Turbulence Observation and Simulation

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2024/06/28 @ AOGS 2024

Motivation

- Turbulence categories
  Convective turbulence
  1. Mountain waves
  2. Clear air turbulence
  3. Wind shear turbulence
  4. Mechanical turbulence

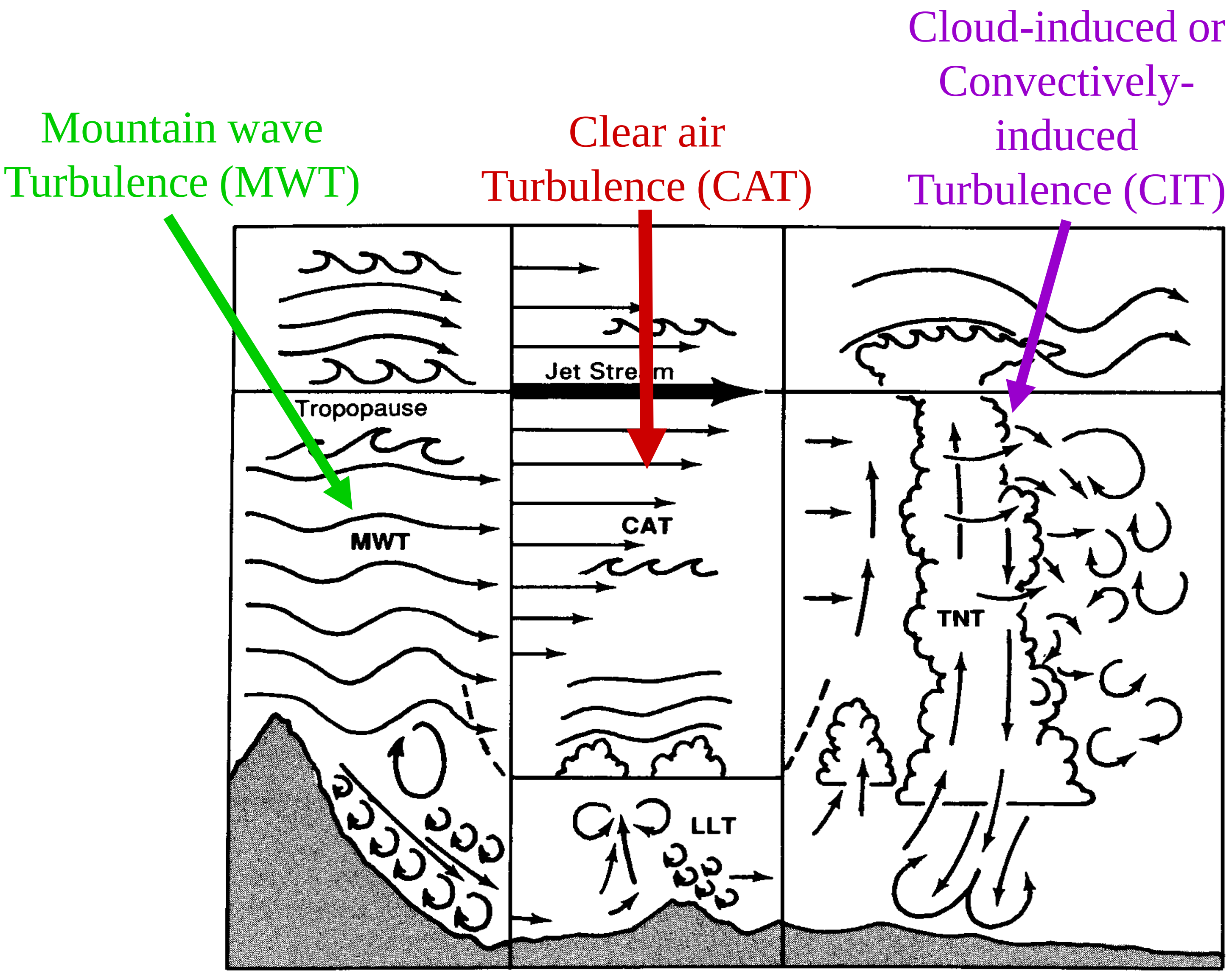


Figure 1-16. Aviation turbulence classifications. This figure is a pictorial summary of the turbulence-producing phenomena that may occur in each turbulence classification.

P. Lester, "Turbulence – A new perspective for pilots," Jeppesen, 1994

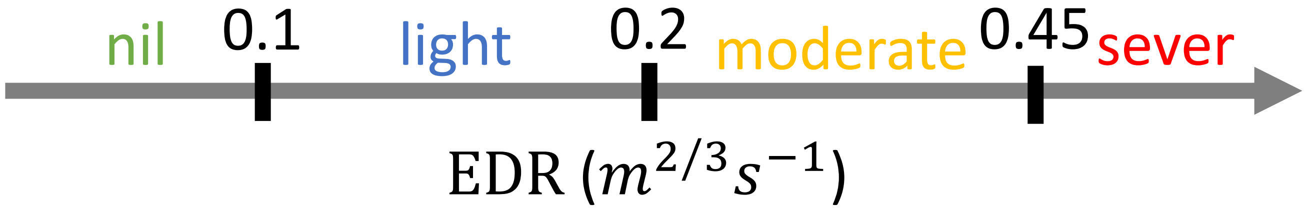
Atmospheric Turbulence Intensity Metric

- **EDR** is the official ICAO and WMO atmospheric turbulence intensity metric. ICAO Annex3 (ICAO 2010): the turbulence shall be reported in terms of the cube root of eddy dissipation rate ($EDR = \epsilon^{\frac{1}{3}}$)
- The EDR is an aircraft-independent measure of turbulence.
- The relationship between the EDR value and the perception of turbulence is a function of aircraft type, and the mass, altitude, configuration and airspeed of the aircraft.

Table 1. Turbulence intensity scaling with respect to eddy dissipation rate (EDR) values.

Turbulence Indicator		Turbulence Peak EDR ($\varepsilon^{\frac{1}{3}}$ unit: $m^{2/3}s^{-1}$)						
		<0.1	0.1–0.2	0.2–0.3	0.3–0.4	0.4–0.5	0.5–0.8	>0.8
Turbulence mean EDR ($\varepsilon^{\frac{1}{3}}$ unit: $m^{2/3}s^{-1}$)	<0.1	0	1	3	6	10	15	21
	0.1–0.2		2	4	7	11	16	22
	0.2–0.3			5	8	12	17	23
	0.3–0.4				9	13	18	24
	0.4–0.5					14	19	25
	0.5–0.8						20	26
	>0.8							27
Turbulence intensity		steady flight	weak turbulence		moderate turbulence		strong turbulence	

(Huang et al. 2019)

