Spatiotemporal Assessment of TEMPO v3 Formaldehyde Retrieval using the Pandonia Global Network

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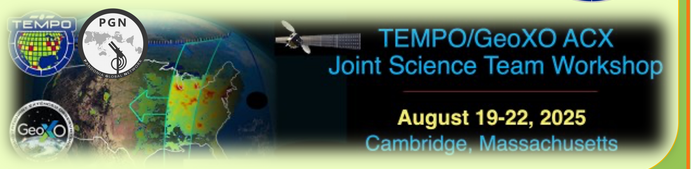


Research Motivation

This research leverages TEMPO's high-resolution, hourly spectral radiance measurements from its geostationary orbit over North America to validate HCHO retrievals against ground-based Pandora observations. Accurately validated TEMPO HCHO columns (ΩHCHO) are then employed to provide key insights into surface air quality and ozone formation, advancing the understanding of photochemical processes and air quality dynamics.

1. Introduction

- The Tropospheric Emissions: Monitoring of Pollution (TEMPO) instrument plays a pivotal role in advancing air quality monitoring at high spatial and hourly resolution over North America.
- While TEMPO's primary focus is on precursor observations to enhance understanding of emissions and atmospheric chemistry when used with air quality models, it also presents an underexplored opportunity to provide direct, model-independent insights into surface air quality and photochemistry.

2. TEMPO Satellite Instruments and ΩHCHO Retrieval

- TEMPO, launched by NASA in April 2023, is a geostationary instrument measuring air pollutants over North America using 290–490 nm and 540–740 nm spectral ranges at 0.57 nm resolution.

TEMPO offers hourly temporal coverage and a spatial resolution of 2 × 4.75 km² at center FORs.

TEMPO pixels with main_data_quality_flag=0, eff_cloud_fraction ≤ 0.2, and SZA < 70° are used within 10 km radius around Pandora.

TEMPO vertical column densities

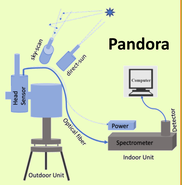
$$\mathrm{VCDs} = \frac{\mathrm{SCDs}}{\mathrm{AMF}}$$

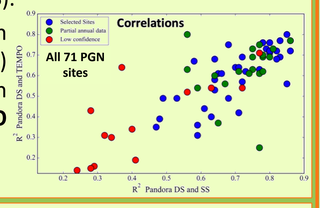
$$\mathrm{AMF} = \int_{\mathrm{atm}} \mathrm{SW}(z, \theta s, \theta v, \phi r, \mathrm{Ps}, \mathrm{A}, \mathrm{C_f}, \mathrm{C_h}) \times \mathrm{S}(z, \mathrm{lat}, \mathrm{lon}, \mathrm{time})\, dz$$

TEMPO scanning from the geostationary orbit

3. Pandora and Performance Metric

- Pandora spectrometers offer an exciting and unique opportunity to both validate satellites and understand local emissions and air quality.
- 36 most valid Direct-Sun Pandora sites are chosen for TEMPO validation (**Rawat et al., 2024, AMT**)
- Rawat et al. filtering method increased ΩHCHO data by 26–90% (DS) and 16–90% (SS).
- **Pandora DS sites selection** based on the following criteria: 1) **$R^2 \geq 0.45$**, 2) sites with **mean differences** less than **50%** between **DS and SS ΩHCHO** with complete seasonal coverage.
- PGN sites require careful evaluation.

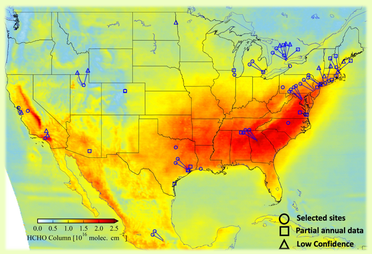




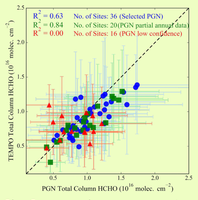
4. TEMPO v3 ΩHCHO agrees well with Pandora

- TEMPO ΩHCHO is well correlated with Pandora observations with an annual average R^2 between 0.63 and 0.85 across 36 Pandora sites.

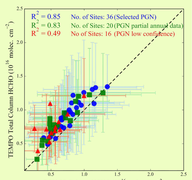
TEMPO HCHO column during July 2024



Spatial correlation between TEMPO and Pandora.



Direct-Sun show a correlation of **R^2 = 0.63** for the 36 selected sites, **R^2 = 0.84** for newer PGN sites, and zero **R^2** for low-confidence sites.

