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

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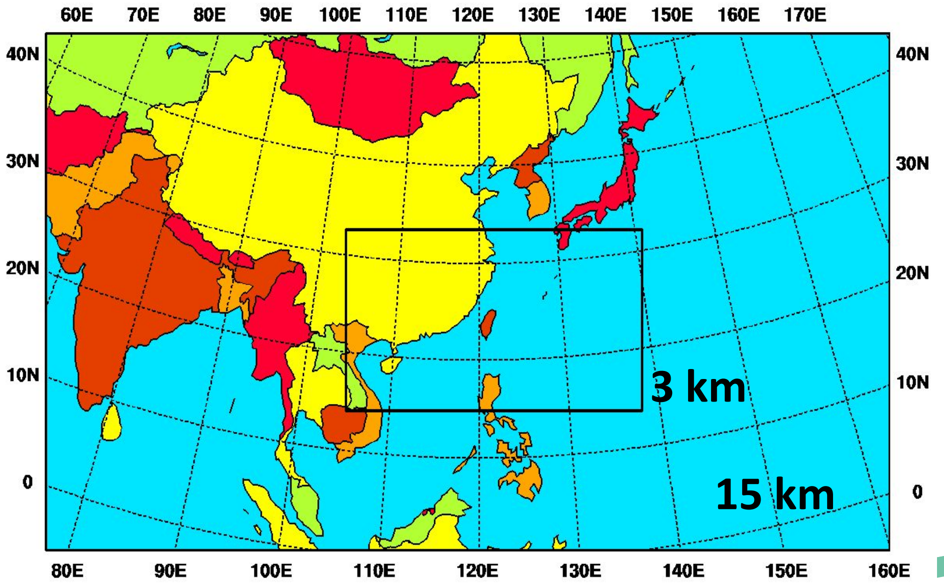
Current Configuration of CWA regional NWP system

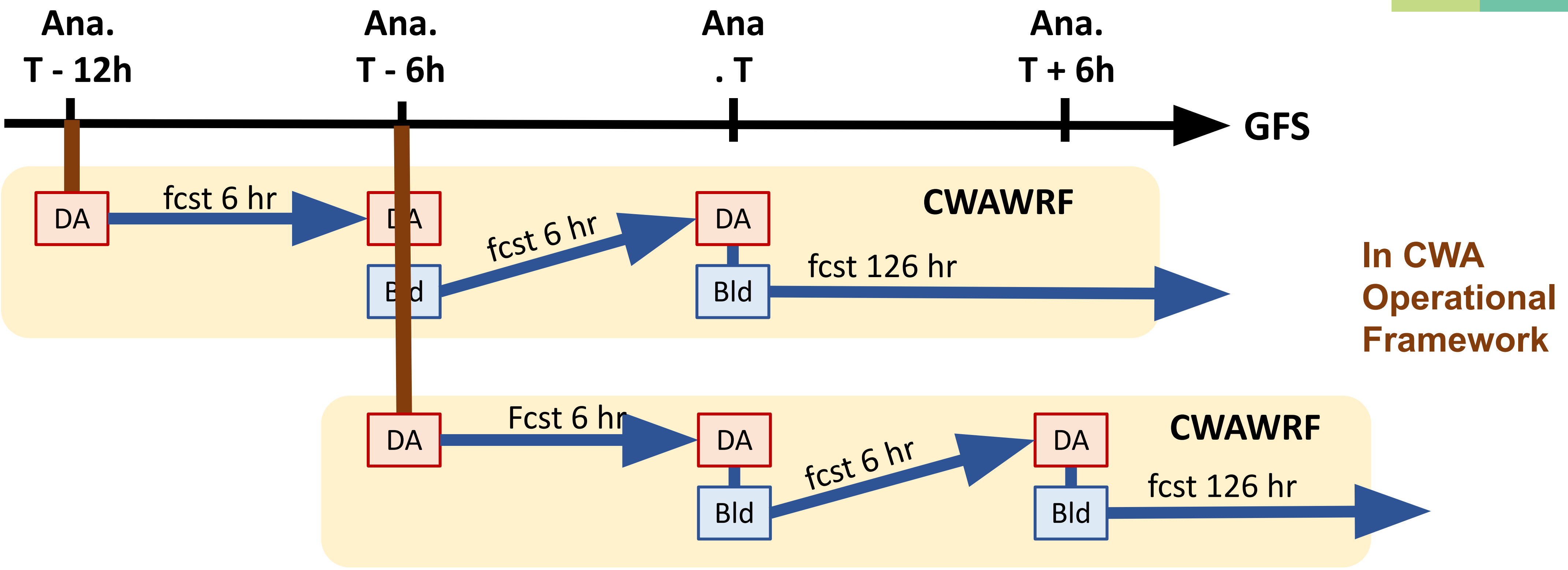
- **CWAWRF, the regional numerical weather prediction system in Central Weather Administration (CWA) of Taiwan**
  - Weather Research & Forecasting (WRF) Model v4.4.2 / WRF Data Assimilation (WRFDA) v3.9.1
  - A parent domain (dx = 15 km) and a nested domain (dx = 3 km).
  - 52 vertical levels and model 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

