



RELATIONSHIPS BETWEEN AIRCRAFT ROUTES AND TURBULENCE-RELATED WEATHER DATA

Yoichi Nakamura¹ & Atsushi Senoguchi¹

¹Air Traffic Management Department, Electronic Navigation Research Institute (ENRI)
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Abstract

Turbulence is one of the major safety concerns in aviation and the future air traffic management (ATM) system needs to manage aircraft trajectories considering weather impacts including turbulence on aircraft operation. However, an accurate prediction of turbulence is hard since it can be caused by many factors and the available information is limited. While Eddy Dissipation Rate (EDR) is one of the important metrics of turbulence, the EDR data can only be along the trajectories of the equipped aircraft and the number of data is small since the equipped aircraft is limited. To manage trajectories using turbulence information strategically, objective indices that can be used for trajectory planning are necessary. Hence, this paper examined the TBindex and precipitation data at the points where EDR data were recorded. While only precipitation data could not explain the area where aircraft encountered turbulence, it was demonstrated that TBindex has the potential that can be used for generating turbulence avoidance trajectories.

Keywords: Air Traffic Management, Severe Weather Avoidance, Turbulence, EDR

1. Introduction

Turbulence is one of the major safety concerns in aviation. Severe turbulence could lead to injuries of passengers and crew. It is desirable that all the aircraft avoid the area with strong turbulence for operational safety and passenger comfort. On the other hand, an accurate prediction of turbulence is difficult since it can be caused by many factors and the available information is limited. One of the available observation data of turbulence can be obtained from a pilot report (PIREP)[1]. When an aircraft in flight encounters turbulence, the pilot reports its location and intensity. However, the intensity is subjective and the time lag may lead to inaccuracy of the location. Recently, applications of Eddy Dissipation Rate (EDR) data have been propelled for more accurate information. EDR is a measure of turbulence, which is calculated and reported automatically by the aircraft [2]. The International Air Transport Association (IATA) has developed Turbulence Aware that provides pilots and flight dispatchers with EDR data for safer flights [3]. While EDR data is actual and accurate, the EDR data can only be reported along the trajectories of the equipped aircraft. The number of data is small since the equipped aircraft is limited. For the future improvement of Air Traffic Management (ATM) system, aircraft trajectories should be planned considering turbulence information strategically. For this purpose, objective indices that can be used for trajectory management are necessary.

There are many researches to estimate turbulence [4-7]. EDR was estimated on the basis of the wind speed variance and it was demonstrated that the proposed method measured EDR with reasonable accuracy [4]. The EDR estimation method with quick access recorder (QAR) data was proposed in [5]. EDR was compared to vertical gust velocity and strong correlations were demonstrated [6]. EDR was estimated using the content of the Mode-S EHS/ADS-B in [7]. On the other hand, the accuracy and coverage area strongly depend on the methods and available data source. Therefore, we aim to establish the objective indices using turbulence related data for Japanese airspace. As a first step, EDR data was compared to two different kinds of data; TBindex [8] developed by Japan Meteorological Agency (JMA) and precipitation data [9] observed by weather

radar. Through the comparison between the data, the availability of the data for the future ATM system including a management of severe weather avoidance trajectories was examined.

2. Weather Data

We used three kinds of data related to turbulence: EDR, TBindex, and precipitation data. The details are explained in this section.

2.1 EDR

EDR is the official index defined in ICAO for measuring turbulence [8]. We used EDR data observed around Japan region collected by IATA from July 1, 2021 to December 31, 2021. EDR data includes time, latitude, longitude, pressure altitude, EDR peak and average values. Figure 1 shows the example of distribution of EDR data. Figure 2 shows the histogram of EDR peak values. Turbulence shall be considered severe, moderate, light, nil when the peak value of the cube root of EDR exceeds 0.7, above 0.4 and below or equal to 0.7, above 0.1 and below or equal to 0.4, and below or equal to 0.1, respectively. As these figures show, the number of data that corresponds to moderate or more was limited and most of the data recorded was categorized as light and nil.

