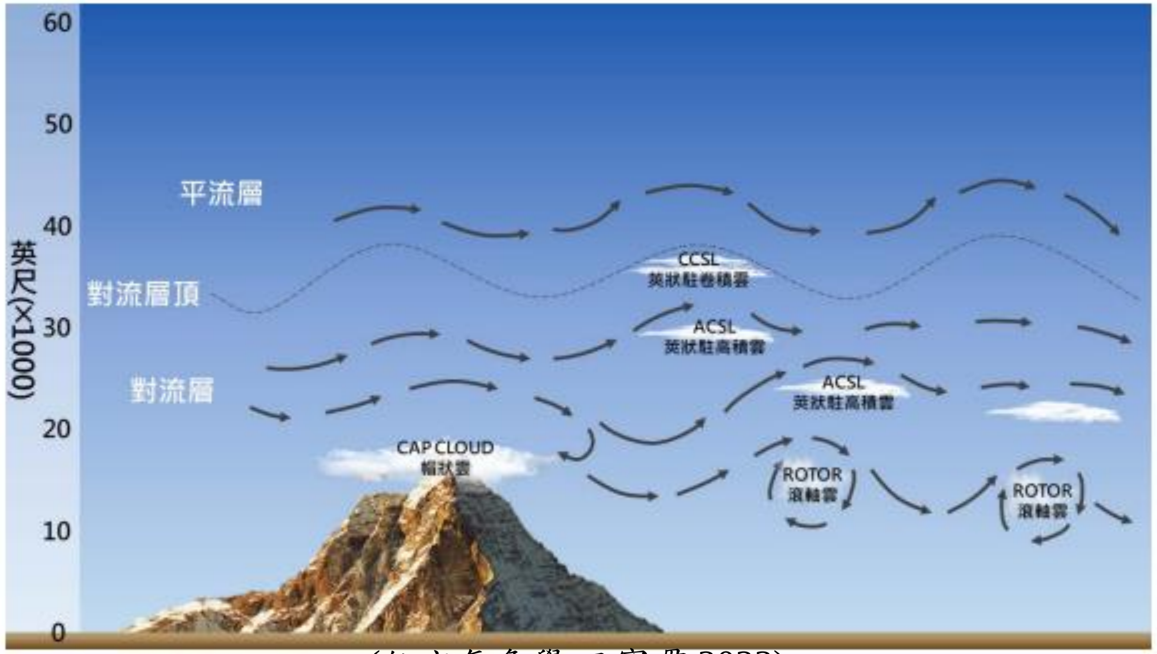
Turbulence Observation and simulation

Po-Hsiung Lin, Chen-Wei Chung
Department of Atmospheric Sciences, National Taiwan University

2024/01/31 @ARAM, AMS Baltimore

Motivation
大氣亂流的四類原因



(航空氣象學 王寶貫 2023)

- Turbulence categories
  - Convective turbulence 大氣熱對流
  - Mechanical turbulence 地形舉升亂流
  - Mountain waves山岳波
  - Wind shear turbulence 風切軟動
- 航空氣象傳統用Pilot Reports (PIREPs)來備註空中航路的亂流

氣象諮詢

航空氣象產品清單

- JMDS
- AWOS display
- 雷達
- 衛星
- 越洋衛星
- 風場
- 溫度場
- 結冰高度
- 溼度
- 亂流
- 積冰
- 航路
- 機場觀測資料
- 機場天氣預報
- 天氣警告資訊
- 顯著天氣報文
- 顯著天氣圖(png)
- 高空風及溫度預報圖(png)
- 天氣分析圖(png)
- 空中報告
- 探空預報
- 相關網站
- 天氣簡報
- 颱風簡報
- 檔案下載
- 回主畫面
- 回到首頁

交通部民用航空局航空氣象服務網
Aeronautical Meteorological Service Page

歡迎使用航空氣象服務網

- 使用左邊的航空氣象產品選單選擇想要觀看的產品
- 按下每個網頁上方的標題圖片，連結至說明檔取得說明資訊
- 建議先閱讀小秘訣，以從AOAWS-WMDS獲得最佳的結果
- 航空氣象產品中有關預報之解釋及使用說明

1.基於氣象資料在時空分布上之變異性、預報技術之限制及部分氣象要素定義之局限
值。同樣，當預報指出在某個時間某氣象要素會出現或發生改變，該時間應被理解為

2.氣象單位發布一個如例行機場預報之新預報後，應理解為自動取消以前所發布之同

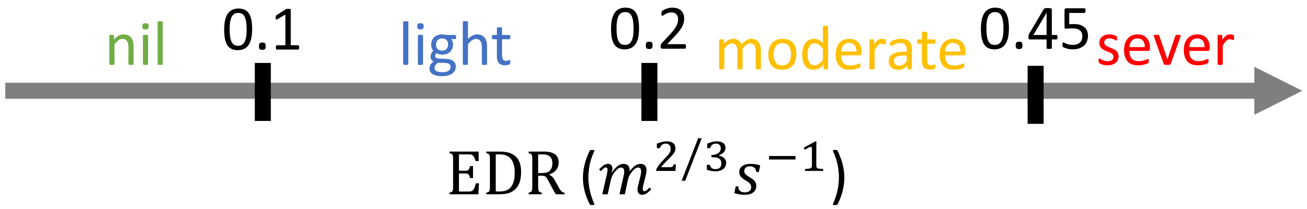
Atmospheric Turbulence Intensity Metric
亂流強度的物理學定義與強度分類

- **EDR** (Eddy Dissipation Rate) 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)

Algorithms to Estimate EDR θ

(1)Kolmogorov Energy Spectrum (Kolmogorov, 1991)

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

(2)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 θ

(3)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

(4)ADSB EDR (Kopeć et al. 2016)

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

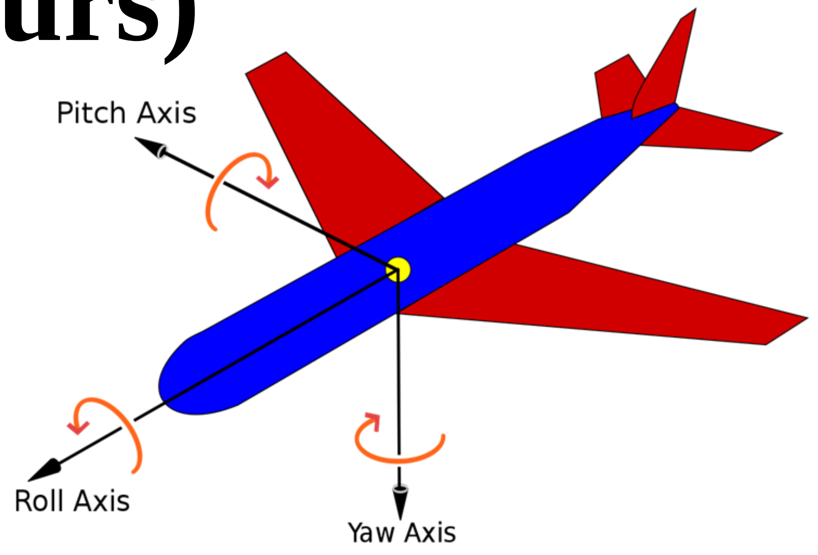
B: an adjustable constant accounting for the unknown responsiveness factor of the aircraft
σ_T: standard deviation of acceleration measurements in a set period of time T
V: true air speed (TAS) of the aircraft

EDR Observation Approaches

- Derive from Doppler lidar (Chan 2010) (scanning)
- Derive from radiosonde sounding (Ko et al. 2019) (point)
- Derived Equivalent Vertical Gust velocity (DEVG) (Pratt and Walker 1954)
- Derive from aircraft vertical motion (Huang 2019) (3D)

EDR Observation Approaches (ours)

- Derive from aircraft vertical motion (Huang 2019)
- Onboard vertical wind-based (Sharman et al. 2014)



空速 | 加速度/速度 | 飛機姿態/角度

Table 3. Parameters in the QAR data used for EDR estimation.

Field Name	Interpretation	Unit
IAS	Indicated Airspeed	m/s
VRTG	Vertical acceleration	g
RALT	Radio altitude	feet
PITCH	Control column position	degree
IVV	Instantaneous lifting velocity	feet/min
ROLL	Control wheel position	degree
AOAL	Angle of attack left	degree
AOAR	Angle of attack right	degree
HEIGHT	Height	feet
MACH	Mach Number	-
LATP	Present Positon Latitude	degree
LONP	Present Position Longitude	degree
WIN_SPDR	Wind speed FMC	knot
WIN_DIR	Wind Direction computed	knot

(Huang 2019)

TABLE 1. List of required parameters and minimum update frequencies for the vertical winds–based EDR algorithm.

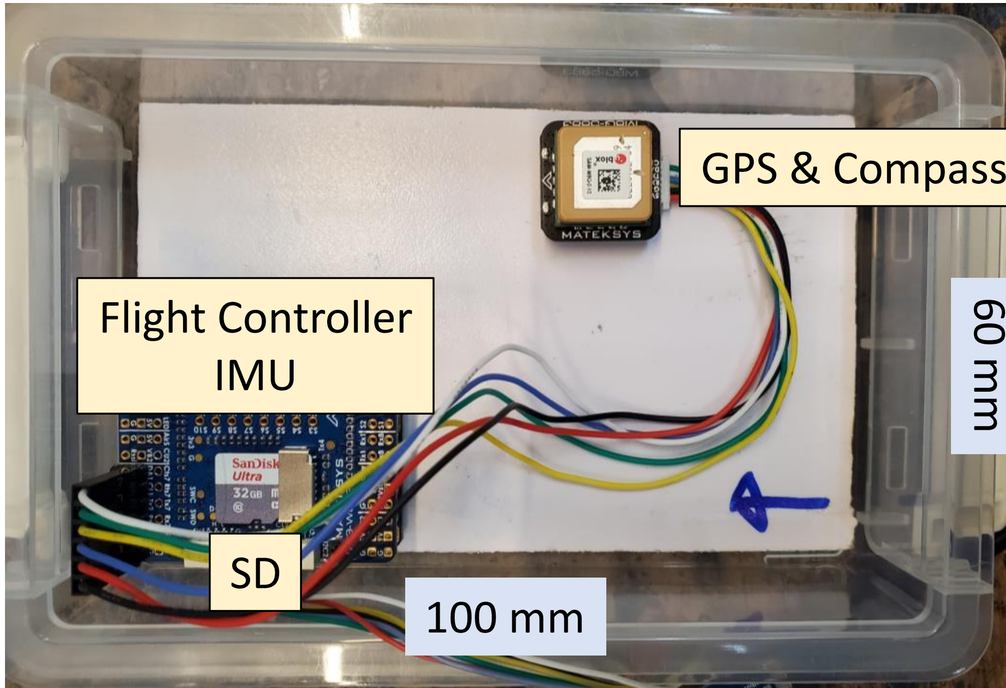
Parameter	Symbol	Units	Min recommended sampling frequency (Hz)	Min recommended precision
Required parameters				
Aircraft type	—		—	
True airspeed	V_T	$\mathrm{m\,s^{-1}}$	4	$0.036\,\mathrm{m\,s^{-1}}$
Left vane angle of attack (+ = nose up)	α_L	°	4	0.05°
Right vane angle of attack (+ = nose up)	α_R	°	4	0.05°
Pitch (+ = nose up)	θ	°	4	0.02°
Roll (+ = right wing down)	φ	°	4	0.02°
IVV (+ = upward)	IVV	$\mathrm{m\,s^{-1}}$	4	$0.0051\,\mathrm{m\,s^{-1}}$
Parameters useful for initial verification				
UTC date and time	—		4	0.125 s
Lat		°	1	0.0002°
Lon		°	1	0.0002°
Pressure alt	z	ft MSL	4	
Vertical acceleration		g	4	0.003 g
Current aircraft weight	W	lb	4	100 lb
Wind speed		kt	1	1 kt
Wind direction		°	1	1°

