THE PEGASOS PROJECT

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CEOS AC-VC #22, Leiden, The Netherlands & Online, 1 – 4 June 2026

PEGASOS consortium

Product **E**valuation of **G**EMS L2 via **A**ssessment with **S**5P and **O**ther **S**ensors

- 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 GEMS and TEMPO 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**

PEGASOS Phase 3? (>2027)

- **GEMS**
- **TEMPO**
- **Sentinel-4?**

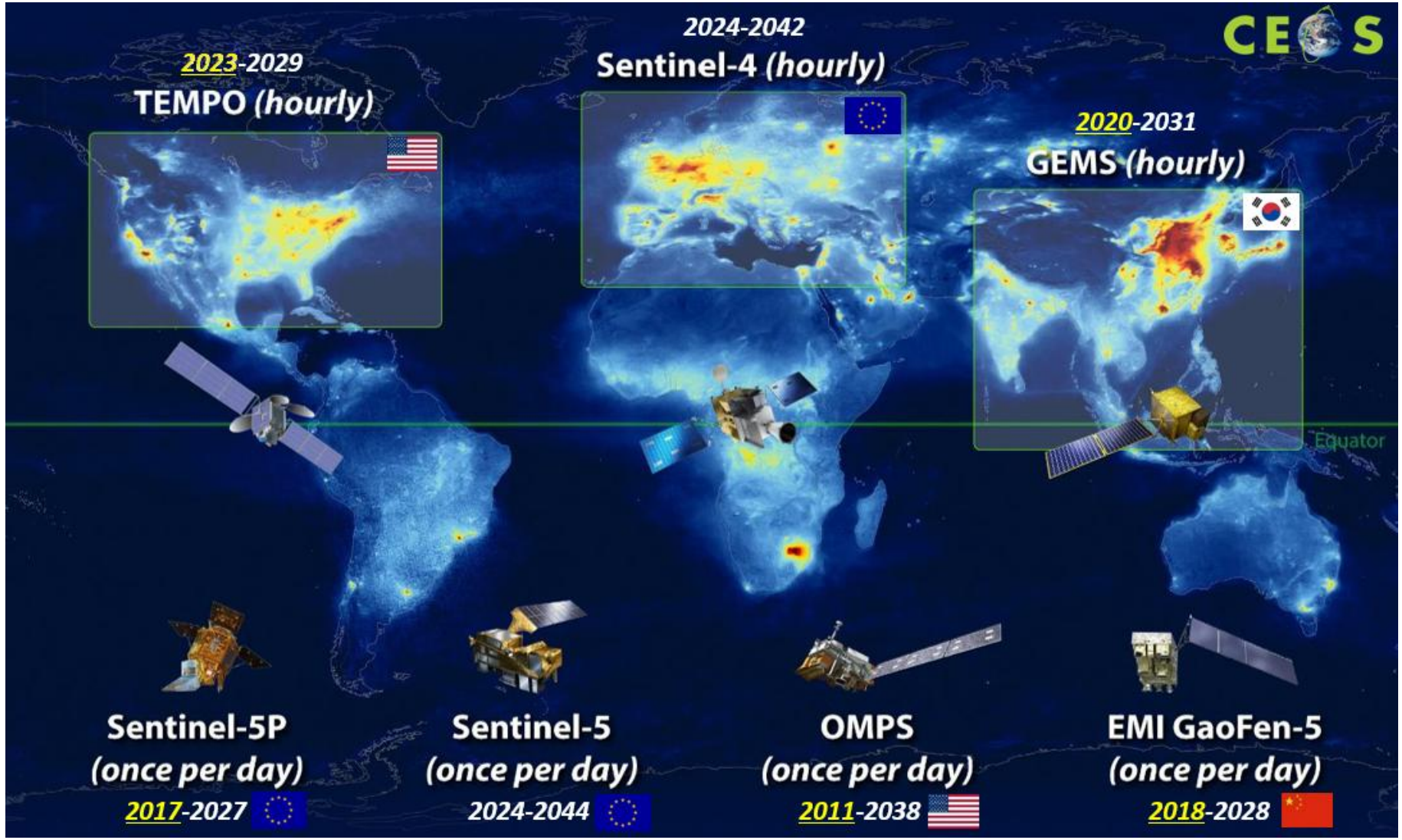
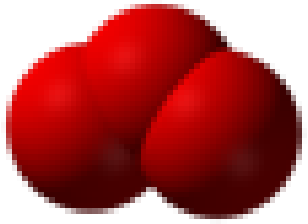
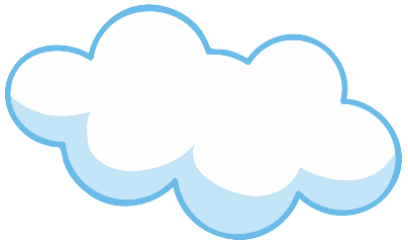


image courtesy: CEOS

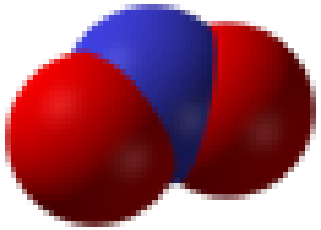
GEMS and TEMPO L2 products evaluated by PEGASOS



Ozone
total



Clouds
fraction
height



Nitrogendioxide
total
trop.
strat.

Aerosols
index
opt.depth
layer height

used for the comparisons:

- Phase 1: also SO_2, HCHO, O_3 profile, tropospheric ozone and surface properties
- Phase 2: limited to total Ozone, NO_2, Clouds, Aerosols

EXAMPLES (I): GEMS

Total Ozone

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

Results:

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

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

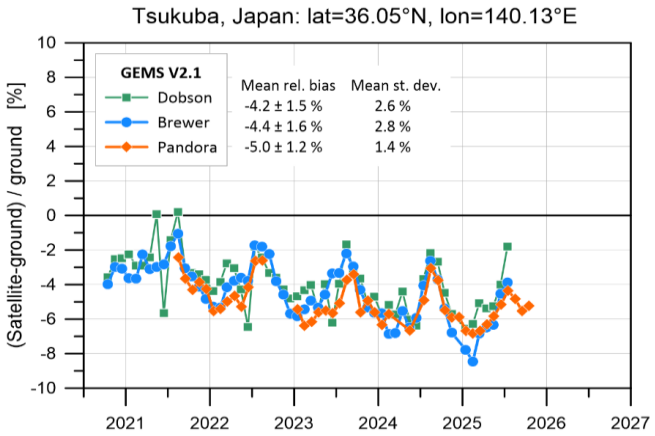
Pearson correlation coefficient ≥ 0.9, showing a very good agreement between GEMS and the reference measurements

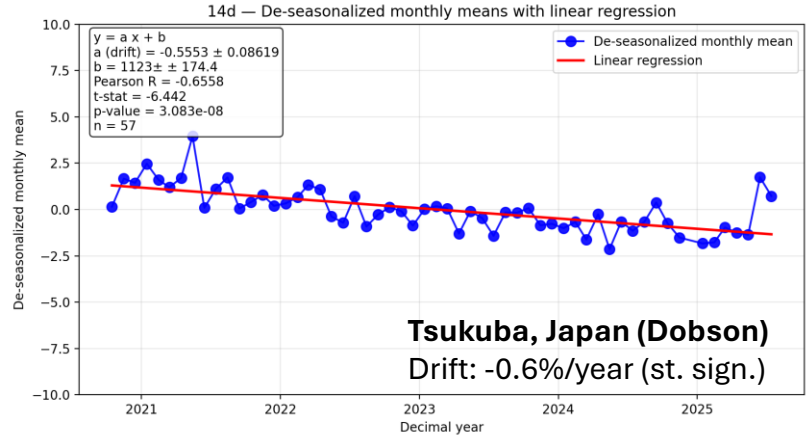
Clear non-unity slope (< 0.9-1): higher underestimation for high TOCs (North, winter)

