



AI與數值預報的雲端共舞 — 研發混合機器學習與數值模式之新 一代颱風預報系統--**AITWRF**

徐驊、陳得松、鄭浚騰、劉正欽、
林伯勳、蕭玲鳳、蔡子衿、連國淵、
蔡雅婷、黃康寧、沙聖浩、張保亮

中央氣象署 科技發展組

致謝:數值組**NCS**小組、富士通陳登舜

115年第四十屆天氣分析與預報研討會
2026/9/2

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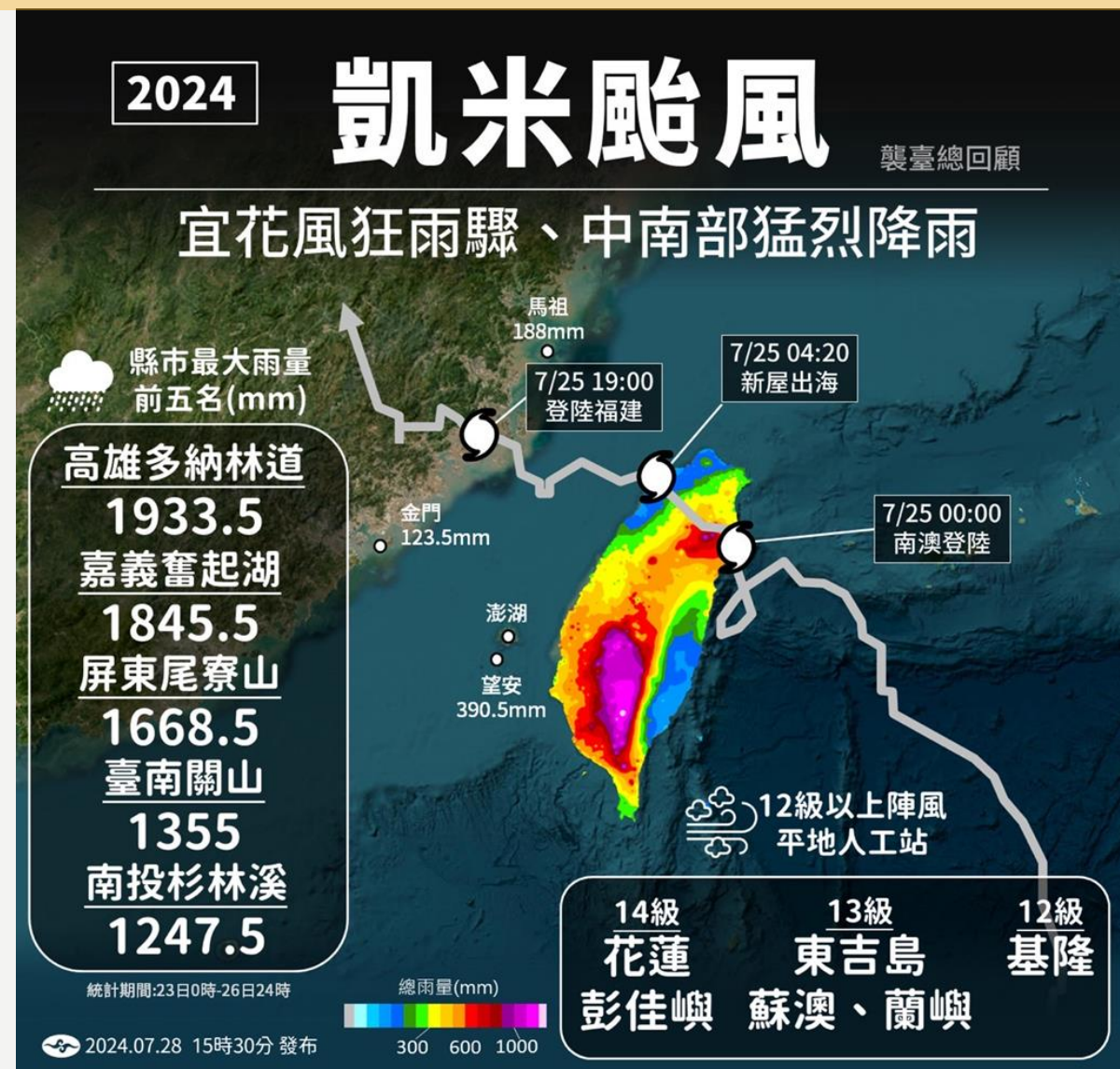
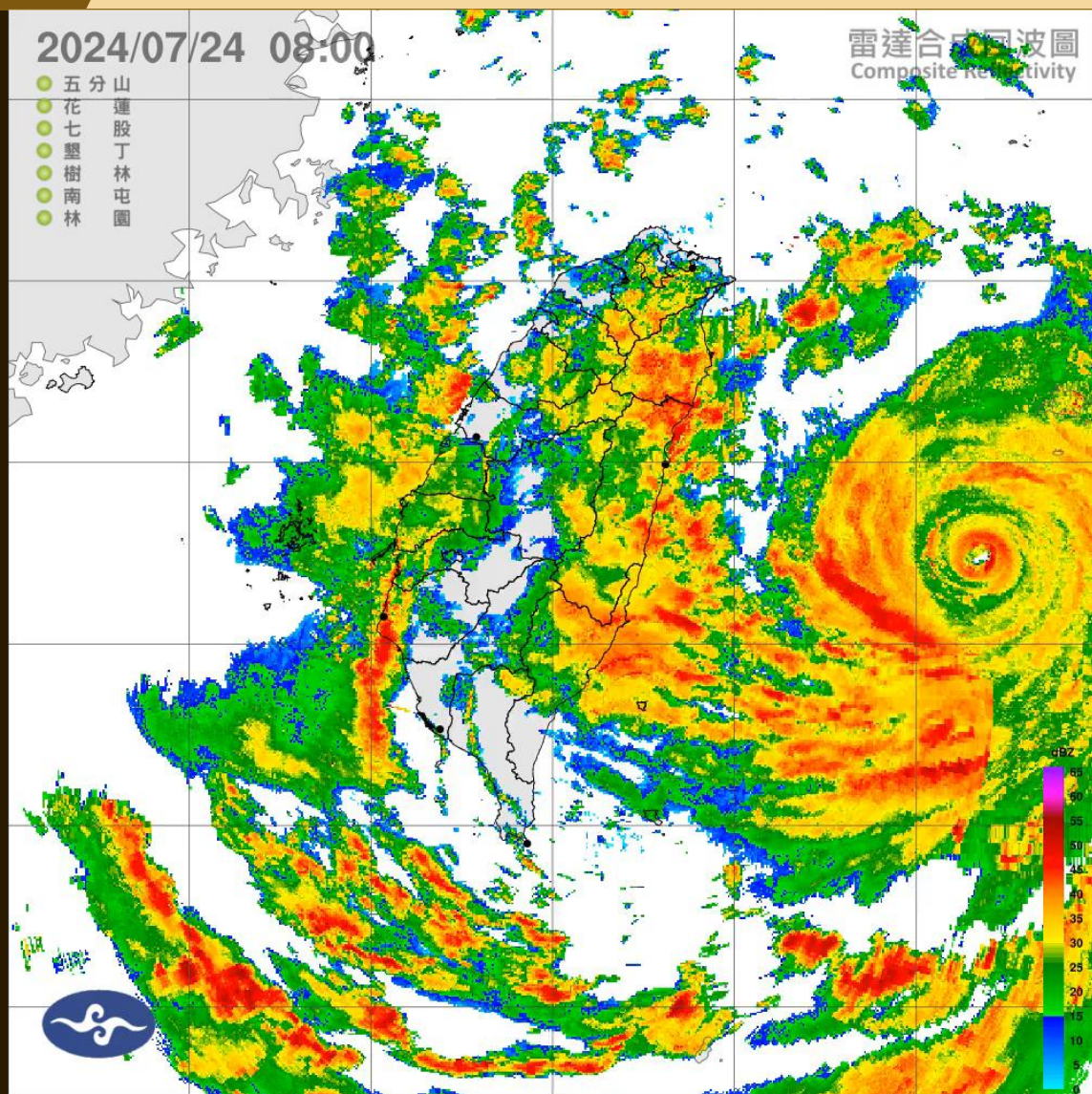
1.

動機



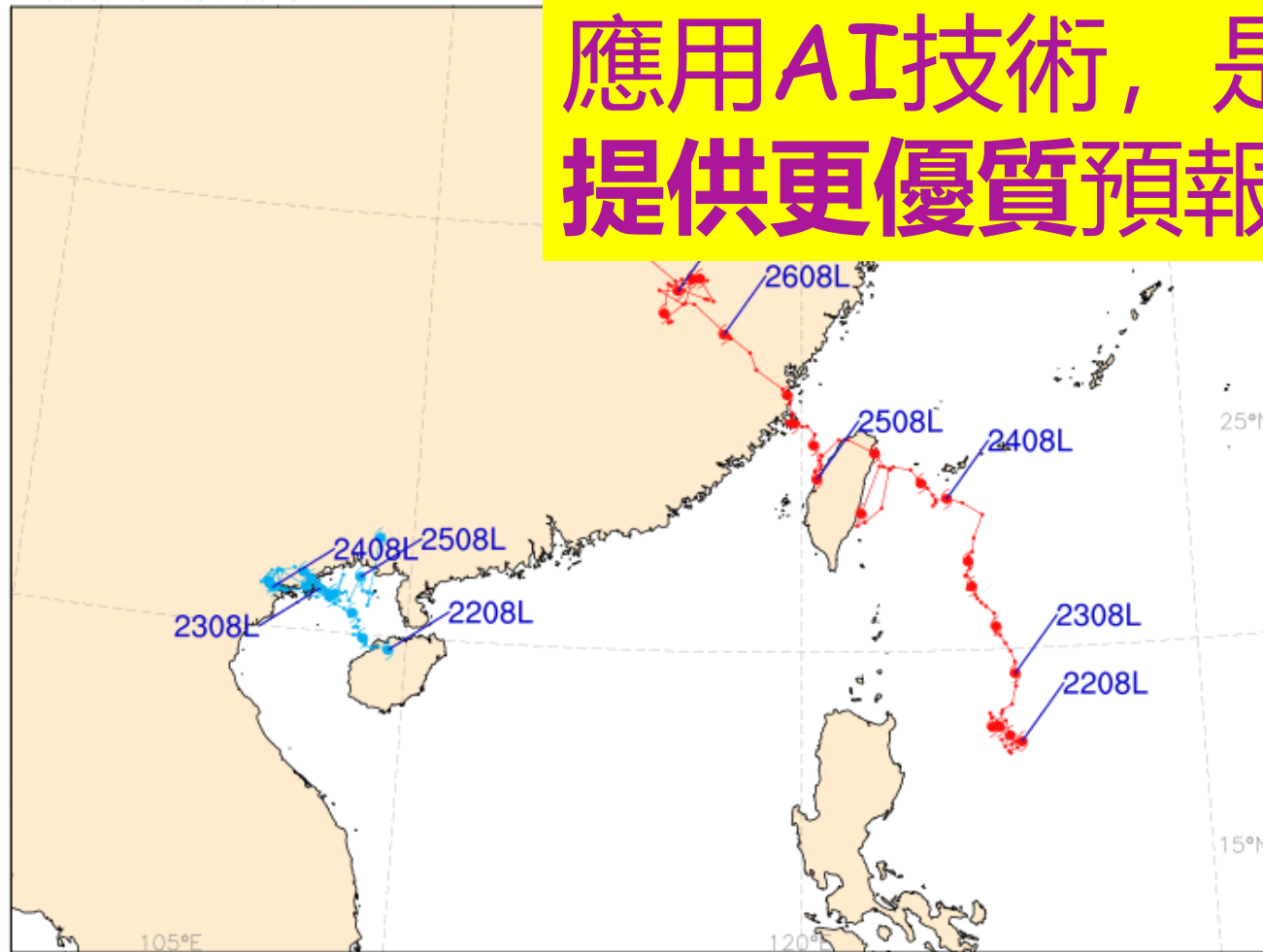
Gaemi颱風

台灣東部外海受地形效應路徑打轉，極端降雨



2024/07/2200 UTC, 凱米颱風登陸前約2.5天, TWRP預報颱風將於台灣東部海面打轉

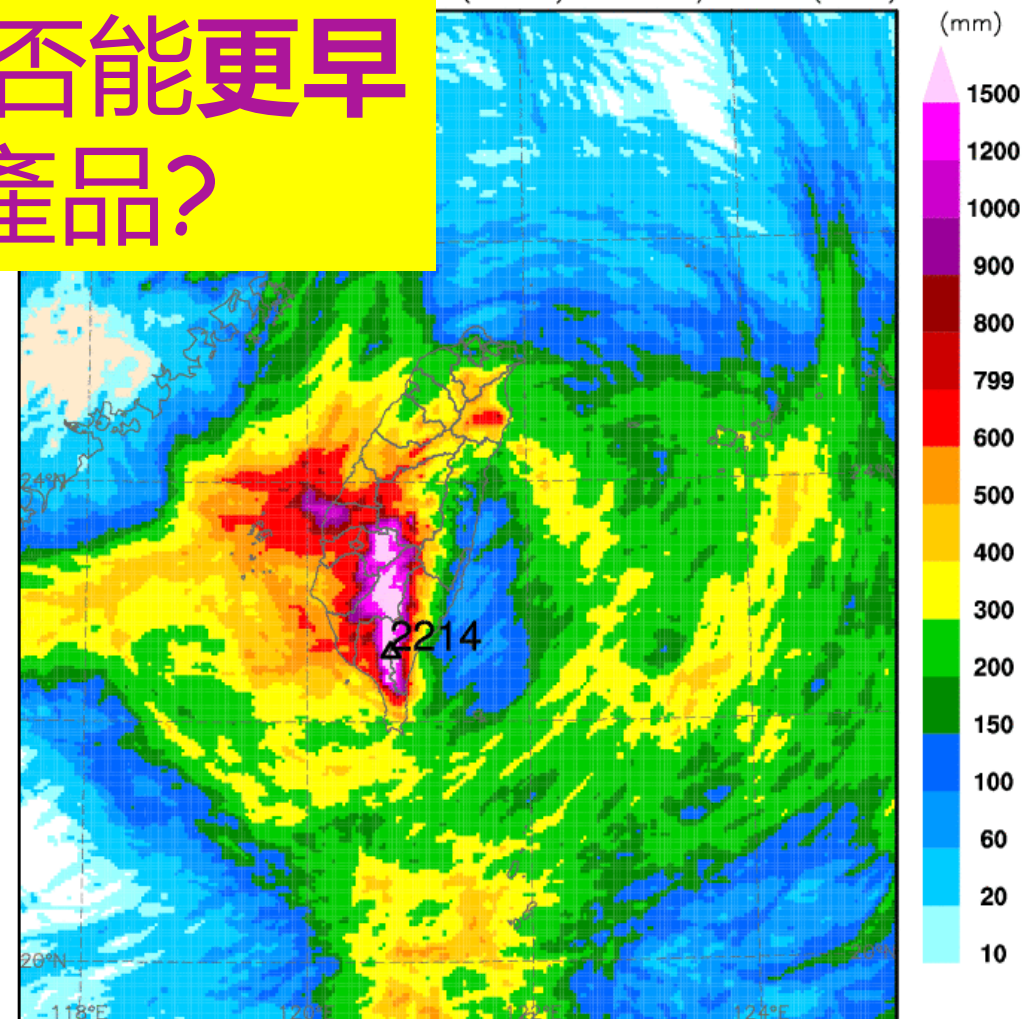
CWA/TWRF (3km) Typhoon Track Forecast
Initial at 2024072200 SLP



應用AI技術，是否能更早
提供更優質預報產品？

TOTAL PRECIPITATION(mm) (000-096)

Valid at 26 JUL 2024 00UTC(+096) CWA/TWRF (3km)



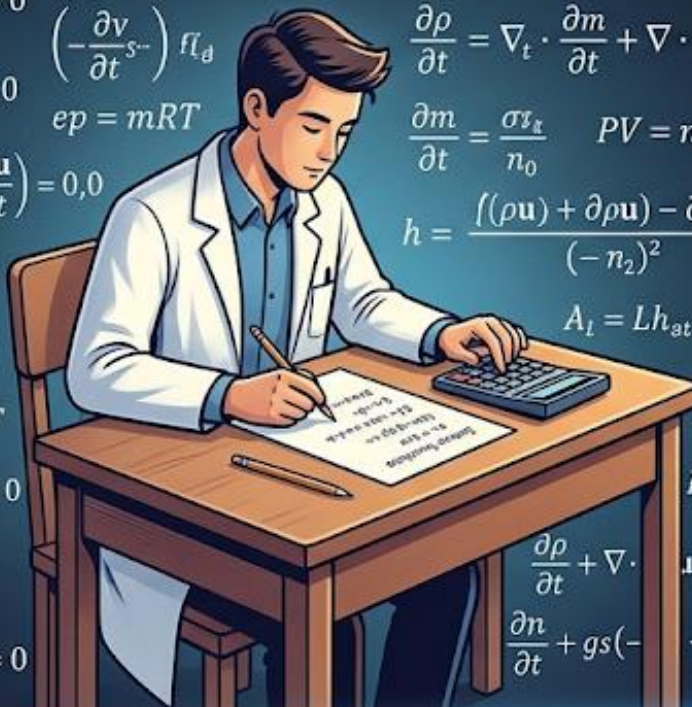
Initial at 22 JUL 2024 00UTC

若將傳統電腦數值預報模式比喻為「按公式解題的學生」，AI模型就像是一個「看了40年考古題並背下所有物理變量連動規律的天才」(又快又好)

CONTRASTING APPROACHES TO WEATHER FORECASTING

TRADITIONAL NWP MODEL: "STUDENT SOLVING FORMULAS"

UNDERSTANDS PHYSICS BY SOLVING EQUATIONS.



$$\frac{\partial m}{\partial t} + \frac{\partial v \mathbf{u}}{\partial t} = 0$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

$$\left(-\frac{\partial v}{\partial t} s \right) \Pi_d$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

$$ep = mRT$$

$$\frac{\partial u}{\partial t} = -\left(\frac{\partial}{\partial t} + \frac{\partial \mathbf{u}}{\partial t} \right) = 0,0$$

$$k(t_b + pRT) = 0$$

$$\frac{\partial \rho}{\partial t} + \nabla_2 \frac{\partial \mathbf{u}}{\partial t} = 0$$

$$n_a = PV = nRT$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

$$E_s = \left(\frac{\partial u_i^1}{\partial t} \right)$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

$$n_{tR} = \frac{\partial v_{tR}}{r}$$

$$e_n = 1,2 T$$

$$\frac{\partial \rho}{\partial t} = \nabla_t \cdot \frac{\partial m}{\partial t} + \nabla \cdot (v e_s)$$

$$\frac{\partial m}{\partial t} = \frac{\sigma r_k}{n_0} \quad PV = nRT$$

$$h = \frac{f(\rho \mathbf{u}) + \partial \rho \mathbf{u}}{(-n_2)^2}$$

$$A_l = Lh_{at} = \frac{T}{\partial t}$$

$$E_k = 0$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

$$\frac{\partial n}{\partial t} + gs(- + RT)$$

TRADITIONAL NWP: Student with textbook knowledge.

