



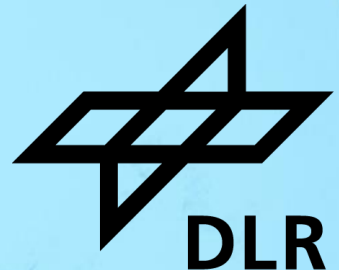
Sharing is
encouraged

THE PEGASOS PROJECT: EVALUATION OF GEO-RING DATA WITH LEO AND GROUND BASED MEASUREMENTS

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PEGASOS consortium

Product Evaluation of GEMS L2 via Assessment with S5P and Other Sensors



- DLR
 - German Aerospace Center
 - Remote Sensing Technology Institute
- AUTH
 - Aristotle University of Thessaloniki
 - Laboratory of Atmospheric Physics
- BIRA-IASB
 - Royal Belgian Institute for Space Aeronomy
- IUP-UB
 - University of Bremen
 - Institute for Environmental Physics



ESA - ESRIN



Main objective

- Evaluation of  and  L2 data products using
 - a) LEO sensors (TROPOMI and other space-borne instruments)
 - b) ground-based instruments/networks

a)	b)
TROPOMI / S5P	Brewer
OMI / Aura	Dobson
GOME-2 / MetOp	Ozonesondes
IASI / MetOp	FTIR
VIIRS / S-NPP	MAX-DOAS
CALIOP / CALIPSO	PGN
AMI / GK-2A	NDACC

Geo-Ring for Air Quality

PEGASOS Phase 1 (2023-2024)

- GEMS

PEGASOS Phase 2 (2025-2026)

- GEMS
- TEMPO

Future

- EarthCARE!
- Sentinel-4?

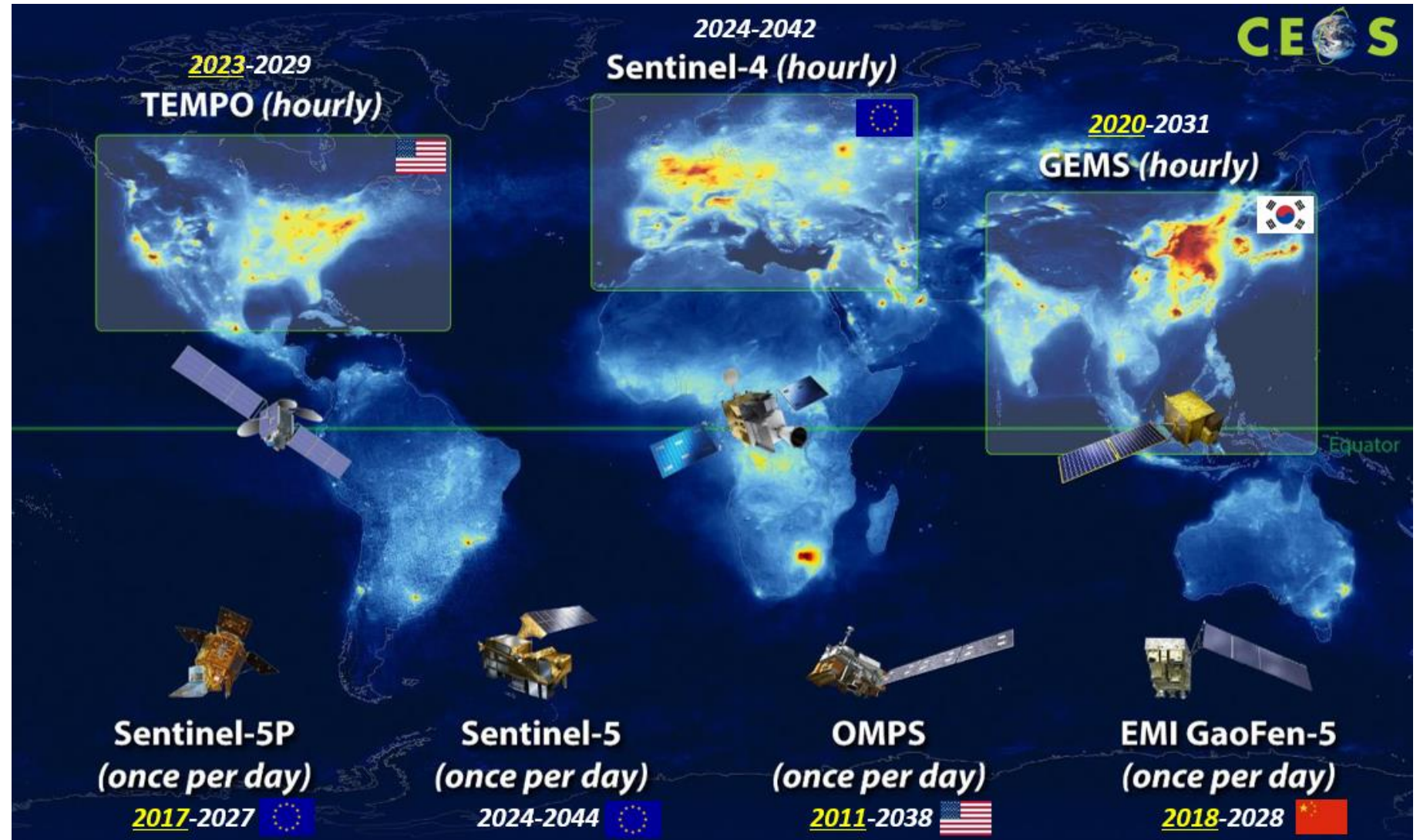
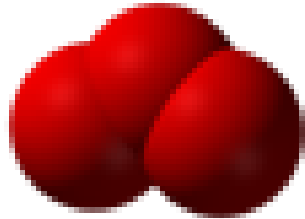


image courtesy: CEOS

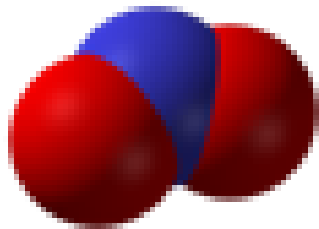
GEMS and TEMPO L2 products evaluated by PEGASOS



Ozone
total



Clouds
fraction
height



Nitrogendioxide
total
trop.
strat.



Aerosols
index
opt.depth
layer height

used for the comparisons:

- Phase 1: also SO₂, HCHO, O₃ profile, tropospheric ozone and surface properties
- Phase 2: limited to total Ozone, NO₂, Clouds, Aerosols

EXAMPLES (I): GEMS

Results:

5 years of **GEMS O3T v2.1** data showed:

Mean relative bias w.r.t. gr-based stations and other satellite missions: -4 %

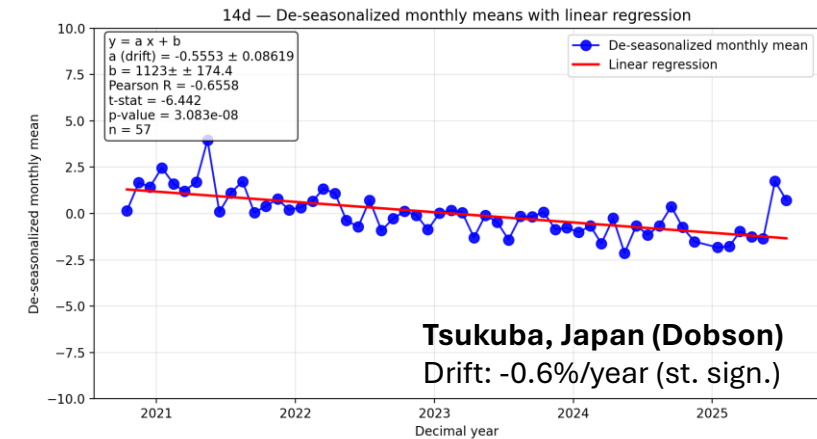
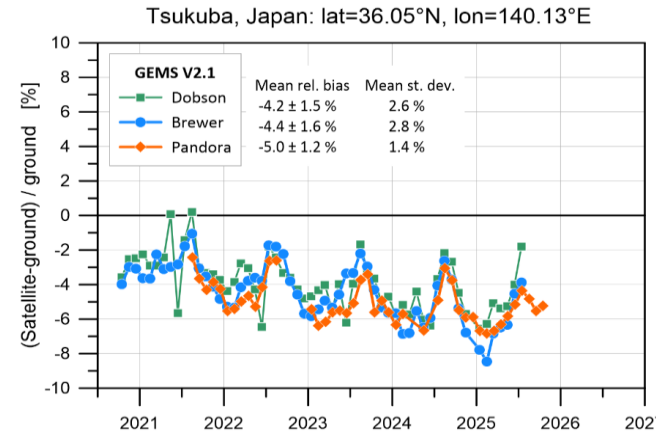
Pearson correlation coefficient ≥ 0.9 , showing a very good agreement between GEMS and the reference measurements

