中央氣象署
Central Weather Administration

國立中央大學
National Central University

Advancing Sounding Capabilities within the Atmospheric Boundary Layer Using Multirotor Unmanned Aerial Vehicle

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114 年39th天氣分析與預報研討會（A8 創新觀測與應用）

Sep. 3rd, 2025 @CWA

大氣系統是3維運動模式，氣象觀測也要是立體化

地面氣象觀測系統

探空氣球、落送探空儀（dropsonde）觀測資料

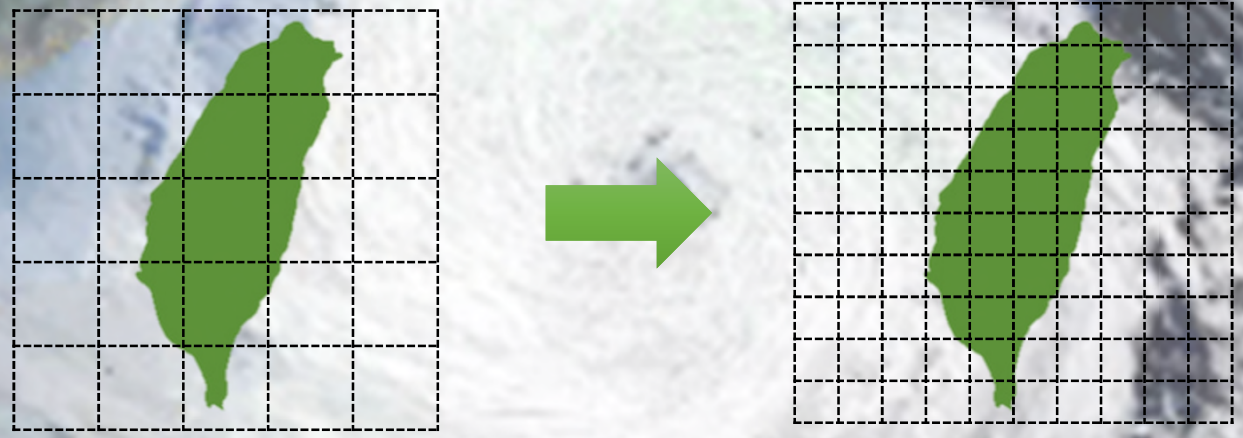
遙測資料：衛星、雷達、光達、剖風儀...

不同尺度的天氣系統，需要不同的觀測資料

中尺度對流系統（Mesoscale Convective System，MCS）

劇烈天氣：積雲發展、雷雨胞(系統)...

隨著數值預報模式解析度的提昇，更高解析度的觀測資料之需求亦隨之增加



中央氣象署地面氣象觀測網

氣象觀測

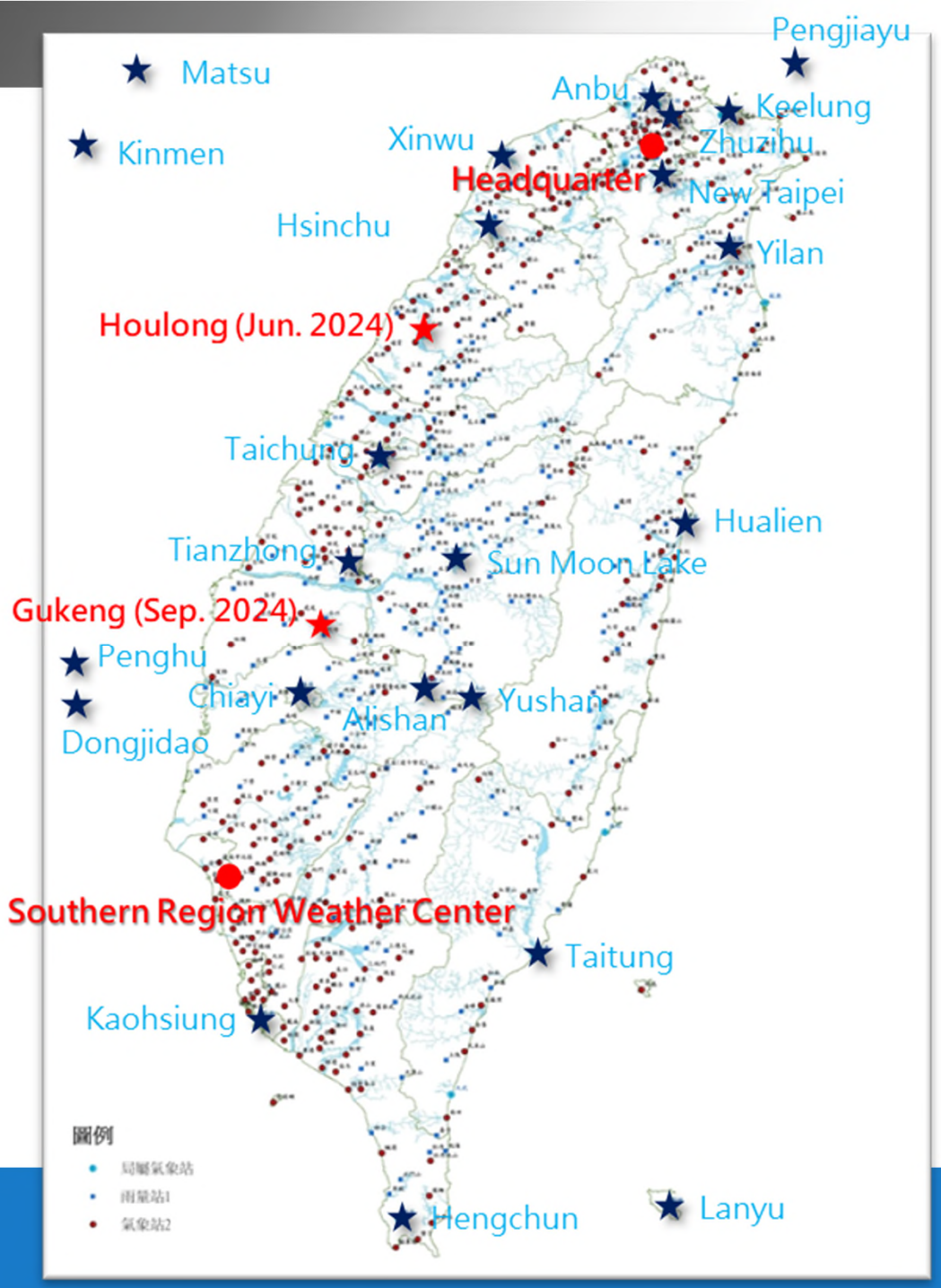
- 25座綜觀氣象站 (有人氣象站)
- 553座自動氣象站
- 147座自動雨量站

} 700 座

- 4 座高空氣象觀測站
  - 新北、彭佳嶼(包括**臭氧探空**觀測)、花蓮及東沙(委由海軍協助施放)
  - 另有3座隸屬於空軍的高空氣象觀測站(澎湖、屏東、綠島)
- 25座閃電偵測站

大氣物理化學觀測

- 1座臭氧全量觀測站(Brewer) - 臺北
- 蘭嶼背景大氣觀測站
  - CO, CO_2, CH_4, H_2O
- 標準大氣輻射觀測站
  - 玉山、蘭嶼、嘉義



提昇大氣邊界層觀測能力

大氣邊界層觀測資料缺乏

探空氣球：

- ✕ 時空解析度不足
- ✕ 探空氣球於大氣邊界層內僅能提供約10分鐘的氣象觀測資料。

衛星：

- ✕ 衛星資料近地面精確度與垂直解析度較差

光達：

- ✕ 200公尺內有觀測限制

剖風儀：

- ✕ 100公尺以內無觀測資料

to et al., 2021)

數值預報結果改進

模式預報改進(霧)

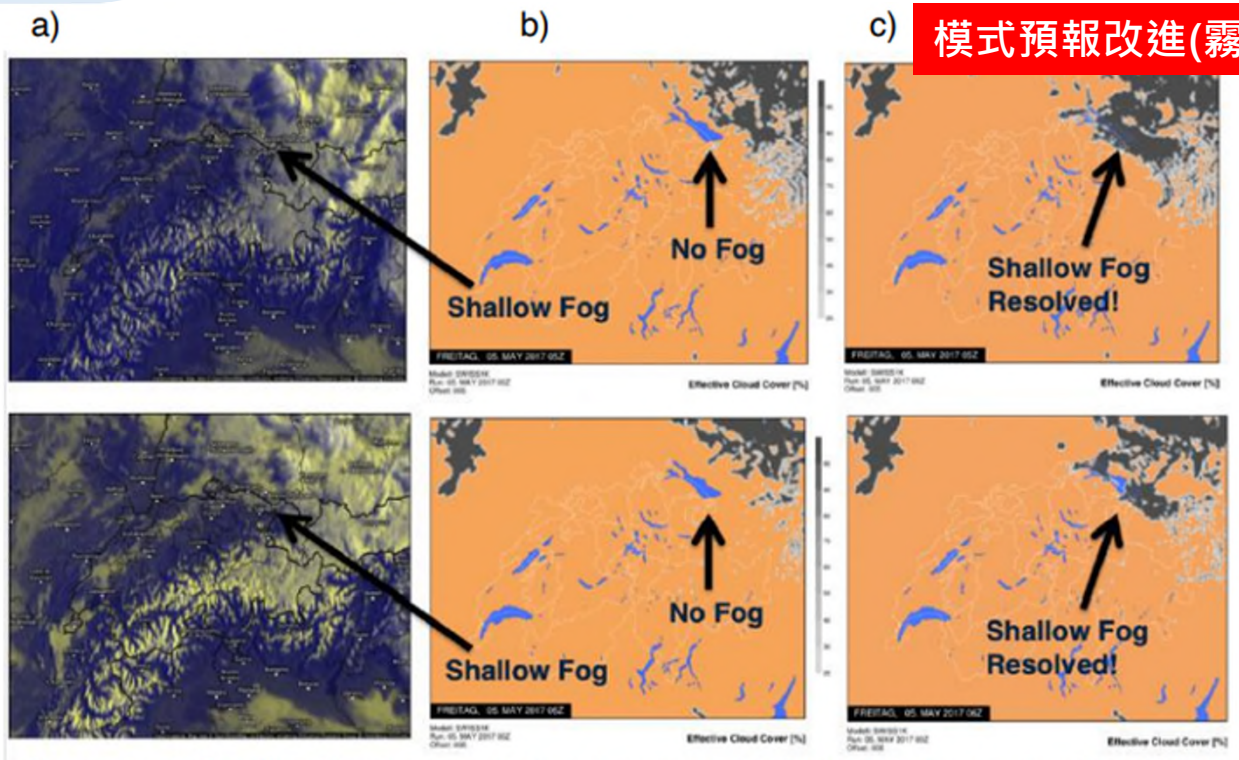


Figure 4: a) Satellite cloud cover during the event, b) SWISS1k forecasts without Meteodrone data, c) SWISS1k forecasts with Meteodrone data

