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Recent progress in GNSS-RO satellite data assimilation at the Korean Integrated Model (KIM)

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1. Background

- We have been steadily promoting the use of the new GNSS-RO satellite data for **Korean Integrated Model (KIM)**.
  - KIM was developed by Korea Institute of Atmospheric Prediction Systems (KIAPS) for about 9 years(2011-2019) and KMA started operating in April 2020.
  - Addition of three new GNSS-RO data in 2023 improved upper-temperature and consequential error reduction in long-term predictions.
    But, resulted in geopotential height degradation in southern hemisphere mid- and upper levels.

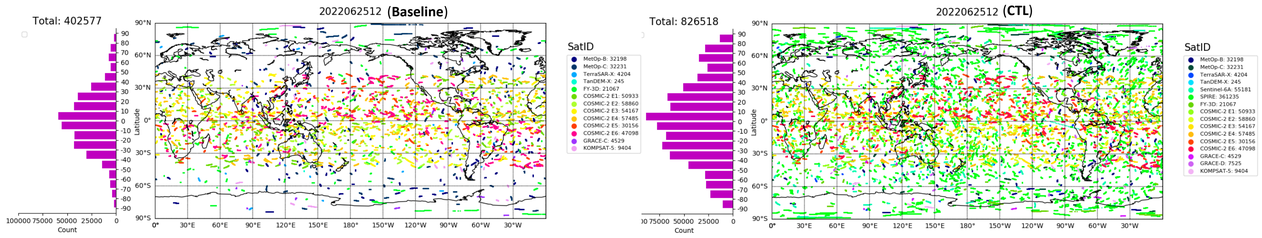
2015	2020(OP~)	2021	2022	2023	2024(ing)
MetOp-A/B/C	KOMPSAT-5	COSMIC-2	GRACE-C	Sentinel-6A	Spire
COSMIC-1	FY-3C/D			Spire	(NOAA)
TerraSAR-X				(EUMETSAT)	
TanDEM-X				GRACE-D	

< New GNSS RO of Korean Integrated Model >

- In order to improve the forecast performance of the middle and lower levels of the atmosphere, experiments were conducted to adjust the observation error of GNSS-RO data and its effect was analyzed.

2. Data

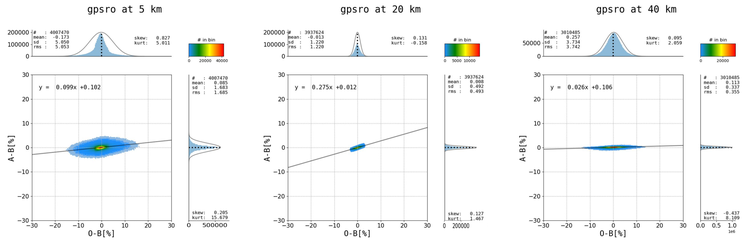
- Three new GNSS-RO(Sentinel-6A, Spire, GRACE-D)
  - The new of GNSS-RO data in the first time of the experiment contributed significantly to the resolution of observation gaps in high-latitude (especially the Ocean, South and North Pole).
  - With the addition of new data, **the data has doubled** compared to the previous data and is evenly distributed across the world.



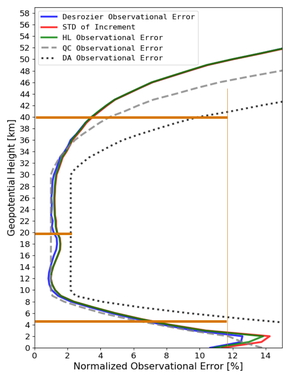
< Distribution of the pre-processed GNSS-RO observation locations at the first time of cycle (left) before and (right) after adding new data >

3. Methods

- Fraction of observation error → Observation impact with O-B and A-B → **slope** of a linear regression equation
  - Core region(20km): GNSS-RO observations have a significant impact (slope: 0.275)
  - Upper(40km): Very large observation error, so little impact from observation (slope: 0.026)
  - Lower(5km): Observation error is large, but the impact of observation is so large (slope: 0.099)



Observation impact is approximately 4 times greater at 5 km than at 40 km using similar obs. error
☞ **Doubles fraction of observation error** to reduce observation impact **under 10km**

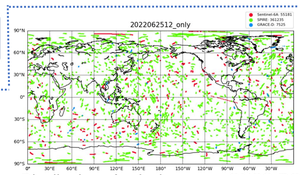


<Observation error of GNSS-RO>

✓ The dotted line represents the observation error of the GNSS-RO applied to data assimilation in KIM, and the normalized observation error is similar at 5 km and 40 km.