Clear non-unity slope ($< 0.9-1$): higher underestimation for high TOCs (North, winter)

A drift of $-0.5\%/year$ w.r.t. reference measurements

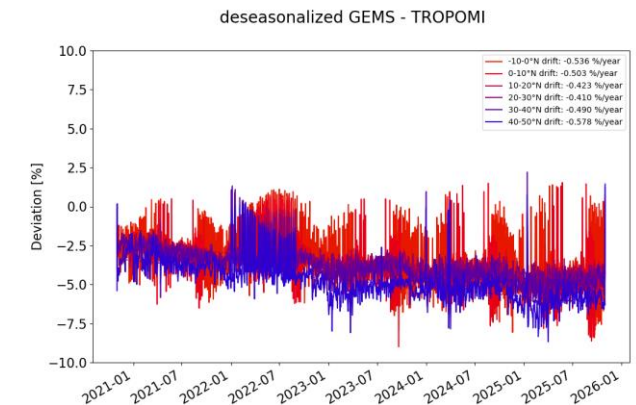
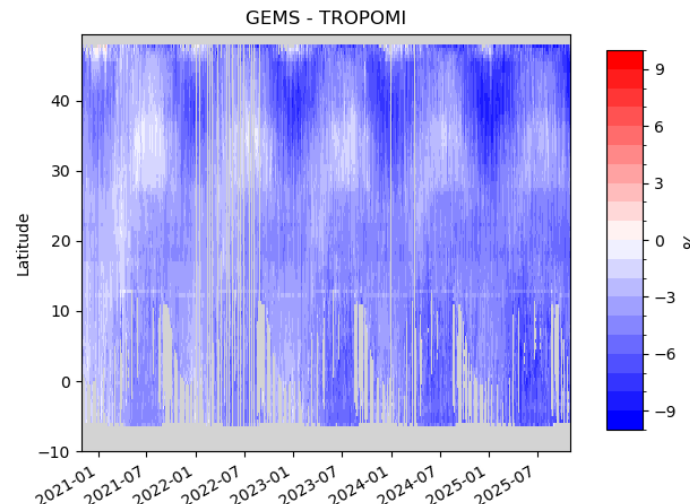
North – South gradient with an annual cycle that differs per latitude:

- Very good agreement during summer months at high latitudes and winter months at tropics ($\pm 1\%$).
- During winter months and for higher latitudes GEMS underestimates total ozone by up to -7%



Left: Time-series of the mean relative bias (%) of GEMS O3T observations w.r.t. ground-based reference measurements from Brewer, Dobson and Pandora at Tsukuba, Japan.

Right: For the same station, the de-seasonalized monthly mean time series of the GEMS vs Dobson comparisons.



Left: The mean percentage difference between the O3T observations from GEMS and TROPOMI over the GEMS FOV.

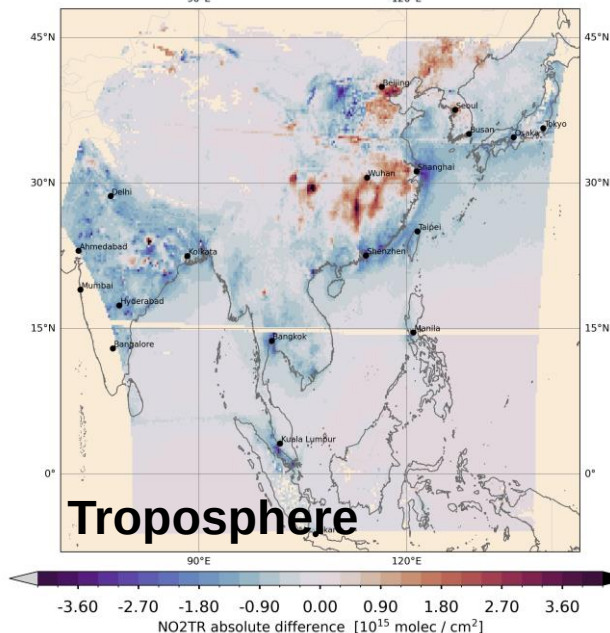
Right: De-seasonalized sat-to-sat differences per latitude belt.

Results:

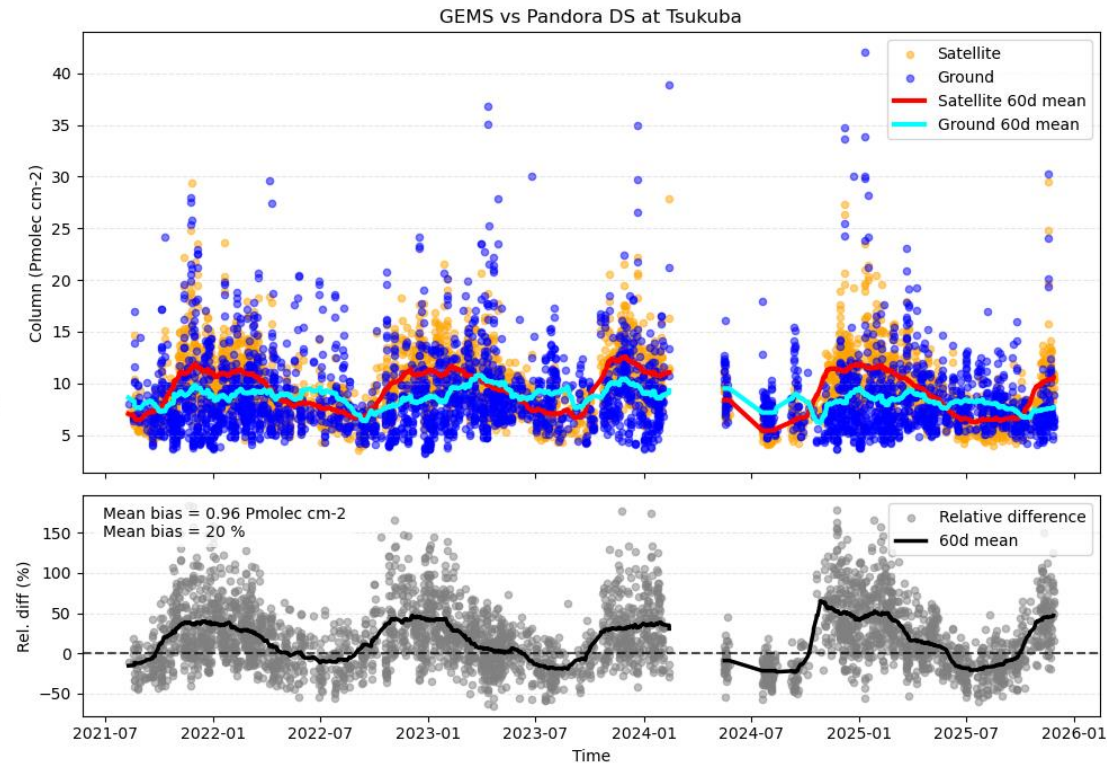
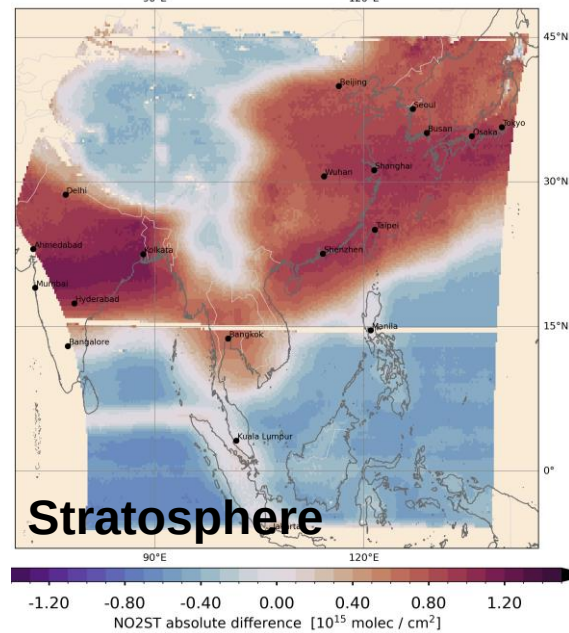
We compared GEMS NO₂ V3 and TROPOMI V2.8 for a three month period (2025/12 – 2026/02).