(Sharman et al. 2014)

Our simple airborne sensor box (SASB)

- FC (H743) NT$2275
  - Inertial Motion Unit (IMU) ICM-42688-P
    - Accelerometer 加速度
    - Gyroscope
    - Magnetometer 飛機姿態
- GPS & Compass NT$950
  - GPS SAM-M8Q 位置、時間
  - Compass QMC5883L 航向
- Using Extend Kalman Filter (EKF) to integrate INS and GPS

空速

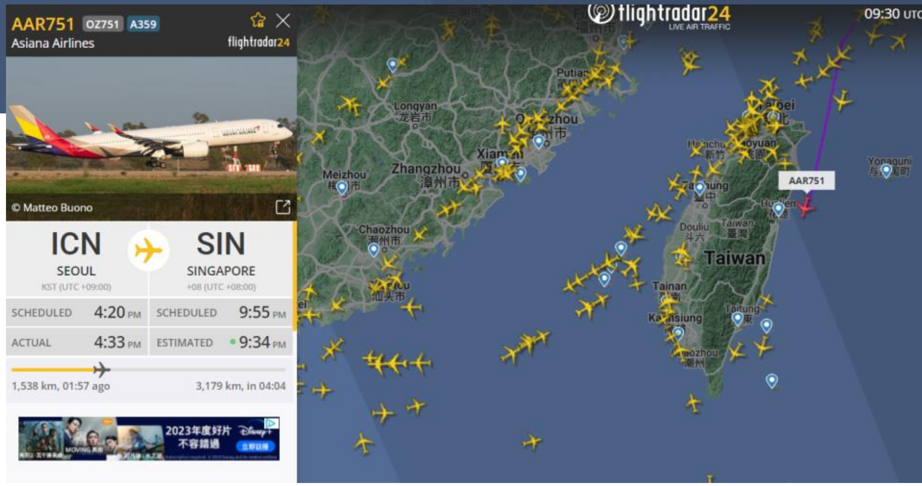


ADSB/Automatic Dependent Surveillance Broadcast

- 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
- 常見欄位
  - 空速(TAS、IAS)、馬赫數、經緯度、高度、風向、風速、機外氣溫

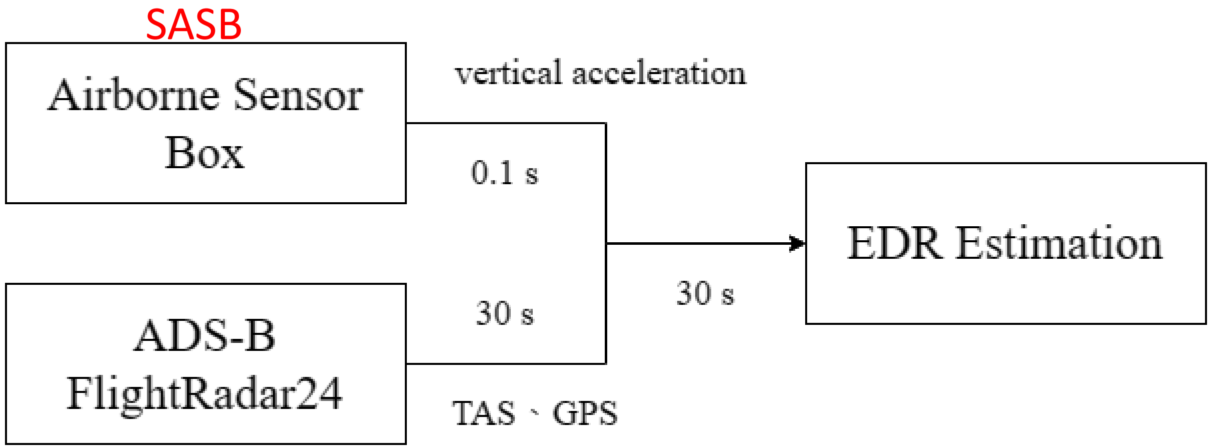
現今流行的**flightdar 24 APP**


flightradar24
LIVE AIR TRAFFIC
09:29 UTC
Find flights, airports and more
LOG IN
VIEW Map
Most tracked flights LIVE
1. WOLF0011 EUFI 852
Coningsby QCY – N/A
2. N/A K35R 832
Mildenhall MHZ – N/A
3. N/A K35R 772
Mildenhall MHZ – N/A
4. WOLF0012 EUFI 620
Airport disruptions LIVE
Tijuana TIJ 5.0
12°C 60° 4 kts 4.3
Amsterdam AMS 3.6
-1°C 150° 8 kts 5.0
Taiwan


AAR751 OZ751 A359
Asiana Airlines
flightradar24
© Matteo Buono
ICN
SEOUL
SIN
SINGAPORE
SCHEDULED 4:20 PM
SCHEDULED 9:55 PM
ACTUAL 4:33 PM
ESTIMATED 9:34 PM
1,538 km, 01:57 ago
3,179 km, in 04:04
flightradar24
09:30 UTC
AAR751
Taiwan

Data Processing

- 取樣頻率：
  - 加速度(IMU): 50 Hz
  - 飛機姿態(ATT): 25 Hz
  - 經緯度座標(GPS): 5 Hz
  - ADS-B: 20s
- 資料處理流程：



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

Overload Increment

$$\Delta n = VRTG - 1$$

$VRTG$: vertical acceleration of the flight

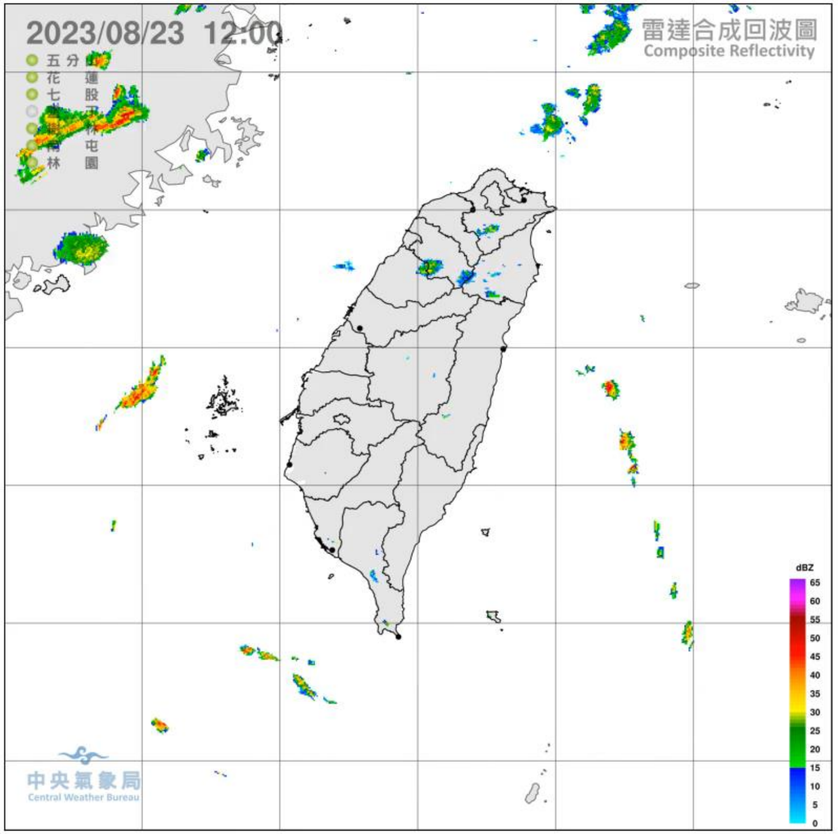
Table 4. Air turbulence intensity and the corresponding overload increments.

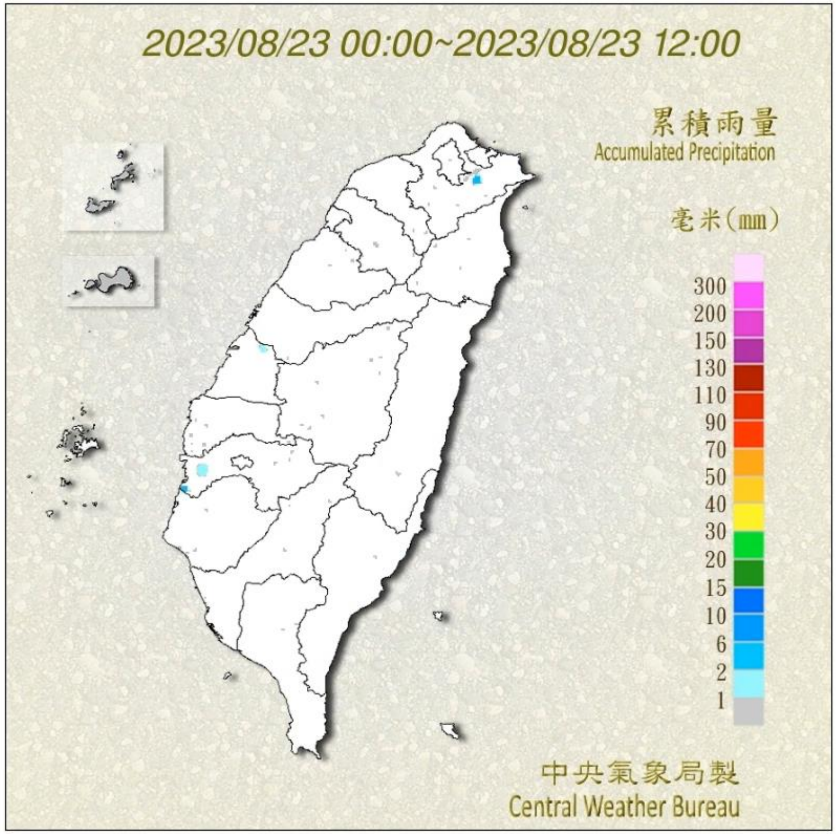
Turbulence Intensity	Overload Increment Range (g)
steady flight	$\|\Delta n\| \leq 0.2$
weak turbulence	$0.2 < \|\Delta n\| \leq 0.5$
moderate turbulence	$0.5 < \|\Delta n\| \leq 0.8$
strong turbulence	$\|\Delta n\| > 0.8$