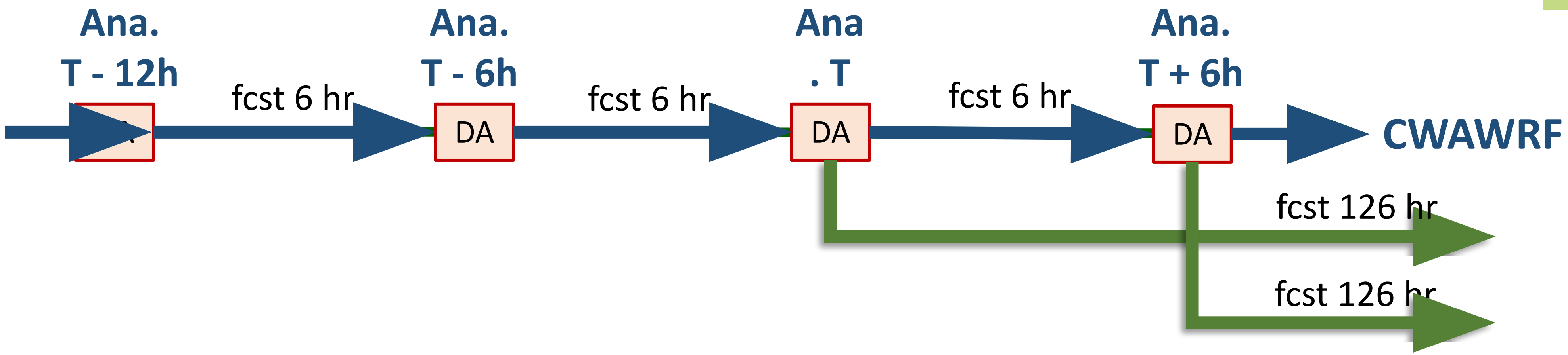


Partial Cycling with Analysis Blending



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

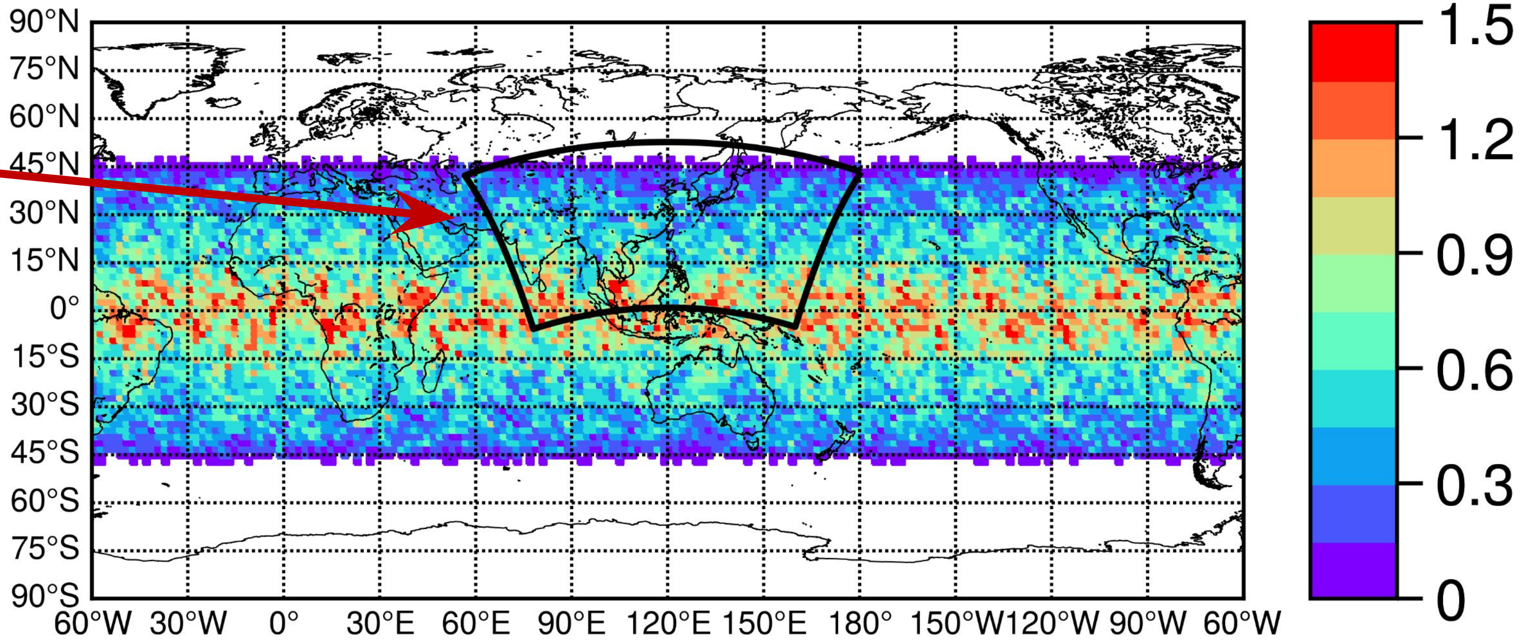
By assimilating the FS7/C2 RO Refractivity data into CWAWRF , several improvements were identified:

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

(Chen et al. 2022)

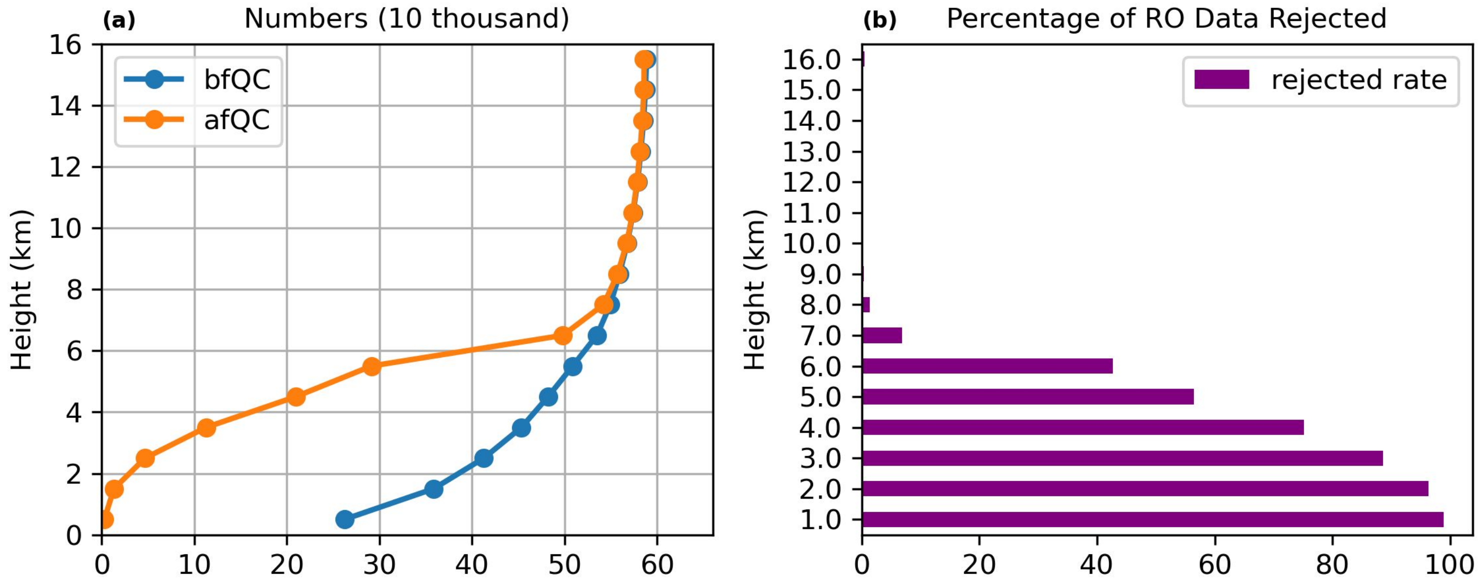
Mean daily FS7/C2 RO profile count in 2x2-degree boxes (15 Aug to 7 Sep 2020)

CWAWRF 15 km-resolution domain



RO Quality Control (QC) and Analysis Increment

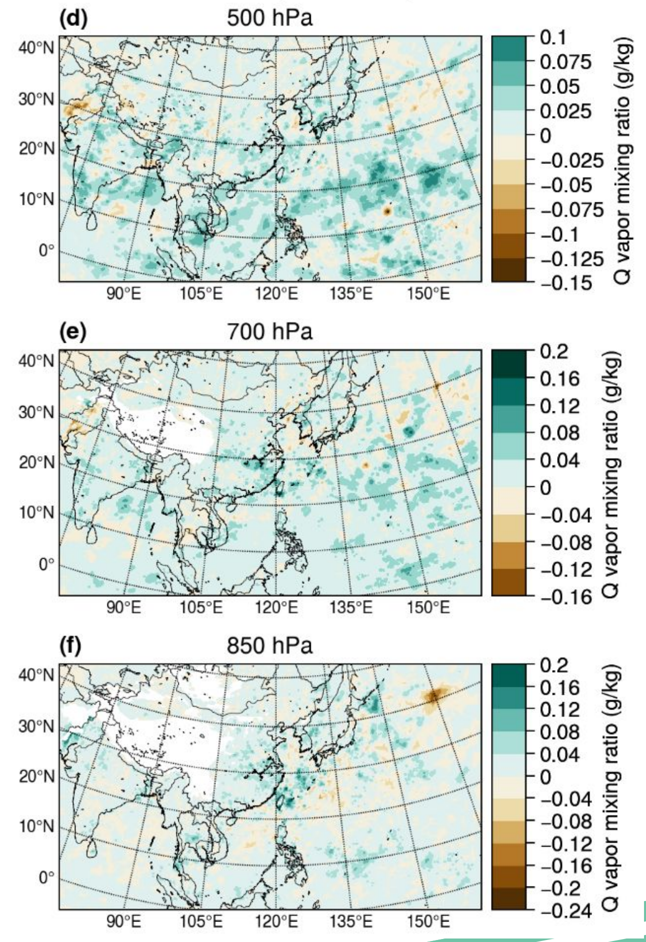
The FS7/C2 RO Data counts in 2020/08/15 12Z ~ 2020/09/07 12Z



*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)