- **Total** column difference AD = -0.3 ± 0.6 Pmolec/cm², **tropospheric** AD = -0.2 ± 0.5 Pmolec/cm² (higher bias over polluted areas, low bias over India), **stratospheric** AD = 0.13 ± 0.6 Pmolec/cm².
- The positive bias in the North changes to negative biases over the ocean in the South. That compensates with tropospheric columns in the total columns.

GEMS4 - TROPOMI, 2025.12-2026.02: $\bar{O} = -0.24$ PMC; $\sigma_1(\bar{O}) = 0.5$ PMC



- TROPOMI, 2025.12-2026.02: $\bar{O} = 0.13$ PMC; $\sigma_1(\bar{O}) = 0.6$ PMC



Tsukuba (NIES, Japan) Pandora PGN: Reasonable correlation (0.63) and RMSE (37%), but **peculiar positive bias** in local winter.

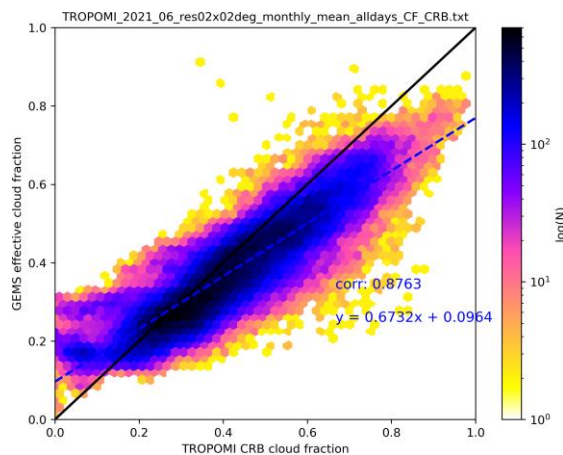
Results:

We applied OCRA CF retrieval to GEMS L1 and compared with GEMS CLD V3.

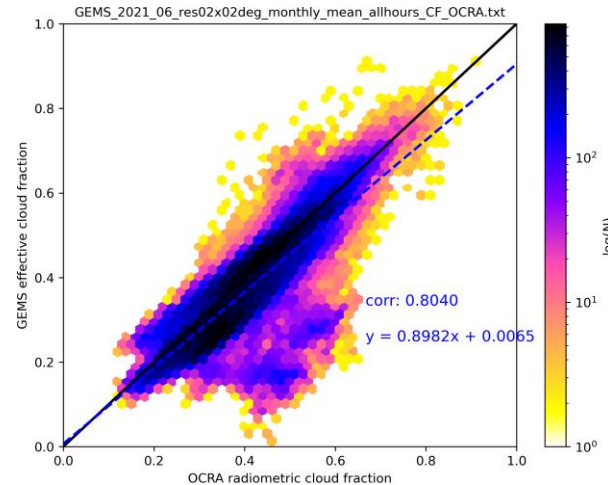
- high correlation (0.80) and slope close to unity
- shape of zonal mean CF agrees very well

We compared GEMS CLD V3 and TROPOMI CRB

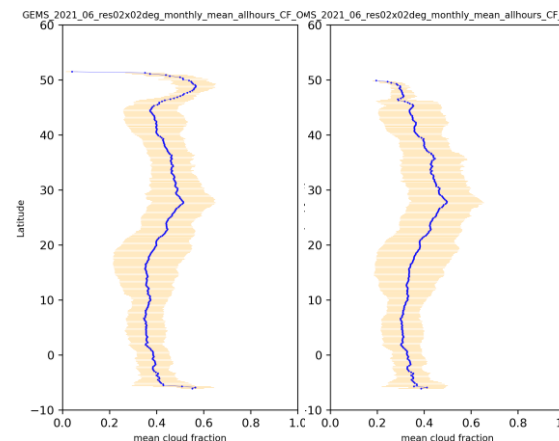
- CF has very high correlation (0.88)
- CP difference depends on cloud altitude
 - low clouds: small positive difference
 - high clouds: small negative difference



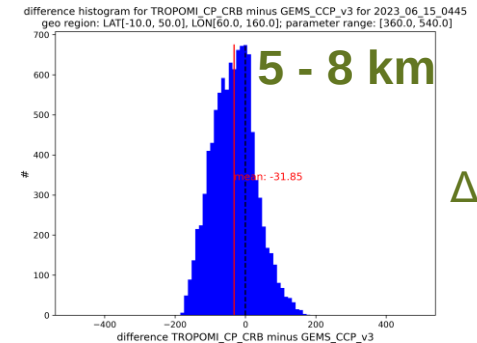
cloud fraction comparisons
TROPOMI vs. GEMS



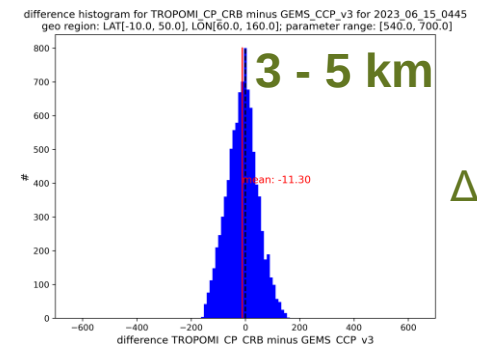
OCRA CF vs GEMS CLD V3



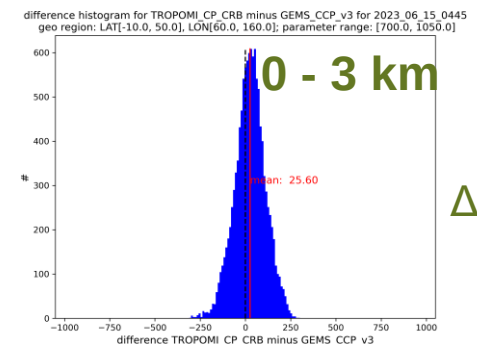
Zonal mean CF from OCRA
(left) and GEMS V3 (right)



