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Combined data assimilation of airborne and ground-based GNSS ZTDs

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Introduction

In this study, we aim to improve the numerical weather models (NWMs) by assimilating both airborne and ground-based GNSS ZTDs using WRF model. We obtained airborne GNSS zenith total delays (ZTDs) from an unmanned aerial vehicle (UAV) and ground-based GNSS ZTDs from static stations. We then designed various cases, including no GNSS ZTDs assimilation, only airborne GNSS ZTDs assimilated, only ground-based GNSS ZTDs assimilated and combined data assimilation of airborne and ground-based GNSS ZTDs. Finally, cases were compared among each other as well as to external data sets including ERA5 reanalysis and radiosonde.

GNSS ZTDs

- ✓ Ground-based ZTDs were obtained from static stations in post-processing mode while airborne ZTDs were obtained from highly-kinetic UAV in simulated real-time mode.
- ✓ Both processed in Precise Point Positioning (PPP) mode.

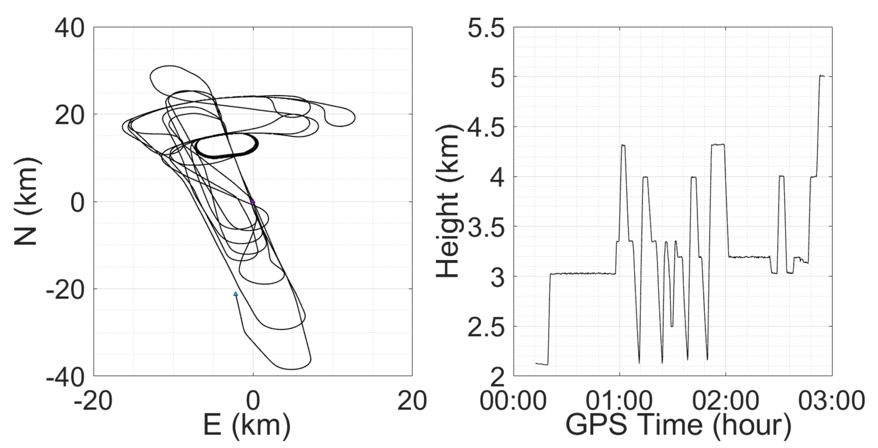

Fig.1 UAV trajectory

Tab. 1 GNSS ZTDs processing configurations

Scheme	GNSS data processing	
	Ground-based	Airborne
platform	Crustal Movement Observation Network of China	Highly-kinetic UAV
Observations	GPS dual frequency ion-free	BDS dual frequency ion-free
Spatial coverage	Single point	80 km in horizontal and 3 km in vertical **(Fig.1)**
Temporal resolution	300 s	0.1 s (10 Hz)
Estimator	Least squares method (LSQ)	Square root information filter (SRIF)
Precise Products	IGS SP3 orbits and satellite clocks	Archive IGS real-time products
Processing mode	PPP	PPP
Coordinates	Constant parameter	Kinetic parameter
Software	PANDA (Shi et al. 2008)	In-house GMET
ZTD model	Fixed stochastic model	Dynamic stochastic model (Zhang et al. 2022)
ZTD accuracy	Around 8 mm	Around 16 mm

WRF data assimilation (WRFDA) experiment

WRF settings

- ✓ NCEP GFS products, 0.25°×0.25°, 3 hour forecast.
- ✓ Three domains, with spatial resolution of 9 km, 3 km, and 1 km (**Fig. 2a**).

