Tracking wildfire emissions of CO, NH_3, and HCOOH in Southeast Asia from FengYun-4B/GIIRS

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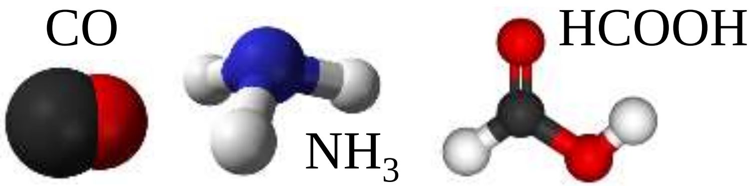
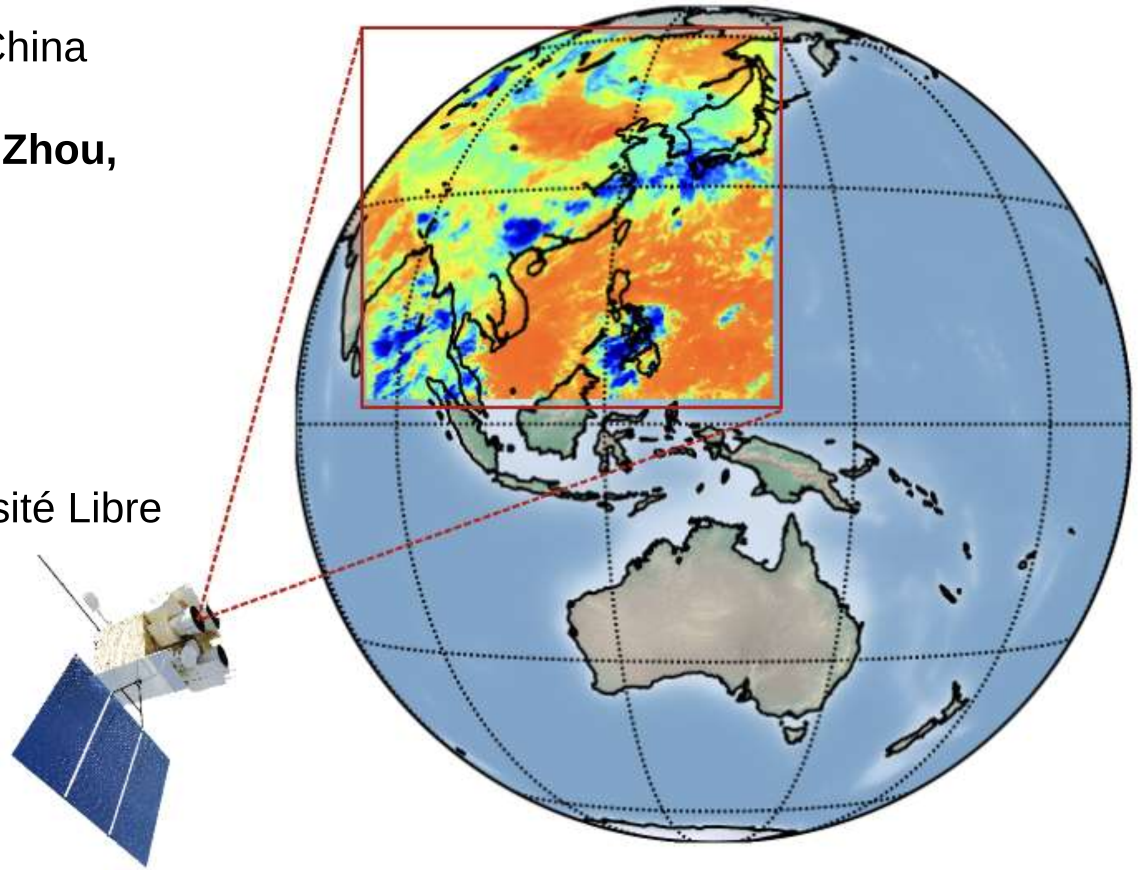
- **Bruno Franco, Lieven Clarisse, Martin Van Damme** (Université Libre de Bruxelles)