模式預報改進(降雨)

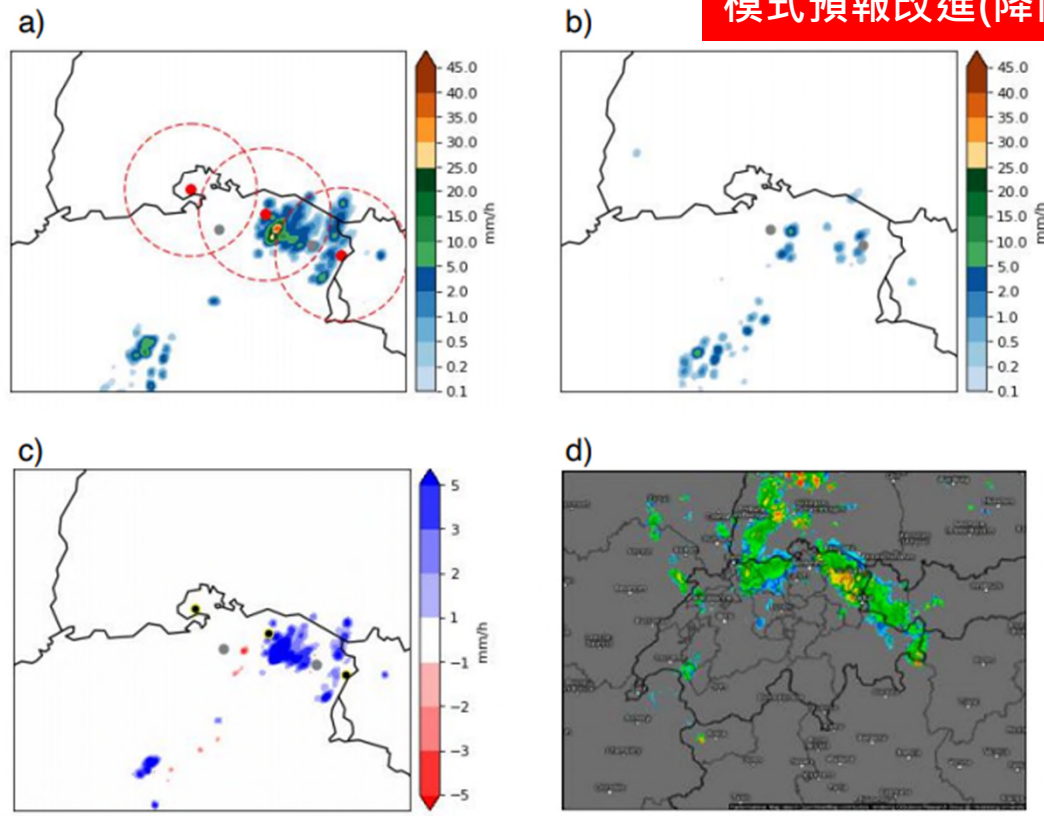


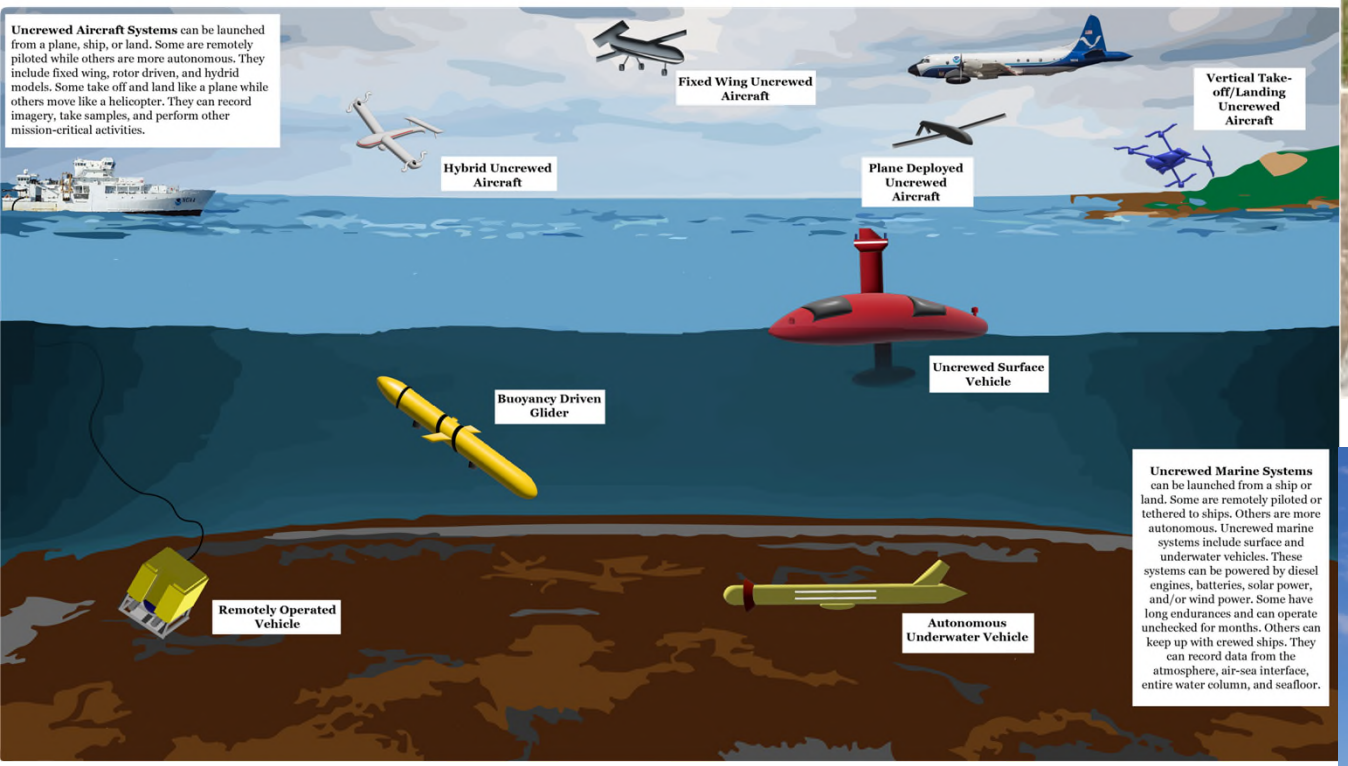
Figure 5: a) Precipitation in the model forecast with Meteodrone, b) Precipitation in the model forecast without Meteodrone, c) Difference between models with and without Meteodrones, d) Radar image of precipitation during the event

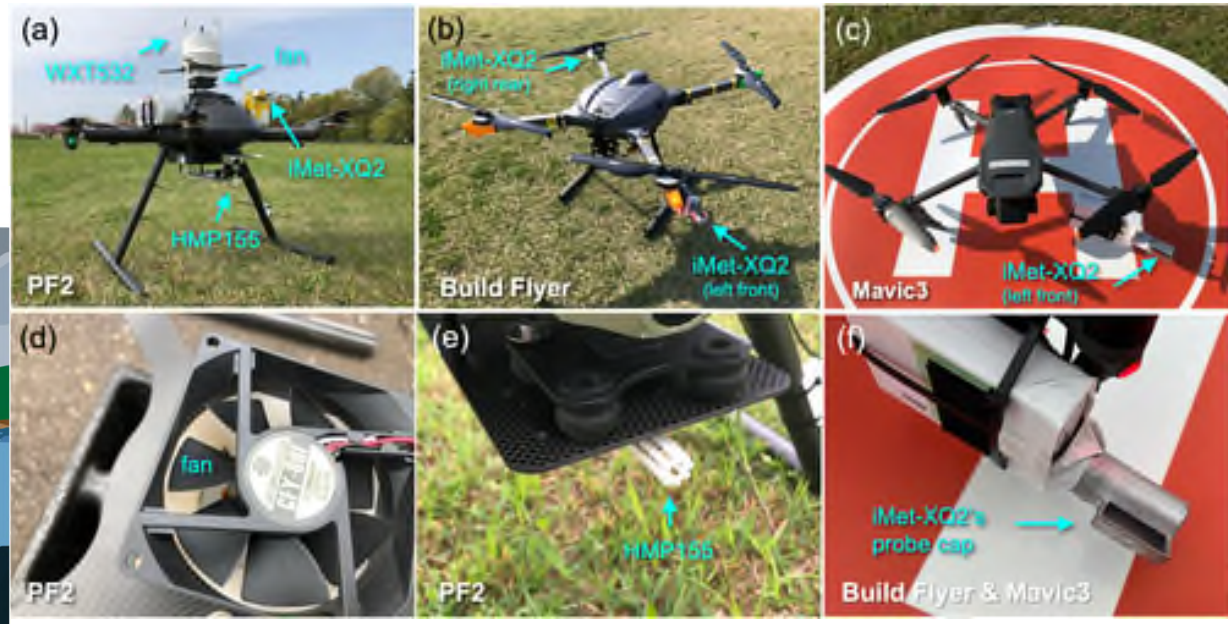
Meteomatics Report 2020

國外無人機應用

NOAA
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
U.S. DEPARTMENT OF COMMERCE