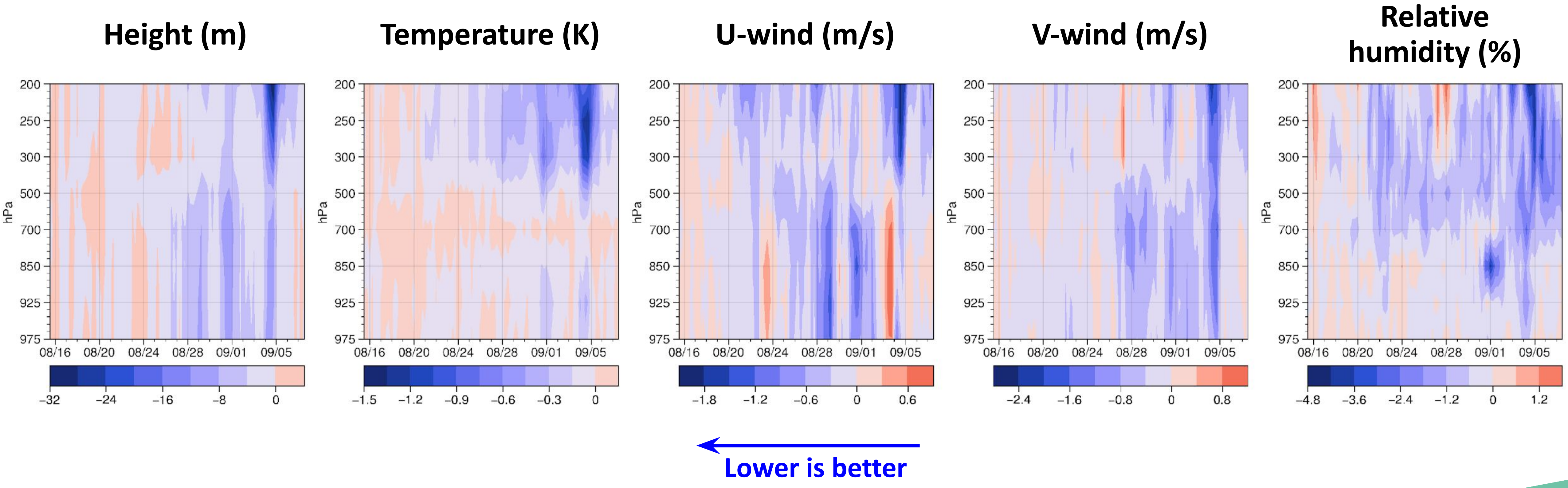


RO Impact on the Synoptic Forecasts

[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)

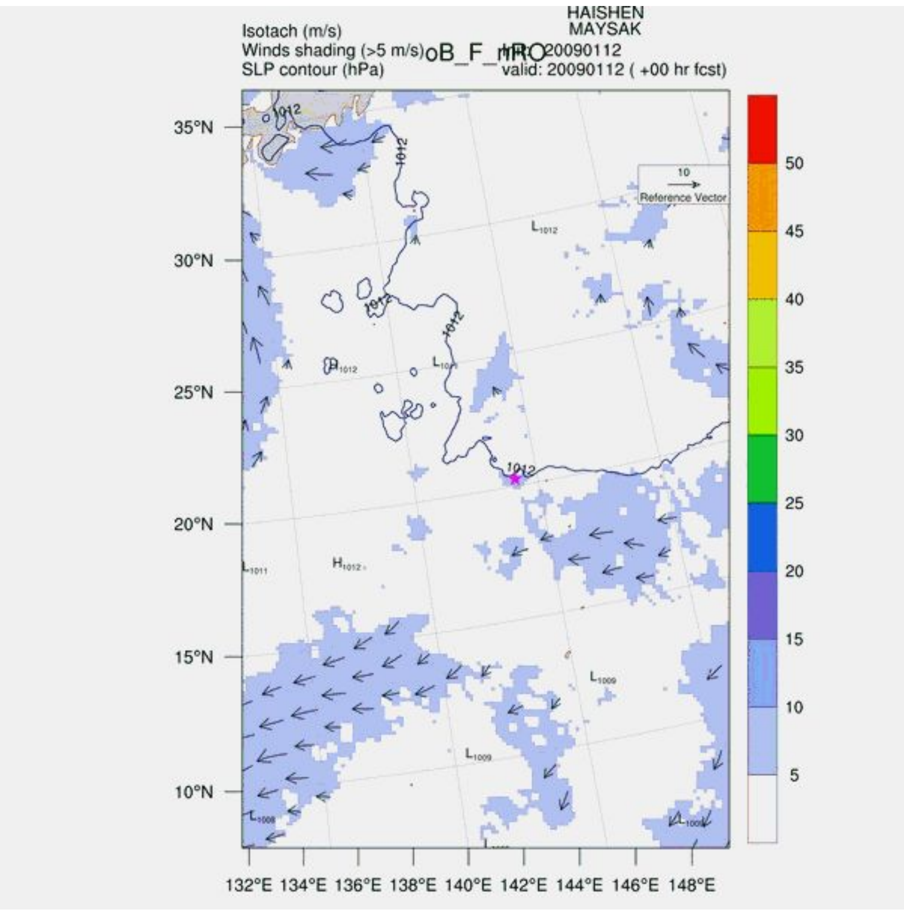


RO Impact on the Typhoon Analysis

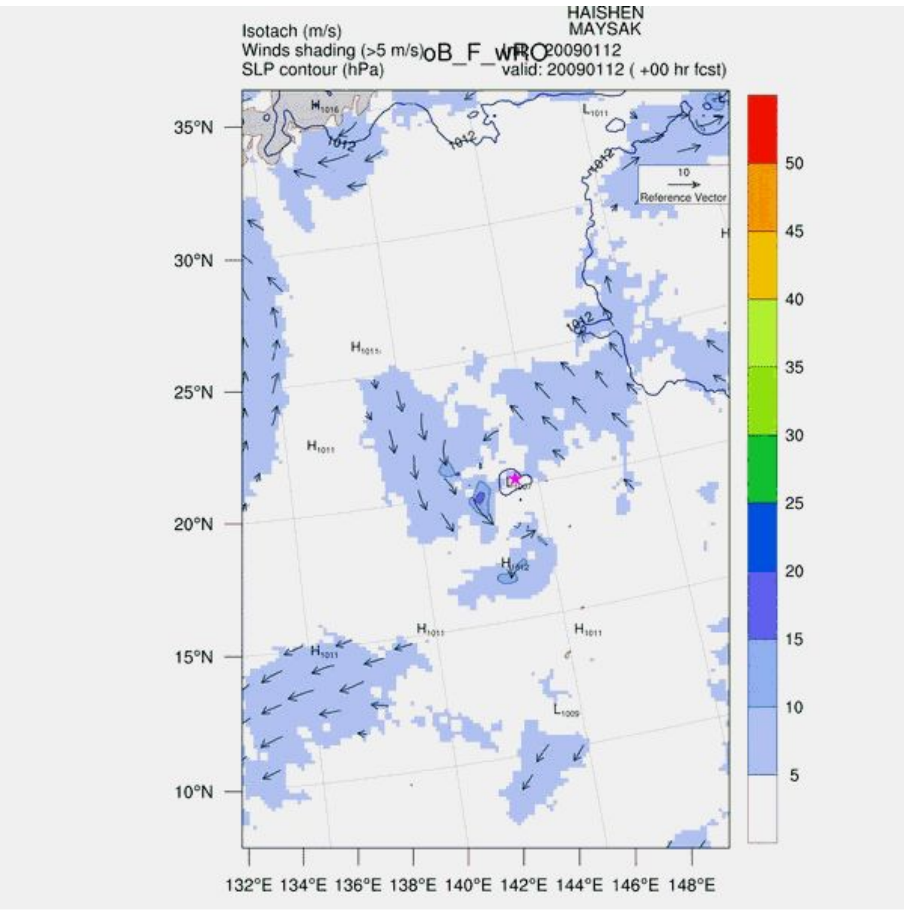
FS7/C2 RO data assimilation helps the regional NWP system to develop a realistic typhoon structure in its analysis (i.e., initial conditions for model forecast).