AI MODE: "GENIUS MEMORIZING PATTERNS"

ABSORBING DATA STREAMS

MASSIVE DATASET (ERA5 REANALYSIS, 40 YEARS)

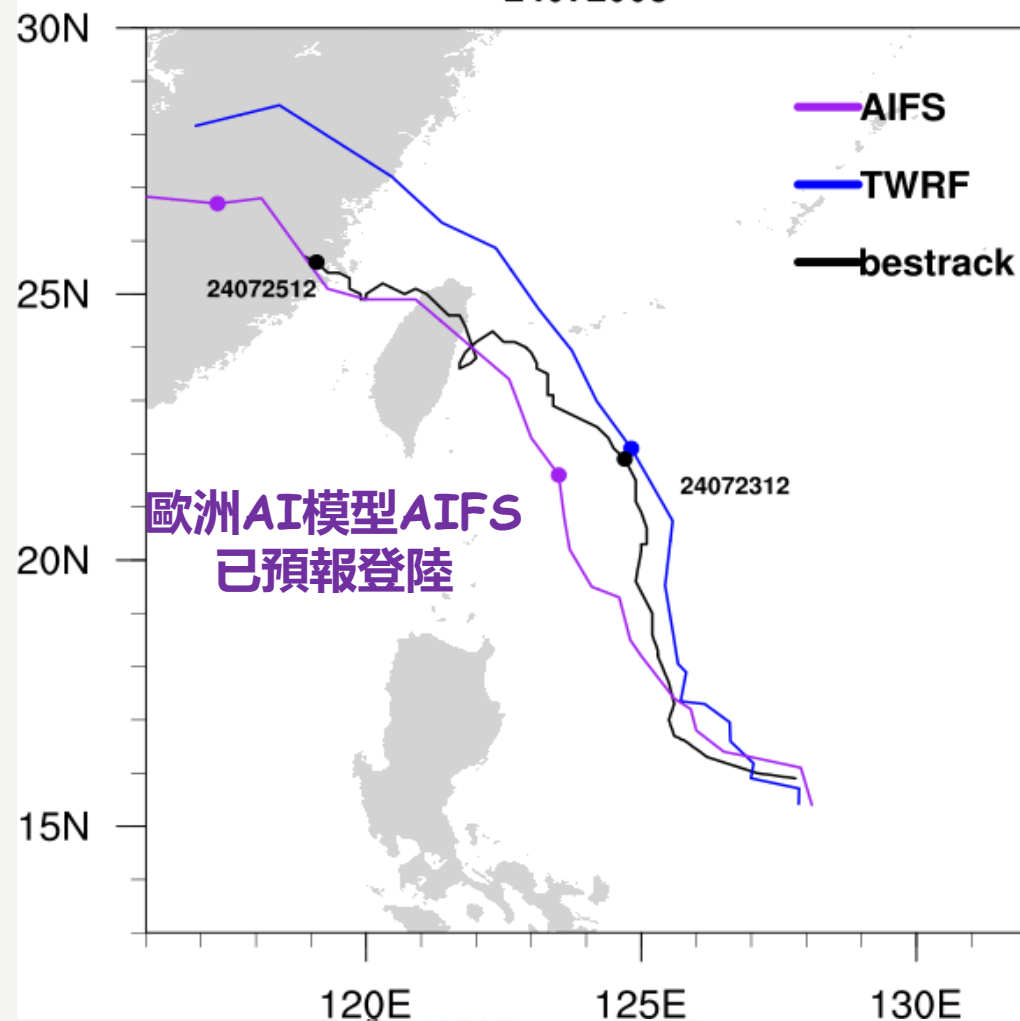
DISCOVERS CAUSALITY FROM MASSIVE DATA PATTERNS.



AI MODE: Genius with deep pattern memory (40 years).

2024/07/20 06UTC, 凱米颱風登陸前約**4.5天**,
當時大部分的NWP模式預報凱米颱風將從台灣北部海面掠過

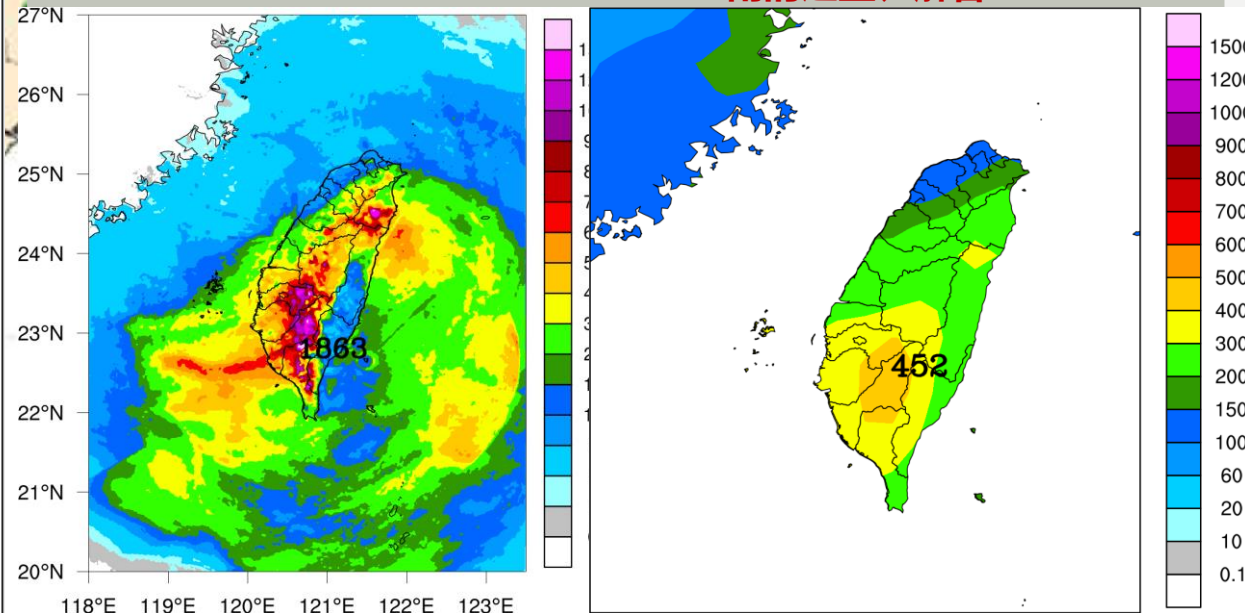
Multiple Deterministic Model Ensemble Typhoon Track Forecast
24072006



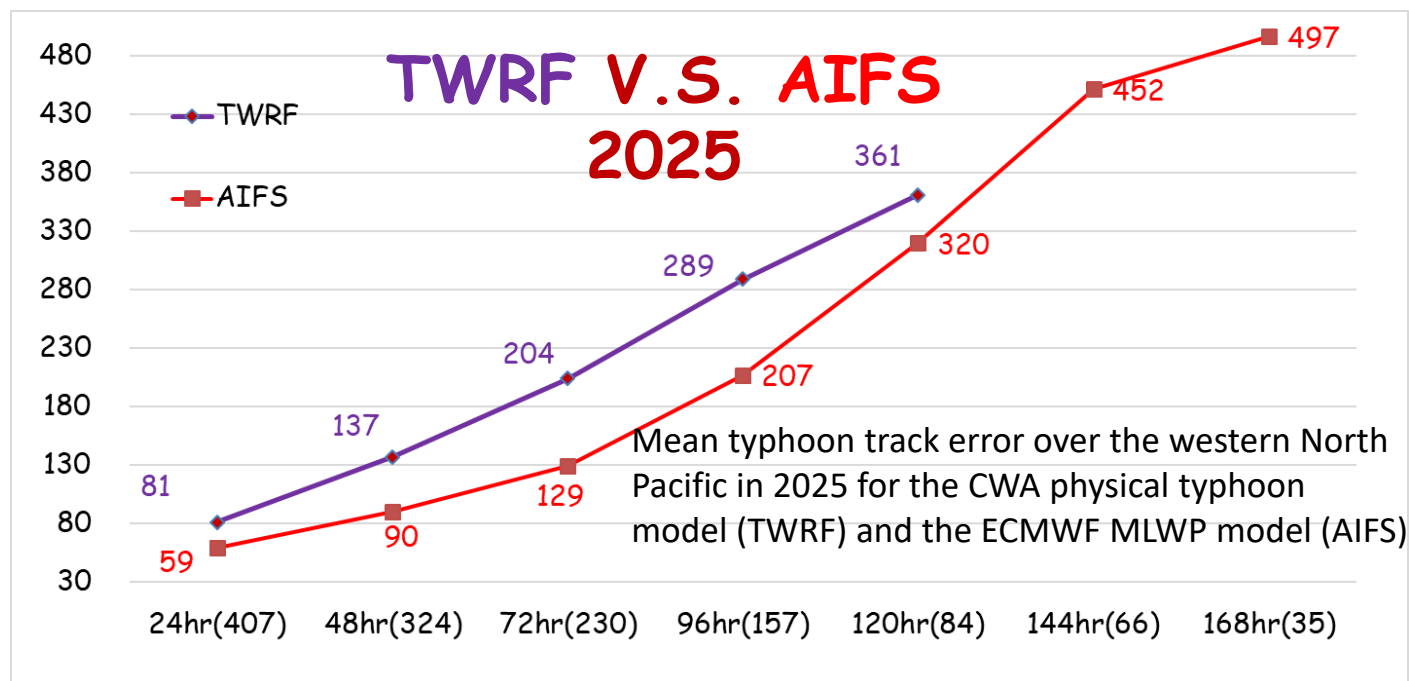
累積時間 7/23 12 - 7/25 12UTC

QPESUM

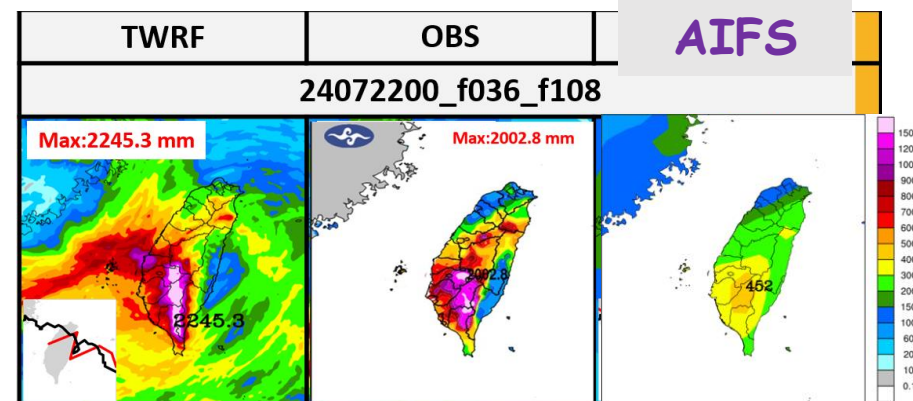
AIFS 雨量值嚴重不足
考古題庫(28公里)內並無強風豪
雨的題型、解答



1. AI 天氣預報模式最大的強項，就是對「大環境的大氣局勢」抓得很準，所以預報颱風未來路徑非常厲害。但像 AIFS 這類的 AI 模式，解析度只有約 28 公里，沒辦法看清颱風內部的細節，所以對於颱風會有多強、風雨到底多大，它就抓不太準。
2. 相反地，我們傳統的區域數值模式（像我們解析度達 3 公里的 TWRF）雖然有時對大環境的方向感不如 AI 模式，預報較長時間容易走偏；但它的強項在於「細節刻畫」，能夠較精準地預報出台灣複雜地形下的強風、暴雨和地形效應。
3. 為了把這兩者的優點結合起來，本研究特別研發了新一代的颱風預報系統——AITWRF，它把 AI 的「大局觀」和物理NWP模式的「細節掌控」完美截長補短、融合在一起。



The MLWP models significantly underestimated the precipitation associated with Typhoon Gaemi (2024)



2.

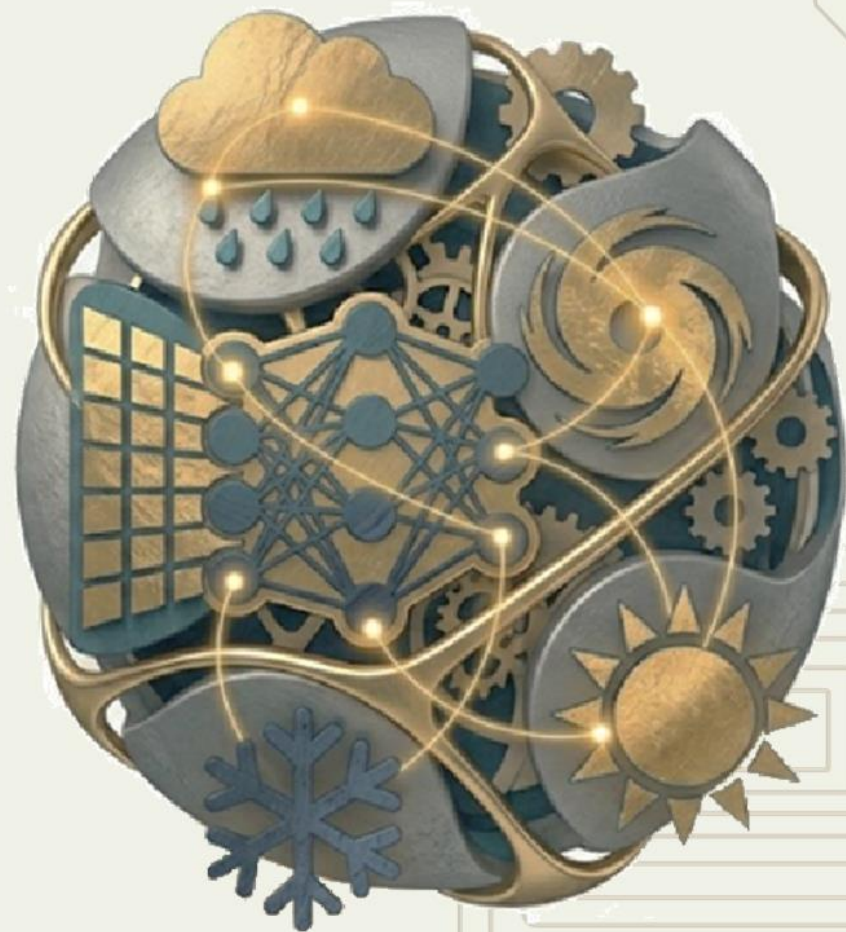
目標

打造一套結合「AI」與「物理NWP模式」的混合型颱風預報系統(AITWRF)。這套系統的做法，是擷取 AIFS 這類 AI 模式最擅長的「大局觀」（也就是帶領颱風前進的大方向導航），再配上我們 TWRF 這種高解析度模式最厲害的「在地細節特寫」——能看懂台灣複雜的山脈地形，進而算出哪裡可能會颶大風、哪裡可能會下暴雨。簡單來說，就是把 AI 的「方向感」和傳統模式的「較精準風雨預報」無縫融合在一起，截長補短。



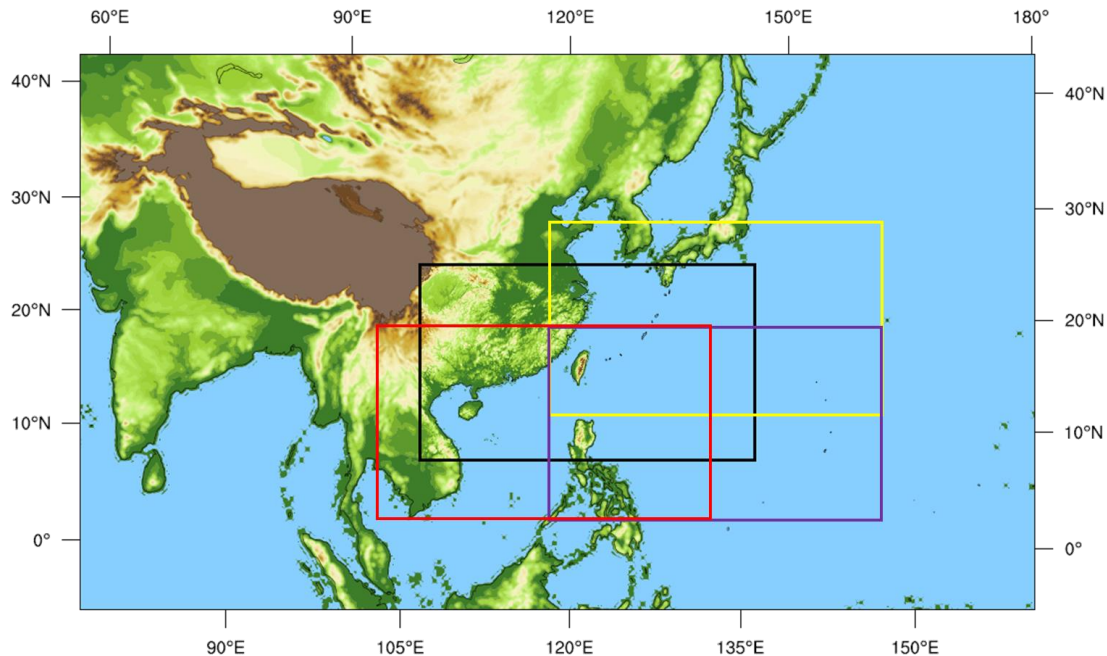
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研發策略