気象庁
Japan Meteorological Agency

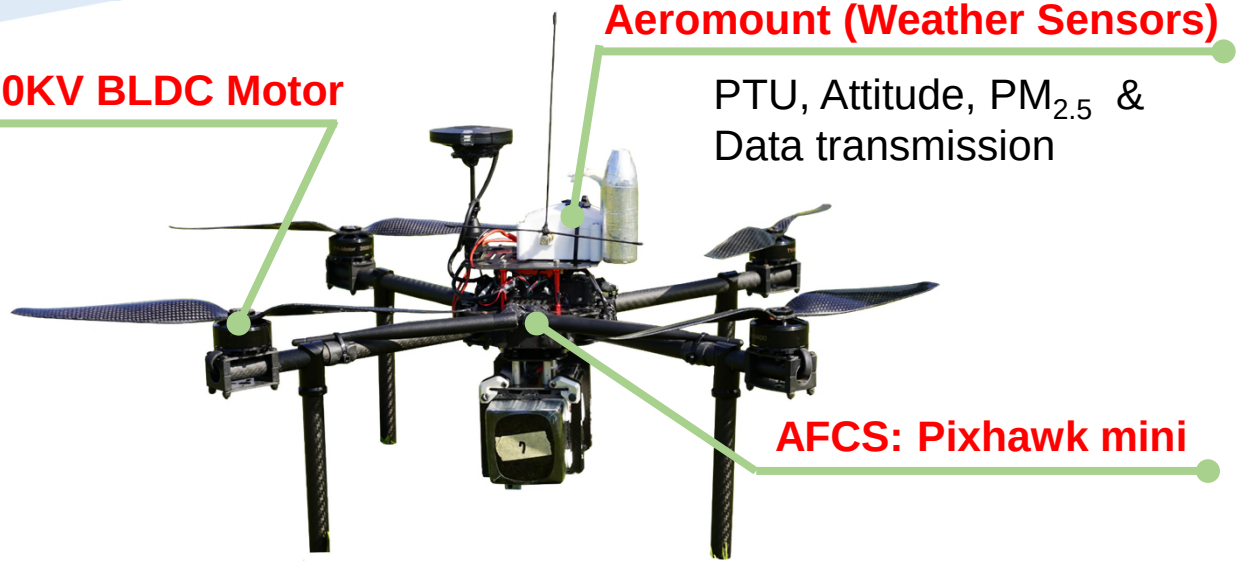




meteomatics

交通部中央氣象署
Central Weather Administration

UAV Observation System



無人機載具性能	
機架材質	探纖
尺寸	39.6 × 39.6 × 32.5 (公分)
軸距	56 (公分)
飛行高度	**3000 公尺** (安全操作範圍)
操作時間	30 minutes (無負載)
最大負載	**1 kg**
飛行速度	**3.5 m/s** (垂直爬升速度)
抗風能力	**14.0 m/s** (陣風) (蒲福風級 **7級陣風**)
電池容量	Li-Po (6S 10400 mAh)
導航系統	**GNSS & RTK**
空機重量	1.41 kg (含電池)
防水程度	**全機防塵防水** **(全天候觀測作業)**

Aeromount 氣象微感測器

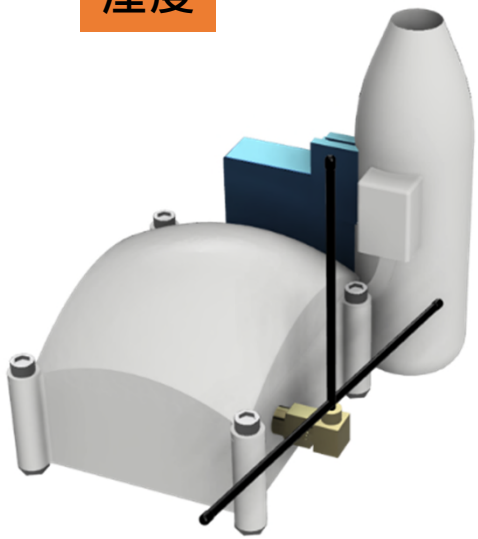
$PM_{2.5}$

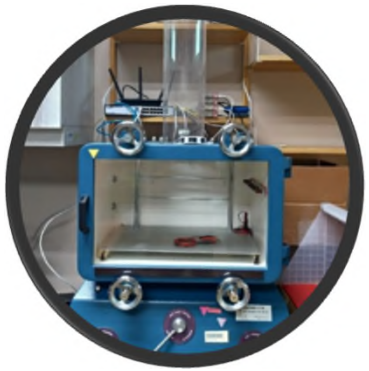
溼度

氣溫

風向與風速
(姿態反演)

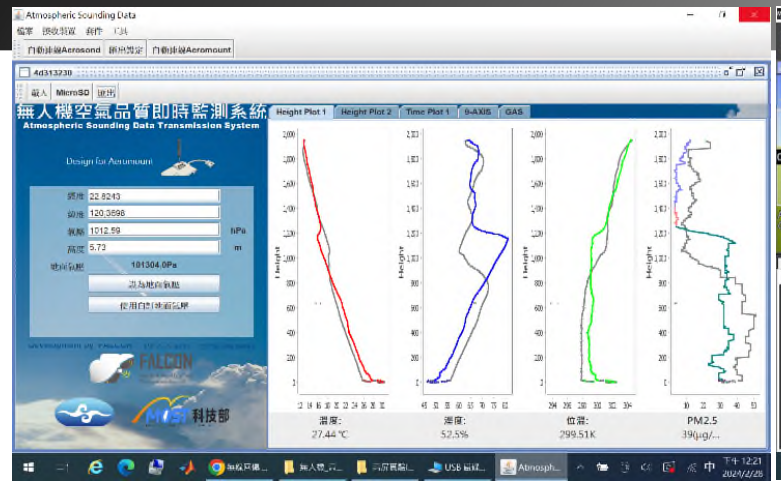
氣壓





- 感應元件皆經由實驗室標準件進行校正
- 與實際觀測(觀測塔、剖風儀、探空儀)進行平行比對

觀測資料處理



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(m), agl,	(m), asl,	(hPa), P,	(°C), T,	(%), RH,	(ug/m^3), PM1,	(ug/m^3), PM25,	(ug/m^3), PM10,	(m/s), ws,	(°), wd,	(K), theta,	(°C), Td,	(g/kg), q,	(g/kg), mixR,	(K), Tv,	(K) thetav
2.5,	26.5,	1000.99,	31.28,	72.51,	7,	8,	10,	3.58,	232.70,	304.35,	25.74,	20.59,	21.02,	308.26,	308.17
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12.5,	36.5,	999.70,	30.87,	72.82,	6,	8,	10,	3.44,	225.75,	304.05,	25.41,	20.22,	20.64,	307.77,	307.80
17.5,	41.5,	999.30,	30.79,	72.88,	7,	9,	10,	3.43,	221.58,	304.00,	25.35,	20.15,	20.57,	307.67,	307.74
22.5,	46.5,	998.65,	30.67,	72.97,	6,	9,	10,	3.37,	214.31,	303.94,	25.25,	20.05,	20.46,	307.54,	307.65
27.5,	51.5,	997.99,	30.55,	73.05,	6,	8,	10,	3.33,	207.65,	303.88,	25.16,	19.95,	20.36,	307.40,	307.58
32.5,	56.5,	997.49,	30.44,	73.13,	6,	9,	10,	3.30,	201.16,	303.81,	25.07,	19.85,	20.26,	307.27,	307.49
37.5,	61.5,	997.14,	30.33,	73.21,	6,	9,	10,	3.26,	197.16,	303.73,	24.98,	19.76,	20.16,	307.14,	307.39
42.5,	66.5,	996.50,	30.22,	73.28,	6,	9,	10,	3.14,	189.66,	303.68,	24.90,	19.67,	20.07,	307.01,	307.32
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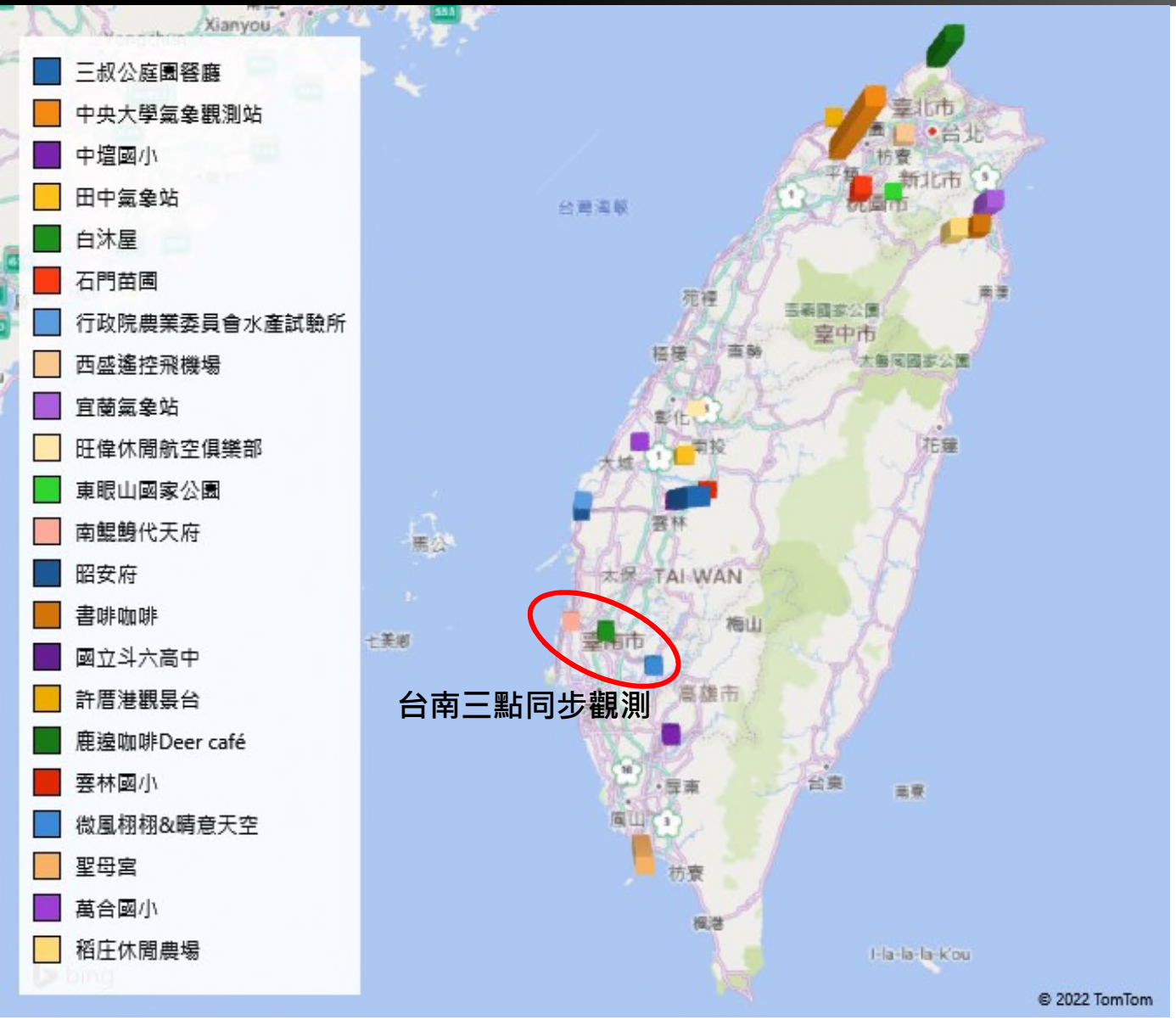
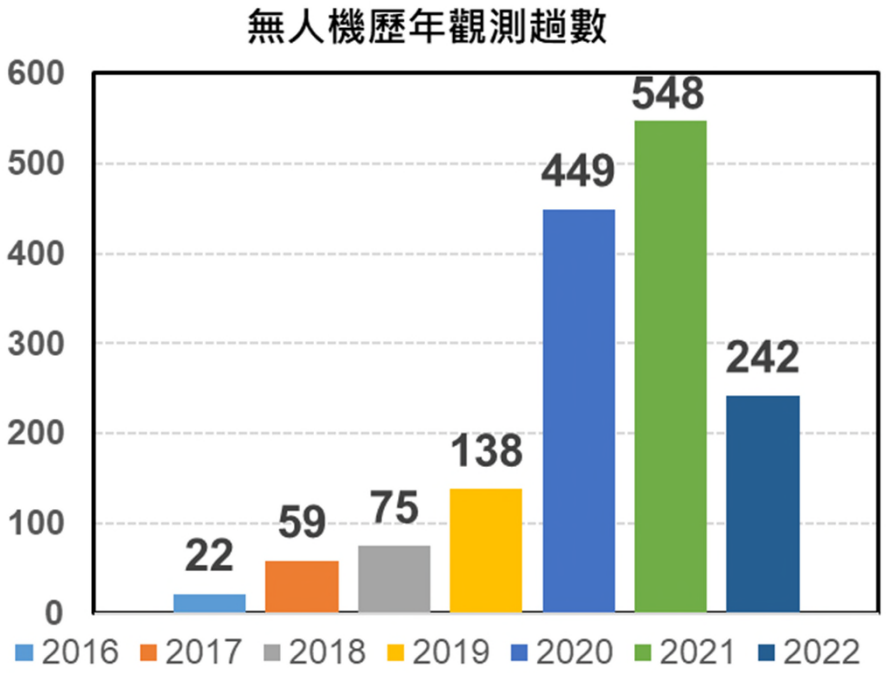
57.5,	81.5,	994.88,	30.00,	73.44,	8,	10,	10,	3.16,	172.63,	303.59,	24.71,	19.49,	19.88,	306.75,	307.20
62.5,	86.5,	994.41,	29.94,	73.48,	7,	10,	10,	3.09,	171.09,	303.57,	24.67,	19.44,	19.83,	306.68,	307.17

