Evaluation of GEMS formaldehyde vertical column densities during ASIA-AQ

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1. Introduction and objectives

- Formaldehyde (HCHO), a byproduct of the oxidation of VOCs, serves as a key indicator for providing observational constraints on VOC emissions.
- The Geostationary Environment Monitoring Spectrometer (GEMS) has been providing hourly HCHO vertical column densities (VCDs) across East Asia since August 2020.
- This study evaluates the latest version (version 3) of the GEMS HCHO product by comparing it with data from ground-based (Pandora and MAX-DOAS) and airborne observations.
- Based on the ground-based MAX-DOAS observations, we asses the sensitivity of the air mass factor (AMF) to different chemical transport model simulations during the ASIA-AQ campaign.

2. Data

2.1. GEMS HCHO product

- GEMS HCHO retrieval derives slant column density through the direct fitting method using observed radiance references and absorption cross-sections (Table 1).
- Air mass factors are calculated using scattering weights look-up-table and a priori profile of HCHO from GEOS-Chem 0.25° x 0.3125° simulations.

Table 1. Fitting parameters and input data of the GEMS HCHO retrieval algorithm

Product version	version 3 (preliminary)
Fitting window (calibration window)	329.3–358.6 nm (326.3–361.0 nm)
Fitting method	Direct fitting [González Abad *et al.*, 2015]
Absorption cross-sections	HCHO, O_3, NO_2, BrO, O_4, Ring effect, polarization sensitivity
Polynomials	Third order
Reference spectrum	120–150°E (Fig. 3) three-day running mean zonal mean radiances (three-day running mean) Filtering option: cloud fraction < 0.4
Background correction	Variable background concentrations in the radiance reference sector

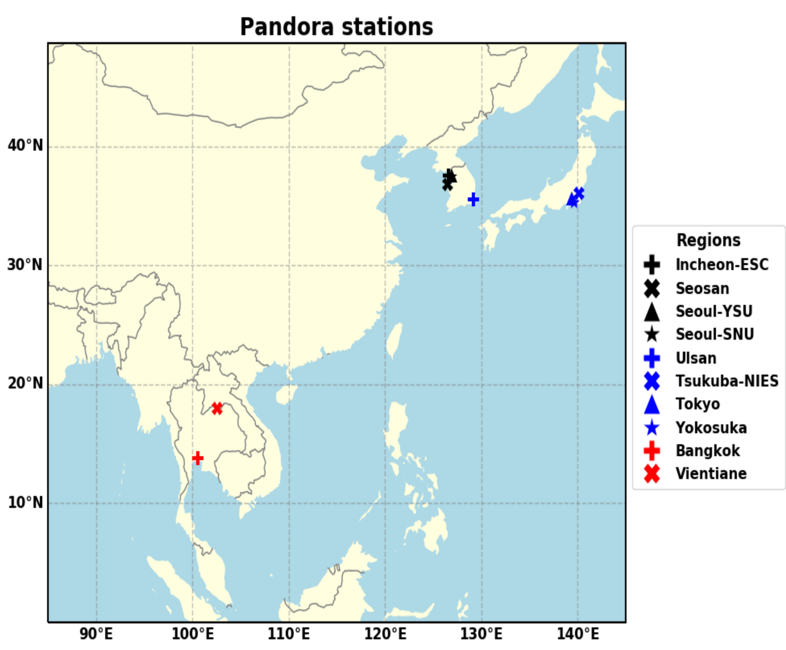

Figure 1. Pandora stations selected for the validation.