- Inflation factor of observation error
  - Adjust observation error based on cost function of observation
    - Reference: A study on improvement of the observation error for optimal utilization of COSMIC-2 GNSS-RO data [KMS, Atmosphere, 33(1), 2023]

Increased observation error to reduce observation impact across levels
☞ **Doubles inflation factor of observation error** to reduce observation impact of **entire atmospheric levels**



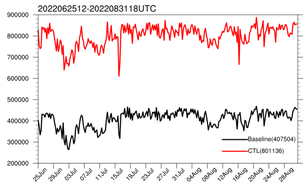
< Distribution of only three new GNSS-RO >

✓ New data is evenly distributed across world and has significantly more Spire

- Experiment design
  - Model: KIM(v3.8), Add three new GNSS-RO and adjust observation errors
  - Period: 2022.06.25.~08.31.(Verification: 2022.07~08., two months)
  - Validation method: Comparison with ECMWF **IFS analysis** fields

Name of EXP.	New GNSS-RO	Description(Inflation factor, Error fraction of lowest level)
Baseline	X	2.2, 20%
CTL	O	2.2, 20%
EXP_zfrac		2.2, **40%**
EXP_obserr		**3.1**, 20% (Consideration of doubling the data: 2.2×√2=3.1)

$$RMSE_{EXPs} = \sqrt{\frac{(EXPs - IFS)^2}{N}} \qquad \text{Improvement Rate} = \frac{RMSE_{Baseline} - RMSE_{EXPs}}{RMSE_{Baseline}} \times 100 \qquad Z = \frac{\bar{X} - \mu}{\sigma/\sqrt{n}}$$