Geostationary Interferometric Infrared Sounder

China’s FengYun meteorological satellites

风 雲

Wind Clouds

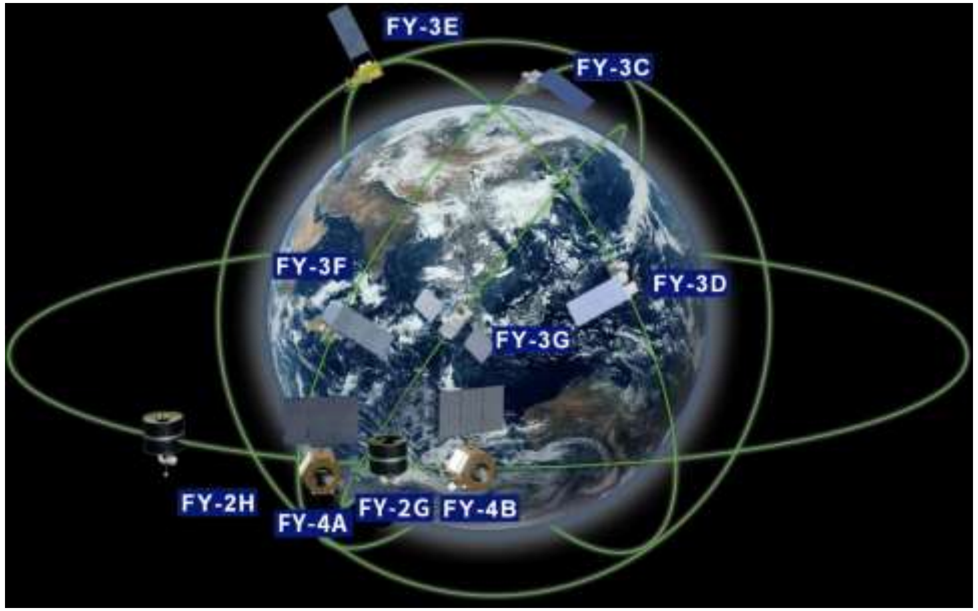
- The FengYun meteorological satellites:
  Odd number series (FY-1, FY-3) polar-orbiting
  Even number series (FY-2, FY-4) geostationary

- Alphabet table is used, e.g., the ‘FY-4B’ means the second satellite in the FY-4 geostationary series.

- Primary goal: **Numerical Weather Prediction** (water vapor; temperature; wind, clouds et al.) Other goals: Monitoring atmospheric **radiation**, **air pollutants** and **GHGs**

- All L1 (spectra) and higher level data products are publicly available through the National Satellite Meteorological Center (https://nsmc.org.cn/)

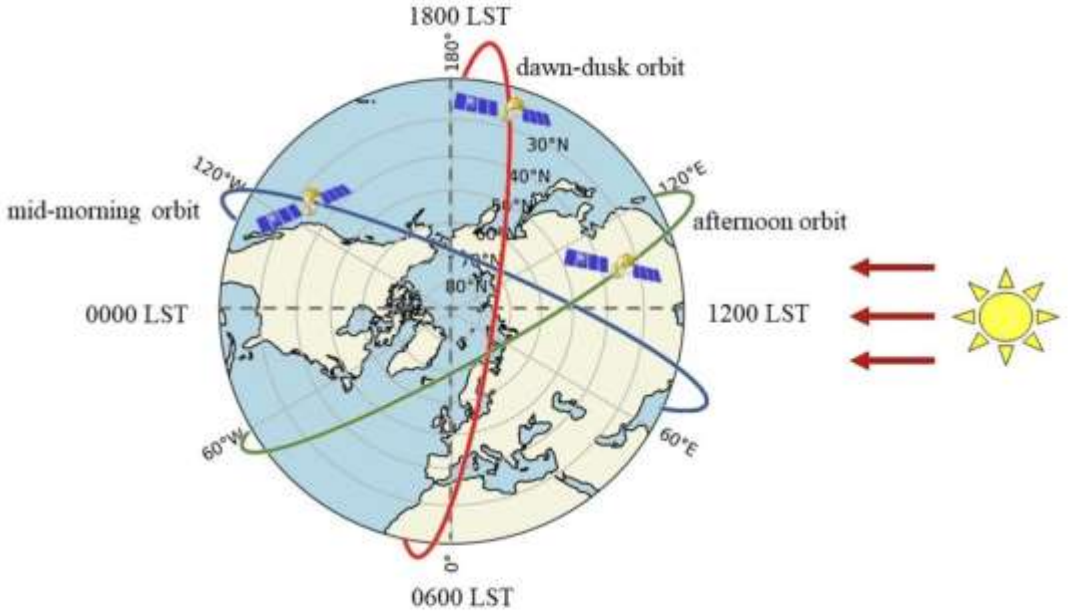
- Hyperspectral infrared sounders:
  HIRAS: Hyperspectral Infrared Atmospheric Sounder
  GIIRS: Geostationary Interferometric Infrared Sounder