2.2. Pandora HCHO product

- 10 Pandora stations in GEMS scan domain (Figure 1)
  - ✓ February 2022–May 2024

2.3. ASIA-AQ HCHO dataset

- **Multi-model ensemble simulations**
  - ✓ Spatial resolution of 9 km over Korean Peninsula, with hourly data for February 2024
  - ✓ Consists of five ensemble members from WRF-Chem, CMAQ, and WRF-GC simulations
  - ✓ Emission inventory: ASIA-AQ v3.0 (anthropogenic) and MEGAN (biogenic)
- **DC-8 airborne observations**
  - ✓ 16 flights conducted over East Asia between January 24 and March 25
- **MAX-DOAS product**
  - ✓ Hourly mean preliminary MAX-DOAS HCHO product for February 2024 from University of Suwon (USW)
  - ✓ The MAX-DOAS HCHO VCDs in this study are calculated using geometric AMF.

3. GEMS HCHO evaluation results

3.1. GEMS vs. Pandora

- Figure 2a shows good agreement (r=0.62–0.79) of GEMS HCHO with Pandora observations across East Asia despite some negative biases (NMB ~-27 %) in Southeast Asian cities.
- HCHO VCDs peak from May to June in Northeast Asian cities due to biogenic VOC emissions, while those in southeast Asian cities, which peak in March, are mainly from biomass burning emissions.
- In Figure 2b, GEMS HCHO show consistent diurnal variations with those of Pandora.
- HCHO VCDs in megacities (Incheon, Seoul, Ulsan, Vientiane) or industrial areas (Seosan) typically show two diurnal peaks, likely linked to the morning and late afternoon rush hours.