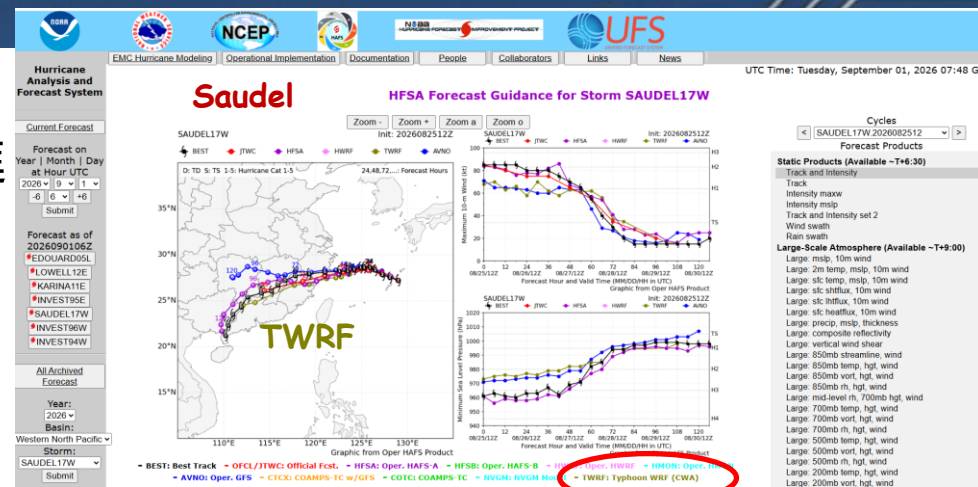
TWRF 簡介

TWRF 系統是我們氣象署專門為亞洲地區量身打造的「颱風專用區域預報模式」。過去十幾年來，我們團隊做了不少的研發和改進，證明了這套系統的預報能力還算不錯。它現在的預報結果，會直接**即時**被放在美國國家氣象局 (NOAA/NCEP) 的「颶風分析預報系統 (HAFS)」**官網**上展示，供各國大氣學研作業單位參用！

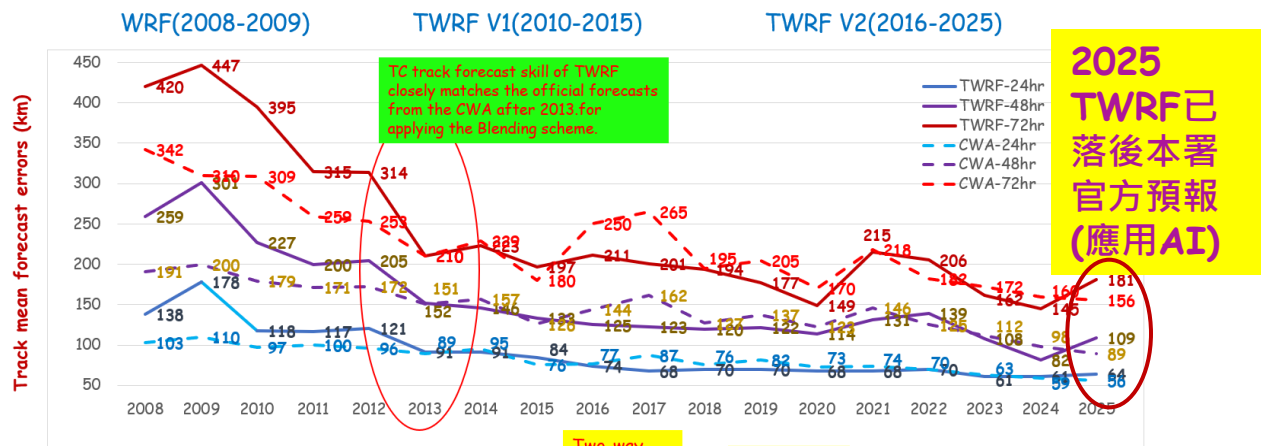


TWRF domain coverage (15/3km)

- *可依颱風初始位置選定3km模式範圍
- *預報時更新EC海溫場



Comparison between TWRF & CWA for the TC Track Forecast Errors



2025 TWRF已落後本署官方預報(應用AI)



Hsiao et al. 2010, 2012, 2013, 2015, 2020

我們這個混合系統 AITWRF，使用的是一種叫做FDDA**波譜納進**(Spectral Nudging: SN)的技術。它的原理很像一個「過濾網」：它只會把 AI (AIFS) 預報裡最厲害、最精準的**大方向大環境氣流**抓過來，**牢牢拉住我們的 TWRF 模式的大局**，確保它不走偏。但在同時，它會適度放手，讓 TWRF 模式自己的物理大腦去發揮，**自由演繹出台灣在地的中小尺度風雨變化**。

1. 將歐洲中心 (ECMWF) 的觀測分析資料及 AI 模式 (AIFS) **未來 7天**的天氣預報資料，「放進」我們 TWRF 模式的精細網格裡。
2. 這些被放進網格的 AI 資料，就會在 TWRF 模式一邊運算、一邊預報的過程中，透過前面提到的「大尺度導引 (SN)」技術發揮作用。它的核心運算公式長這樣：

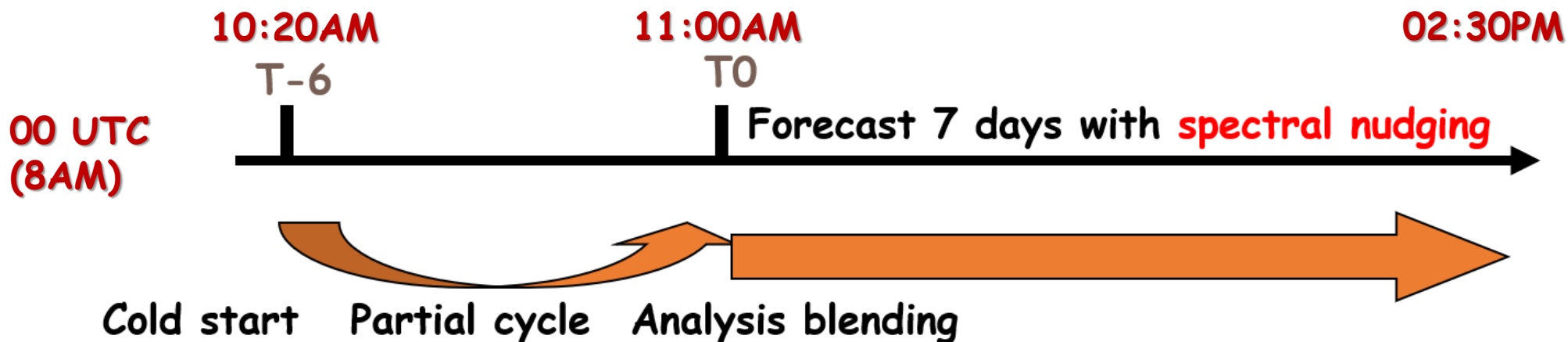
$$F_{nd} = F_{TWRF} + \omega[F_{AIFS} - F_{TWRF}]_{LS}$$

ω : nudging relaxation factor
LS: large-scale features

- * For the SN variables, we only used **the U, V, T without Q**
- * For the SN length scales, we selected the **1,000 km as the cutoff wavelength**.
- * **SN is excluded in PBL** to preserve complex surface forcing and topography effect, as the AI model's vertical resolution is insufficient constrain the detailed boundary layer physics within TWRF

AITWRF流程架構

Flow Chart of AITWRF



作戰策略：以00 UTC(8AM)之AITWRF作業為例

- 使用前一run 18UTC之AIFS資料(00UTC約3PM才到位)做為Spectral Nudging的目標場
- 規劃10:20AM進行partial cycle
- 11:00開始預報作業
- 預計14:30完成未來7天174小時預報 (144 nodes)

Design of Experiment

EXP	TWRF	AITWRF_UVT	AITWRF_UV	AITWRF_UV_dt10s
WRF version			4.4.2	
Resolution (km)			15/3	
Time step (s)			90/18	
Model top (hPa)			50	
Vertical levels			52	
ICBC		AIFS (13 levels, 0.25° lat/lon resolution)		
SN data	-----	AIFS (13 levels, 0.25° lat/lon resolution)		
SN variable	-----	U, V, T	U, V	U, V
SN wave length (km)	-----		1000	
SN frequency (integration step)	-----	1	1	10

TWRF and AITWRF configurations and experimental design

Western North Pacific typhoons during 2024–2025 (9 typhoons, 45 forecasts), selected to evaluate track forecast performance.

- 2024 Typhoon Gaemi (3) 、 Shanshan (5)
- 2025 Typhoon Francisco (4) 、 Co-may (4) 、 Krosa (8) 、 Podul (6) 、 Ragasa (5) 、 Neoguri (5) 、 Fung-wong (5)

* Numbers in parentheses indicate the experiment number of forecasts

4.

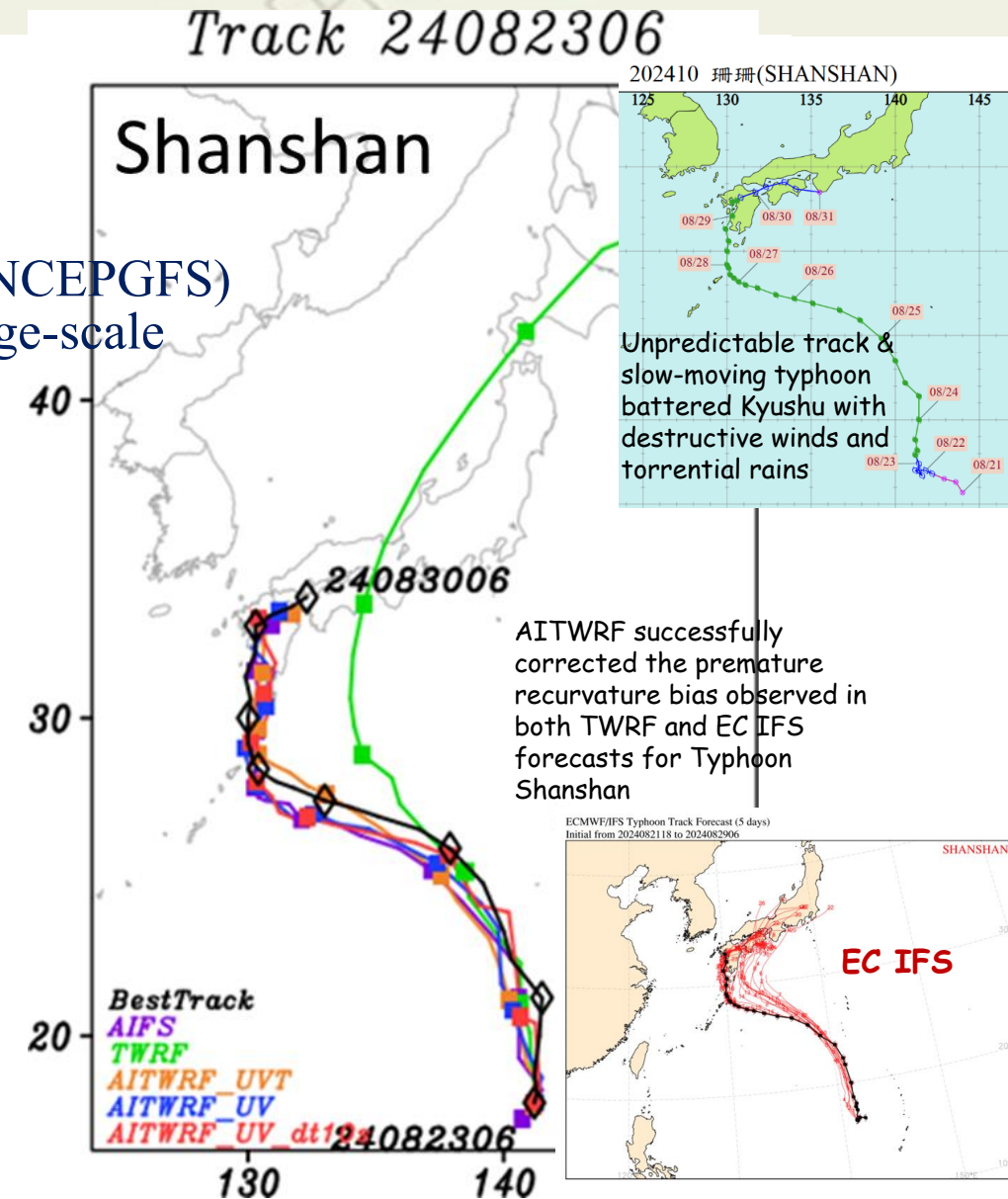
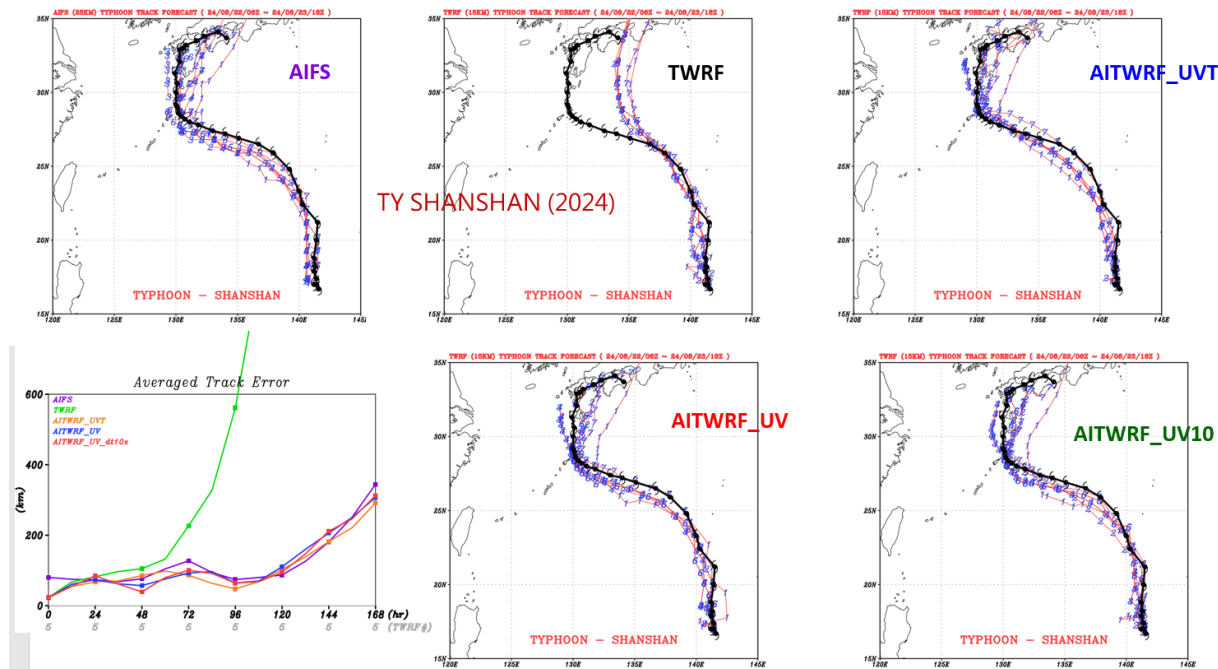
實驗結果



Three representative cases are selected to illustrate the differences among AITWRF configurations and their impact on track prediction.

2024 Typhoon Shanshan — Most NWP models show premature recurvature bias, 5-day forecast error nearly 1000 km

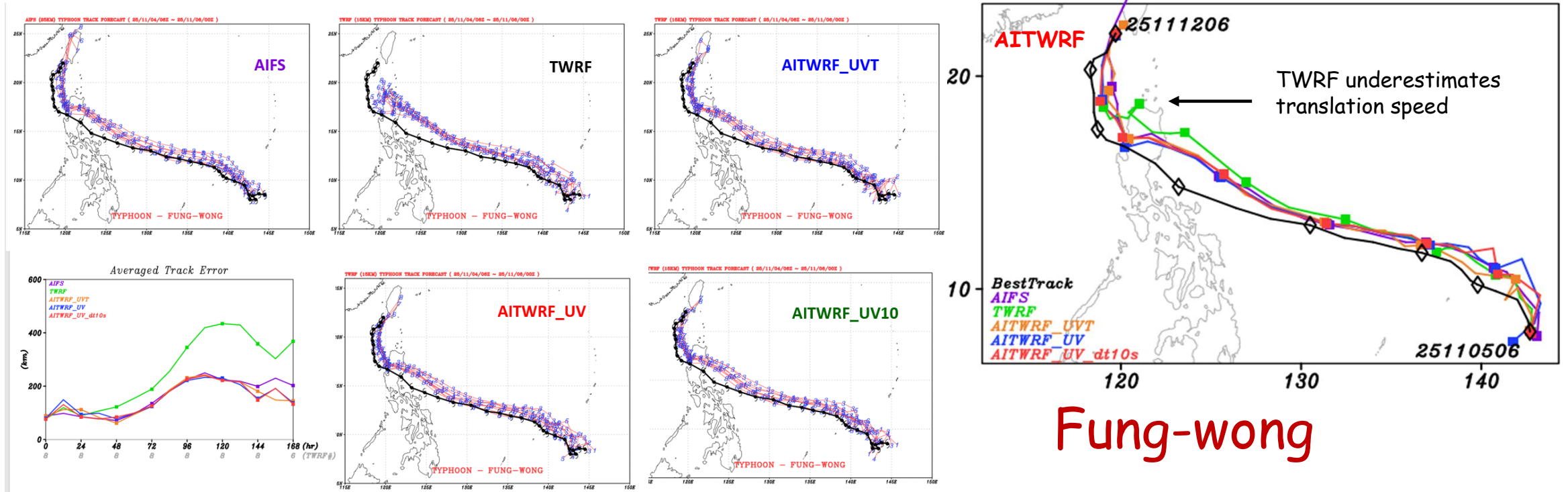
1. AITWRF tracks are closer to AIFS and better aligned with observations
2. Corrects the premature northward turning in TWRF(ECIFS/NCEPGFS)
3. Demonstrates that spectral nudging effectively constrains large-scale circulation toward AIFS



Three representative cases are selected to illustrate the differences among AITWRF configurations and their impact on track prediction.