實際應用成果-飛行紀錄(累積超過千趟次的飛行觀測)



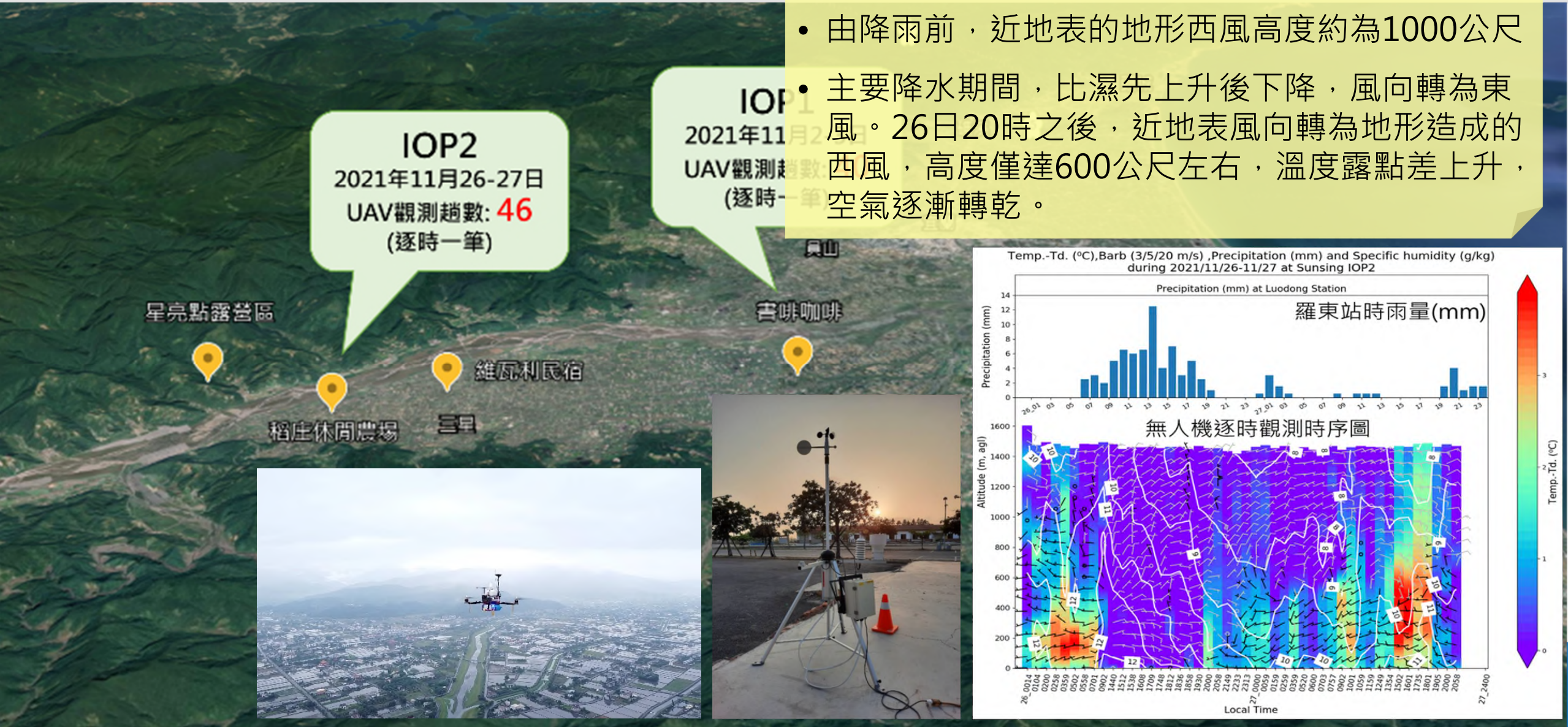
應用議題：

- 大氣邊界層結構分析
- 空氣污染事件監測
- 降雨事件觀測
- 海陸風環流系統觀測



應用於實際天氣作業-宜蘭地區降雨事件觀測

- 我們在宜蘭地區分別於2021年11月2~3日及11月26~27日進行2次的密集觀測(IOP)
- 於48小時每小時進行無人機垂直觀測，並架設臨時地面氣象站，以探討宜蘭降雨事件中天氣系統的特性



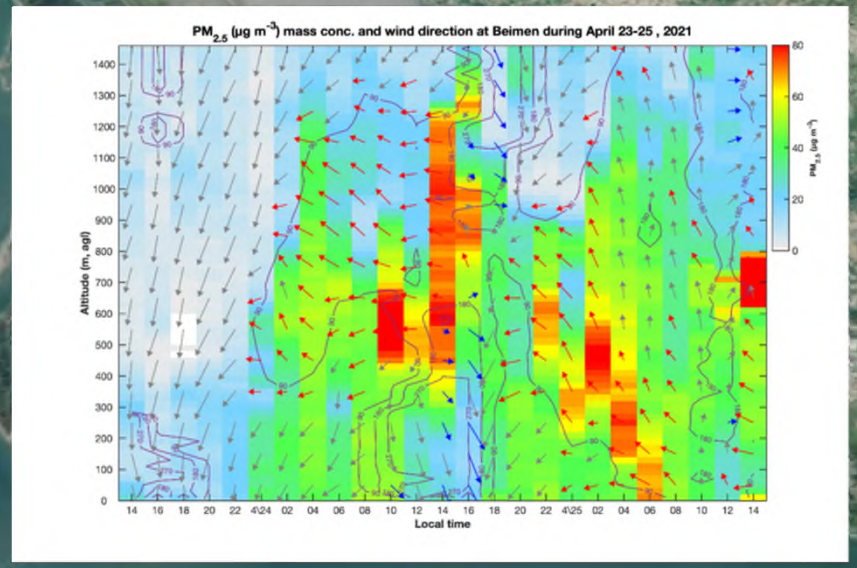
- 由降雨前，近地表的地形西風高度約為1000公尺
- 主要降水期間，比濕先上升後下降，風向轉為東風。26日20時之後，近地表風向轉為地形造成的西風，高度僅達600公尺左右，溫度露點差上升，空氣逐漸轉乾。

