

Detection of Severe Turbulence Induced by Convection Using Numerical Modeling Over North Sumatra on 24 October 2017

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Abstract

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Severe turbulence,
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Lognormal mapping,
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This study diagnosed the severe turbulence event over North Sumatra on 24 October 2017 using numerical modeling and lognormal mapping of eddy dissipation rate (EDR). The Weather Research and Forecasting model was used to reproduce the convective environment associated with the event, and the simulated cloud field was evaluated against Himawari-8 visible imagery. The model reproduced the main convective band and the overall organization of the deep convective clouds reasonably well. Two raw turbulence diagnostics, $|w|$ and $|w|/Ri$, were then converted to EDR using the lognormal mapping technique. Both diagnostics showed distributions broadly consistent with a lognormal shape, indicating their applicability for EDR conversion. The resulting EDR fields showed that the $|w|$ based mapping produced a broader and more distinct moderate-to-severe turbulence area near the reported encounter location than the $|w|/Ri$ based mapping. These results suggest that the severe turbulence event was dynamically consistent with convection-induced turbulence and that the $|w|$ based EDR mapping, a more realistic representation of the reported turbulence intensity.

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INTRODUCTION

Atmospheric turbulence in the free atmosphere is one of the most important aviation weather hazards because it can produce in-flight injuries, operational disruption, and structural stress on aircraft (Gultepe, 2019). In general, aviation turbulence is classified according to its generation mechanism into clear-air turbulence, mountain-wave turbulence, and convectively induced turbulence (CIT) (Sharman & Pearson, 2017; Sharman, et al., 2014). Among these, CIT is particularly challenging for flight operations because it is closely related to transient convective processes and can occur both within clouds and in apparently clear air near active convection (Lane, et al., 2012).

Near-cloud turbulence (NCT), which is often regarded as a form of out-of-cloud CIT, has received increasing attention because aircraft may encounter severe turbulence above or adjacent to convective clouds even when the flight path itself is located outside the visible cloud boundary. Previous studies showed that such turbulence can be generated by convective gravity waves, localized shear instability, overturning isentropes, and reduced Richardson number in the environment surrounding deep convection (Sharman, et al., 2012; Trier, et al., 2012; Sharman, et al., 2014). In this regard, turbulence reported operationally as clear-air turbulence is not always unrelated to convection, particularly in regions where deep convective activity is widespread and rapidly evolving.

This issue is especially relevant over the Maritime Continent and the Indonesian region, where deep convection develops frequently under tropical environmental conditions. A notable case occurred over North Sumatra on 24 October 2017, when a commercial aircraft en route from Jakarta to Medan encountered severe turbulence during descent. Although the event was initially reported as clear-air turbulence, satellite analysis and subsequent numerical investigation indicated that large convective clouds were present near the turbulence location. High-resolution WRF-ARW simulation further suggested that the turbulence was associated with a near-cloud environment located about 300–700 m above the cloud top, where low Richardson number, enhanced turbulent kinetic energy (TKE), and vertical wind shear induced by convective outflow were evident. These results imply that the event is more appropriately interpreted in the framework of convection-induced severe turbulence rather than as purely nonconvective turbulence (Verayanti & Kusuma, 2021).

For objective evaluation of turbulence intensity, the cube root of eddy dissipation rate (EDR) has become the standard metric used in aviation meteorology because it provides an aircraft-independent measure of turbulence severity. In contrast to conventional indices such as vertical acceleration alone, EDR allows a more consistent comparison across aircraft types and observing systems (Sharman & Pearson, 2017; . EDR can be estimated directly from in situ aircraft data using the inertial-range technique based on the Kolmogorov spectrum, and such estimates have been widely used in automated turbulence reporting and climatological analysis. More recently, EDR-based approaches have also been extended to observational and forecasting applications for convective turbulence (Pearson & Sharman, 2017).