In operation FengYun satellites by Sept 2024
Source: http://www.nsmc.org.cn/

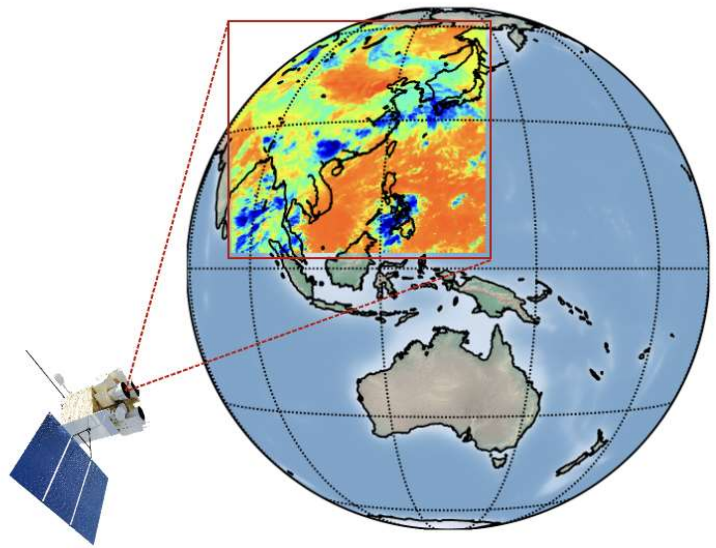
Hyperspectral Infrared Sounders

HIRAS: Hyperspectral Infrared Atmospheric Sounder



- FY-3D/HIRAS: afternoon orbit (2am/pm)
  Data from 2019
- FY-3E/HIRAS-II: dawn-dusk orbit (5:30am/pm)
  Data from 2022
- FY-3F/HIRAS-II: mid-morning orbit (10am/pm)
  Data from 2024

GIIRS: Geostationary Interferometric Infrared Sounder



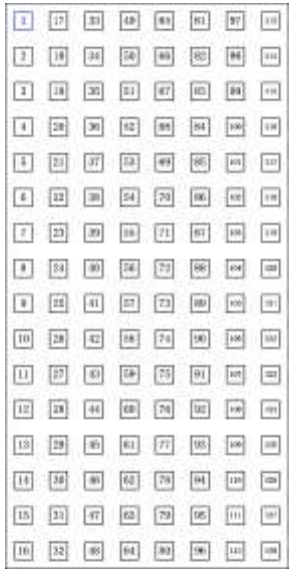
- FY-4A/GIIRS, 105°E (migrated to 86.5°E from 2024.03)
  Retired.
  Data from 2019 to early 2024.
- FY-4B/GIIRS, 133°E (migrated to 105°E from 2024.03)
  Data from mid 2022.

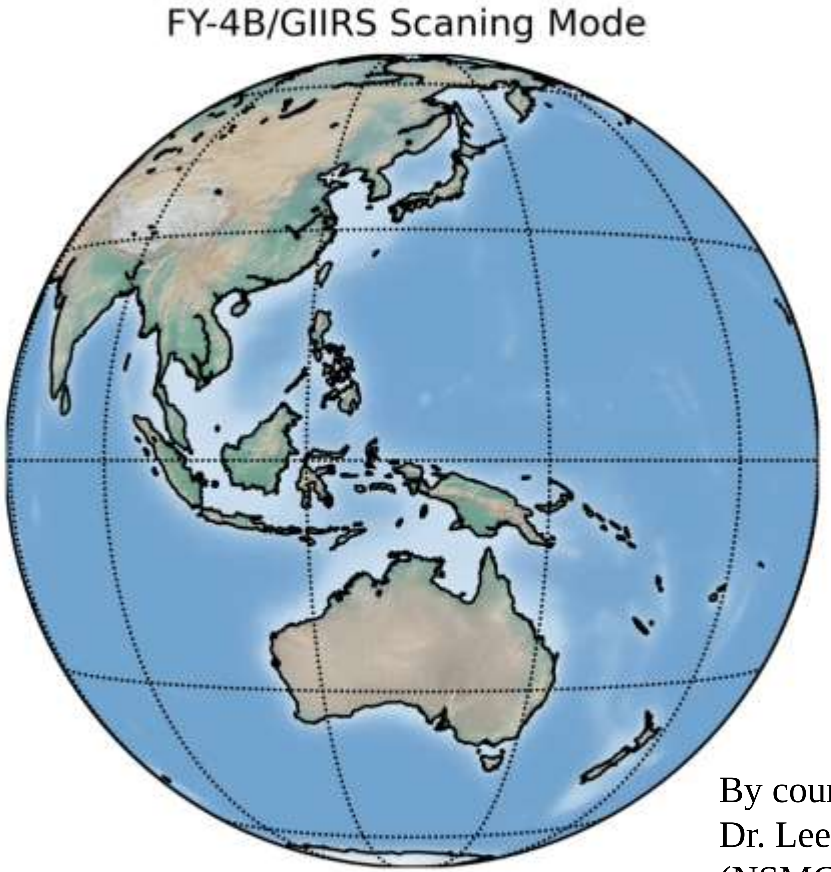
Refs: http://www.nsmc.org.cn/nsmc/en/satellite/index.html

The Geostationary Interferometric Infrared Sounder (GIIRS)

- GIIRS scans the Earth in a “step-stare” mode: Each field of view collects16×8 interferograms
- A typical GIIRS scan: 27 fields-of-regard (FORs)
- The observation region comprises 27 FORs×12 Scans.
- One coverage takes about 2.0 hours. 12 maps in a day covers day and night.
- Footprint size at Nadir: about 12 by 12 km.
- 133°E (before 2024-02-01), 105°E (after 2024-03-05)
- FY-4C/GIIRS, planned to launch in late 2025