2025 Typhoon Fung-wong — The movement track is highly unusual and exceptional

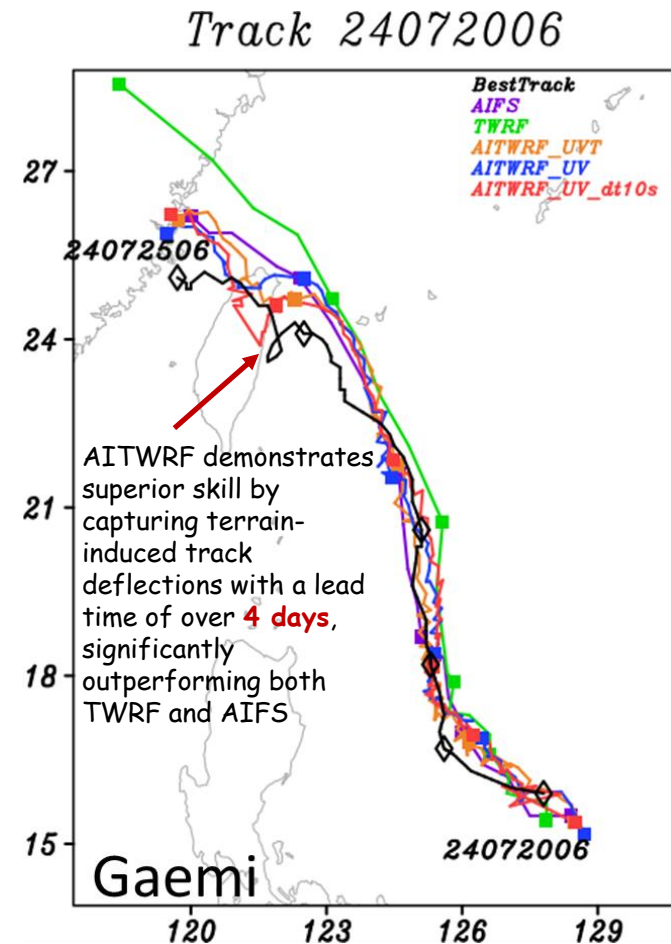
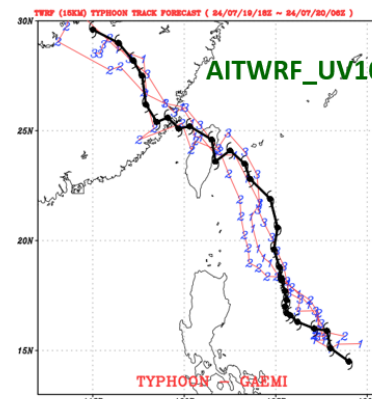
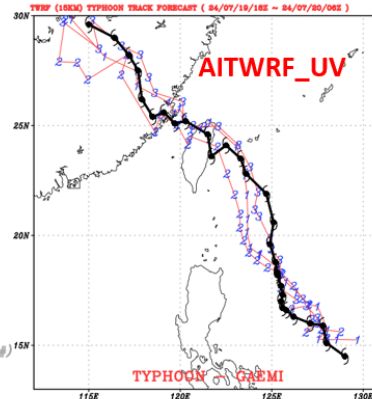
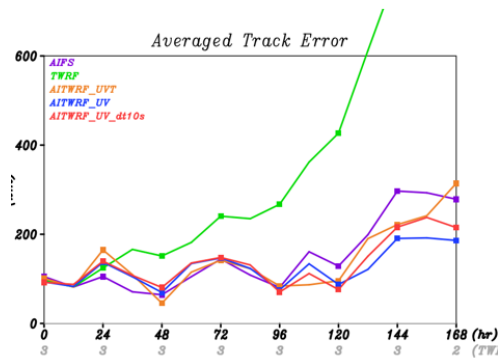
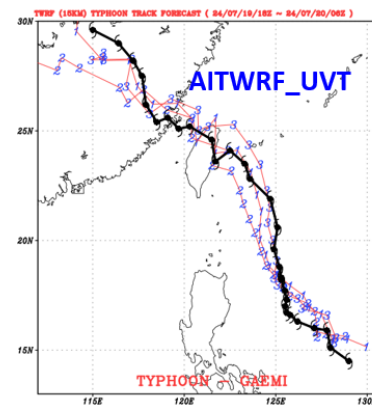
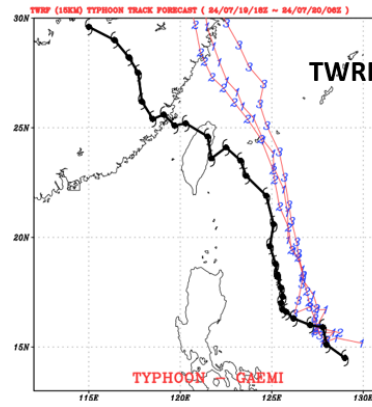
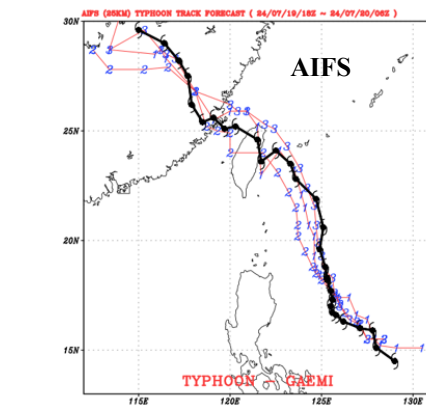
1. TWRP underestimates translation speed
2. AITWRF provides the most accurate track evolution, improves both timing and position of the storm



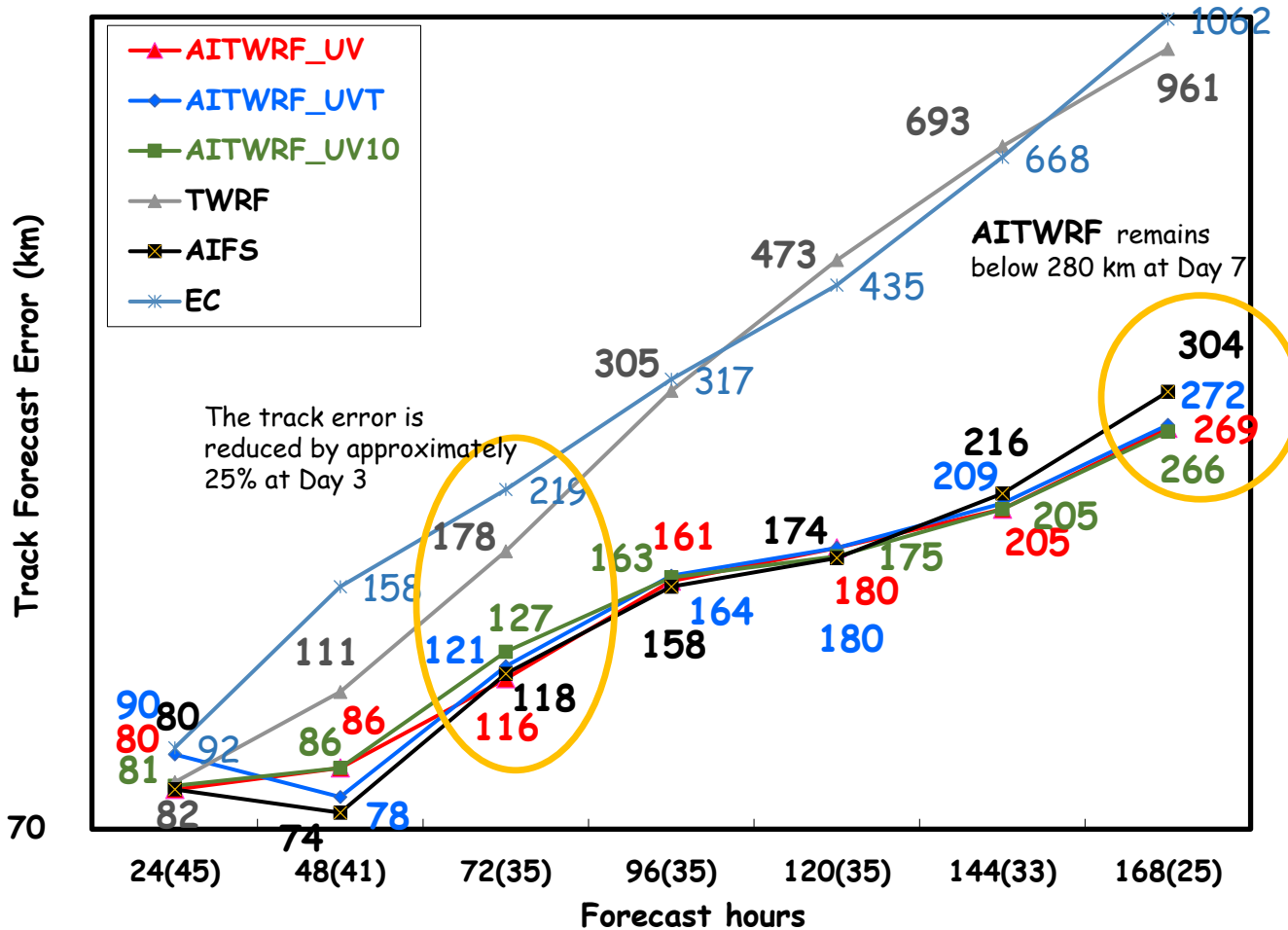
Three representative cases are selected to illustrate the differences among AITWRF configurations and their impact on track prediction.

2024 Typhoon Gaemi — Terrain-Induced Track Deflection

By leveraging the synergy between AIFS's large-scale feature representation and TWRF's high-resolution dynamical modeling, AITWRF captures terrain-induced track deflection earlier than both standalone models. This success underscores AITWRF as an **advanced, physically consistent, and logically sound total solution** for typhoon forecasting.



2024 、 2025 (9 typhoons, 45 cases)



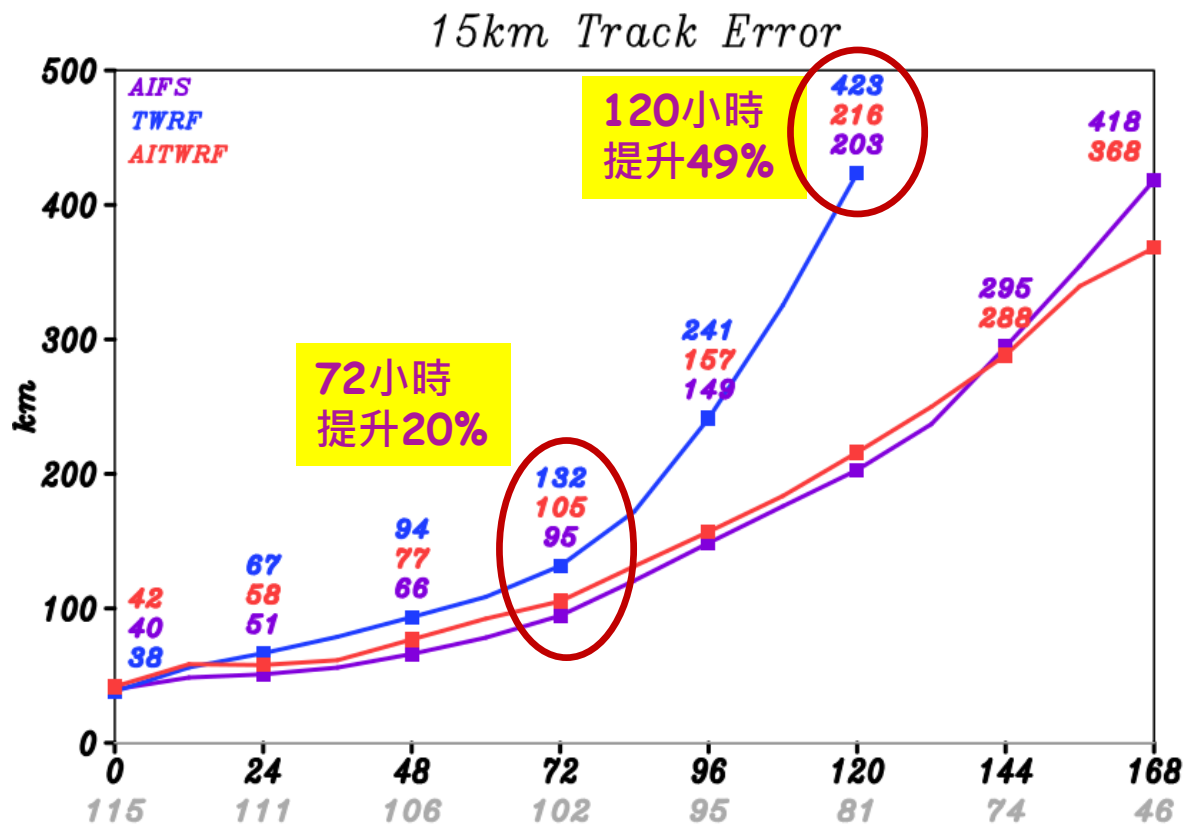
The larger errors in these experiments can be attributed to the **selection of cases where operational TWRP & EC struggled**, combined with our focus on **extending the forecast range to 7 days**. Many of these cases were in the **initial stages of cyclogenesis** (e.g., TD), which inherently increases forecast uncertainty.

各實驗設計結果相近，考慮運算資源，將以 AITWRF-UV10 進行作業

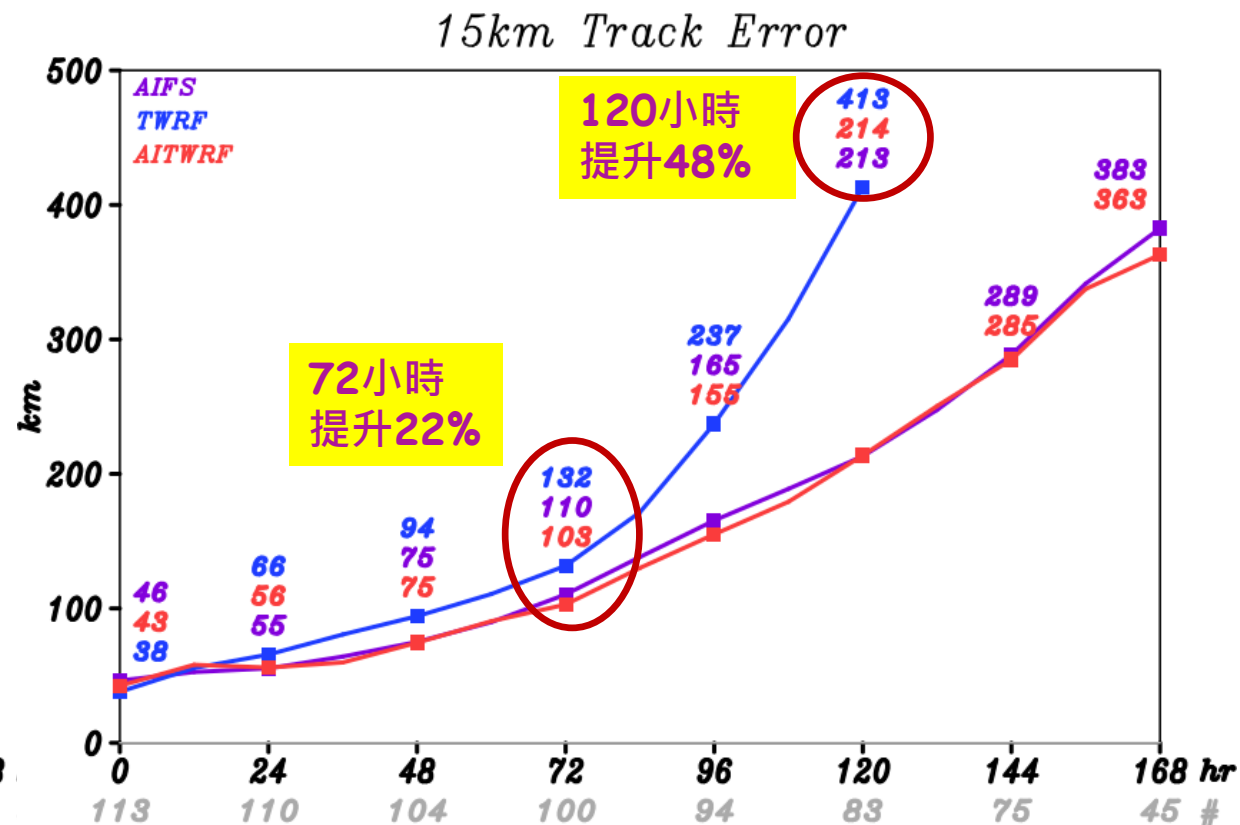
AITWRF(15km) 實驗, 2024 ~ 2026年, 14個颱風 115 個案

#	Year	Typhoon	Initial Time (UTC)	Cases no.
1	2024	GAEMI 凱米	7/19 18 ~ 7/22 06	14
2	2024	SHANSHAN 珊珊	8/22 06~18、8/23 06、8/23 18	5
3	2025	KROSA 柯羅莎	7/24 06 ~ 7/25 00	4
4	2025	CO-MAY 竹節草	7/24 00 ~ 7/25 00	5
5	2025	FRANCISCO 范斯高	7/24 00 ~ 7/24 18	4
6	2025	PODUL 楊柳	8/7 06 ~ 8/8 18	7
7	2025	NEOGURI 浣熊	9/17 18 ~ 9/18 12	4
8	2025	RAGASA 樺加沙	9/17 18 ~ 9/18 12	4
9	2025	FUNGWONG 鳳凰	11/4 06 ~ 11/6 00	8
10	2026	SINLAKU 辛樂克	4/10 12 ~ 4/13 00、4/14 18 ~ 4/16 00	17
11	2026	JANGMI 薔蜜	5/27 06 ~ 5/28 06	5
12	2026	MEKKHALA 米克拉	6/19 06 ~ 6/22 00、6/22 12 ~ 6/23 06	16
13	2026	HIGOS 無花果	6/22 12 ~ 6/23 06	4
14	2026	BAVI 巴威	7/1 18 ~ 7/2 06、7/2 18 ~ 7/3 18、7/5 18 ~ 7/7 06、 7/8 18、7/9 06、7/10 00	18
Total		2024 ~ 2026年, 14個颱風		115

15 km Track Error



AIFS(當趟)