$\Delta = -32$ hPa



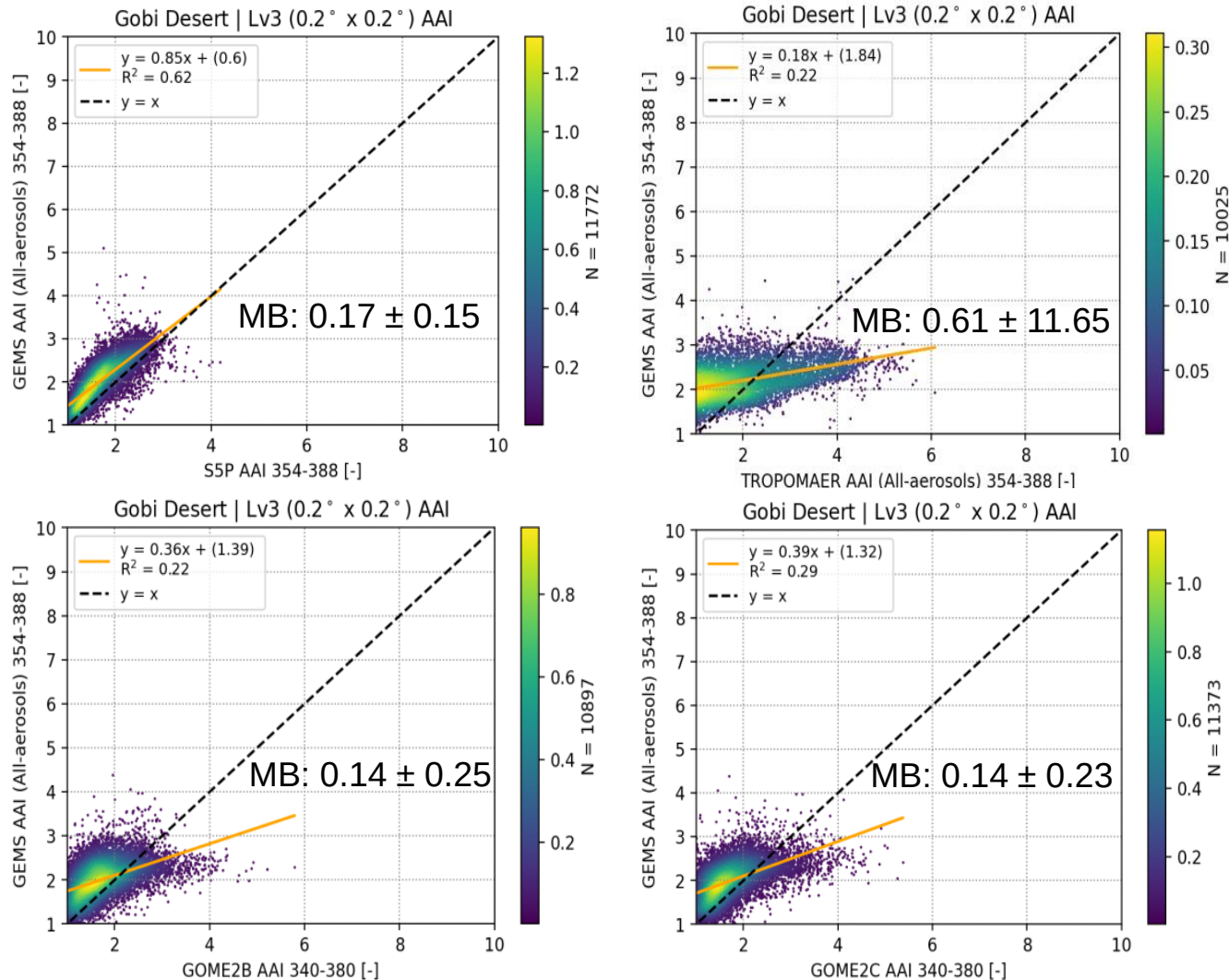
$\Delta = -11$ hPa



$\Delta = +26$ hPa

cloud pressure differences
TROPOMI – GEMS in hPa

GEMS Aerosol Index (v2.1) Validation over Gobi Desert



GEMS AOD (v2.1) Validation over Gobi Desert

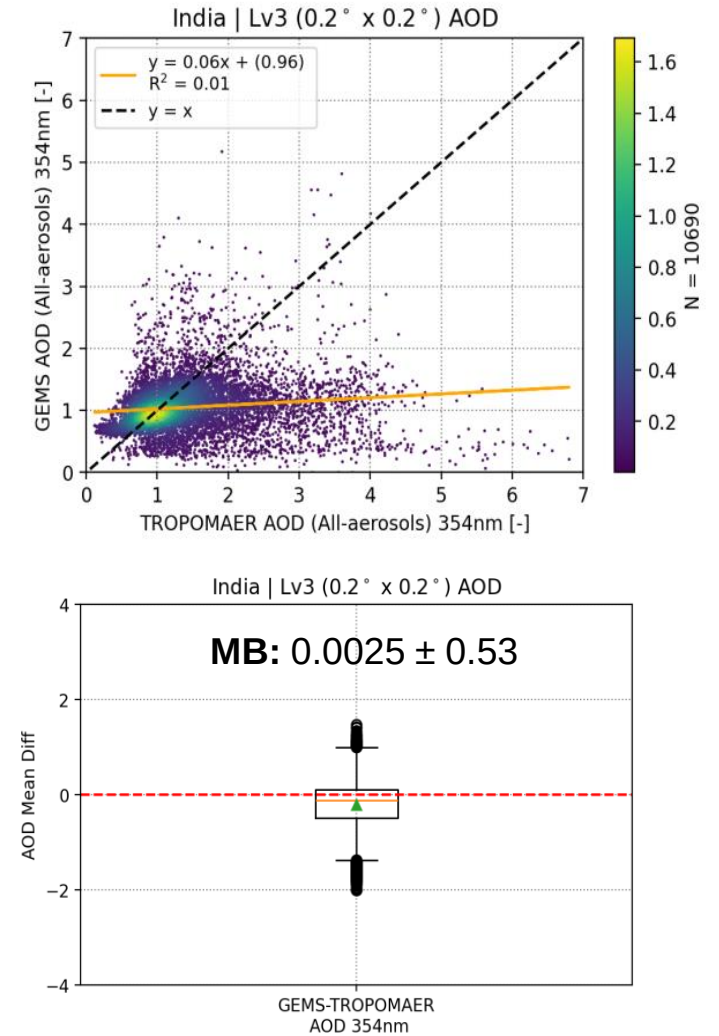


Figure 1. Density scatterplots of AAI over the Gobi Desert (0.2° x 0.2°), for GEMS against (top left) TROPOMI, (top right) TROPOMAER, (bottom left) GOME-2B, GOME-2C (bottom right).

Figure 2. Evaluation of aerosol optical depth (AOD) across all case studies over India, comparing TROPOMAER and GEMS.