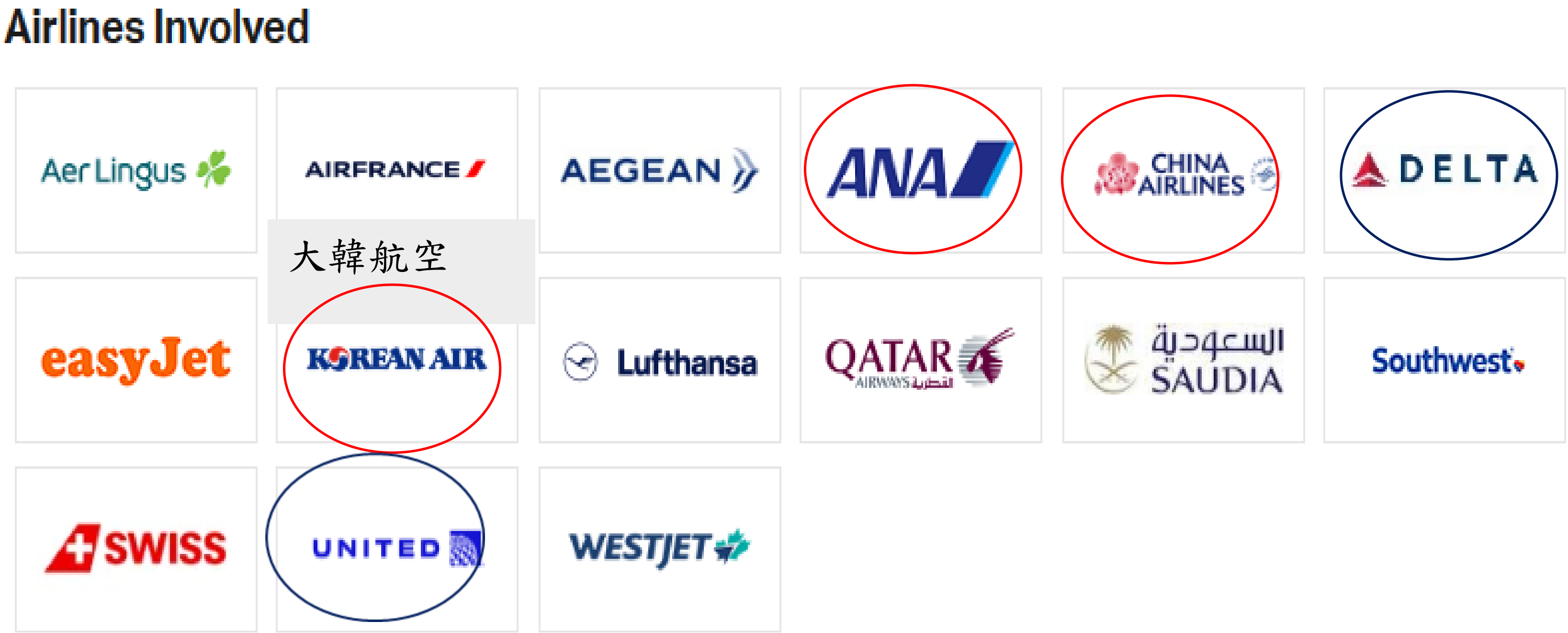


(ICAO 2010)

Motivation(1)

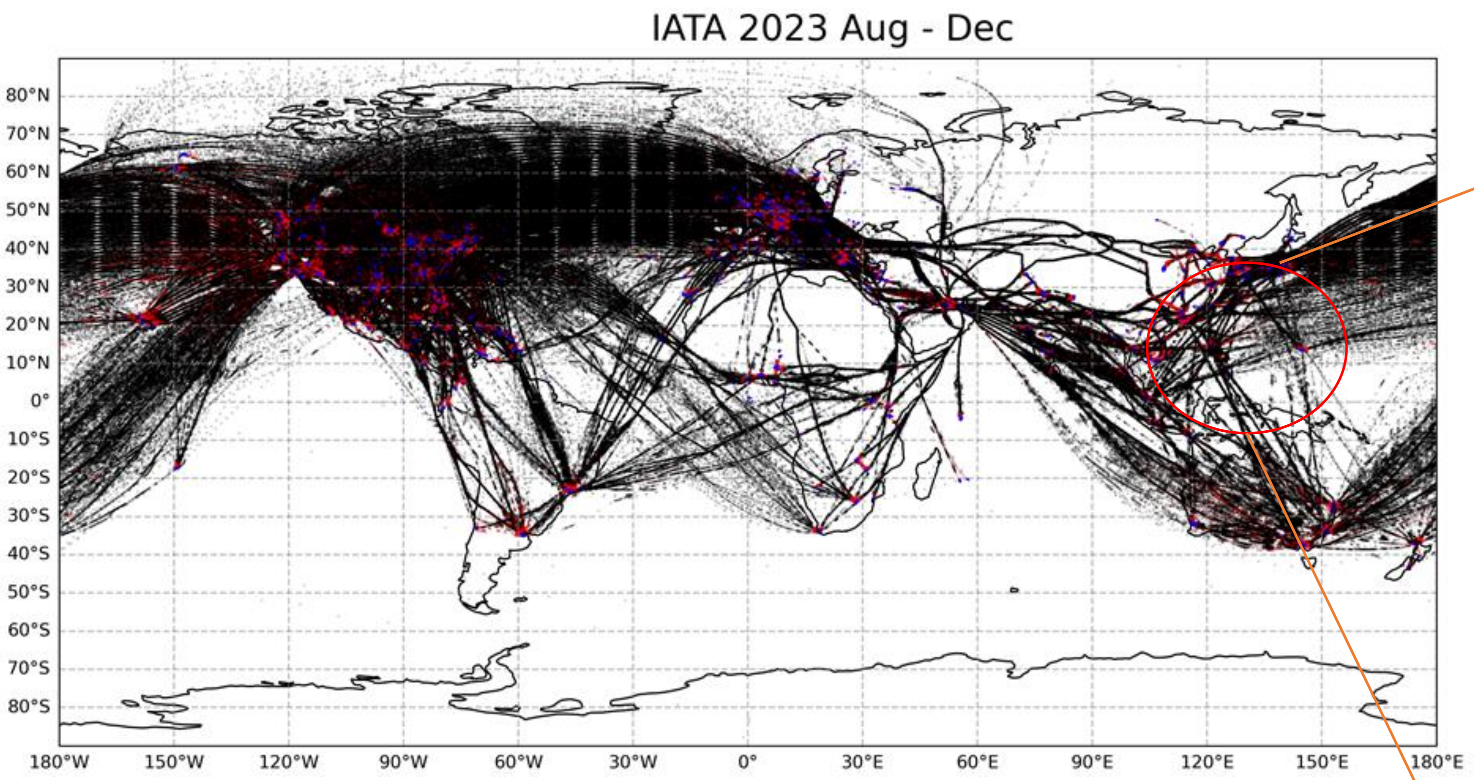
IATA Turbulence Aware Program (TAP)

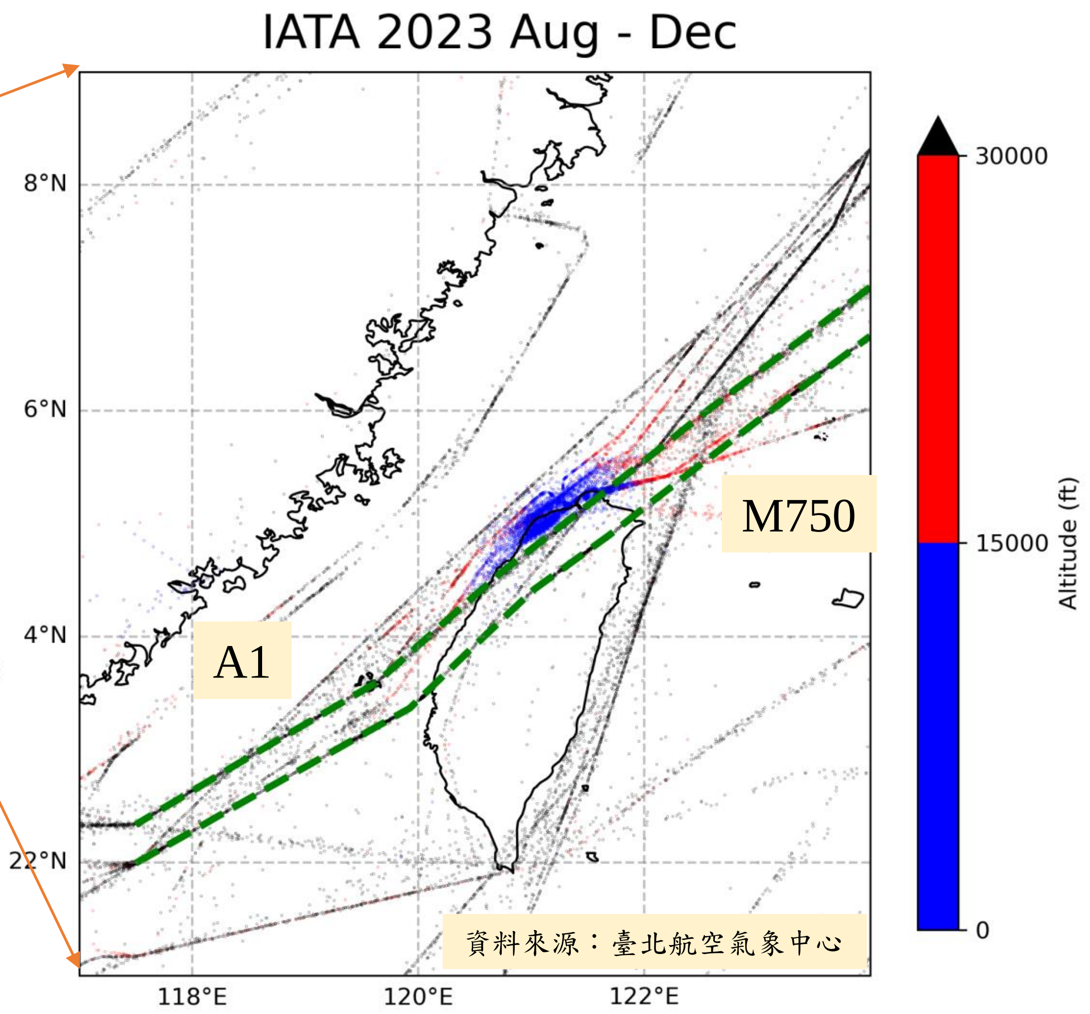
- International Air Transport Association (IATA)
- Used NCAR/RAL turbulence Algorithm
- Airlines in Asia：