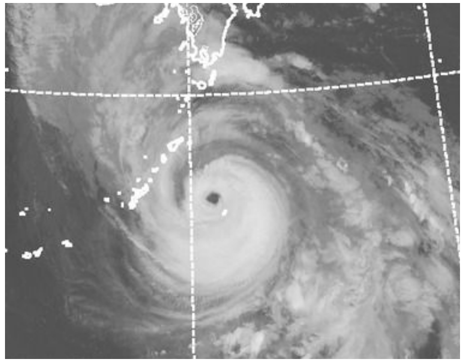
Typhoon Haishen

no_RO



with_RO





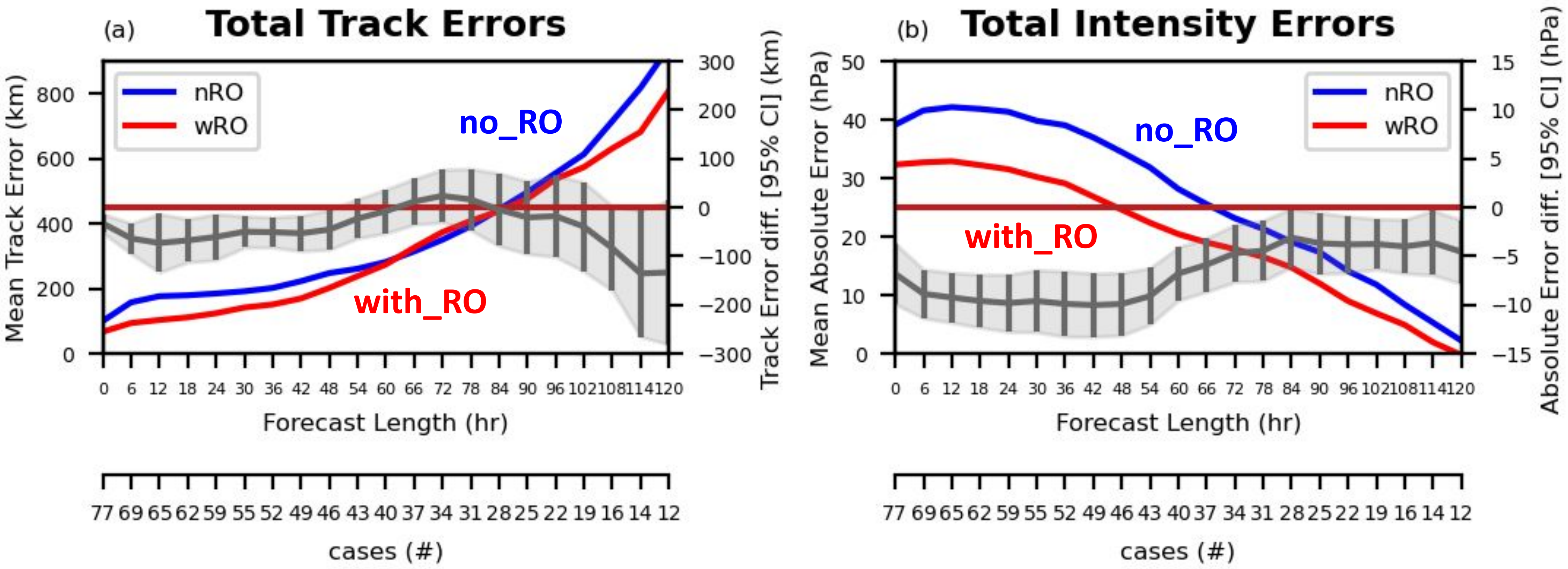
Himawari satellite image of Typhoon Haishen

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

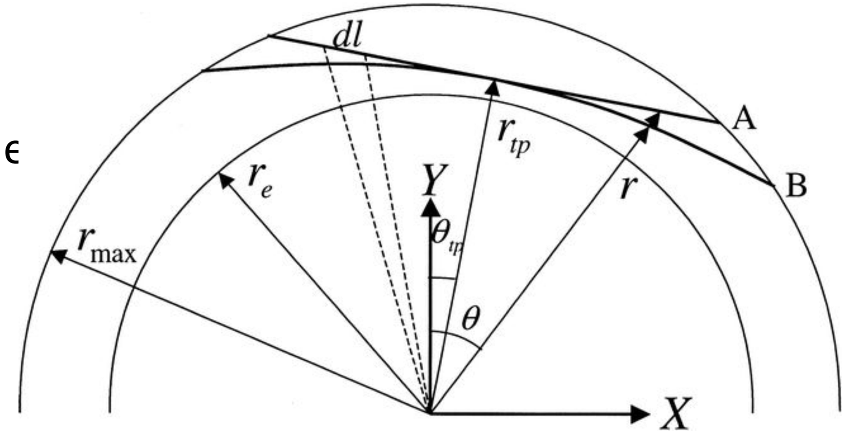
- RO refractivity is **operationally** assimilated in CWAWRF via a **local observation operator** that assumes the RO retrieved refractivity is representative of a local point.

- 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)

pseudo excess phase $S = \int N \, dl$; l 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.

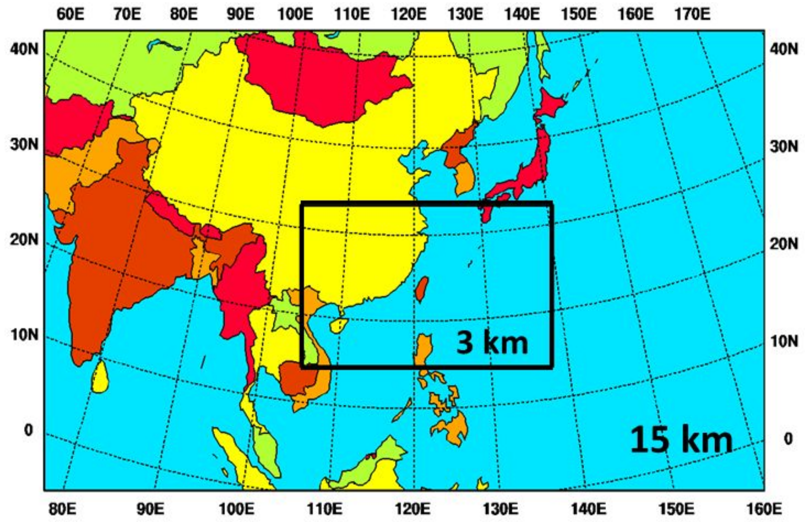
Local vs. Nonlocal RO Observation Operators

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

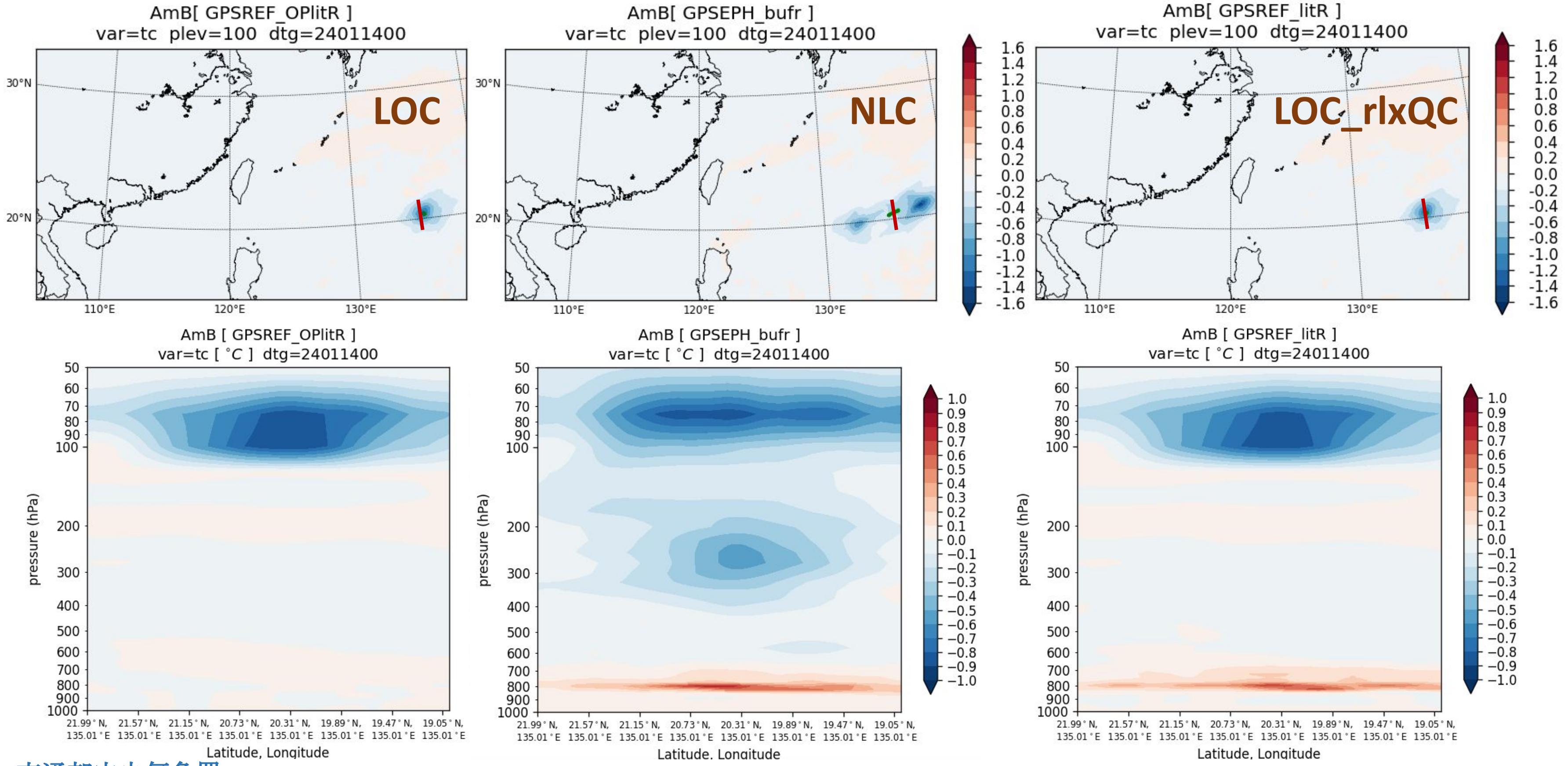
- Continuous cycling (CC) with 5 days spin-up
- Experiment period:
  - 21 Jul 2023 00 UTC to 04 Aug 2023 12 UTC
  - 72-hr forecasts initialized at every 00 UTC and 12 UTC, total 30 forecast cases
  - Assimilated observations: The same as the operational regional NWP system in CWA



