CEOS AC-VC June 2025

Validation and Early Applications of the Tropospheric Emission: Monitoring of POllution

Nitrogen dioxide and Formaldehyde using Pandora and TropOMI

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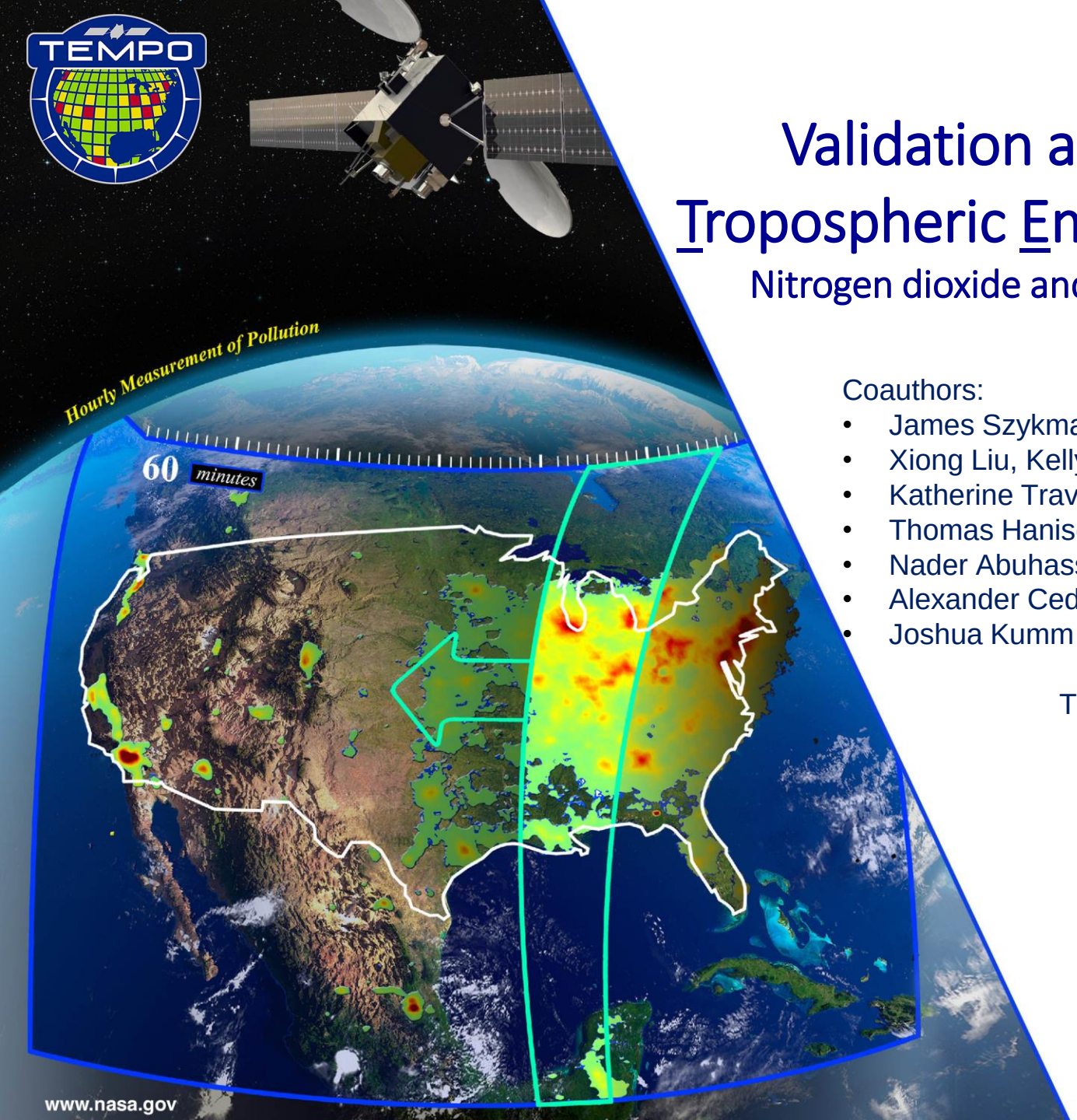
- Nader Abuhassan, SciGlob
- Alexander Cede, LuftBlick
- Joshua Kumm and Zhen Qu, North Carolina State University

Thanks to the rest of the TEMPO Validation Team!

***Disclaimer**: The views expressed in this presentation are those of the authors and do not necessarily reflect the views or policies of the U.S. Environmental Protection Agency.*



Validation Efforts Help Advance TEMPO

TROPOSPHERIC EMISSIONS:

MONITORING OF POLLUTION (TEMPO) PROJECT

Validation and Quality Assessment of the TEMPO Level-2 Trace Gas Products

[December XX 2024]

Prepared by the TEMPO Validation Team and TEMPO Ad-hoc Validation Working Group

Plan: available –https://tempo.si.edu under documents

Report: Draft ***under review***

https://github.com/barronh/tempodash

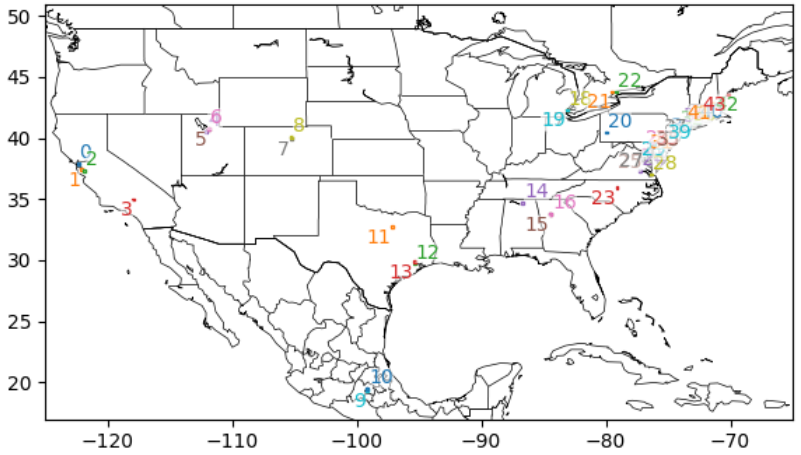
- **Validation TEAM enhanced TEMPO mission**
  - 65+ contributors led by Jim Szykman (EPA) and Brad Pierce (UW-SEC) in collaboration with Science Team, NASA, NOAA, and SAO.
  - Expanded the Pandonia Global Network of Pandoras
  - Feedback about version 1 priori profile and unrealistic AMF spatial variation helped improve versions 2 and 3
  - Validation report submitted to NASA
  - including results shown today…
- ***EPA's Analysis System V3 – Aug 2023 to present***
  - V3 Nitrogen dioxide correlates well with Pandora and TropOMI.
  - V3 Formaldehyde correlates well with Pandora ...
- ***Example Applications of TEMPO with CMAQ***
  - Model evaluation and emissions inference.
  - Surface concentration experiments
  - *Very preliminary and expanding!*
- ***Applications presume validation!***

TEMPO Validation Methodologies

➢ Correlative measurements : TropOMI and Pandora Spectrometers

- Pandora stations: best ground-based validation dataset available for total vertical columns.
- TropOMI: state-of-the-art satellite retrievals at similar spatial resolution.

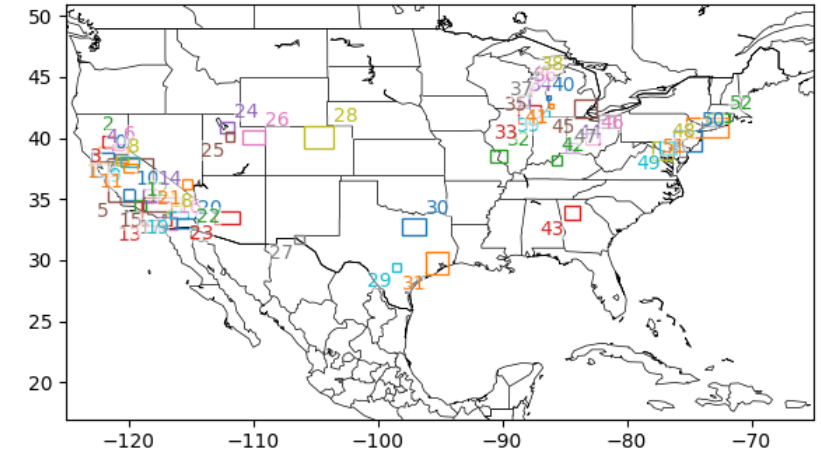
➢ 96 Analysis Regions: Pandonia Global Network and Ozone Nonattainment Areas.