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

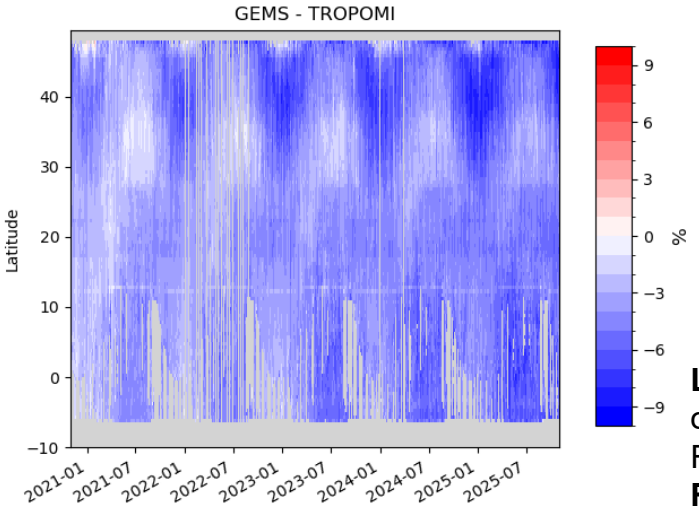
North – South gradient with an annual cycle that differs per latitude:

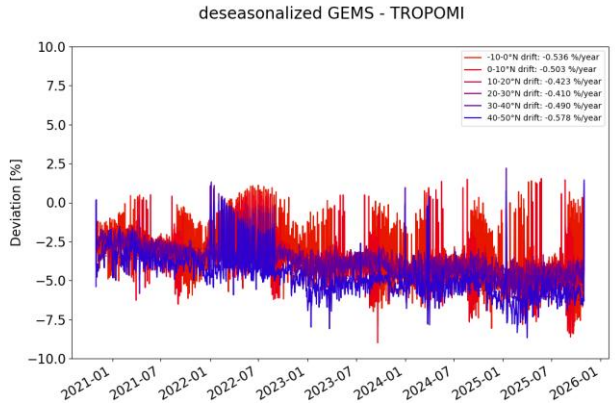
- Very good agreement during summer months at high latitudes and winter months at tropics (± 1%).
- During winter months and for higher latitudes GEMS underestimates total ozone by up to -7%





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-seasonalzed 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.

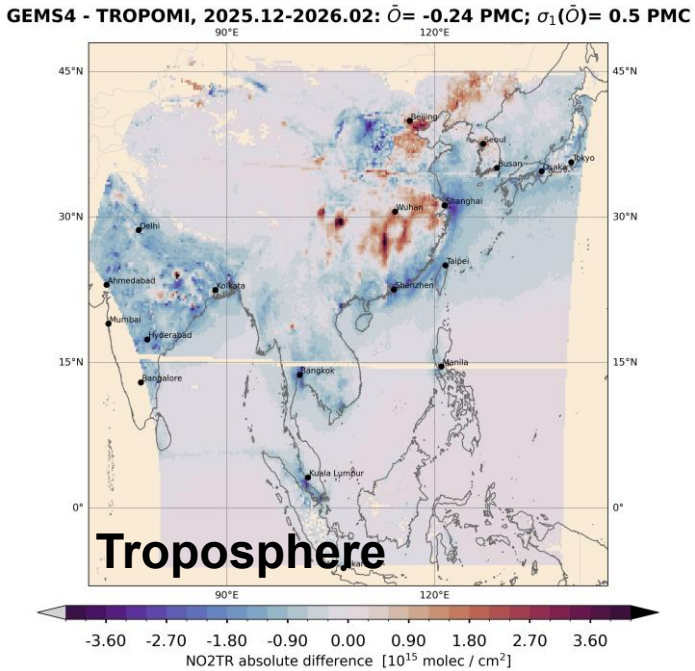
NO_2

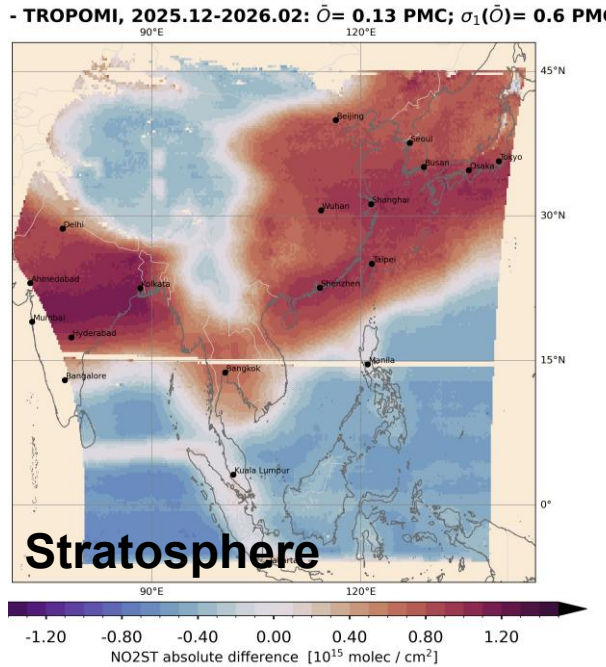
Team: K.-U. Eichmann, I. de Smedt, C. Vigouroux, G. Pinardi, S. Compernolle, T. Verhoelst, S. Seo

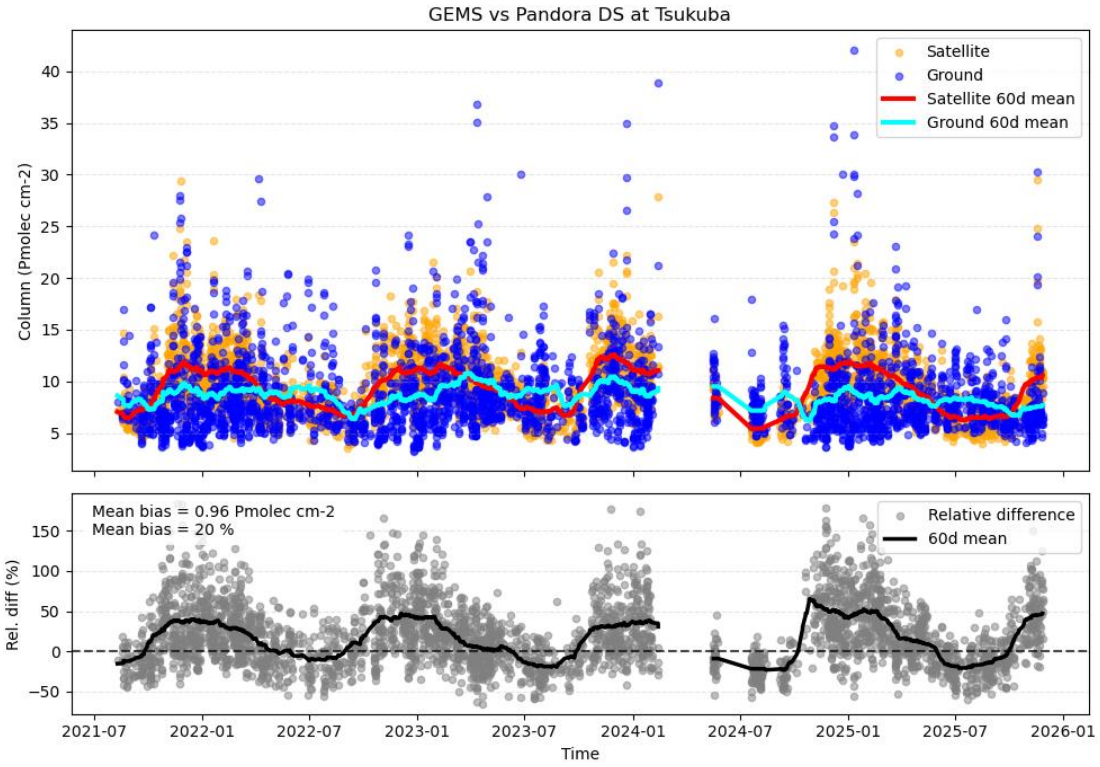
Results:

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.