Despite its usefulness, direct observation of EDR is still limited in space and time, especially over regions where in situ flight data are sparse. For this reason, the use of numerical weather prediction output and remotely sensed variables as proxies for EDR has become an important research direction. Kim et al. demonstrated that radar spectral width associated with convective clouds can be converted to EDR through a lognormal mapping technique (LMT), producing values consistent with aircraft-derived EDR in a CIT event. Their study also showed that convection-permitting WRF simulation can reproduce the convective environment and provide model-based EDR estimates that are comparable with observationally derived EDR, despite some timing error in the simulated convection. This approach is meaningful because it provides a bridge between model-resolved convective structures and an objective turbulence metric used in aviation operations (Kim, et al., 2021).

However, application of this framework to turbulence cases over Indonesia remains very limited. The previous numerical study for the 24 October 2017 North Sumatra event mainly focused on the physical mechanism of near-cloud turbulence, including the role of cloud-top cooling, breaking gravity waves, low Richardson number, and vertical shear (Verayanti & Kusuma, 2021). Although that study successfully explained the dynamical environment of the event, the turbulence intensity was primarily discussed using dynamical indicators such as TKE and Richardson number rather than through an objective EDR-scale framework (Verayanti & Kusuma, 2021). Therefore, there is still a need to extend the diagnosis of this event by translating model-derived turbulence-related variables into EDR space, so that the diagnosed intensity can be interpreted more consistently within the operational aviation turbulence framework.

Based on the above, this study aims to diagnose the severe turbulence event over North Sumatra on 24 October 2017 using numerical modeling and lognormal EDR mapping. In particular, this study examines whether the convective environment reproduced by the numerical model can explain the observed severe turbulence and whether the corresponding model-derived diagnostics can be mapped into EDR values consistent with the reported event. By combining the dynamical interpretation of near-cloud turbulence with the objective EDR framework, this study is expected to provide a more physically consistent and operationally relevant assessment of convection-induced severe turbulence over Indonesia (Verayanti & Kusuma, 2021).

Overview of the 24 October 2017 Turbulence Event

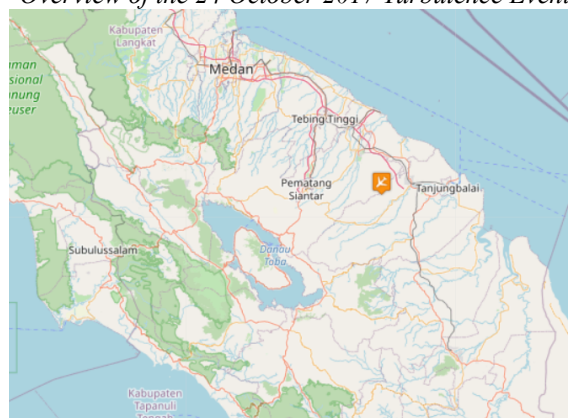


Figure 1. The estimated location of turbulence from NTSC report data.

According to KNKT (2017), a Batik Air Boeing 737-800 aircraft, registered PK-LBY, encountered severe turbulence while en route from Soekarno–Hatta International Airport, Jakarta (CGK), to Kualanamu International Airport, Medan (KNO). The aircraft departed from Jakarta at 15:25 LT (08:25 UTC). During the pre-flight preparation, the flight crew noted that the terminal weather forecast for Medan indicated a possibility of thunderstorms with visibility of 4 km.

During the descent phase, the pilot turned the aircraft to avoid clouds along the route toward Medan. When the crew recognized the potential for turbulence, the seat belt sign was turned on. At 09:59 UTC, the

aircraft encountered severe turbulence at an altitude of approximately 24,500 ft, and the autopilot was unintentionally disengaged. The turbulence lasted for about 20 s, during which the recorded vertical acceleration ranged from 2.334 g to -0.482 g. The pilot manually controlled the aircraft for 17 s, continued the descent, and then reengaged the autopilot.

After the turbulence encounter, the cabin crew checked the cabin condition and found that one passenger in the aft lavatory and one flight attendant in the aft galley were seriously injured. The aircraft then continued the descent, and the pilot informed the company operation personnel that the aircraft had encountered severe turbulence and that medical assistance was required upon arrival (KNKT, 2017).