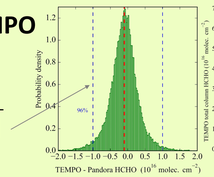


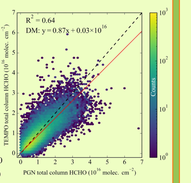
Sky-Scan show a strong correlation, with **R^2 = 0.85** for the 36 selected sites, **R^2 = 0.83** for newer PGN sites, and **R^2 = 0.49** for low-confidence sites.

SS shows higher correlation but low-biased ΩHCHO vs. TEMPO; and the 36 selected DS sites are used for further analysis.

Spatiotemporal correlation of TEMPO with 36 selected DS Pandora sites.

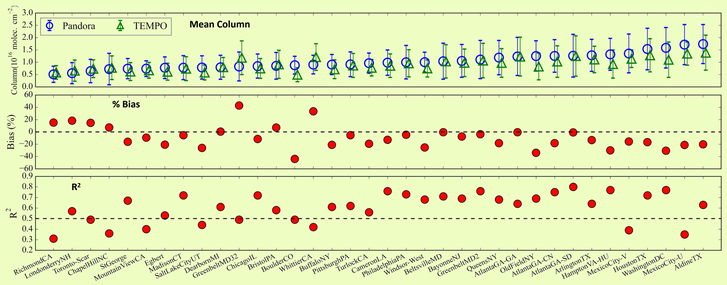
- The difference distribution is near-Gaussian, centered at –0.1×10¹⁶ molec cm⁻², with 96% within TEMPO's precision limit and 76% within ±1σ, indicating strong agreement.



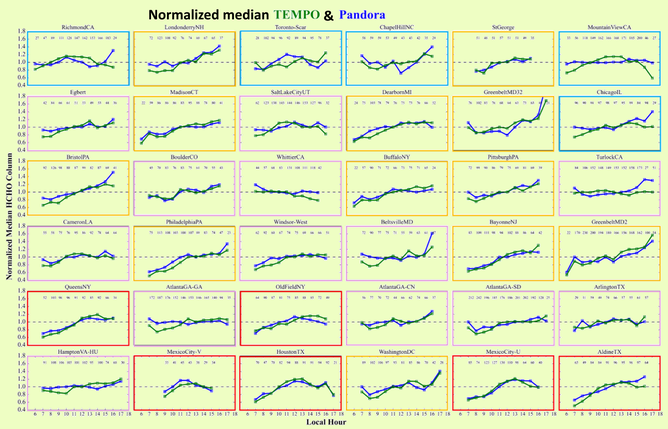


5. Pandora and TEMPO agree on the relative ΩHCHO magnitude from site to site

- TEMPO shows a **small bias of -2 ± 20% at lower ΩHCHO** (< 1.0×10¹⁶ molecule cm⁻²) and a **larger underestimation of -22 ± 5% at higher ΩHCHO** (> 1.5×10¹⁶ molecule cm⁻²).

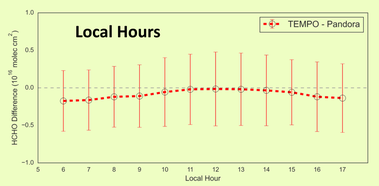


6. Diurnal Comparisons between Pandora and TEMPO ΩHCHO during ozone period (May to Oct)



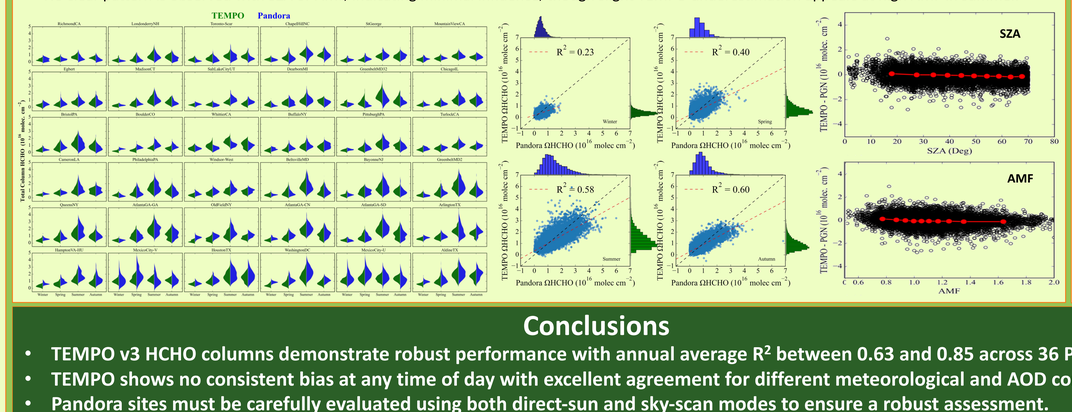
- At 31 PGN sites, TEMPO and Pandora exhibit similar diurnal patterns in ΩHCHO, including steady daytime levels, gradual increases, and midday peaks; however, TEMPO struggles to capture these patterns at several western PGN sites.