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

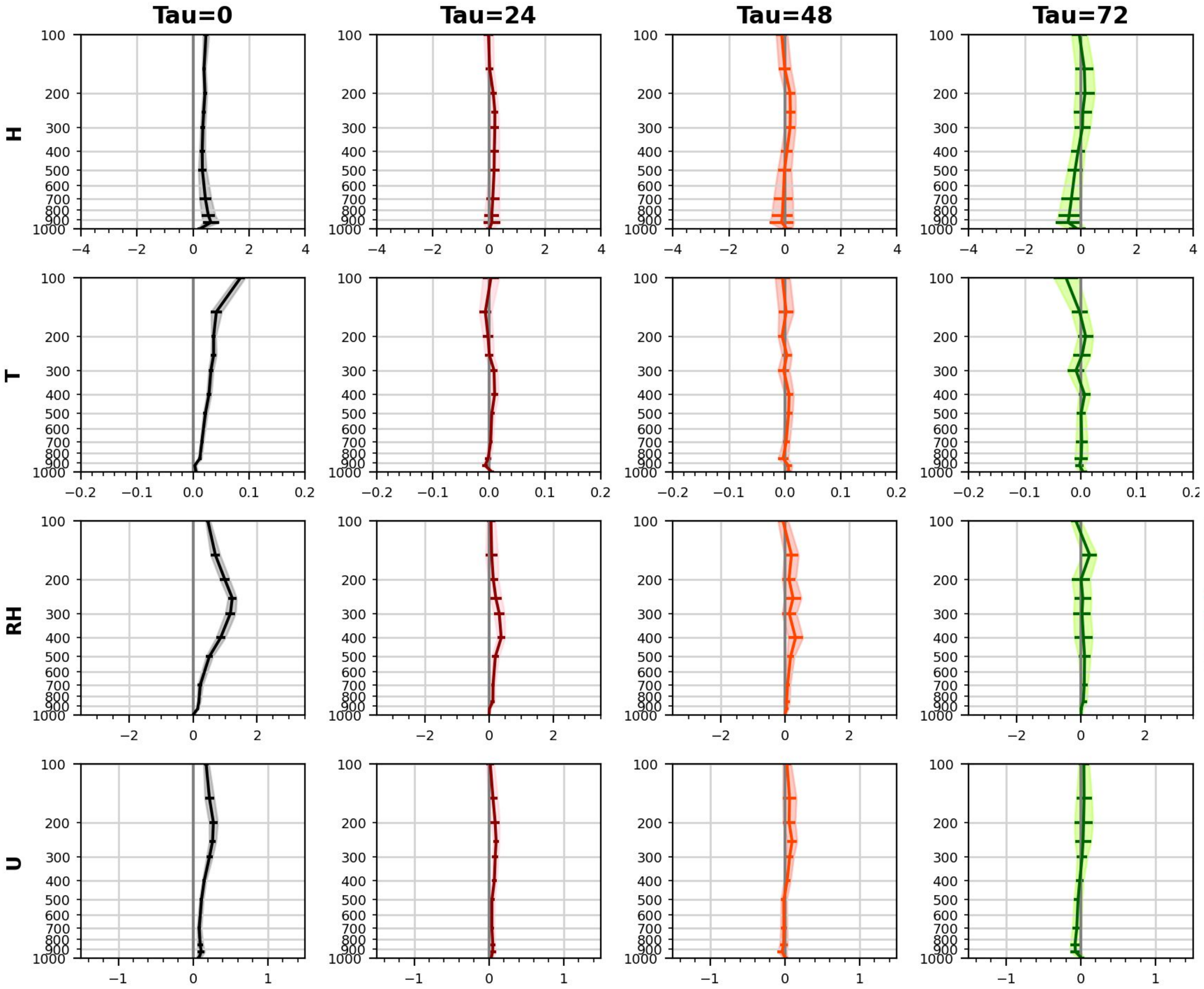
*gross error check, qc_dndz, qc_dndz2, qc_pcnt



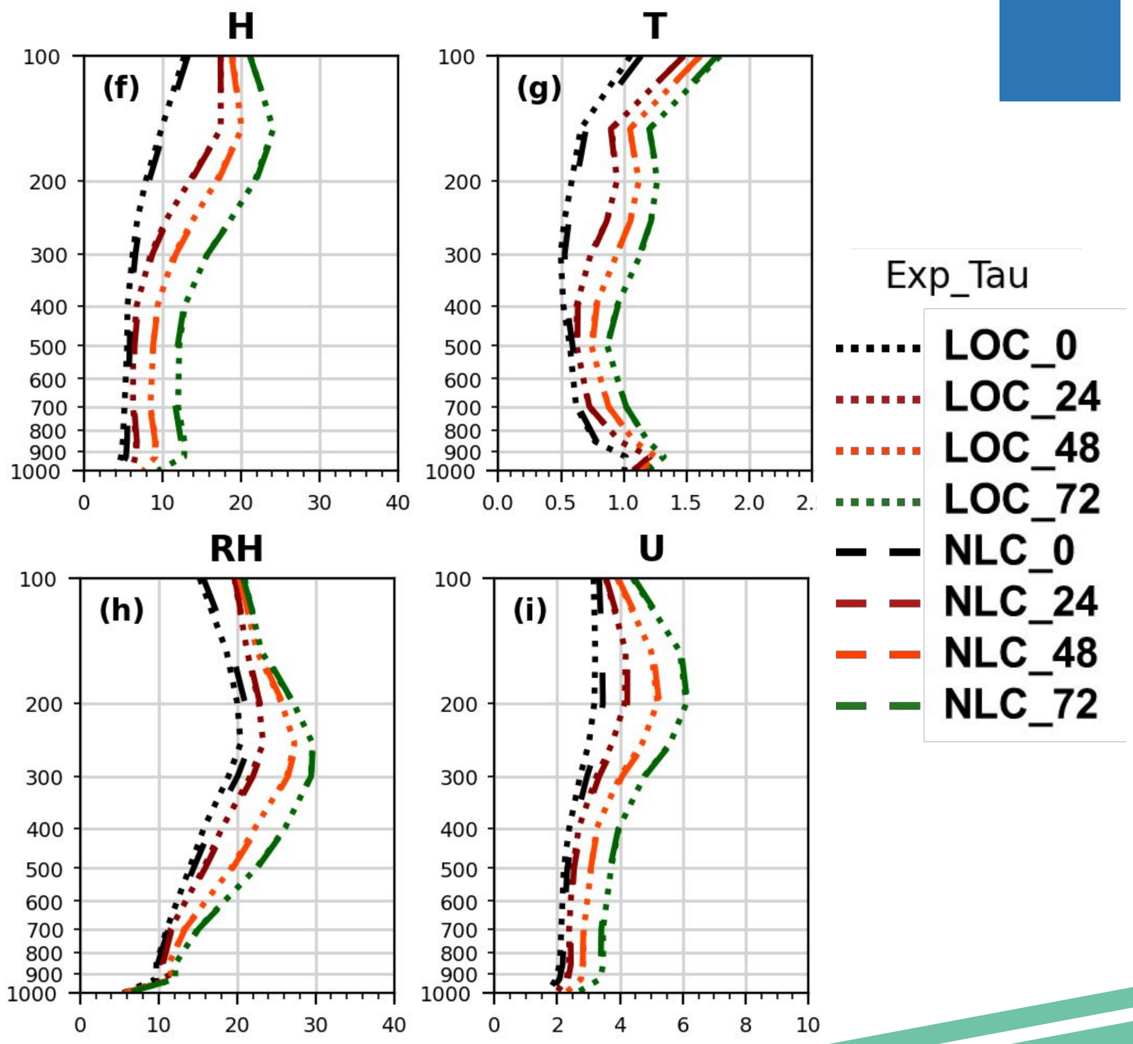
- Upper: The analysis increments of single refractivity data with different FS7/C2 data types and operators.
- Lower: Same as above, but for the cross section along longitude 135° E.
- The RO QC in CWA OP is stricter.
- The analysis increments of NLC are more elliptical.