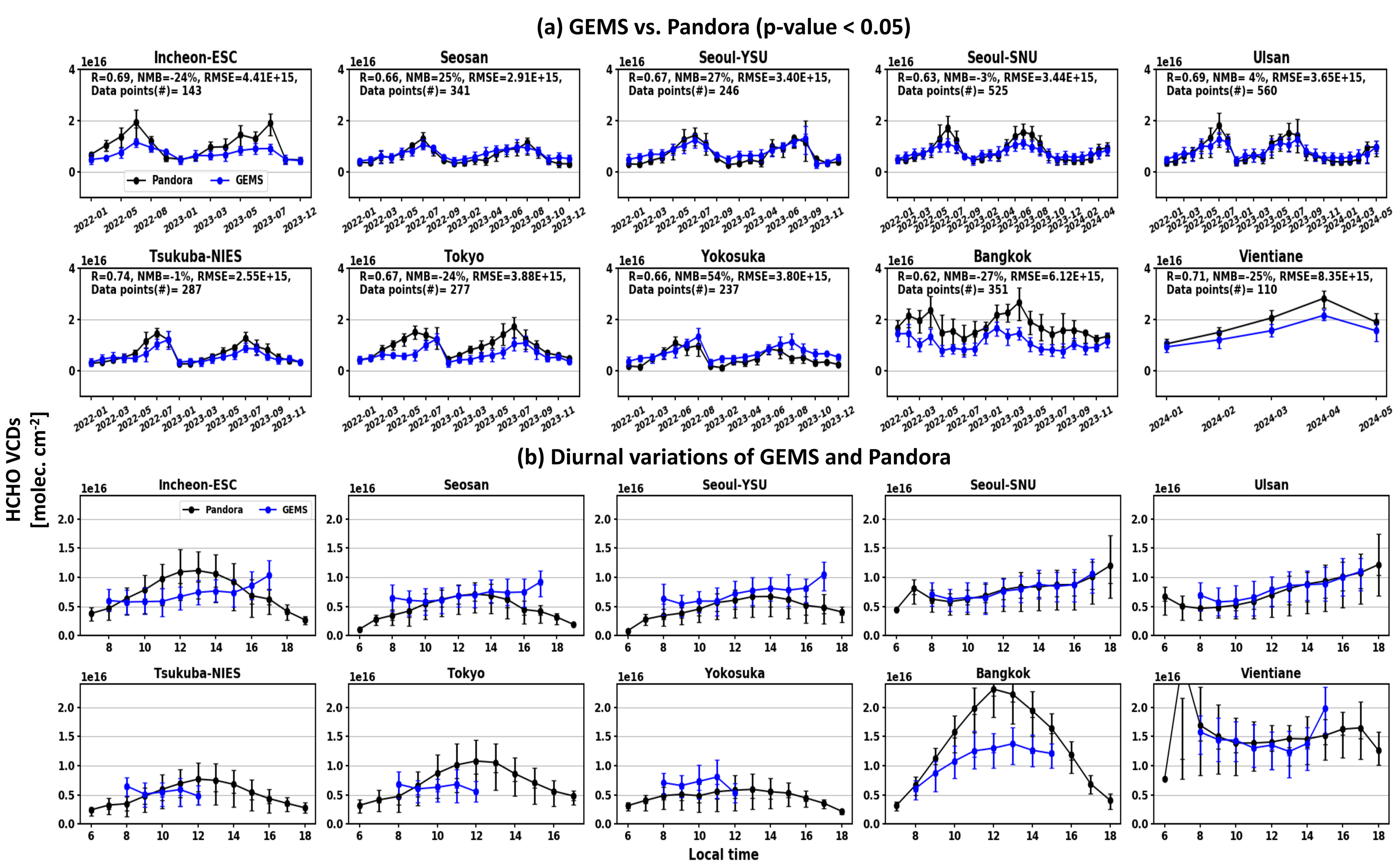

Figure 2. (a) Monthly mean HCHO VCDs of GEMS version 3 (black) and Pandora (blue) across 10 Pandora stations in East Asia. (b) Diurnal variations of HCHO VCDs over the same period as in (a). Error bars show the 25th, 50th, and 75th percentiles, with markers indicating monthly means. The statistics are derived from daily mean data.

3.2. GEMS vs. DC-8

- GEMS HCHO was compared with DC-8 observations by re-griding both datasets onto a 0.1° x 0.1° co-location grid.
- The DC-8 HCHO mixing ratios were converted to VCD by assuming a uniform HCHO concentration from surface up to 2 km altitude.
- Despite some noise in the GEMS data, mean DC-8 HCHO VCDs well aligns with the GEMS's spatial pattern (Figure 3).
- GEMS shows 18–31 % lower VCDs than DC-8, except for Thailand (NMB=7 %).
- DC-8 consistently shows higher HCHO VCDs over the ocean compared to GEMS.
- Despite spatial and temporal co-location, DC-8 HCHO VCDs should be interpreted with caution, as they are significantly affected by varying flight altitude.

