# Assimilation of GNSS Radio Occultation Data in CWA's Regional NWP System: Operational Use and Recent Development

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13 Sep 2024

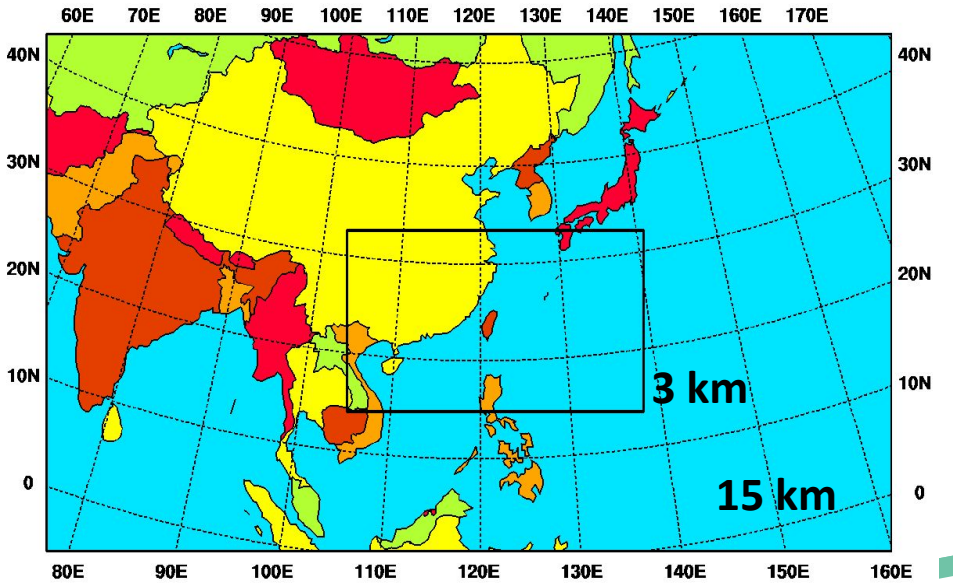
COSMIC / JCSDA Workshop and IROWG-10 Meeting

# Current Configuration of CWA regional NWP system

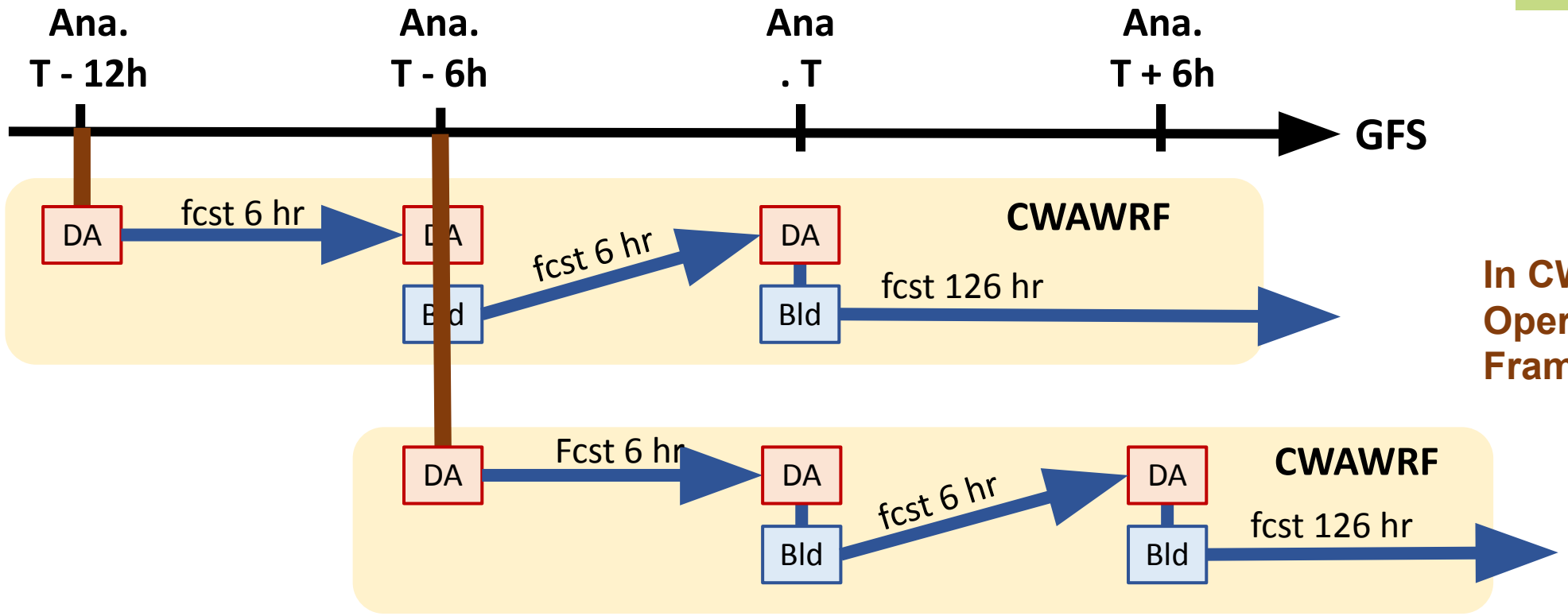
- **CWAWRF, the regional numerical weather prediction system in Central Weather Administration (CWA) of Taiwan**
  - Weather Research & Forecasting (WRF) Model v4.4.2 / WRF Data Assimilation (WRFDA) v3.9.1
  - A parent domain (dx = 15 km) and a nested domain (dx = 3 km).
  - 52 vertical levels and model top is at 20 hPa
  - **Hybrid 3DEnVar,** with flow-dependence background error covariance from the CWA EAKF
  - **Partial cycling with analysis blending**
  - Forecast length: 126 hours, 4 times per day (00, 06, 12 and 18 UTC)

- Operationally Assimilated Observations :
  Synoptic observations (SYNOP), ship observations (SHIP), meteorological terminal aviation weather reports (METAR), soundings (TEMP), airplane reports (AIREP), buoys (BUOY), ground-based GPS zenith total delay data (GPSZD) and FORMOSAT-7/COSMIC-2 (FS7/C2) RO **refractivity** (GPSRF), profiler data (PROFL; only used in outer domain)