Domain-averaged Verification (15-km domain)

23072100 ~ 23080412 WD01 Exp[NLC] – Exp[LOC] RMSE differences with CI=95

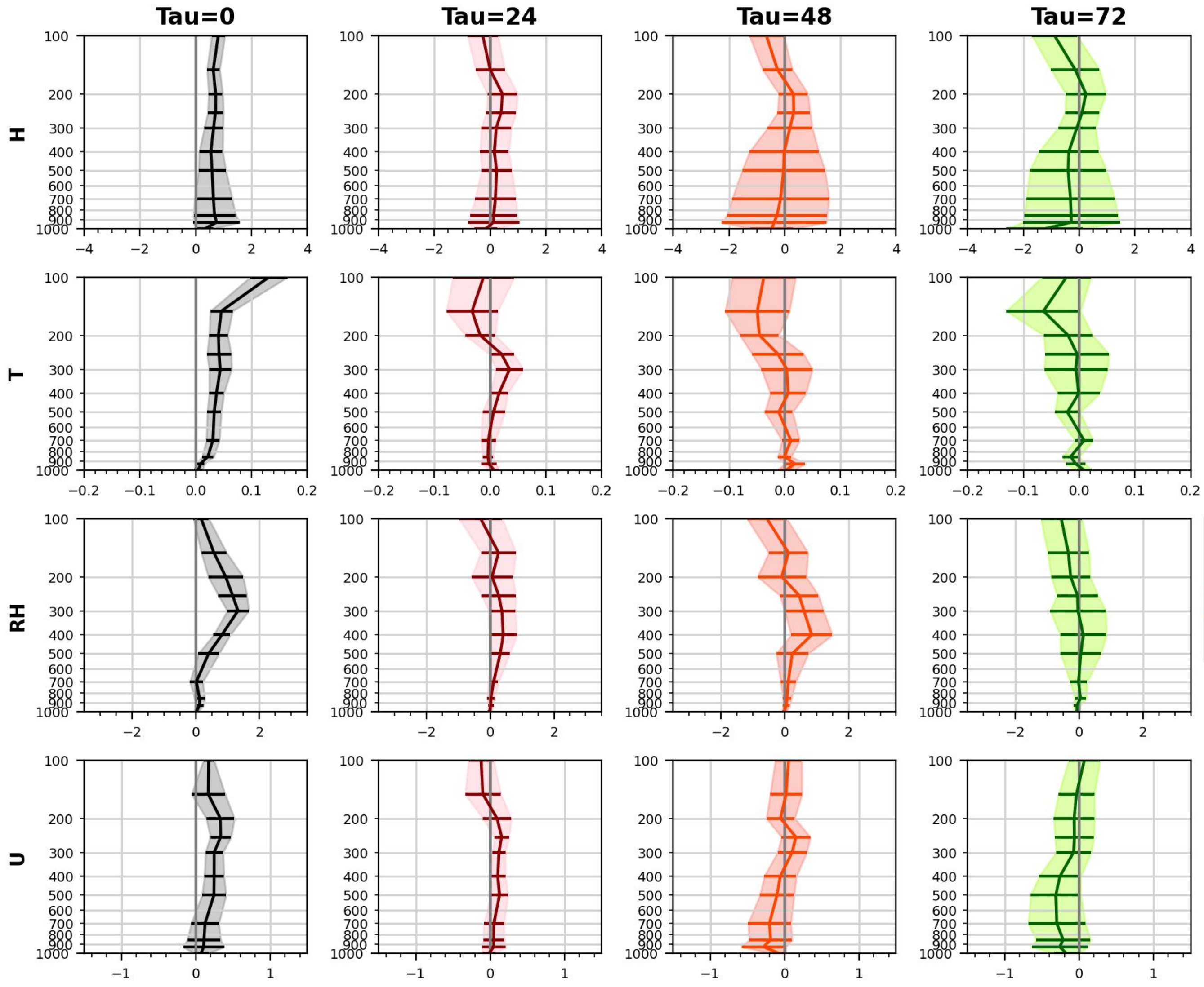


RMSE (forecast verified against ECMWF 0.1 ° analysis)