0: RichmondCA
1: MountainViewCA
2: SanJoseCA
3: EdwardsCA
4: SouthJordanUT
5: SLC-Hawthorne
6: SLC-UT
7: BoulderCO
8: BoulderCO-NCAR
9: MexicoCity-UNAM
10: MexicoCity-Vallejo
11: ArlingtonTX
12: HoustonTX
13: AldineTX
14: HuntsvilleAL
15: AtlantaGA
16: Atl-S.DeKalb
17: DearbornMI
18: SWDetroitMI
19: Windsor-West
20: PittsburghPA
21: Downsview
22: Toronto-Scarborough
23: ChapelHillNC
24: CharlesCityVA
25: WashingtonDC
26: BeltsvilleMD
27: GreenbeltMD
28: HamptonVA-HU
29: PhiladelphiaPA
30: BristolPA
31: NewBrunswickNJ
32: BayonneNJ
33: ManhattanNY-CCNY
34: BronxNY
35: QueensNY
36: WestportCT
37: CornwallCT
38: OldFieldNY
39: NewHavenCT
40: MadisonCT
41: LondonderryNH
42: EastProvidenceRI
43: CapeElizabethME

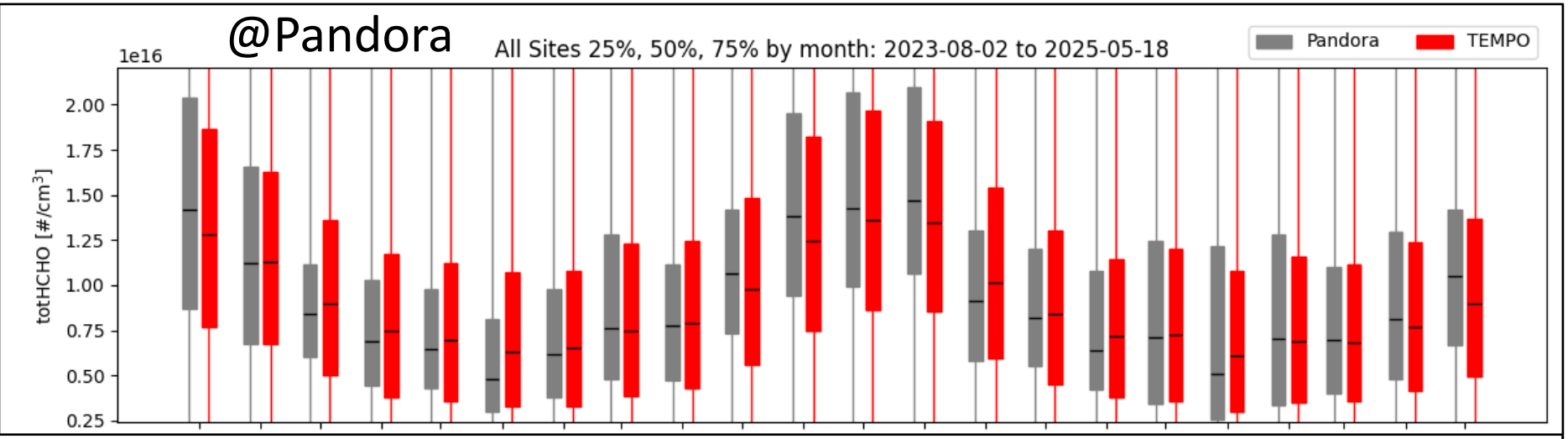
- 44 **Pandora** stations
- Most stations in the east

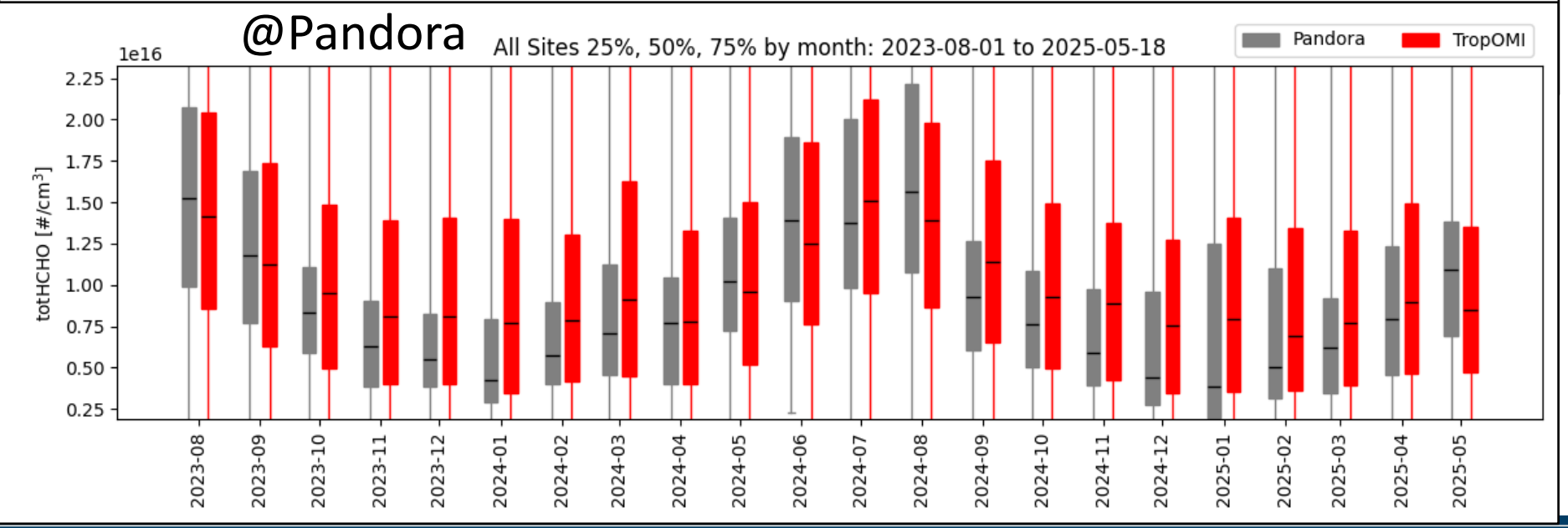
- 52 **Nonattainment Areas**
- Better spatial coverage
- Of special interest for emissions control



0: S.Francisco
1: Sacramento
2: Tuscan_Buttes
3: Chico
4: Sutter_Buttes
5: S.Joaquin
6: Nevada_Co
7: Amador_Co
8: Calaveras_Co
9: Tuolumne_Co
10: S.Luis_Obispo
11: Mariposa_Co
12: Ventura_Co
13: LA-S_Coast
14: East_Kern
15: LA-Desert
16: S.Diego
17: Pechanga
18: Morongo
19: Coachella_Val
20: Imperial_Co
21: Las_Vegas
22: Yuma
23: Phoenix
24: Salt_Lake
25: Provo
26: Uinta_Basin
27: El_Paso
28: Denver
29: S.Antonio
30: Dallas
31: Houston
32: St_Louis
33: Chicago
34: Milwaukee
35: Sheboygan
36: Manitowoc_Co
37: Door_Co_Rev
38: Door_Co
39: Benton_Harbor
40: Muskegon
41: Allegan_Co
42: Louisville
43: Atlanta
44: Cincinnati
45: Detroit
46: Columbus
47: Cleveland
48: Washington
49: Baltimore
50: Philadelphia
51: New_York
52: Connecticut

Pandora totHCHO Validation
Aug 2023 to May 2025





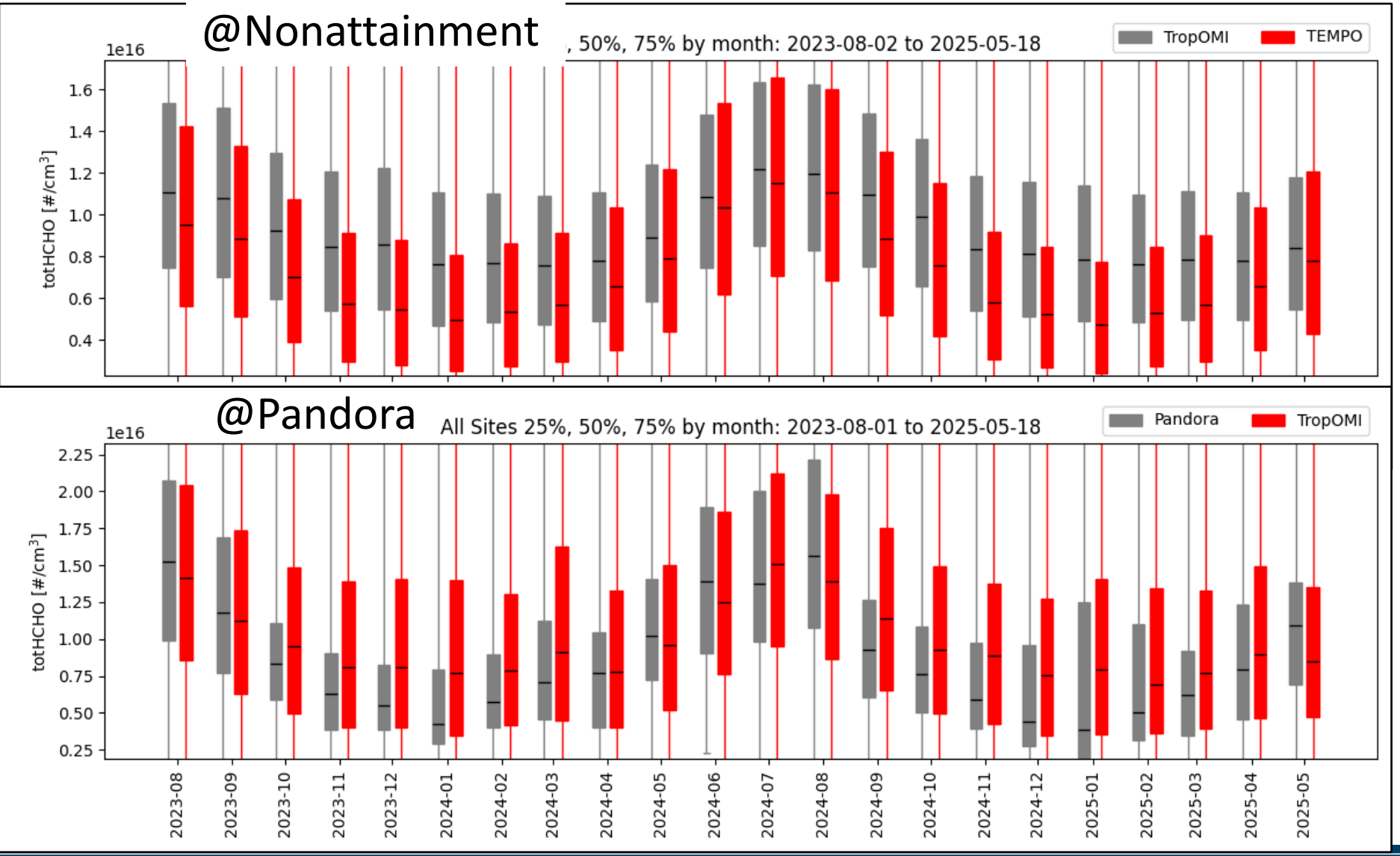
line: 50% boxes: 25%-75%
Solid Boxes: Mon-Fri

TEMPO captures seasonal pattern (r=0.98) with good bias (NMB=-3%)

TropOMI captures seasonal pattern (r=0.91), but high in winter (NMB=+12%)

- **Smaller variability in TropOMI**
- **TropOMI high-biased for low HCHO?**

TropOMI totHCHO Evaluation
Aug 2023 to May 2025



line: 50% boxes: 25%-75%
Solid Boxes: Mon-Fri

TEMPO captures TropOMI seasonal pattern (r=0.94) with lower winter values, which is likely good.