IATA - Turbulence Aware Platform

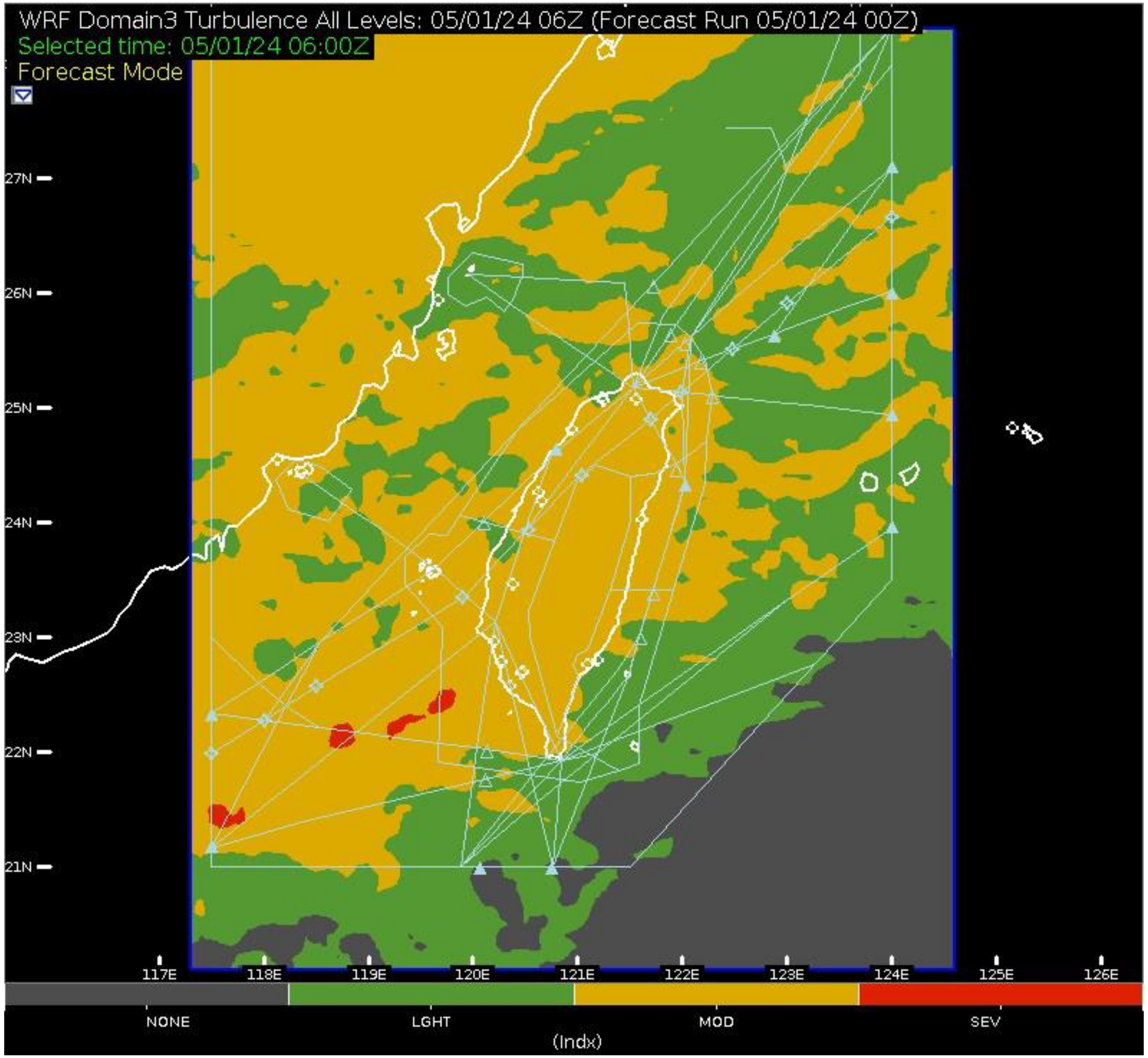
Motivation (2)





TAIPEI FIR
Transfer Layer
FL 130

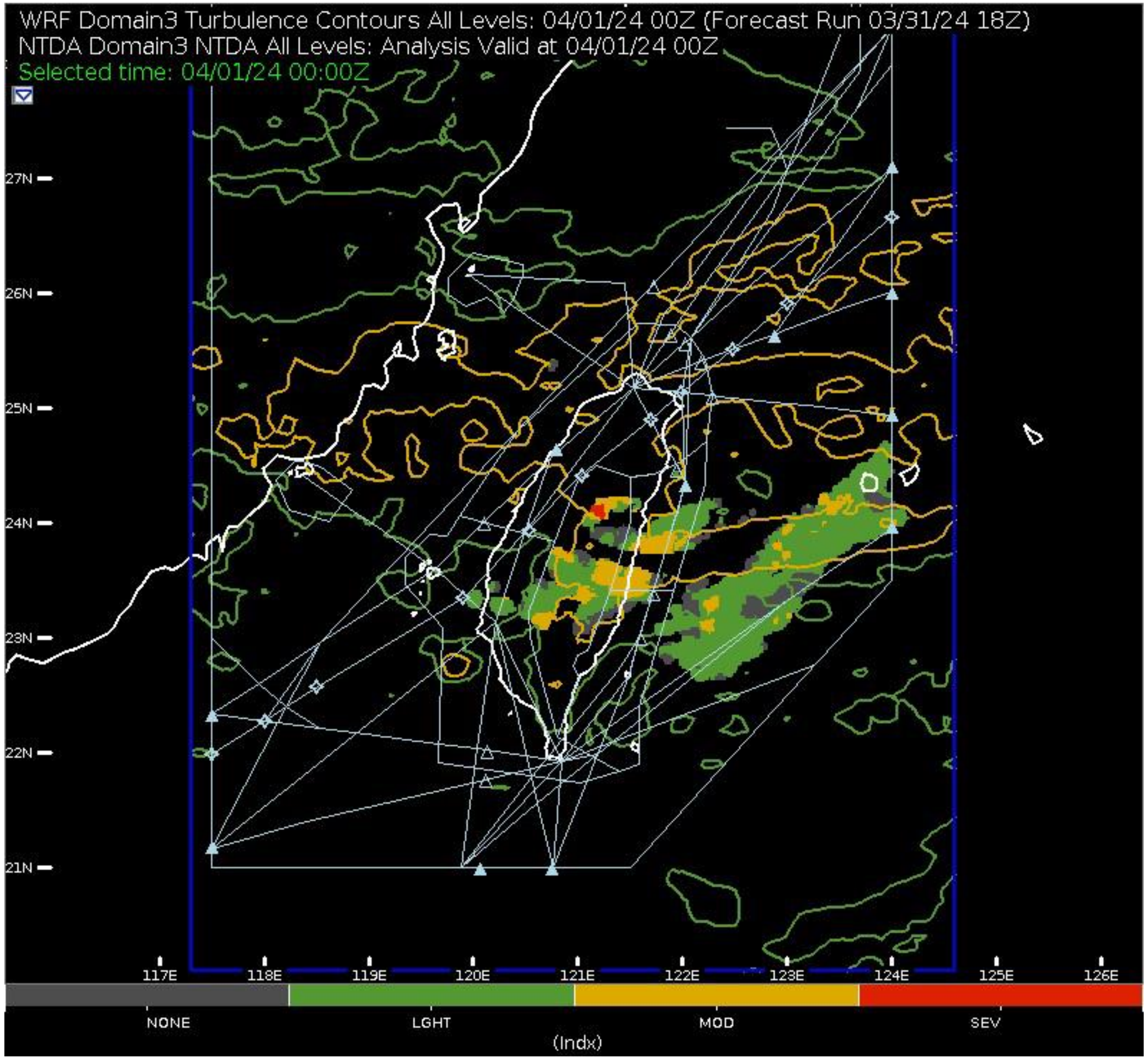
NCAR/RAL product__ GTG4（Graphical Turbulence Guidance version 4）