Border color	Diurnal profile variations
Red	Increasing ΩHCHO from morning, peaking in the afternoon, and declining in the evening.
Yellow	Increasing ΩHCHO throughout the day.
Magenta	Little to no change in ΩHCHO throughout the day
Cyan	Discrepancy between Pandora and TEMPO ΩHCHO



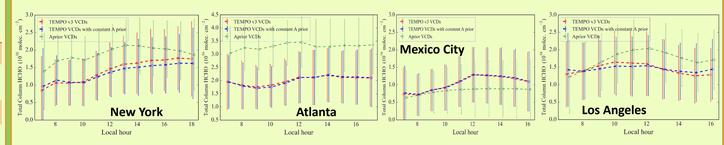
7. Seasonal Comparisons between Pandora and TEMPO ΩHCHO

- Seasonal median ΩHCHO peaks in summer (1.30 for Pandora, 1.20 for TEMPO ×10¹⁶ molec cm⁻²), with summer values 28–66% higher than other seasons for both instruments. The overall correlation (R^2) between Pandora and TEMPO ΩHCHO is higher during warmer seasons.
- No clear pattern is observed with SZA or AMF, indicating minimal influence, though slight TEMPO underestimation appears at high AMF in summer.



8. Sensitivity Analysis of TEMPO ΩHCHO Retrieval (Jul 2024)

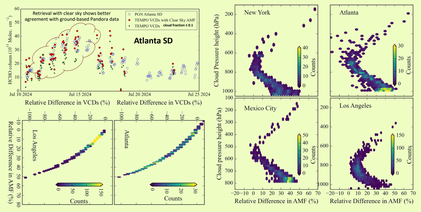
- **A-priori Influence** in the diurnal variation of TEMPO HCHO via reconstructed AMF (**new VCDs**) shows minimal influence in diurnal shape with some contribution in early and late hours.
- Still the *a priori* diurnal variations has a minor impact of 3 – 14% on TEMPO VCDs.



Influence of Cloud Properties on Scattering Weight Calculations

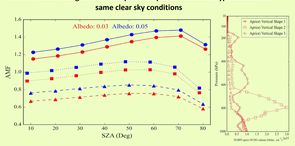
$$\mathrm{SW} = (1-\Phi) \times \mathrm{SW\_clear} + \Phi \times \mathrm{SW\_cloud}$$

- The influence of cloudy SW on VCDs is assessed using clear SW for pixels with cloud fraction ≤ 0.1, showing AMF differences up to 0.8 and HCHO VCDs differences of 10 - 25 × 10^{15} molecules cm⁻².
- In addition to **cloud fraction**, **cloud pressure height** has a notable impact on AMF adjustments.

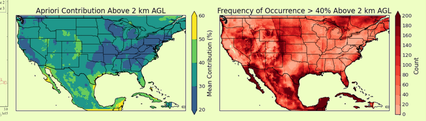


AMF Sensitivity to A-priori Vertical Shapes and Albedo

AMFs variation using 3 GEOS-CF a priori shapes and 2 albedo types under the same clear sky conditions

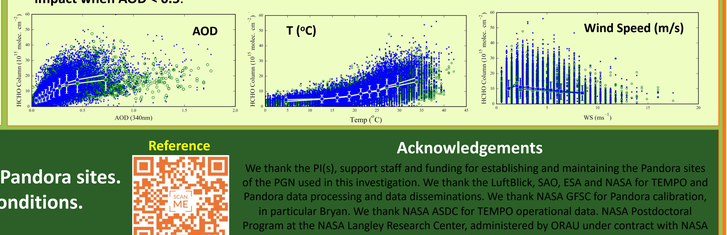


- A priori vertical shape has a greater influence than albedo on AMF sensitivity and values.



9. Performance under Different Meteorological and Aerosol Loading Conditions

- TEMPO captures ΩHCHO variability driven by meteorology, aligns with Pandora, and **shows little aerosol impact when AOD < 0.5**.



Conclusions

- **TEMPO v3 HCHO columns demonstrate robust performance with annual average R^2 between 0.63 and 0.85 across 36 Pandora sites.**
- **TEMPO shows no consistent bias at any time of day with excellent agreement for different meteorological and AOD conditions.**
- **Pandora sites must be carefully evaluated using both direct-sun and sky-scan modes to ensure a robust assessment.**

Reference

Acknowledgements

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