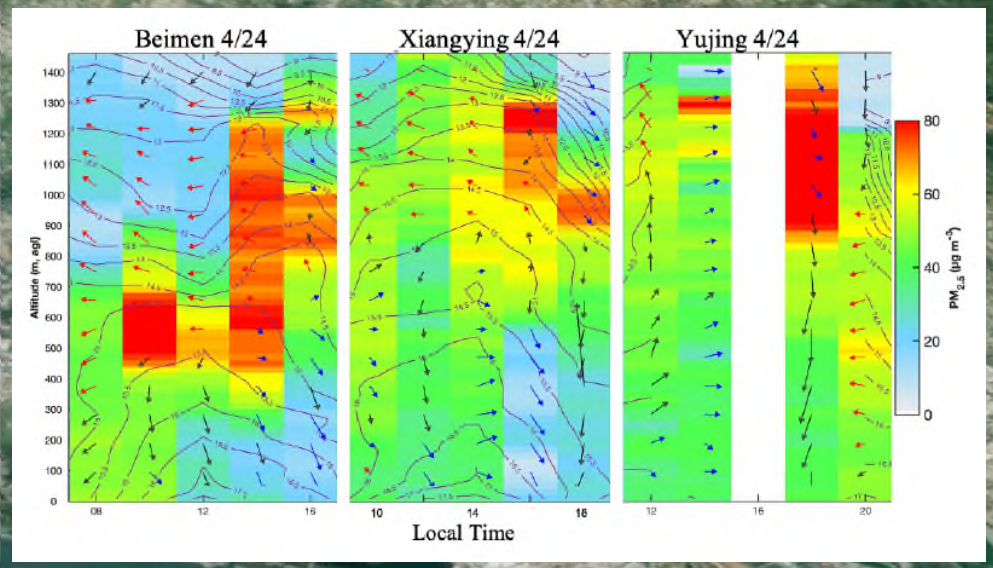
應用於實際天氣作業-台南地區海陸風環流系統觀測

- 探討南部地區典型海陸風垂直結構日夜變化及
- 2021/04/23~25，於台南市北門、下營和玉井
- 整合氣象站氣象資料與環保署空氣品質監測資

北門

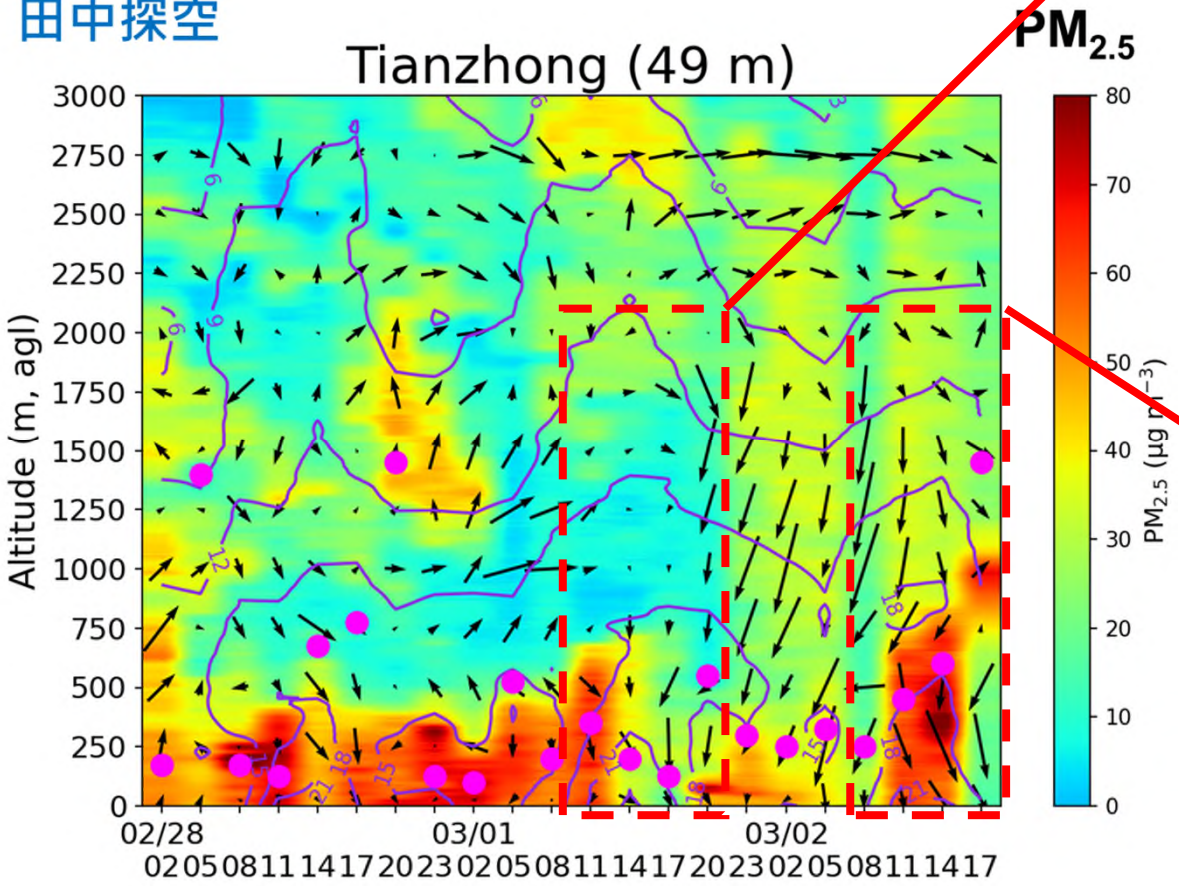
- 海風影響的範圍於中午過後逐漸由台南沿海傳輸到近山區，垂直方向的影響範圍也同步增加
- 空氣品質的變化上，海風前緣常有$PM_{2.5}$污染物的累積，而在前緣通過後$PM_{2.5}$濃度則會明顯的下降
- 由無人機所觀測的$PM_{2.5}$垂直剖面觀測資料顯示，污染物經由海風引起的垂直運動，會再透過東風迴流帶回至海岸



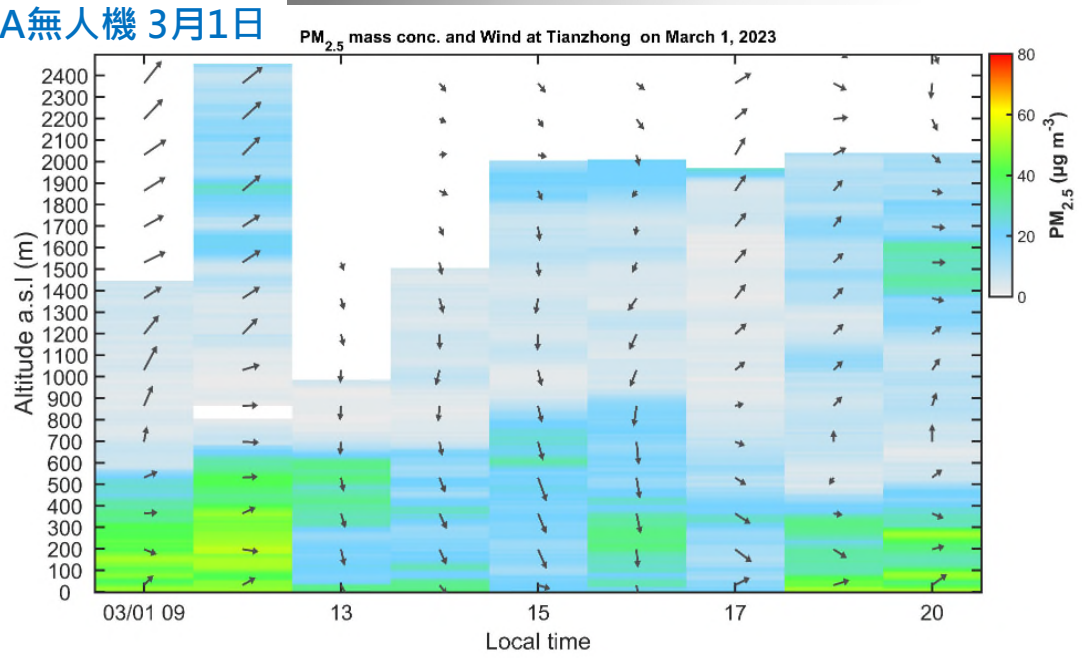


應用於實際天氣作業-2023年T-POMDA觀測部署

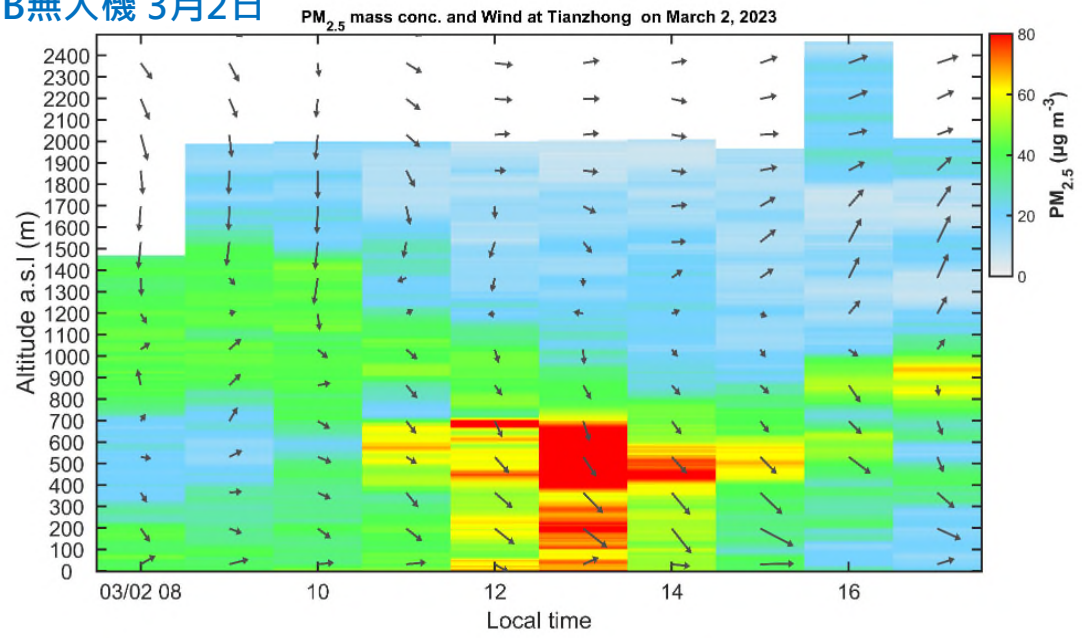
田中探空



CWA無人機 3月1日



CWB無人機 3月2日



應用於實際天氣作業-2024年WMO UAS Demonstration Campaign

應用於實際天氣作業-2024年WMO UAS Demonstration Campaign

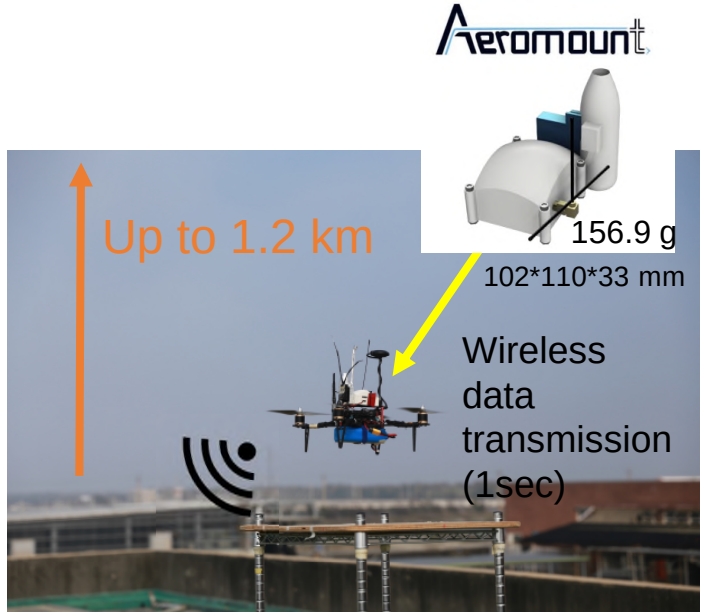
Enter 0 for 0, L for <25%, M for 25-75%, and H for >75%.