Taipei FIR
Source: CAA

06Z, 05/01, 2024

NCAR/RAL product_ NTDA（NCAR Turbulence Detection Algorithm）



Taipei FIR
Source: CAA

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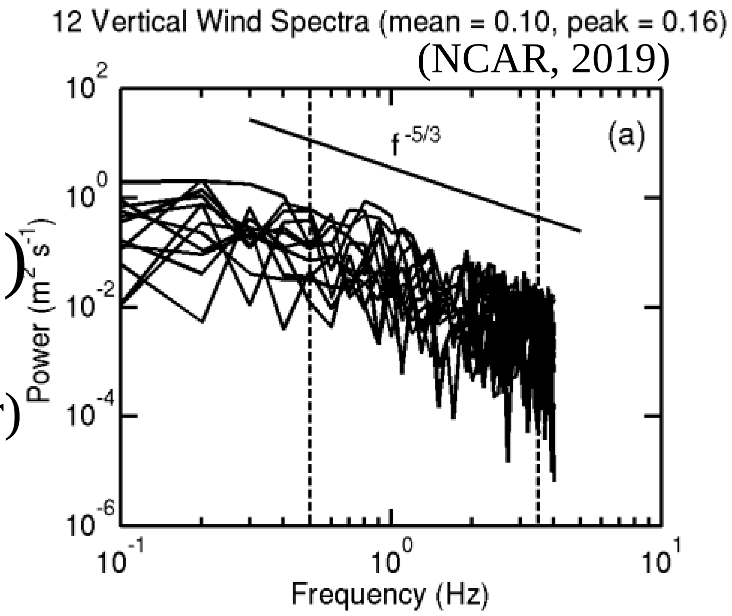
Algorithms to Estimate EDR



- **Kolmogorov Energy Spectrum** (Kolmogorov, 1991)

  $E(k) = A\epsilon^{2/3}k^{-5/3}$ ($E(k)$: energy spectrum, A: constant, k: wave number)

- **Onboard vertical wind-based** (Lenschow 1972, Sharman et al. 2014)

$$w = V_T(\sin\alpha_b \cos\theta \cos\varphi + \sin\beta \cos\theta \sin\varphi - \cos\alpha_b \cos\beta \sin\theta) - \mathrm{IVV} - M\dot{\theta}\cos\theta$$

$$\hat{S}_k^w = \frac{2}{f_s m}\left|\sum_{j=0}^{m-1} w_j^{\mathrm{dT}} e^{-2i\pi jk/m}\right|^2$$

$$\hat{\varepsilon}^{1/3} = \left(\frac{\gamma^2}{k_h - k_l + 1}\sum_{k=k_l}^{k_h}\frac{\hat{S}_k^w}{S_k^{\mathrm{model}}}\right)^{1/2}$$

w: the vertical wind estimate from True Air Speed
θ: Inertial Navigation System
IVV: Instantaneous Vertical(lifting) Velocity

Algorithms to Estimate EDR

- **Accelerometer-based EDR** (Cornman et al. 1995)

$$\hat{\varepsilon}_w^{1/3} = \hat{\sigma}_{\ddot{z}}/F(f_l, f_h) \quad \hat{\sigma}_{\ddot{z}}^2 = \int_{f_l}^{f_h} |H(f)|^2 \hat{S}_w(f)\,df \quad F(f_l, f_h) = \left[\int_{f_l}^{f_h} |H(f)|^2 \phi_w(f)\,df\right]^{1/2}$$

σ_z: the variance in the aircraft's vertical acceleration
S_w: the temporal vertical wind spectrum
H: the product of the aircraft vertical acceleration response function and bandpass filter

- **ADS-B EDR** (Kopeć et al. 2016)

$$\epsilon = B\sigma_T^3 V^{-1}$$

B: an **adjustable constant** accounting for the unknown responsiveness factor of the aircraft
σ_T: standard deviation of acceleration measurements in a set period of time T
V: true air speed (TAS) of the aircraft

Automatic Dependent Surveillance – Broadcast

- Automatic
  - 全自動、不須仰賴任何人為介入
- Dependent
  - 使用飛機的GPS、IMU等系統數據
- Surveillance
  - 用於監控飛機的狀態
- Broadcast
  - 由飛機定時廣播，地面站/衛星/其他飛機接收廣播訊息 (Free for public)
- Variavles:
  - TAS、IAS(air speed)、latitude/longtitude、height、wind speed/direction、temperature

https://www.flightradar24.com/23.76,120.61/7

Automatic Dependent Surveillance – Broadcast

ADS-B

Messages	TC	Ground (still)	Ground (moving)	Airborne
Aircraft identification	1–4	0.1 Hz	0.2 Hz	0.2 Hz
Surface position	5–8	0.2 Hz	2 Hz	-
Airborne position	9–18, 20–22	-	-	2 Hz
Airborne velocity	19	-	-	2 Hz
Aircraft status	28	0.2 Hz (*no TCAS RA and Squawk Code change*)		
		1.25 Hz (*change in TCAS RA or Squawk Code*)		
Target states and status	29	-	-	0.8 Hz
Operational status	31	0.2 Hz	0.4 Hz (*no NIC/NAC/SIL change*)	
			1.25 Hz (*change in NIC/NAC/SIL*)	

ADS-B message transmission rates (ADS-B version 2)

ADS-B/Mode-S

The system could include an adaptable Downlinked Aircraft Parameters (DAP) field that invokes a popup with the following information from Mode-S and ADS-B aircraft:

- Magnetic Heading
- True Track Angle
- Indicated Airspeed/Mach Number
- Groundspeed
- Track Angle Rate
- True Airspeed
- Roll Angle
- Selected Altitude
- Vertical Rate

The 1090MHz Riddle (mode-s.org)

ICAO (2018) ADS-B IMPLEMENTATION AND OPERATIONS GUIDANCE DOCUMENT

ADSB/mode-S EHS to estimate EDR (Kopeć et al. 2016)

$$\epsilon = B\sigma_T^3 V^{-1}$$

B: an **adjustable constant** accounting for the unknown responsiveness factor of the aircraft (~1 in our study)

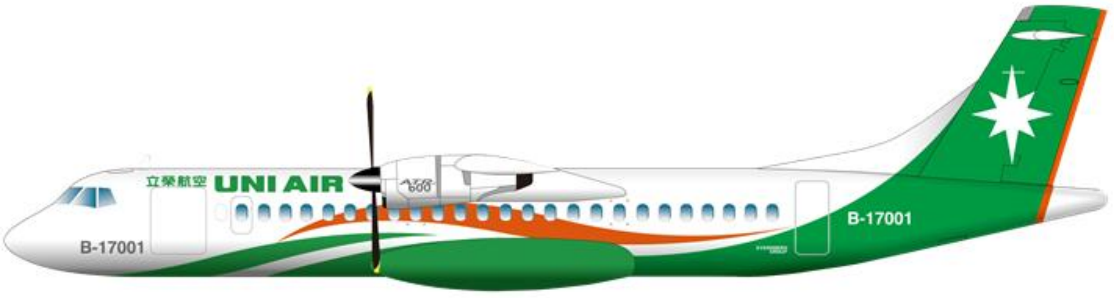
σ_T: **standard deviation of acceleration** measurements in a set period of time T (recorded from ISTAB)

V: true air speed (TAS) of the aircraft (ABSB)

