day period westward moving wave disturbances in the lower troposphere as well as disturbances in the upper troposphere through the lower stratosphere. Liebmann and Hendon (1990) discovered lower tropospheric MRG (mixed Rossby-gravity) wave modes over the equatorial Pacific from the European Center for Medium-Range Weather Forecasts (ECMWF) data. Takayabu and Nitta (1993) detected a 3–5 day disturbance which is associated with MRG wave type in the central Pacific near the dateline and with a tropical depression (TD) type in the tropical western Pacific. Numaguti et al. (1995) found a 4–5 day period wind variation in the equatorial western Pacific during TOGA-COARE IOP which can be explained by a westward-propagating MRG wave disturbance. Over equatorial Indonesia which is located between the Indian and Pacific Ocean, Widiyatmi et al. (1999) detected a spectral peak with a period near 4 days (Quasi 4 Day Mode; Q4DM) with a boundary layer radar (BLR) at Serpong (6°S, 107°E) (near Jakarta, Java) during rainy seasons in 1992–1995. Objective analysis wind data in the 1992/93 rainy season show that Q4DM moves westward and is suppressed in the western part of the Indonesian Archipelago.

Eastward moving disturbances with a temporal scale of about ten days or longer have also been frequently observed, of which the longer modes are called intraseasonal oscillations (ISO) (e.g., Nakazawa 1988; Nitta et al. 1992; Hashiguchi et al. 1995b). Zonal wind variations associated with such disturbances are in general much larger than meridional components, suggesting Kelvin-wave-like features. On the basis of the horizontal winds observed by BLR at Serpong and cloud distributions observed by GMS during the TOGA-COARE period, Hashiguchi et al. (1995b) showed a wind reversal from easterly to westerly which was associated with an eastward moving super cloud cluster (SCC). Nitta et al. (1992) showed a convective system and low level winds propagate along the equator from the Indian Ocean to the western Pacific. When SCC developed from the convective system in the Indian Ocean approached Sumatera, the westerly wind burst (WWB) associated with SCC was blocked by elevated topography over Sumatera and the low level disturbance was unable to cross the Island smoothly. Recently Murata et al. (2001) have reported another evidence of a eastward propagating disturbance blocked by Sumatera Island.

Not only the blocking of eastward propagating disturbances and WWB as mentioned above but also modification of the westward moving Q4DM after passing Serpong (which means over Sumatera) was shown in Fig. 6 of Widiyatmi et al. (1999). Therefore, elevated topography over the Indonesian region, such as over Sumatera, may play an important role in modifying most disturbances passing over equatorial Indonesia. There are many other observational studies on eastward and westward moving disturbances originated from the Indian and the Pacific Oceans, but such a feature of the modification of those disturbances passing over equatorial Indonesia is still little known. Observational studies on pre-modified and modified disturbances over equatorial Indonesia, especially using the actual observed data, are important to clarify mechanisms of such modification of the disturbances. Since equatorial disturbances such as SCC have been known to influence the earth’s climate through ENSO over the Pacific and the dipole mode oscillation over the Indian Ocean (Saji et al. 1999), the observational studies over Indonesia are also important to understand the earth’s climate.

In this study, we present a comparison of wind velocity frequency spectra observed with BLR network over equatorial Indonesia and pay attention to the disturbances with the temporal scale of about 3–6 days. At present, three BLRs are operated at Bukittinggi (0°, 100°E, 864 m above mean sea level), Serpong (6°S, 107°E, 50 m) and Biak (1°S, 136°E, 40 m) in Indonesia (see Fig. 1) which represent western, southern and eastern parts of the Indonesian Archipelago, respectively. This alignment of the BLRs which can provide horizontal wind data with high time resolution (~ 1 min) is very valuable for large-scale disturbances with a zonal wavelength of some thousands of kilometers.
and a periodicity of a few days, because operational rawinsonde observations are not sufficient in this region. The BLR data with a high height resolution (≈100 m) also facilitate a detailed description of the vertical structure of the lower atmosphere.