Form Completed	UAS Operator Name	Affiliation	WMO Operator_ID (one ID per operator per country)	Location	4/1 Mon	4/8 Mon	4/15 Mon	4/22 Mon	4/29 Mon	5/6 Mon	5/13 Mon	5/20 Mon	5/27 Mon	6/3 Mon	6/10 Mon	6/17 Mon	6/24 Mon	7/1 Mon	7/8 Mon	7/15 Mon	7/22 Mon	7/29 Mon	8/5 Mon	8/12 Mon	8/19 Mon	8/26 Mon	9/2 Mon	9/9 Mon	9/16 Mon	9/23 Mon	9/30 Mon
x	Konrad Bärfuss	TU Braunschweig	043	Ny Ålesund,	0	0	0	0	0	0	M	M	M	M	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
x	Konrad Bärfuss	TU Braunschweig	044	Gardelegen, (	H	H	H	H	H	H	M	M	H	0	0	H	M	M	M	0	0	0	M	H	H	H	0	M	0	0	0
	Tony Davila	Knight Technical Solutions	045	Huntsville, Al	M	M	M	M	M	L	L	L	L	L	L	L	L	L	H	H	H	H	H	H	H	H	M	M	M	M	M
	Carlo Wang	National Central University	046	Tianzhong, T	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	L	H	L	L	L
	Ben Pickering	Menapia Ltd.	047	United Kingd	0	0	0	0	0	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H
	Ben Pickering	Menapia Ltd.	048	TBD, Oklahoma (flight week)																								H			
	David Brus	FMI	049	Pallas/Sodan	H	H	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
	David Brus	FMI	050	Jokioinen, Fi	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
x	Sterling Cripps	Landing Zones Canada	051	Alberta, Cana	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H
	Jennifer Fowler	NASA Langley Research Center	052	Fort Drum, N	L	H	L	H	L	H	L	H	L	H	L	L	H	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Jun Inoue	NIPR	053	Arctic Ocean	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	M	M	M	0	0
	Paul Stevens	Voltitude Ltd	054	Cabo Verde	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	H	H	H	H	H
x	Filip Najman	Meteopress	056	Litvínov, Czec	M	H	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	H	M	M	L	0	0	M	L	M
x	Nathan Dunn	InterMet Systems	057	Grand Rapids	M	M	0	0	0	M	M	M	M	M	M	M	M	M	M	M	M	M	0	0	0	0	0	0	0	0	0
	Nathan Dunn	InterMet Systems	058	TBD, Oklahor	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	H	0	0	0
	Carlo Wang	National Central University	059	Taipei, Taiwa	0	0	0	0	0	0	0	0	0	0	0	0	0	H	H	H	H	H	H	H	H	H	0	0	0	0	0
	Carlo Wang	National Central University	060	Taoyuan, Tai	0	H	0	0	0	0	0	0	0	0	0	0	0	H	H	H	H	H	H	H	H	H	0	0	0	0	0
	Sean Bailey	University of Kentucky	061	Bloomington,	0	H	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
x	Carlo Wang	National Central University	062	Kaohsiung, T	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
x	Darek Baranowski	IG PAS	063	Poland (varic	0	0	0	0	0	0	0	0	0	0	0	M	0	0	0	0	0	0	H	H	0	0	0	H	H	M	M
	Andreas Platis	University of Tübingen	064	Stötten, Gerr	0	M	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Tyler Bell	CIWRO	065	Butler, OK, US	0	0	0	0	H	M	M	M	M	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Tyler Bell	CIWRO	066	Seiling, OK, U	0	0	0	0	H	M	M	M	M	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Tyler Bell	CIWRO	067	Alva, OK, USA	0	0	0	0	H	M	M	M	M	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Jakub Kákona	ThunderFly s.r.o.	068, 069	Starý Vestec, Soběslav, (2 locations in Czechia)						0	0	L	L	L	M	M	M	H	H	H	H	H	H	H	H	H	H	H	H	H	H

應用於實際天氣作業-2024年WMO UAS Demonstration Campaign

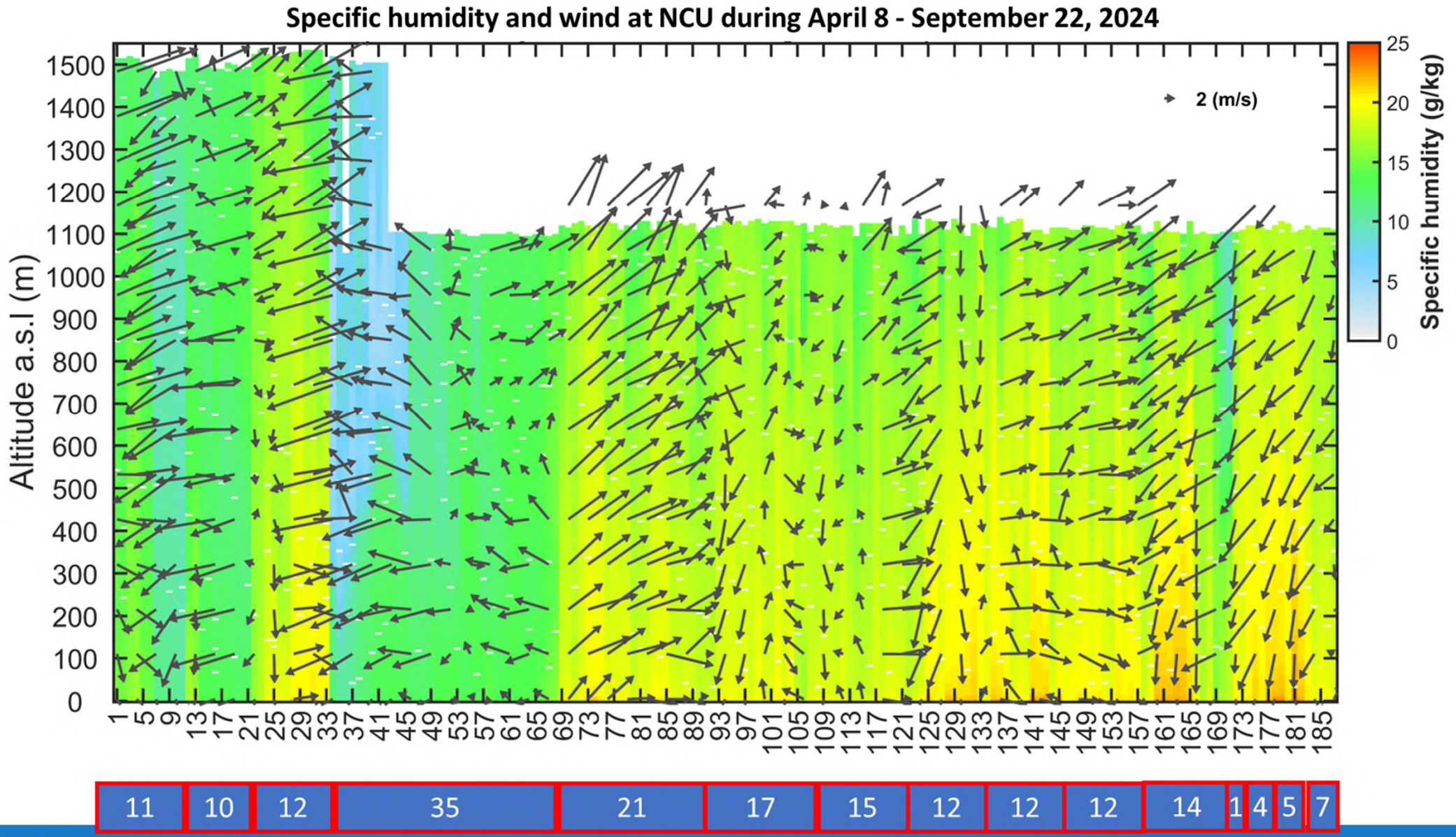
Date	Number of flight
2024.04.08-04.09	11
2024.04.23-04.24	10
2024.05.30-05.31	12
2024.06.04-06.05	35
2024.07.11-07.12	21
2024.07.15-07.16	17
2024.07.30-07.31	15
2024.08.06-08.07	12
2024.08.12-08.13	12
2024.08.18-08.19	12
2024.09.01-09.02	14
2024.09.10	1
2024.09.18	4
2024.09.20	5
2024.09.22	6

Total: 187 flights



	Temp	RH	P	WS	WD	$PM_{2.5}$
Accuracy	±0.3 ℃	±2%	±1.0 hPa	±0.5 m /s	< 10°	±10 μg $/m^3$
Resolution	0.01 ℃	0.01%	0.01 hPa	0.1 m/s	0.1°	1 μg/m^3