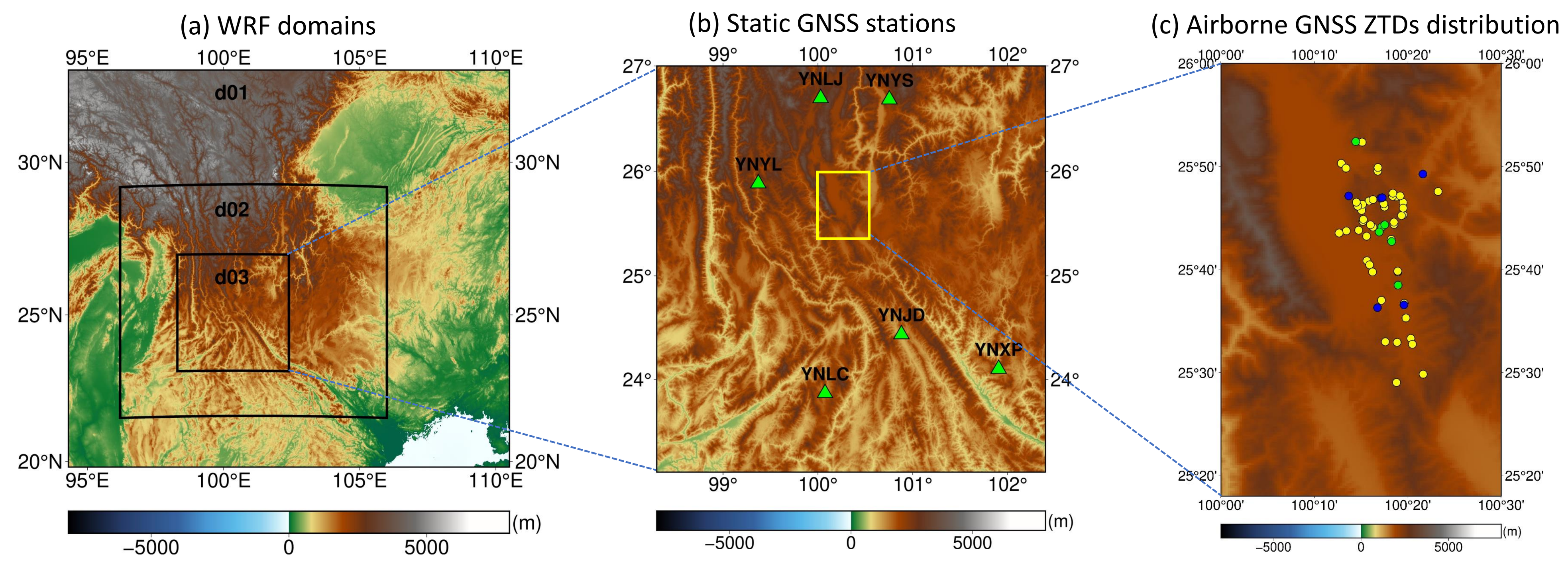

Fig.2 WRF experiment settings

WRFDA settings

- ✓ Ground-based GNSS ZTDs: six stations at 01:00 UTC (**Fig. 2b**).
- ✓ Airborne GNSS ZTDs: thinned to Green 10 min, blue 5 min, and yellow 1 min (**Fig. 2c**) and were compensated with the ZTD temporal change based on ERA5.
- ✓ 3D-Var method. ZTDs in 30 min before and after DA time were assimilated (**Fig. 3**).
- ✓ **A total of 7 cases are designed as shown in Tab. 2.**

Tab. 2 WRFDA experiment design

Case	Assimilated GNSS ZTDs	
	Ground-based	Airborne
CTRL	×	×
G	√	×
A01	×	1 min
A05	×	5 min
A10	×	10 min
GA01	√	1 min
GA05	√	5 min
GA10	√	10 min

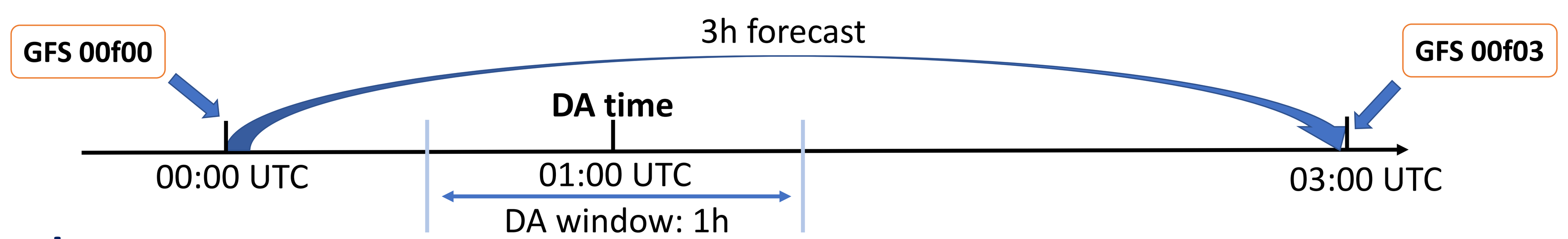

Fig.3 WRFDA procedure

Results

Humidity gain after DA

- The specific humidity profile of the GFS-driven background and the gain for each case above all the GNSS stations are plotted in **Fig. 4.**

- **Sub results**
  - a) Humidity decreased if only ground-based GNSS ZTDs were assimilated.
  - b) Humidity increased if only airborne GNSS ZTDs were assimilated.
  - c) Humidity increased in the low pressure layers while decreased in the upper pressure layers if both ground-based and airborne GNSS ZTDs were assimilated.