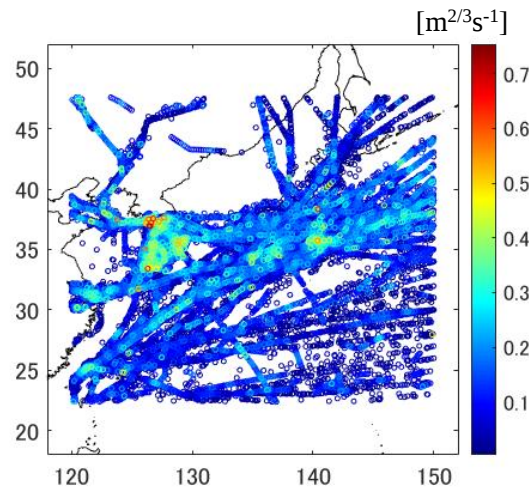


Figure 1 – Distribution of EDR data.

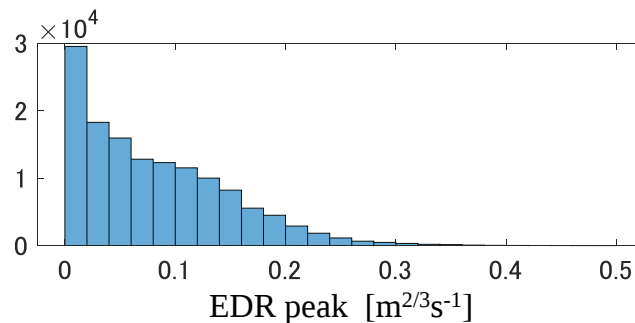


Figure 2 – Histogram of EDR peak values.

2.2 TBindex

TBindex was developed to predict various kinds of turbulence including Clear-air Turbulence (CAT) and provided by JMA [9]. The TBindex is defined to predict moderate or greater turbulence optimally at the threshold 3.0. Figure 3 shows an example of TBindex at flight level (FL) 250. As the figure shows, the TBindex covering Japan is provided. There is a high probability that the turbulence is observed at the area where TBindex is more than three. TBindex is calculated using numerical

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weather prediction (NWP) models. The initial data of NWP is every three hours and up to ten hours predictions can be used.

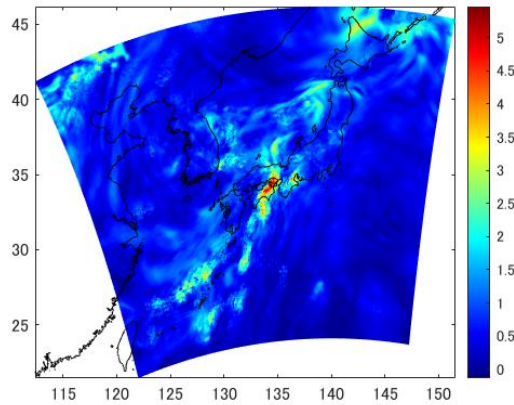


Figure 3 – Distribution of TBindex at FL250.

2.3 Precipitation

The precipitation data provided by JMA [10] was used for this study. The Grid Point Value (GPV) of precipitation intensity and echo top can be used. The intensity data with 1 km resolution and the echo top data with 2.5 km resolutions for the area covering Japan are provided every 10 minutes. Figure 4 shows an example of precipitation intensity and echo top distributions. Radar echo intensity observed by weather radar is converted to precipitation intensity. The GPV covers the latitudes range from 20 to 48 N and longitudes range from 118 to 150 E. The gray area denotes outside of weather radar coverage and white area means no echo is observed. The echo top data is provided by odd-numbered altitude in km. Therefore, it should be noted that the echo top values include the error of about 1 km (3,281 ft). Also, while clouds with the turbulence like a cumulonimbus cloud consisting of droplets or ice particles can be detected with the precipitation data, CAT cannot be detected.