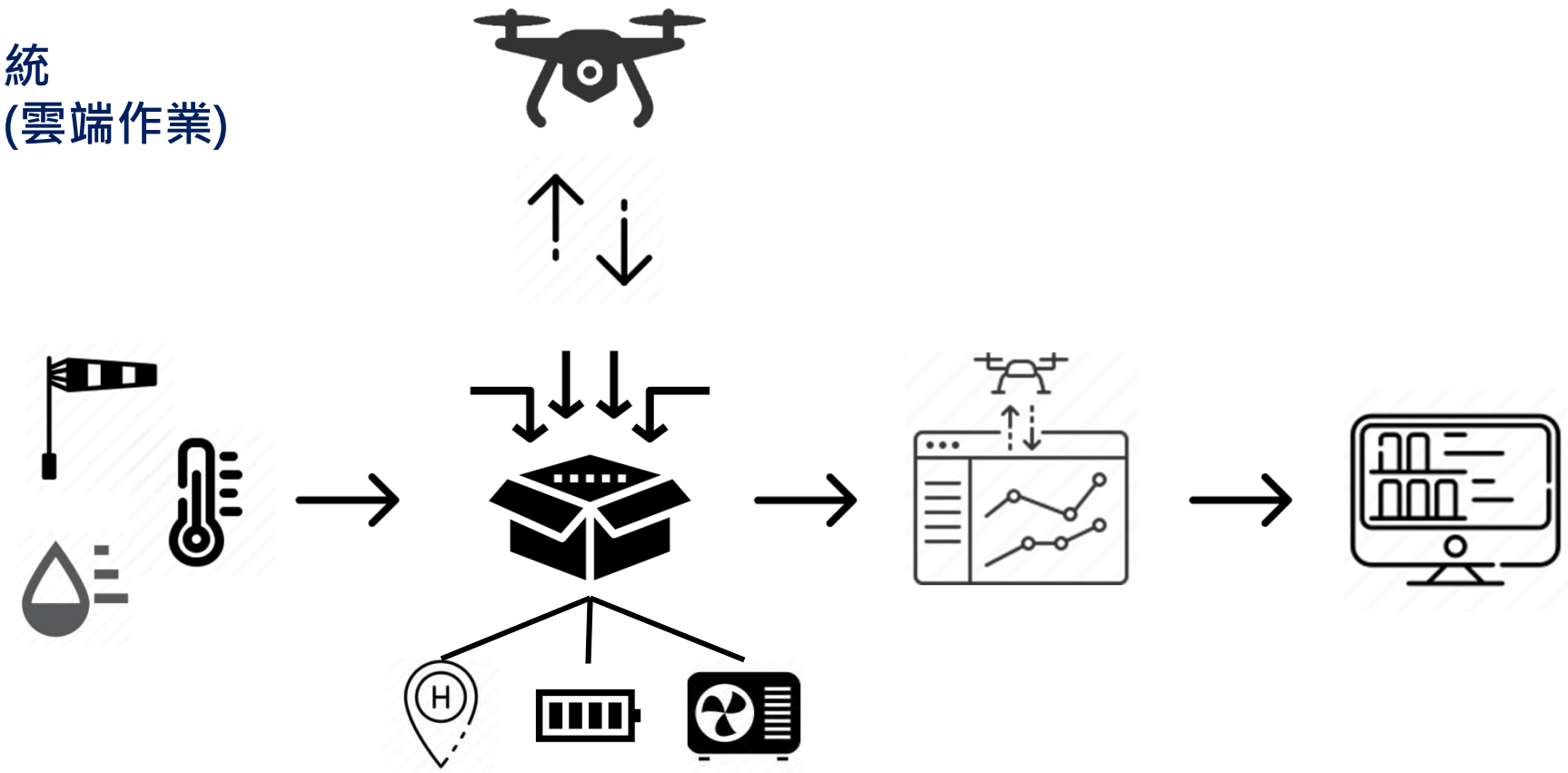
應用於實際天氣作業-2024年WMO UAS Demonstration Campaign



無人機氣象觀測系統自動化

- 無人機氣象觀測起降平台系統

✓ 無人機載具收納艙
✓ 具防風、防雨、耐高低溫等功能
✓ 機體乾燥功能
✓ 電力保養、管理與充電系統
✓ 無人機自動飛行管理系統(雲端作業)
✓ 地面氣象觀測資料整合
✓ 觀測資料即時展示
✓ 資料接收與回傳



大氣邊界層垂直剖面觀測系統（自動化作業）

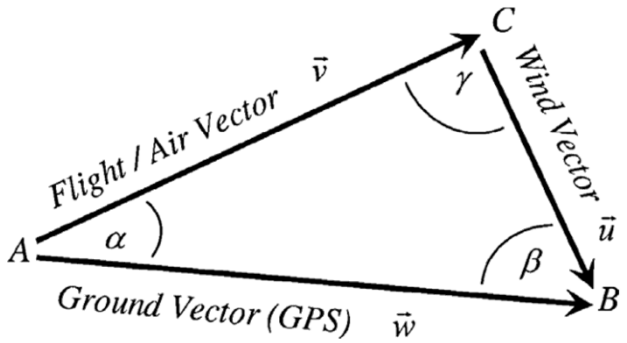
	探空氣球	微型探空	UAV
觀測高度	32公里	8-12公里	1.5-3公里 *6公里
施放成本	高 (NT 12,000/ US 375)	中 (NT 3,000/ US 90)	低 (NT 400/ US 13)
時間解析度	6–12小時	每小時	每小時
空間解析度	200公里	50公里	200公里
觀測參數	基本PTU	基本PTU	基本PTU
擴充性	低 (需外掛固定模組)	低 (需外掛固定模組)	高 (模組化設計)
機動性	低	中	高
劇烈天氣作業	適用性高	適用性高	適用性低
回收性	X (一次性)	X (一次性)	O (重複使用)

感謝聆聽

Thank You for listening

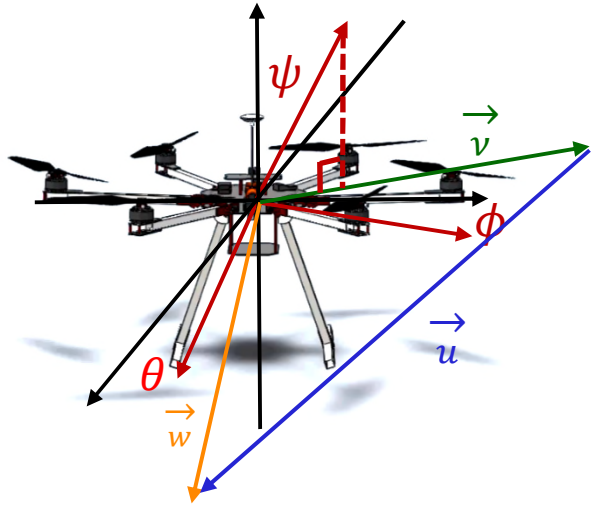
If you’re interested and have any advice, please feel free to contact us via the mail: adenins@cwa.gov.tw

Wind triangle:



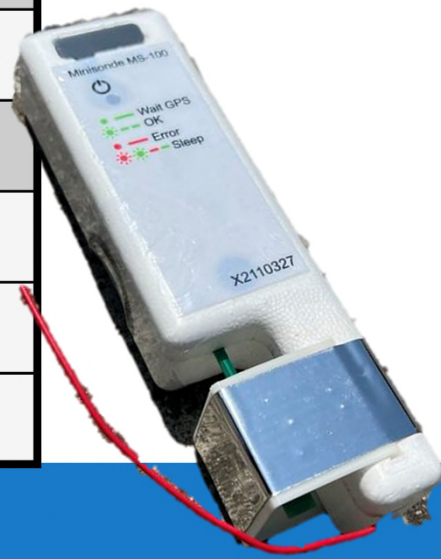
Calm

Breeze

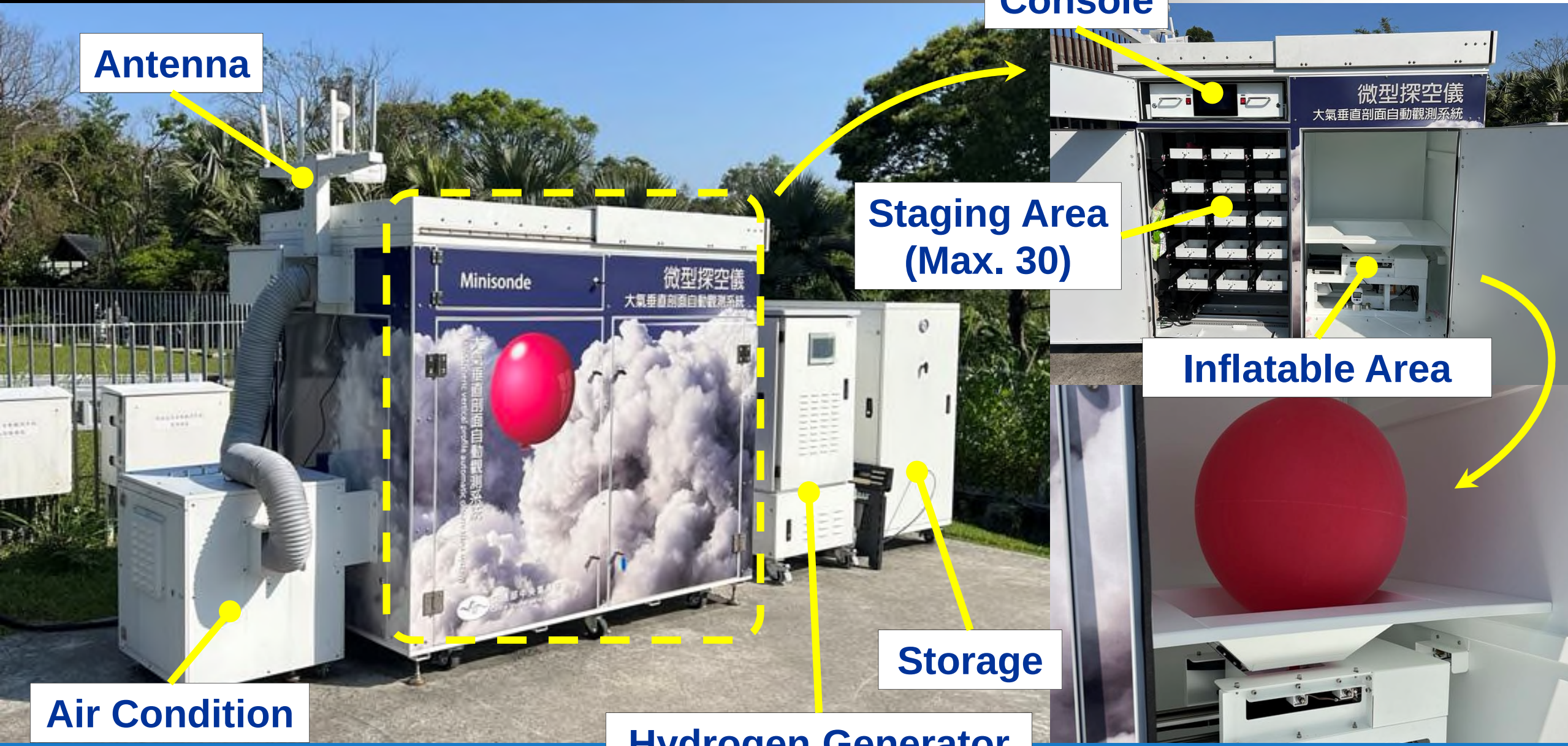


Mini-Sonde Observation System

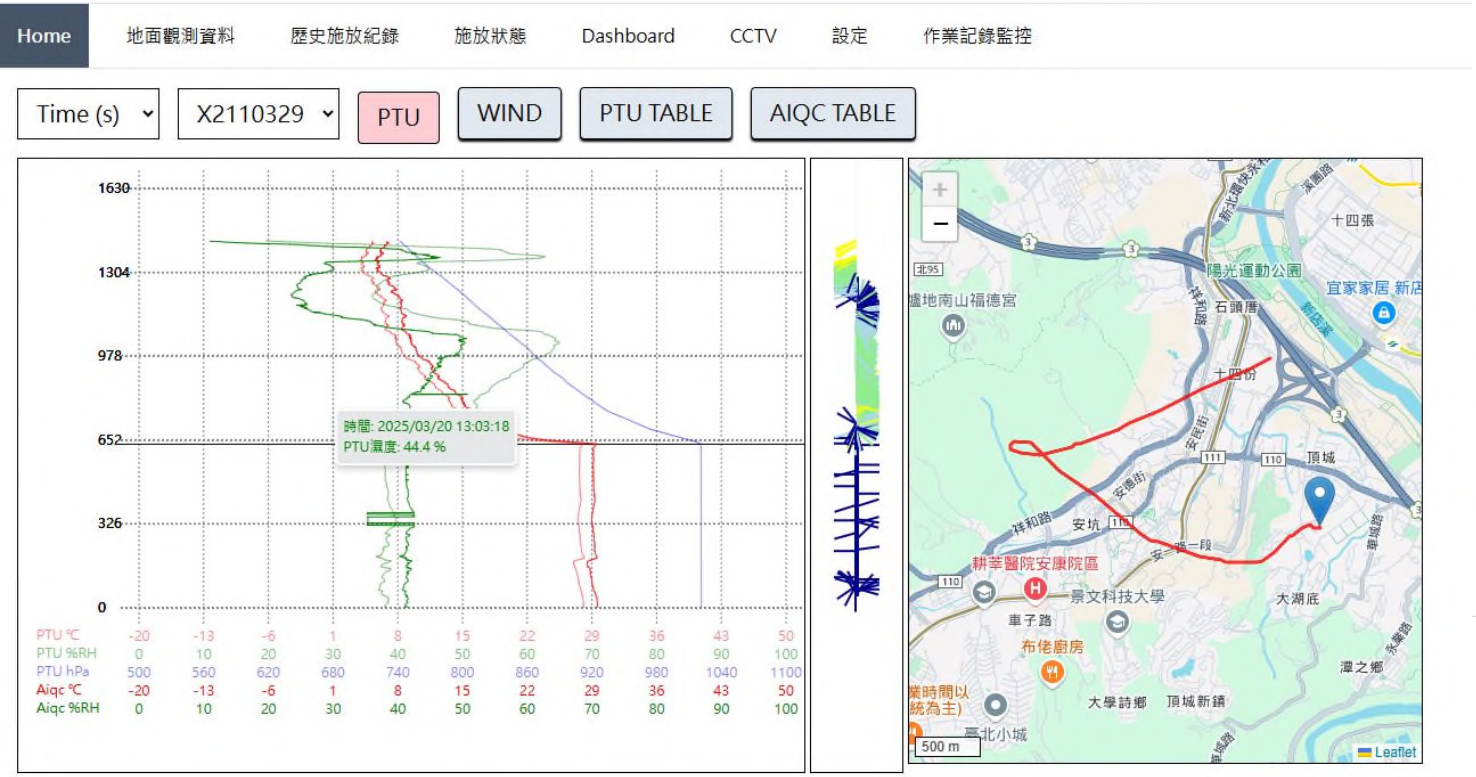
Mini-Sonde MS-100 Specifications			
Temperature (Digital Thermometer)		**Wind Speed**	
Chip	TI HDC3022	**Resolution**	0.01 m/s
Range	**-40℃ to 125℃**	**Wind Direction**	
Resolution	0.01℃	**Range**	0° to 360°
Humidity (Capacitive Digital Hygrometer)		**Data Transmission (LoRa)**	
Chip	TI HDC3022	**Frequency**	**400 MHz to 406 MHz**
Range	**0% to 100%**	**GNSS (REYAX RYS3520)**	
Resolution	0.01%	**Systems**	GPS, GLONASS, Galileo, BeiDou
Pressure		**Bacis Information**	
Chip	Bosch BMP581	**Battery**	**Energizer L92 (Lithium)**
Range	**300 to 1250 hPa**	**Weight**	**34 g**
Resolution	0.01 hPa	**Dimensions**	15 × 4.5 × 3 (cm)



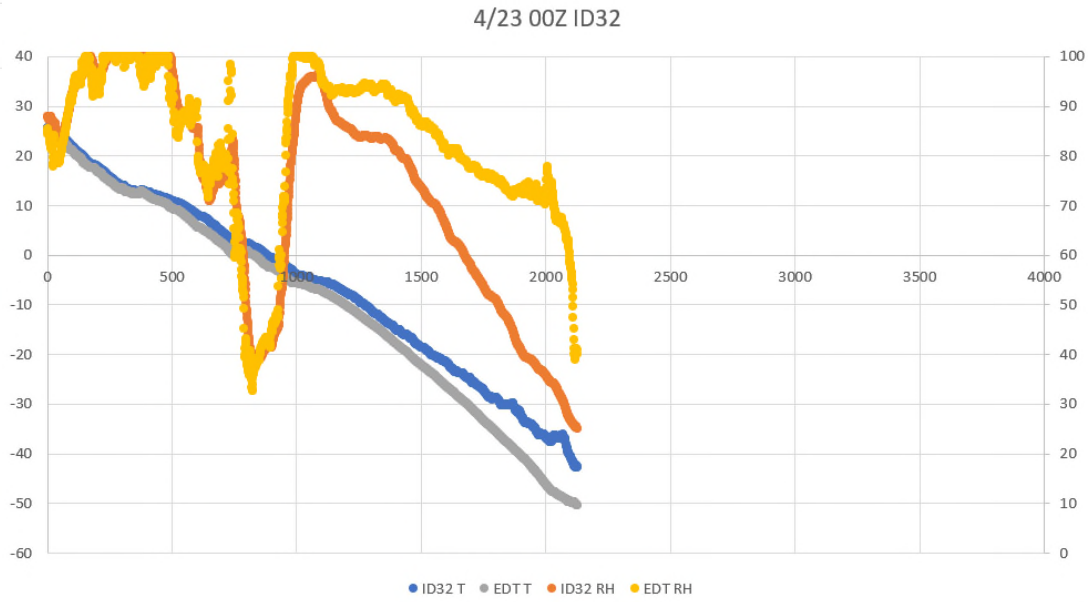
Mini-Sonde Observation System

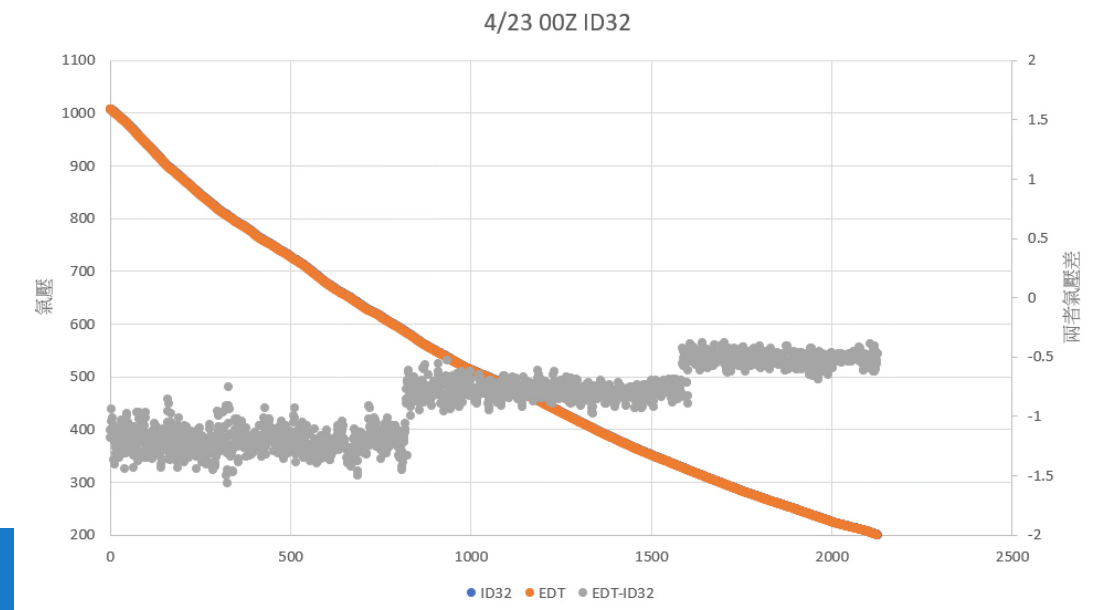


Mini-Sonde Observation System



MS-100 vs RS-41





AIQC

Hung-Chi Kuo, Ting-ShuoYo, HungjuiYu, Shih-Hao Su, Ching-Hwang Liu, and Po-HsiungLin, 2024: Data quality control and calibration for mini-radiosonde system “Storm Tracker” in Taiwan. EGUsphere2024, 1-23 . DOI: 10.5194/egusphere-2024-661