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

Clouds

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

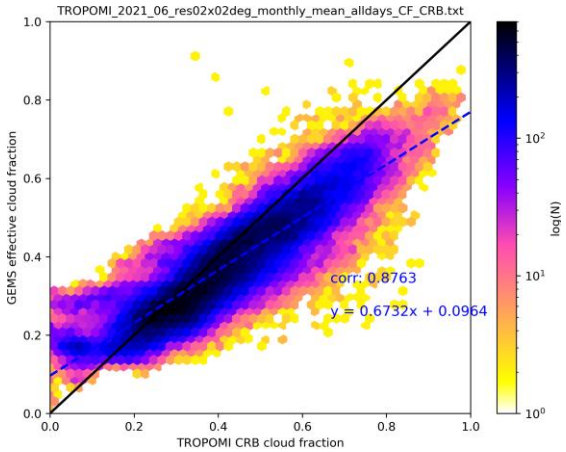
Results:

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

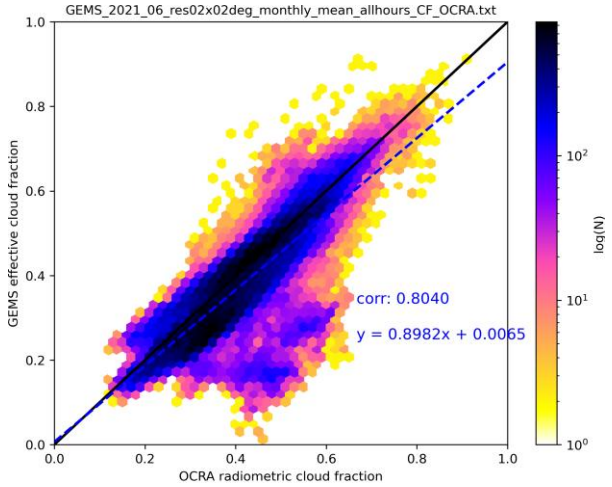
- high correlation (0.80) and slope close to unity
- shape of zonal mean CF agrees very well

We compared GEMS CLD V3 and TROPOMI CRB

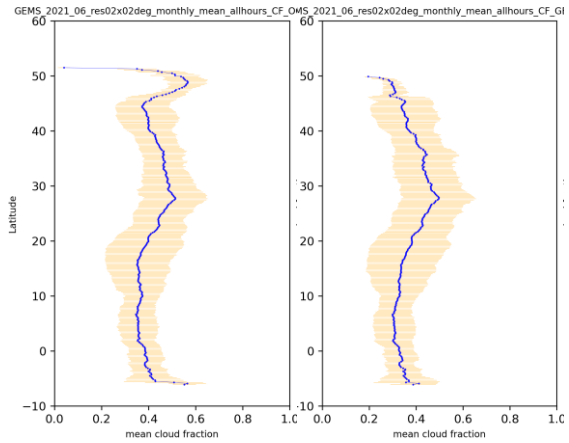
- CF has very high correlation (0.88)
- CP difference depends on cloud altitude
  - low clouds: small positive difference
  - high clouds: small negative difference



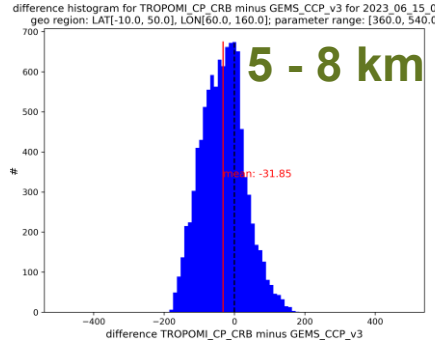
cloud fraction comparisons TROPOMI vs. GEMS



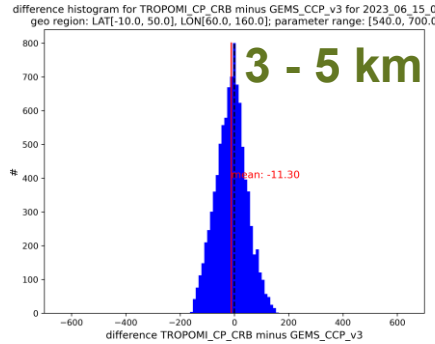
OCRA CF vs GEMS CLD V3



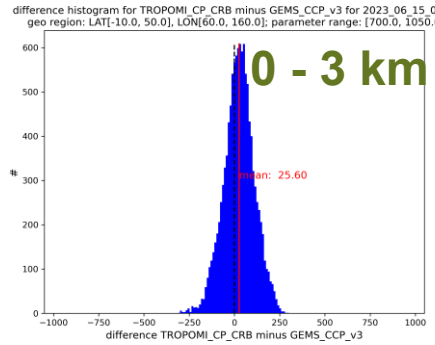
Zonal mean CF from OCRA (left) and GEMS V3 (right)