Detector layout
(16×8 interferograms)





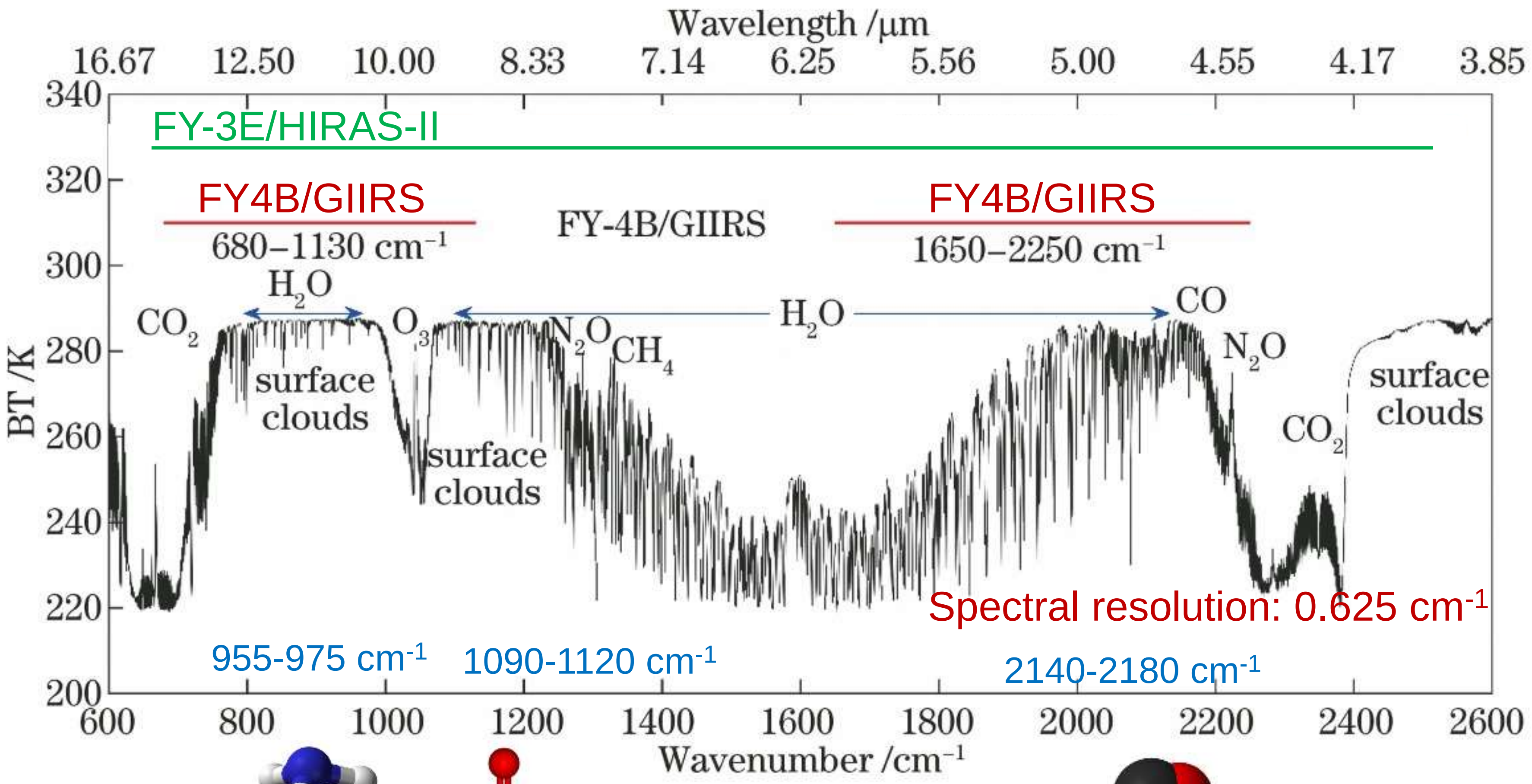
By courtesy of
Dr. Lee Lu
(NSMC)

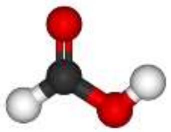
Spectral windows for retrieving CO, NH_3, and HCOOH

- **Carbon Monoxide (CO)**
  (1) incomplete combustion primarily from biomass and fossil fuel; (2) effective tracer for air pollution and carbon emissions.

- **Ammonia (NH_3)**
  (1) primary source from agriculture activities; (2) negative environmental impacts on biodiversity, water bodies, terrestrial ecosystems, and global and local climate.

- **Formic Acid (HCOOH)**
  (1) one of the most abundant volatile organic compounds (VOCs); an important source of atmospheric acidity; (2) direct emissions from vegetation, biomass and biofuel burning, and fossil fuel combustions; secondary formation by photochemical processes.