TropOMI captures Pandora seasonal pattern (r=0.91), but high in winter (NMB=+12%)

- **Smaller variability in TropOMI**
- **TropOMI high-biased for low HCHO?**

totHCHO Diurnal Validation

TEMPO L2 vs Pandora Total HCHO

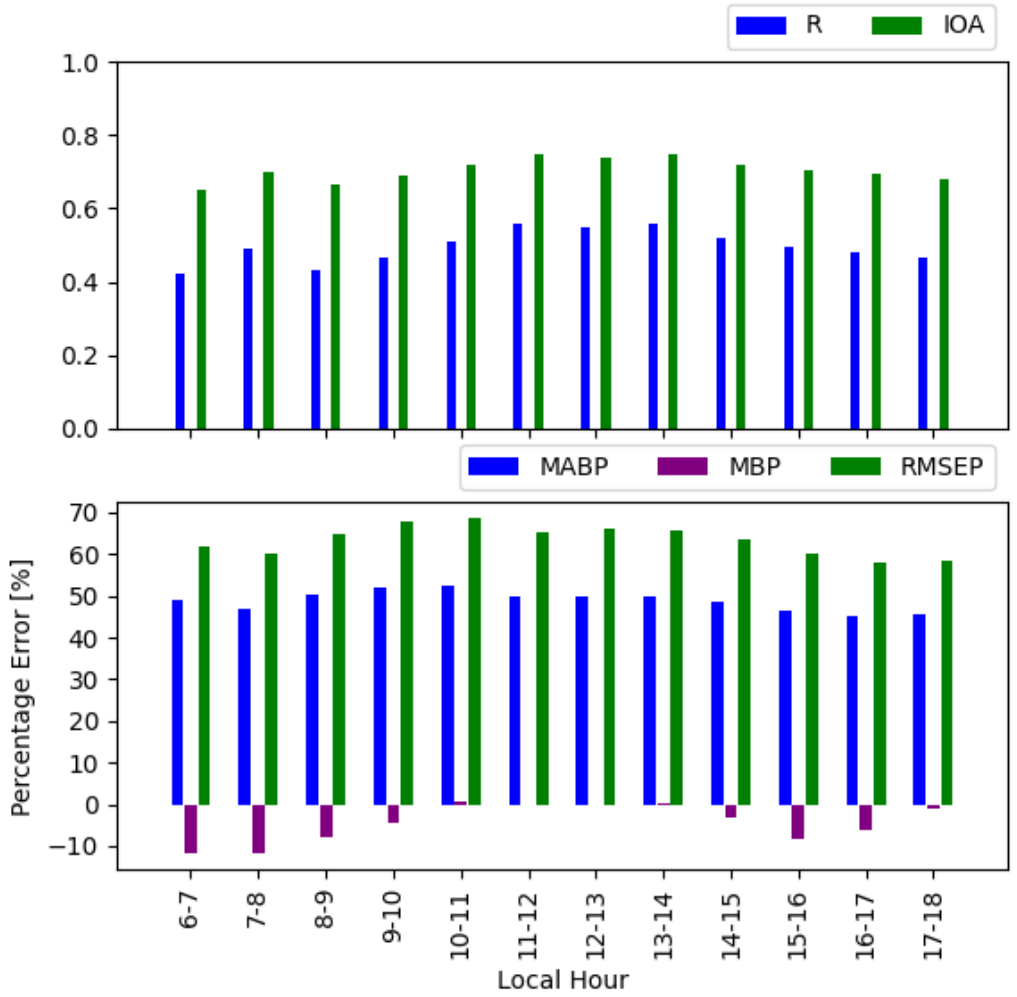
Agreement: Correlation (R) and Index of Agreement (IOA)

Generally moderate agreement

- Small variation in performance
- Peaks at mid-day R=0.5

Bias and error worst in morning

- 6-7, 17-18LST : Few observations
- 7-10 and 15-17 show lower biases than mid-day