GEMS Aerosol Height (v2.1) Validation [January to October 2025] – Eastern Asia

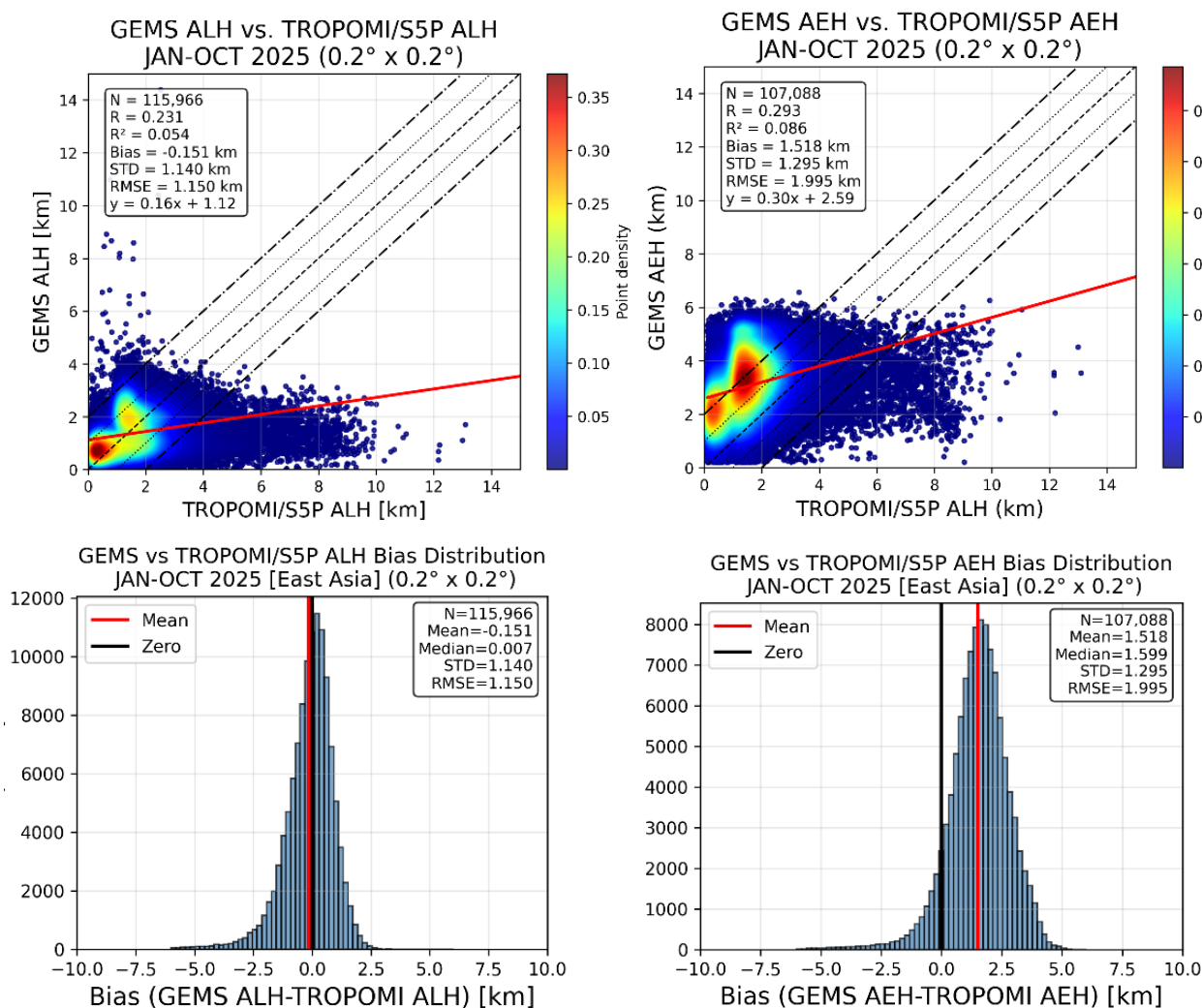


Figure 3. (Top) Density scatter plots of GEMS ALH (left) and AEH (right) with TROPOMI. (Bottom) Histograms showing the distribution of differences between GEMS ALH and TROPOMI ALH.

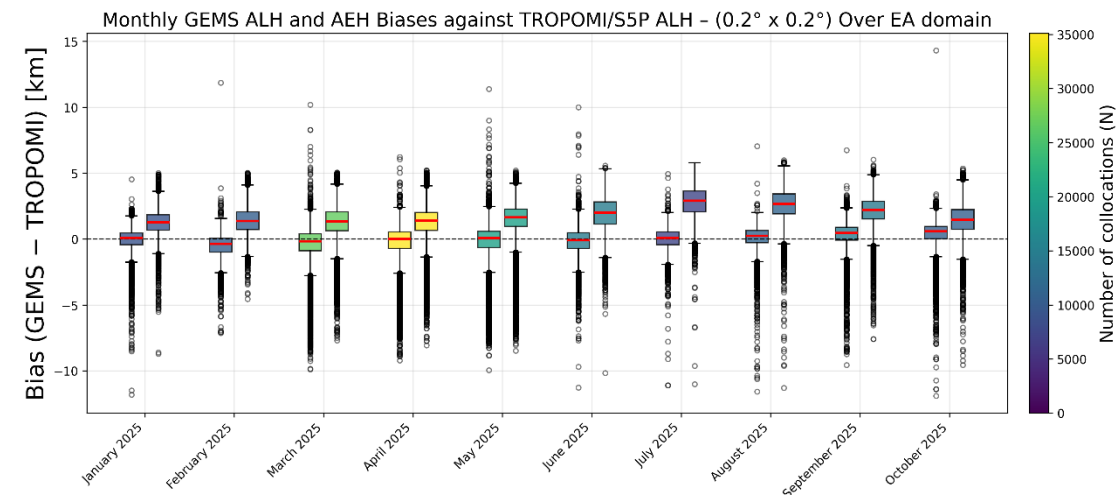


Figure 4. Box plots of ALH bias between GEMS (v2.1) and TROPOMI/S5P.

- **TROPOMI vs GEMS ALH** (R = 0.23 / MB: -0.15±1.14 km)
- **TROPOMI vs GEMS AEH** (R = 0.29 / MB: 1.52±1.29 km)

The GEMS retrieves both the ALH and AEH products by independent algorithm processes:

- **AEH:** O₄ SCD (DOAS, L1C, pre. corrected) → **Layer Midpoint**
- **ALH:** Opt. Estim. (AOD, SSA, a priori) → **Densest Layer altitude**

Consistent offset between ALH - AEH due to different definitions!

EXAMPLES (II):





Total Ozone

Team: K. Garane, S. Compennolle, K.-P. Heue, T. Verhoelst



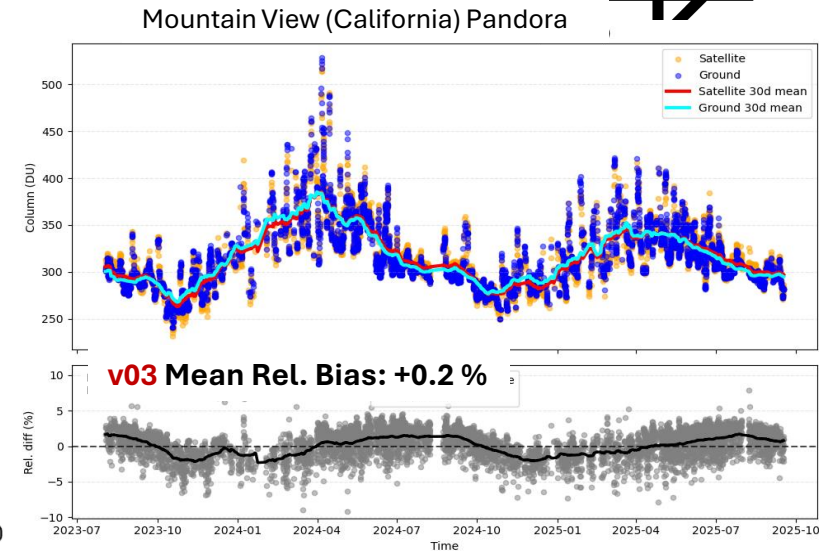
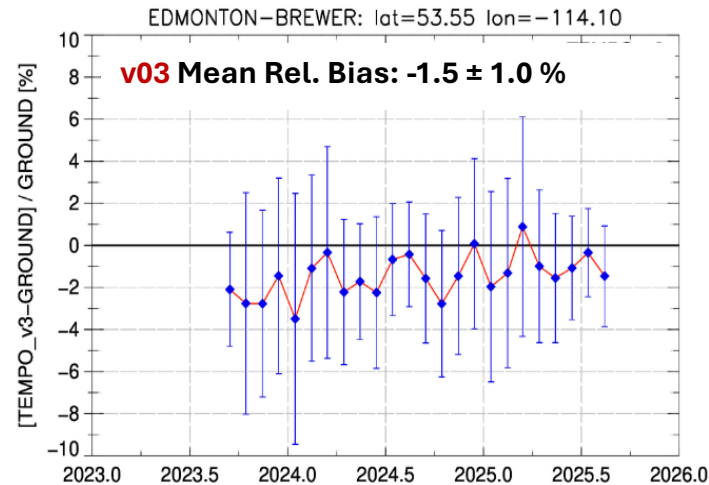
Results:

TEMPO O3T v03 (2 years of data) :

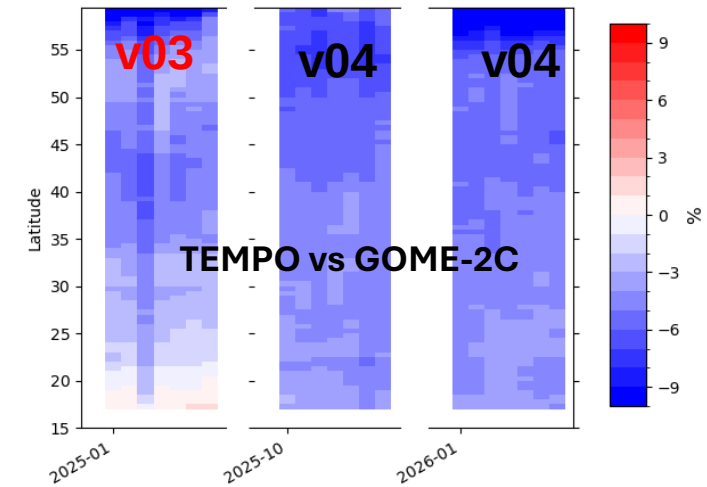
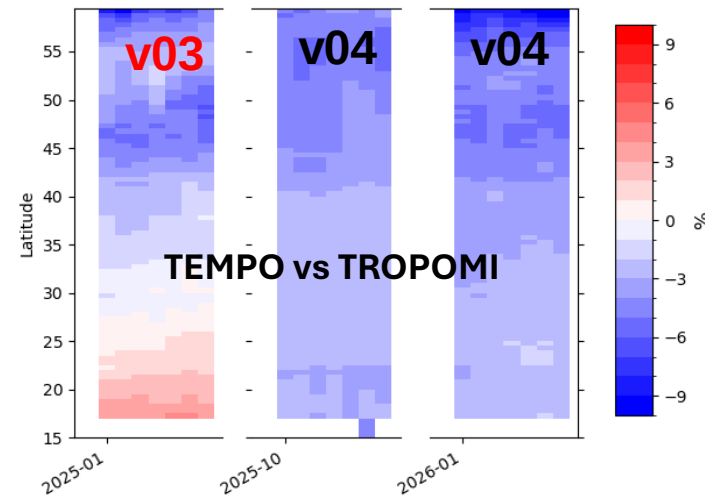
- Mean relative bias: -1.5 to -2 %
- Pearson R > 0.95
- Important North – South gradient:
 - Tropics: Very good agreement ($\sim +1\%$)
 - North: negative biases w.r.t. ground-based observations and other satellite sensors ($\sim -4\%$)

TEMPO O3T v04 data (3.5m of data):

- Mean relative bias: -2 to -3.5 %
- Pearson R > 0.97
- Improved North – South gradient: almost stable bias across all latitudes



Time-series of the mean relative bias (%) of **GEMS O3T v03** w.r.t. ground-based reference measurements from the Edmonton Brewer station (**left**) and the Mountain View Pandora station (**right**)

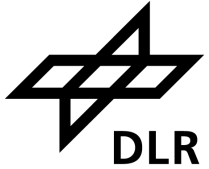


The mean percentage differences between the O3T observations from TEMPO (v03 and v04) and TROPOMI (**left**), GOME-2C (**right**) over the GEMS FOV.



NO₂

Team: K.-U. Eichmann, I. de Smedt, C. Vigouroux, G. Pinardi,
S. Compernelle, T. Verhoelst, S. Seo

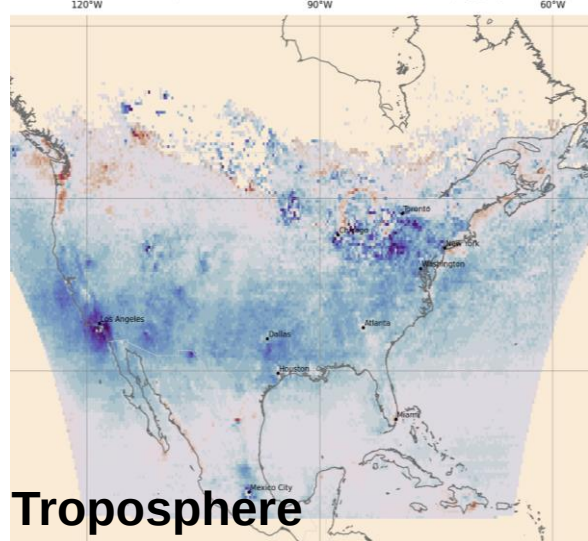


Results:

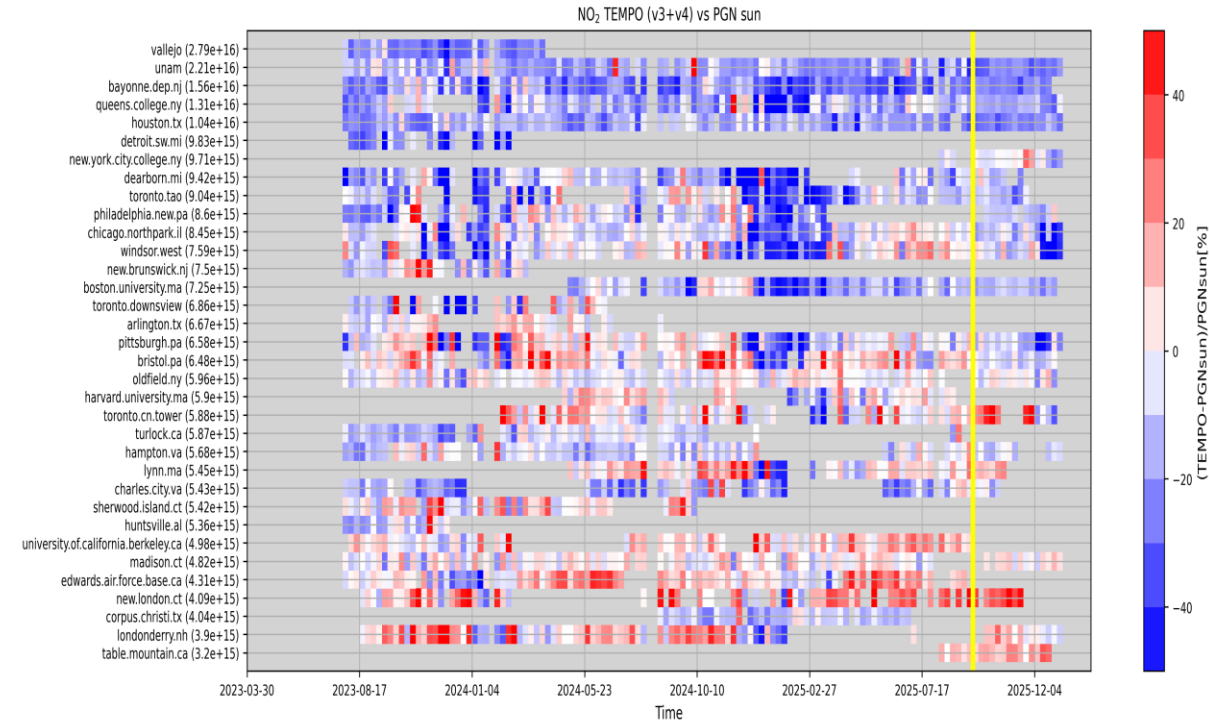
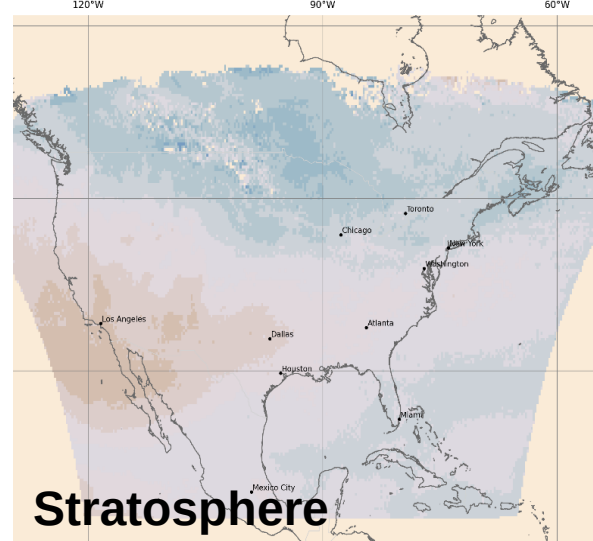
We compared TEMPO NO2 V4 and TROPOMI V2.9 for a two month period (2025/12 – 2026/01).