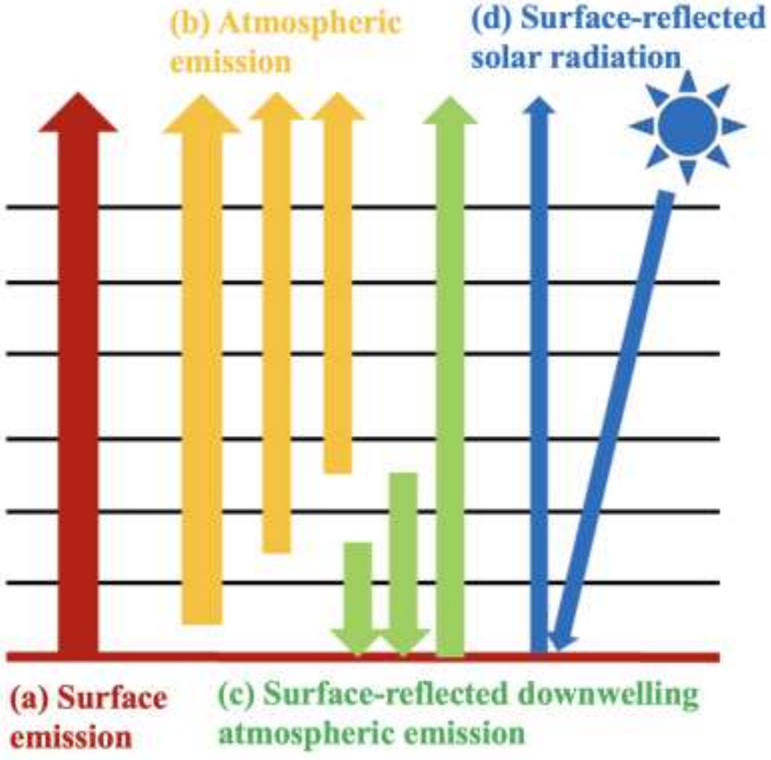
NH_3   HCOOH

CO 

Refs: e.g., Clarisse et al. 2009, 2010; Clerbaux et al. 2009; Hurtmans et al. 2012; Pommier et al. 2016; Franco et al., 2018.

The FengYun Geostationary satellite Atmospheric Infrared Retrieval (FY-GeoAIR) algorithm

- **The forward RT model**: built from RT thoery, with approximations following the RT models for TES and IASI (Clough et al. 2006; Hurtmans, et al. 2012).
- **State vector**: target gases, interfering gases, surface T, AtmosT profile (scale factor), surface emissivity (polynomial scale factor)
- **Data sources for the a priori**: ECMWF-ERA5; ECMWF-CAMS; Emissivity from U. Wisconsin.
- **Model grids**: from surface to TOA; ~1km/layer for the bottom 12km, and ~5km/layer for the above.
- **A priori CO/HCOOH/NH_3 profiles**: A static a priori (any significant perturbation may indicate information from the spectra, not the a priori, especially diurnal changes).
- **Cloud screening**: based on the cloud cover product from AGRI, a multi-spectral imager on FY-4B.
- **Retrieval ouputs**: Profile of the target gas, a posterior error, averaging kernel (for computing DOFS)

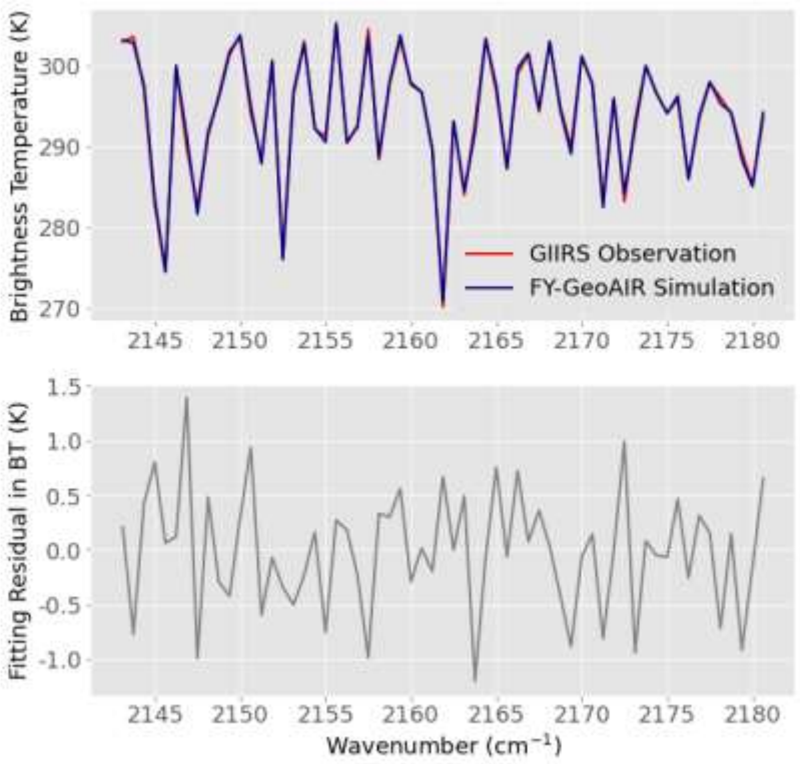


Zeng et al. 2023a, AMT

FY-GeoAIR: optimal estimation based retrieval algorithm

FY-GeoAIR: FengYun Geostationary satellite Atmospheric Infrared Retrieval algorithm

The goal of **optimal estimation:** is to find a solution for the state vector such that the simulated spectra from the RT model best fit the measured spectra.



fitting residual closes to spectral noise.