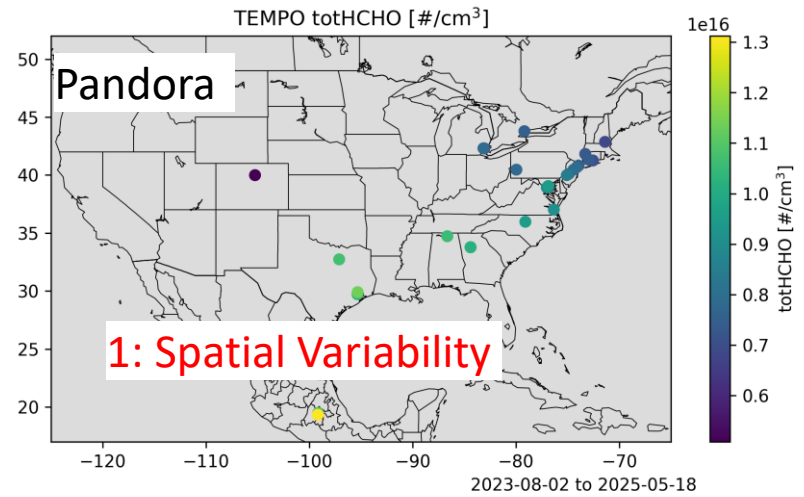
Err as % Mean

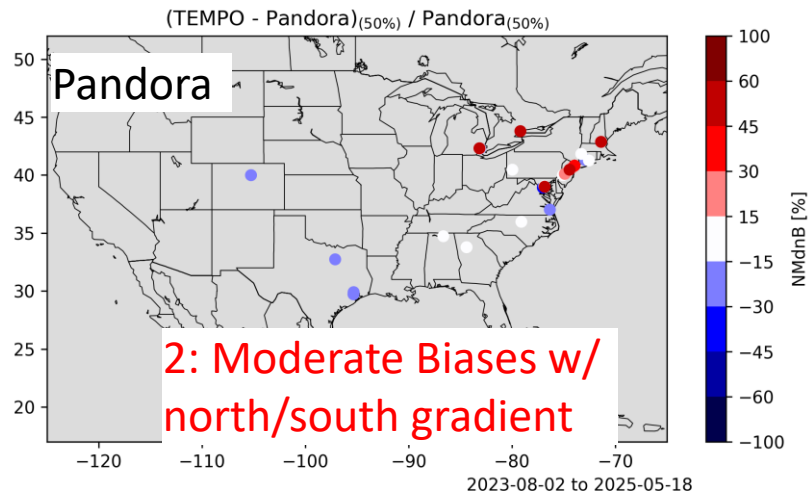
Mean Abs Bias

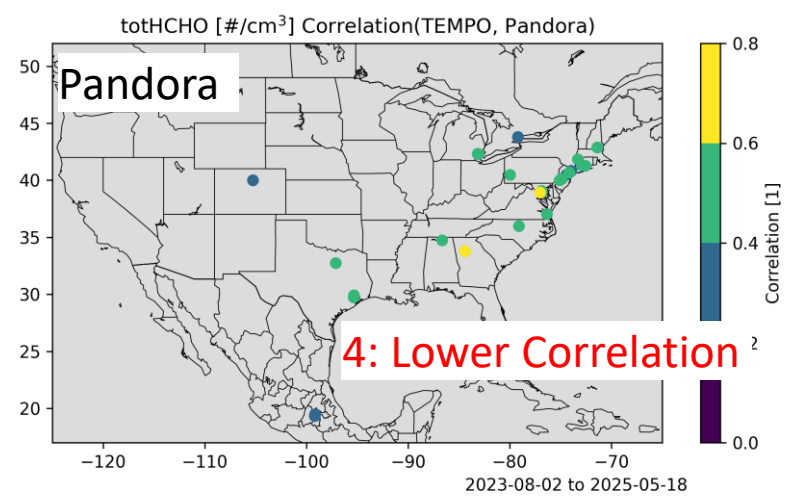
Mean Bias

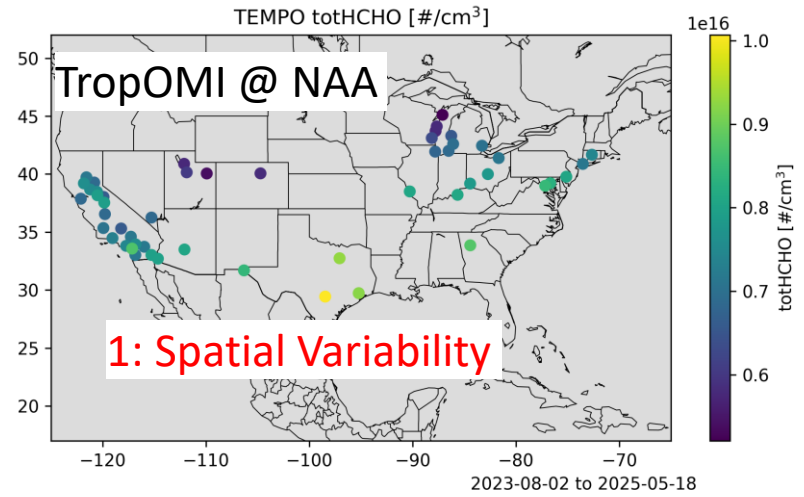
RMSE

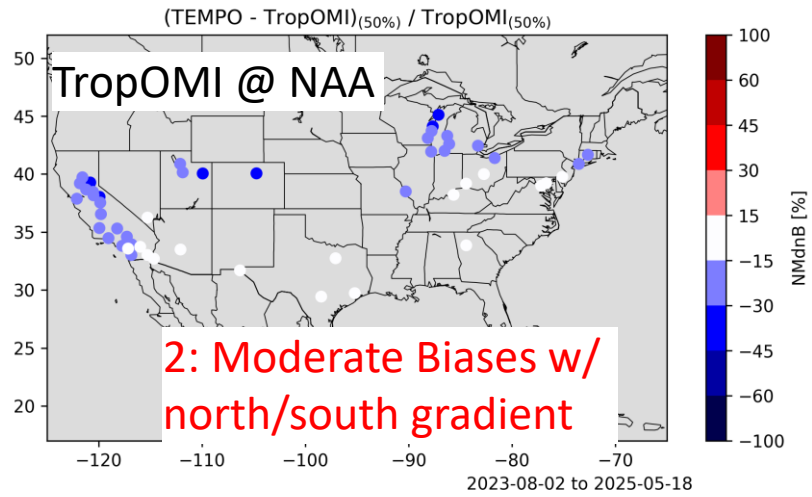
Site-level totHCHO Evaluation Available

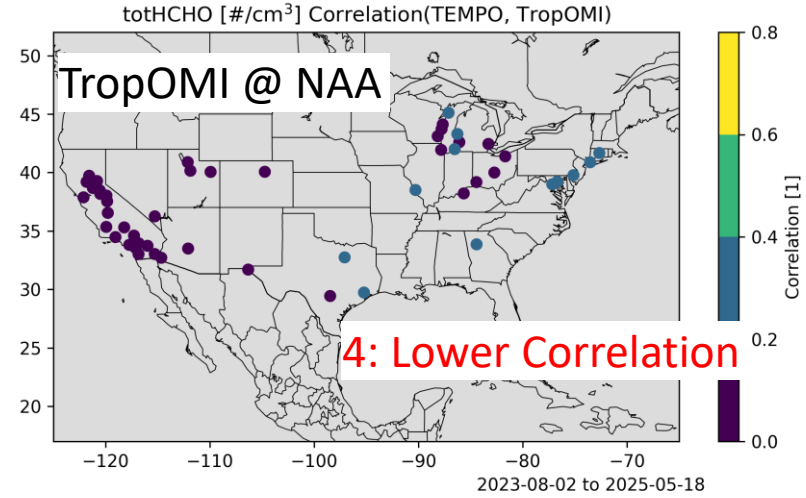






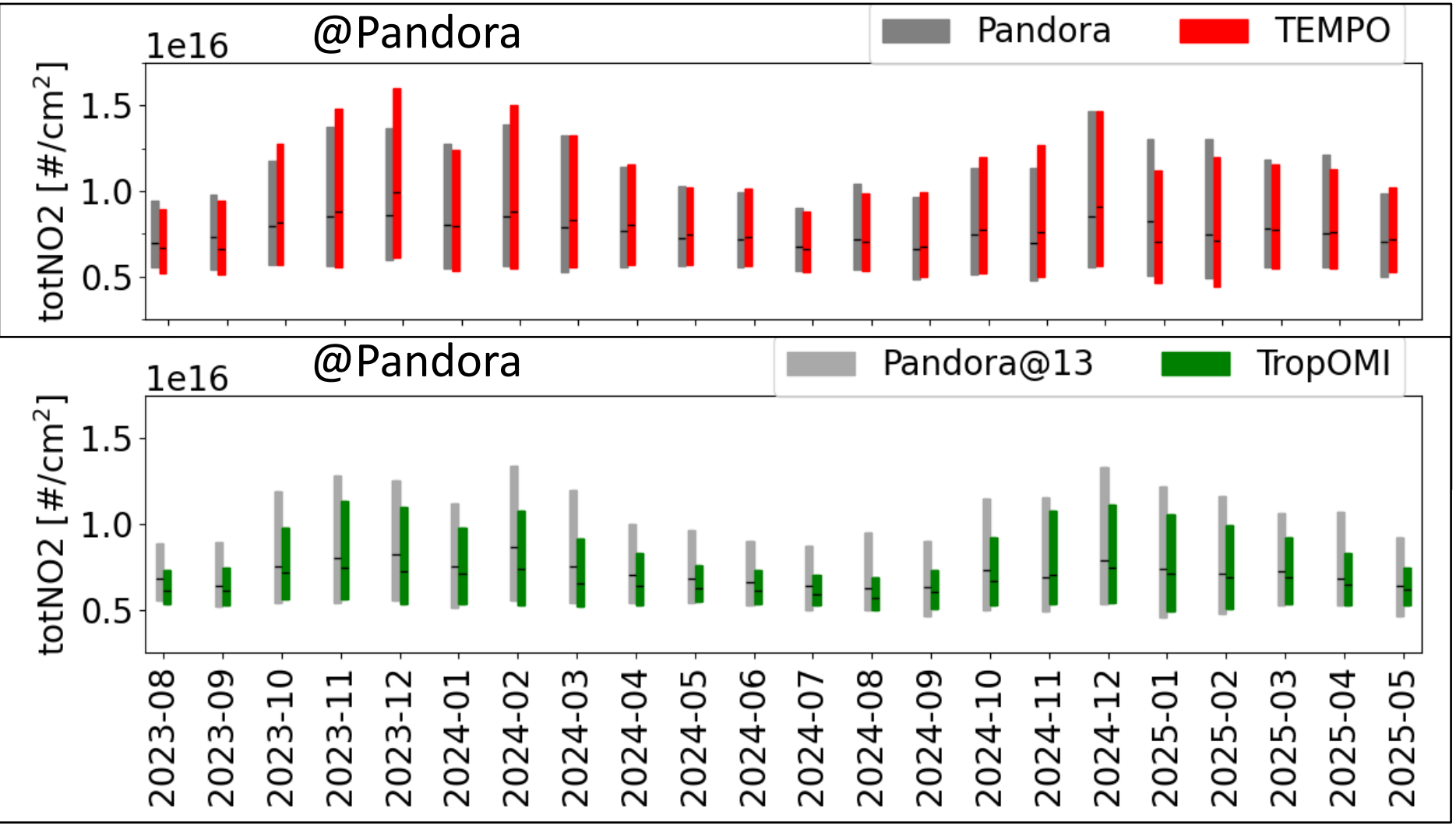






Summaries and site-level analysis at https://gaftp.epa.gov/Air/aqmg/bhenders/share/TEMPO/README.html

Pandora totNO$_2$ Validation Aug 2023 to May 2025



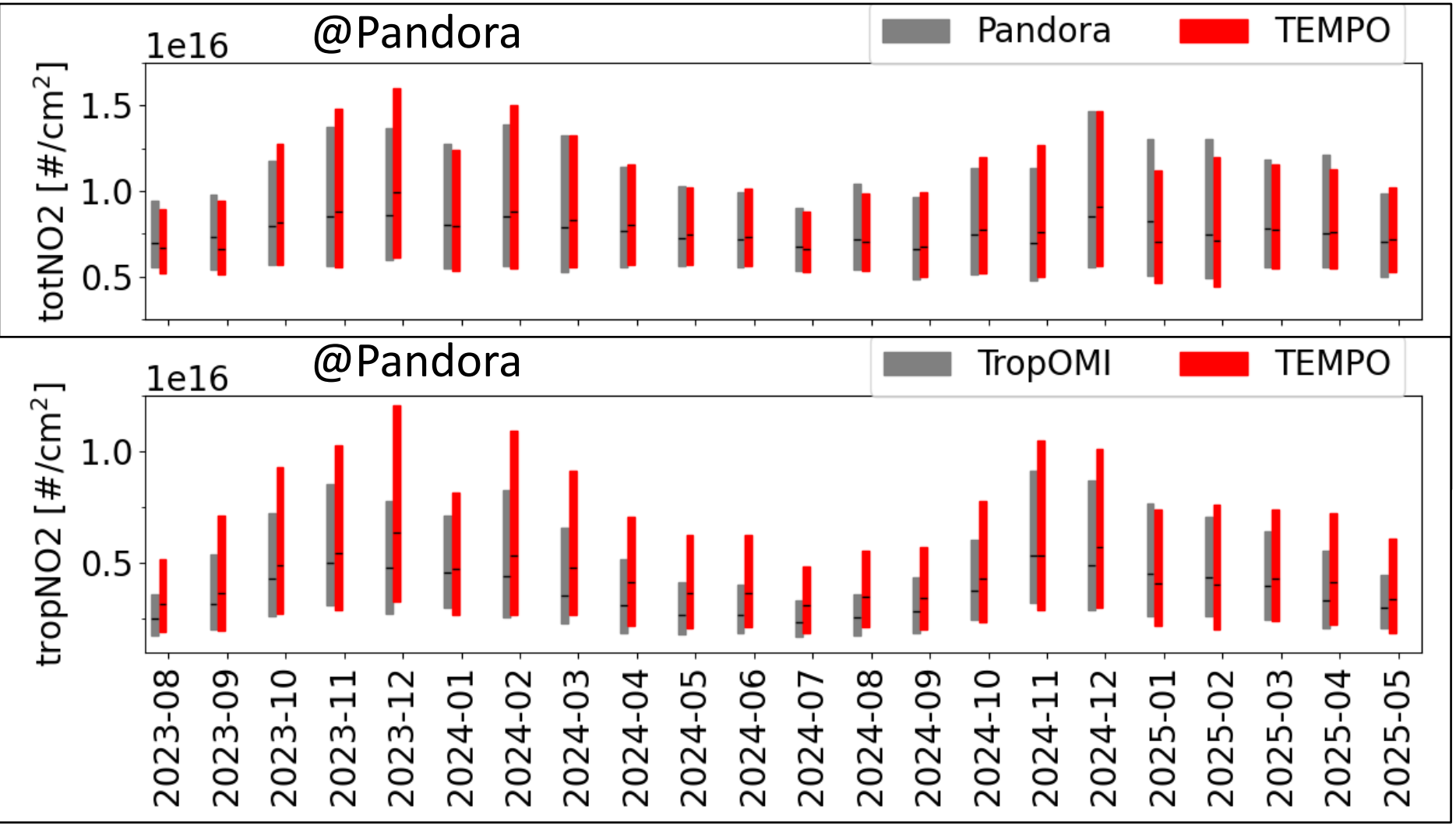
line: 50% boxes: 25%-75%
Solid Boxes: Mon-Fri