RESEARCH METHOD

This study investigated the severe turbulence event over North Sumatra on 24 October 2017 using numerical model output and satellite observations of convective cloud structure. The numerical simulation was performed with the Advanced Research version of the Weather Research and Forecasting model (WRF-ARW), while the initial and lateral boundary conditions were obtained from the NCEP GDAS/FNL analysis with a horizontal resolution of 0.25° and a temporal interval of 6 h (Skamarock, et al., 2019). The model was integrated for 36 h from 00:00 UTC 23 October to 12:00 UTC 24 October 2017 in order to allow sufficient development of the mesoscale environment and the convective systems prior to the turbulence event (Verayanti & Kusuma, 2021).

The model output used in this study included three-dimensional wind components, potential temperature, pressure, geopotential height, vertical velocity, simulated radar reflectivity, and cloud-top temperature (Verayanti & Kusuma, 2021). These variables were used to examine the convective environment and to derive turbulence-related diagnostics associated with vertical motion and dynamical instability near the turbulence region. In particular, the magnitude of vertical velocity and the combined diagnostic of vertical velocity and gradient Richardson number were used as the main turbulence indicators (Kim, et al., 2021).

For observational reference, Himawari-8 visible imagery was used to identify the spatial pattern and temporal evolution of the convective clouds around the turbulence location. The observed cloud pattern was then qualitatively compared with the modeled cloud-top temperature and composite reflectivity in order to assess whether the WRF simulation reproduced the organization and development of the convective clouds associated with the event (Verayanti & Kusuma, 2021). In this study, radiosonde data were not used because the primary objective was to evaluate the convective cloud structure represented by the model and its relation to the diagnosed turbulence field.

The numerical simulation was conducted with WRF-ARW using two nested domains with horizontal grid spacings of 9 and 3 km, respectively, over the North Sumatra region, as shown in Figure 2. The outer domain was designed to represent the larger-scale atmospheric environment, while the inner domain was intended to resolve the convective structure more explicitly near the turbulence region (Verayanti & Kusuma, 2021).

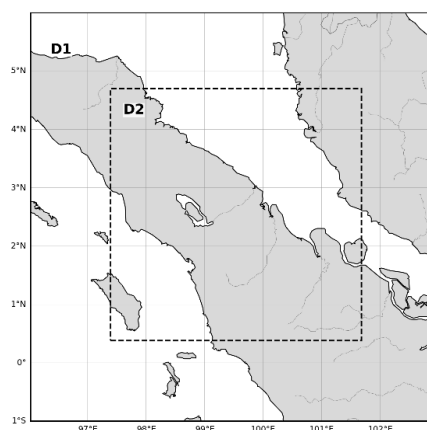


Figure 2. Locations of model domains 1 and 2.

The physical parameterizations were selected by combining the North Sumatra case configuration and the EDR-oriented modeling framework (Verayanti & Kusuma, 2021). The Thompson microphysics scheme was used to represent cloud microphysical processes associated with deep convection and mixed-phase hydrometeors (Thompson, et al., 2009). The Mellor-Yamada Nakanishi Niino planetary boundary layer scheme was applied to represent turbulent vertical mixing in the lower atmosphere (Nakanishi & Niino, 2009).

Longwave and shortwave radiation were calculated using the Rapid Radiative Transfer Model for GCMs, and land-surface processes were represented by the Unified Noah land-surface model (Chen & Dudhia, 2001). The Kain-Fritsch cumulus parameterization was applied only to the 9 km outer domain, whereas convection was treated explicitly in the 3 km inner domain (Kain, 2004). This configuration was used to maintain consistency with the model-based turbulence diagnosis of Kim et al. while preserving the case setup used for the North Sumatra event.

Table 1. Configuration for WRF-ARW

Zone and Options	Domain 1	Domain 2
Resolution	9 km	3 km
Time step	30 s	10 s
Microphysical scheme	Thompson [13].	
Boundary layer scheme	MYNN [14].	
Radiation scheme	RRTMG for longwave and shortwave radiation [15].	
Land surface process	Unified Noah land-surface model [16].	
Cumulus parameterization scheme	Kain-Fritsch [17].	–

To assess the realism of the simulated convection, the horizontal cloud pattern in Himawari-8 visible imagery was compared with the modeled cloud-top temperature and composite reflectivity. Agreement in the location, organization, and development of the convective clouds was used as the main basis for evaluating whether the model was able to reproduce the convective environment associated with the turbulence event (Verayanti & Kusuma, 2021).