Major absorbing gases: CO, H_2O, CO_2, O_3, N_2O

Backup slides for RT and retrieval algrithm inputs.

FY-GeoAIR: optimal estimation based retrieval algorithm

FY-GeoAIR: FengYun Geostationary satellite Atmospheric Infrared Retrieval algorithm

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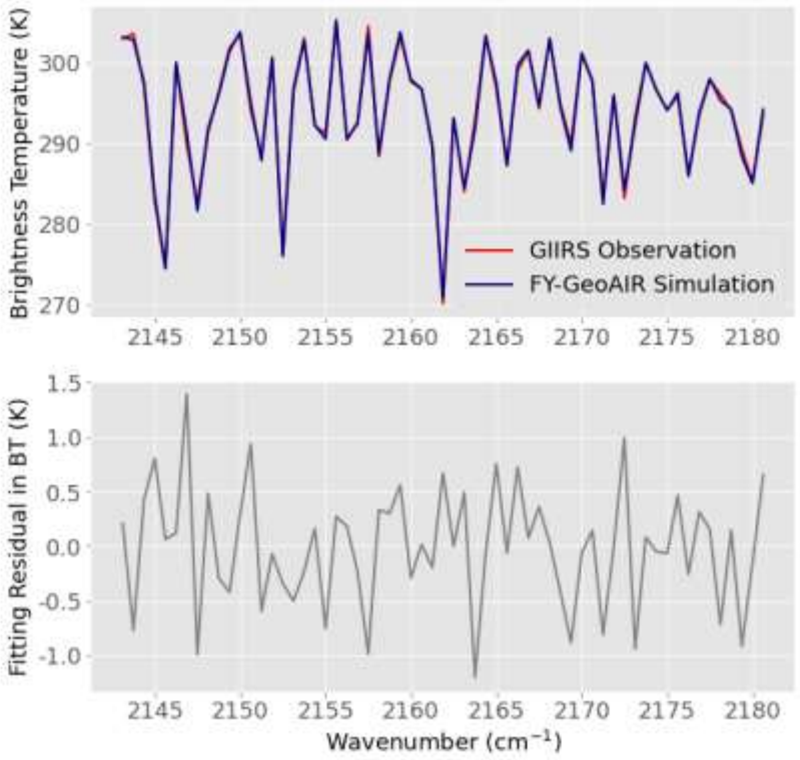


fitting residual closes to spectral noise.

Major absorbing gases: CO, H_2O, CO_2, O_3, N_2O

Backup slides for RT and retrieval algrithm inputs.

The solution from the retrieval algorithm is the state vector which minimizes the following cost function:

Observation | Forward Model | Observation error covariance

$$\chi^2 = [\mathbf{y} - \mathbf{F}(\mathbf{x}, \mathbf{b})]^T \mathbf{S}_\varepsilon^{-1} [\mathbf{y} - \mathbf{F}(\mathbf{x}, \mathbf{b})] + (\mathbf{x} - \mathbf{x}_a)^T \mathbf{S}_a^{-1} (\mathbf{x} - \mathbf{x}_a),$$

State Vector | A Priori | A Priori Error Covariance

The Levenberg-Marquardt modification of the Gauss-Newton method is used to search the solution.

The **state vector** includes CO or NH_3 or HCOOH profiles, H_2O profile, scale factors for the columns of the remaining interference gases, surface skin temperature, and scale factor for the atmospheric temperature profile.

Zeng et al. 2023a, 2023b, AMT

Wildfire CO, NH_3, HCOOH columns from FY-4B/GIIRS

(a) Fire emissions in Southeast Asia

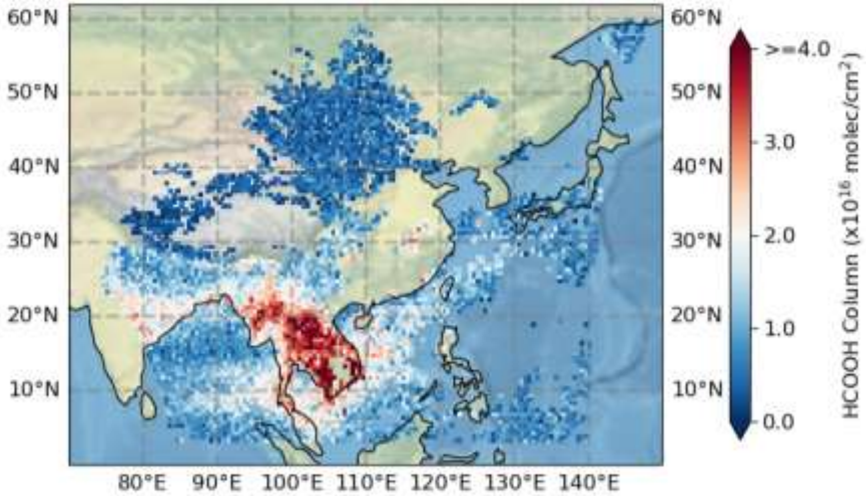
(a) Intense fire emissions in Southeast Asia (Jan to Apr)
#slash-and-burn agriculture;
#loggers use fire to clear roads and lands
#cool and dry weather