- **Total** column difference is -0.19 ± 0.5 Pmolec/cm2, **tropospheric** AD= -0.27 ± 0.3 Pmolec/cm2, **stratospheric** AD= -0.07 ± 0.1 Pmolec/cm2.
- There is still a very **low bias near LA** in the tropospheric column. This is partly compensated by a high bias in the stratosphere.

TEMPO4 - TROPOMI, 2025.12-2026.01: $\bar{\Delta} = -0.27$ PMC; $\sigma_1(\bar{\Delta}) = 0.3$ PMC



TEMPO4 - TROPOMI, 2026.01-2026.01: $\bar{\Delta} = -0.07$ PMC; $\sigma_1(\bar{\Delta}) = 0.1$ PMC

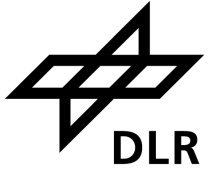


Time series of the relative differences between TEMPO v3 and v4 and PGN (@EVDC) total NO₂ measurements at the 34 PGN sites with meaningful temporal coverage.



Clouds

Team: V. Molina García, R. Lutz, D. Loyola



Results:

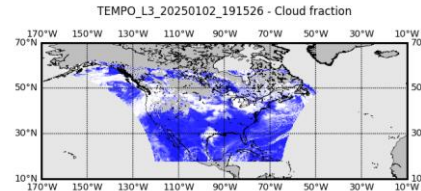
TEMPO CLDO4 v03 (2025-01-01 to 2025-01-07) :

- Regional averaged comparisons TEMPO vs S5P for cloud fraction and cloud-centroid pressure
- Cloud Fraction (CF):**
 - Mean difference of -0.014
 - Differences between S5P cloud fraction and TEMPO cloud fraction behave symmetric around 0.0
- Cloud-Centroid Pressure (CCP):**
 - Mean difference of -23.776 hPa
 - S5P cloud-centroid altitudes are slightly higher than TEMPO cloud-centroid altitudes

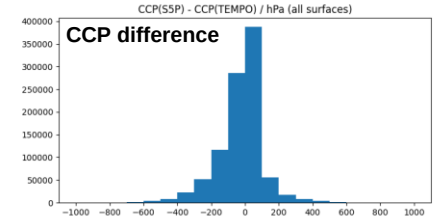
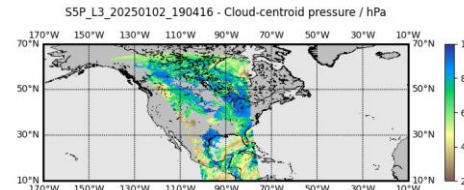
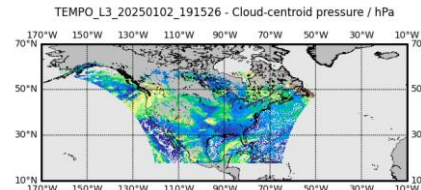
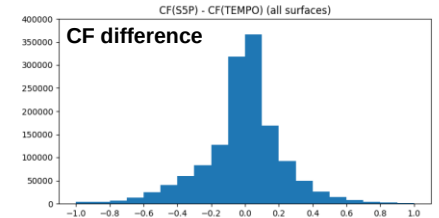
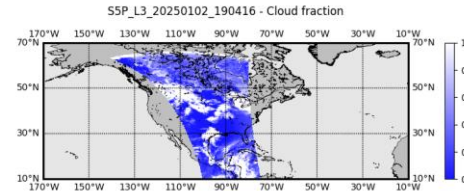
TEMPO CLDO4 v04 (2025-10-01 to 2025-10-07 and 2026-01-01 to 2026-01-07):

- Direct pixel-by-pixel comparisons with custom TEMPO OCRA algorithm for cloud fraction
- Cloud Fraction (CF):**
 - Mean difference of +0.172
 - TEMPO CLDO4 CF does not reach 1 so often as TEMPO OCRA CF, even for big cloud structures
 - TEMPO CLDO4 CF behaves better at high zenith angles, where TEMPO OCRA CF tends to saturate

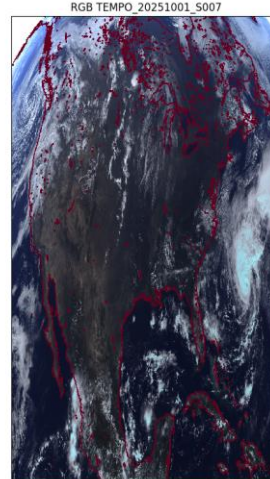
TEMPO 2025-01-02 19:15:26



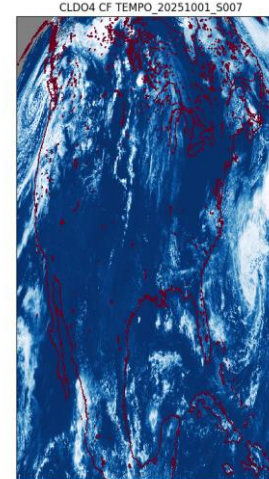
S5P 2025-01-02 19:04:16



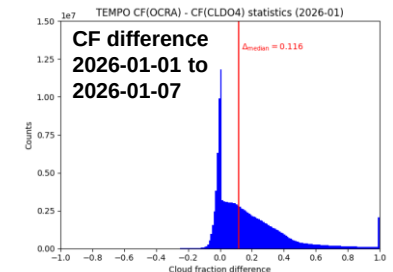
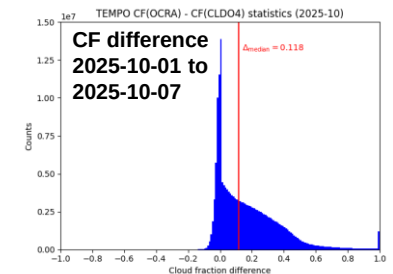
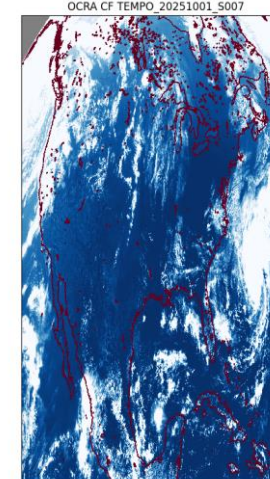
TEMPO 2025-10-01 S007