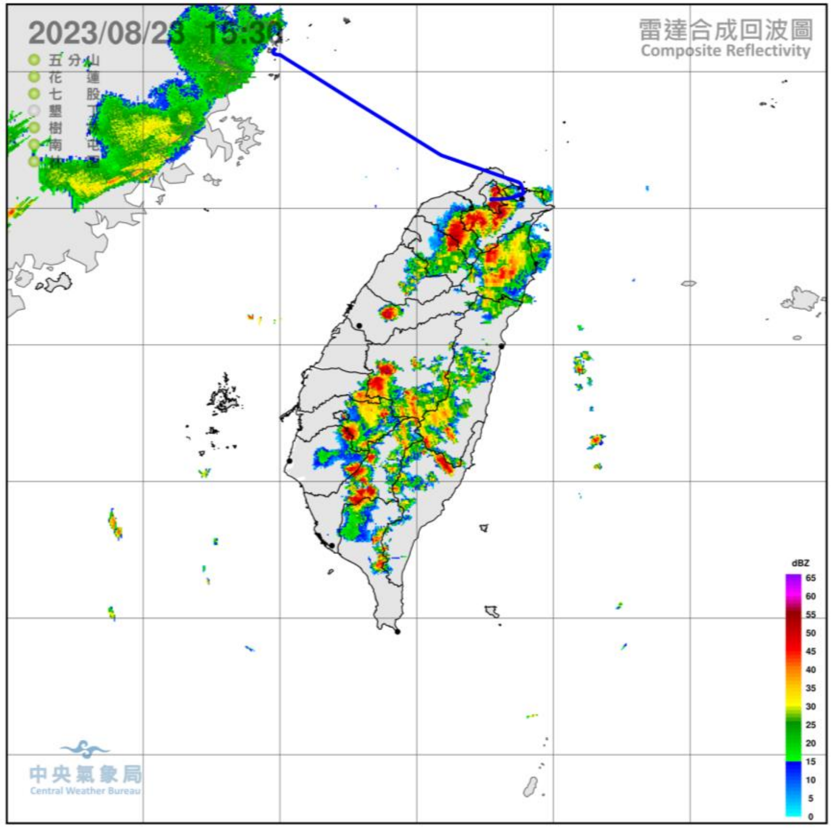
(Huang 2019)

Case 1 –summer afternoon thunderstorm at RCSS (Taopei Songshuan airport)

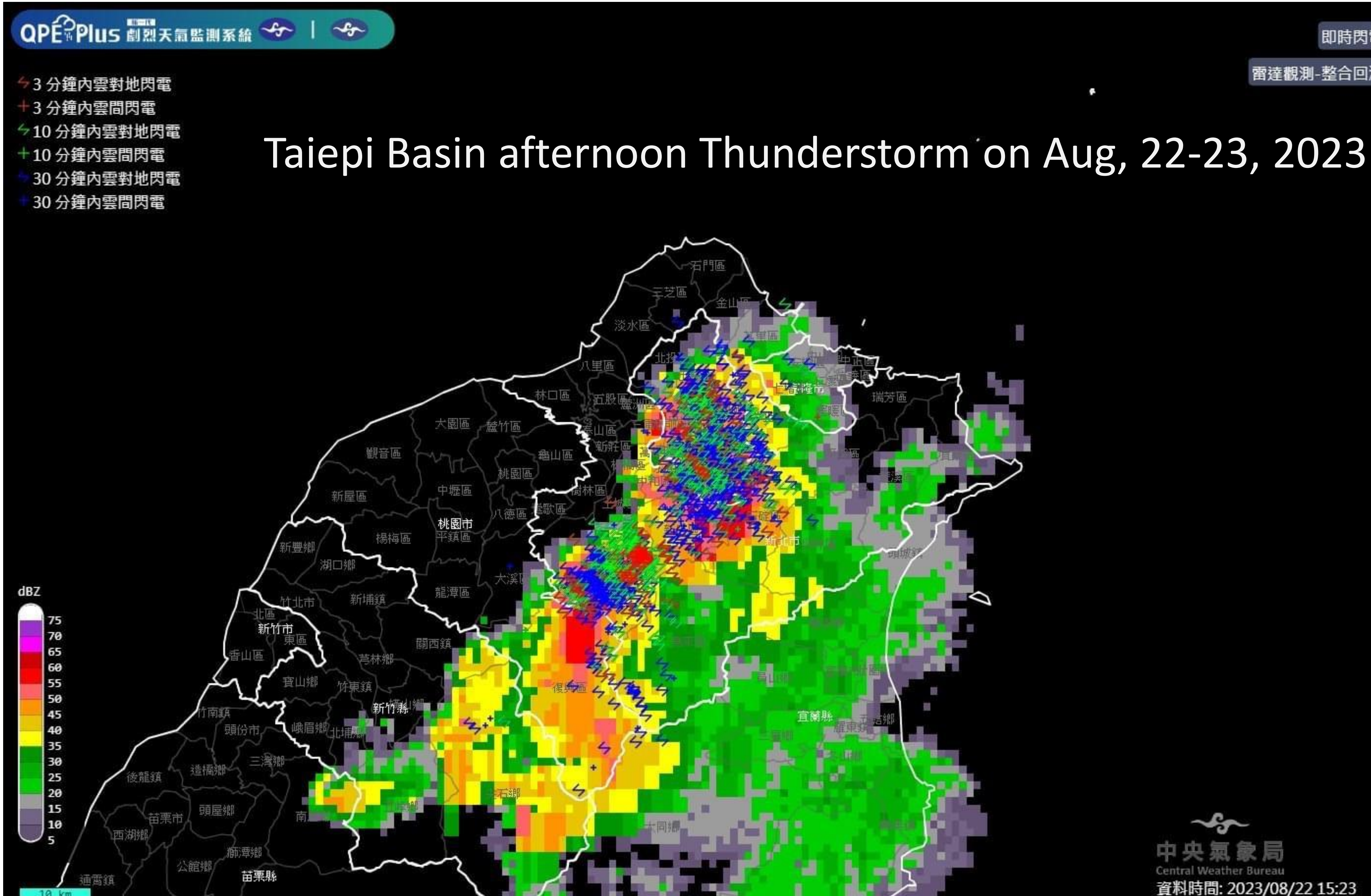
- RCFG – RCSS ATR 72-600 **B7-8762** 15:00~16:00 Lst