Examples: 11 April 2023, local noontime

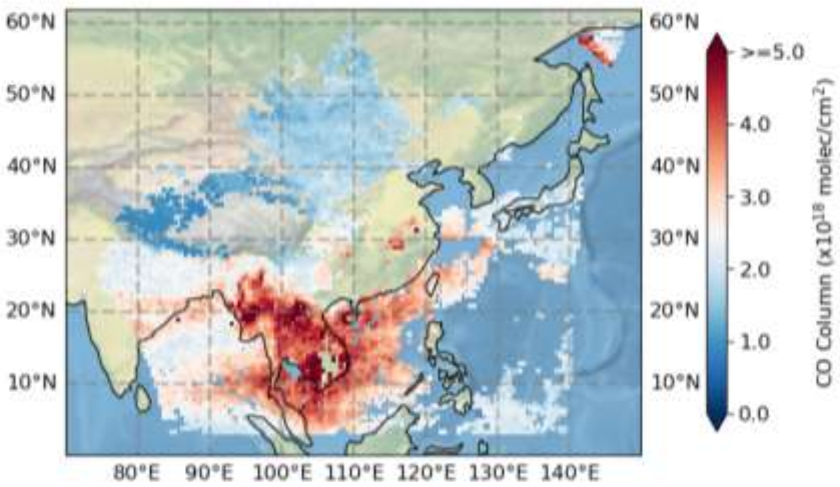
Wildfire CO, NH_3, HCOOH columns from FY-4B/GIIRS

(a) Fire emissions in Southeast Asia

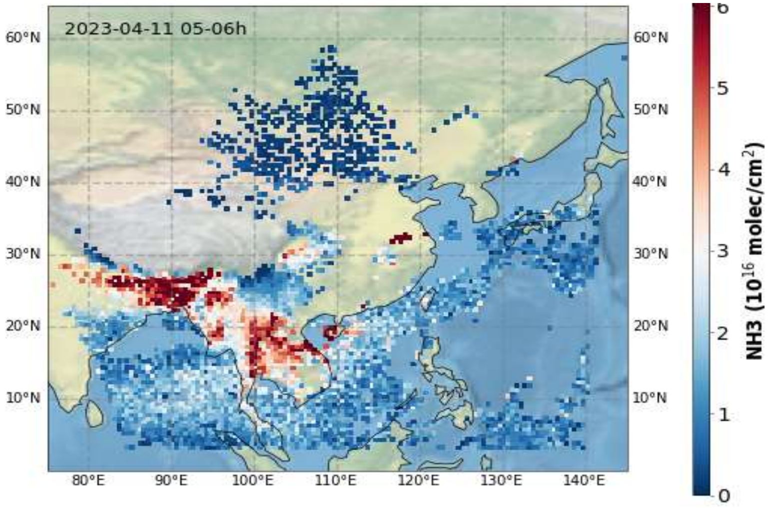
(c) HCOOH column retrievals



(b) CO column retrievals



(d) NH_3 column retrievals



(a) Intense fire emissions in Southeast Asia (Jan to Apr)
#slash-and-burn agriculture;
#loggers use fire to clear roads and lands
#cool and dry weather