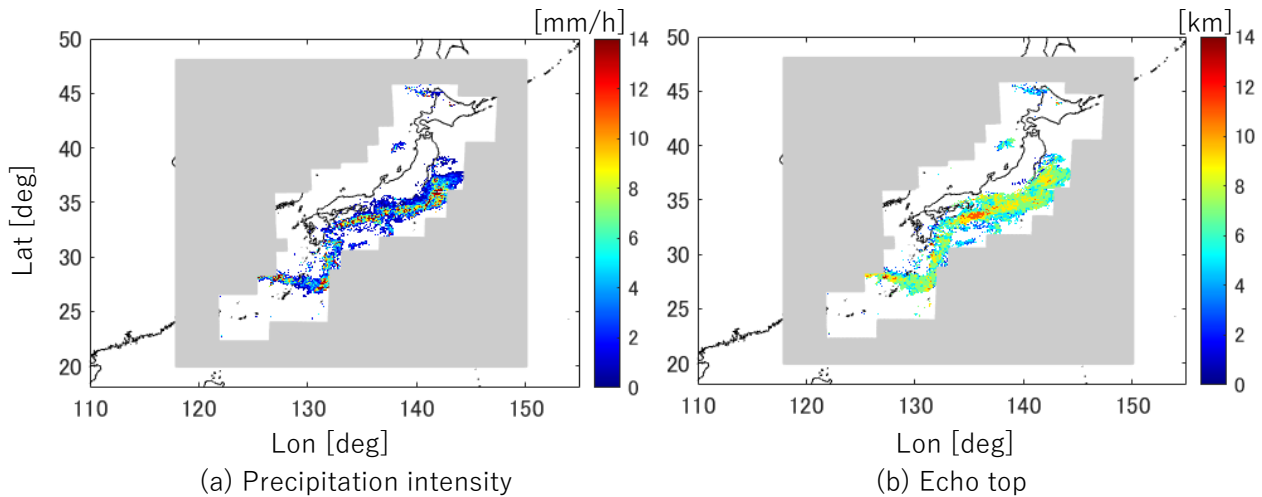


Figure 4 – Distribution of precipitation intensity and echo top.

3. Methods

We compared three kinds of weather data; EDR, TBindex, and precipitation intensity. Since the coverage area of each data is different, the overlapped area of coverage areas is focused on as shown in figure 5. The green and blue areas denote the areas of TBindex and weather radar, respectively. The magenta area denotes the overlapped area of the two. The EDR data recorded

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inside the target area was extracted for this study. For each time, latitude, longitude, pressure altitude of the EDR data points, TBindex and precipitation values were extracted.

To get TBindex values at the arbitrary time and points, TBindex was interpolated in time and space by liner interpolation. Here, there are multiple TBindex data that represents the same time; for example, five hours prediction data generated by the initial data at 3:00 and two hours prediction data generated by the initial data at 6:00 both represent the data at 8:00. For the interpolation, we used the combination of two data so that the prediction time is minimized since the accuracy tends to decrease as the prediction time gets longer.

To get precipitation values at the arbitrary time and points, the intensity and echo top data was interpolated in time and space by liner interpolation. The pressure altitude of the EDR point is converted to geometric altitude. For each pressure altitude, the geopotential height was obtained using Meso Scale Model (MSM) provided by JMA [11]. The geometric altitude was obtained using the following equation [12]:

$$h = \frac{rH}{r-H} \quad (1)$$

where r is the nominal earth's radius, h and H denote geometric height and geopotential height, respectively. The precipitation with echo top that is relatively high compared to the flying altitude is considered to affect the aircraft. Hence, precipitation data is filtered comparing the altitude of points and echo top.