In this paper we deal with quasi-4-day mode disturbances in general spectral features of horizontal wind velocities observed during 1996–1999 by the Indonesian BLR observation network mentioned above. In Section 2, we describe the data and the analysis method used in this study. In Section 3, we show the results of the spectral analysis. In Section 4 we discuss scientific findings, in particular on the modification of equatorial wave disturbances over the Indonesian maritime continent. Finally, we present our conclusions in Section 5.

2. Data and analysis method

The Serpong-BLR with an operating frequency of 1357.5 MHz has been operated under a collaboration between RASC (Radio Science Center for Space and Atmosphere of Kyoto University, Japan), BPPT (Agency for Assessment and Application of Technology, Indonesia) and LAPAN (National Institute of Aeronautics and Space, Indonesia) since November 1992 (Hashiguchi et al. 1995a). The Bukittinggi-BLR with an operating frequency of 1357.5 MHz has been operated under a collaboration between RASC, BPPT and BMG (Indonesian Meteorological and Geophysical Agency) since August 1998 (Renggono et al. 2001). The Biak-BLR with an operating frequency of 915 MHz has been operated under a collaboration between NOAA (National Oceanic and Atmospheric Administration, USA) and LAPAN (Carter et al. 1995).

Data sets of horizontal wind profiles with a height resolution of 100 m obtained by BLRs at Bukittinggi, Serpong and Biak have been used in this study. Although the altitudes of the stations are different from one to another, in this paper we plot the data at height from the ground of each radar site in all figures. The wind data derived from Serpong and Bukittinggi-BLRs have been averaged every 30 min in order to adjust the time interval to that of Biak-BLR, which is already set to 30 min. Data analysis has been done mainly for the periods of December–January–February (DJF), corresponding to the rainy season in Jawa, and June–July–August (JJA), corresponding to the dry season there. The power spectral density has been calculated using the same method as in Hashiguchi et al. (1997) and Widiyatmi et al. (1999).

For Serpong and Biak spectral features in JJA 1996 and DJF 1996/97 will be discussed in this paper, since during these periods there are few data gaps compared with other observation periods. For the Bukittinggi-BLR at which continuous observations were started from August 1998, they will be discussed in order to compare them with those at Serpong. Because since July 1997 the Biak-BLR has not been operated due to technical difficulties, and in July and August 1999 there are too many missing data at Serpong, a spectral feature for JJA 1999 will be discussed only at Bukittinggi. There are no simultaneous observations at all three BLR stations, but we can show some general characteristics of spectral features such as dominant modes and spectral slopes.

The horizontal features of disturbances are described utilizing global objective analysis data (GANAL) compiled by the Japan Meteorological Agency (JMA), which are reliable to a certain extent because not only the data from Indonesian rawinsonde stations but also those from Singapore and surrounding stations in Malaysia, and Australia, are included in the analysis process. A band-pass filter with the cut-off period of 3–6 days is applied to these data. These are similar to techniques used in Widiyatmi et al. (1999).

3. Results

3.1 Wind variations at each station

First we examine the unfiltered zonal and meridional wind components observed by Serpong and Biak BLRs in January 1997 (see Fig. 2). Concerning the zonal wind, westerly is in general dominant at both stations, and is stronger at Biak than at Serpong except for the last about 10 days. At Serpong, the westerly becomes very weak (sometimes
Fig. 2. Time-height cross-sections of zonal ((a) and (b)) and meridional ((c) and (d)) winds observed by Serpong ((a) and (c)) and Biak-BLRs ((b) and (d)) in January 1997.
Fig. 3. Time-height cross-sections of daily-averaged zonal ((a) and (b)) and meridional ((c) and (d)) winds observed by Serpong ((a) and (c)) and Biak-BLRs ((b) and (d)) during DJF 1996/97.
changed to weak easterly) with intervals of several days. The interval of appearance of such very weak zonal wind at Serpong is about 7 days, although various shorter variations are also included within the interval. Tall echoes corresponding to rainfall appear with intervals from less than 1 day to 4 days. On the other hand, concerning the meridional component, the dominant wind is changed from northerly in lower heights to southerly in upper heights in particular at Biak. Such meridional wind variations seem to have periodicities of 5–7 days. We cannot say what is the dominant mode (and when it appears strongly) in this unfiltered plot, but we find that there are various disturbances with time scales of a few days.