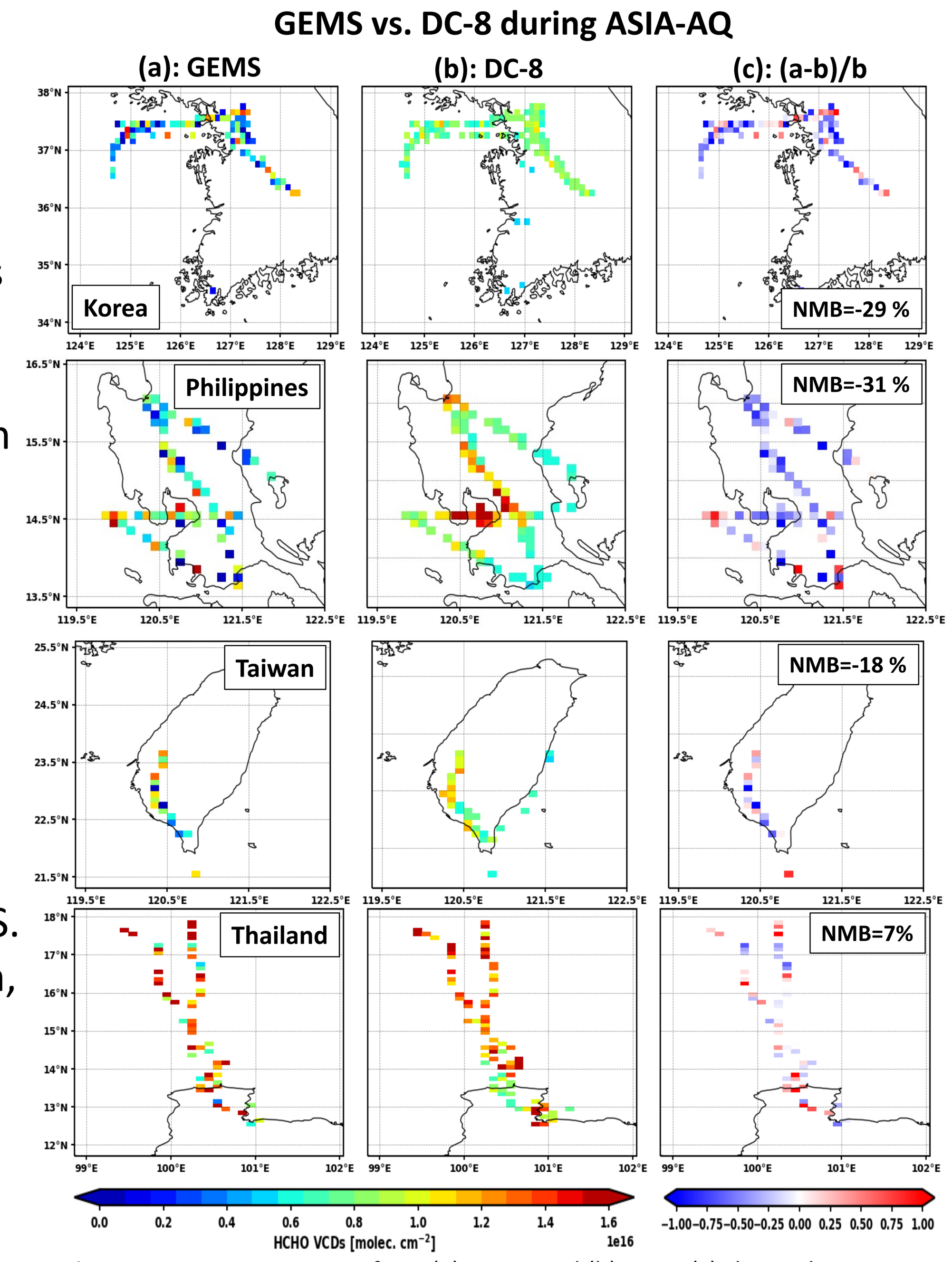

Figure 3. Mean HCHO VCDs from (a) GEMS and (b) DC-8. (c) shows the relative differences (a – b)/b. *DC-8 HCHO product acquisition: Glenn Wolfe, NASA GSFC*

4. HCHO retrieval sensitivity to input data

4.1. AMF sensitivity to different a priori profile

- The current GEMS a priori profile, based on August 2020–July 2021 simulations, could cause systematic biases in GEMS AMF when applied to present conditions.
- In Figure 4, the ensemble profile shows HCHO VSFs two–three times lower in the surface and higher in 800–600 hPa range than the GEMS a priori profile, especially during morning hours (10–11 KST, r=0.52–0.60).
- The AMFs show the highest relative differences in 10 KST (38–57 %), primarily due to the VSF differences and high geometric conditions, thereby increasing reliance on model accuracy.