TEMPO captures seasonal pattern (r=0.82) with good bias (NMB=3%)

TropOMI captures seasonal pattern (r=0.88), but low (NMB=-14%)

- **Smaller variability in TropOMI**
- **TropOMI low-biased for high NO2?**

TropOMI totNO$_2$ and tropNO$_2$ Eval *@Pandora* Aug 2023 to May 2025



line: 50% boxes: 25%-75%
Solid Boxes: Mon-Fri

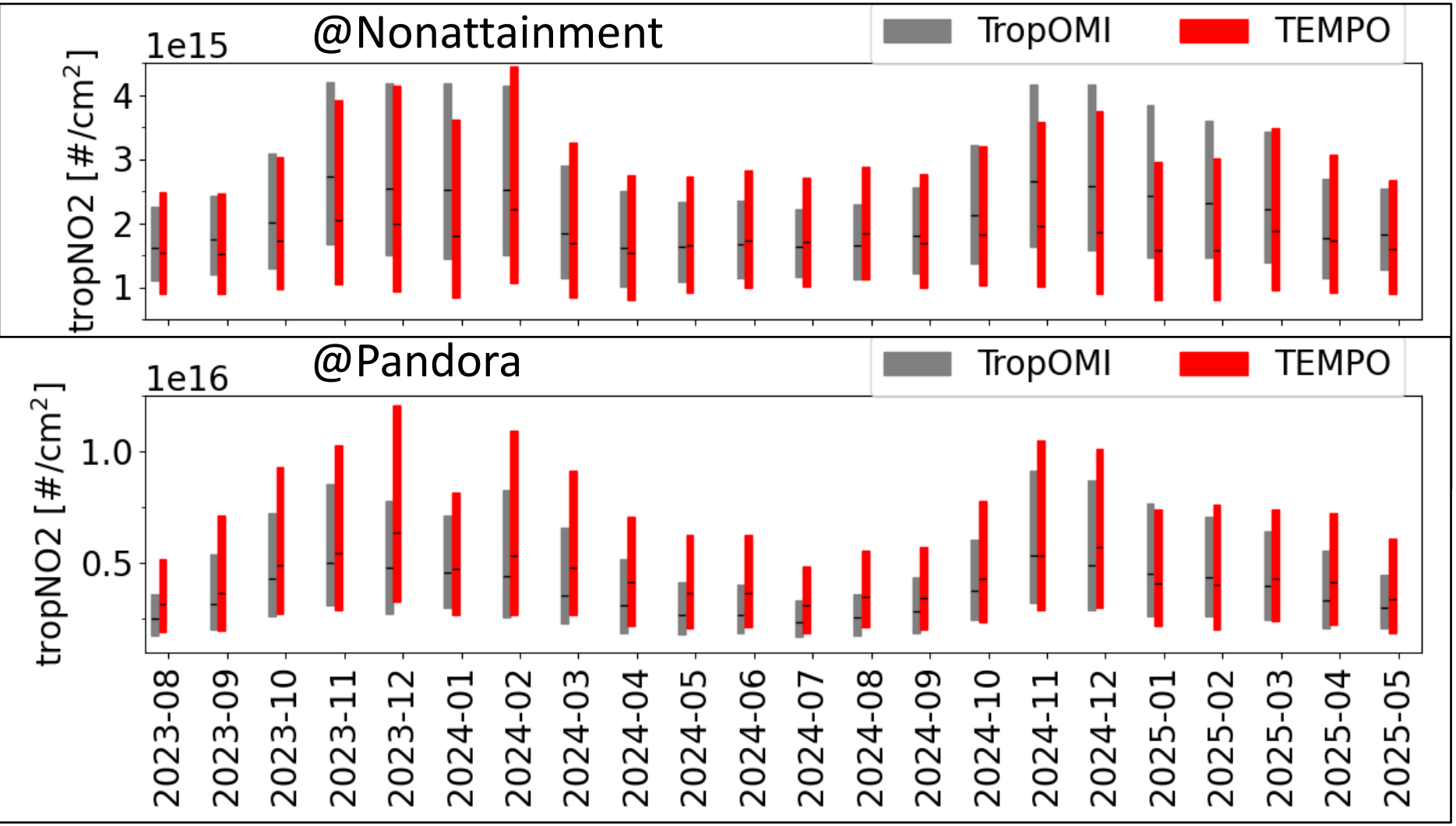
TEMPO captures Pandora seasonal pattern (r=0.82) with good bias (NMB=3%)

<u>Using TropOMI as a reference</u>

As expected, TEMPO is higher than TropOMI (NMB=+19%)

So, you might expect TEMPO to be high biased over Nonattainment Areas (NAA)

TropOMI totNO$_2$ and tropNO$_2$ Eval *@All Intersections* Aug 2023 to May 2025



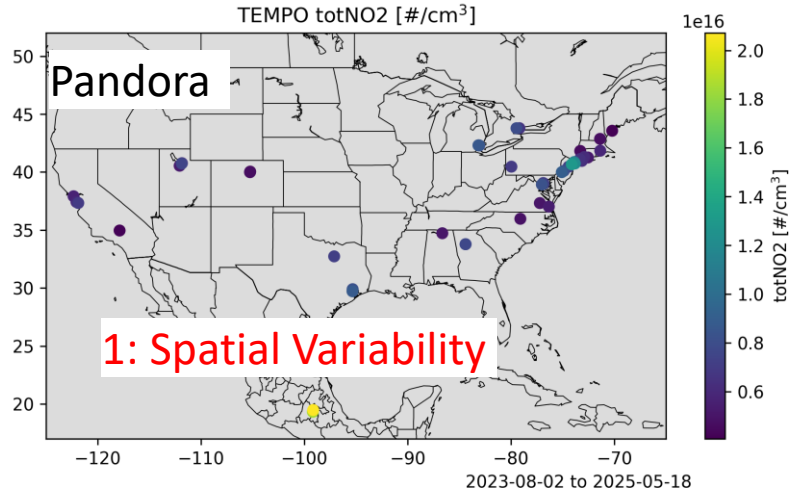
line: 50% boxes: 25%-75%
Solid Boxes: Mon-Fri

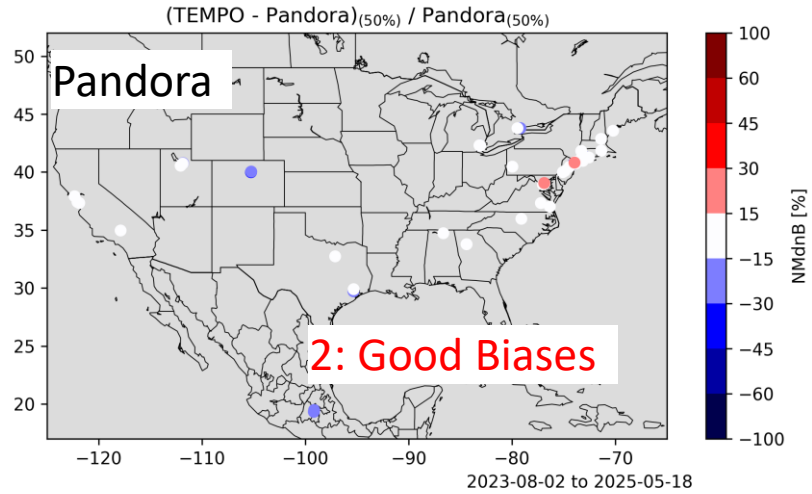
Unexpectedly TEMPO has lower NAA values (NMB=-11%)

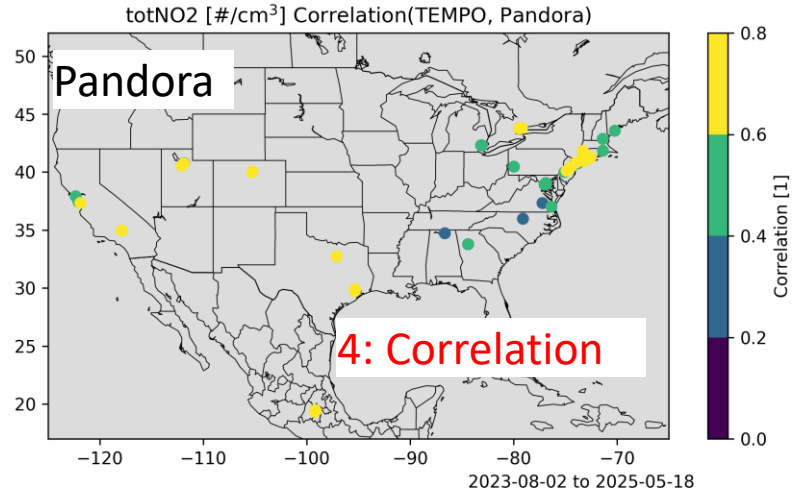
- **Pandora sites are typically in urban areas, mostly in the west**
- **NAA cover urban, but area dominated by suburbs/rural and area-wise are in the west (California).**
- **TropOMI may have a high-bias at low NO2?**

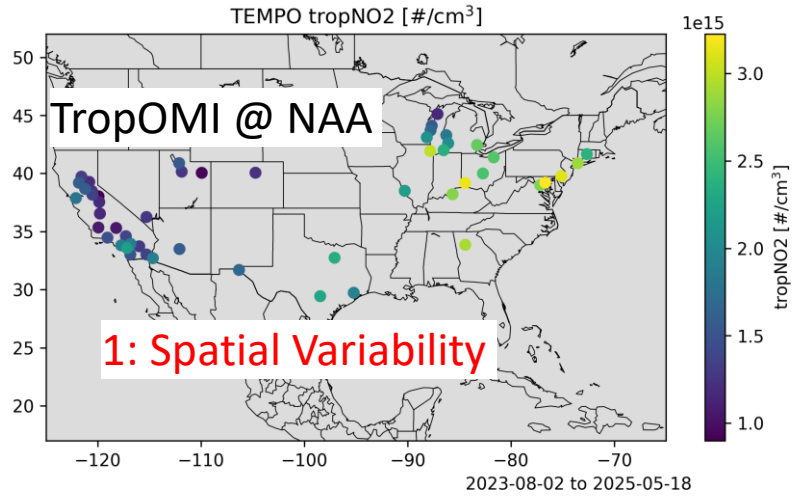
Need Pandoras at strategic suburban ad rural locations to provide ground truth.