Figure 3 shows time-height cross-sections of daily-averaged zonal wind at Serpong and Biak during DJF 1996/97. Strong westerly appeared in December and February, and this zonal wind oscillation is a part of tropical intra seasonal oscillation (ISO). The westerly regime seems to start a little bit earlier at Serpong than at Biak, which suggests the longer mode is propagating eastward. In the meridional component, a shorter period (less than 10 days) oscillations are dominant (see Figs. 3(c) and (d)). We can see that shorter periodicity of around 3–6 days is dominant at levels of higher than 1 km, starting from around the middle of December 1996. It is seen more clearly at Biak in the meridional wind component, and seems to be lasting longer than at Serpong. In Figs. 3(d) and (c), until the end of February the alternation band between northerly and southerly in the shorter period of 3–6 day mode at Biak still continues to exist while at Serpong it has already disappeared.

3.2 Spectra at each station

Figure 4 shows the mean power spectral density calculated at lag 512 (data time interval is 30 min) in the height ranges of 0.6–0.8 and 1.3–1.5 km for zonal and meridional wind components at Serpong and Biak in JJA 1996 (upper panels) and DJF 1996/97 (middle panels), and at Bukittinggi in DJF 1998/99 (lower panels). In general, the spectral densities at Serpong during DJF 1996/97 are larger than those of JJA 1996 in almost all the height and frequency ranges for both wind components, while differences between DJF 1996/97 and JJA 1996 at Biak are not clear. Because Serpong is located at 6°S while Biak is at 1°S, the seasonal contrast of convective activity is stronger at Serpong with a maximum in the boreal winter.

In DJF 1996/97, the zonal wind spectra for periods longer than 10 days at Biak are stronger than those at Serpong for both height ranges, while the spectra at the height range of 1.3–1.5 km for periods shorter than 10 days at Serpong are stronger. The meridional wind spectra at Serpong are stronger than those at Biak in most height and frequency ranges, the differences being clearer in the 1.3–1.5 km height range. In JJA 1996, the meridional wind spectra at Biak are stronger than at Serpong in almost all the frequency range in the height range of 0.6–0.8 km, and for periods longer than 4 days in the height range of 1.3–1.5 km. The zonal wind spectra for periods longer than about 4 days in JJA 1996 and 10 days in DJF 1996/97 at Biak are stronger than those at Serpong. Another difference between the spectra at Serpong and Biak is that the spectra for the higher height range are stronger at Serpong, while at Biak the spectra are similar in both height ranges. The spectral features at Bukittinggi share a similarity with those at Serpong with respect to stronger amplitude at the higher altitude range, and with those at Biak with respect to stronger amplitude for the zonal wind rather than the meridional wind.

As suggested originally by Hashiguchi et al. (1997), the spectral slope for periods shorter than around 1 day is close to –1, which is confirmed commonly for all three stations over equatorial Indonesia and for both rainy and dry seasons. On the other hand, for periods longer than around 10 days we note that the spectral slope of the zonal component at Biak appears to be the steepest among the three sites. However, we do not consider such features in detail in this paper, but focus ourselves into periods between 3 to 6 days which have been studied by our preceding paper (Widiyatmi et al. 1999) for different years (1992–95).