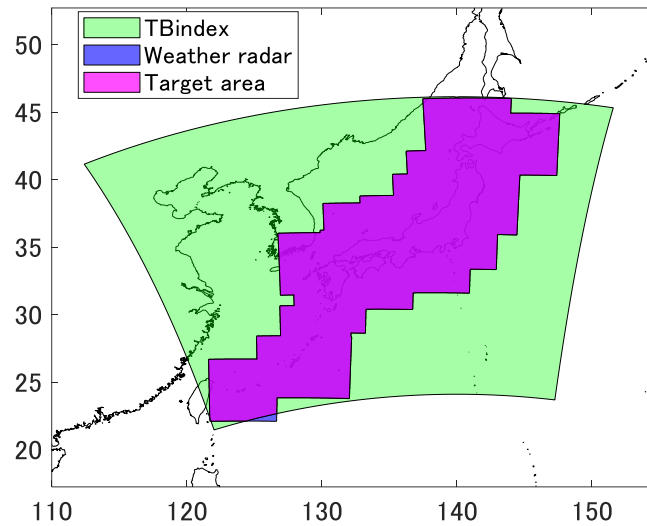


Figure 5 – The data coverage areas.

4. Results

4.1 Analyzed Data

We extracted 27,462 points where EDR data was recorded. Table 1 shows the number of extracted data with respect to categories defined by ICAO [3]. As the table shows, the most of extracted data was categorized as nil and no EDR data corresponding severe was recorded.

Table 1 – Extracted EDR data with respect to categories

Nil (≤ 0.1)	Light (0.1-0.4)	Moderate (0.4-0.7)	Severe ($0.7 <$)
21,506 (78.31 %)	5,936 (21.62 %)	20 (0.07 %)	0

4.2 Relationships between EDR and TBindex

TBindex values where EDR values were recorded were examined. Figure 6 shows the scatter plot

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of EDR peak values and TIndex. The correlation coefficient was 0.36. Since there was no strong correlation between two data from the figure, TIndex values are divided into five categories and the ratio included in each EDR categories was examined as shown in Figure 7. TIndex values of 15 percent of the data among the extracted points that were categorized as moderate were higher than 3.0. In the same way, the TIndex values of 10 percent of the data that were categorized as moderate were less than 0.5. While the TIndex is defined to predict moderate or greater turbulence at the threshold 3.0, the percentage that the TIndex could predict accurately was small. On the other hand, it was indicated that the TIndex values tend to be high as turbulence gets stronger. For example, TIndex values of Approximately 50 percent of light or greater turbulence were higher than 1.0 while only that of 25 percent of nil were higher than 1.0.

Since TIndex is a prediction and time interval of initial data is three hours, some prediction errors occur. Additionally, it is difficult to predict turbulence at a specific point. To predict turbulence area more accurately for future operation, further consideration is necessary.

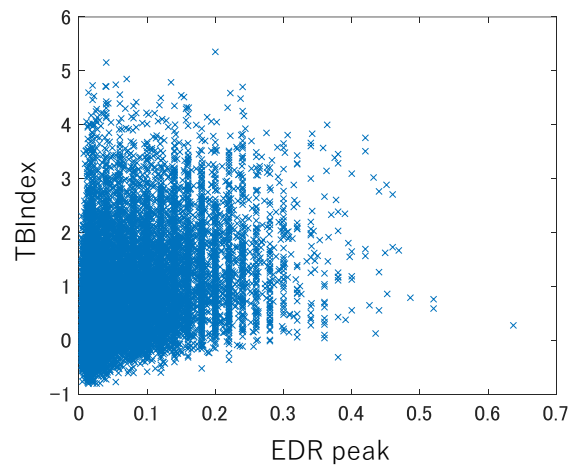


Figure 6 – Relationships between EDR peak values and TIndex.