Δ = -32 hPa



Δ = -11 hPa



Δ = +26 hPa

cloud pressure differences TROPOMI – GEMS in hPa

Aerosols

Team: K. Michailidis, P. Fountoukidis, P. Hedelt, D. Balis

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

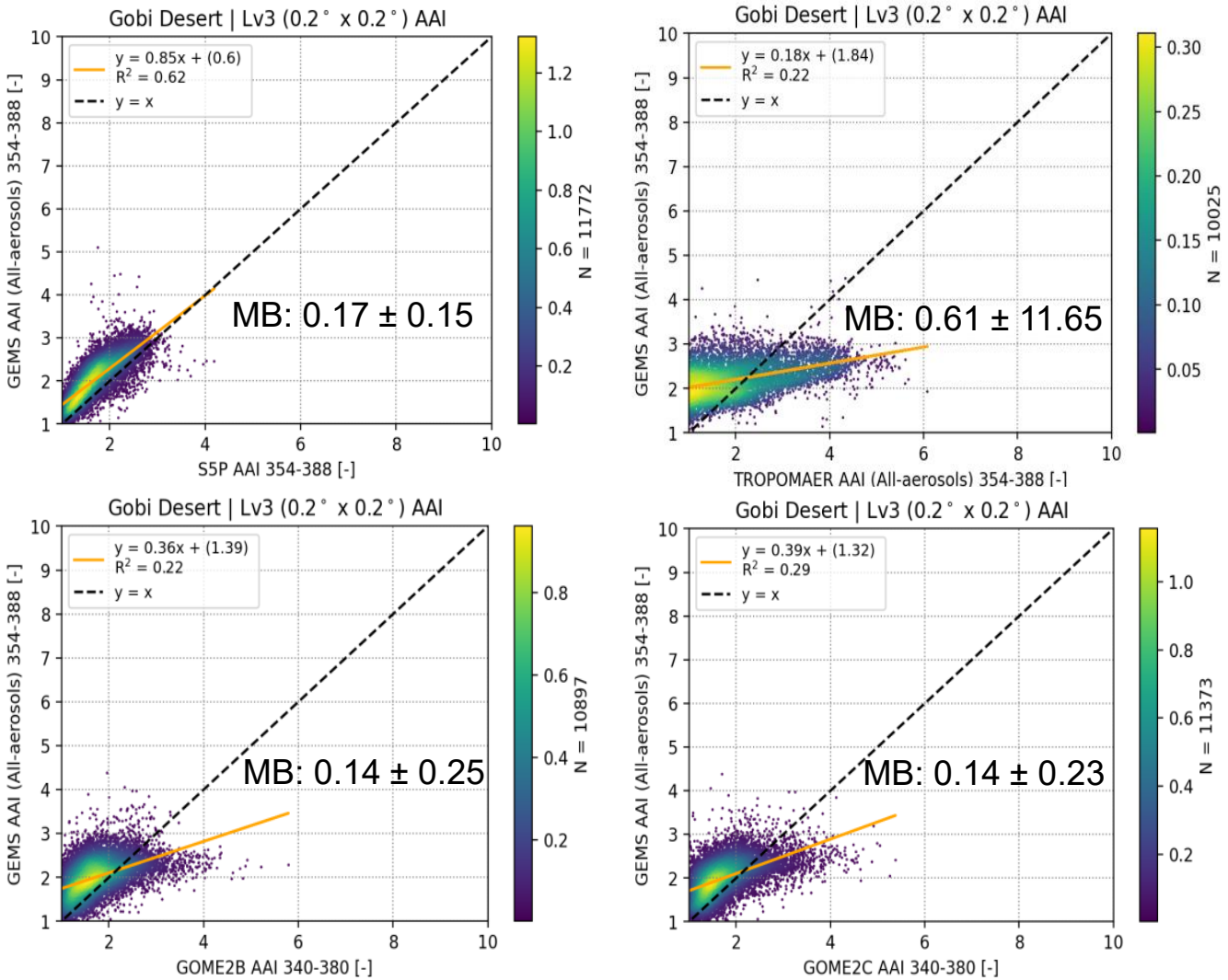


Figure 1. Density scatterplots of AAI over the Gobi Desert (0.2° × 0.2°), for GEMS against (top left) TROPOMI, (top right) TROPOMAER, (bottom left) GOME-2B, GOME-2C (bottom right).

GEMS AOD (v2.1) Validation over Gobi Desert

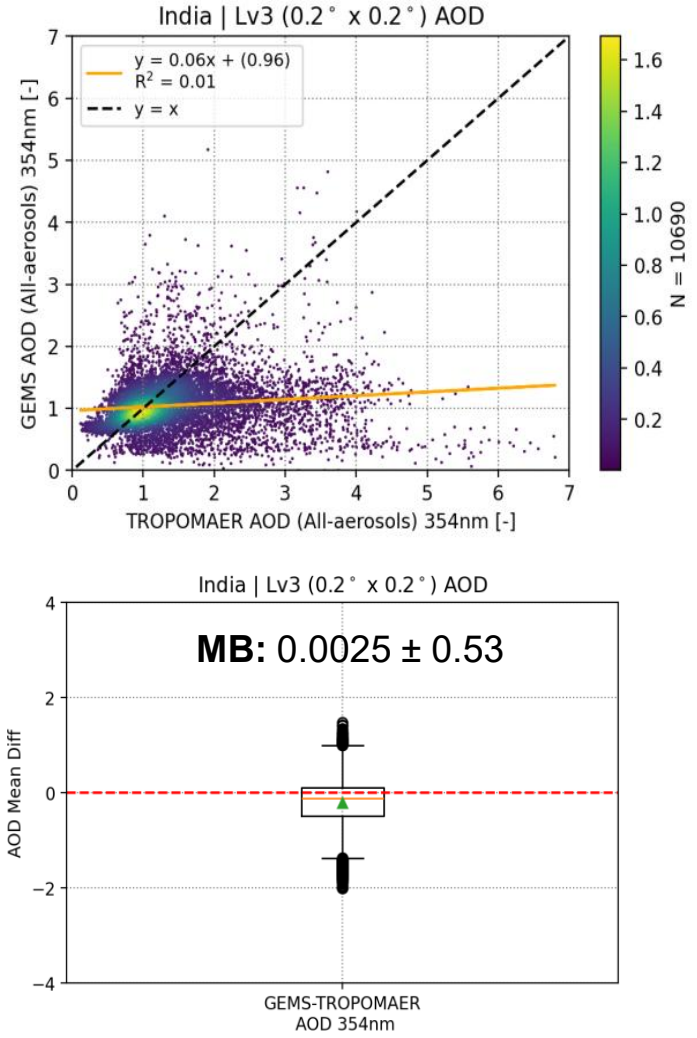


Figure 2. Evaluation of aerosol optical depth (AOD) across all case studies over India, comparing TROPOMAER and GEMS.

Aerosols

Team: K. Michailidis, P. Fountoukidis, P. Hedelt, D. Balis

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

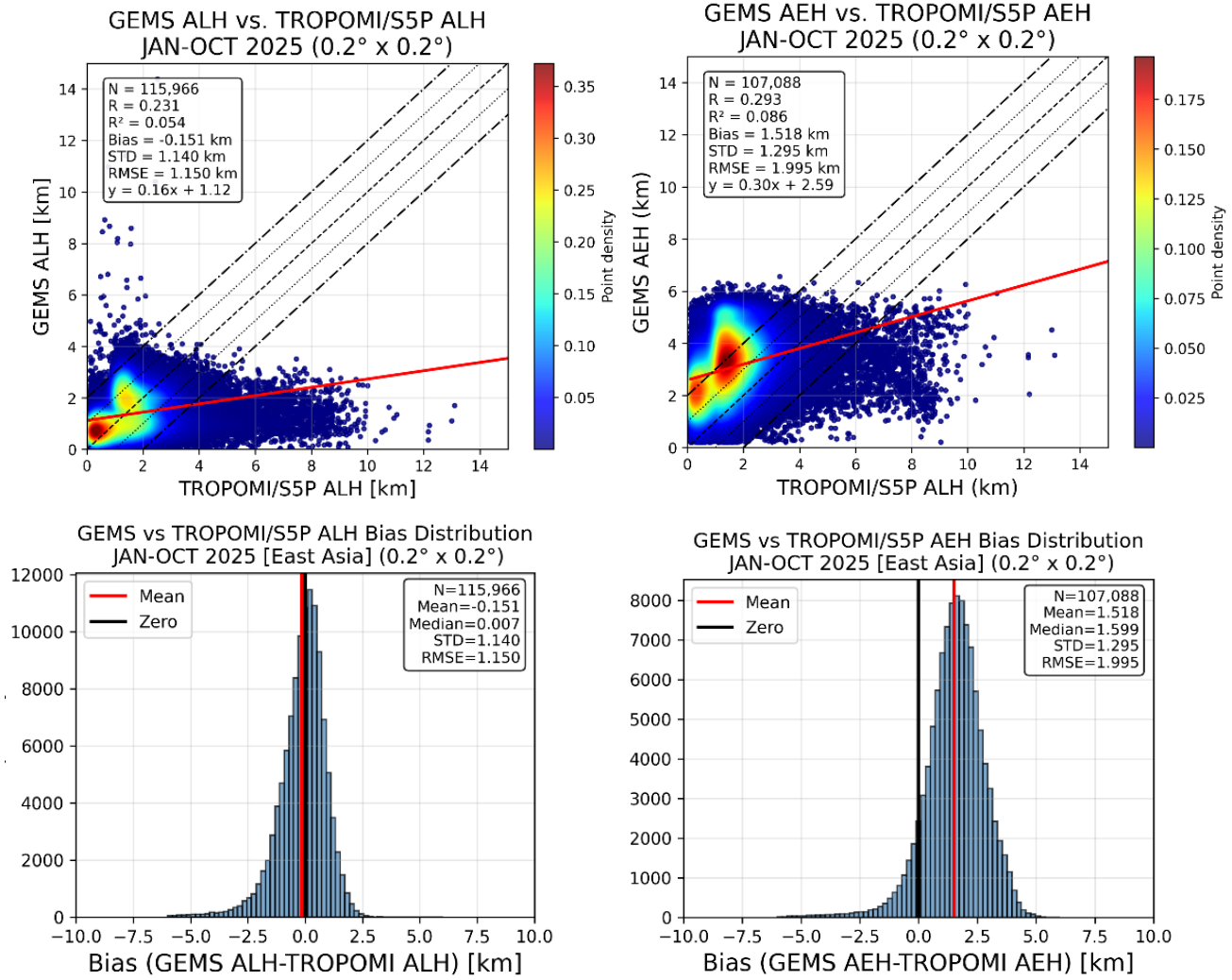


Figure 3. (Top) Density scatter plots of GEMS ALH (left) and AEH (right) with TROPOMI. (Bottom) Histograms showing the distribution of differences between GEMS ALH and TROPOMI ALH.