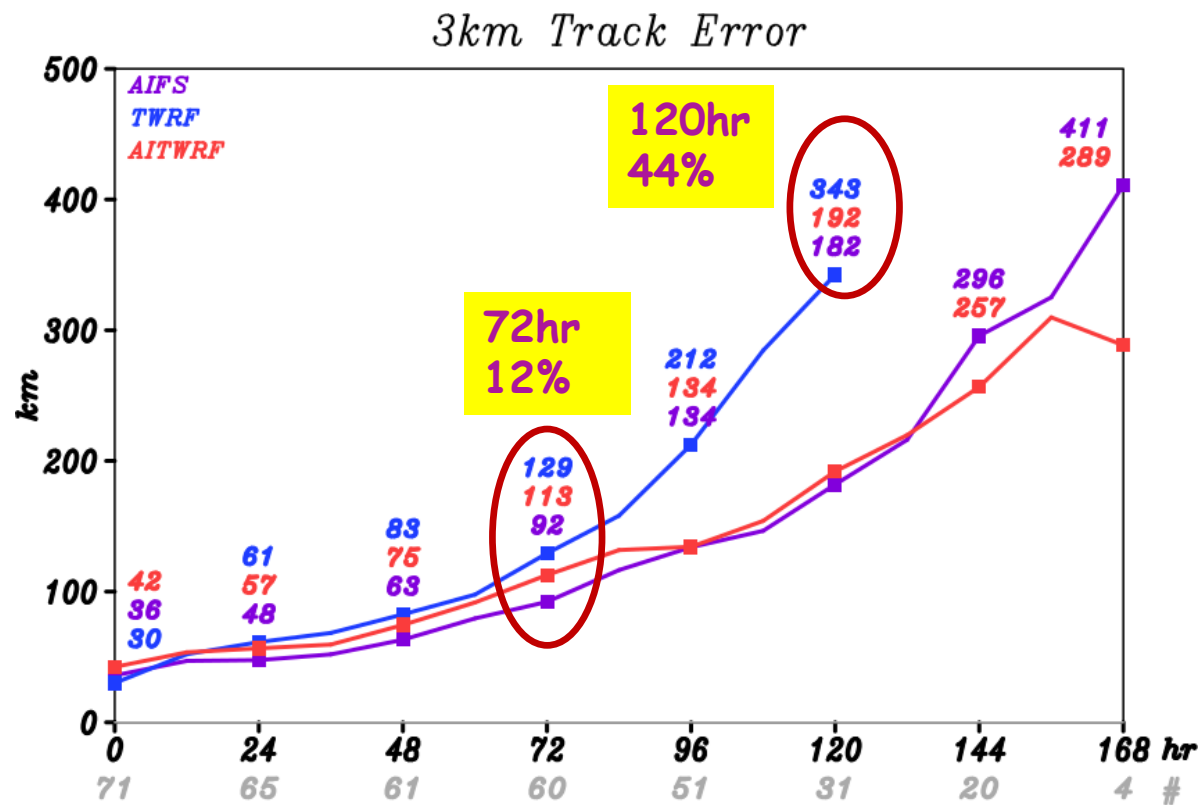
AIFS-6(前一run)

AITWRF(3km) 實驗, 2024 ~ 2026年, 11個颱風 71 個案

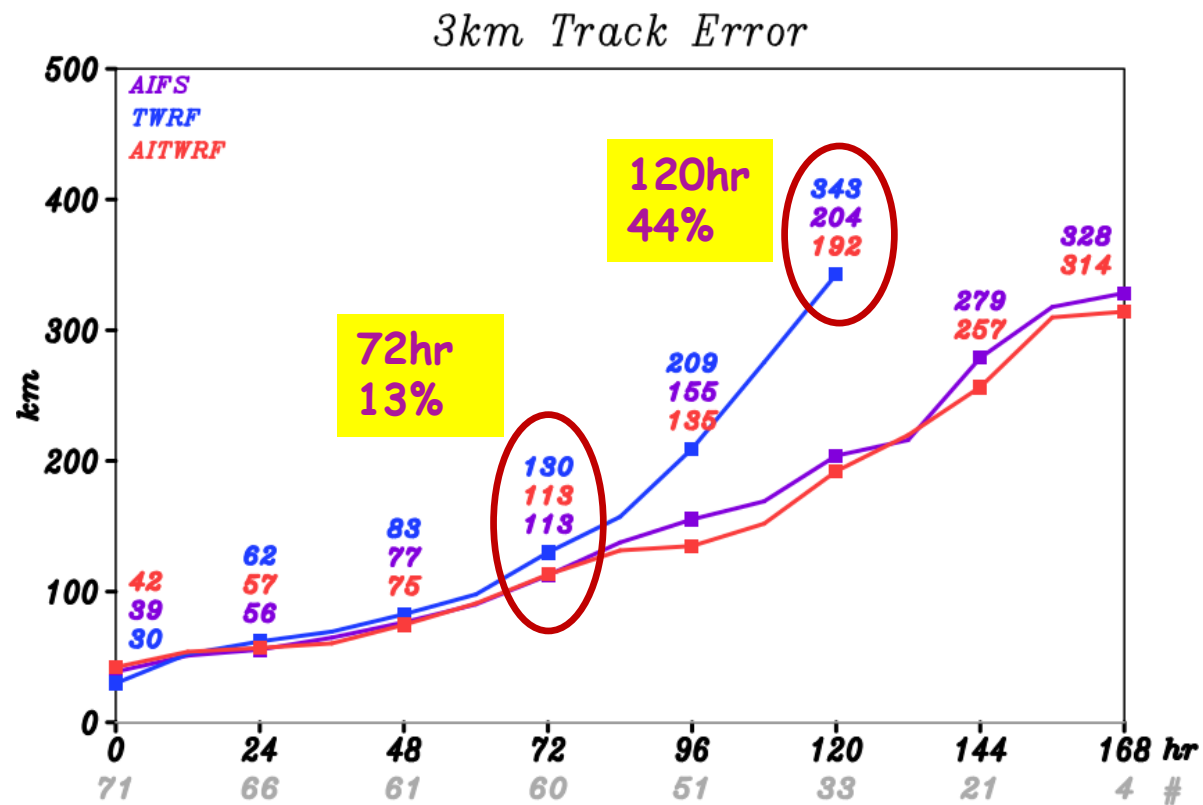
#	Year	Typhoon	Initial Time (UTC)	Cases no.
1	2024	GAEMI 凱米	7/19 18 ~ 7/23 00	14
2	2024	SHANSHAN 珊珊	8/23 06 ~ 8/23 18	2
3	2025	CO-MAY 竹節草	7/24 00 ~ 7/25 00	5
4	2025	FRANCISCO 范斯高	7/24 00 ~ 7/24 18	4
5	2025	PODUL 楊柳	8/7 06 ~ 8/8 18	7
6	2025	RAGASA 樺加沙	9/18 12	1
7	2025	FUNGWONG 鳳凰	11/5 18 ~ 11/6 00	2
8	2026	SINLAKU 辛樂克	4/14 18 ~ 4/16 00	6
9	2026	JANGMI 薔蜜	5/27 06 ~ 5/28 06	5
10	2026	MEKKHALA 米克拉	6/19 06 ~ 6/22 00 ~ 6/22 12 ~ 6/23 06	16
11	2026	BAVI 巴威	7/5 18 ~ 7/6 00 ~ 7/6 12 ~ 7/7 06 ~ 7/8 18 ~ 7/9 06 ~ 7/10 00	9
Total		2024 ~ 2026年, 11個颱風		71

AIFS upgrade to V2 on May 12, 2026

3 km Track Error

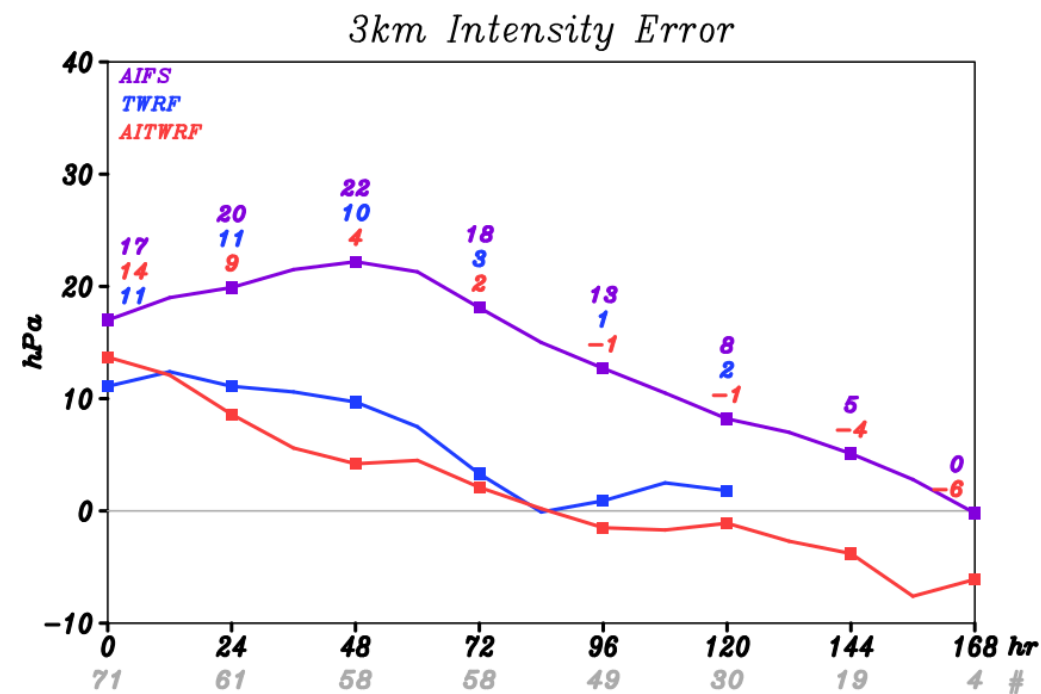
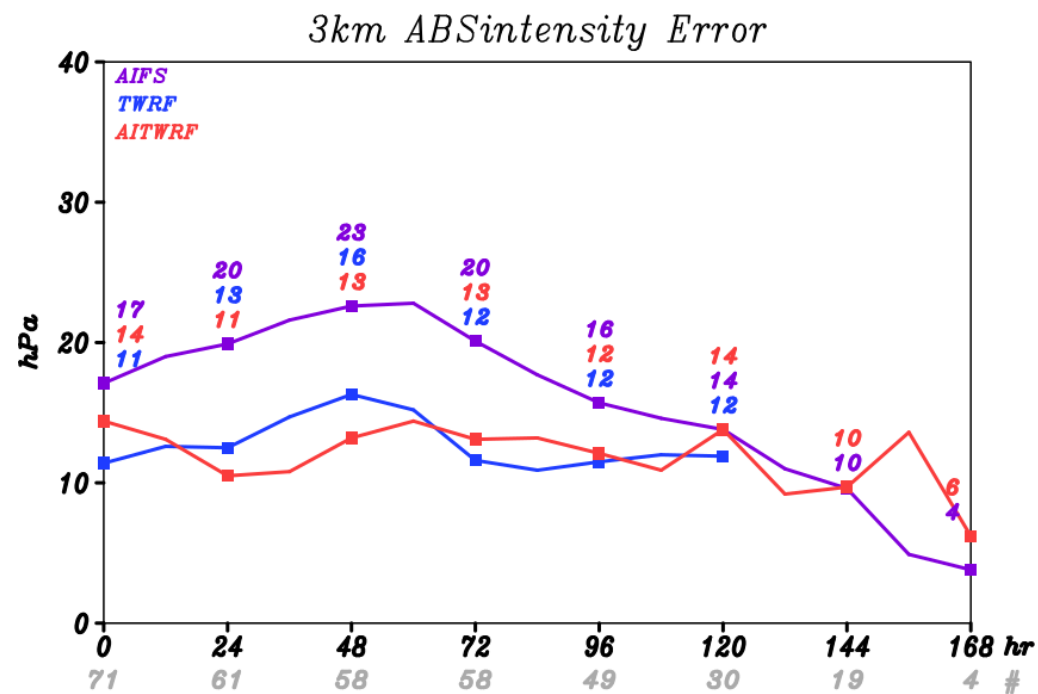


AIFS(當趟)



AIFS-6(前一run)

3 km Intensity Error

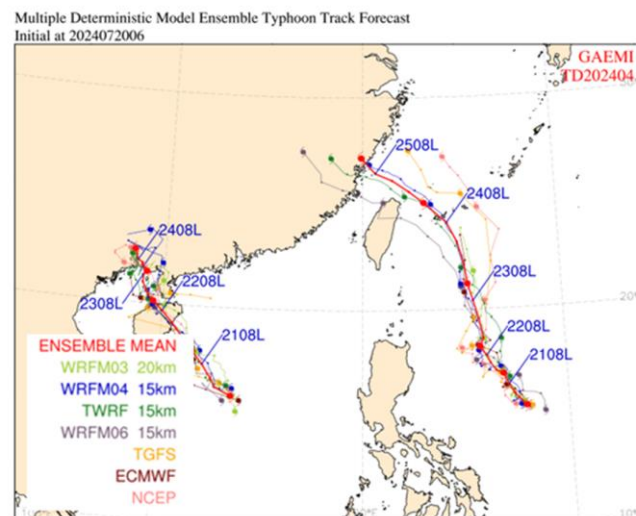
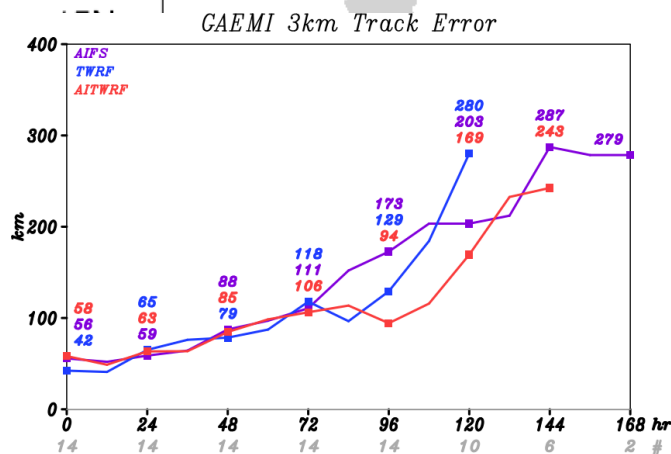
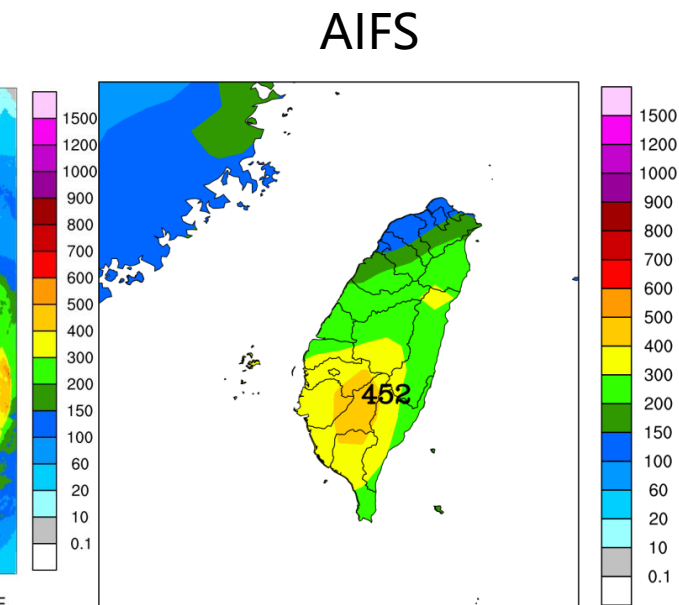
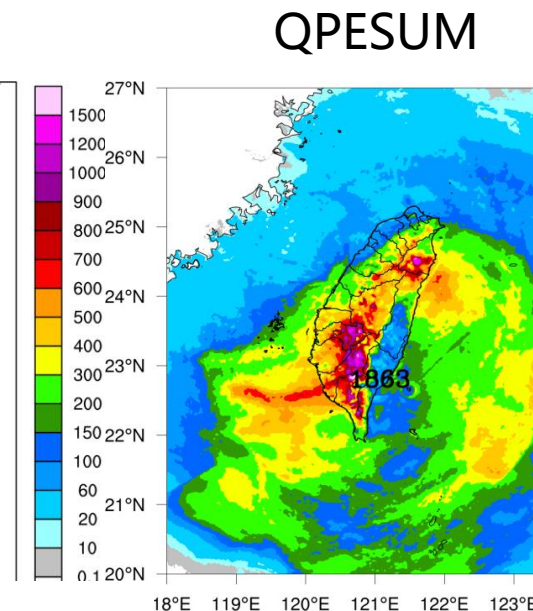
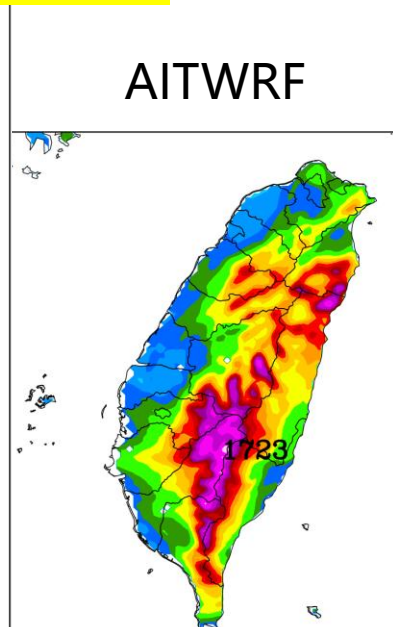
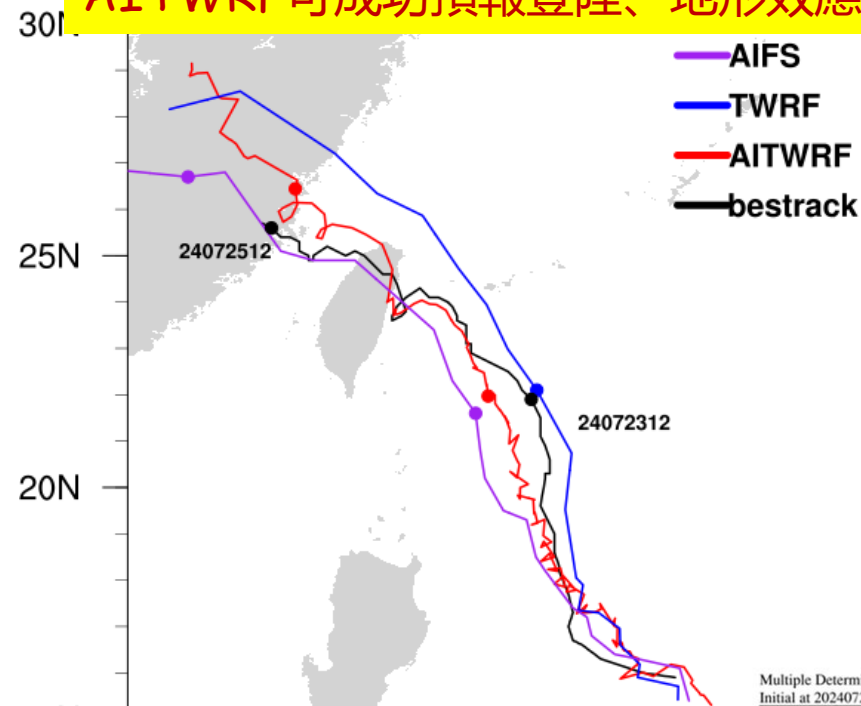