The turbulence diagnosis was then performed using model-derived vertical velocity and the gradient Richardson number (Kim & Cun, 2012). The gradient Richardson number was calculated as:

$$Ri = \frac{\frac{g}{\theta} \frac{\partial \theta}{\partial z}}{\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2}$$

Where g is gravitational acceleration, θ is potential temperature, z is height, and u and v are the horizontal wind components. Low values of Ri indicate an environment favorable for dynamical instability and turbulence generation, particularly when strong vertical shear coexists with weak static stability. Following Kim et al., two raw turbulence diagnostics were considered, namely the magnitude of vertical velocity $|w|$ and the combined diagnostic $|w|/Ri$, because these variables are effective for detecting convectively induced turbulence in model output (Kim., et al., 2021).

The raw turbulence diagnostics were converted into the cube root of eddy dissipation rate, EDR, using the lognormal mapping technique. This method assumes that both the turbulence diagnostic and EDR follow a lognormal distribution and relates them by:

$$\ln(EDR) = a + b \ln(D)$$

where D denotes the raw turbulence diagnostic. The slope b and intercept a were computed as:

$$b = \frac{C_1}{SD[\ln(D)]}$$

and

$$a = C_2 - b \langle \ln(D) \rangle$$

where $SD[\ln(D)]$ is the standard deviation of the natural logarithm of the diagnostic, $\langle \ln(D) \rangle$ is its mean, and C_1 and C_2 are the climatological constants of the EDR distribution (Pearson & Sharman, 2017). Following Sharman and Pearson, $C_1 = 0.4235$ and $C_2 = -2.248$ were used for the EDR conversion. The distribution of each raw diagnostic was constructed in logarithmic space using 50 bins, and the fitting was focused on the right-hand side of the histogram to emphasize the range associated with light-or-greater turbulence, as in Kim et al.. After the coefficients were obtained, EDR was estimated directly from the model-derived turbulence diagnostic using the above mapping equation (Sharman & Pearson, 2017; Kim., et al, 2021).

The final analysis focused on the horizontal and vertical distribution of the modeled EDR in relation to the simulated convective cloud field. Areas of enhanced EDR were interpreted together with cloud-top temperature, reflectivity, vertical velocity, and Richardson number to determine whether the severe turbulence event over North Sumatra was dynamically consistent with convection-induced turbulence in the near-cloud environment (Verayanti & Kusuma, 2021).

RESULT AND DISCUSSION

Figure 3 shows the horizontal distribution of the observed and simulated convective cloud fields over North Sumatra at 10:00 UTC. As shown in Figure 3c, the Himawari-8 visible image indicates a well-organized convective cloud field extending from the northwestern part of the domain toward the southeastern part of North Sumatra. The observed cloud pattern is characterized by a broad convective band over the western and central parts of the region, with more localized convective elements embedded to the south of Lake Toba. Figure 3b shows that the WRF cloud-top temperature field reproduces this general distribution reasonably well, as indicated by the elongated area of low cloud-top temperature over the same sector. In particular, the model captures the major convective zone extending from the west of Lake Toba to the southeastern part of the domain, where colder cloud tops are evident.