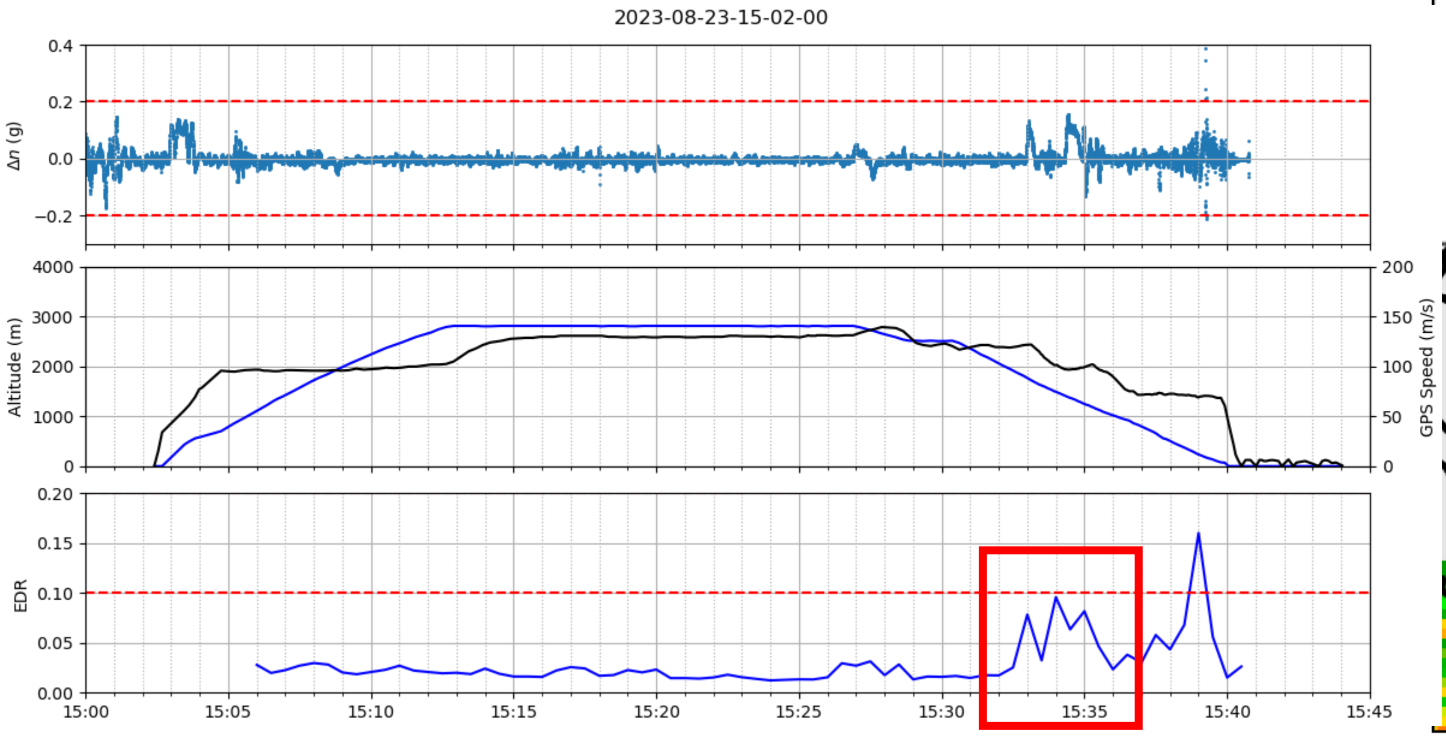


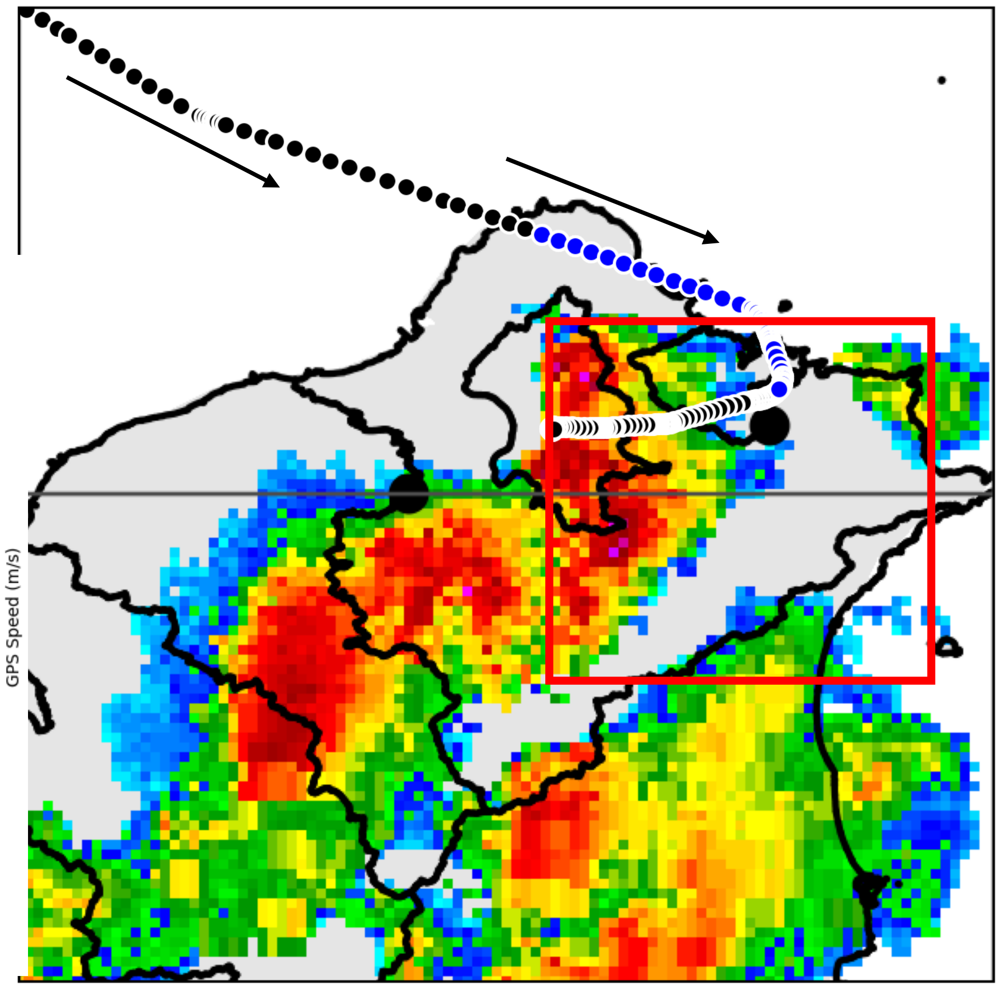


Taiepi Basin afternoon Thunderstorm on Aug, 22-23, 2023



Case 2A: RCFG –> RCSS *ATR 72-600* (B7-8762) 15:00~16:00 Lst

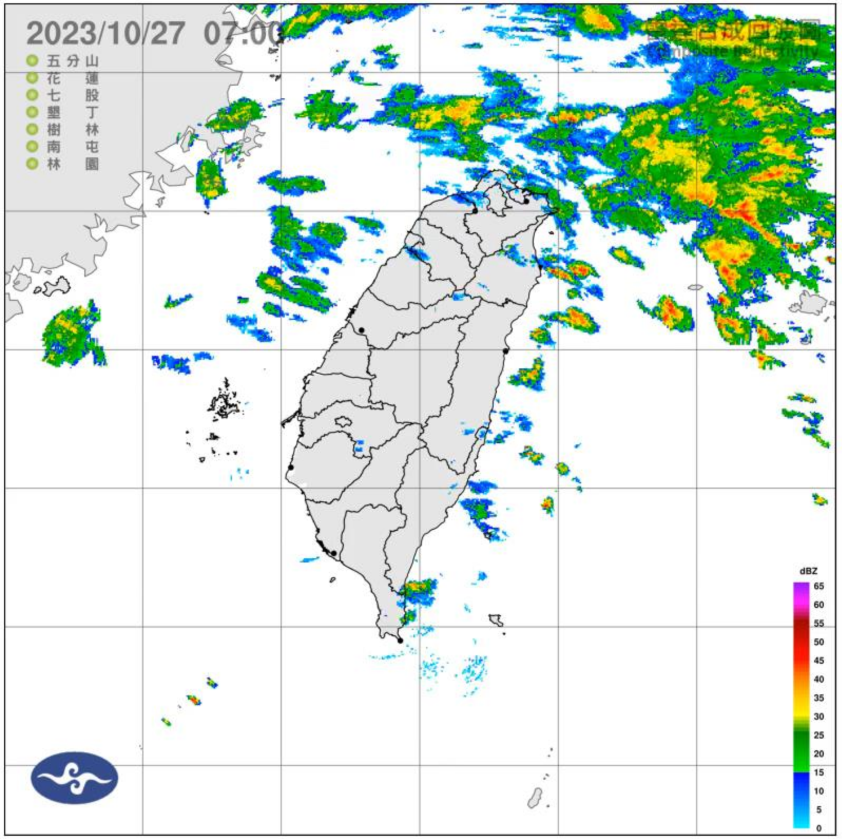


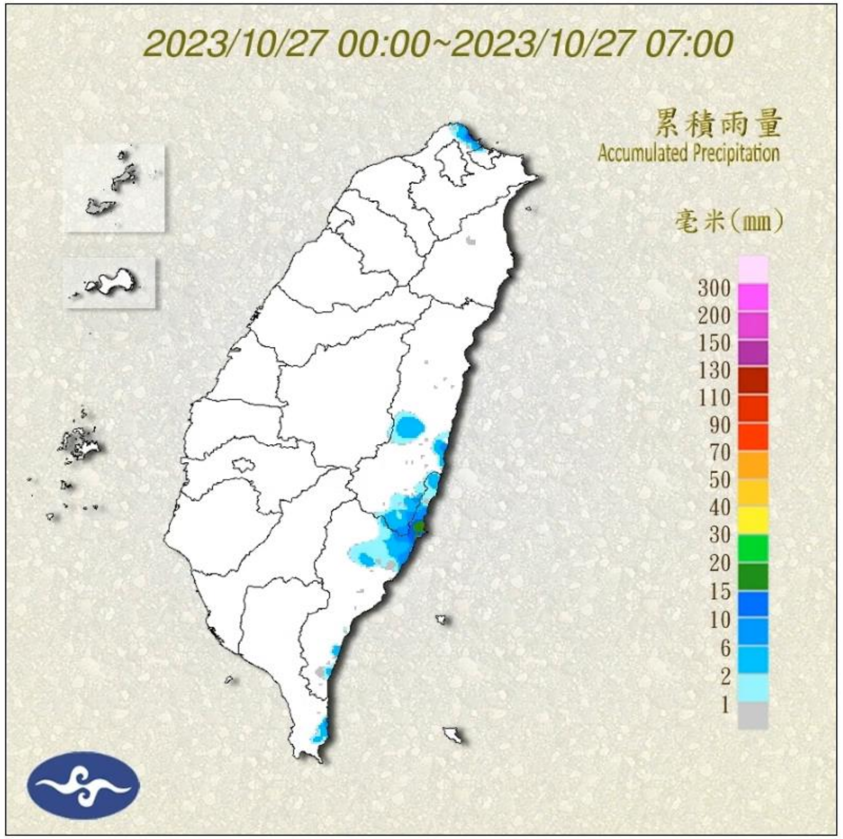


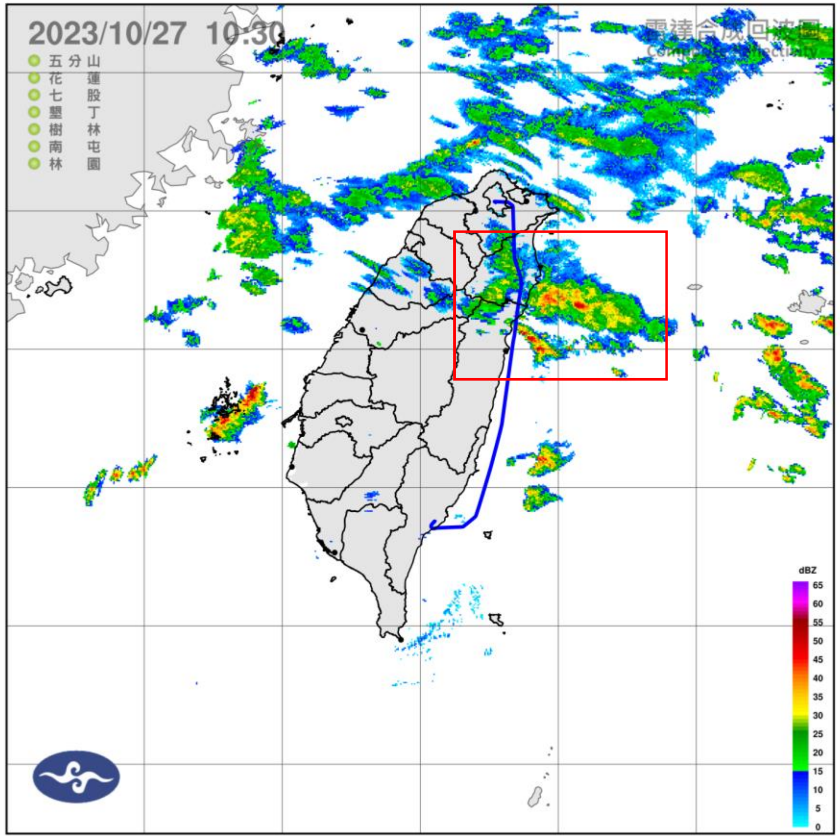
3:00 ~3:45pm

Case 2 – Autumn Frontal weather RCSS-RCFN

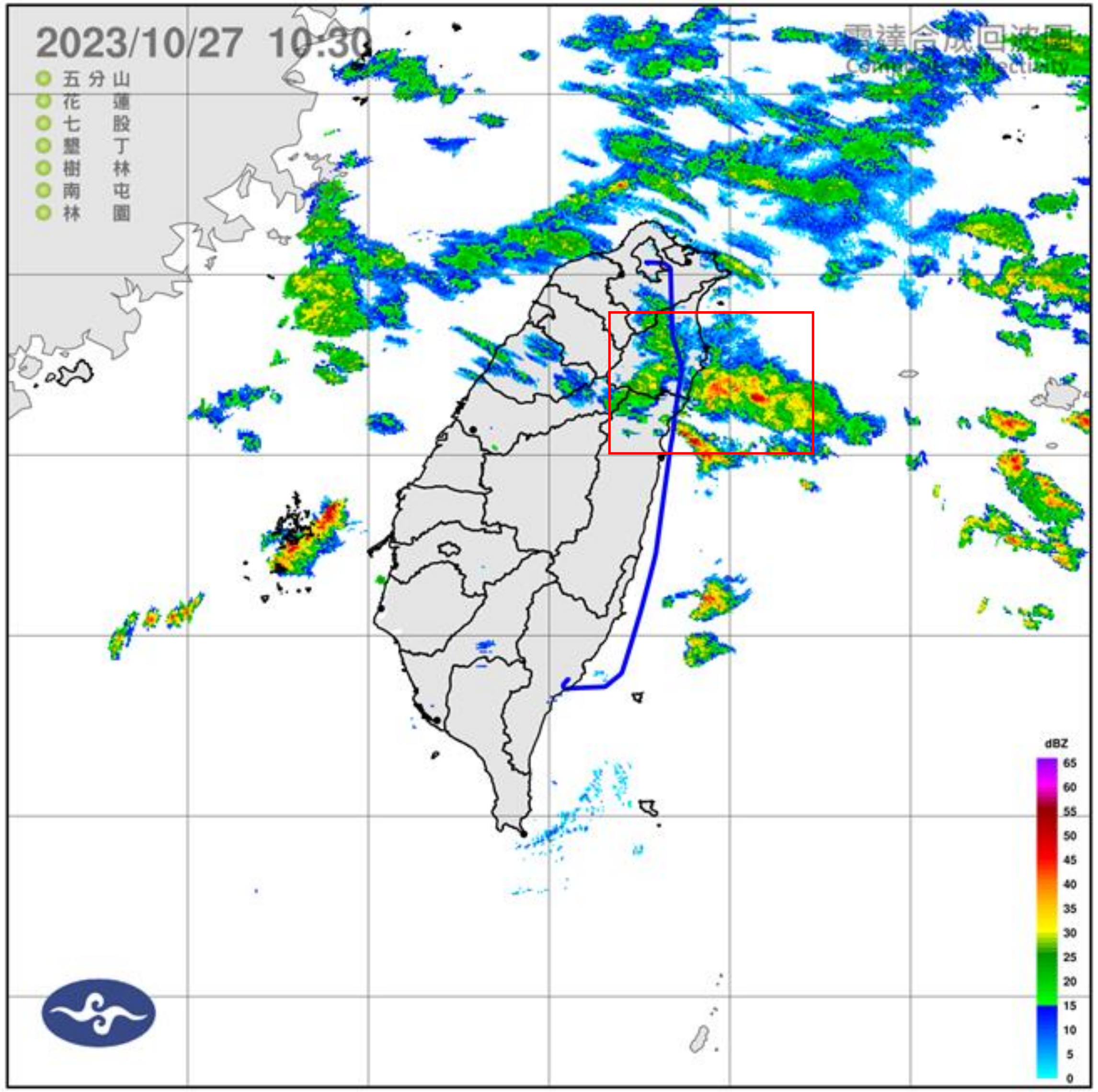
- ATR 72-600 B7-8721 10/27, 2023 10:00 ~ 11:00 Lst