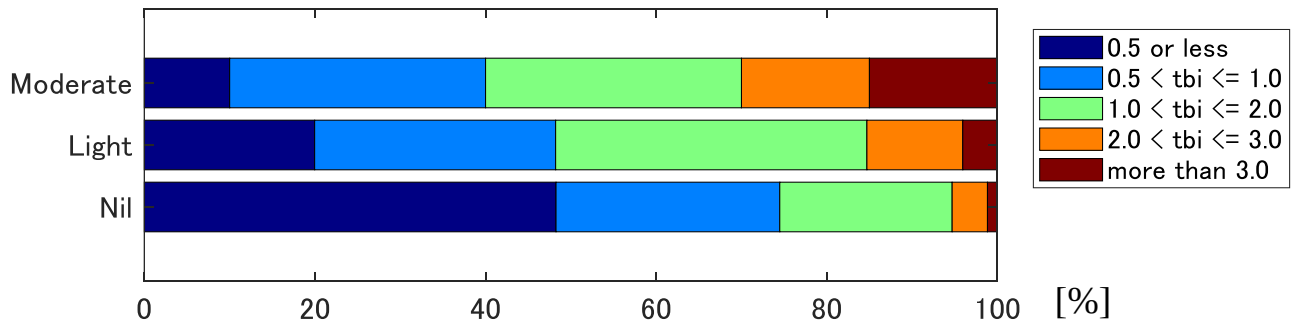


Figure 7 – Ratios of TIndex for each EDR category.

4.3 Relationships between EDR and Precipitation

Figure 8 shows the scatter plot of EDR peak values and precipitation intensity. Here, only the precipitation data with the echo top is higher than a specific altitude is considered and vertical thresholds are set to 0 km and 3 km. The vertical threshold 3 km means that the precipitation data whose echo top is higher than the flying altitude subtracted by three is considered as target data. The number of target data reduces as the vertical threshold decreases. In the figure, N denotes the number of target data. The correlation coefficients of vertical thresholds of 0 km, 3 km were 0.26, 0.14, respectively. Since the number of target data was 9579 out of 27462 even when the vertical threshold was set to 3 km, it was demonstrated that there was no precipitation at most of the points where EDR data was recorded. In addition, correlation coefficient was low. Figure 9 shows the ratio of precipitation intensity in the same way as figure 6. The precipitation intensity values (pi) are divided

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into five categories. N/A means the ratio of the data where no precipitation affecting aircraft is observed. The precipitation intensity tends to be high as turbulence gets stronger while there were few precipitations. In the aircraft operations, most of the aircraft avoid the area with high precipitations for operational safety. This could be one of the reasons that there was no precipitation for most of the data. On the other hand, it was demonstrated that the light or greater turbulence occurred where there was no precipitation. This suggests that to only precipitation is not enough for appropriate severe weather avoidance trajectory.

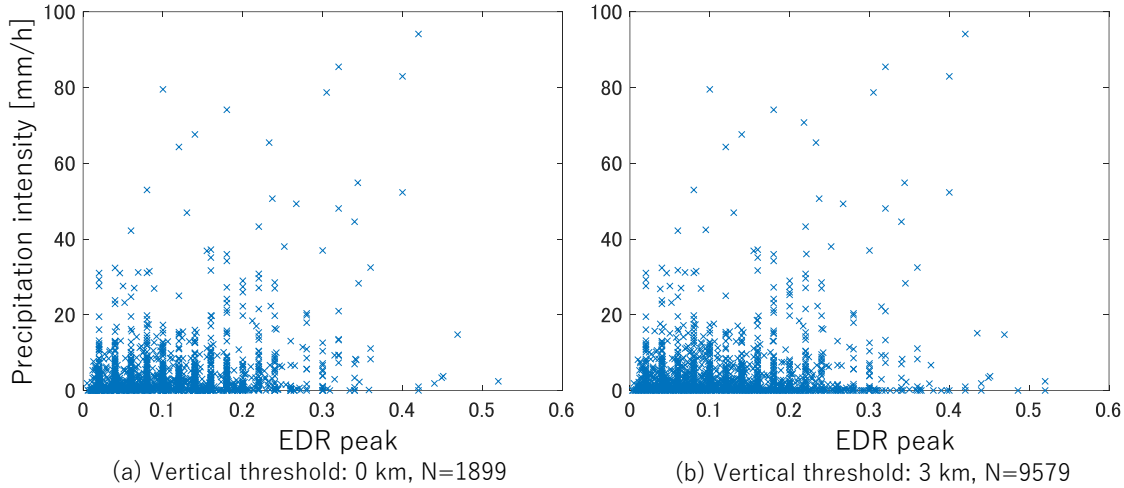


Figure 8 – Relationships between EDR peak values and precipitation intensity.