ATR72-600

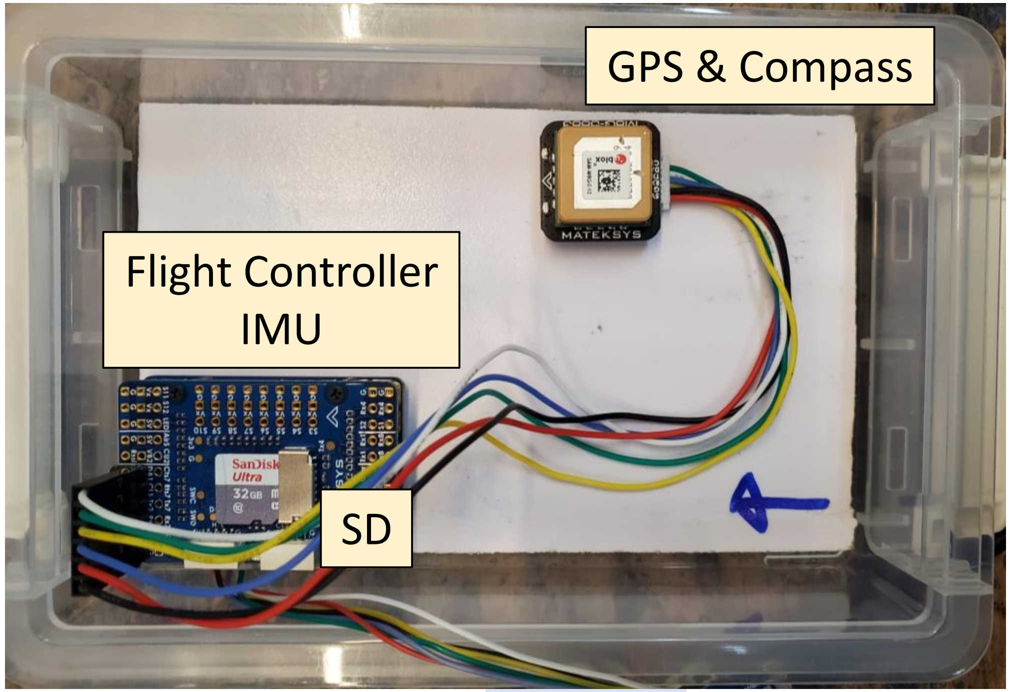
	ATR 72-600
Maximum Take-off Weight	23,000kg
Maximum Landing Weight	22,350kg
Maximum Zero Fuel Weight	21,000kg
Maximum Payload Weight	7,400kg
Maximum Fuel Load	5,000kg

ATR 72-600 Aircraft | ATR Aircraft (atr-aircraft.com)



In-Situ Airborne Turbulence Box (ISTAB) is asscepted by airport security check

- FC (H743)
  - Inertial Motion Unit (IMU) ICM-42688-P
    - Accelerometer 加速度
    - Gyroscope
    - Magnetometer 飛機姿態
- GPS & Compass
  - GPS SAM-M8Q 位置、時間
  - Compass QMC5883L 航向
- Using Extend Kalman Filter (EKF) to integrate INS and GPS



60 mm

100 mm

Data Processing

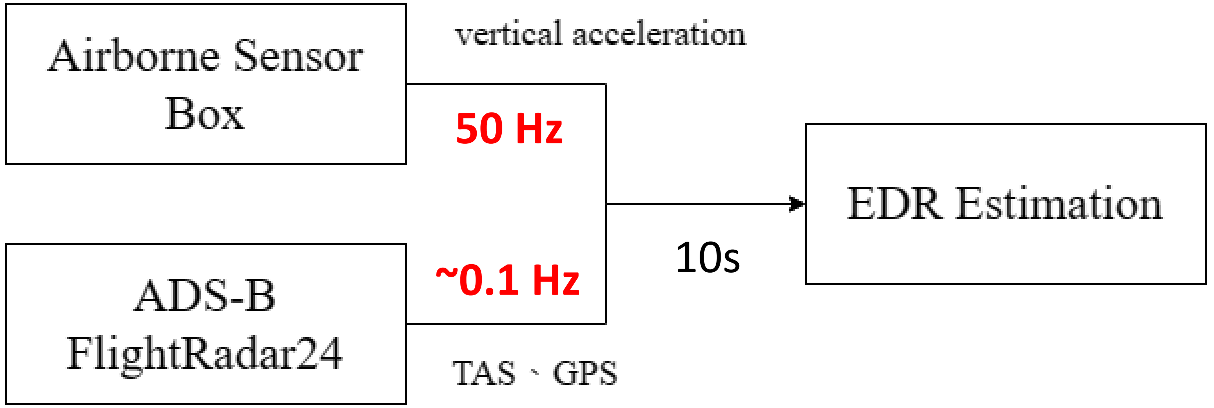
- 取樣頻率(ISTAB)：
  - 加速度(IMU): 50 Hz
  - 飛機姿態(ATT): 25 Hz
  - 經緯度座標(GPS): 5 Hz
  - ADS-B: 0.1 Hz

AMDAR REFERENCE MANUAL

Practical application — The output vertical accelerations are band pass filtered to match the response integral and σ_o^2 is estimated from the standard deviation of running 10-second samples of the filtered values. The pass band is currently set at 0.1 to 0.8Hz.

(WMO 2003 AMDAR)