AITWRF、TWRP優於AIFS

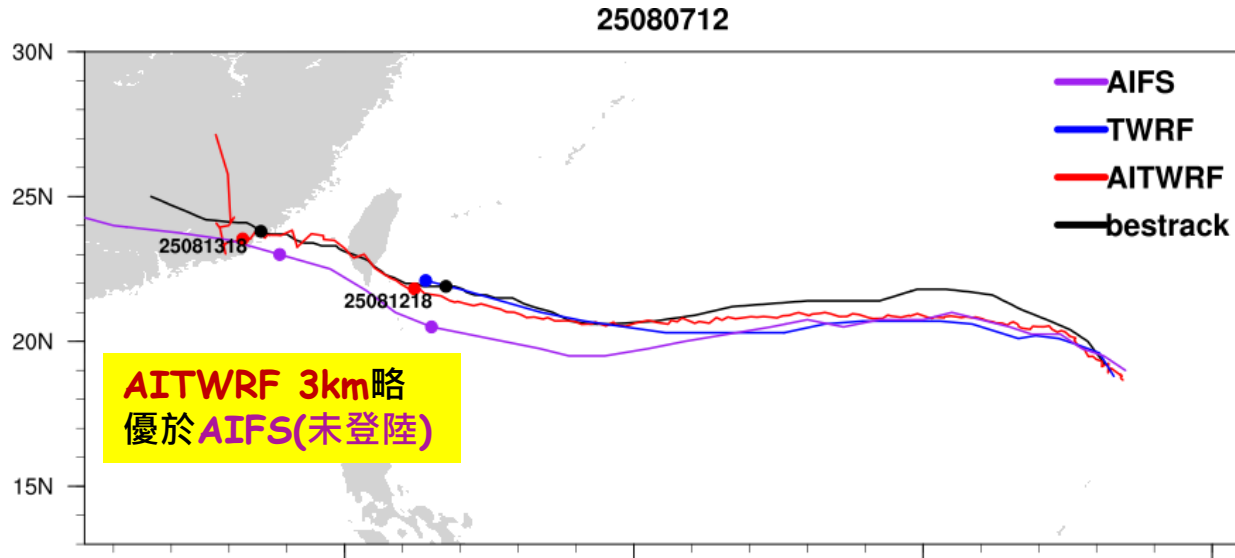
2024/07/20 06UTC, 凱米颱風登陸前約4.5天

AIFS 預報登陸，但地形效應不明顯
AITWRF可成功預報登陸、地形效應、雨量

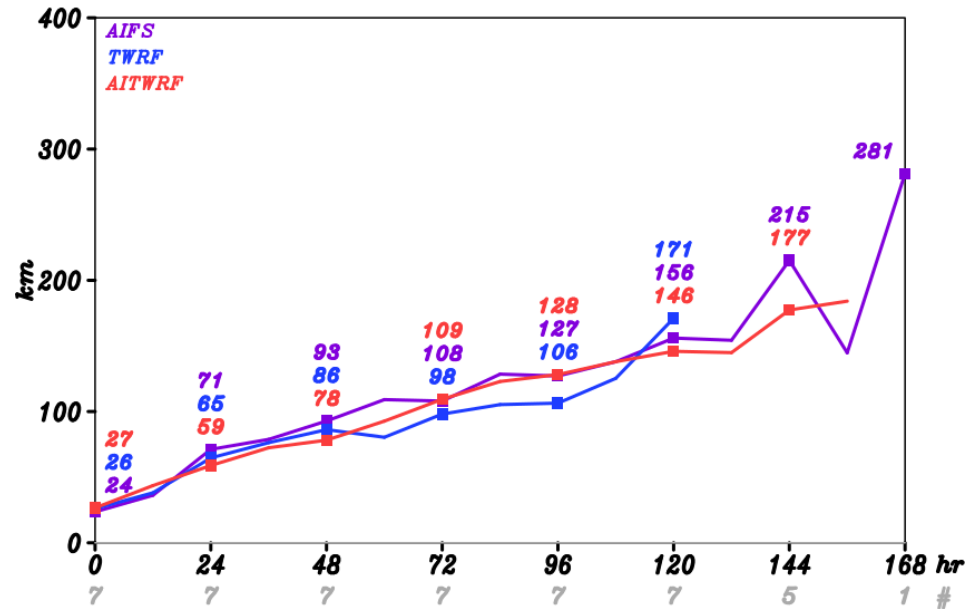
累積時間 7/23 12Z – 7/25 12Z



楊柳颱風：2025/08/07 12UTC(登陸前5.5天)

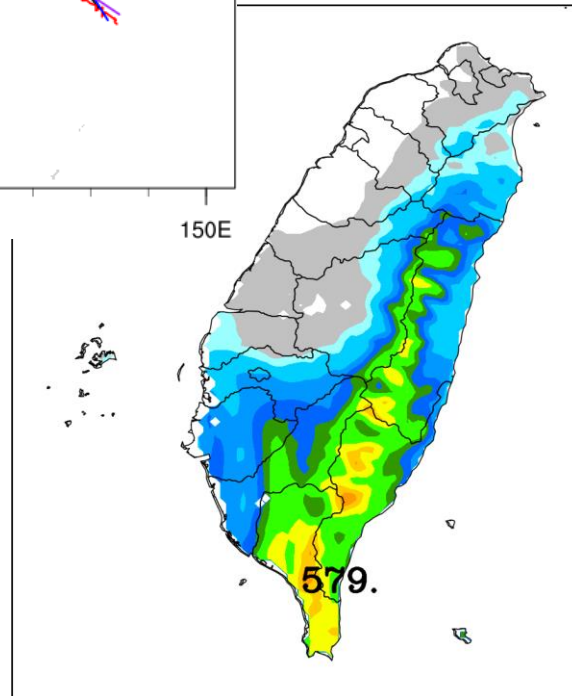


PODUL 3km Track Error

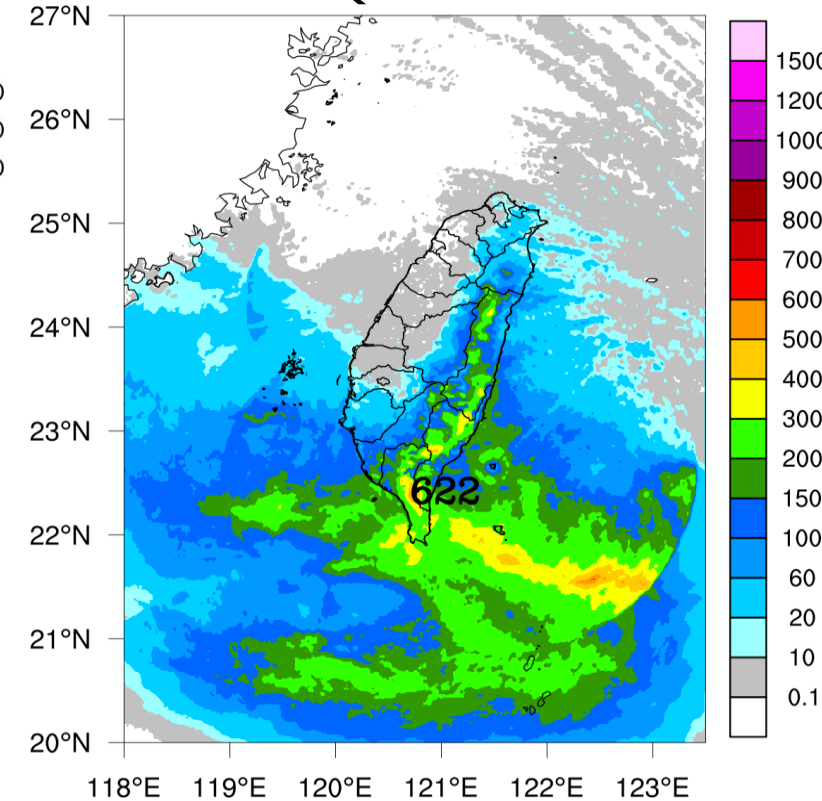


累積時間 8/12 18Z – 8/13 18Z

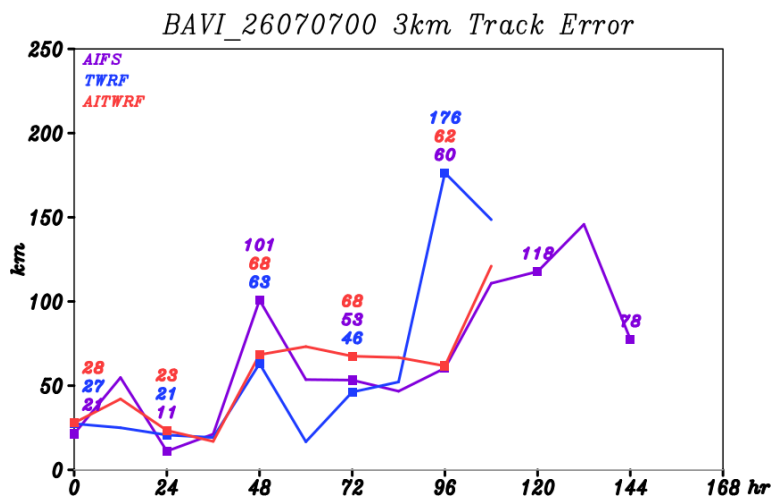
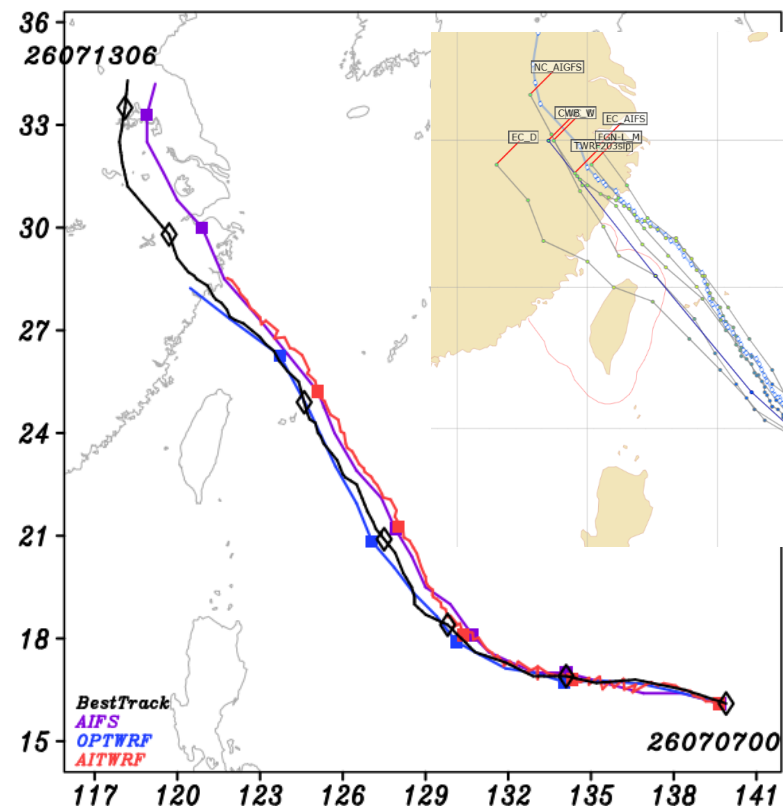
AITWRF



QPESUM



Track 26070700



2026/07/07 00UTC, 巴威颱風陸警前
約3天, EC/NCEP...預報偏南較近臺灣

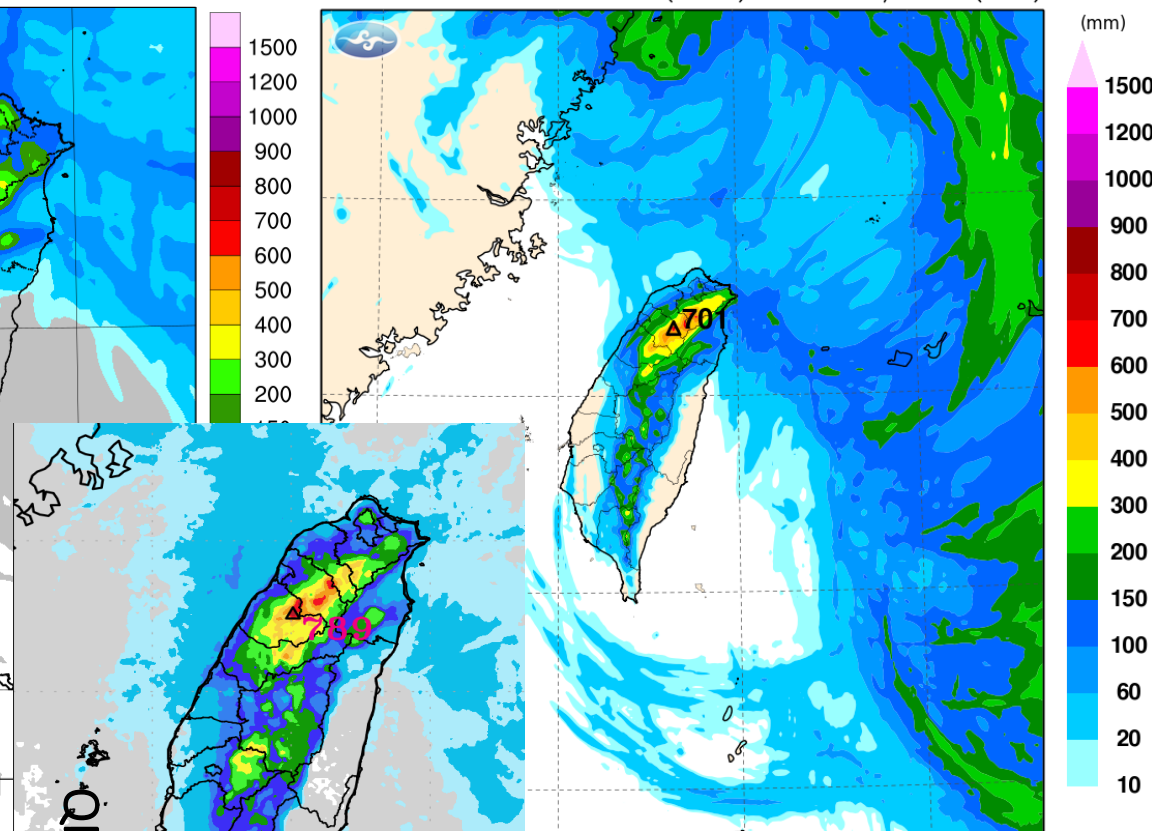
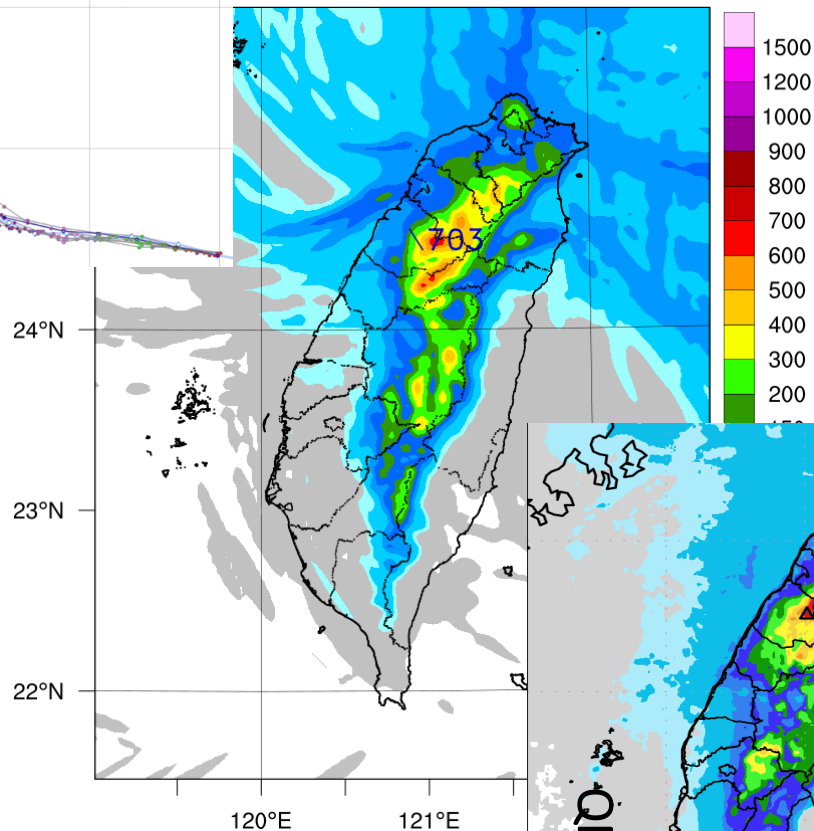
AITWRF(3km)稍北

TWRP(3km)稍快

TOTAL PRECIPITATION(mm) (009-114)

Valid at 11 Jul 2026 18UTC(+114)

CWA/TWRP (3km)