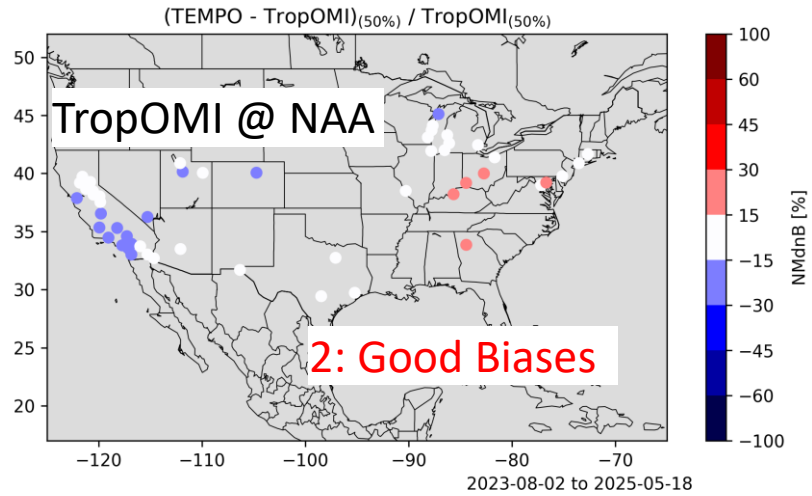
Site-level $totNO_2$ and $tropNO_2$ Eval Available

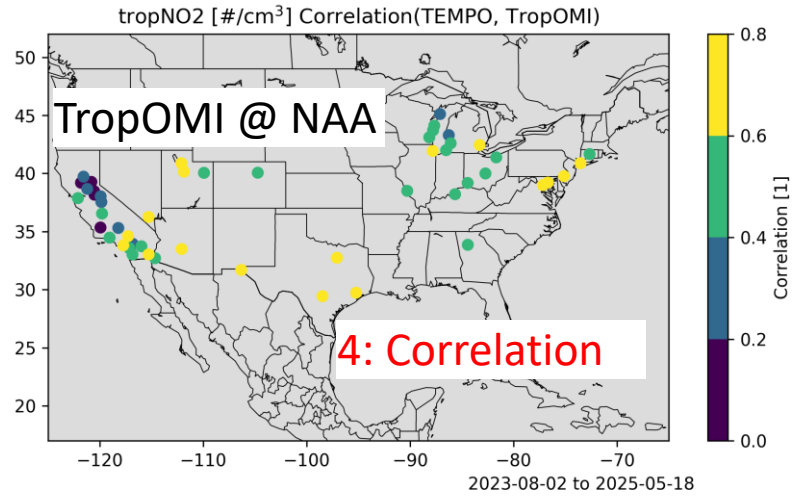












Summaries and site-level analysis at https://gaftp.epa.gov/Air/aqmg/bhenders/share/TEMPO/README.html

Seasonal and Diurnal Performance is Consistent

TEMPO L2 vs Pandora Total NO2

Agreement: Correlation (R) and Index of Agreement (IOA)

Generally strong agreement

- Increasing correlation from 6-11 LST
- 10-17LST correlation generally good

Bias and error worst in morning

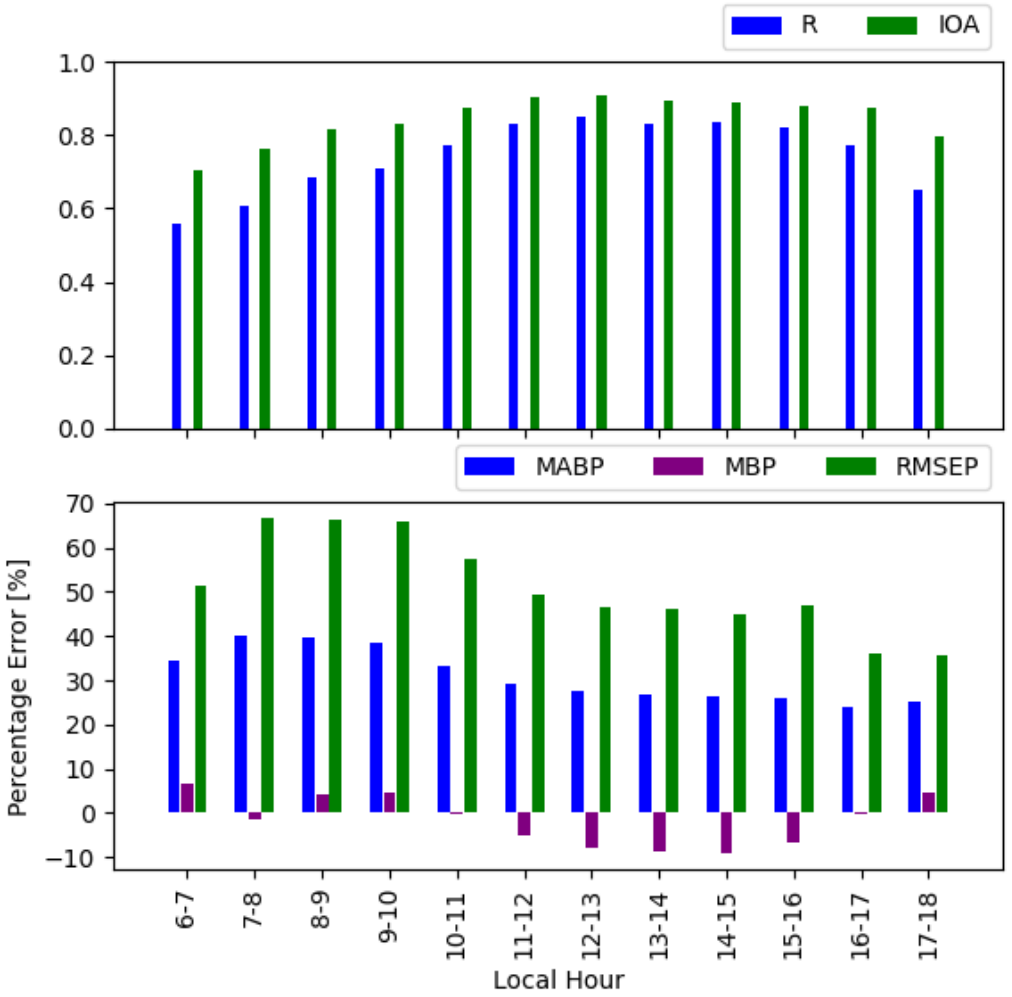
- 6-7 LST : Few observations
- 7-10:59 LST : the RMSE and MAB increase
- 11-15:59 LST error statistics are better
- 16-17:59 dropping again

Err as % Mean

Mean Abs Bias

Mean Bias

RMSE

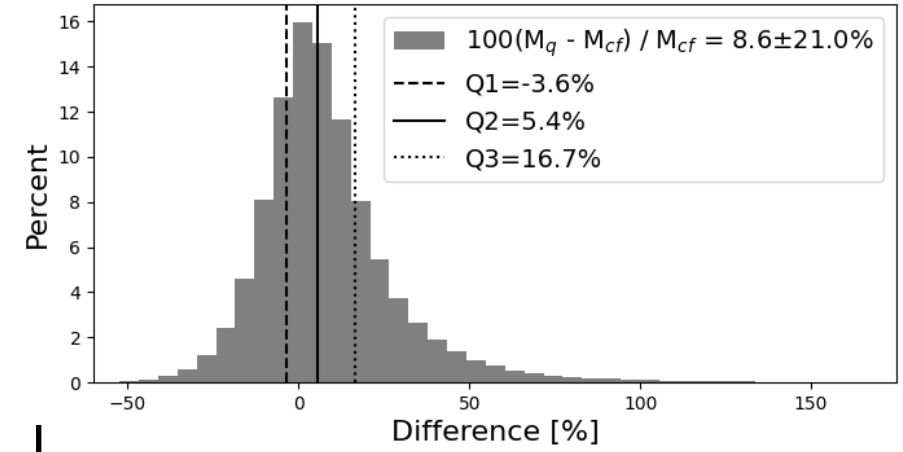


Early Applications

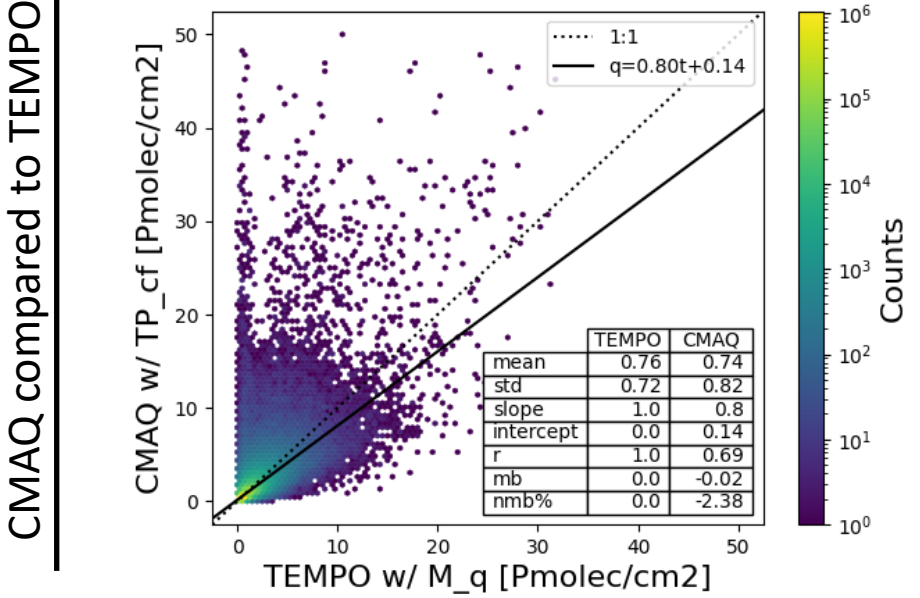
TEMPO L2 vs Preliminary CMAQ Application