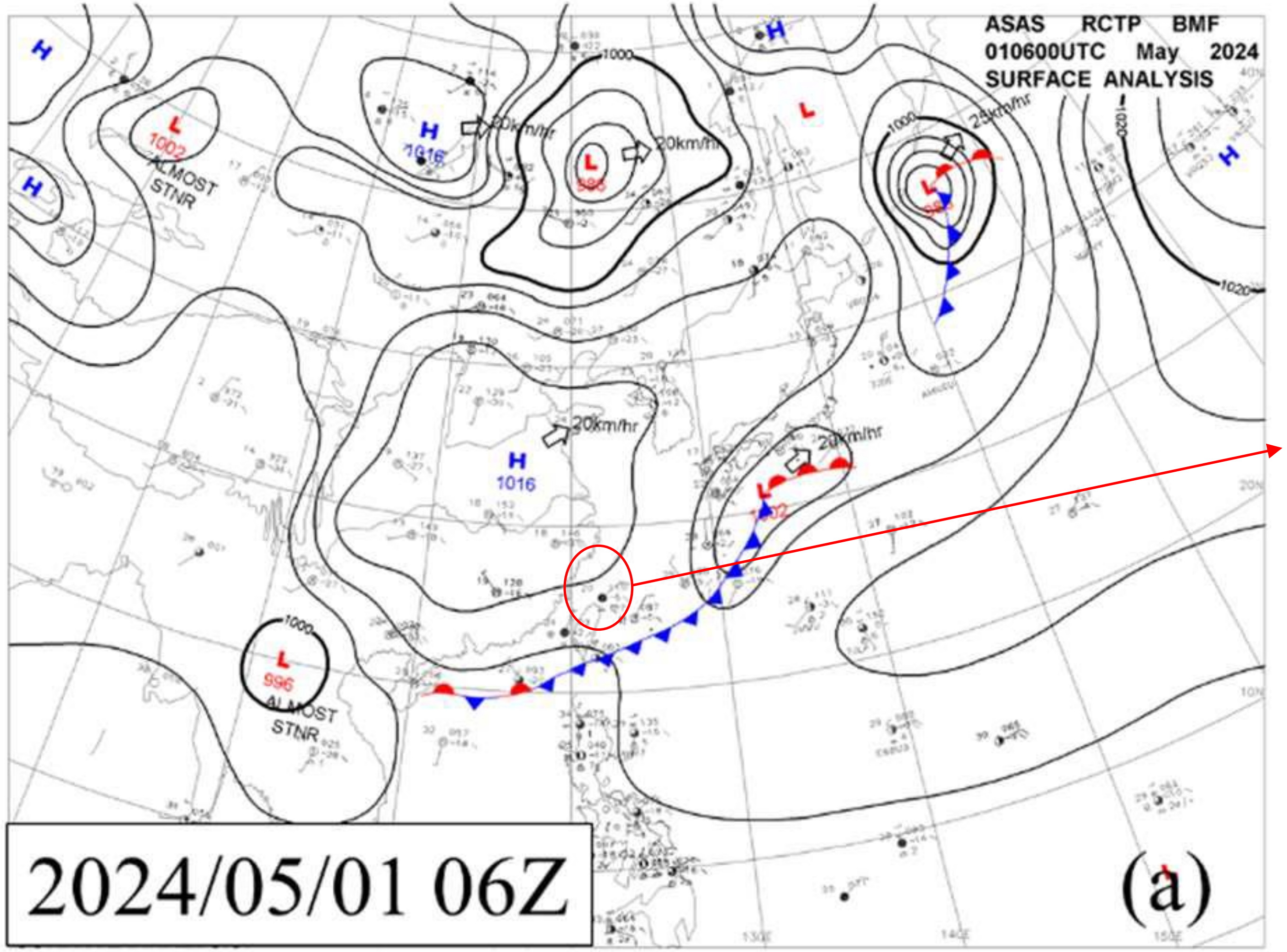
- 資料處理流程：

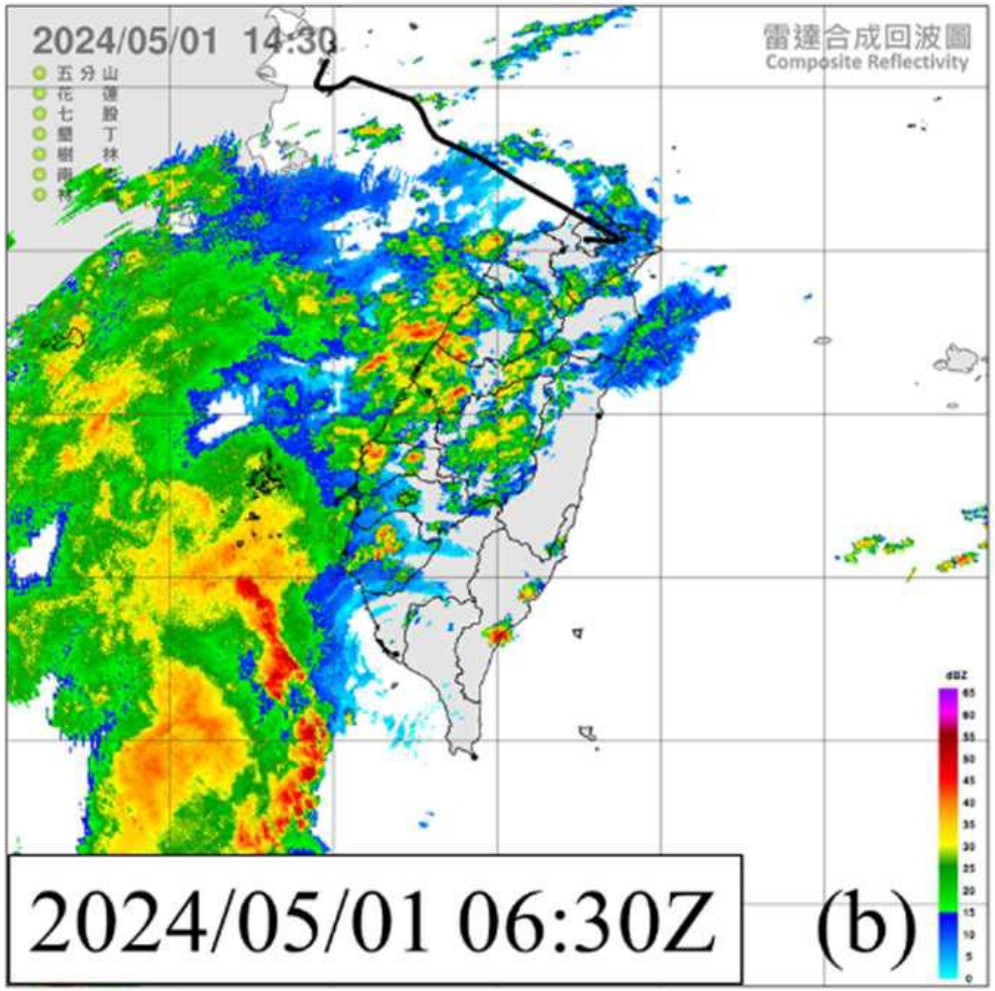


$$\epsilon = B\sigma_T^3 V^{-1}$$

2024/05/01 06Z

UNI B7-8761 ， 2024/05/01 06:14Z take-off from Taipei TSA, land at 2024/05/01 06:56Z Matsu LZN 。