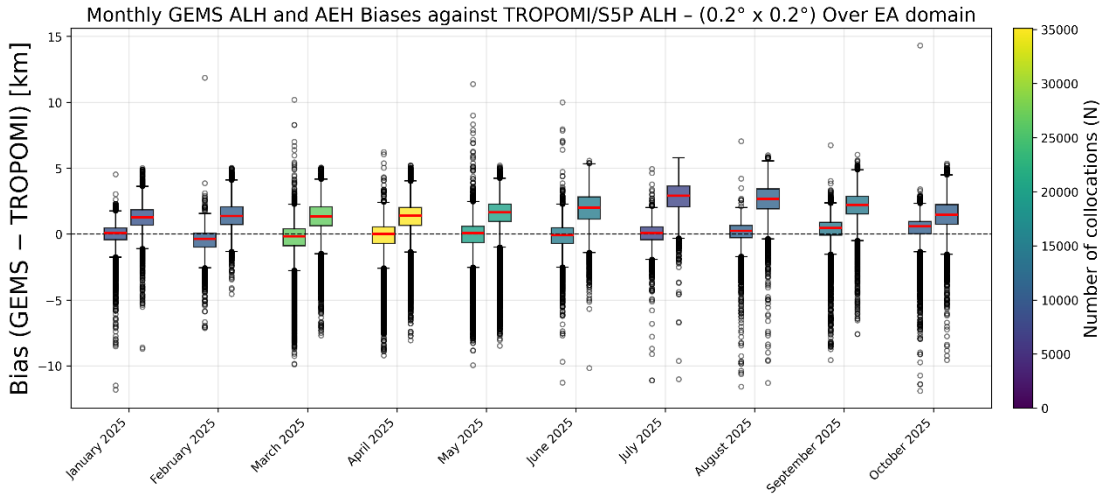


Figure 4. Box plots of ALH bias between GEMS (v2.1) and TROPOMI/S5P.

- **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:** O_4 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. Compernolle, K.-P. Heue, T. Verhoelst

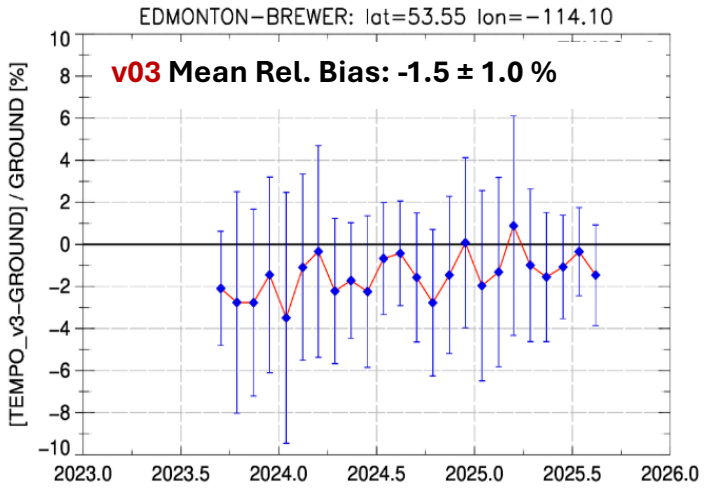
Results:

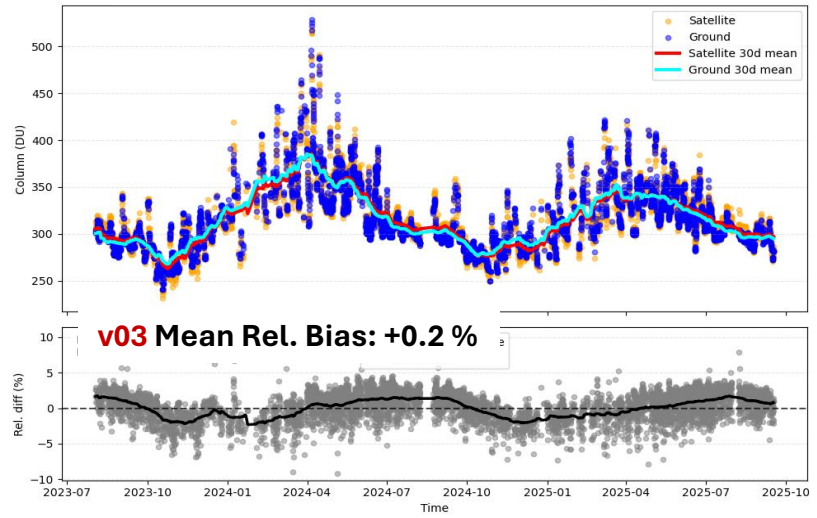
TEMPO O3T v03 (2 years of data) :

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

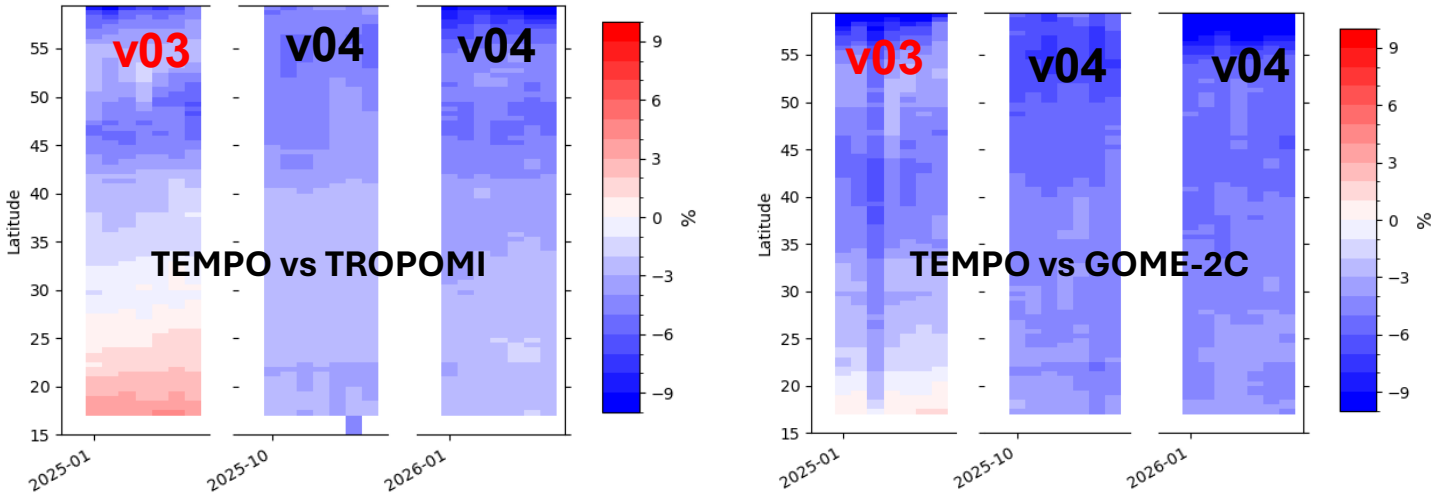
TEMPO O3T v04 data (3.5m of data):

- **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.