Figures 5 and 6 show the vertical distributions of the energy-content form of frequency spectra at lag 256 (data time interval is 30 min) of the zonal and meridional wind velocity fluctuations observed with the three BLRs in the same periods as shown in Fig. 4. As mentioned in Section 2, the energy-content form can more clearly show dominant modes in the physical domain (contribution to variance in a time series). In this form, a negative slope (such as for the shorter periods at all the stations and for the longer periods in the zonal wind at Biak, as mentioned in the previous paragraph) and a flat portion in the usual spectral density plot become a almost constant and increasing with fre-
Fig. 4. Frequency spectra of the zonal (left panels) and meridional (right panels) wind components observed with BLRs at Serpong (dotted-dashed curves) and Biak (solid curves) in height ranges of 0.6–0.8 and 1.3–1.5 km for JJA 1996 (upper panels), DJF 1996/97 (middle panels) and at Bukittinggi for DJF 1998/99 (lower panels). The results for the height range of 1.3–1.5 km are multiplied by $10^2$ to separate spectral curves. Two vertical solid lines and a dashed line indicate 10, 4 and 1 day periods, respectively.
Fig. 5. Energy-content plot of frequency spectra of the zonal wind components observed with BLRs at Bukittinggi (left panels), Serpong (middle panels) and Biak (right panels) for JJA 1996, DJF 1996/97, DJF 1998/99 and JJA 1999. The vertical lines indicate 10, 4 and 1 day periods from left to right.
Fig. 6. Same as Figure 5, but for meridional wind components.
frequency, respectively. This makes a spectral peak much clearer. In this paper we concentrate mainly on the disturbances having periodicities of 3–6 days which appear at Serpong in the zonal and meridional components in DJF 1996/97 at the height of about 1.4 km, and as a weaker peak in JJA 1996 at around 4 days. They also appear around 3–6 days at Biak in the meridional wind component in DJF 1996/97 at heights higher than 2.5 km. Peaks of about two days are shown in the zonal wind component at Serpong as well as at Bukittinggi in DJF 1998/99 around 1.7 km height and another peak of about three days at Bukittinggi (note that the 1.7 km height at Bukittinggi is equivalent to the altitude of about 2.5 km) in JJA 1999. A vertical peak train of which the frequency becomes gradually lower (period becomes longer) with increasing height is observed in the meridional wind component in DJF 1998/99 at Bukittinggi. Thus, some similarities in the periodicities between Serpong and Biak (3–6 days) and between Serpong and Bukittinggi (quasi two days) are revealed from the frequency spectra of BLR wind velocities.

The spectra at Serpong during a rainy season (DJF 1996/97) are stronger than those during a dry season (JJA 1996) for both wind components. Because in the vicinity of the equator the seasonal variations of background field are unclear and not homogeneous over Indonesia (Okamoto et al. 2001), seasonal contrast between DJF 1996/97 and JJA 1996 at Biak may be different with those at Bukittinggi although they are both close to the equator. Differences between DJF 1998/99 and JJA 1999 at Bukittinggi (two rainy seasons exist in the equinoxes; see Hamada et al. 2001) are not so striking as at Serpong between DJF 1996/97 and JJA 1996. We note that the spectra at Serpong during DJF 1996/97 which corresponded to the initial phase of the strong 1997/98 El Nino are much stronger than DJF 1998/99 which was in the midst of a La Nina event.

3.3 Bandpass filtering

Most of the observed disturbances of 3–6 days, such as reported in Liebmann and Hendon (1990), Takayabu and Nitta (1993) and Widiyatmi et al. (1999), have a westward moving property. If this 3–6 day disturbance has a westward moving property, we would expect that the phase over Biak must be ahead of Serpong since Serpong is located about 3200 km (29° in longitude) westward apart from Biak.

Let us see the phase relations in time domain in Fig. 7 which shows a 4.5–5.5 day band pass filtered meridional wind observed by Serpong and Biak BLRs in January 1997 at the height of about 1.5 km. We could find a clear wave-like curve at Serpong as well as at Biak from the beginning to at least the middle of January 1997. At Serpong it has a larger amplitude than at Biak, and has positive peaks at around 110 hours and 260 hours (5 and 11 January) at Serpong while a positive peak at around 130 hours and 290 hours (6 and 12 January) at Biak. Biak seems to have a longer periodicity than Serpong, and this is consistent with results of the spectral analyses in the previous subsection.

Figure 8 shows 3–6 day band pass filtered time-longitude distributions of meridional wind obtained from GANAL data during January 1997 at standard pressure levels of 850 hPa (~1.5 km altitude from the mean sea level) and 700 hPa (~3.1 km) along the latitudes of Serpong and Biak. Almost similar patterns between Serpong and Biak, revealed from Fig. 8, support the expectation of large scale disturbances (vertical and north-south phase structures) inferred from individual spectra in the previous section. Some westward moving phase structures revealed from Fig. 8 (more prominent in the 700 hPa rather than 850 hPa) from the beginning of January to around 20 January are consistent with the band-passed wind variations observed at the two BLR sites shown in Fig. 7.