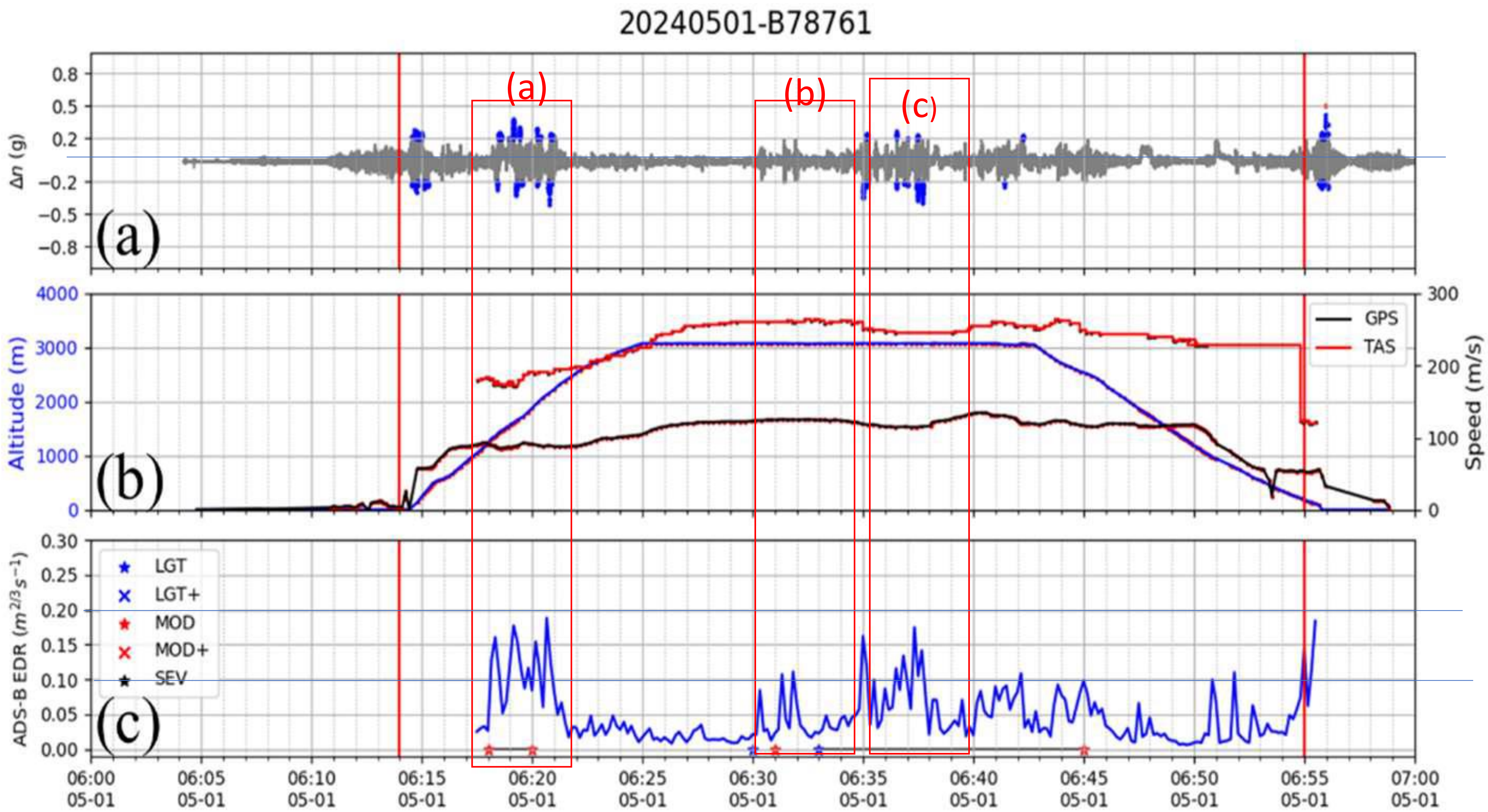
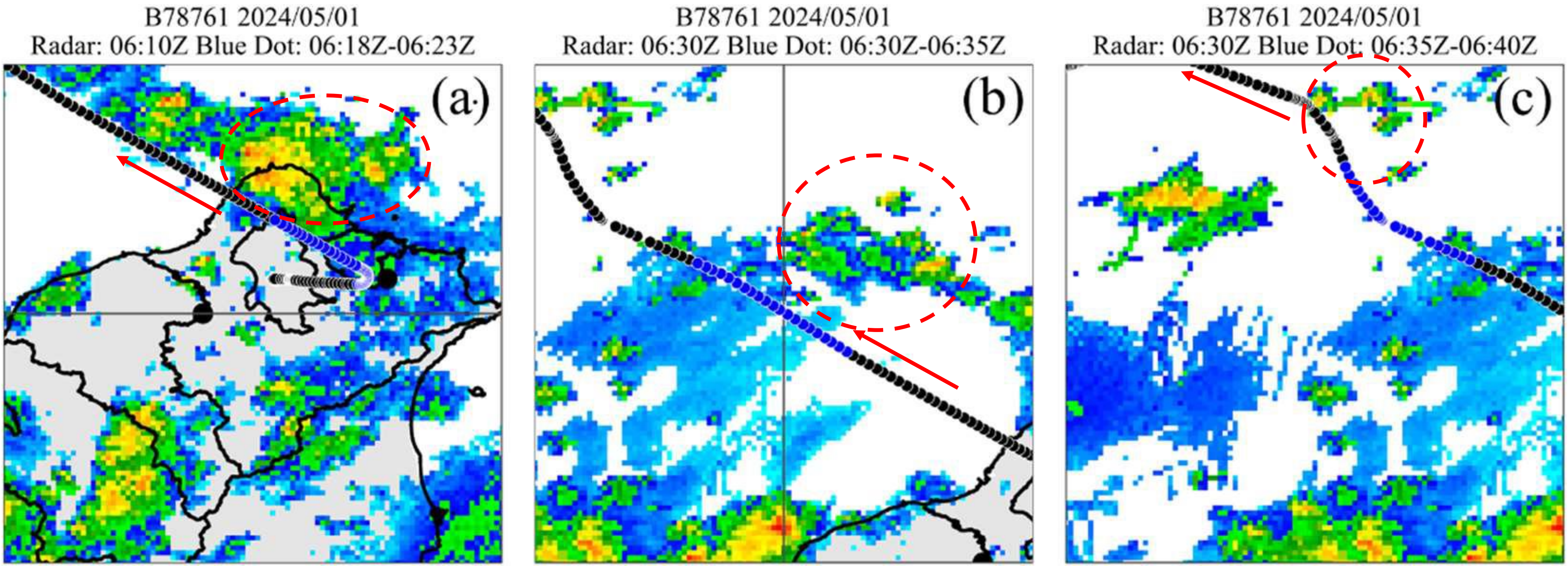
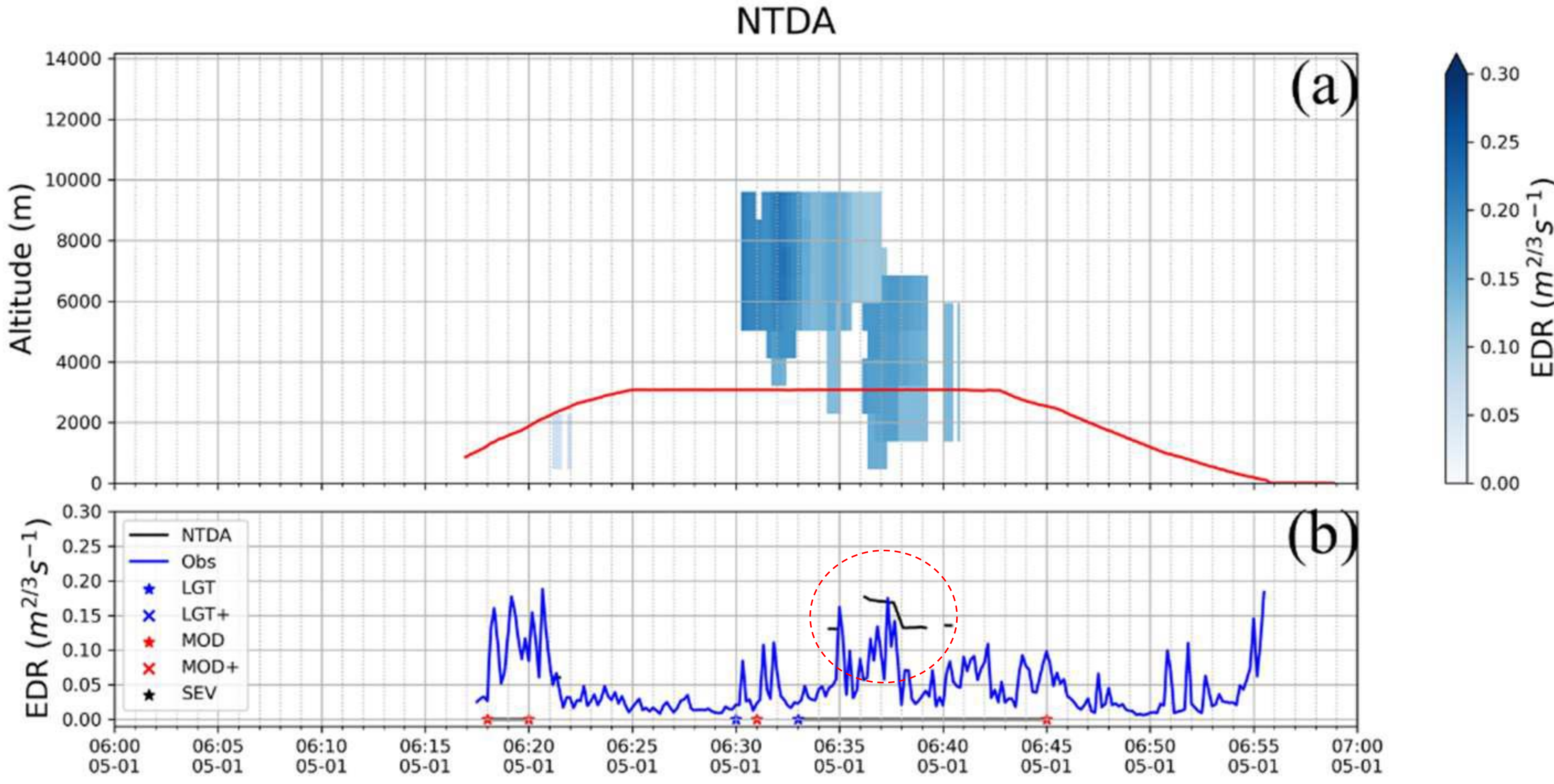

20240501-B78761
(a)
(b)
(c)
Δn (g)
Altitude (m)
Speed (m/s)
GPS
TAS
ADS-B EDR ($m^{2/3}s^{-1}$)
LGT
LGT+
MOD
MOD+
SEV
06:00 05-01
06:05 05-01
06:10 05-01
06:15 05-01
06:20 05-01
06:25 05-01
06:30 05-01
06:35 05-01
06:40 05-01
06:45 05-01
06:50 05-01
06:55 05-01
07:00 05-01

圖 4 - 3 (a):
06:18Z Taipei Yang-Ming Mountain TERRAIN Edge (climb)，2000 m feight
圖 4 - 3 (b)
06:30Z spark convection
圖 4 - 3 (c)
06:35Z small convection cloud nearby





NTDA
(a)
Altitude (m)
14000
12000
10000
8000
6000
4000
2000
0
0.30
0.25
0.20
0.15
0.10
0.05
0.00
EDR ($m^{2/3}s^{-1}$)
(b)
EDR ($m^{2/3}s^{-1}$)
NTDA
Obs
LGT
LGT+
MOD
MOD+
SEV
06:00 05-01
06:05 05-01
06:10 05-01
06:15 05-01
06:20 05-01
06:25 05-01
06:30 05-01
06:35 05-01
06:40 05-01
06:45 05-01
06:50 05-01
06:55 05-01
07:00 05-01