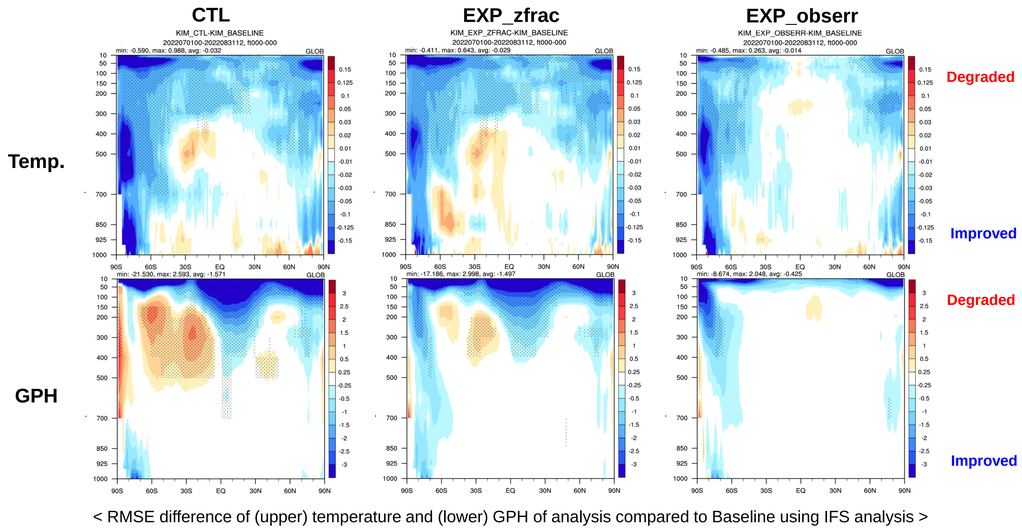


< Number of GNSS-RO >

✓ The number of new data is about twice as large as before

4. Results

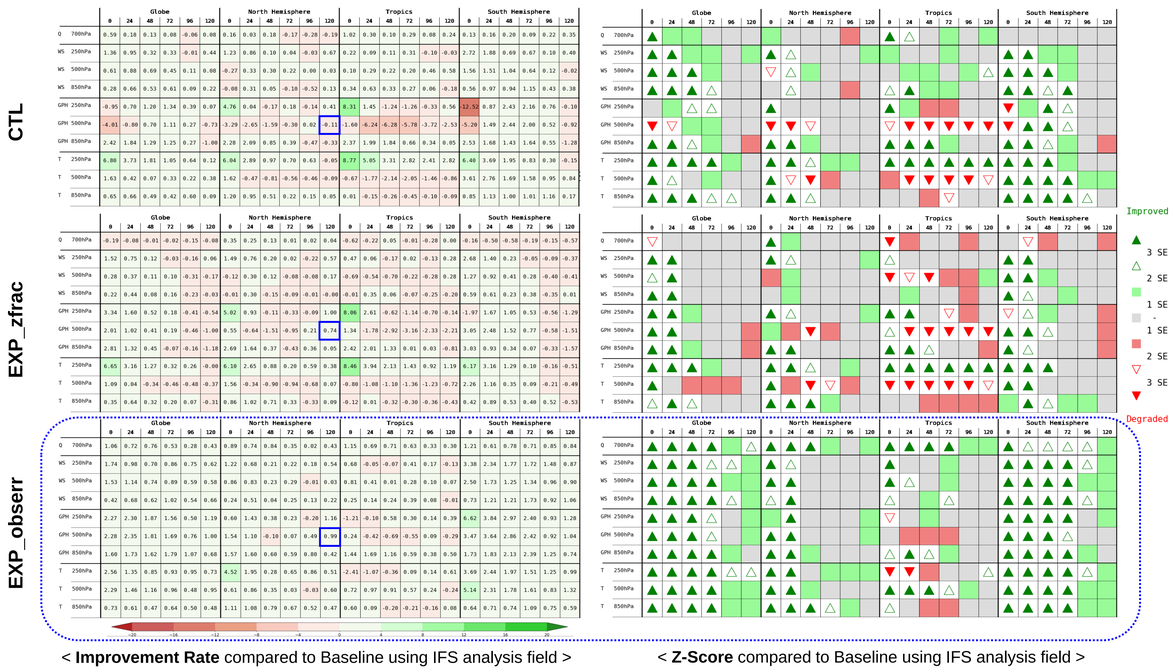
- Evaluation of **analysis performance** compared to Baseline
  - **T**
    - (CTL) Degradation in the middle layers of the southern hemisphere (SH) and lower layers except Antarctica
    - (EXP_zfrac) Improvement in the lower layers of the northern hemisphere, degradation in the mid- and lower layers of the SH
    - (EXP_obserr) Improvement in most areas except the tropics upper layer
  - **GPH**
    - CTL, EXP_zfrac, and EXP_obserr experiments improve the performance of the areas over the SH



< RMSE difference of (upper) temperature and (lower) GPH of analysis compared to Baseline using IFS analysis >

EXP_zfrac has lower temperature performance compared to CTL, but geopotential height is improved
EXP_obserr has lower tropics upper temperature performance compared to CTL, but overall geopotential height is improved

- Evaluation of **forecast performance** compared to Baseline
  - The degraded performance of the mid-layers geopotential height in the CTL is the weakest in the EXP_obserr.
  - The EXP_zfrac with twice fraction of the error applied only to less than 10km altitude is similar in high layer compared to CTL, but 850-500hPa temperature degradation is noticeable in the tropics.
  - Increasing the observation error across all layers leads to a decrease in upper layer temperature performance compared to the CTL, but results in an overall improvement in prediction accuracy.



< **Improvement Rate** compared to Baseline using IFS analysis field >

< **Z-Score** compared to Baseline using IFS analysis field >

Northern Hemisphere 500hPa 5-day forecast GPH improvement rate(%): (CTL) -0.11, (EXP_zfrac) 0.74, **(EXP_obserr) 0.99**
RMSE improvement rate shows a **significance** of 3 sigma levels until **72 hours** prediction
☞ **Results of EXP_obserr show the most improved forecast performance**

5. Conclusion

- Conducted an impact assessment on the adjustment of GNSS-RO observation errors
  - Observation error adjustment reduces the rate of temperature prediction improvement, decreases the negative effect of GPH
  - Improved model prediction performance increasing **observation error better entire layers, than only in the lower** (below 10km)

Three new GNSS-RO + inflation factor(3.1) ☞ **Real-time operation in the KIM(v3.9) (Start date: 14 May, 2024)**

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