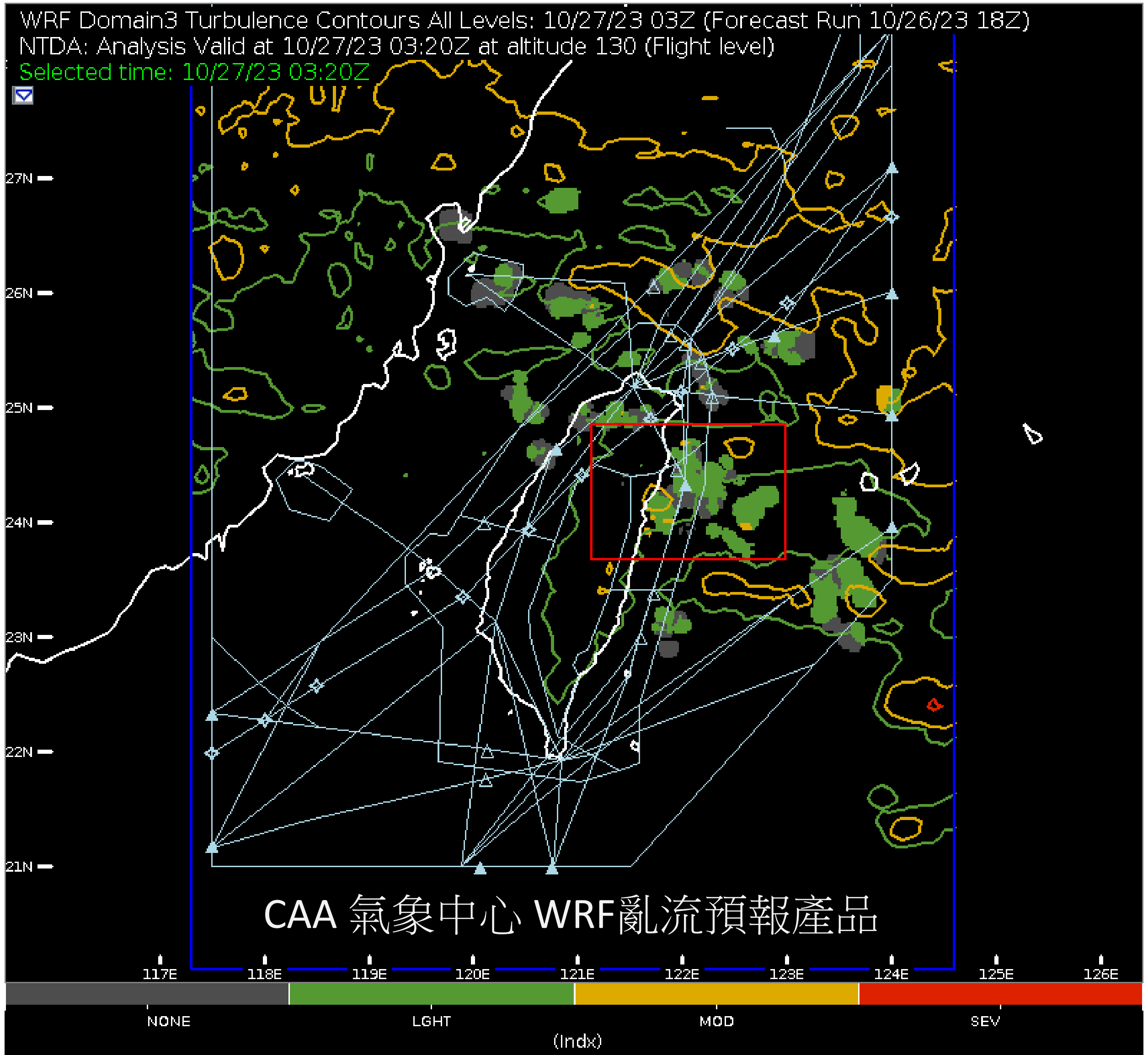




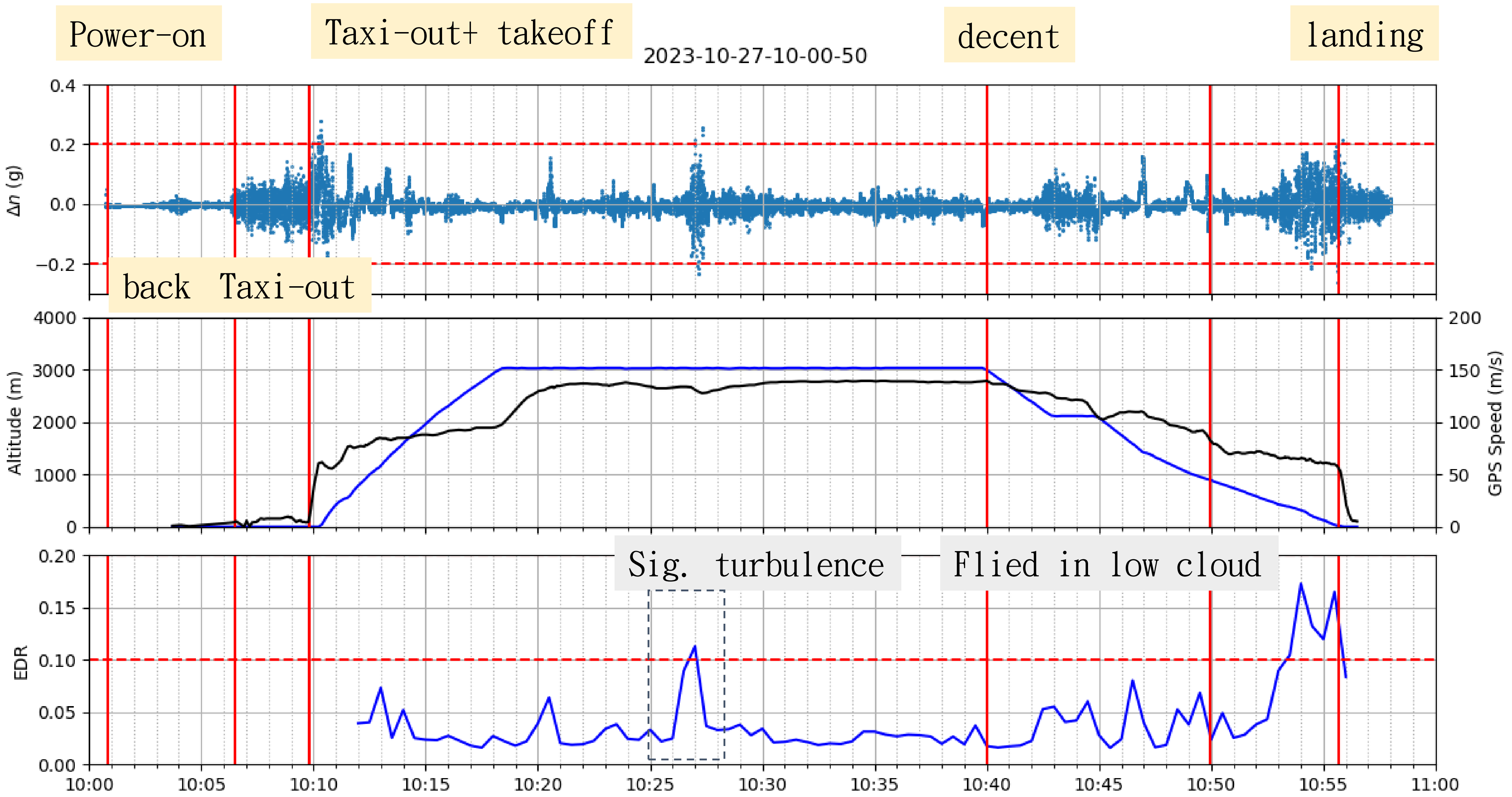


AVAIATION service of CAA Taiwan _ webnise for NCAR/WRF turbulence forecast





Autumn Frontal weather RCSS->RCFN (10-11:00am)
Time evolution of ASAB



Case 2 – 2023/10/27 松山-豐年 B7-8721