We find a positive phase passing near Biak around 6 January in Figs. 8(c) and (d), which is corresponding to a positive peak at Biak in Fig. 7 around 6 January. This peak arrives at the longitude of Serpong around 11 January, which corresponds to the positive peak at Serpong around 11 January in Fig. 7. Similar identification using
Fig. 8. Time-longitude sections of 3-6 day band pass filtered meridional wind of GANAL data over equatorial Indonesia at the height of 850 (lower panels) and 700 hPa (upper panels) along the latitude of Serpong (left panels) and Biak (right panels).

Fig. 8 can be done also for peak around 1 January at Biak and that around 5 January at Serpong shown in Fig. 7. Therefore wavlike variations observed at the two stations are both due to a wave with a westward phase velocity of 700 km day$^{-1}$ and a zonal wavelength of about 3500 km, which is quite similar to Q4DM found in Widiyatmi et al. (1999). This features are commonly found in the four time-longitude sections in Fig. 8, although (b) and (d) are for different altitudes, and (a) (c) and (b) (d) are for different latitudes. This may suggest that the wave structure is in phase in the vertical and in the north-south in the horizontal.

In energy–content spectral plottings for the period including the case mentioned above (DJF 96/97 panels in Figs. 5 and 6), we find the spec-
Fig. 9. Horizontal distributions of 4.5–5.5 day band pass filtered GANAL wind data at 700 hPa for 00 (left panels) and 12 (right panels) UT on 4–8 January 1997. + marks (from left to right) indicate the locations of Bukittinggi, Serpong and Biak. The vortex like shape is indicated by solid curves with arrow.
tra are distributed around four days or shorter at Serpong and around four days or longer at Biak. (It should be noted that the usual spectral density plottings in Fig. 4 are for heights lower than 700 and 850 hPa levels, and that the results include somewhat different features). If we take a look carefully on this time-longitude figure, we can see that some phases are changing the inclinations between the longitude range, and they seem steeper in the eastern side and flatter in the western side. This implies that wave parameters (not only period but also phase velocity and wavelength) may be slightly changed in this observational area. Therefore the results obtained by spectral analysis of BLR data and those obtained by filtered analysis of GANAL data are consistent. Furthermore, mid-January disturbances coming from the Pacific ocean seem to undergo a modification just in a region near Biak. This is different from the case of November 1992 reported by Widiyatmi et al. (1999). In November 1992 the disturbance was modified in the western part of the Indonesian region, while during January 1997 some disturbances could pass the elevated region of Indonesia, even Sumatera, smoothly and others were modified in the eastern part of the Indonesian region.

Figure 9 depicts horizontal distributions of 4.5 to 5.5 day band-pass filtered GANAL winds, which show westward moving vortex-like patterns from 4 to 8 January 1997 at 700 hPa. A pair of clockwise and counterclockwise circulation patterns appears on 4 January over the region covering Bukittinggi, Serpong and Biak. One day later these patterns propagate westward at a distance of about 700 km, and another counterclockwise circulation appears in the western side (around Biak). These three patterns of counterclockwise-clockwise-counterclockwise circulation move westward together with the phase speed of about 700 km day\(^{-1}\). We can also roughly confirm the zonal wavelength of about 3500 km from the zonal extent of pairs of clockwise-counterclockwise or counterclockwise-clockwise patterns. In this case we could identify these circulation patterns with mixed Rossby-gravity (MRG) wave like patterns.

4. Discussions

We shall discuss the possibility of the modification of equatorial waves over the Indonesian maritime continent. We have noticed that there are several differences between wave characteristics observed at the three stations. Concerning the zonal wind component at Biak shown in Fig. 2, we have noted that in general westerly dominated during this period (DJF 1996/97). The meridional wind component at Biak changed direction in the observed height range and duration, so that the background (mean) flow had only a weak meridional component and was almost westerly. When the westerly became weaker during late January to early February due to a negative (easterly) phase of ISO, the 3–6 day disturbances propagating over equatorial Indonesia look unclear as shown in Fig. 8, which may be also confirmed in Fig. 2. Considering the hierarchical structures of cloud clusters mentioned in Section 1, we may expect such a preference of activation of the 3–6 day disturbances depending upon the phase of ISO (or SSC), although detailed study is beyond the scope of this paper.