- Focusing on NO2 Applications
  - Model performance evaluation (are columns similar?)
  - Dynamic evaluation (do columns respond to emissions similarly? Using weekend vs weekday
- Case study of convenience Sept 2023
  - Expediated Modeling of Burn Events Results (EMBER)*
    - 2018 anthropogenic emissions
    - 2023 preliminary fire inventory
  - *Longer analysis would be ideal*

Air Mass Factor differences from TEMPO prior



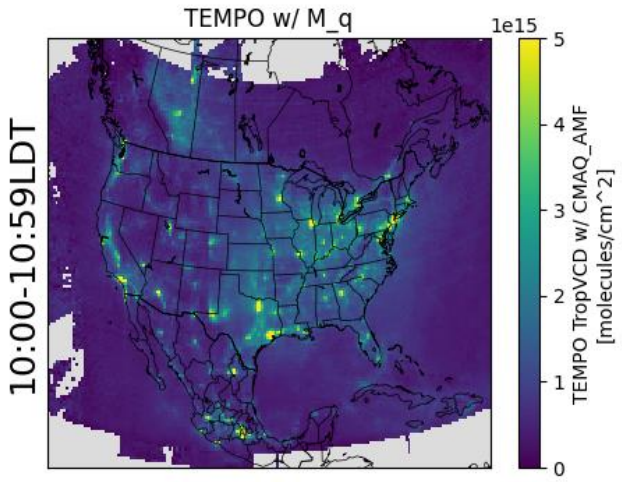
CMAQ compared to TEMPO

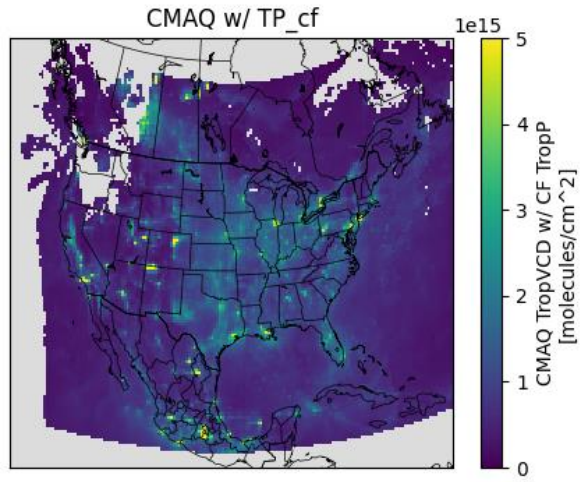


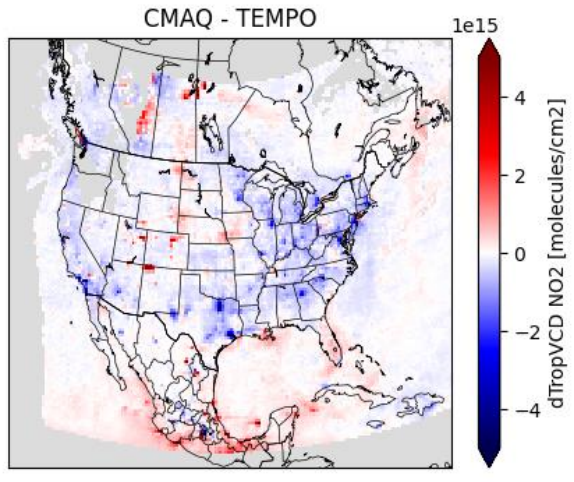
* Simon et al. (10.1016/j.dib.2024.111208) Data in Brief

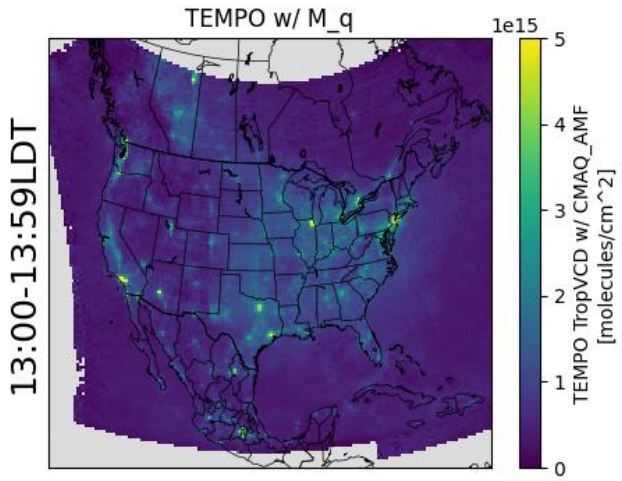
Model Performance Evaluation

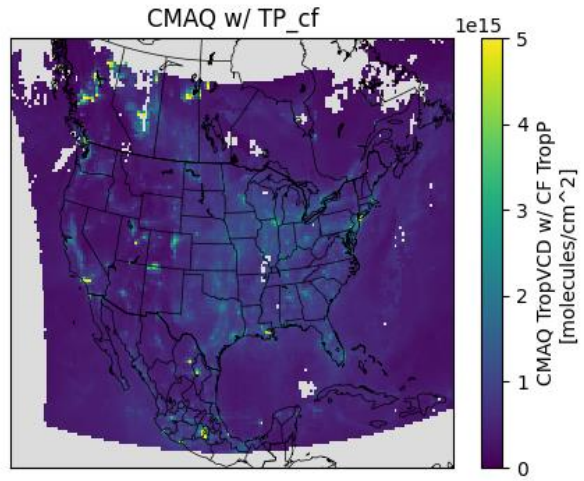
TEMPO L2 vs Preliminary CMAQ Application