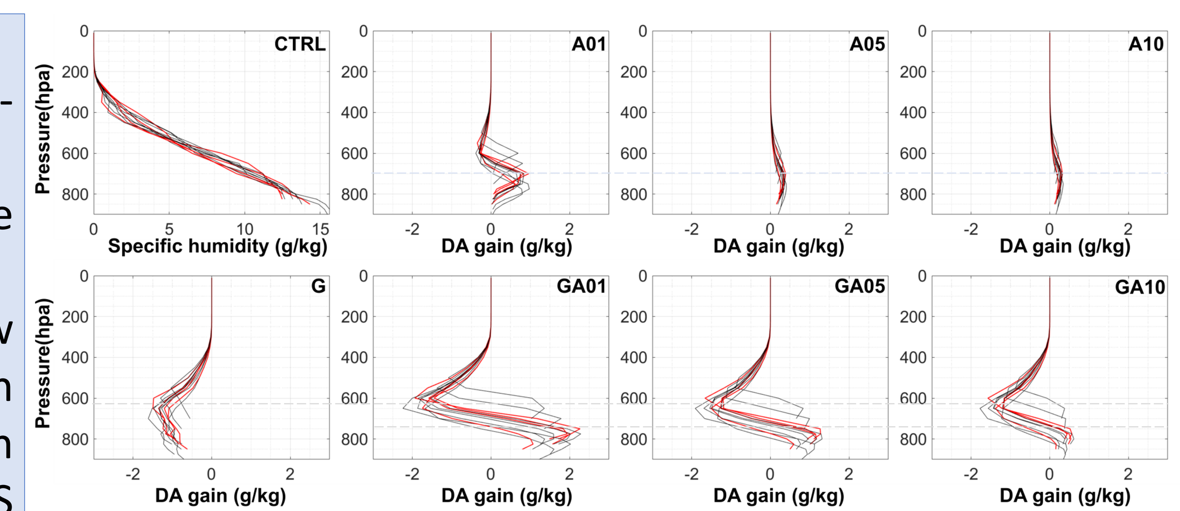

Fig.4 Specific humidity of background and gain for each case

Evaluation based on ERA5

- With ERA5 ZTD as reference, ZTD error of WRF d03 are plotted in **Fig. 5.**
- Bias and RMS of the ZTD error for each case are presented in **Tab. 3**
- **Sub results**
  - a) ZTDs were over-estimated for GFS-driven background and further over-estimated if only airborne GNSS ZTDs were assimilated.
  - b) ZTDs were under-estimated if only ground-based GNSS ZTDs were assimilated.
  - c) The bias and RMS of ZTD error decreased if both ground-based and high resolution airborne GNSS ZTDs were assimilated.