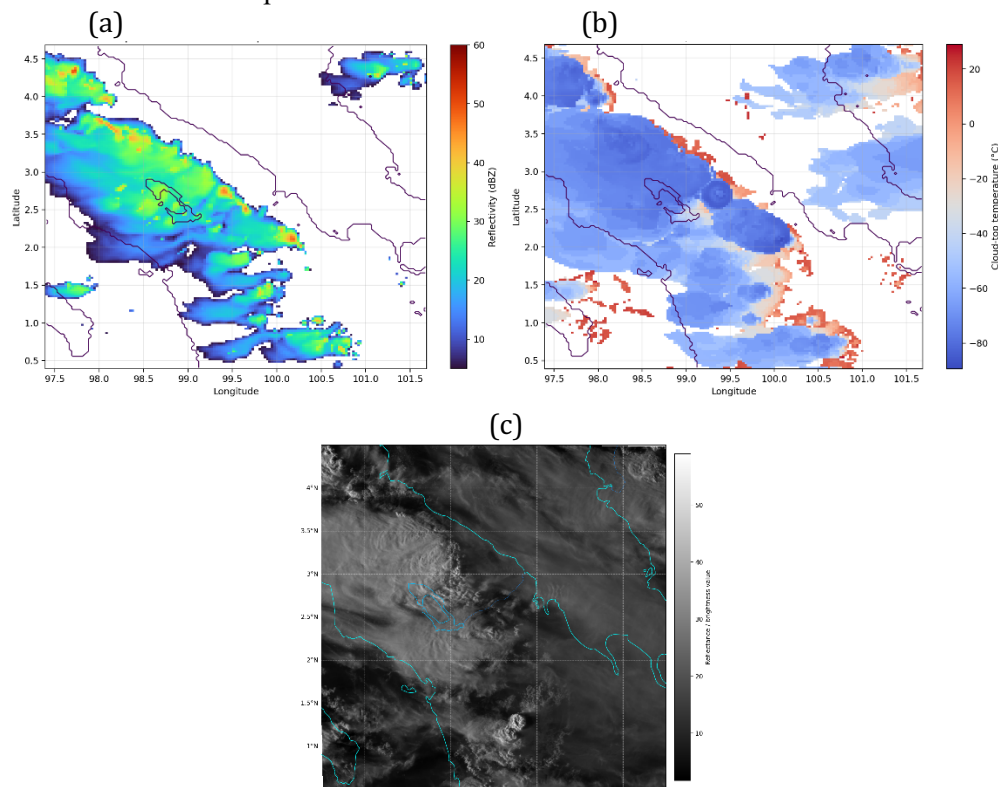


Figure 3. Comparison of the observed and simulated convective cloud fields at 10:00 UTC on 24 October 2017 over North Sumatra: (a) WRF column-maximum reflectivity, (b) WRF cloud-top temperature, and (c) Himawari-8 visible band image.

Figure 3a further shows that the simulated column-maximum reflectivity also exhibits a convective band with enhanced reflectivity along the same northwest–southeast orientation. This is broadly consistent with the cloud pattern seen in Figure 3c, which suggests active deep convection over the western, central, and southern parts of the study area. The reflectivity maxima in the model correspond reasonably well to the bright and textured cloud features in the satellite image, indicating that the model reproduced the main convective cores and their overall spatial organization.

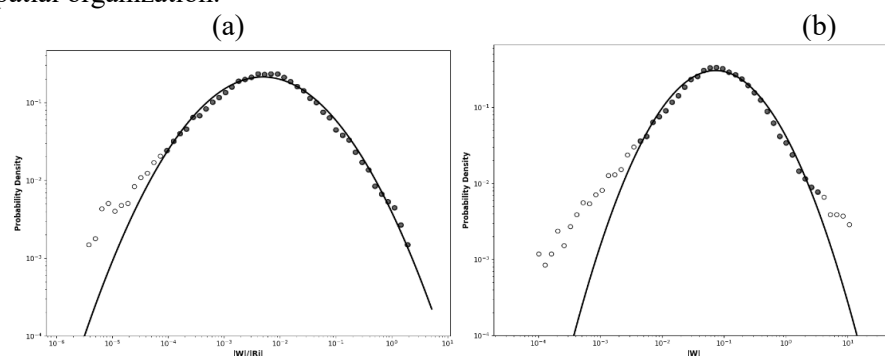


Figure 4. Histograms of the raw turbulence diagnostics and the corresponding lognormal fit curves: (a) $|w|/Ri$ and (b) $|w|$. Open circles indicate the histogram values, and the solid line denotes the fitted lognormal probability density function.

Figure 4 shows the histograms of the two raw turbulence diagnostics and their corresponding lognormal fit curves. In both panels, the distributions are broadly consistent with a lognormal shape, with the fitted curve matching the main body of the histogram reasonably well. This result indicates that both $|w|/Ri$ and $|w|$ have statistical characteristics suitable for conversion to EDR using the lognormal mapping technique.