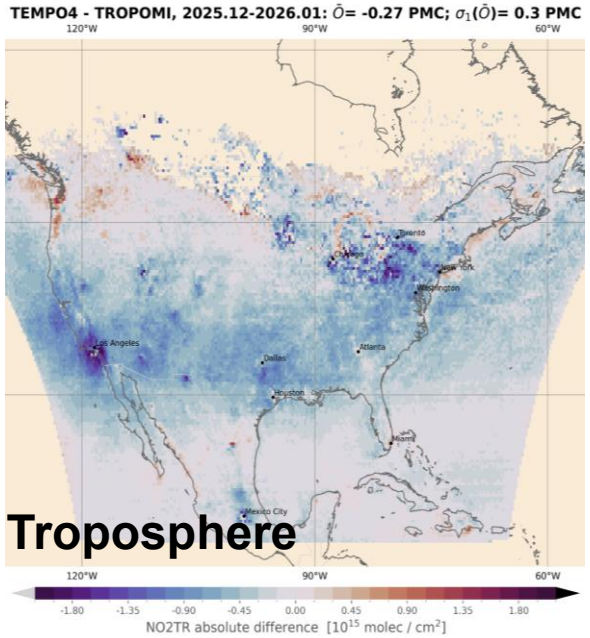
NO_2

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

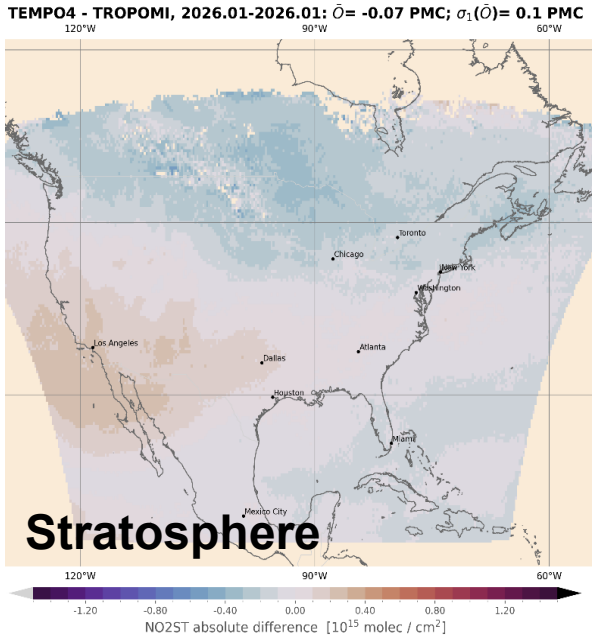
Results:

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

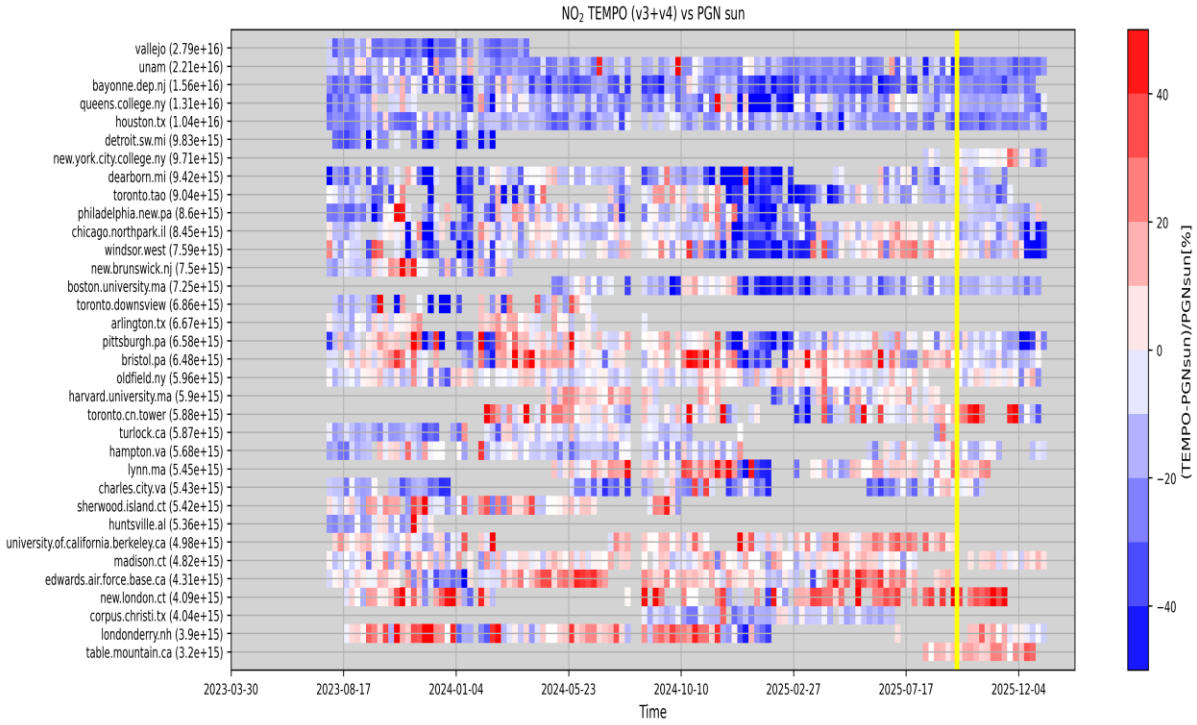
- **Total** column difference is -0.19 ± 0.5 Pmolec/cm2, **tropospheric** AD= -0.27 ± 0.3 Pmolec/cm2, **stratospheric** AD= -0.07 ± 0.1 Pmolec/cm2.
- There is still a very **low bias near LA** in the tropospheric column. This is partly compensated by a high bias in the stratosphere.



Troposphere



Stratosphere



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

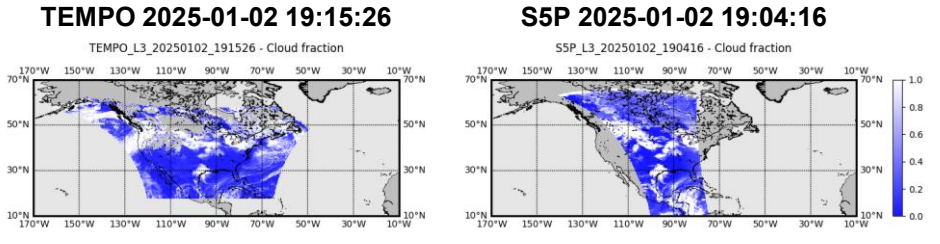
Results:

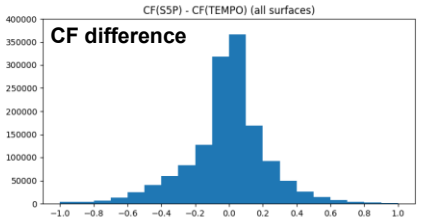
TEMPO CLDO4 v03 (2025-01-01 to 2025-01-07) :

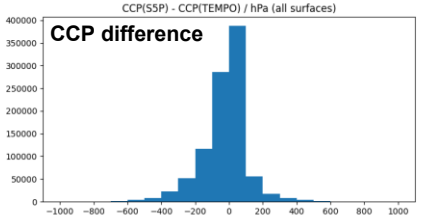
- Regional averaged comparisons TEMPO vs S5P for cloud fraction and cloud-centroid pressure
- **Cloud Fraction (CF):**
  - Mean difference of -0.014
  - Differences between S5P cloud fraction and TEMPO cloud fraction behave symmetric around 0.0
- **Cloud-Centroid Pressure (CCP):**
  - Mean difference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