2026 00UTC

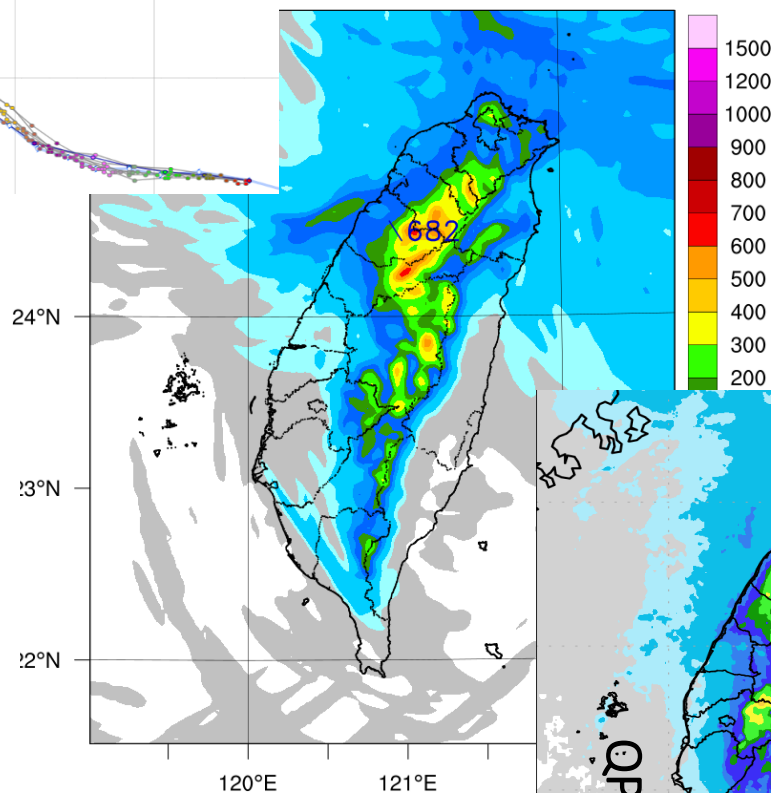
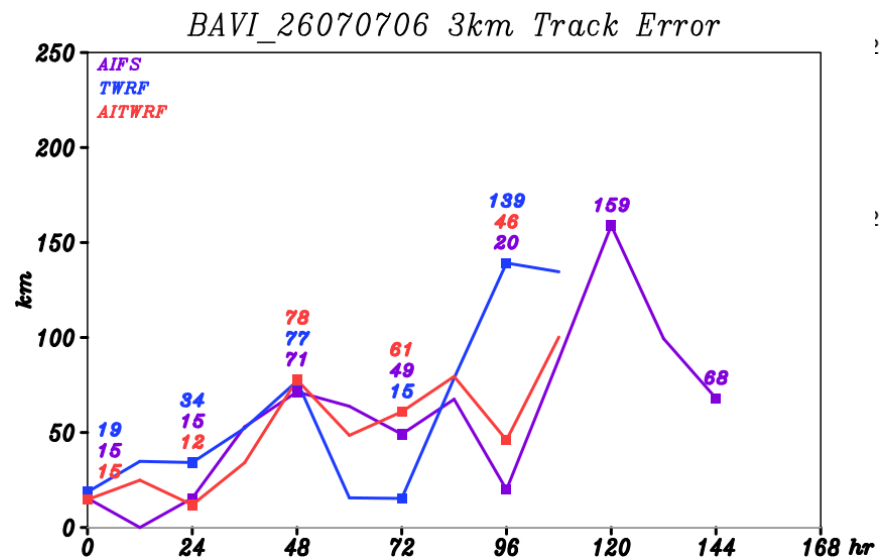
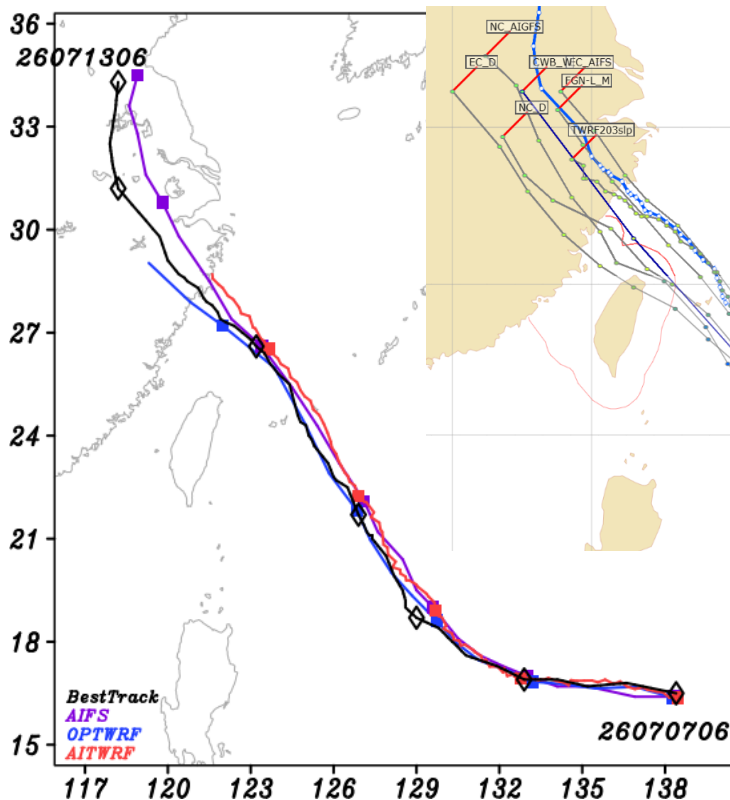
Rainfall period
26071018 ~
26071118 UTC

Track 26070706

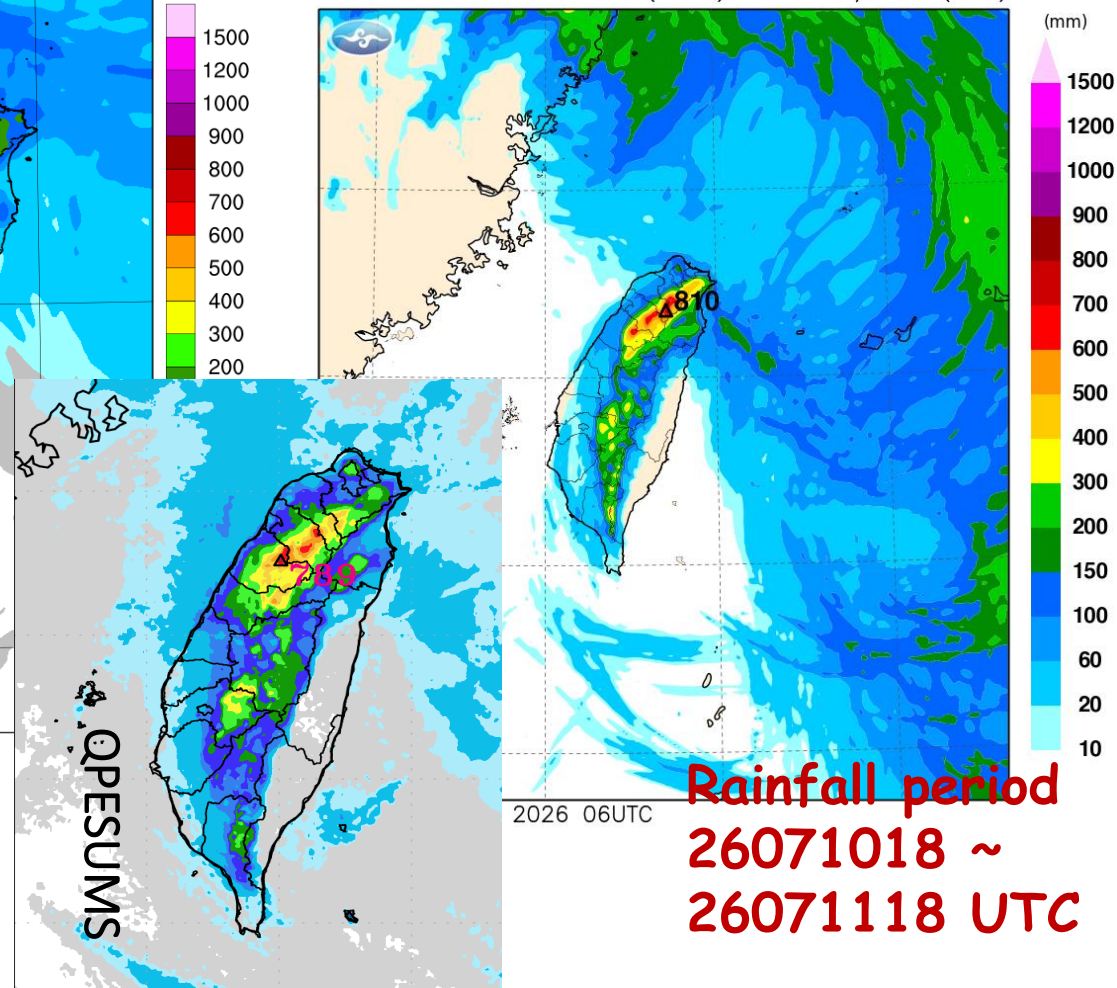
2026/07/07 06UTC, 巴威颱風陸警發佈前
約3天, EC/NCEP...預報偏南較近臺灣

AITWRF(3km)稍北

TWRF(3km)稍快



TOTAL PRECIPITATION(mm) (009-108)
Valid at 11 Jul 2026 18UTC(+108) CWA/TWRF (3km)



Rainfall period
26071018 ~
26071118 UTC

5.

小結

1. AITWRF (3公里) 融合了 AI看清「**大環境大局觀**」的強項，以及 TWRF 預報「**高解析度風雨細節**」優勢。正因如此，它能交出比單純 AI 模式更厲害的成績單，不只颱風路徑報得準(3天、5天路徑預報誤差較TWRF提升10%、40%)，連哪裡可能颶大風、哪裡可能下暴雨，以及台灣複雜山脈地形的影響，都有機會提早較精準掌握，為預報、防災作業爭取更多應變時間。
2. 在「區域型 AI 預報模型」真正成熟之前，AITWRF 混合系統可能是目前高解析度颱風預報的全方位解決方案 (Total Solution) 。
3. 擁有先進系統架構策略之**AITWRF** 預計於**2026年9月8日**上線作業：
 - 可依**颱風**初始位置選定**3km**模式範圍
 - 預報過程輕柔圓融納入**AIFS大尺度**(>1000km)天氣預報場(增加30%運算資源)
 - 預報過程**更新EC海溫場**
 - 預報時效達**7天174小時**
 - 引進GFDL vortex tracker，提供預報颱風中心定位及不對稱暴風半徑

未來工作

- ✓ 本研究建構之結合「AI」與「物理NWP模式」的混合型預報系統，其核心戰略價值在於---

「有機會提供較準確較長天數之高時空解析度大氣預報場」

- 評估並強化AITWRF對西南氣流、梅雨、共伴豪大雨之預報能力
- 以AITWRF驅動更精細與極短期模式
- ✓ 持續優化系統參數、模式範圍，提升預報技術
- ✓ 評估運算資源與預報效能，延長AITWRF預報至8-10天
- ✓ 評估以更好的AI模型做為AITWRF大環境導引目標

感謝



Central Weather Administration 2026

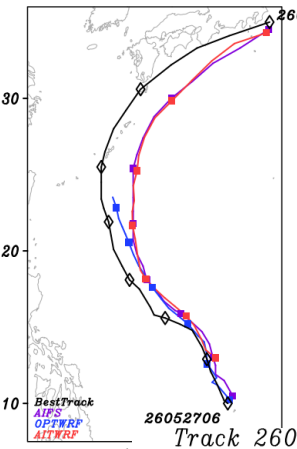
AIFS Single is scheduled for a upgrade to Version 2 (V2) on May 12, 2026

Resolution

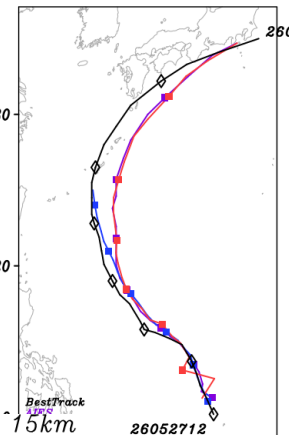
AIFS Single v2 introduces a new pressure level to the stratospheric component.

Model	Horizontal resolution			Vertical resolution [pressure levels] (hPa)
AIFS Single v1.1	N320	~31 km	0.25°	50, 100, 150, 200, 250, 300, 400, 500, 600, 700, 850, 925, 1000
AIFS Single v2				10 (new) , 50, 100, 150, 200, 250, 300, 400, 500, 600, 700, 850, 925, 1000

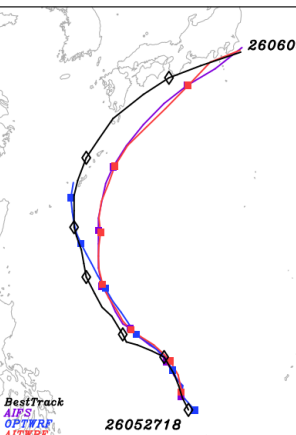
Track 26052706 15km



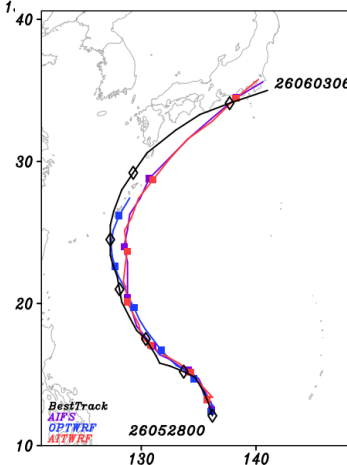
Track 26052712 15km



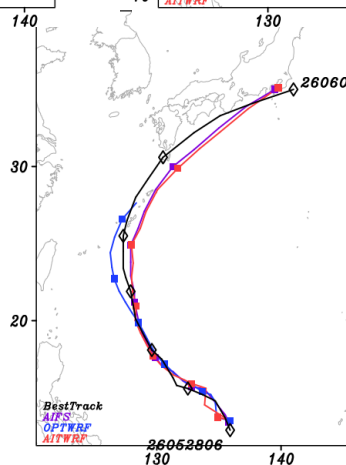
Track 26052718 15km



Track 26052800 15km



Track 26052806 15km



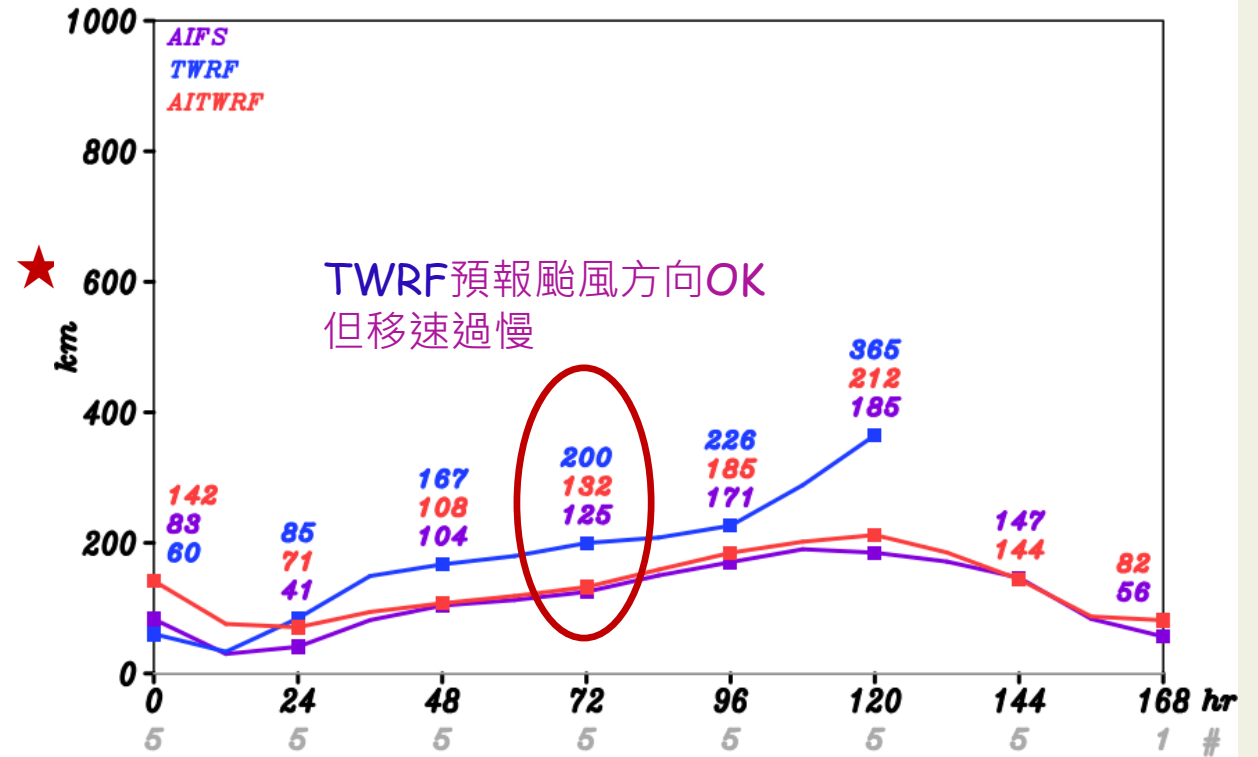
AIFS v1.1(13 levels) → AIFS v2(14 levels)