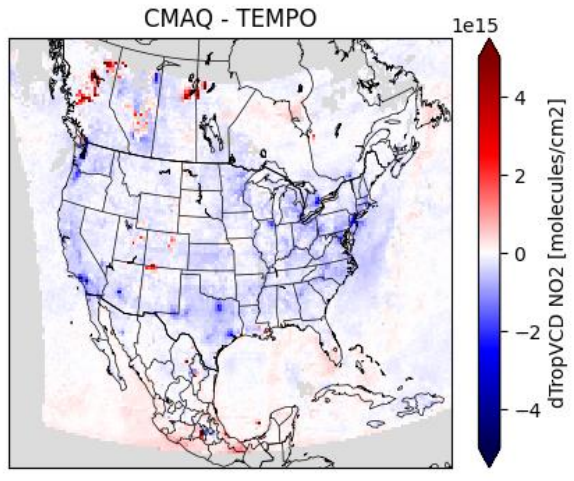












TEMPO TropVCD

CMAQ TropVCD

CMAQ – TEMPO

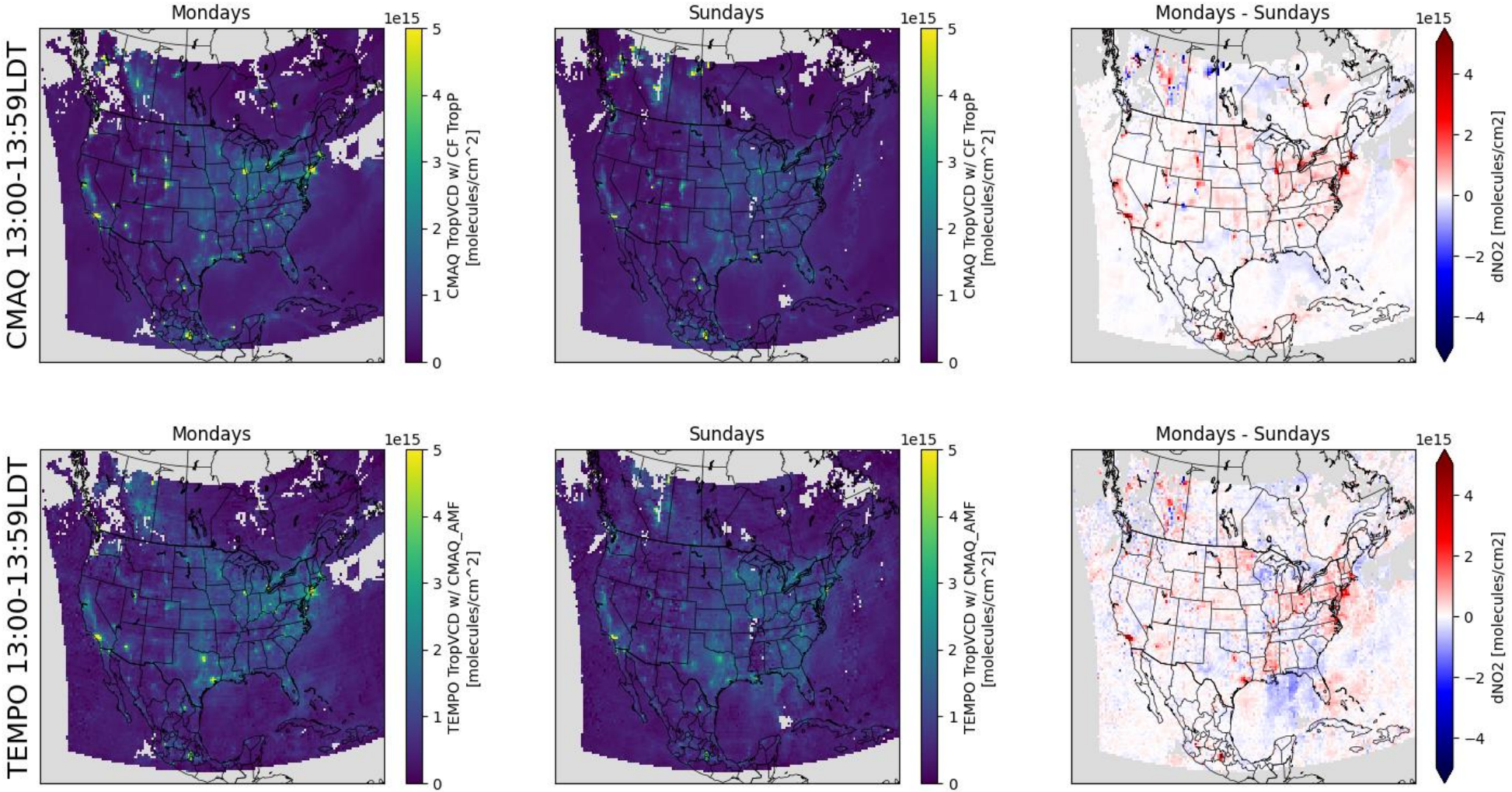
Sept 2023 average

- CMAQ has low biases in many major cities
- TEMPO and CMAQ have larger tropospheric columns in the morning hours (10-11LDT) than at polar overpass.
- Morning differences are larger in absolute scale.

Consistent w/ Nash et al. 2024 (10.5194/egusphere-2024-554), corrects low ozone bias that is largest in the west.

Dynamic Evaluation

TEMPO L2 vs Preliminary CMAQ Application



Monday Magnitude

Sunday Magnitude

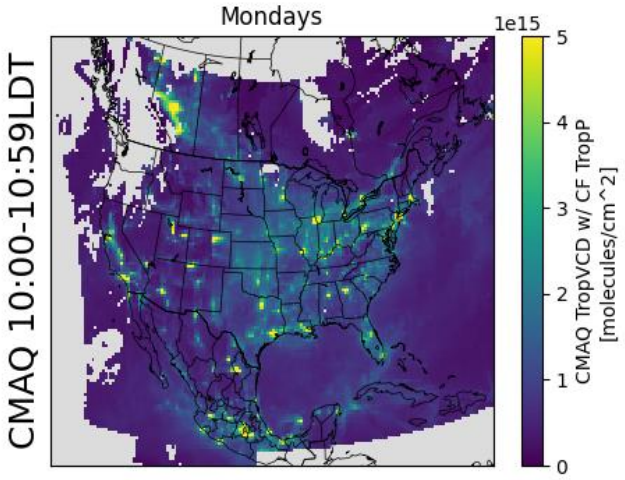
Weekday Increment

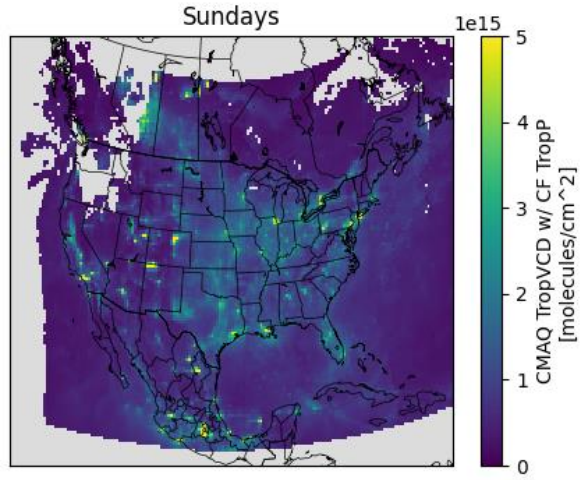
1PM overpass

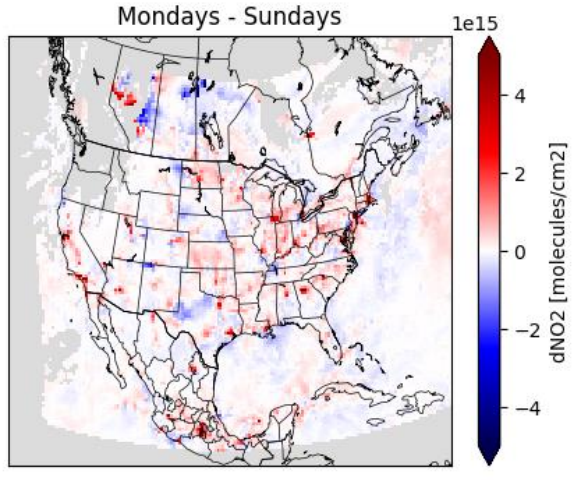
- Weekday/weekend analysis (n=4)
- Tropospheric columns in major cities stand out in both TEMPO and CMAQ
- Mondays larger than Sundays in polluted scenes
- Unexpected differences in Mississippi

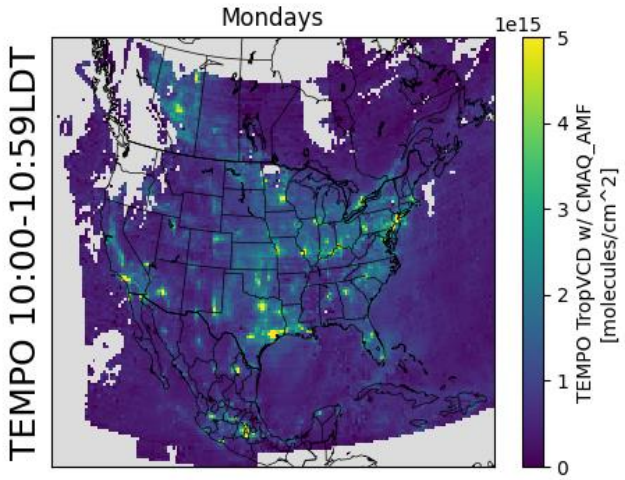
Dynamic Evaluation

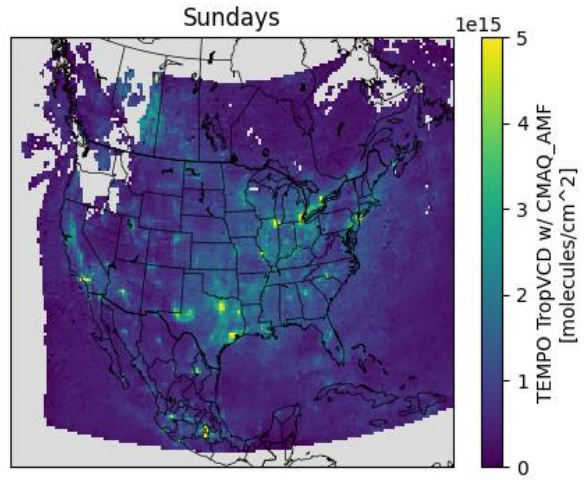
TEMPO L2 vs Preliminary CMAQ Application

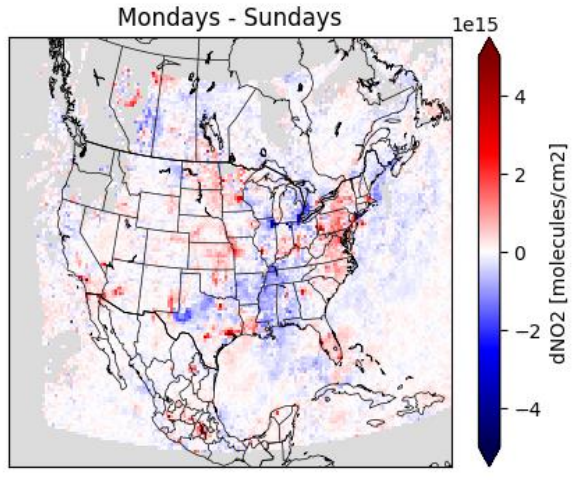












Monday Magnitude

Sunday Magnitude

Weekday Increment

At morning scan

- Weekday/weekend analysis (n=4)
- TEMPO and CMAQ increments over cities are more similar at 10LDT than at 13LDT
- TEMPO has more negative increments than CMAQ in general and over the southeast and Great Lakes in particular.
- TEMPO Chicago increment looks suspect.
- Need longer data to isolate variability vs true difference.

Summary

- Community led validation TEAM helped TEMPO meet validation goals
  - Nitrogen dioxide and formaldehyde results contribute to both the beta and provisional maturity levels.
  - Assessing bias, precision and uncertainty (NO2-02, NO2-04, HCHO-02 and HCHO-04)
  - Inter-site gradients contributes to urban/rural gradient assessments (NO2-01 and HCHO-01)
  - Large pixel-to-pixel variation and data striping remains
  - Reveals strong disagreement between TEMPO and TropOMI HCHO, which is likely an ***improvement***.
- TEMPO shows 2023 CMAQ simulation low-bias
  - Confirms TropOMI results (Kumm AGU presentation)
  - Geostationary coverage would require fewer assumptions in top-down emission adjustments.
- Thanks to:
  - Kelly Chance, SAO, NASA and all the people who helped deliver on the promise of TEMPO!
  - NASA LaRC ASDC for assistance to connect TEMPO to RSIG APIs and increase accessibility!
  - Pandonia Global Network and State and Local agencies for working with EPA to expand Pandora measurements!
  - Research groups and researchers who have contributed their time and analysis in support of TEMPO validation!

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