*In CWA Global model (TGFS), FS7/C2 RO **banding angle** is assimilated



# Partial Cycling with Analysis Blending

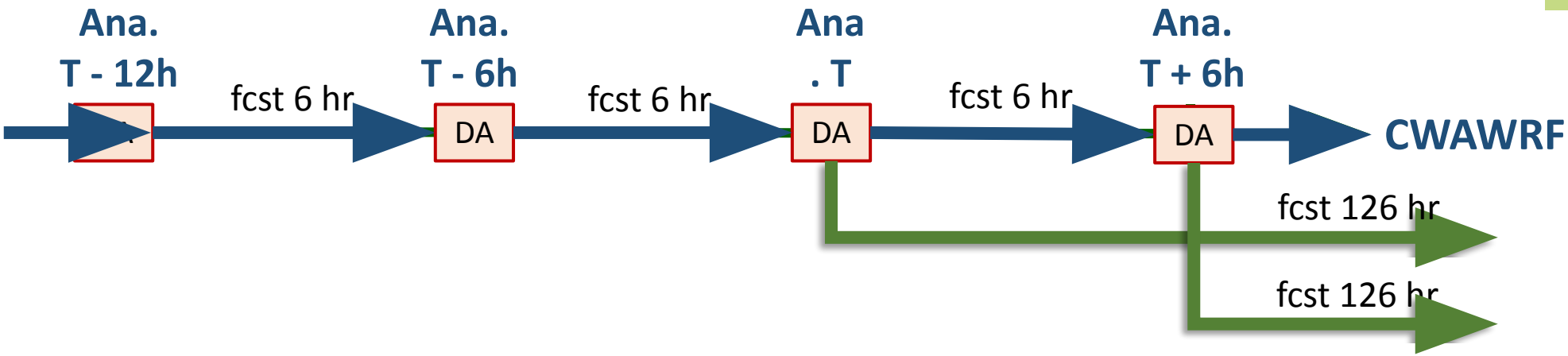



**In CWA Operational Framework**

**However,**

**it is challenging to evaluate the data impact on the regional model forecasts under this framework**

# Continuous Cycling




**Allow sufficient time to accumulate and amplify the effect of FS7/C2 RO assimilation**

# FORMOSAT-7/COSMIC-2 (FS7/C2) Contributions in NWP

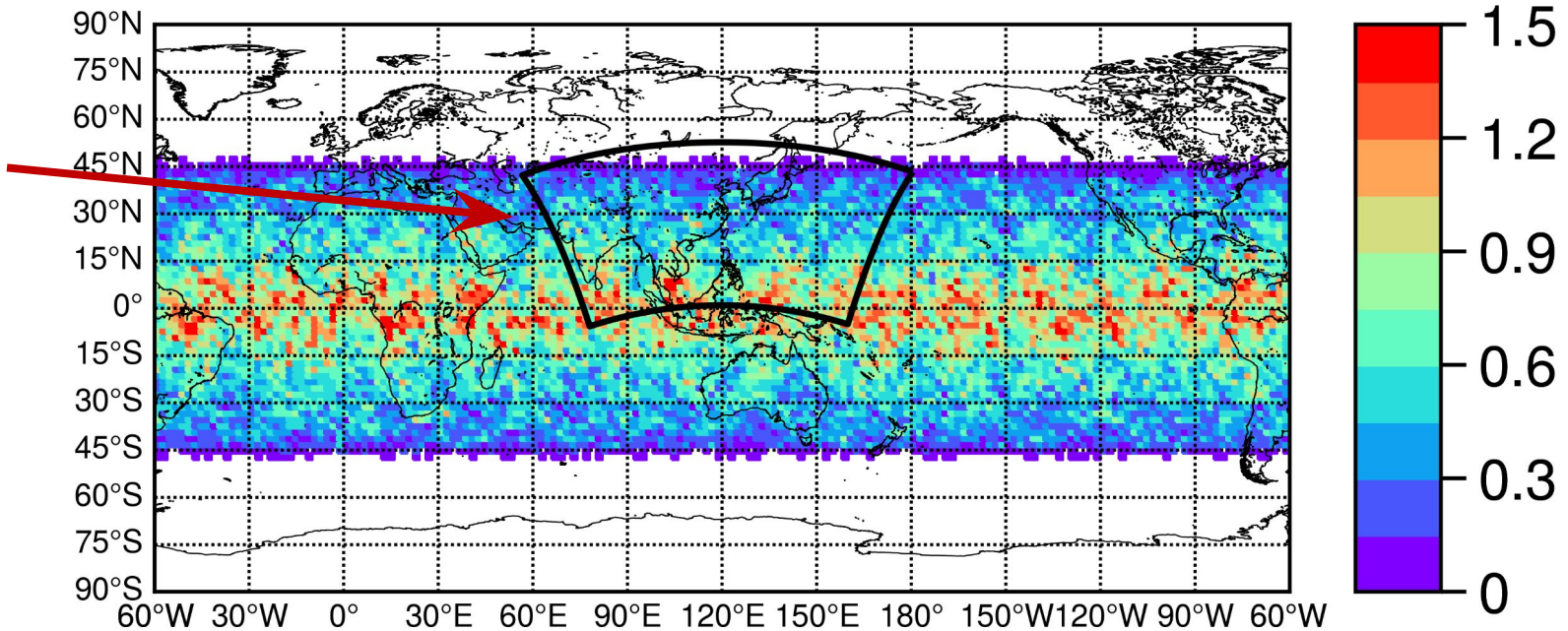
**By assimilating the FS7/C2 RO Refractivity data into CWAWRF , several improvements were identified:**

1. **reduced forecast errors at synoptic scale**
2. **better initial typhoon structures**
3. **reduced the typhoon track errors**

(Chen et al. 2022)

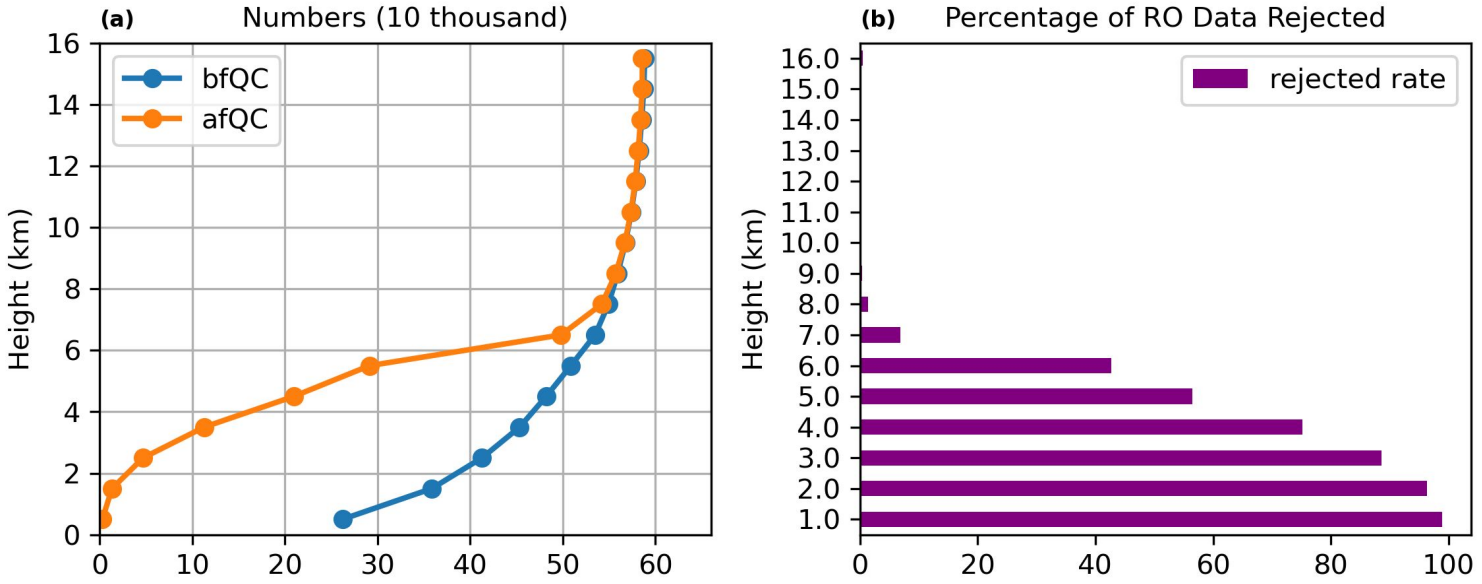
## Mean daily FS7/C2 RO profile count in 2x2-degree boxes (15 Aug to 7 Sep 2020)

**CWAWRF 15 km-resolution domain**



# RO Quality Control (QC) and Analysis Increment

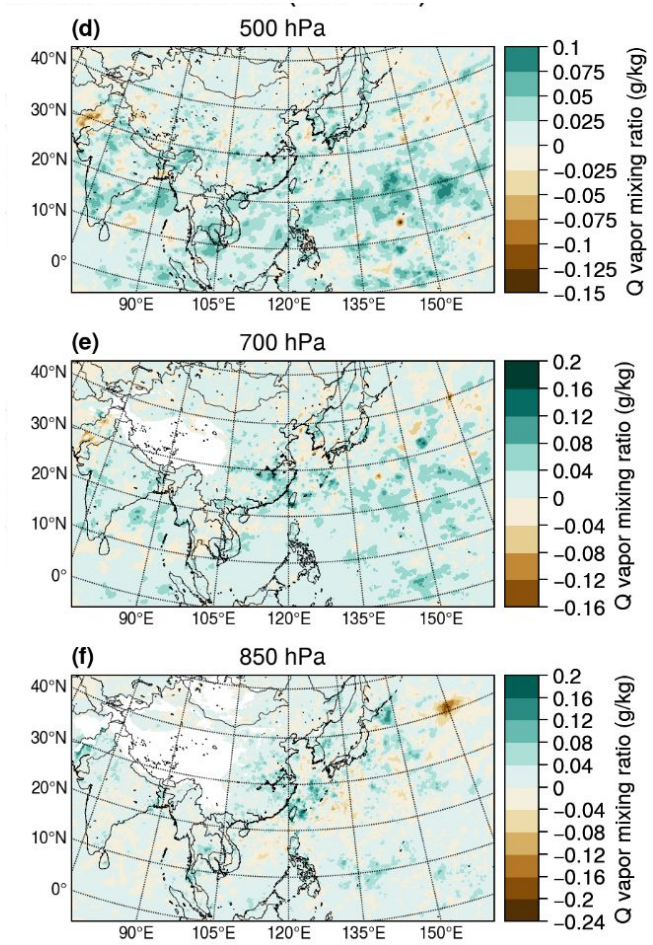
The FS7/C2 RO Data counts in 2020/08/15 12Z ~ 2020/09/07 12Z




*Including gross error check, qc_dndz, qc_dndz2, qc_pcnt setting in WRFDA

[with_RO – no_RO]
Difference in mean analysis increment

QVapor (g/kg)