Model top of AITWRF

50hPa → 20hPa

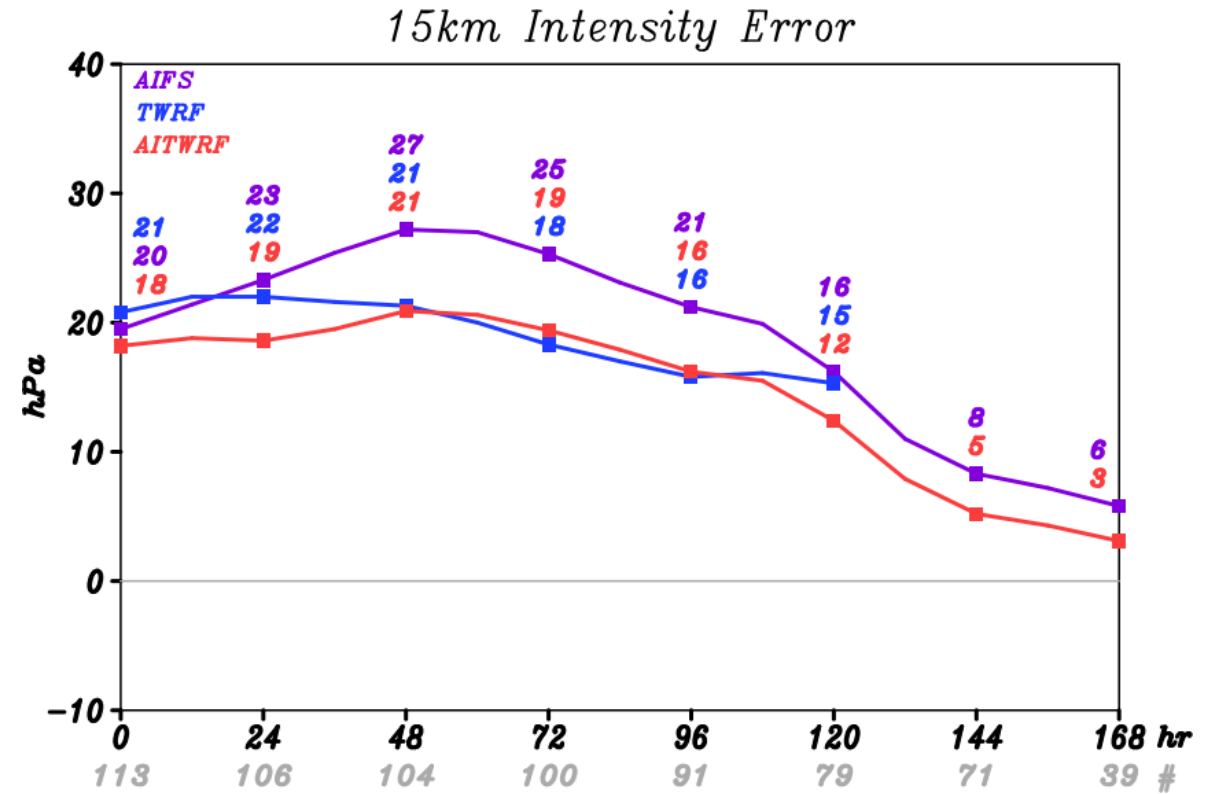
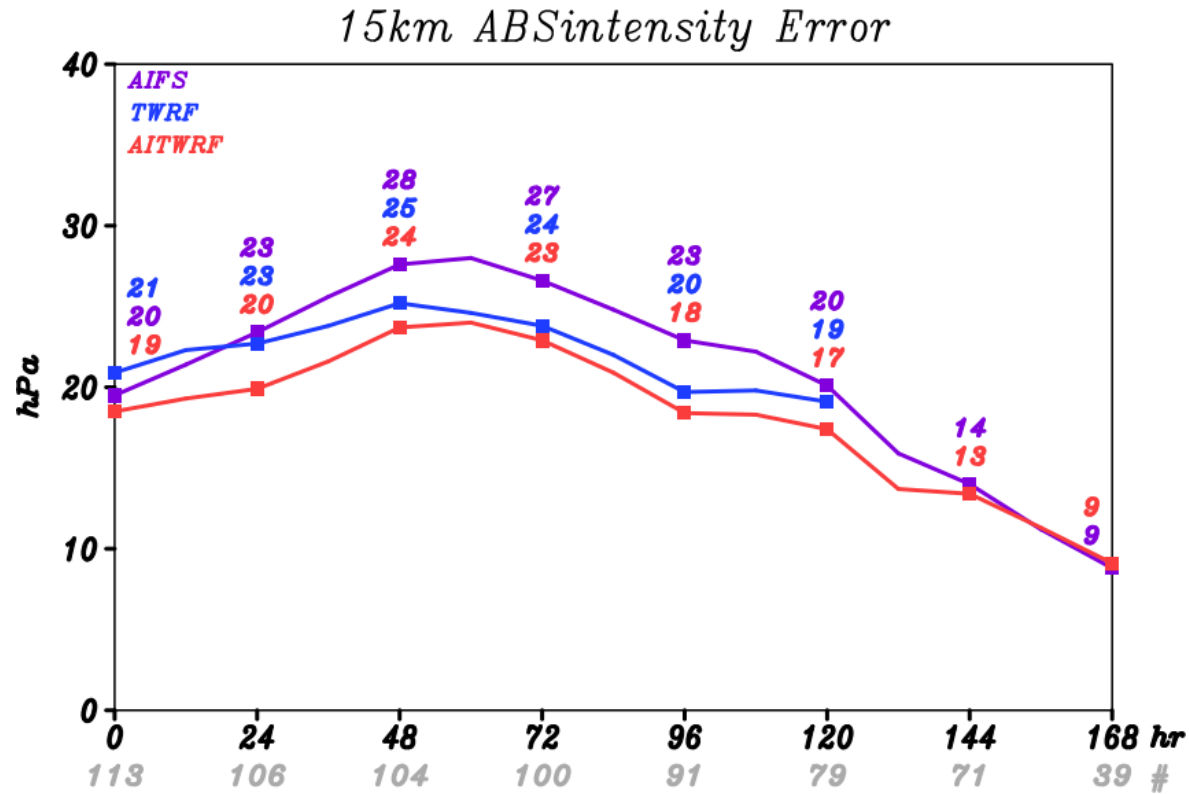
2026 typhoon Jangmi

JANGMI 15km Track Error



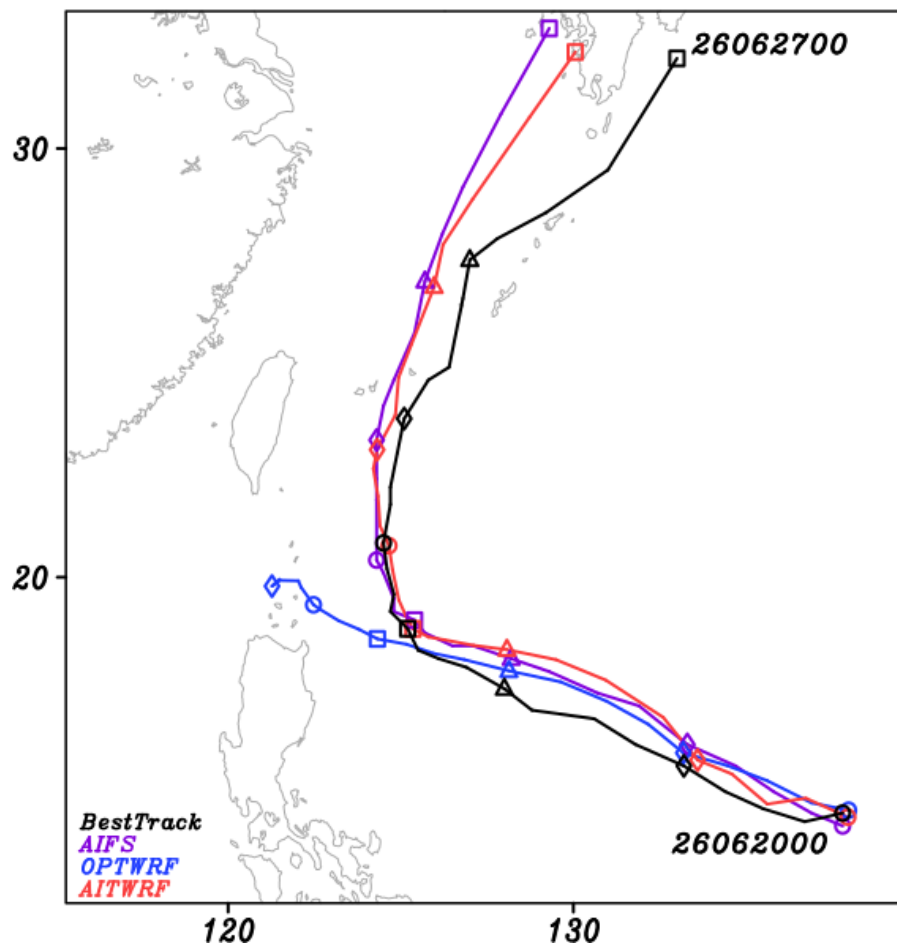
TWRF預報颱風方向OK
但移速過慢

15 km Intensity Error

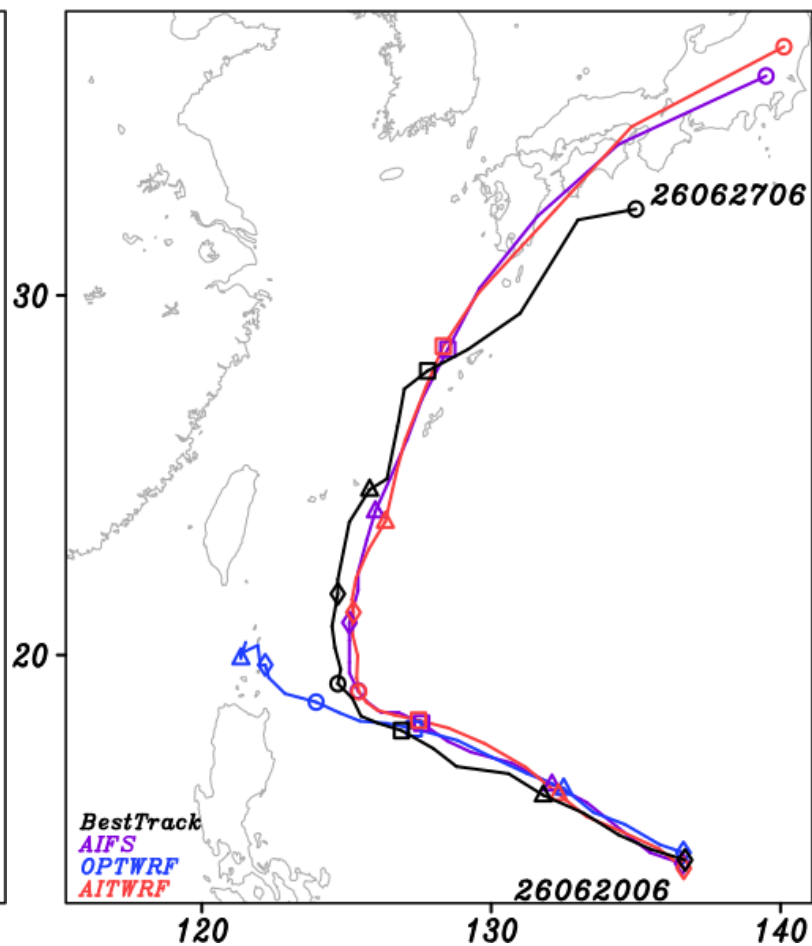


2026 米克拉 颱風

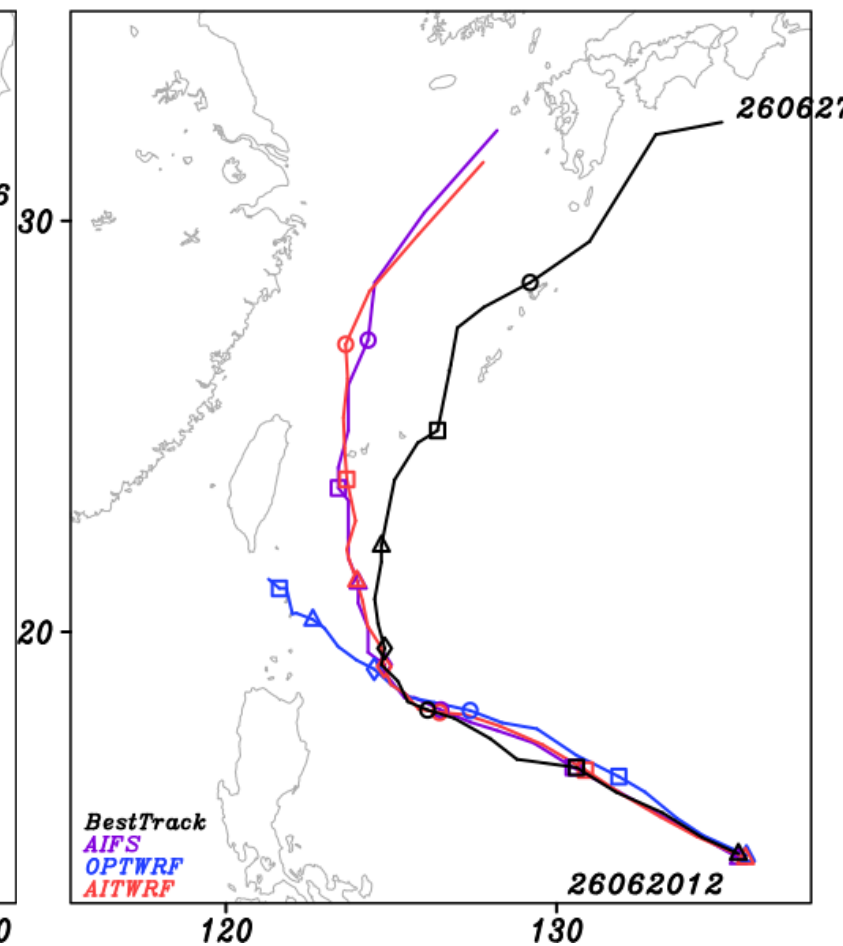
Track 26062000 15km



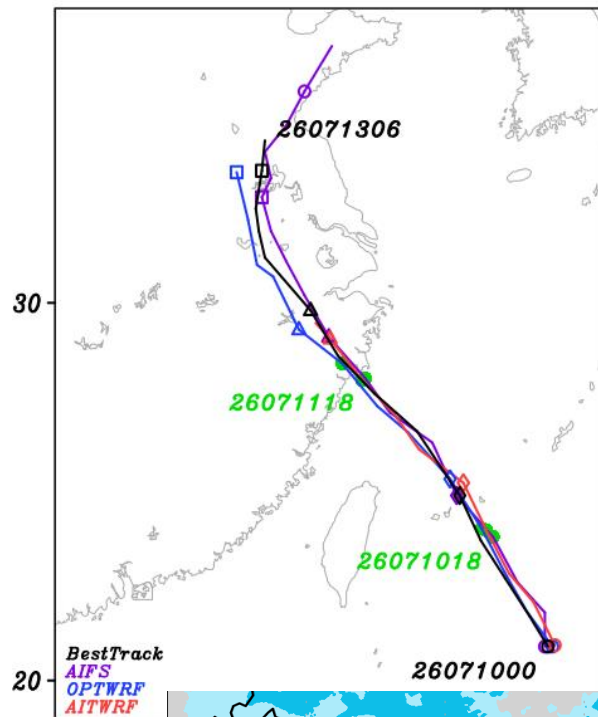
Track 26062006 15km



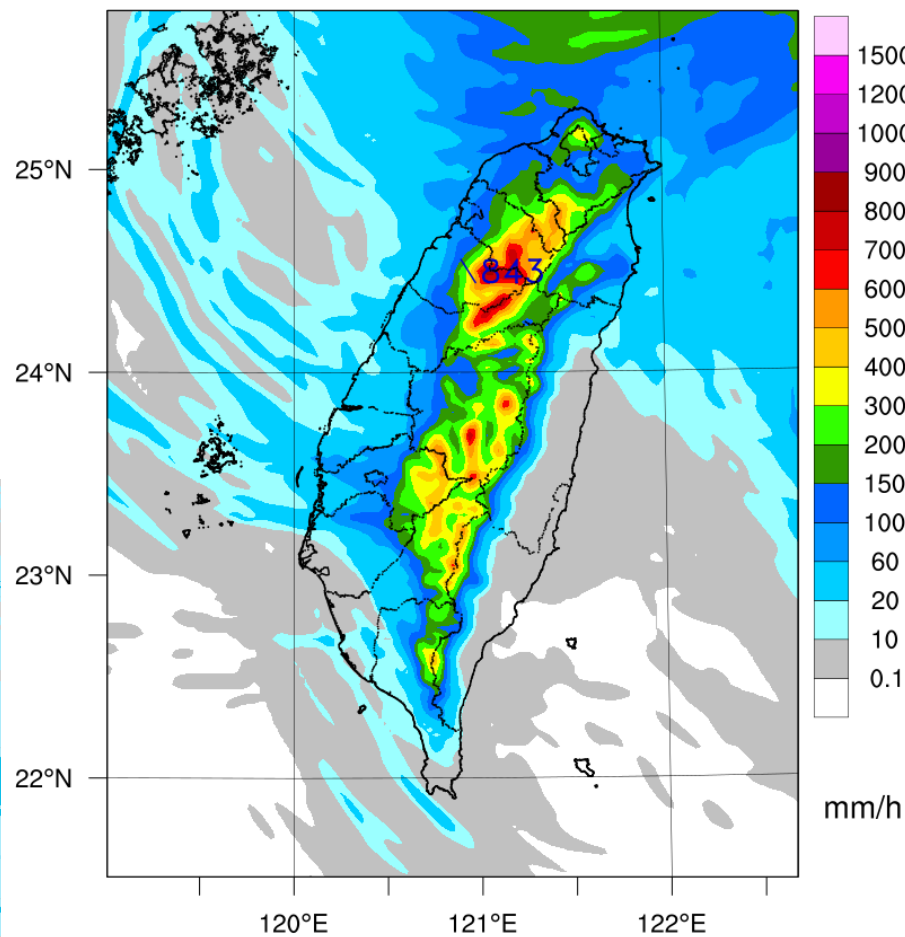
Track 26062012 15km



Track 26071000 3km



AITWRF(3km)

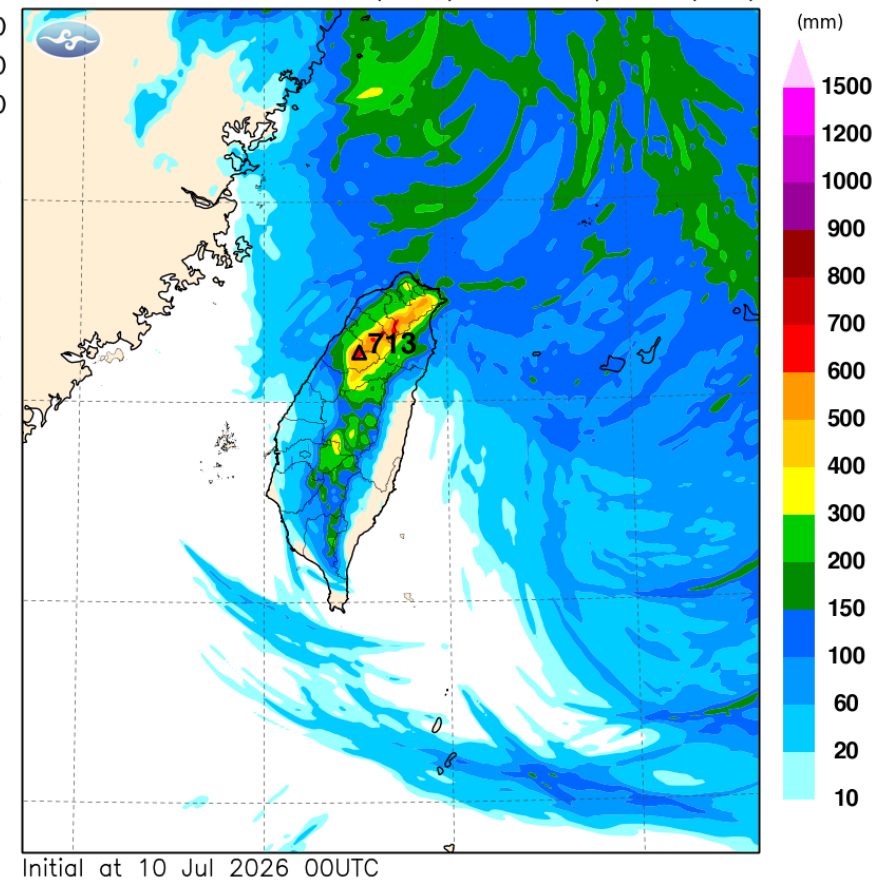


TWRF(3km)

TOTAL PRECIPITATION(mm) (009-042)

Valid at 11 Jul 2026 18UTC(+042)

CWA/TWRF (3km)



QPE SUMS

Open mark: 點; Closed mark: Rainfall period 26071018 ~ 26071118 UTC; AIFS 為-6 forecast