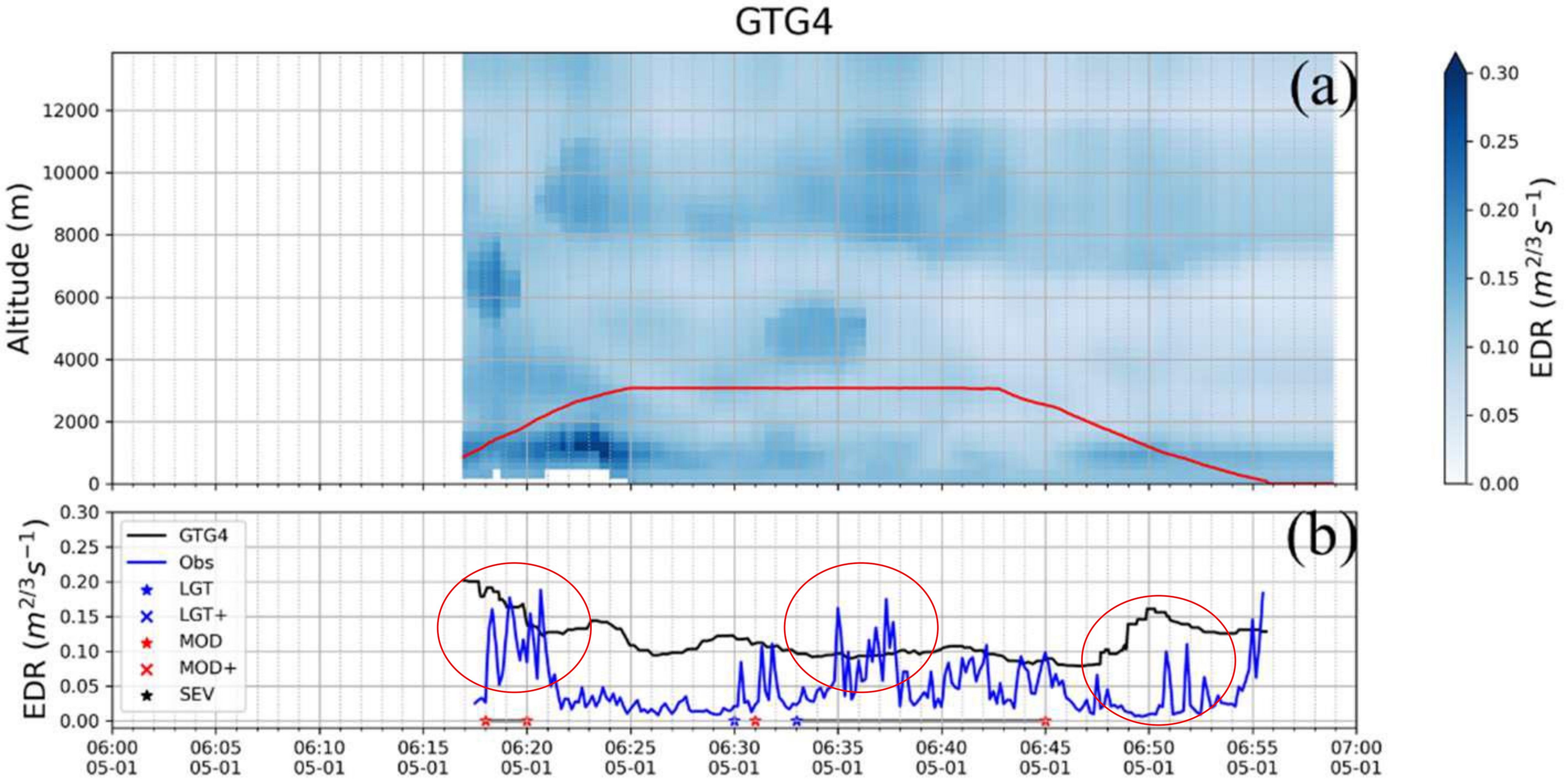
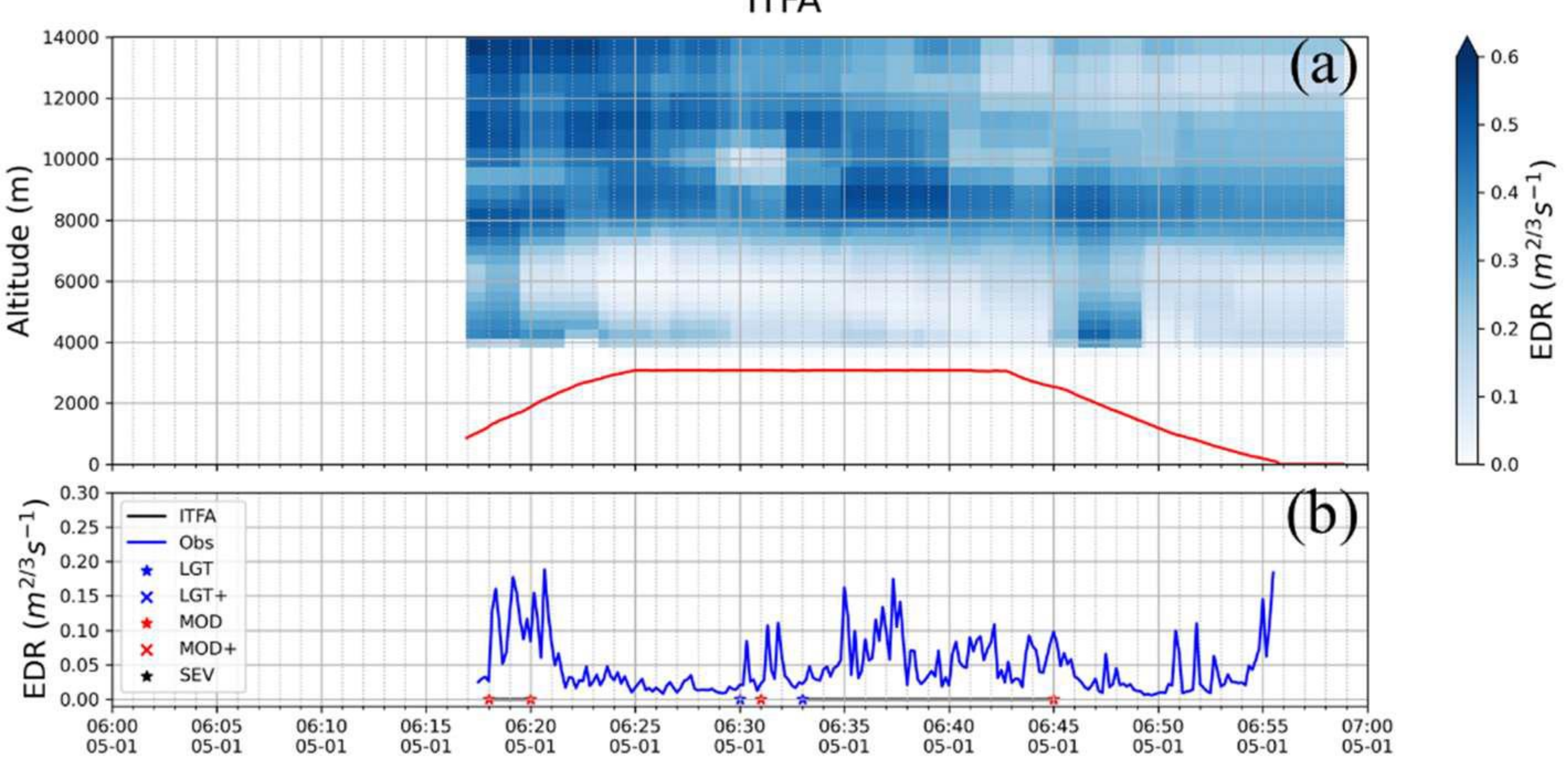


圖 4 - 5、GTG4 與儀器觀測結果比較圖
(a)GTG4 與航行軌跡；(b)GTG4 與本研究之EDR 結果比對



ITFA product is too heigh for TAIPEI domestic airlines. But could be player the references for fly-through internation airlines.
ITFA will be replace by GTN4 next year.

Summaries

1. Our ISTAB in-sity observation is a cheap/easier way to record air turbulence as the ground truth for model simulation
2. ISTAB help Taiwan CAA to vilified NCAR/ARL products (NTDA, GTG4) well in 10 cases of 2023-2024 (same airplane: ATR72-600).
3. ISTAB will be tested in typhoon surveillance flight (Taiwan G100) and reconnamce flight (Japan G400) in 2024-2026.