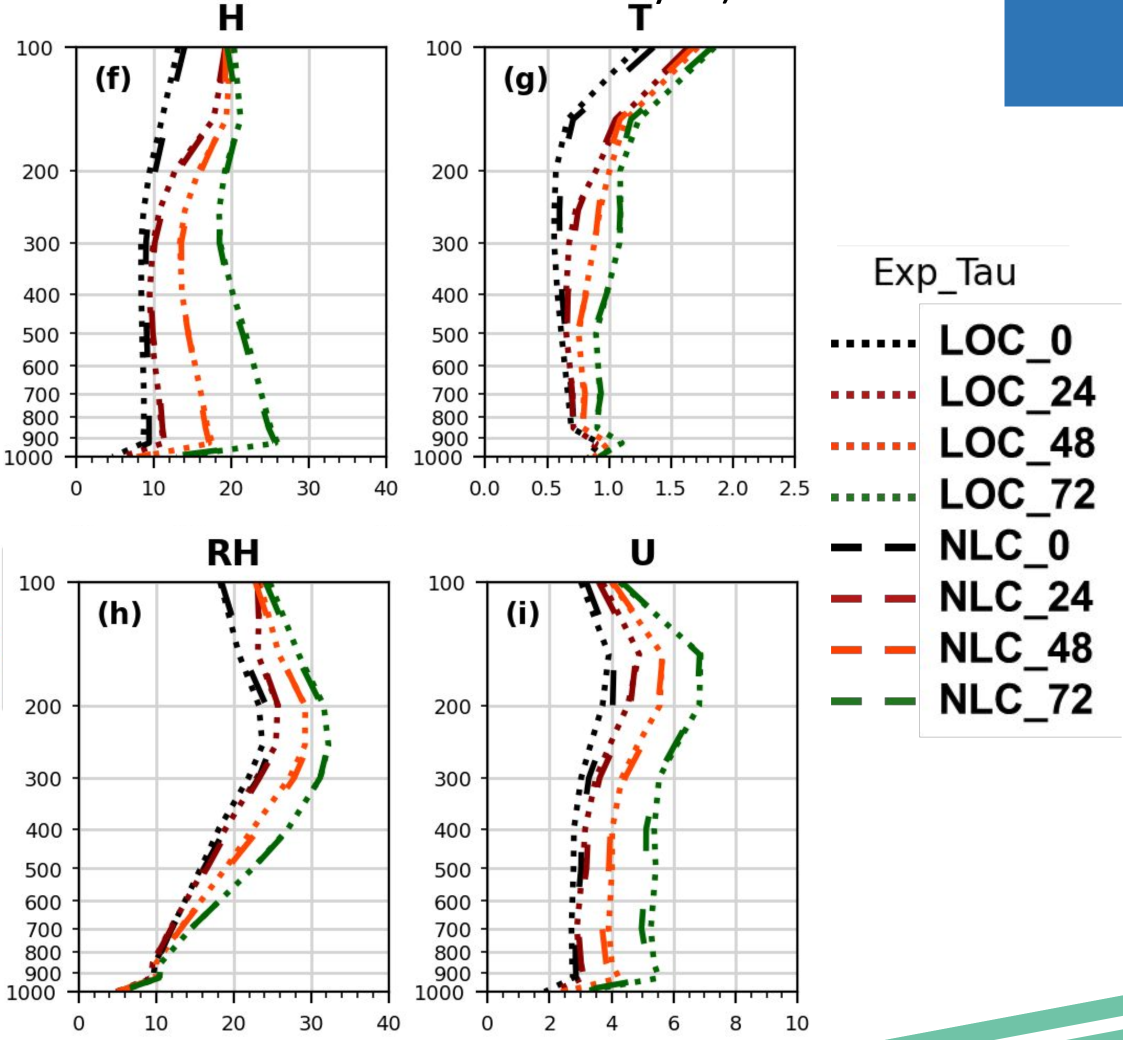


Domain-averaged Verification (3-km domain)

23072100 ~ 23080412 WD02 Exp[NLC] – Exp[LOC] RMSE differences with CI=95

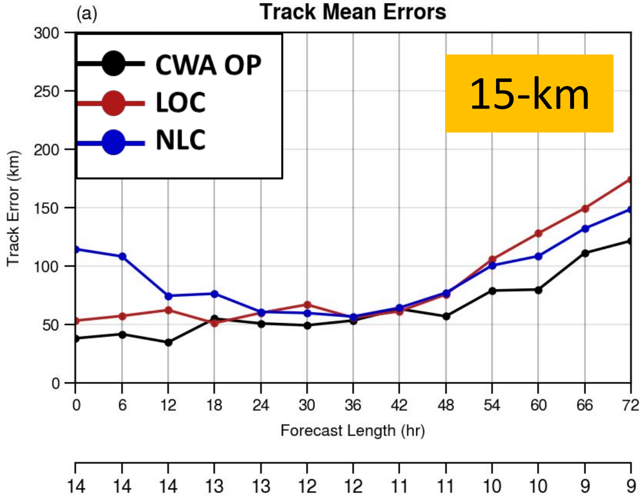


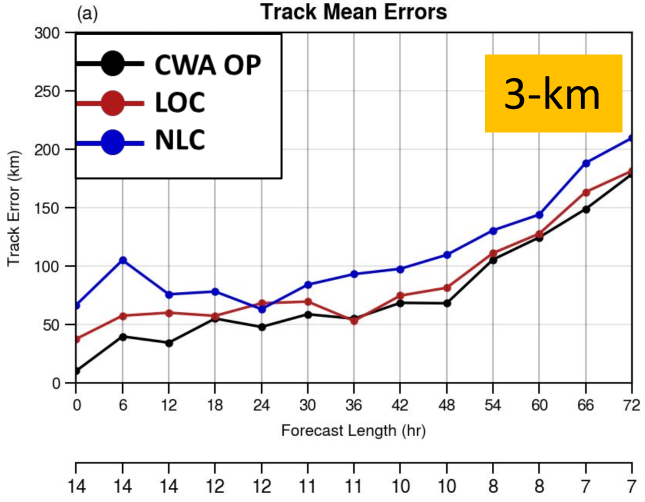
RMSE (forecast verified against ECMWF 0.1 ° analysis)

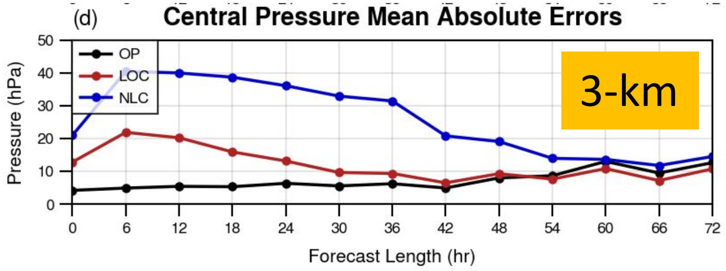


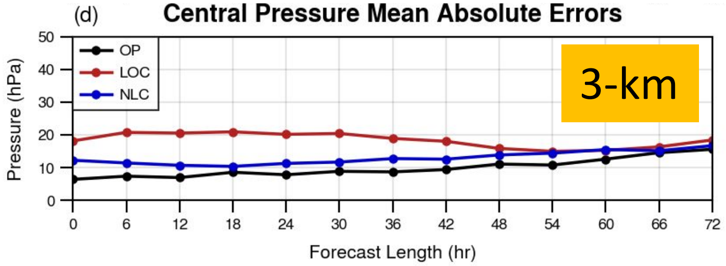
Typhoon track and intensity Verification