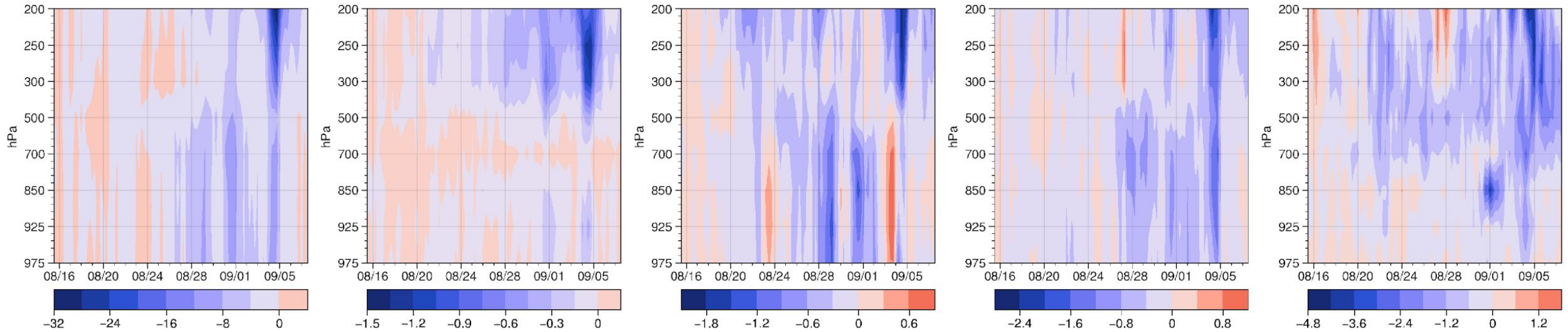
# RO Impact on the Synoptic Forecasts

## [with_RO – no_RO]

## 72-h forecast root-mean-square-error (RMSE) reduction

(in the 23-day assimilation period; averaged over the 15-km domain)

**Height (m)** | **Temperature (K)** | **U-wind (m/s)** | **V-wind (m/s)** | **Relative humidity (%)**



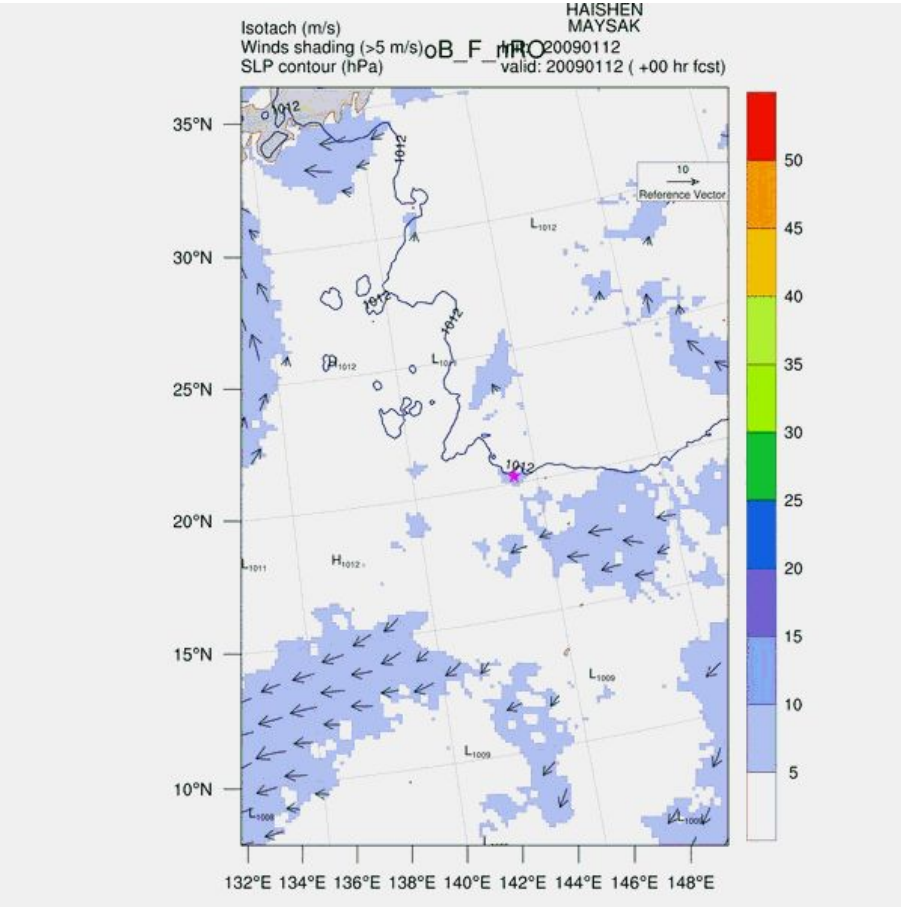

**Lower is better**

# RO Impact on the Typhoon Analysis

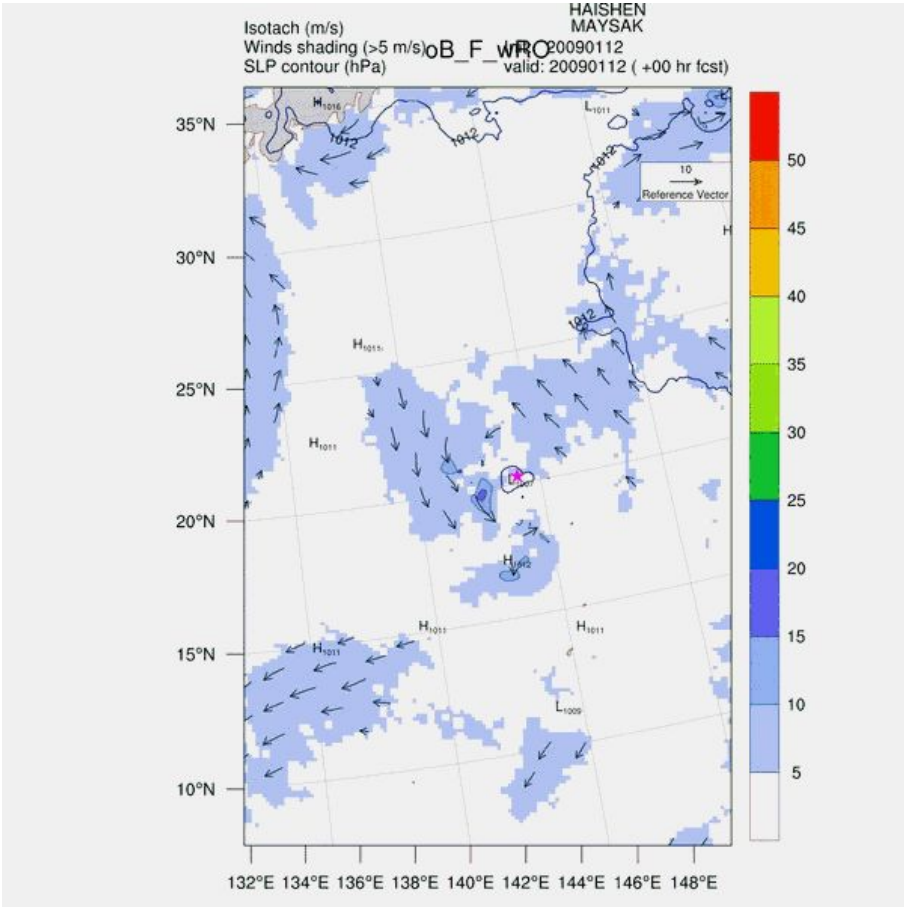
**FS7/C2 RO data assimilation helps the regional NWP system to develop a realistic typhoon structure in its analysis (i.e., initial conditions for model forecast).**