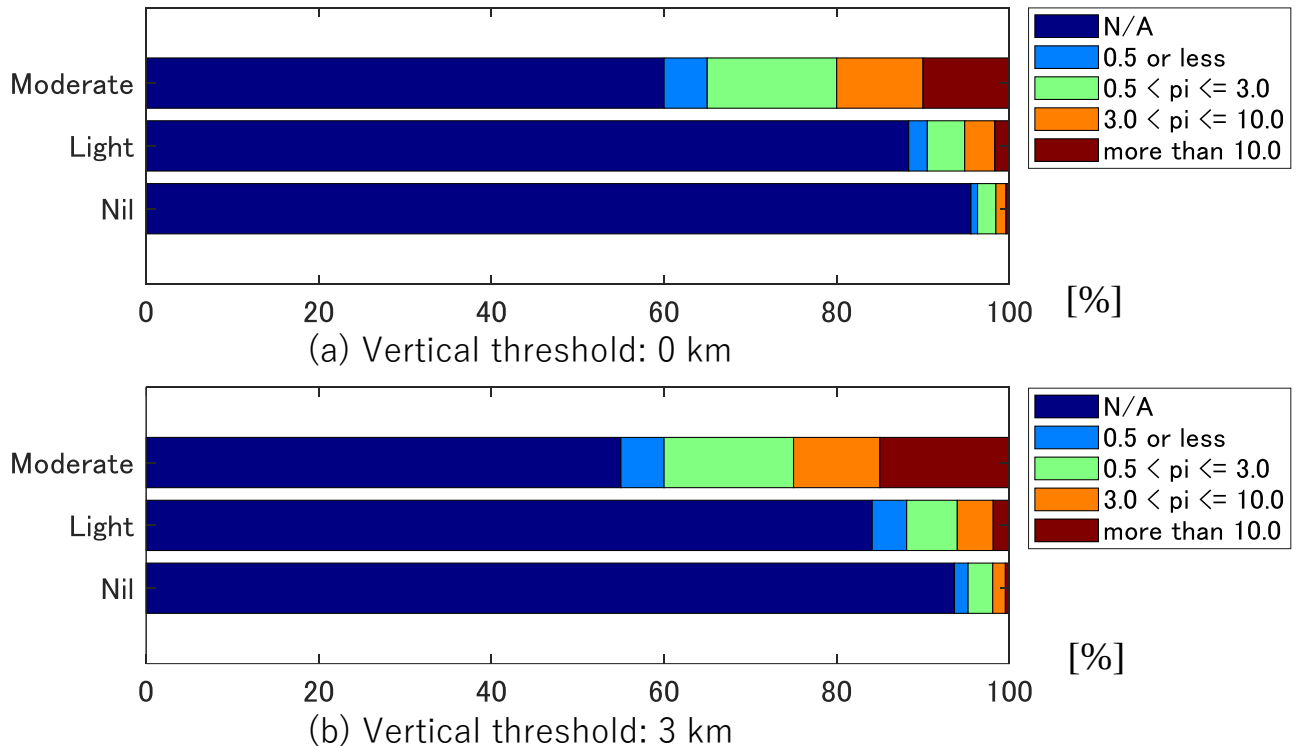


Figure 9 – Ratios of precipitation intensity for each EDR category.

4.4 Discussion

Figure 10 shows an example of traffic near the point when and where the EDR was recorded. Figure 10 (a) shows the TBindex at FL290 and the five routes of aircraft that flew near the point and (b) shows the time history of altitude. The point the EDR was recorded is depicted in magenta and its

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peak value was 0.452 which is categorized as moderate. As the figure shows, three aircraft (no. 2, 3, 5) avoided the area horizontally. Aircraft no. 4 changed the altitude before reaching the point where the EDR was recorded. In this case, it was clearly shown that all the aircraft avoided the area where TIndex is high.