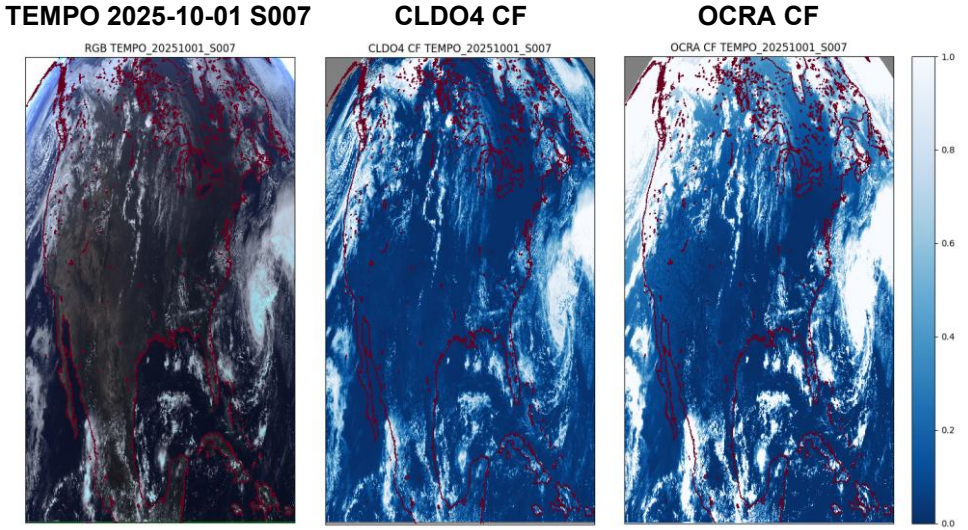
TEMPO CLDO4 v04 (2025-10-01 to 2025-10-07 and 2026-01-01 to 2026-01-07):

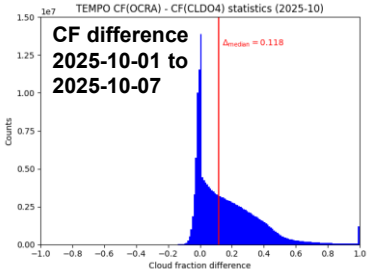
- Direct pixel-by-pixel comparisons with custom TEMPO OCRA algorithm for cloud fraction
- **Cloud Fraction (CF):**
  - Mean difference of +0.172
  - TEMPO CLDO4 CF does not reach 1 so often as TEMPO OCRA CF, even for big cloud structures
  - TEMPO CLDO4 CF behaves better at high zenith angles, where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

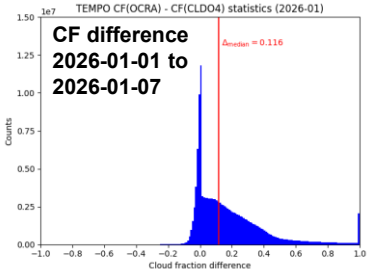












Aerosols

Team: K. Michailidis, P. Fountoukidis, P. Hedelt, D. Balis

AOD - Canadian Wildfire: 19-08-2023

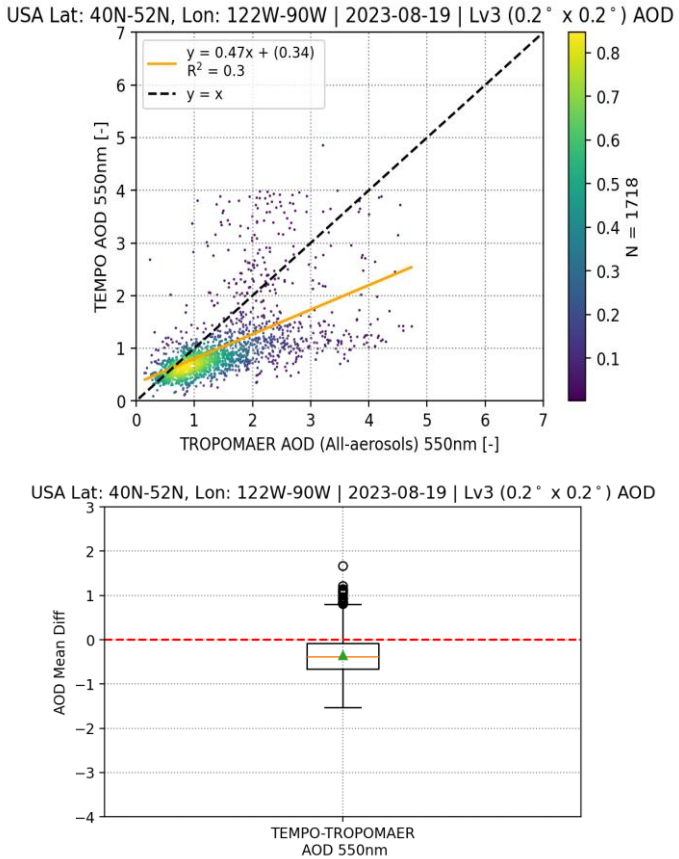


Figure 5. (Upper) Density scatter plots of TROPOMAER (left) against TEMPO AOD. (Bottom) Box-plot of the mean differences.

* *TEMPO L2 OFFL Aerosol data provided by NOAA team within PEGASOS project.*

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

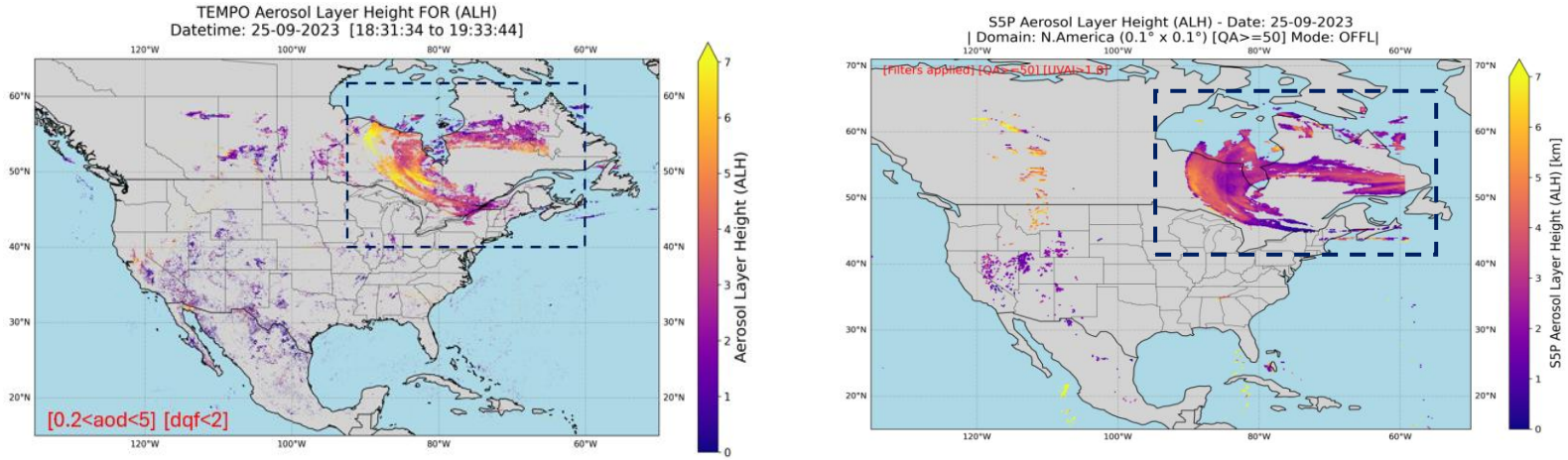


Figure. Spatial distribution of aerosol height products over N.America during an extreme smoke event on 25 September 2023, (left) TEMPOALH (scan10) and TROPOMI/S5P ALH.