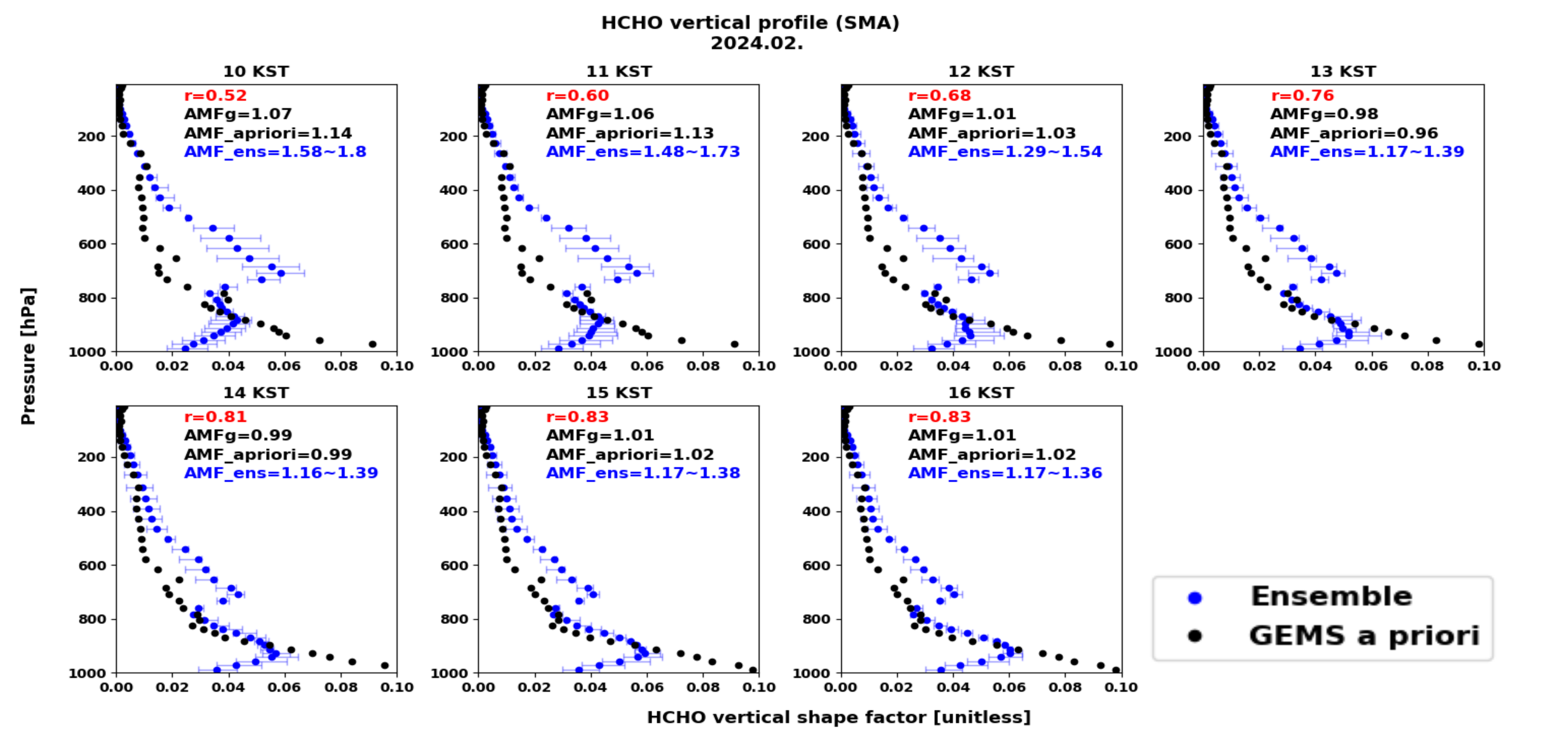

Figure 4. Comparison of mean VSF and resulting AMF derived from the ensemble (blue) and GEMS a priori profile (black) in Seoul Metropolitan Area (SMA) for February 2024. Blue error bar represents 10 % to 90 % of ensemble spreads. AMFg represents geometric AMF.

4.2. Comparison of GEMS HCHO with ensemble and MAX-DOAS observation

- Applying the ensemble profiles to GEMS HCHO significantly reduced the high differences with MAX-DOAS HCHO (NMB: 93 % → 20 %), especially in the morning.