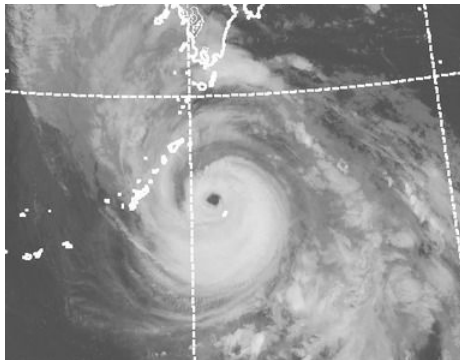
**Typhoon Haishen**

no_RO




with_RO



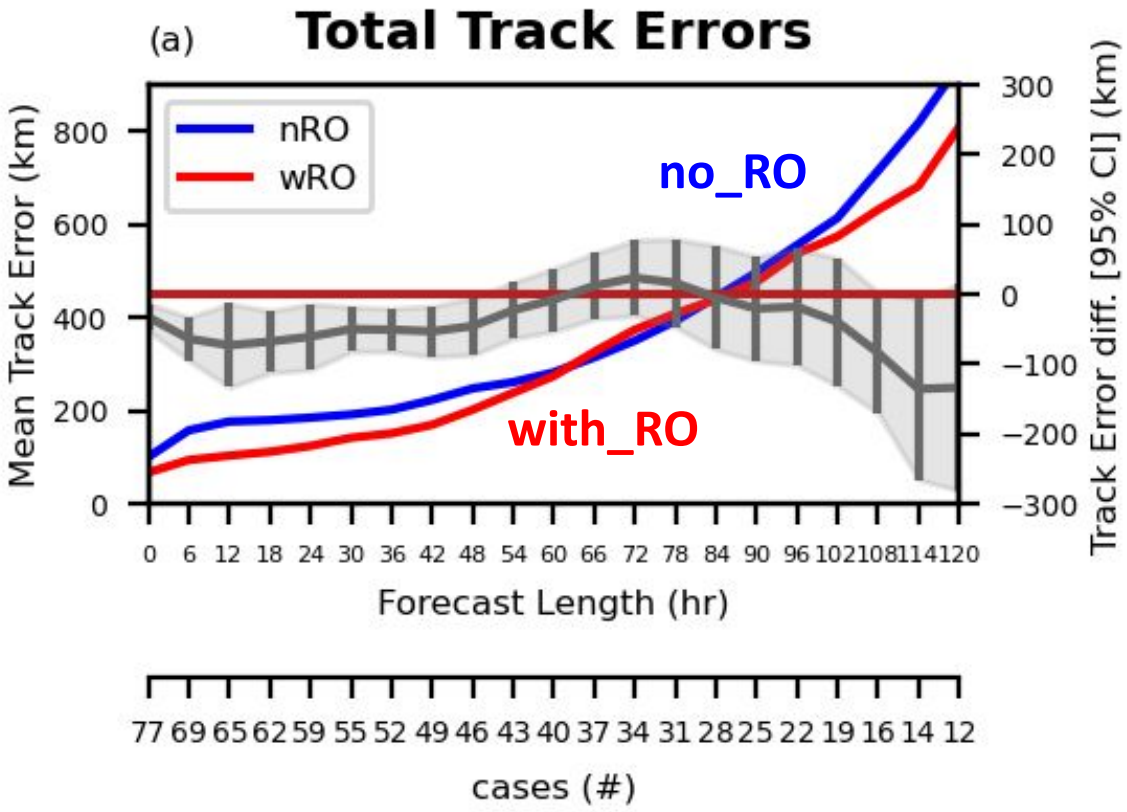
Himawari satellite image of Typhoon Haishen

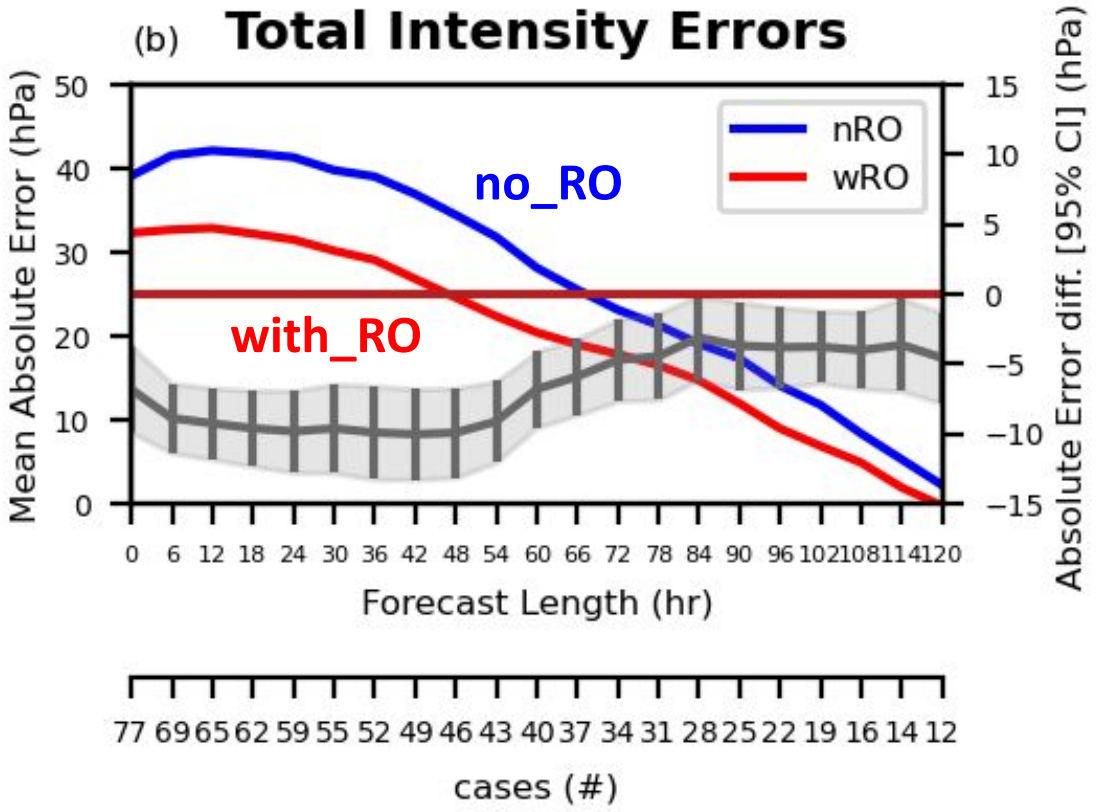
Contour: Sea level pressure (hPa)
Shade: Wind speed (m/s)

# RO Impact on the Typhoon Forecast

**With better initial conditions, FS7/C2 RO data assimilation further improves the typhoon track and intensity forecasts.**

(15 Aug to 7 Sep 2020 , ~75 forecast cases)




(Chen et al. 2022)

# Local vs. Nonlocal RO Observation Operators

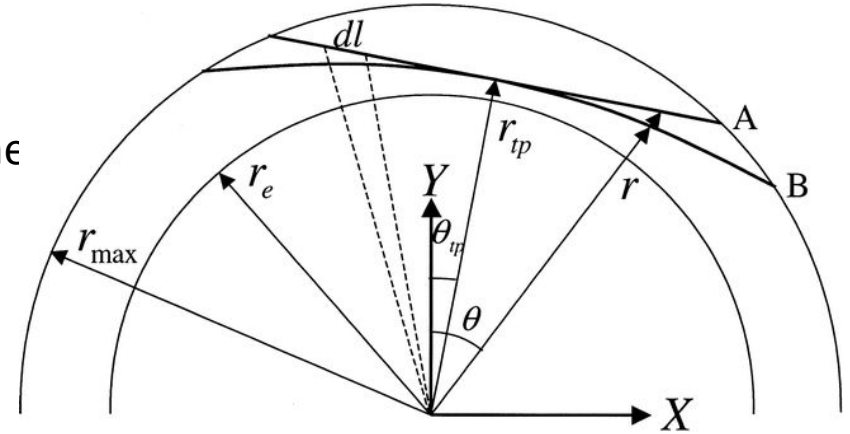
- RO refractivity is **operationally** assimilated in CWAWRF via a **local observation operator** that assumes the RO retrieved refractivity is representative of a local point.

- The local operator calculates RO refractivity without considering the effects of horizontal inhomogeneity around the RO measurements, which can be significant over regions with large horizontal moisture or temperature gradients.

## Nonlocal Excess Phase Operator (Sokolovskiy et al. 2005a)

Considers the atmospheric horizontal refractivity variations by integrating the GNSS RO refractivity using the ray constant step of 5 km along a straight line representing the ray path (Sokolovskiy et al. 2005b; Chen et al. 2009)

$$\text{pseudo excess phase} \quad S = \int N \, dl \, ; \qquad l \text{ is the ray path}$$




Monthly Weather Review 133, 8; 10.1175/MWR2948.1

The nonlocal operator have been implemented into the WRFDA ver. 4.0+ (Chen et al. 2009 and Zhang et al. 2014), which calculates GNSS excess phase on the mean altitude of each model layer.

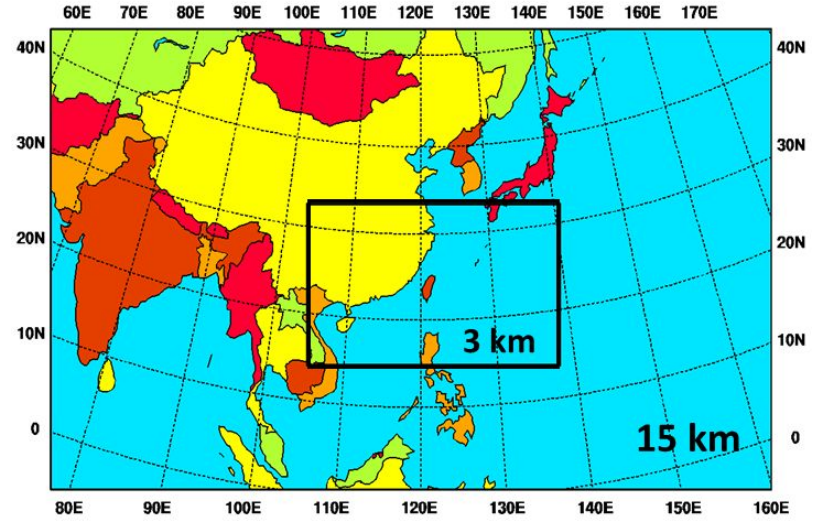
# Local vs. Nonlocal RO Observation Operators

| Aspect | Local Operator | Nonlocal Operator | References |
|---|---|---|---|
| Consideration of Horizontal Gradients | No | Yes | |
| Computational Complexity | Low | High | |
| Sensitivity to Moisture and Temperature Variations | Low | High | Chen et al. (2020) |
| Impact on Tropical Cyclogenesis Detection | Increased probability of detection to 40% | Increased probability of detection to 70% | |
| Applicability to Cyclogenesis Prediction | Less accurate, delayed detection | More accurate, earlier detection | |
| Typhoon Track Prediction | Worse | Better | Chen et al. (2021) |
| Potential Vorticity Analysis | Worse | Better capture TC dynamics | |