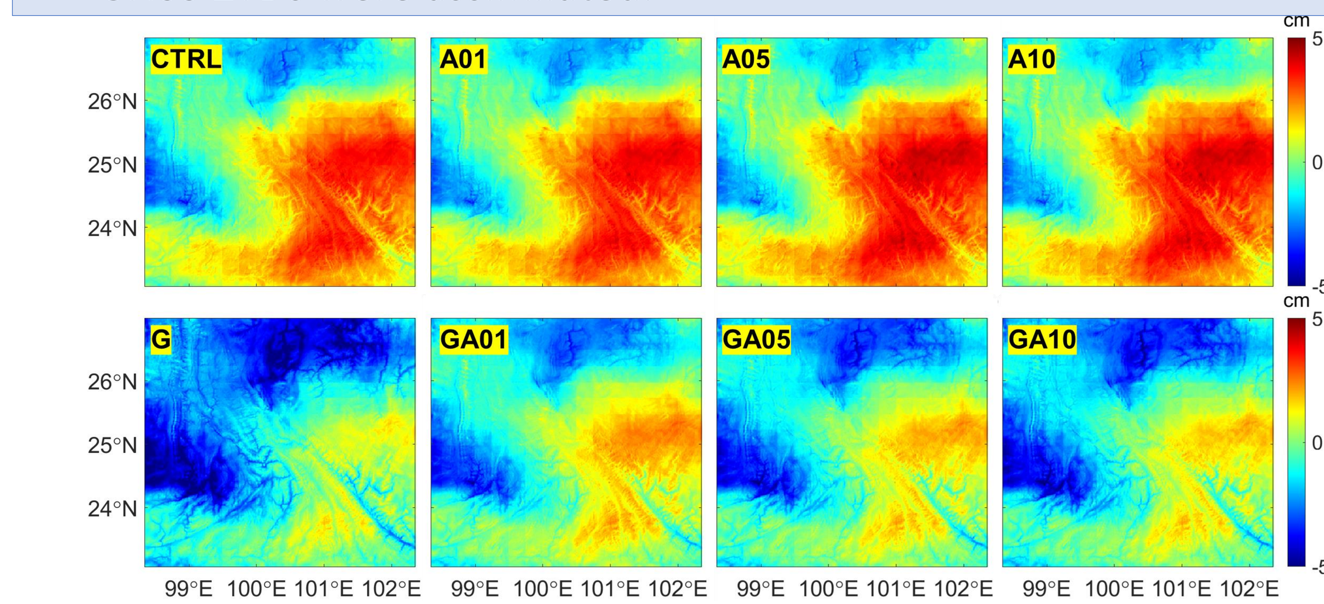

Fig.5 ZTD error (w.r.t. ERA5)

Tab. 3 ZTD error statistics (w.r.t. ERA5)

Analysis	ZTD error (cm)	
	Bias	RMS
CTRL	0.68	1.93
G	-1.63	2.35
A01	0.89	2.00
A05	1.11	2.14
A10	1.05	2.11
GA01	-0.34	1.53
GA05	-0.72	1.70
GA10	-0.95	1.84

Evaluation based on radiosonde

- With radiosonde as reference, the relative humidity (RH) error profile for each case are plotted in **Fig. 5.**
- Bias and RMS of the RH error for each case are presented in **Tab. 4**

- **Sub results**
  - a) GFS-driven background over-estimated RH.
  - b) RH errors were significantly decreased if ground-based GNSS ZTDs were assimilated.
  - c) RH errors were minimum when both ground-based and high resolution airborne GNSS ZTDs were assimilated.

Tab. 4 RH error statistics

Analysis	RH error (%)	
	Bias	RMS
CTRL	9.56	17.08
G	4.79	13.35
A01	8.79	16.19
A05	10.10	17.57
A10	10.05	17.53
GA01	3.12	11.71
GA05	4.12	12.57
GA10	4.32	12.75

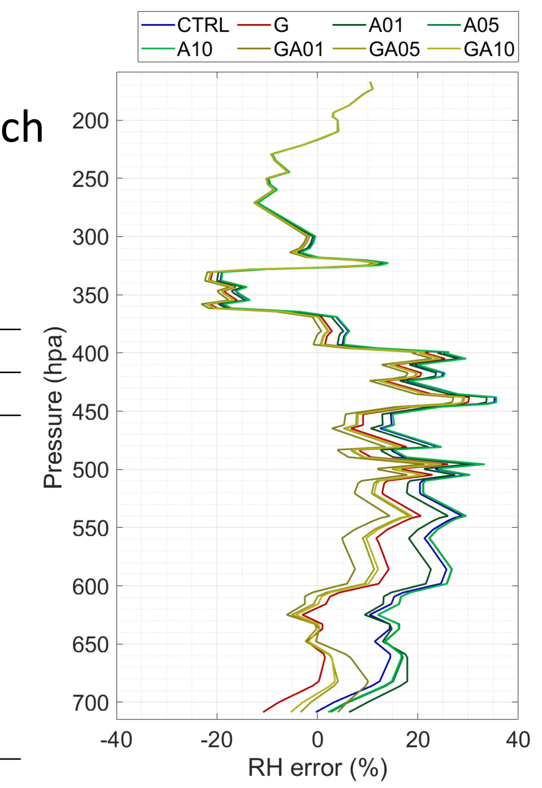

Fig.5 RH error

Summary

- ✓ Combined data assimilation of ground-based and airborne GNSS ZTDs can significantly improve the accuracy of numerical weather models in terms of ZTD and humidity.
- ✓ Combined data assimilation has better performance than merely assimilating ground-based or airborne ZTDs, where airborne ZTDs could help further decrease the humidity bias.
- ✓ When assimilating airborne ZTDs, a higher spatial-temporal resolution leads to a larger improvement.

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Reference:

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