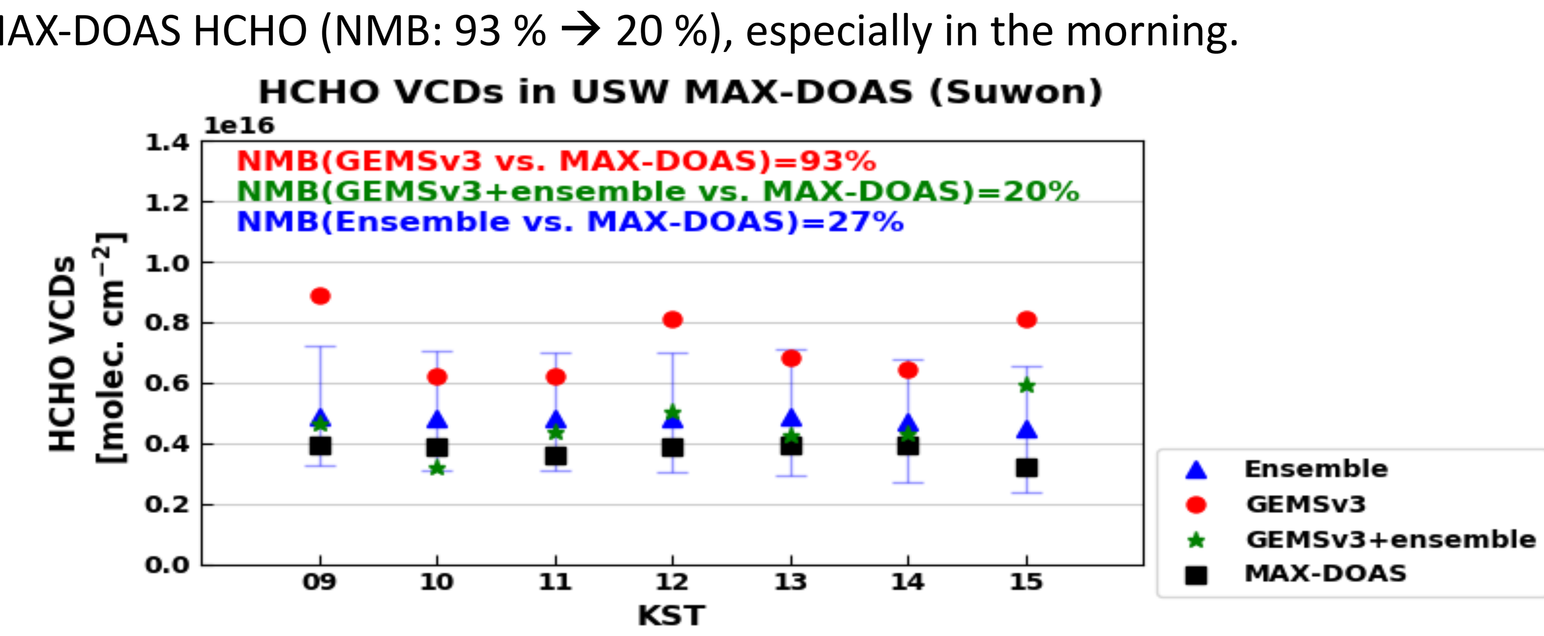

Figure 5. Mean HCHO VCDs from 09:45 to 15:45 KST during February 14–26, 2024: (Blue triangle and error bar) ensemble mean and their ensemble spreads, (Red circle) GEMS v3 product, (Green star) GEMS v3 based on ensemble-simulated AMF, (black square) USW MAX-DOAS product. Averaging kernel smoothing is not applied in this comparison.

5. Summary

- GEMS HCHO closely aligns with Pandora (r=0.62–0.79), showing clear seasonal variations due to biogenic and biomass burning emissions.
- Overall, GEMS well captures Pandora's diurnal variations, despite some discrepancies that are potentially due to the representation error.
- GEMS shows consistent spatial distributions of HCHO with DC-8, despite some low biases.
- Using ensemble-simulated HCHO vertical profiles in GEMS AMF calculations reduces the high positive bias of HCHO VCDs (NMBs against MAX-DOAS: 92 % → 19 %), suggesting the necessity of using near-real-time chemical model simulations in AMF calculations.

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