# Experimental Design

| Exp. | Observation Operator | FS7/C2 RO Refractivity Data Format | RO Data QC | WRF/WRFDA Version |
|---|---|---|---|---|
| LOC | Local | atmPrf (high vertical resolution) | the same as CWA OP (gross error check, qc_dndz, qc_dndz2, qc_pcnt) | 4.4.2 |
| NLC | Nonlocal | NCEP PREPBUFR (low vertical resolution) | Only gross error check | 4.4.2 |

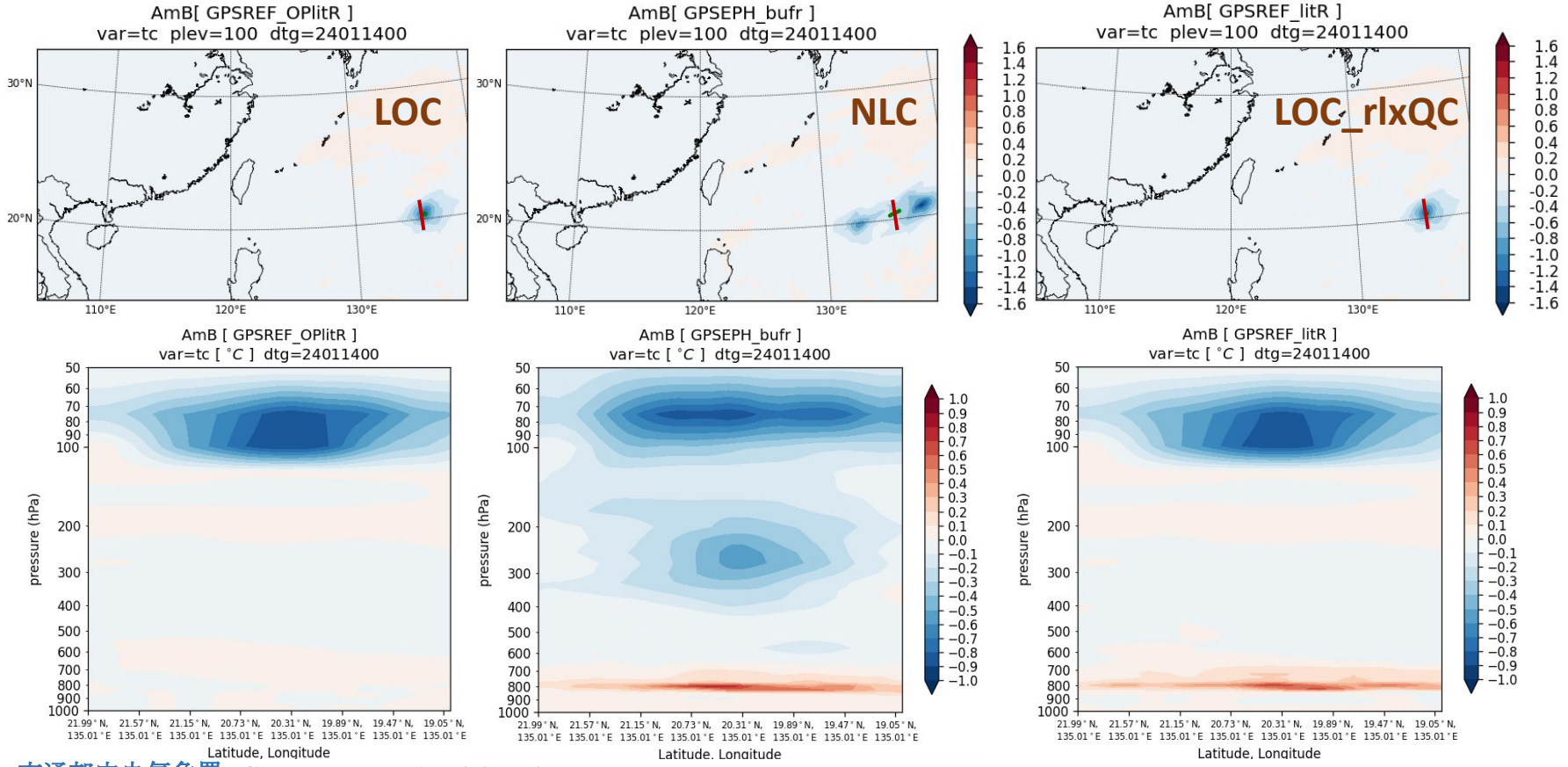
- Continuous cycling (CC) with 5 days spin-up
- Experiment period:
  - 21 Jul 2023 00 UTC to 04 Aug 2023 12 UTC
  - 72-hr forecasts initialized at every 00 UTC and 12 UTC, total 30 forecast cases
  - Assimilated observations: The same as the operational regional NWP system in CWA



# Single-Observation Tests

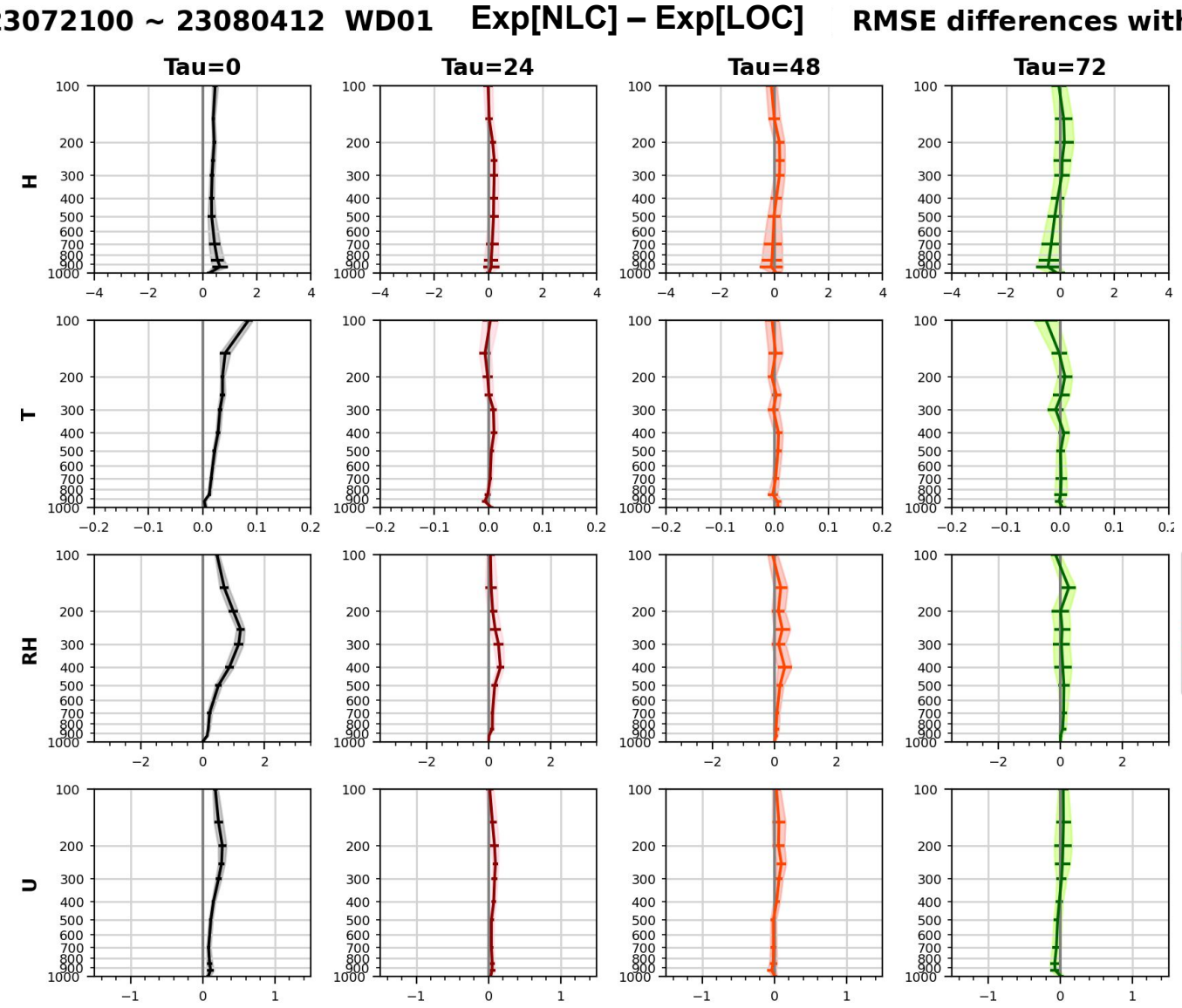
| Exp. | LOC | NLC |
|---|---|---|
| Operator Type | local | nonlocal |
| FS7 Data Format | atmPrf | NCEP PREPBUFR |
| FS7 QC | As same as CWA OP* | Gross Error Check |