CLDO4 CF

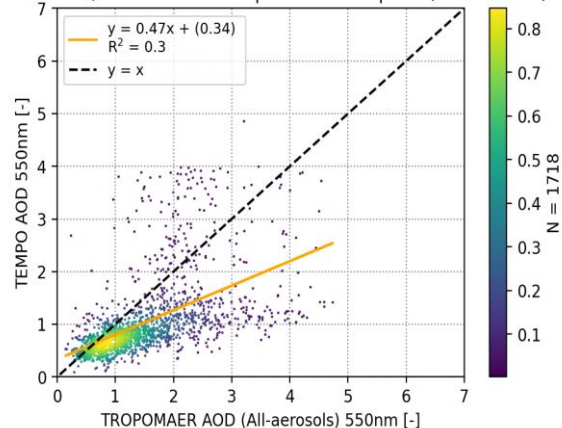


OCRA CF



AOD - Canadian Wildfire: 19-08-2023

USA Lat: 40N-52N, Lon: 122W-90W | 2023-08-19 | Lv3 (0.2° x 0.2°) AOD



USA Lat: 40N-52N, Lon: 122W-90W | 2023-08-19 | Lv3 (0.2° x 0.2°) AOD

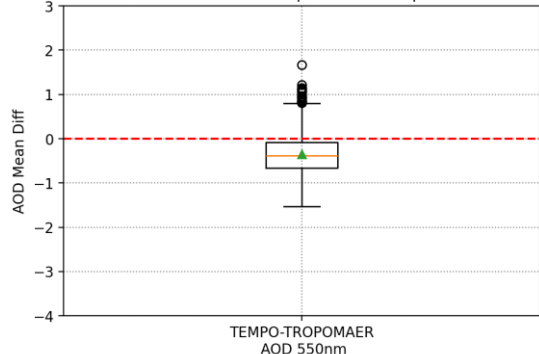
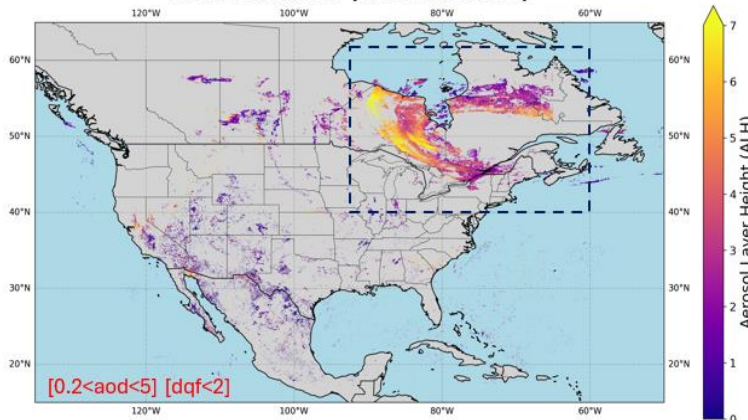


Figure 5. (Upper) Density scatter plots of TROPOMAER (left) against TEMPO AOD. (Bottom) Box-plot of the mean differences.

Aerosol Layer Height [ALH] - Canadian Wildfire: 19-08-2023

TEMPO Aerosol Layer Height FOR (ALH)
Datetime: 25-09-2023 [18:31:34 to 19:33:44]



S5P Aerosol Layer Height (ALH) - Date: 25-09-2023
Domain: N.America (0.1° x 0.1°) [QA>=50] Mode: OFFL

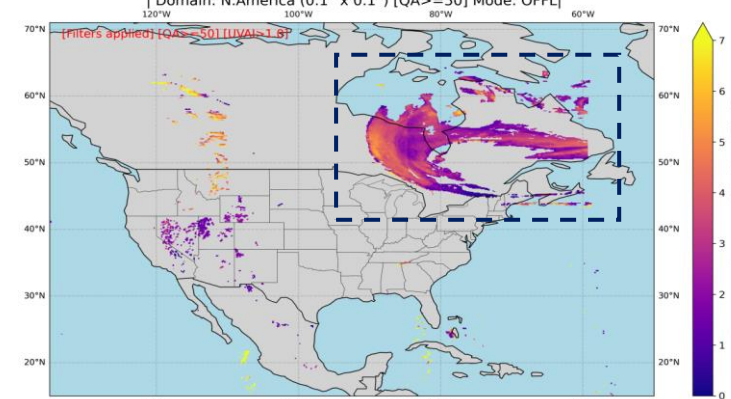
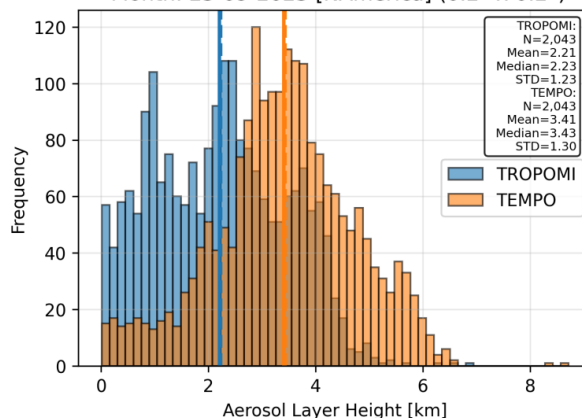
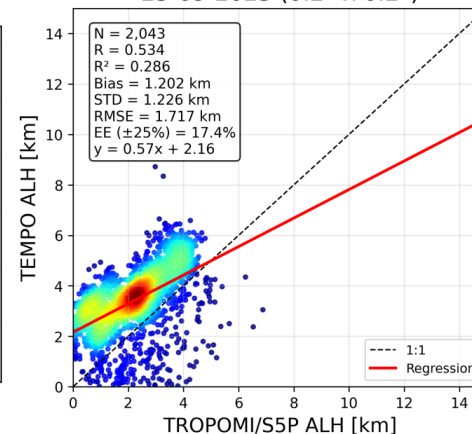


Figure. Spatial distribution of aerosol height products over N.America during an extreme smoke event on 25 September 2023, (left) TEMPOALH (scan10) and TROPOMI/S5P ALH.

TEMPO vs TROPOMI/S5P ALH Distributions
Month: 25-09-2023 [NAmerica] (0.2° x 0.2°)



25-09-2023 (0.2° x 0.2°)



TEMPO vs TROPOMI/S5P ALH Bias Distribution
25-09-2023 [NAmerica] (0.2° x 0.2°)

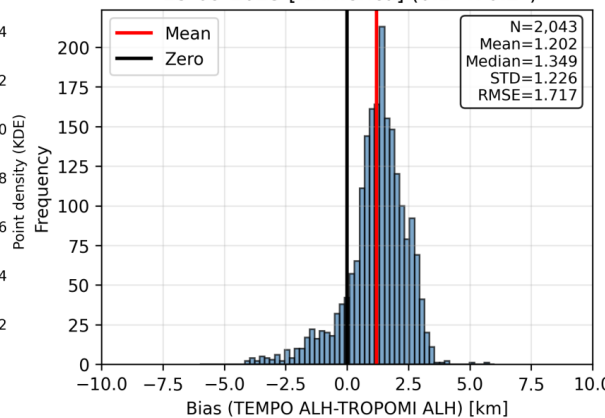
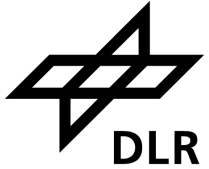


Figure 6. (Left) Frequency distributions of collocated TEMPO & TROPOMI ALH. (Middle) Scatter density plot showing their correlation. (Right) Histogram of absolute differences (TEMPO-TROPOMI), indicating agreement and variability under smoke conditions.

Credits to the PEGASOS team



Timon Hummel, Claus Zehner



Pascal Hedelt, Klaus-Peter Heue, Diego Loyola, Ronny Lutz, Victor Molina Garcia, Sora Seo



Katerina Garane, Konstantinos Michaelidis, Panagiotis Fountoukidis, Dimitris Balis, MariLiza Koukouli

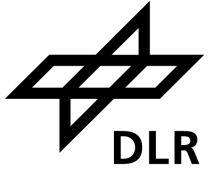


Steven Compernelle, Martine de Maziere, Isabelle de Smedt, Daan Hubert, Arno Keppens, Jean-Christopher Lambert, Gaia Pinardi, Nicolas Theys, Michel van Roozendaal, Tijl Verhoelst, Corinne Vigouroux



Kai-Uwe Eichmann, Mark Weber

Credits to the GEMS and TEMPO teams



We appreciate the good collaboration with the GEMS and TEMPO L2 product developers and their contributions to the PEGASOS project!



Thank you for your attention!

comments or questions? Contact me at ronny.lutz@dlr.de