Moreover, interannual variations of the background flow may explain some of the differences of wave behaviours observed in individual years. Okamoto et al. (personal communication) have suggested a strange behavior of zonal wind at many stations in/around Indonesia during 1996–97. Westerly wind dominance was continued for a longer period and extended for a wider altitude range. Kikuchi et al. (personal communication) have found that the wider altitude range of the westerly appeared for a very large latitudinal range (until about 20°N) in March 1997. These are evidence of WWB prior to the 1997–98 El Nino, which was the biggest El Nino so far observed. Since such WWB in the western side of the Pacific ceases when El Nino starts, the annual variation of tropospheric zonal winds observed at Christmas Island (in the central Pacific) is strongest during La Nina and weakest during El Nino (Gage et al. 1996).

Concerning the longer than 10 days period disturbances revealed in the spectra in the previous section, at Biak the zonal component is much stronger than the meridional one. A similar but weaker feature is observed also at Bukittinggi, and at Serpong is the weakest. A speculation is that the longer (Kelvin-like) modes existing at Bukittingi (the westernmost station) are almost suppressed at Serpong (between the other two stations in longitude) and are activated again at Biak (the easternmost station). Another speculation is that the smaller variance of the Kelvin wave mode is expected at Serpong (6°S) than at Biak or at Bukittinggi (closer to the equator), by adopting the equatorial radius of deformation of 7° suggested by Takayabu (1994).
5. Concluding remarks

Based on BLR wind data during 1996–1999 at Bukittinggi, Serpong and Biak over equatorial Indonesia, general characteristics of spectral features for periods mainly between 1–10 days have been studied. The power spectra of both zonal and meridional wind components in the shorter periods (≤ 1 day) commonly show the tendency of −1 power law of frequency at all the three stations in all the observed periods. For the longer modes (≥ 10 days) the spectral density of the zonal wind is stronger (except for DJF 1996/97 at Serpong) than that of the meridional wind, which is most remarkable at Biak and the spectral slope of the zonal wind component is the steepest there. The westerly regime corresponding to these longer modes starts earlier at Serpong than at Biak, which suggests they propagate eastward like Kelvin-type waves and SCCs.

A 3–6 day component or Q4DM appears around 1.4 km height during DJF 1996/97 at Serpong, and at somewhat higher levels at Biak, although the about two-day component also exists clearly in the zonal wind component both at Serpong and at Bukittinggi. Based on bandpass filtered BLR data at Biak and Serpong and global objective analysis data, we have found that Q4DM observed at Biak and that at Serpong are a common westward moving wave with a zonal wavelength of about 3500 km. The meridional wind structure is almost in phase in the vertical and meridional directions, but such propagation and modification seem to be partly dependent on the distribution of a background westerly. Some of the Q4DM disturbances were able to pass the Indonesian maritime-continent while the others are suppressed in the eastern part of the Indonesian maritime-continent. The disturbance is more prominent at the 700 hPa level than at the 850 hPa level, and when the zonal wind at Biak is a relatively strong westerly.

In a future work we intend to study the modifications of these disturbances in more detail and their annual and interannual variations by using longer period data of the three BLRs as well as rawinsonde data launched over Indonesia.

Acknowledgments

The authors express their hearty thanks to JMA for providing GALAN data on this study. We also thank colleagues at BPPT, LAPAN and BMG who maintain the Serpong- and Bukittinggi-BLRs, and Mr. Sukmadrajat who maintains the Biak-BLR. Thanks are also due to two anonymous reviewers and the editor (Dr. Jun Matsumoto) for their constructive comments. The first author (Ipuk Widiyatmi) is supported by the Ropnaku Program of the Japan Society for the Promotion of Science (JSPS).

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