*gross error check, qc_dndz, qc_dndz2, qc_pcnt

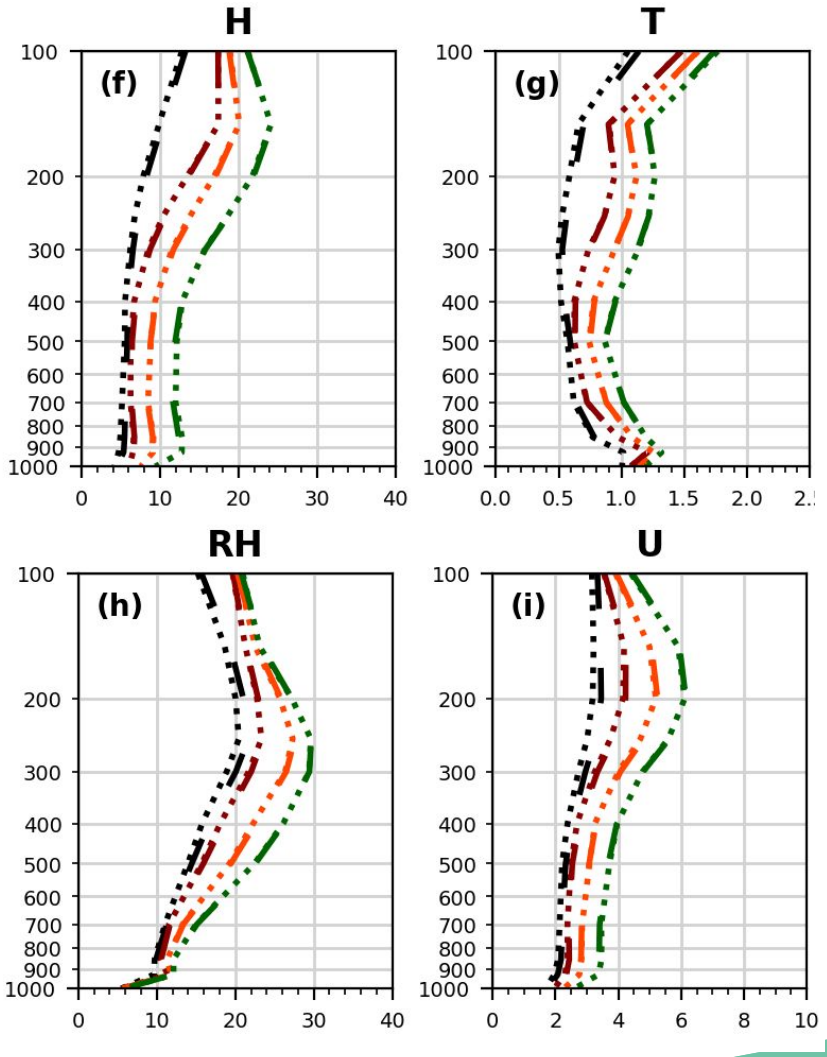



- Upper: The analysis increments of single refractivity data with different FS7/C2 data types and operators.
- Lower: Same as above, but for the cross section along longitude 135° E.
- The RO QC in CWA OP is stricter.
- The analysis increments of NLC are more elliptical.

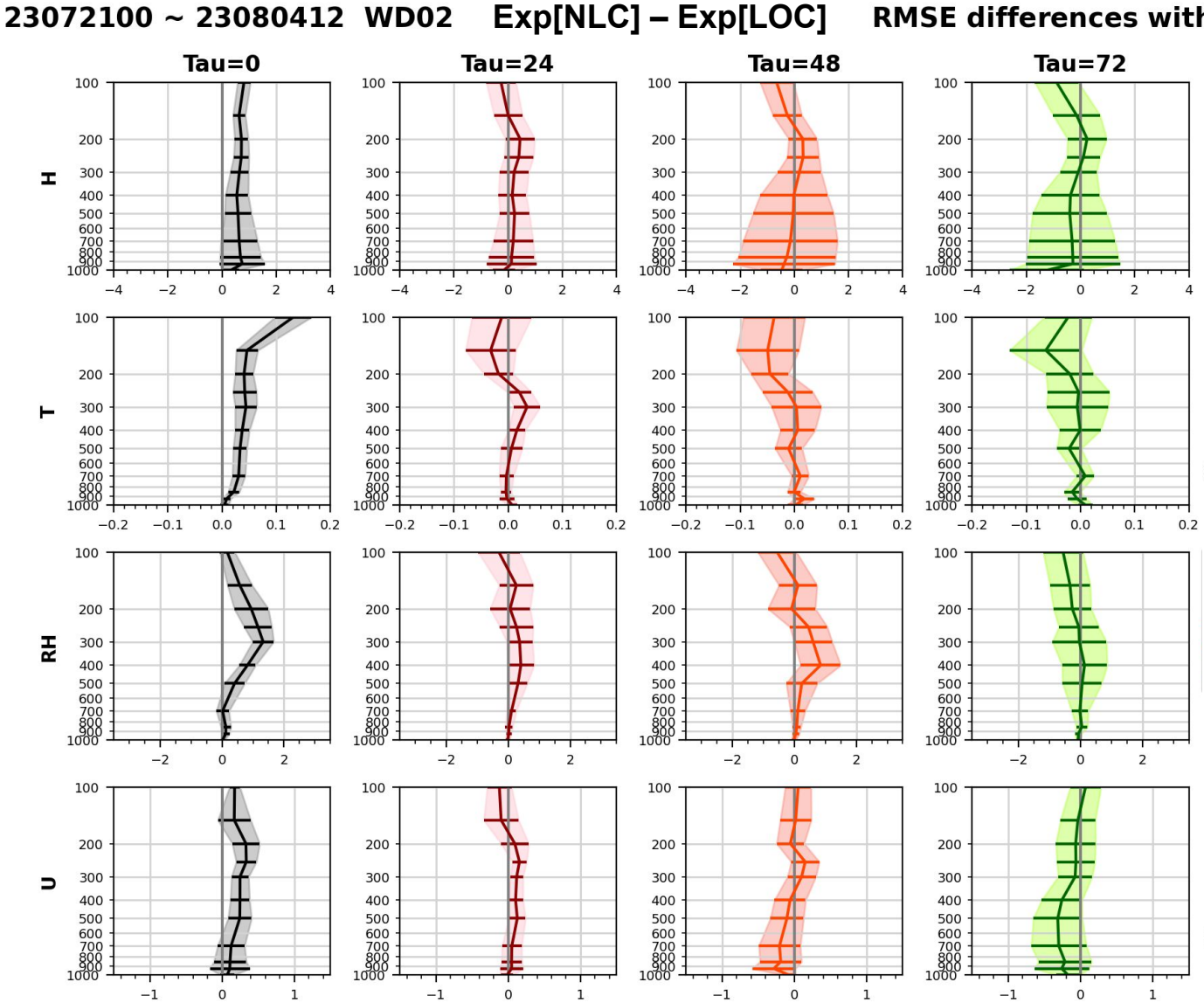
# Domain-averaged Verification (15-km domain)