Additionally, it was also shown that some aircraft changed their altitudes. To explore the reason, TIndex at different flight levels at the same time are shown in figure 11. From the figure, it was shown that overall TIndex values were high at higher altitude but the location where the TIndex values were weak is different locally. This indicates that TIndex can be used for planning appropriate trajectories that avoid the area of turbulence.

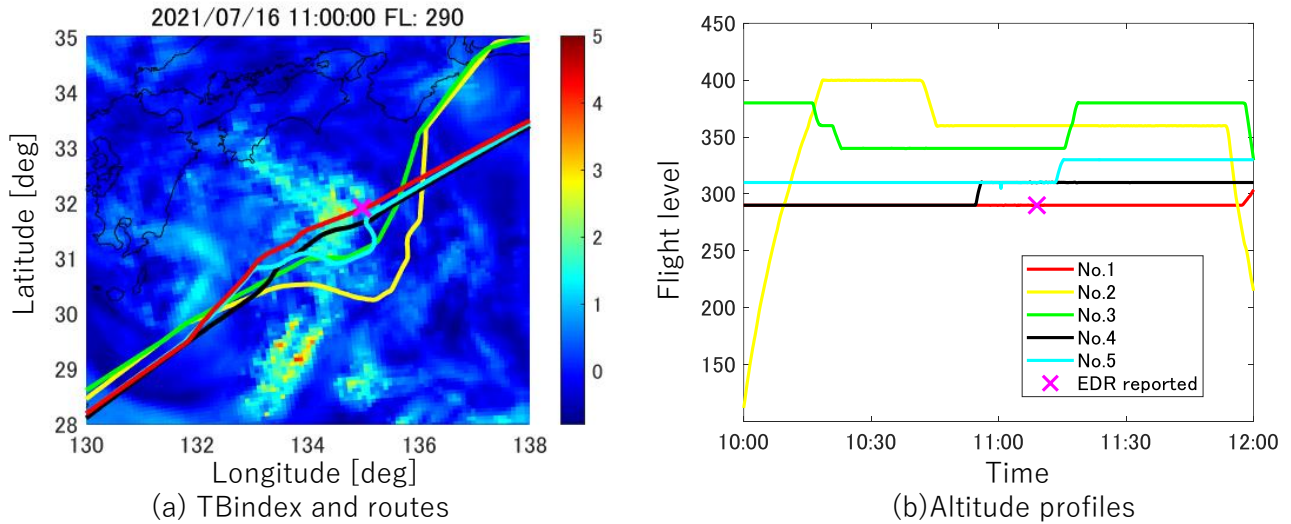


Figure 10 – Trajectories of aircraft flying near the turbulence.

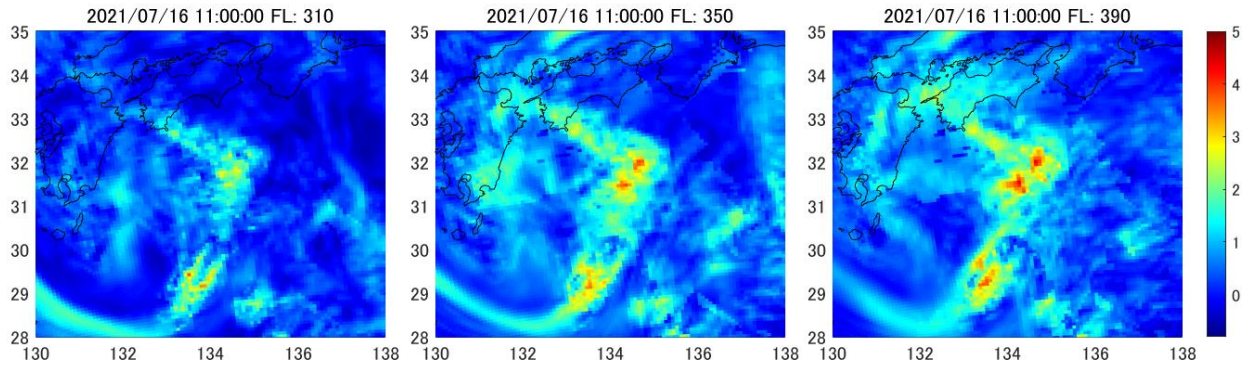


Figure 11 – TIndex at different flight levels.