As shown in Figure 4a, the $|w|/Ri$ diagnostic exhibits a well-defined peak and a relatively smooth decrease toward the higher values, suggesting that the fitted lognormal curve captures the dominant part of the distribution. Figure 4b shows a similar behavior for $|w|$, although some deviation appears at the lower and upper tails. Overall, the agreement between the histogram and the fitted curve suggests that both diagnostics are appropriate for the subsequent EDR conversion, with the main distribution of the raw model output being represented satisfactorily by the lognormal assumption.

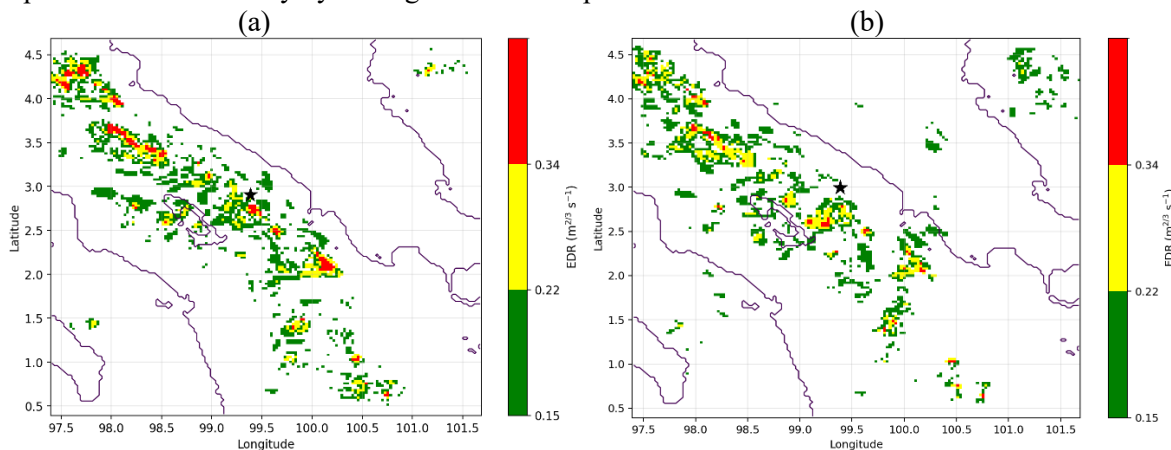


Figure 5. Horizontal distribution of EDR derived from the lognormal mapping technique at the turbulence event time: (a) EDR from $|w|$ and (b) EDR from $|w|/Ri$. The black star indicates the turbulence encounter location. Green, yellow, and red correspond to light, moderate, and severe turbulence, respectively.

Figure 5 shows the horizontal distribution of EDR derived from the two raw turbulence diagnostics by the lognormal mapping technique. The turbulence location is marked by the black star. In Figure 5a, the EDR derived from $|w|$ indicates a broader area of enhanced turbulence intensity around the event location, including moderate-to-severe values. This distribution is more consistent with the reported severe turbulence because the diagnosed high-EDR region is represented more clearly near the encounter point.

By contrast, Figure 5b shows that the EDR derived from $|w|/Ri$ produces only a very limited severe-turbulence area near the event location. Although moderate and light turbulence are still identified around the convective region, the severe signal is much smaller and less distinct than that in Figure 5a. This suggests that, for this case, the EDR estimated from $|w|$ represents the severe turbulence encountered more effectively than the EDR estimated from $|w|/Ri$. Therefore, the $|w|$ based lognormal mapping, it appears to provide a more realistic depiction of the turbulence intensity in the vicinity of the observed event.

CONCLUSION

The severe turbulence event over North Sumatra on 24 October 2017 was closely associated with a convective cloud environment reproduced by the WRF simulation. The comparison with Himawari-8 visible imagery showed that the model captured the main convective band and the overall spatial organization of the observed deep convection with reasonable fidelity. The two raw turbulence diagnostics, $|w|$ and $|w|/Ri$, both satisfied the statistical requirement for EDR conversion through lognormal mapping. However, the EDR derived from $|w|$ represented the turbulence encountered more effectively, as it showed a broader and clearer area of moderate-to-severe turbulence around the reported event location. By contrast, the EDR derived from $|w|/Ri$ produced only a limited severe-turbulence signal near the encounter point. Overall, the results indicate that the event can be interpreted as convection-induced severe turbulence and that $|w|$ based lognormal mapping is more suitable for representing the intensity of this case.

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