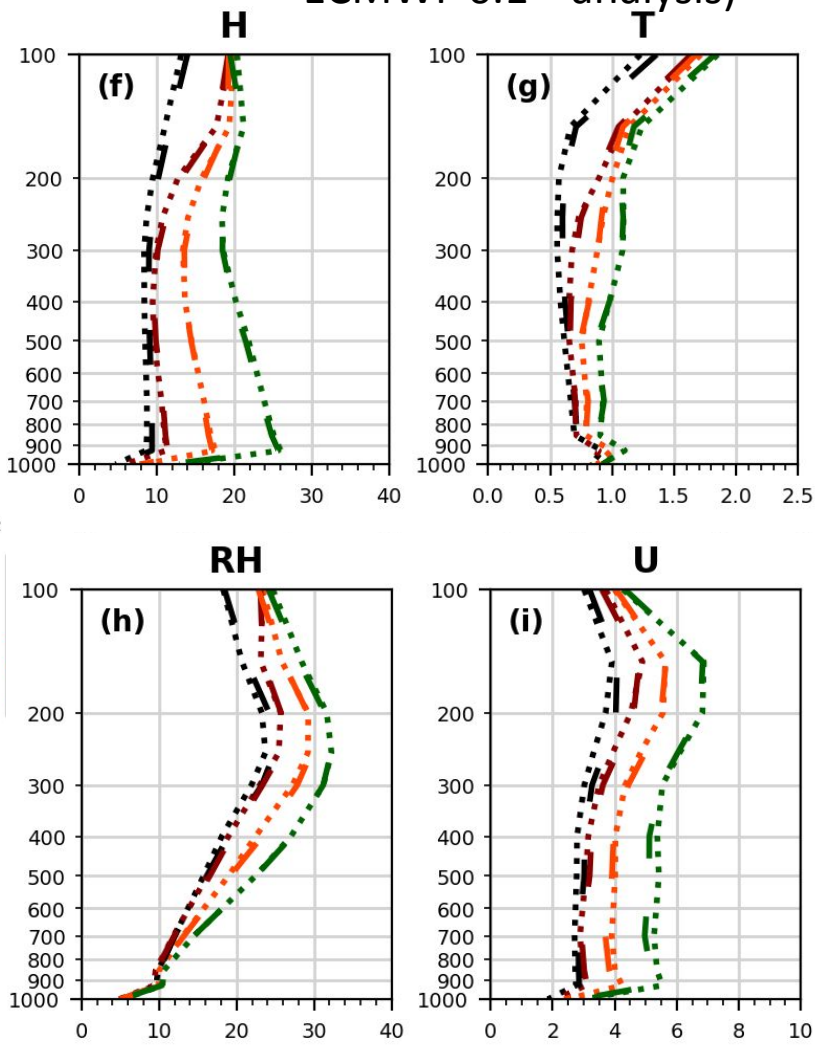

RMSE (forecast verified against ECMWF 0.1 ° analysis)



# Domain-averaged Verification (3-km domain)

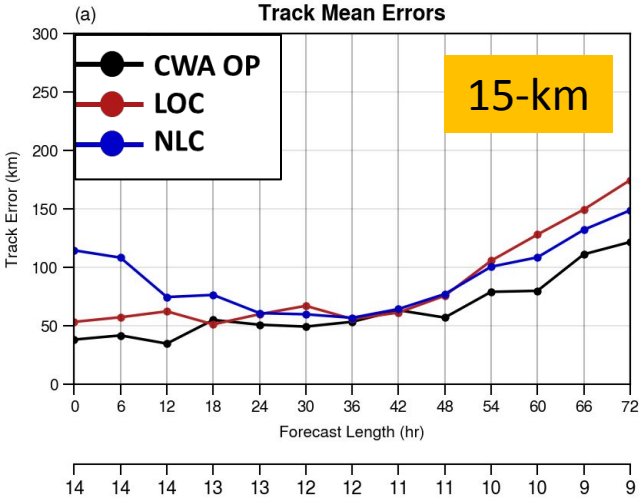


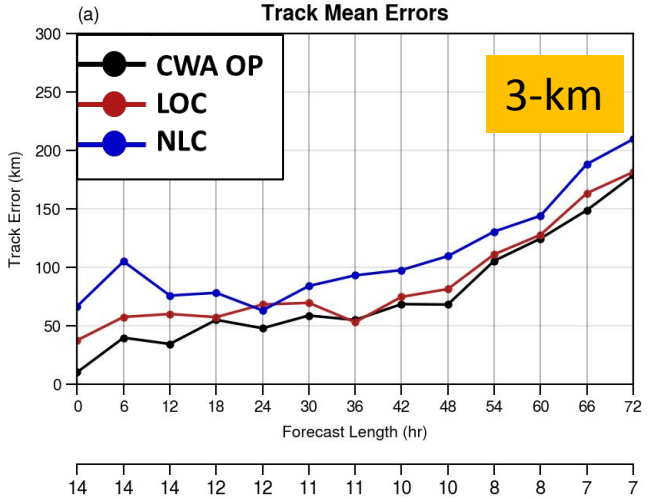

RMSE (forecast verified against ECMWF 0.1 ° analysis)