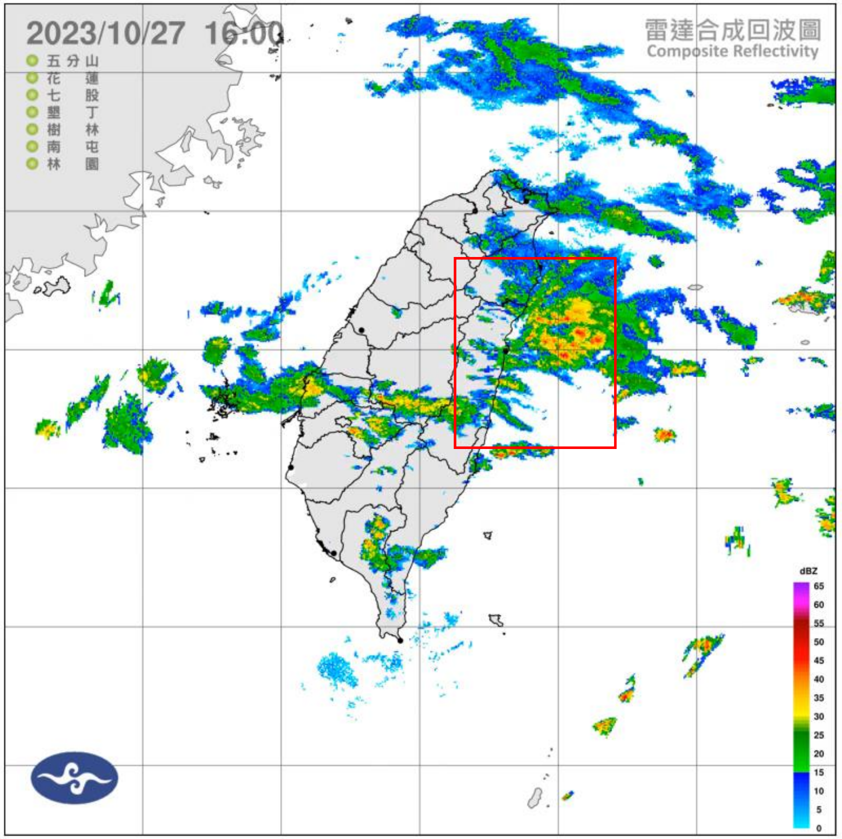
2023-10-27 10:27:08

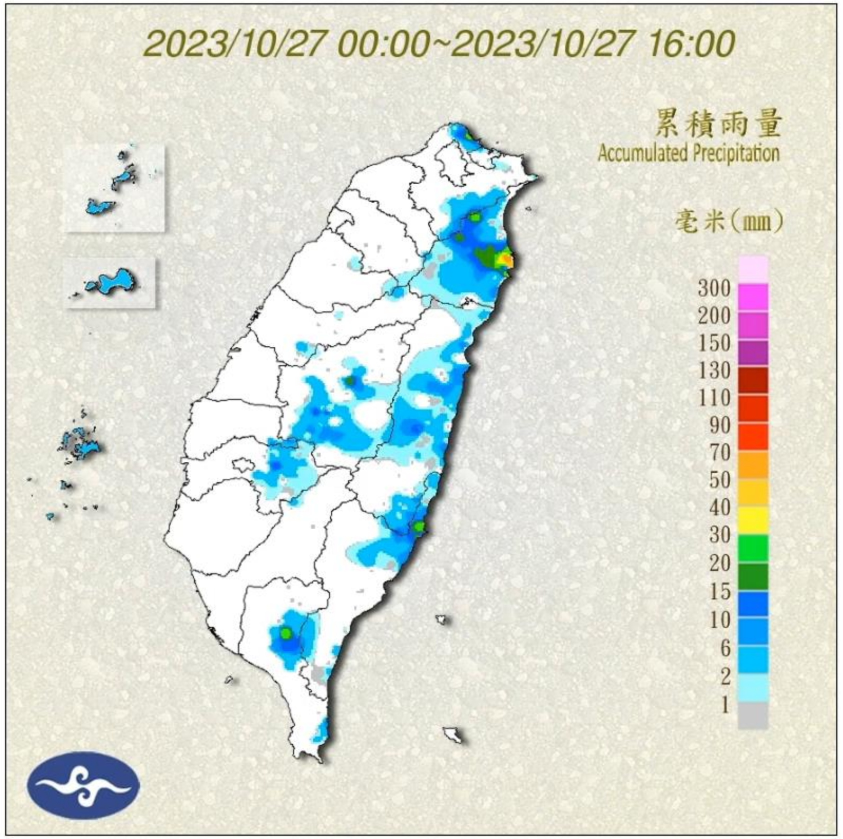
2023-10-27 10:27:44

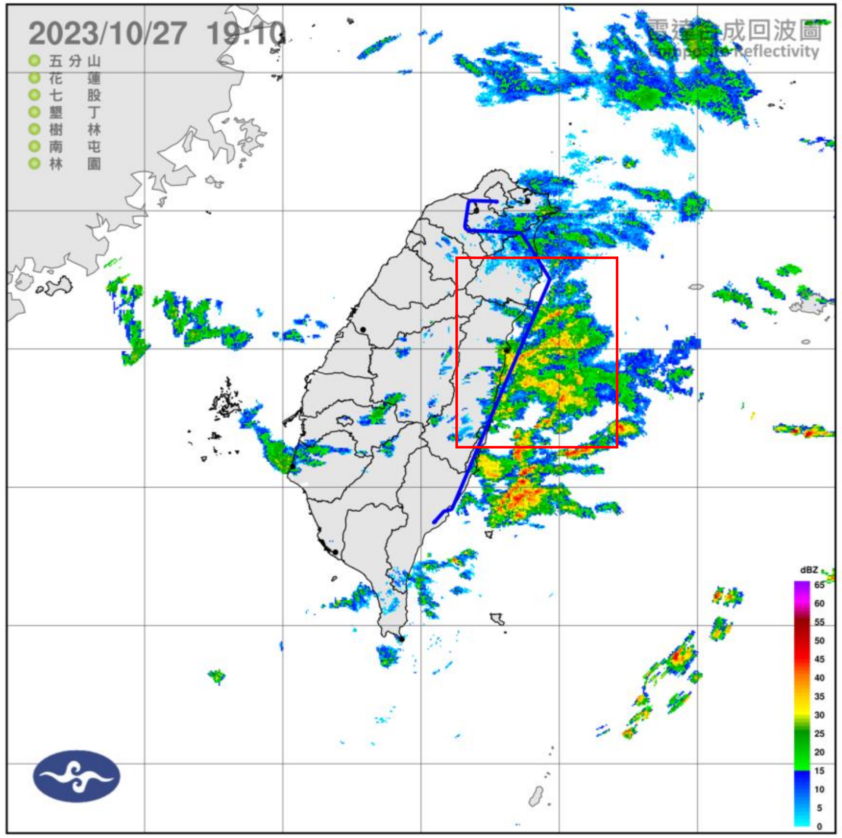
2023-10-27 10:27:46

Case 2B – Case 2A return flight RCFN →RCSS

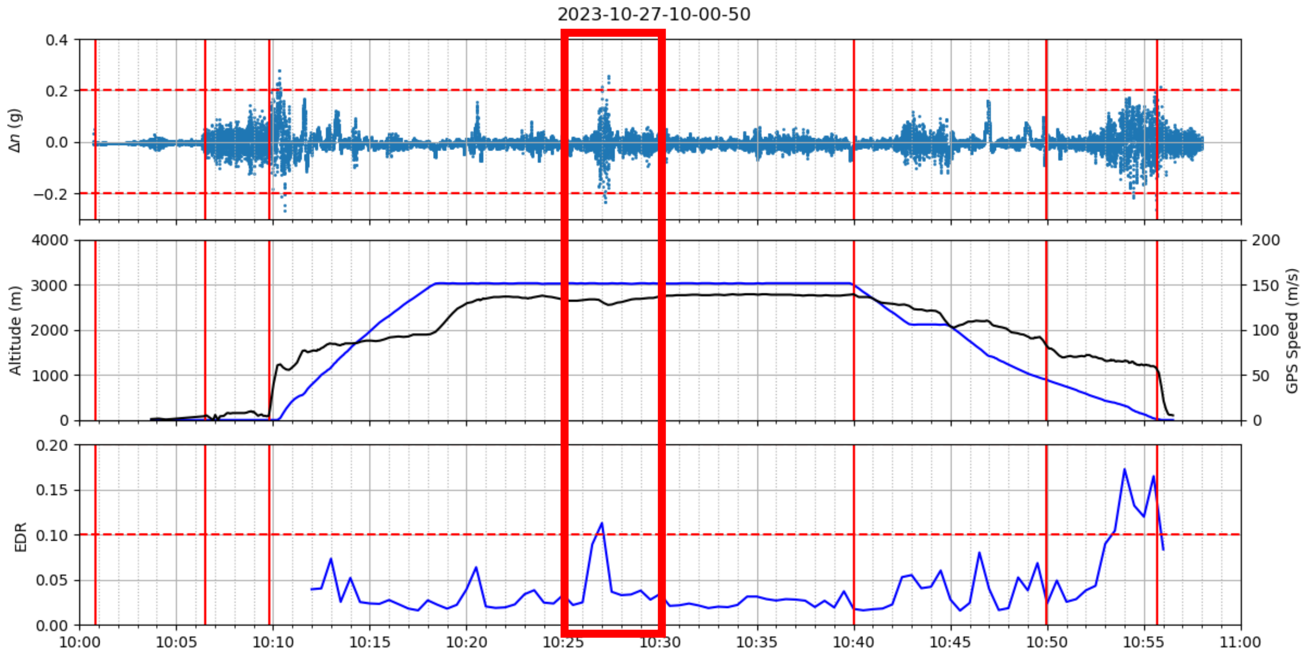
- ATR 72-600 (10/27, 18:40-19:40 Lst)