On the other hand, figure 12 shows another example of the relationships between TIndex and routes, precipitation and route, respectively. Magenta marker denotes the point where EDR was recorded and the EDR peak value was 0.637. In this case, the TIndex of surrounding area where the EDR was recorded was weak. Also, there was no precipitation. Additionally, EDR data was not recorded at the point where the TIndex values was high. To generate turbulence avoidance route, further consideration including additional information is indispensable.

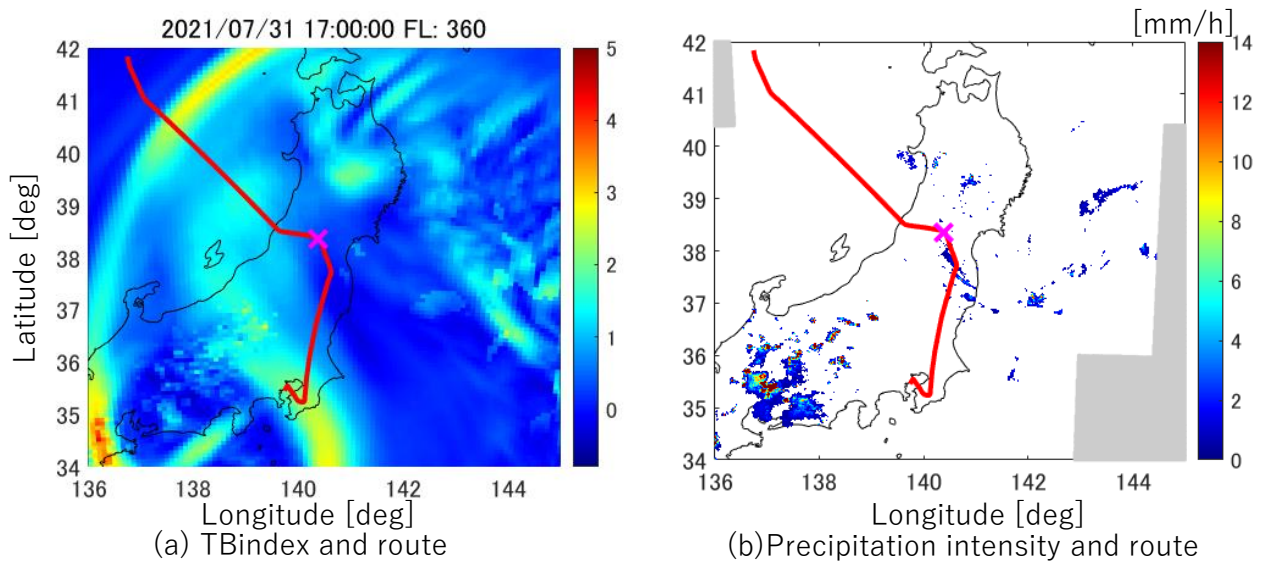


Figure 12 – TIndex and precipitation surrounding the area EDR was recorded.

5. Conclusion

This paper examined the TIndex and precipitation data at the points where EDR data were recorded. While only precipitation data could not explain the area where aircraft encountered turbulence, it was demonstrated that TIndex has the potential that can be used for generating turbulence avoidance trajectories. Since TIndex provides turbulence predictions for three-dimensional space, it could be possible to generate optimal trajectory including horizontal and vertical avoidance. On the other hand, the prediction accuracy of turbulence is not enough when TIndex is only considered. Hence, further analysis is indispensable to make it feasible that the trajectory management considering turbulence information.

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7. Contact Author Email Address

mailto: y-nakamura@mpat.go.jp

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