typhoon DOKSURI







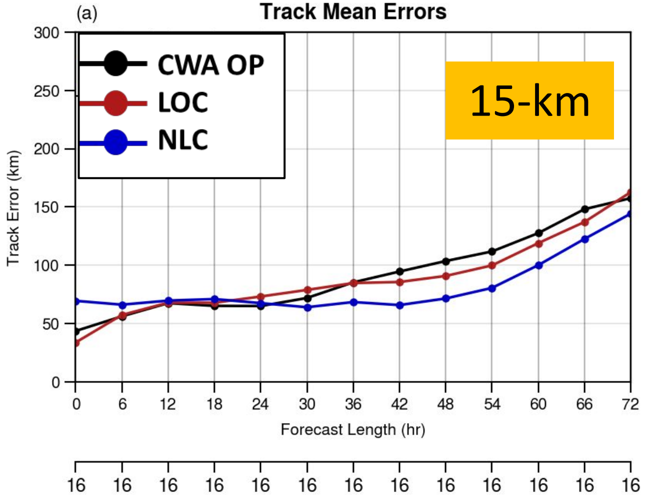


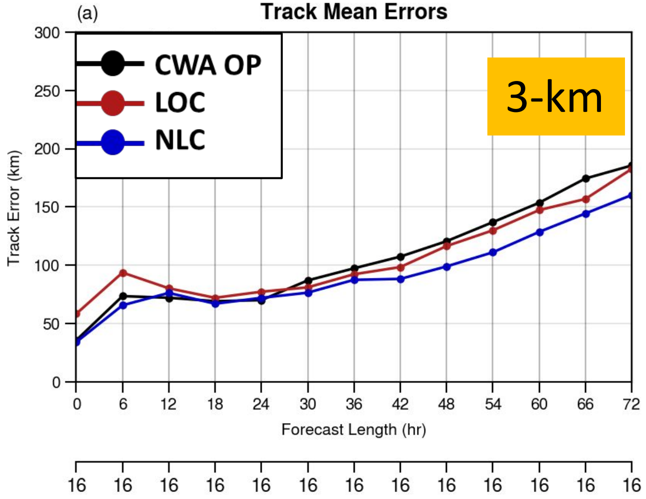
DOKSURI

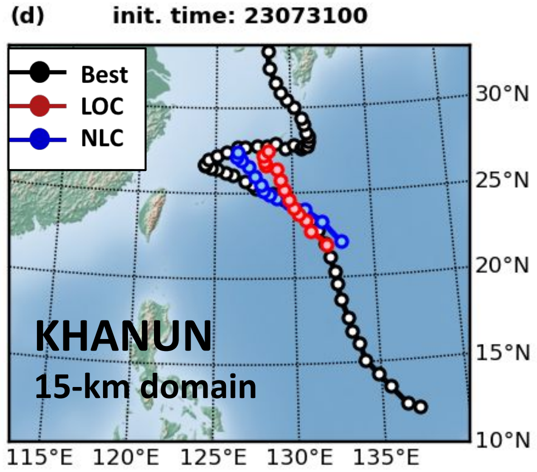
CWA OP
LOC
NLC

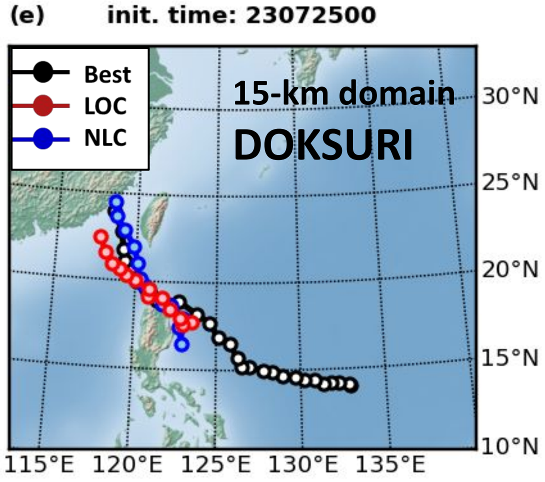
KHANUN

typhoon KHANUN



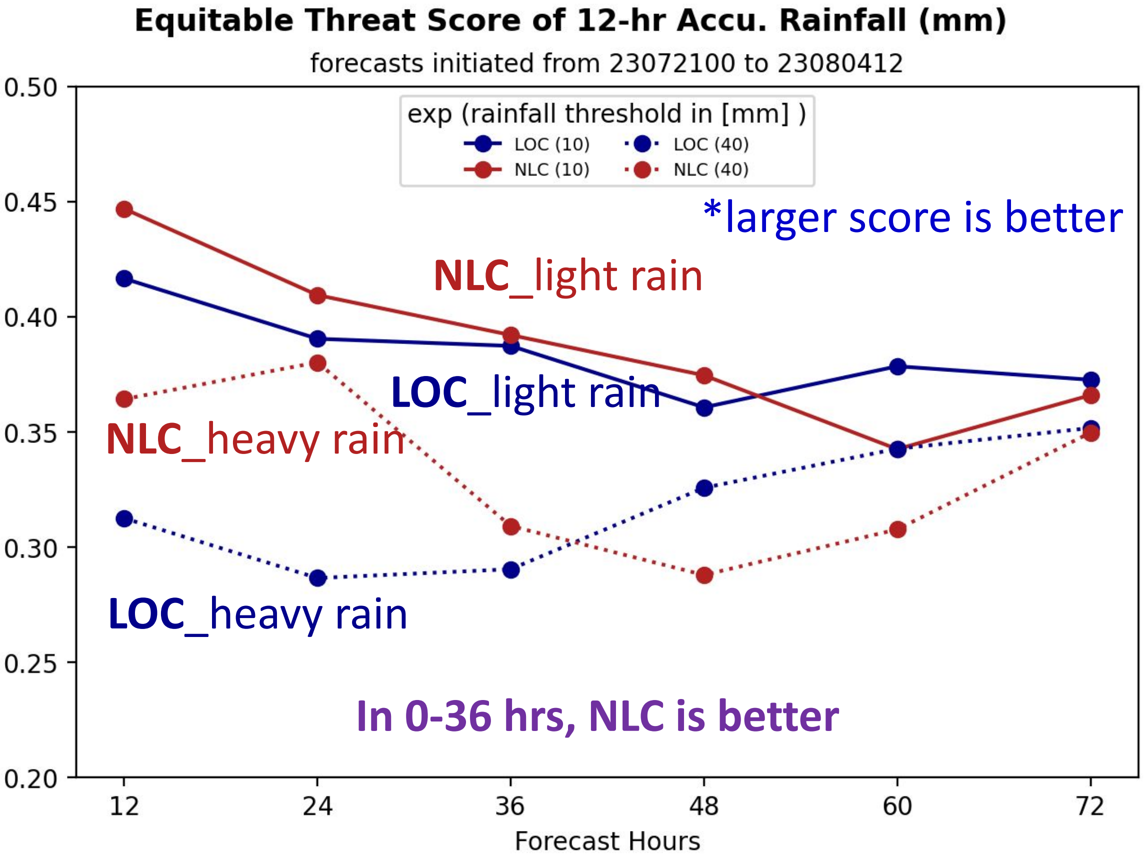


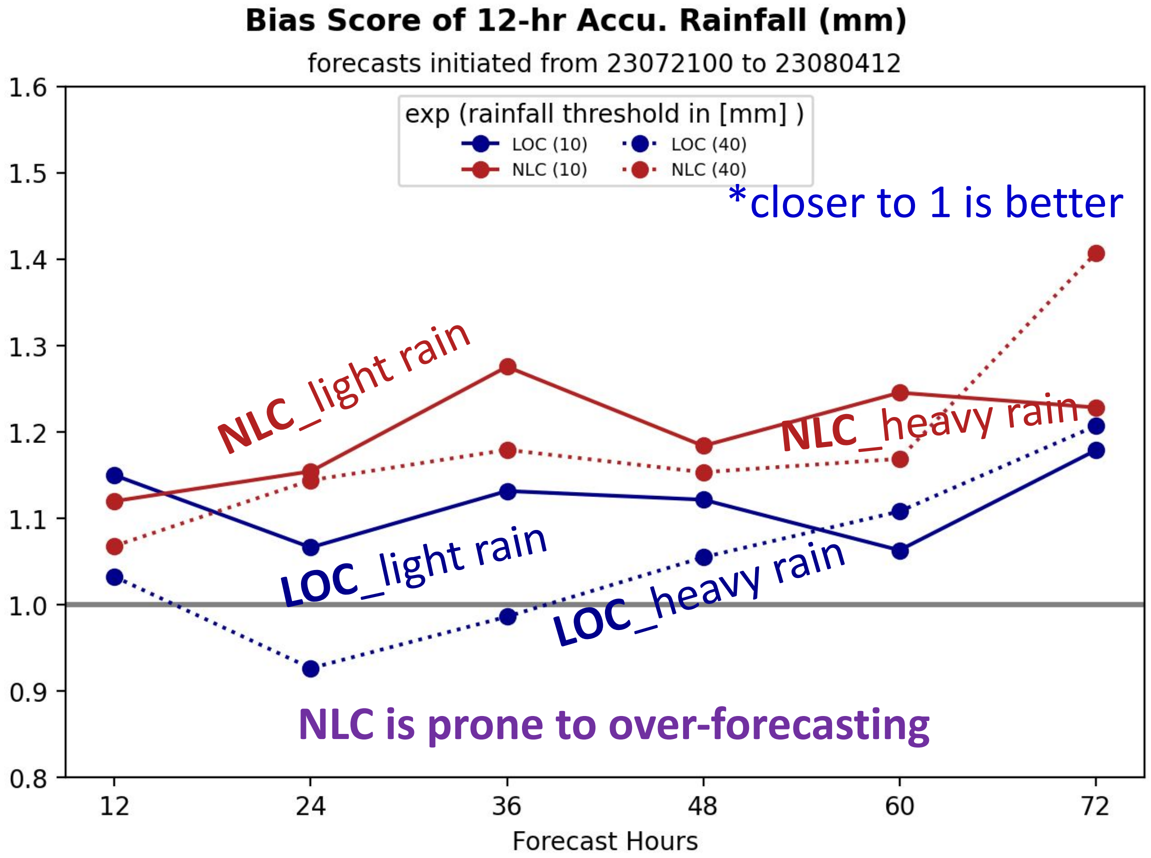




Precipitation Verification

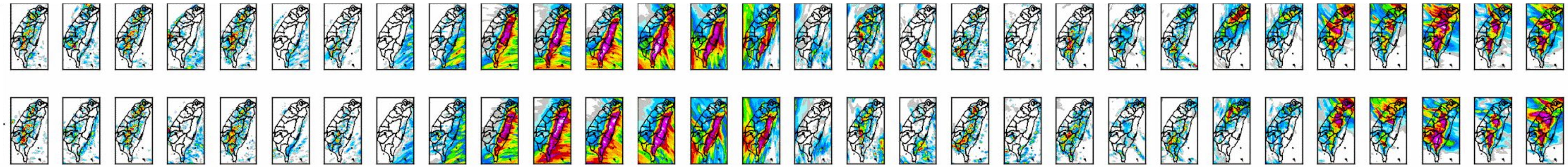
In 3-km domain





LOC

NLC



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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