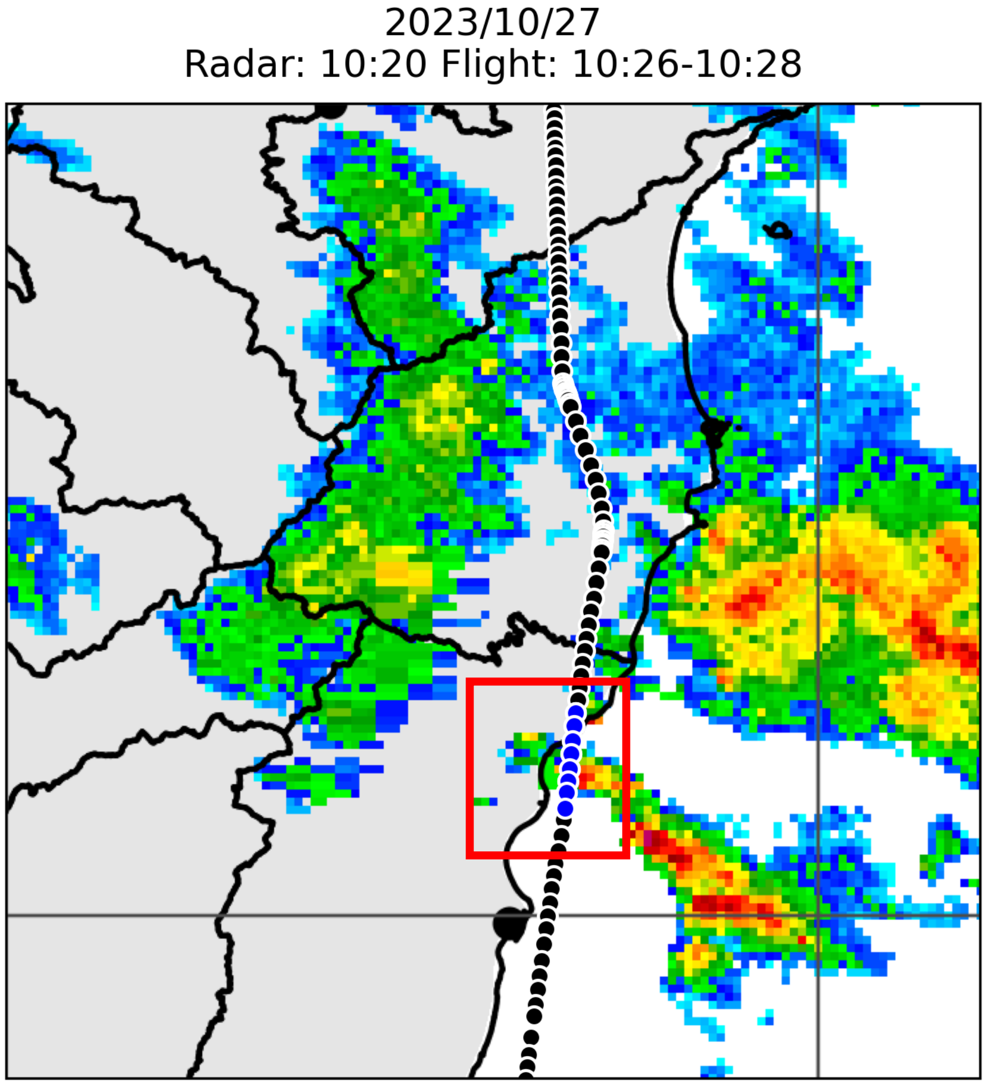






Autumn Frontal weather RCFN->RCSS (18:40-19:40 Pm)
Time evolution of ASAB

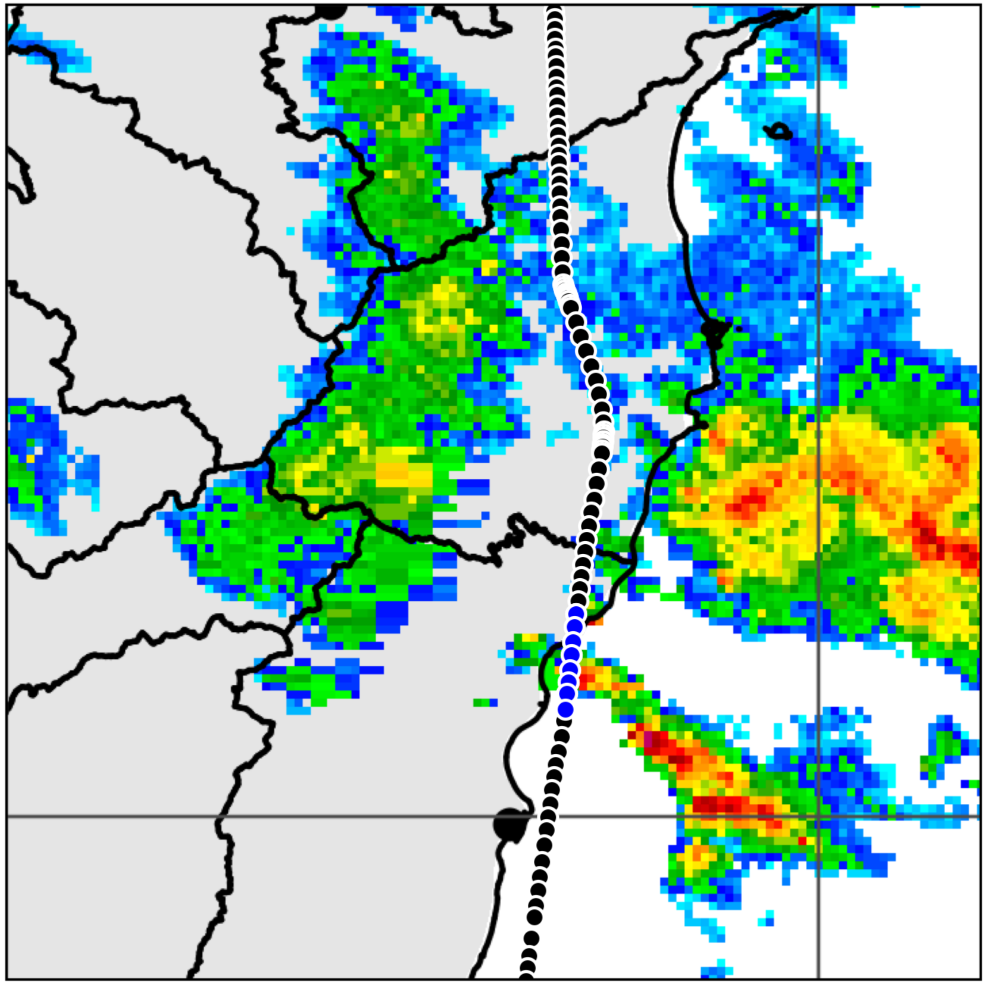


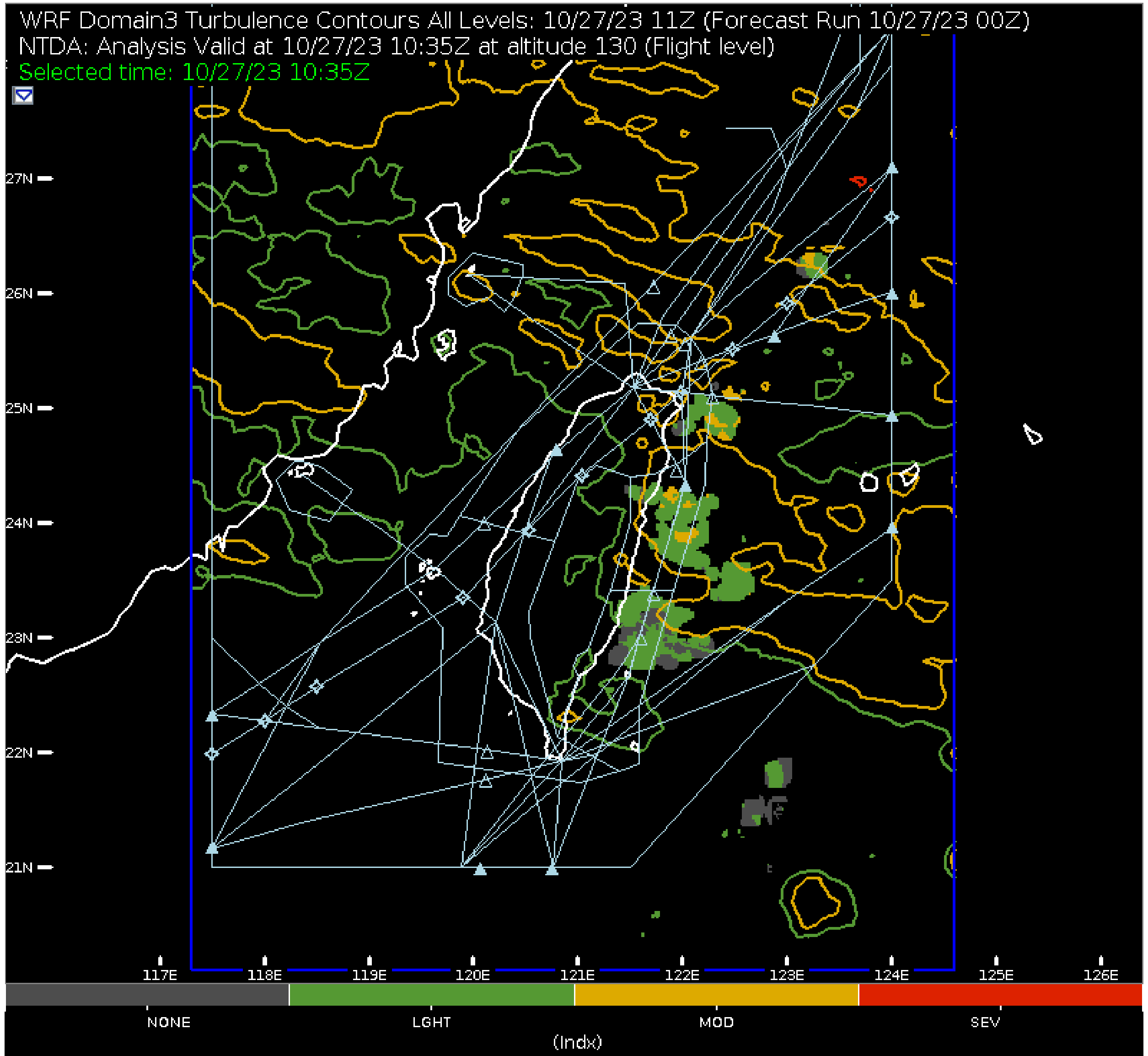


Autumn Frontal weather RCFN->RCSS (18:40-19:40 Pm)

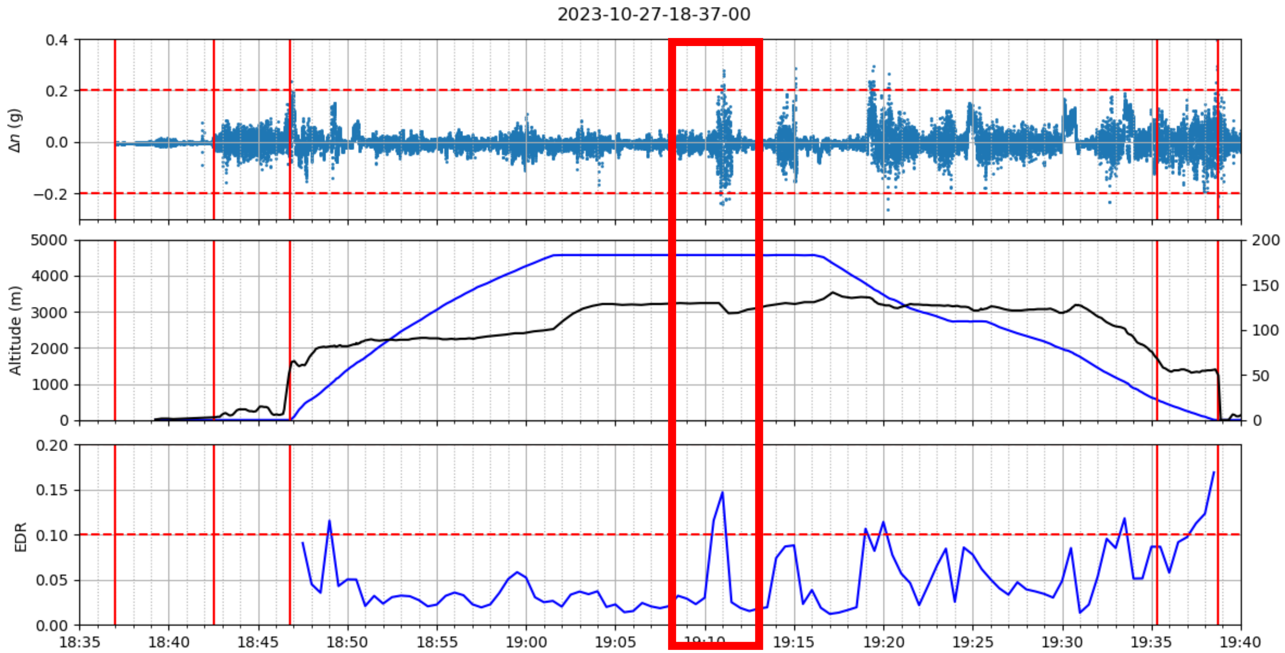
Time evolution of ASAB

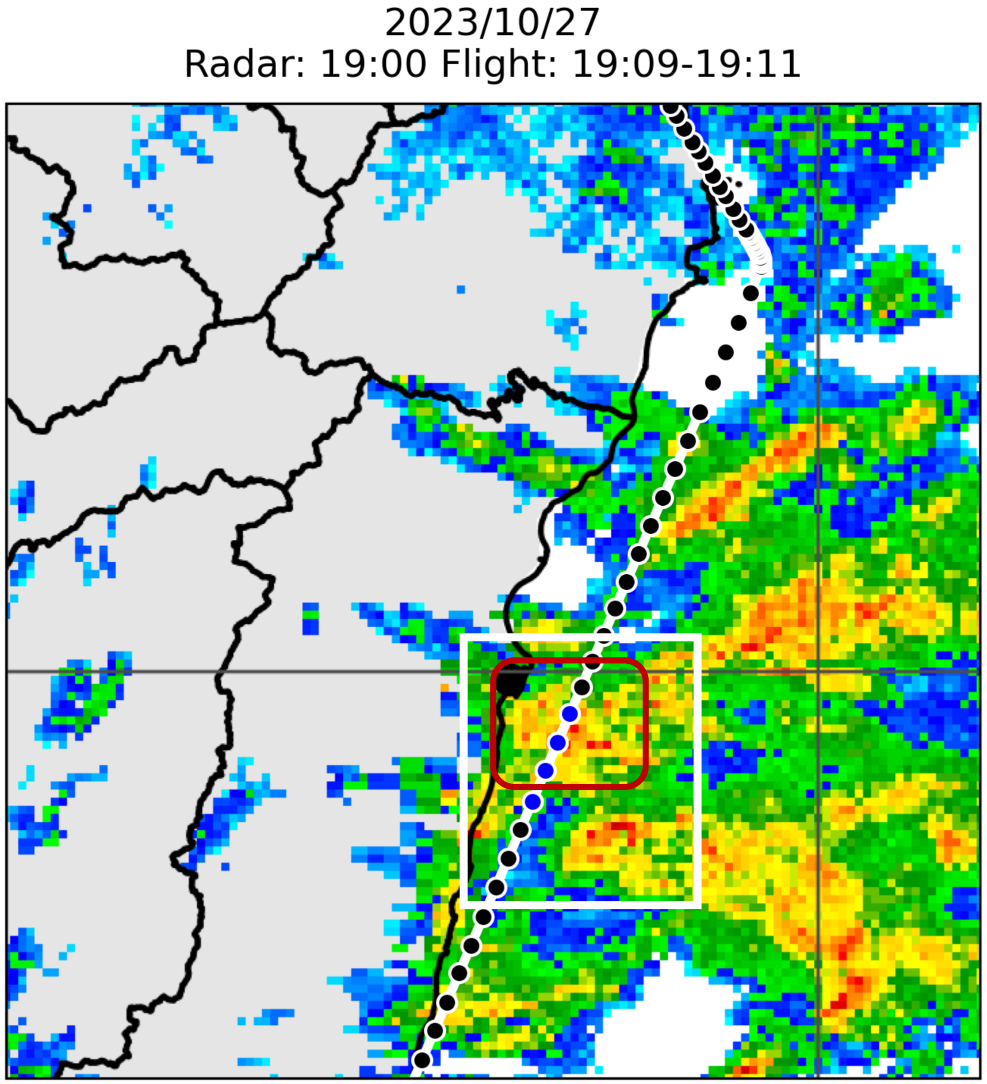
2023/10/27
Radar: 10:20 Flight: 10:26-10:28