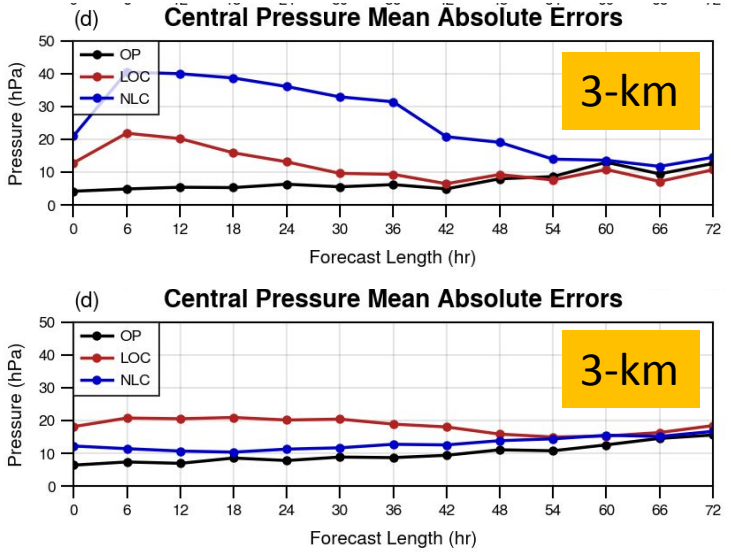


# Typhoon track and intensity Verification

## typhoon DOKSURI



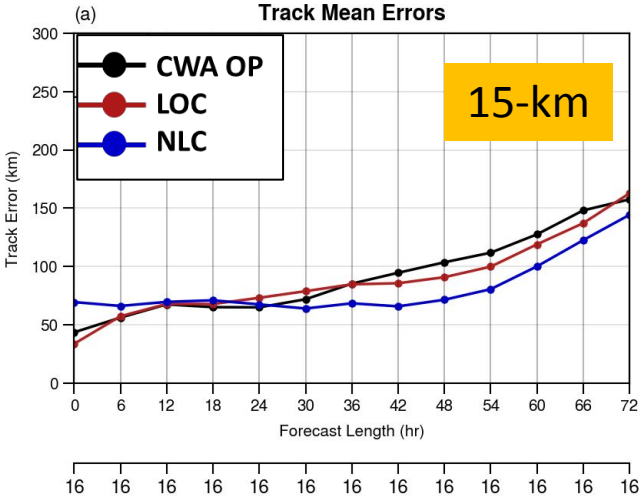



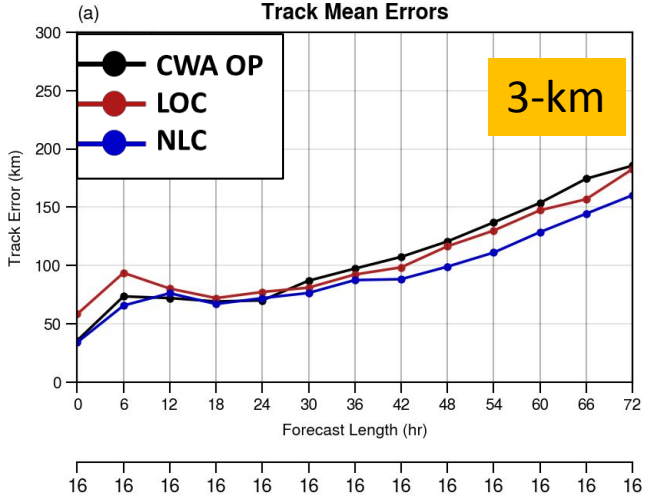

DOKSURI

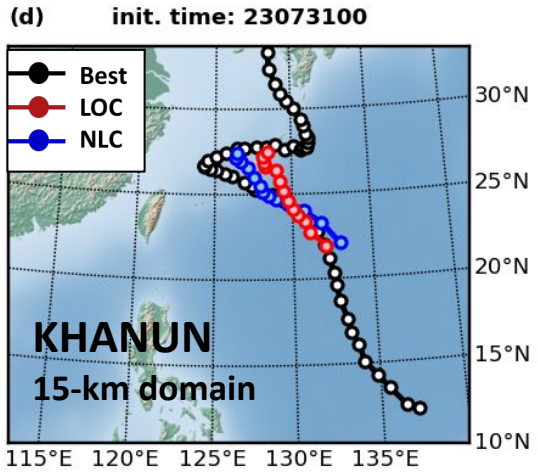
CWA OP
LOC
NLC

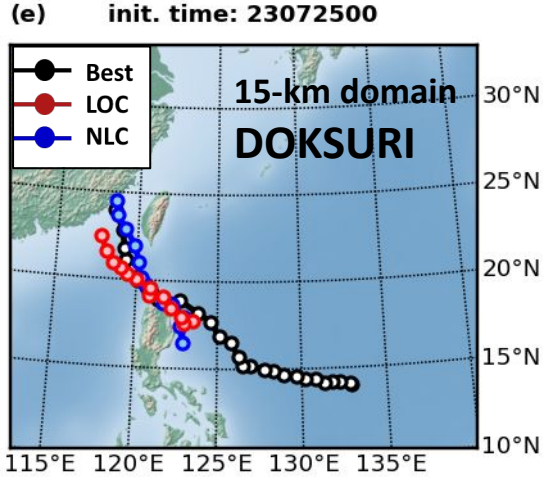
KHANUN

## typhoon KHANUN



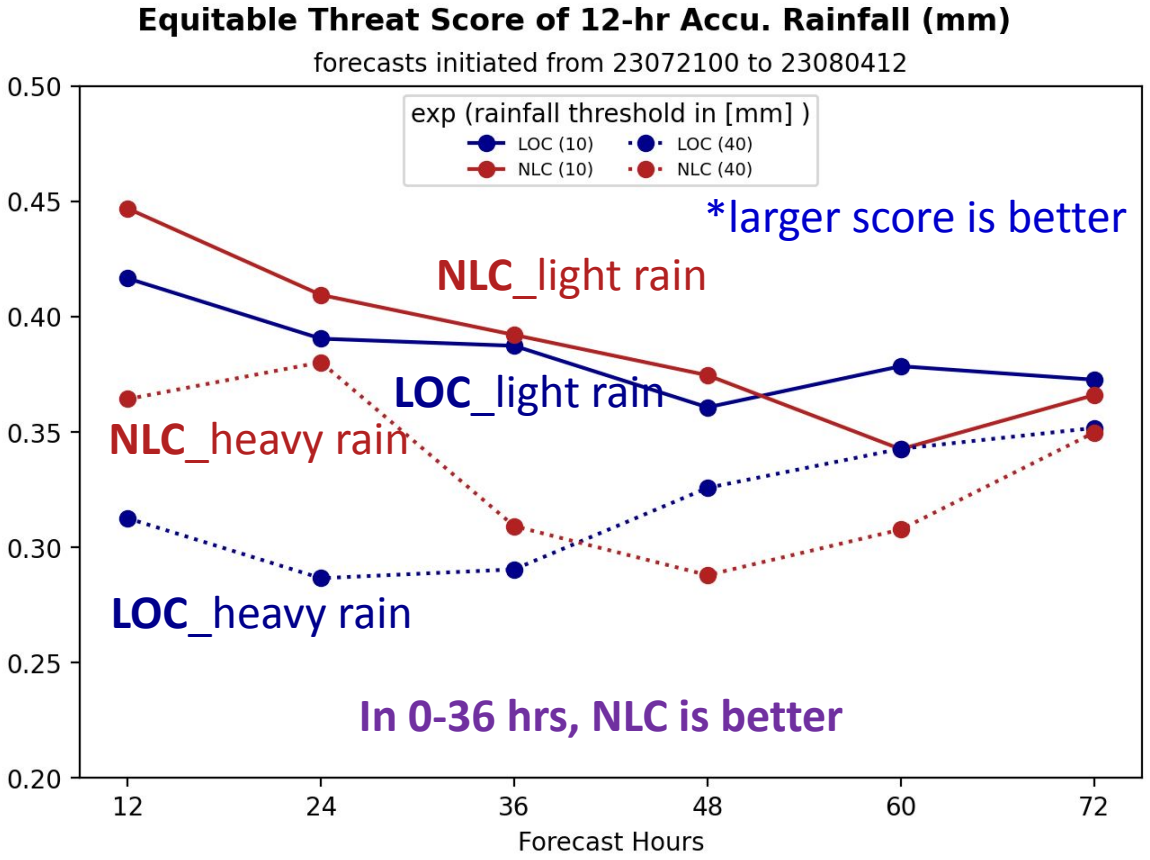



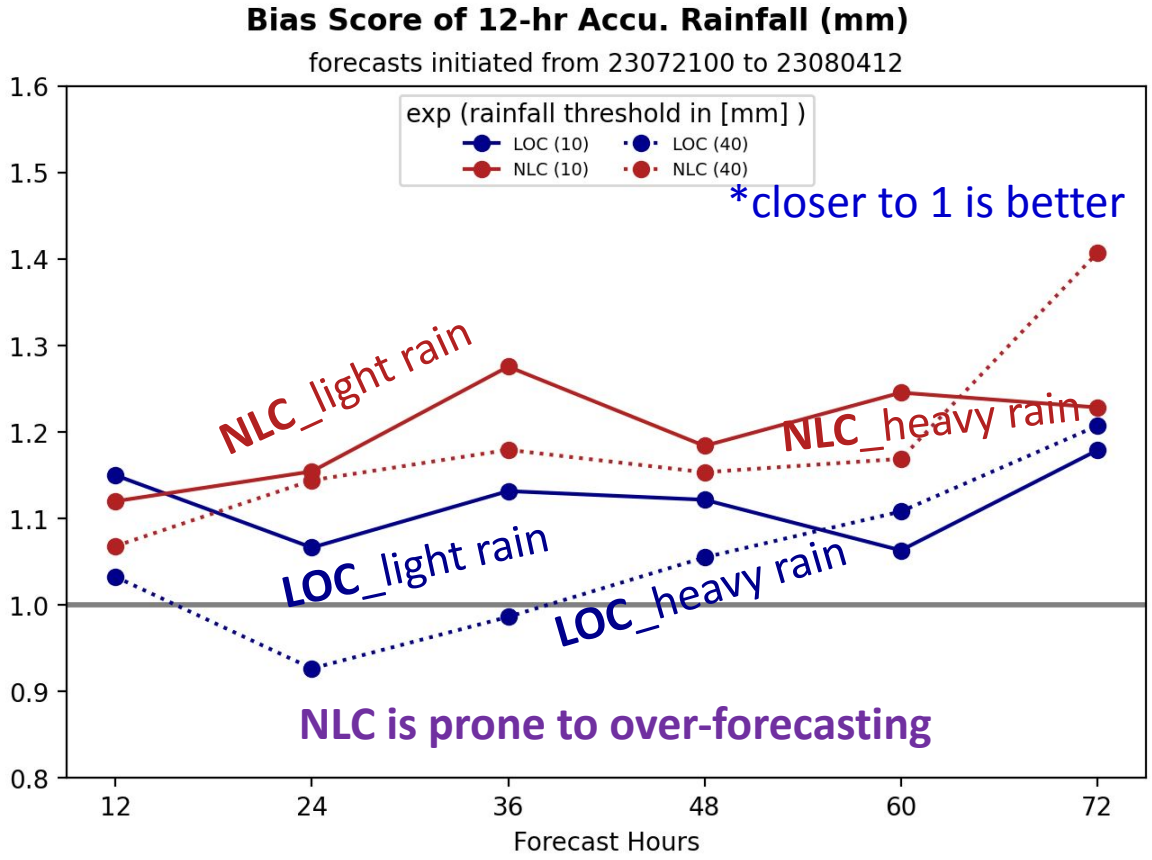



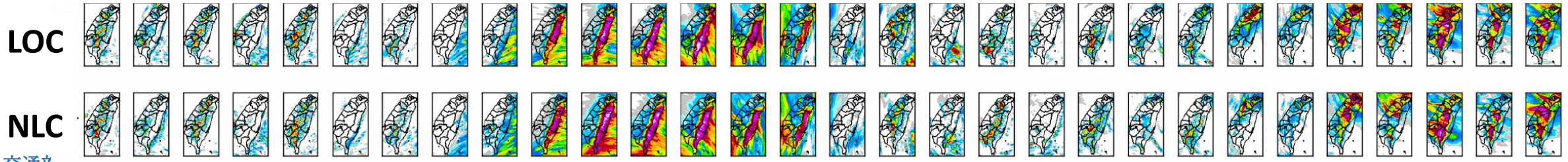



# Precipitation Verification

In 3-km domain



# Summary and Future Work

- FORMOSAT-7/COSMIC-2 RO observations (local refractivity) have been operationally assimilated in the CWAWRF regional NWP system since 2021.
  - It improves the synoptic forecast in geopotential height, temperature, winds and moisture distribution.
  - It also improves the typhoon track and intensity prediction.

- In this study, the nonlocal refractivity operator is investigated with the CWAWRF.
  - This is **the first time** the nonlocal operator for RO assimilation is used in CWA's operational NWP system.
  - Although the domain-wise RMSE of analysis from the nonlocal run is slightly larger than the local run, their differences in forecast (24-72 hours) are insignificant.
  - For typhoon track and intensity forecasts, the results (only for two typhoons) are mixed.
  - For the precipitation forecast, the experiment with the nonlocal operator shows higher ETS in the 0- to 36-hour forecasts, especially for the intermediate precipitation (> 10 mm/12h).
  - The **high computational demand of the nonlocal operator** makes it difficult for operational use: The computational time is ~6 times longer than the local operator.
  - Besides running more cases, **Quality Control (QC)** might also play an important role. We will evaluate the forecast performance under different QC criteria.

# References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