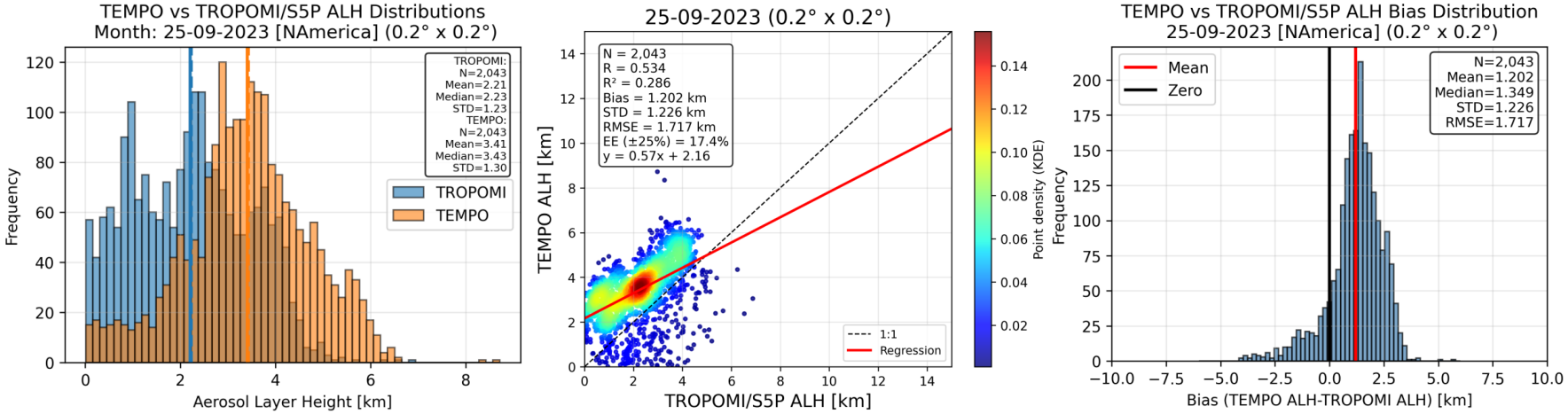


Figure 6. (Left) Frequency distributions of collocated TEMPO & TROPOMI ALH. (Middle) Scatter density plot showing their correlation. (Right) Histogram of absolute differences (TEMPO−TROPOMI), indicating agreement and variability under smoke conditions.

CONSISTENCY AND COMPARABILITY

EDAP maturity matrix

In the PEGASOS project, we try to aim for inter-mission consistency and comparability of our evaluation activities by tailoring the EDAP (Earthnet Data Assessment Project) maturity matrix

Product Information	Product Generation	Ancillary Information	Uncertainty Characterisa-tion	Validation
Product Details	Sensor Calibration & Characterisation Pre-Flight	Product Flags	Uncertainty Characterisation Method	Reference Data Representa-tiveness
Availability & Accessibility	Sensor Calibration & Characterisation Post-Launch	Ancillary Data	Uncertainty Sources Included	Reference Data Quality
Product Format	Retrieval Algorithm Method		Uncertainty Values Provided	Validation Method
User Documentation	Retrieval Algorithm Tuning		Geolocation Uncertainty	Validation Results
Metrological Traceability Documentation	Additional Processing			

Key
Not assessed
Not assessable
Basic
Intermediate
Good
Excellent
Info Not Public

Matrix is

- generated independently for each L2 product
- only filled for properties that we can assess based on availability
- only filled for properties that we can assess within the scope of our project

- The example above shows the topical areas which we assessed so far for GEMS
- To ensure comparable assessments for all three instruments of the Geo-Ring, we'll try to follow a similar approach also for TEMPO and S4
- Thanks to the colleagues from BIRA for their initiative to initiate the tailoring for GEMS!

EDAP maturity matrix

Example for the assessed topics:

Product Details	
Product Name	*Geostationary Environment Monitoring Spectrometer (GEMS) Cloud*
Sensor Name	*GEMS*
Sensor Type	*UV – visible hyper spectrometer [GEMS*
Mission Type	*Single satellite mission*
Mission Orbit	*Geostationary*
Product Version Number	*version 3.0*
Product ID	*CLD*
Processing level of product	*Level-2*
Measured Quantity Name	*Effective Cloud Fraction* *Cloud Centroid Pressure*
Measured Quantity Units	*[-]* *[hPa]*
Stated Measurement Quality	*Error analysis in ATBD, section 3.3*
Spatial Resolution	*Nominal: 7 km N/S x 8 km E/W*
Spatial Coverage	*5°S - 45°N, 75°E - 145°E [GEMS website* *5°S - 45°N, 80°E - 152°E [OS UG]*
Temporal Resolution	*8 times during daytime [GEMS website,* *Between 6 and 10 times depending on*
Temporal Coverage	*Algorithm Version 3.0: up to present*
Point of Contact	*Hyunkee Hong, ESC/NIER, wanju77@ko*
Product locator (DOI/URL)	*https://nesc.nier.go.kr/en/html/cntnts/* *https://nesc.nier.go.kr/en/html/datasv*
Conditions for access and use	*https://nesc.nier.go.kr/en/html/cntnts/*
Limitations on public access	*https://nesc.nier.go.kr/en/html/cntnts/*
Product Abstract	*The GEMS cloud (CLD) retrieval algorith (ECF), cloud centroid pressure (CCP), an through Differential Optical Absorption calibrated radiance obtained from GEM et al. 2020). This document includes bri definition and explanation of CLD L2 da quality flags. The current version is 3.0. [Cloud UG]*

Availability & Accessibility	
Compliant with FAIR principles	*findable: partially fulfilled (e.g. globally unique and persistent identifiers are not easily findable).* *accessible: partially fulfilled (e.g. not all data available via GEMS website). Good improvement by introducing Open-API https://nesc.nier.go.kr/en/html/svc/openapi/explain.do* *interoperable: partially fulfilled (e.g. metadata ar a broadly applicable language like CF Convention* *reusable: partially fulfilled. E.g. data usage licens https://nesc.nier.go.kr/en/html/cntnts/84/etc/pc*
Data Management Plan	*Not available*
Availability Status	*https://nesc.nier.go.kr/en/html/cntnts/91/static/*

Product Format	
Product File Format	*netCDF 4*
Metadata Conventions	*Does not follow metadata conventions like Clima Conventions*
Analysis Ready Data?	*Not assessed. Beyond scope.*

User Documentation	
Product User Guide	*https://nesc.nier.go.kr/en/html/satellite/guide/g* issue 1.3, 9 Dec 2024
ATBD	*https://nesc.nier.go.kr/en/html/satellite/doc/doc* issue 1.5, 9 Dec 2024

Metrological Traceability Documentation	
Document Reference	*Cloud ATBD*
Traceability Chain / Uncertainty Tree Diagram Available	*No. There is an algorithmic traceability chain but no metrological one. An error analysis section is given in the ATBD but no uncertainty budget (e.g., an overview table with a breakdown of the most important sources of uncertainty of the main measurand).*

Product Flags	
Product Flag Documentation	*Available in the user guide. With an example on how flags are constructed.*
Comprehensiveness of Flags	*Reasonable, but not very comprehensive.*

Ancillary Data	
Ancillary Data Documentation	*List of needed input data is provided.*
Comprehensiveness of Data	*Ancillary data could be described in a bit more detail.*
Uncertainty Quantified	*No uncertainty provided with the ancillary data.*

Uncertainty Characterisation Method	
Summary	*Only a pre-launch sensitivity analysis is performed. No final uncertainties based on GEMS data are provided in the ATBD.*
Reference	*Cloud ATBD*

Uncertainty Values Provided	
Summary	*No uncertainty values are provided with the product.*
Reference	-
Analysis Ready Data?	*Beyond of scope.*

Credits to the PEGASOS team

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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