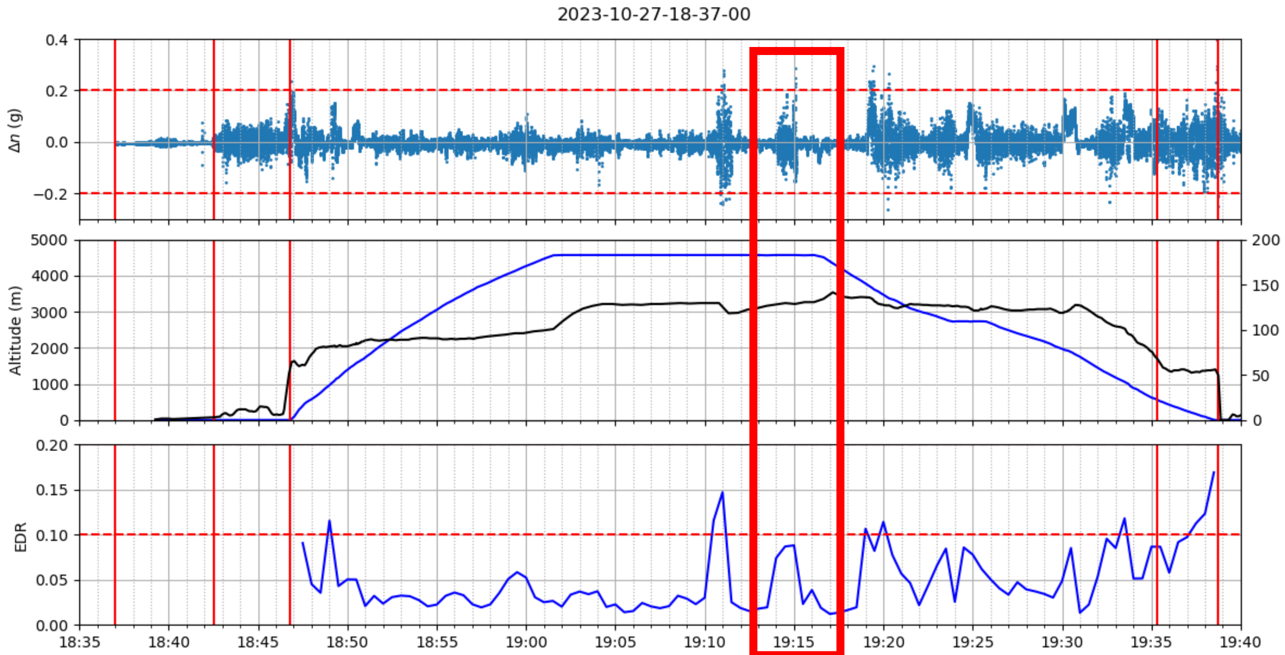


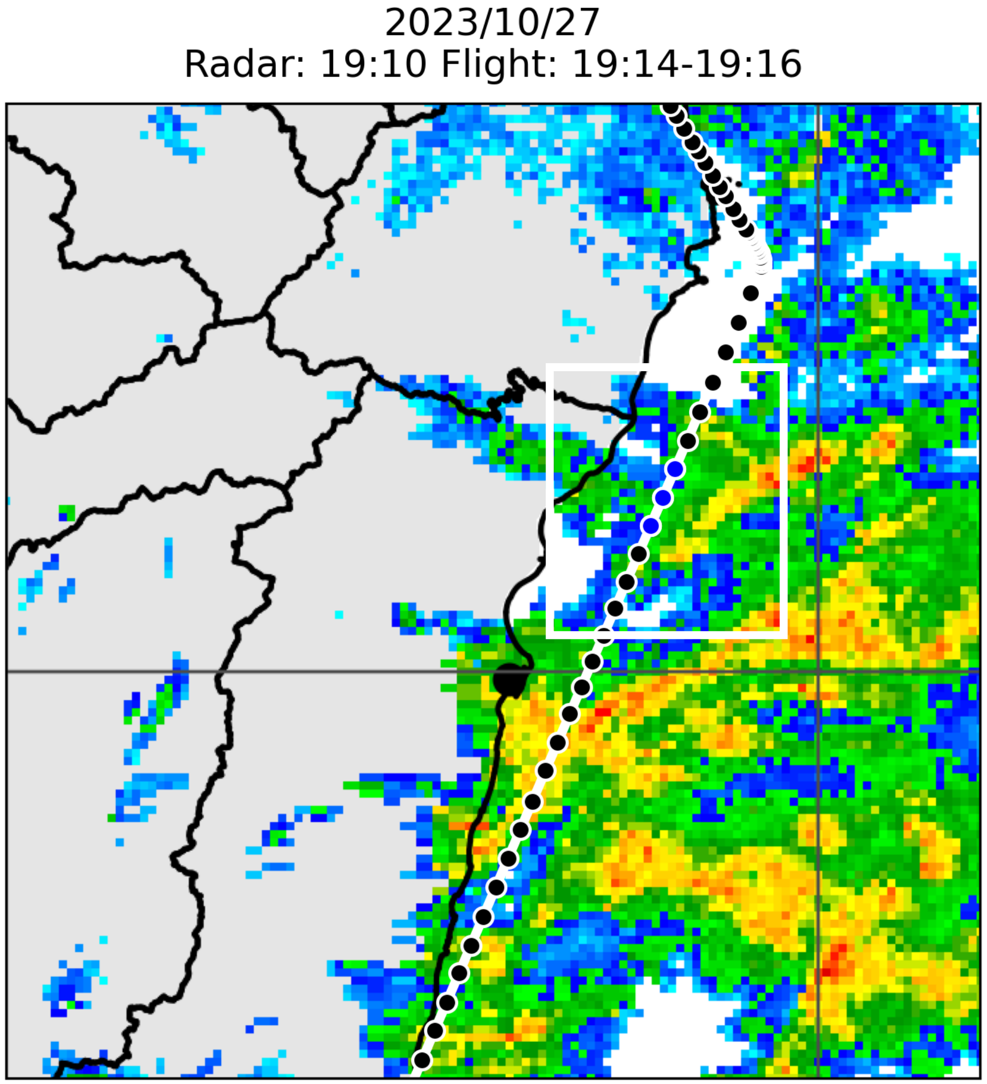
Autumn Frontal weather RCFN->RCSS (18:40-19:40 Pm)
Time evolution of ASAB





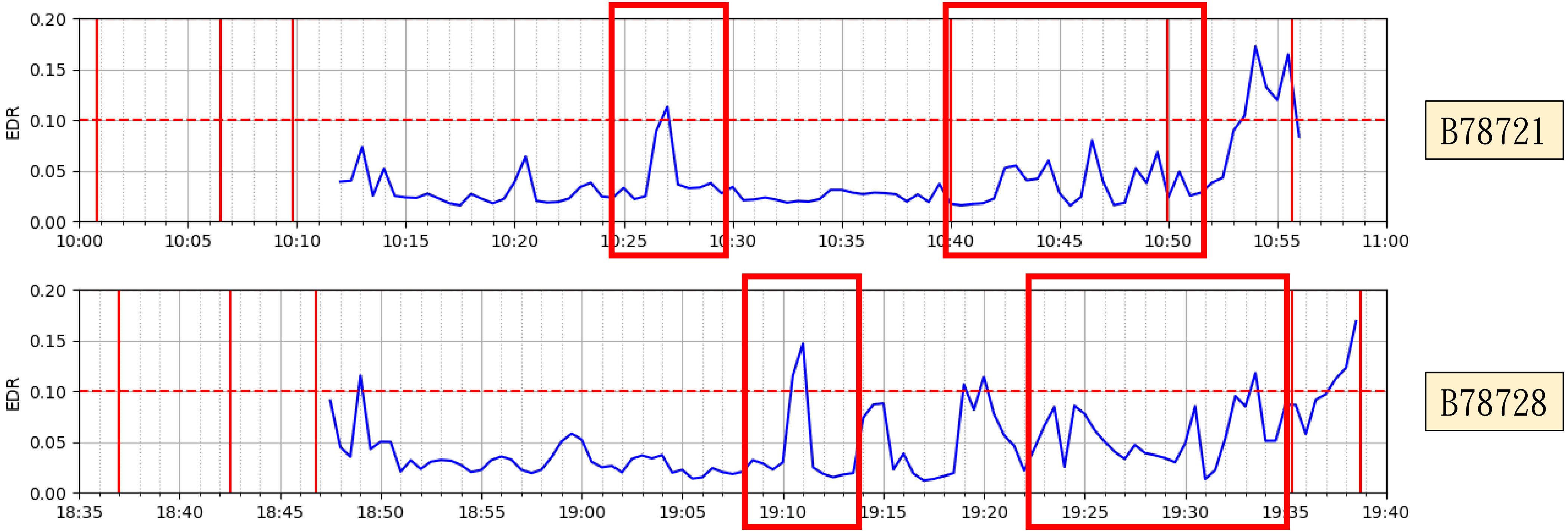
Autumn Frontal weather RCFN->RCSS (18:40-19:40 Pm)
Time evolution of ASAB





Autumn Frontal weather RCFN->RCSS (18:40-19:40 Pm)
Time evolution of ASAB

RCCC->RCFN (10:00-11:00 Am)



RCFN->RCSS (18:40-19:40 Pm)

Summary

- Our tiny/cheaper solution (SASB) plus ADSB dataset our could get the in-air onboard measurement of ATR-600 TURBULENCE AT Taiwan route.
- Our next step is to use fix-wing UAV + ASAB in sever weather.
- We will use this ASAB pack in our western Pacific dropsonde flight mission (Taiwan/G100, Japan/G400) jet airplane in the rainband/eye of typhoon cases.