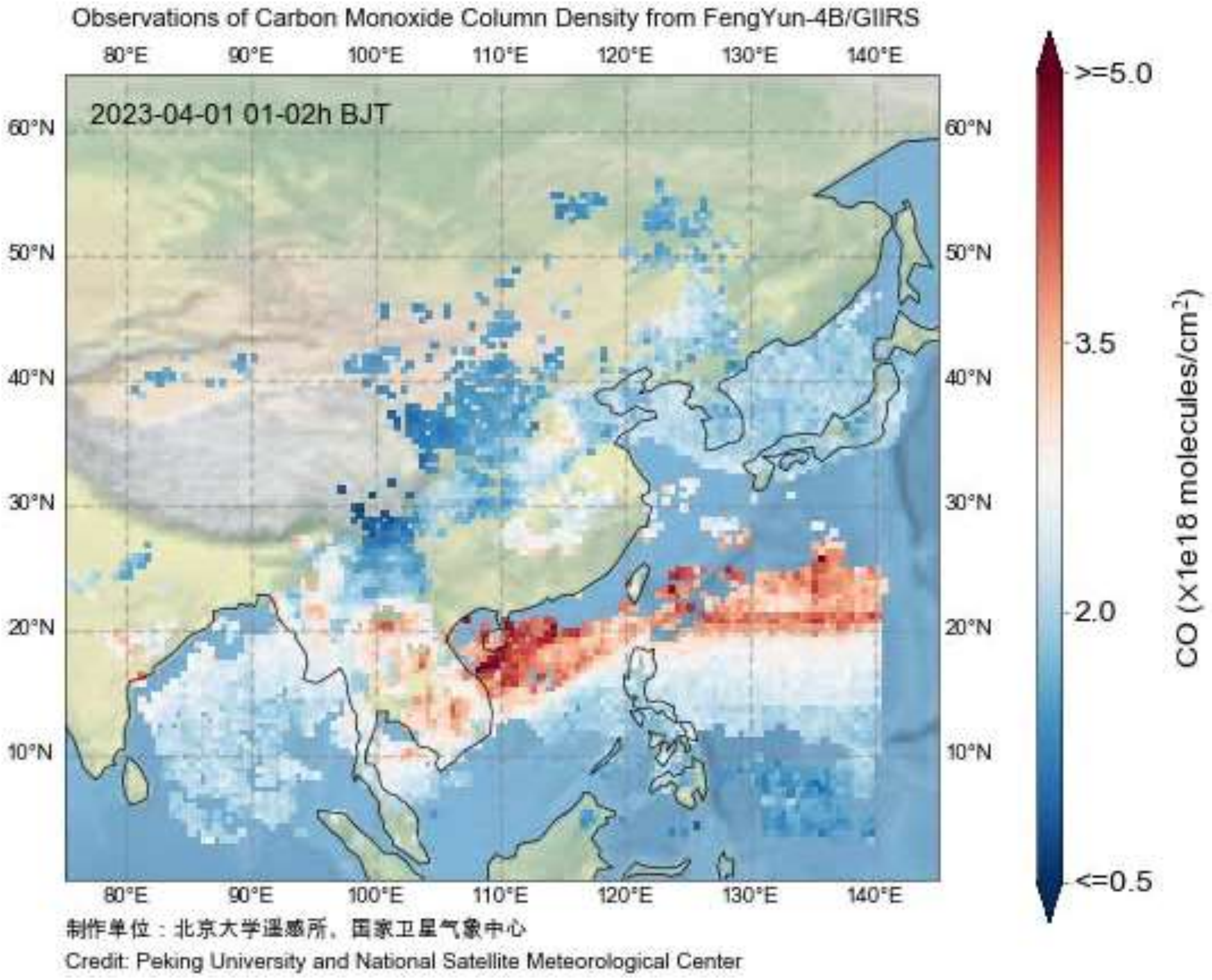
Examples: 11 April 2023, local noontime

(b) CO retrievals from GIIRS tracks the long-range transport (lifetime: weeks to months);

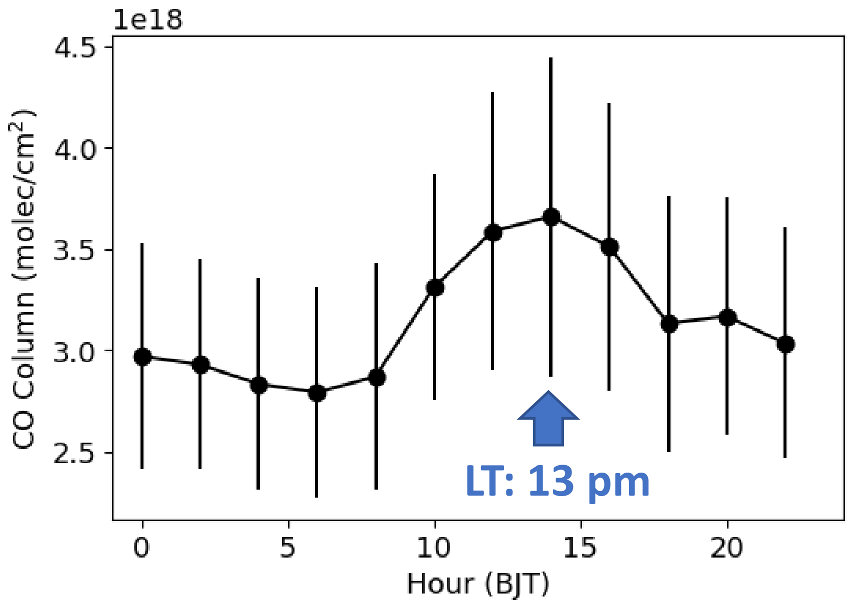
(c) and (d): **HCOOH and NH3** emissions show similar patterns, but with shorter range (shorter lifetime)

Diel cycle of wildfire CO columns from Southeast Asia

Maps of CO columns every 2-hour in Apr 2023



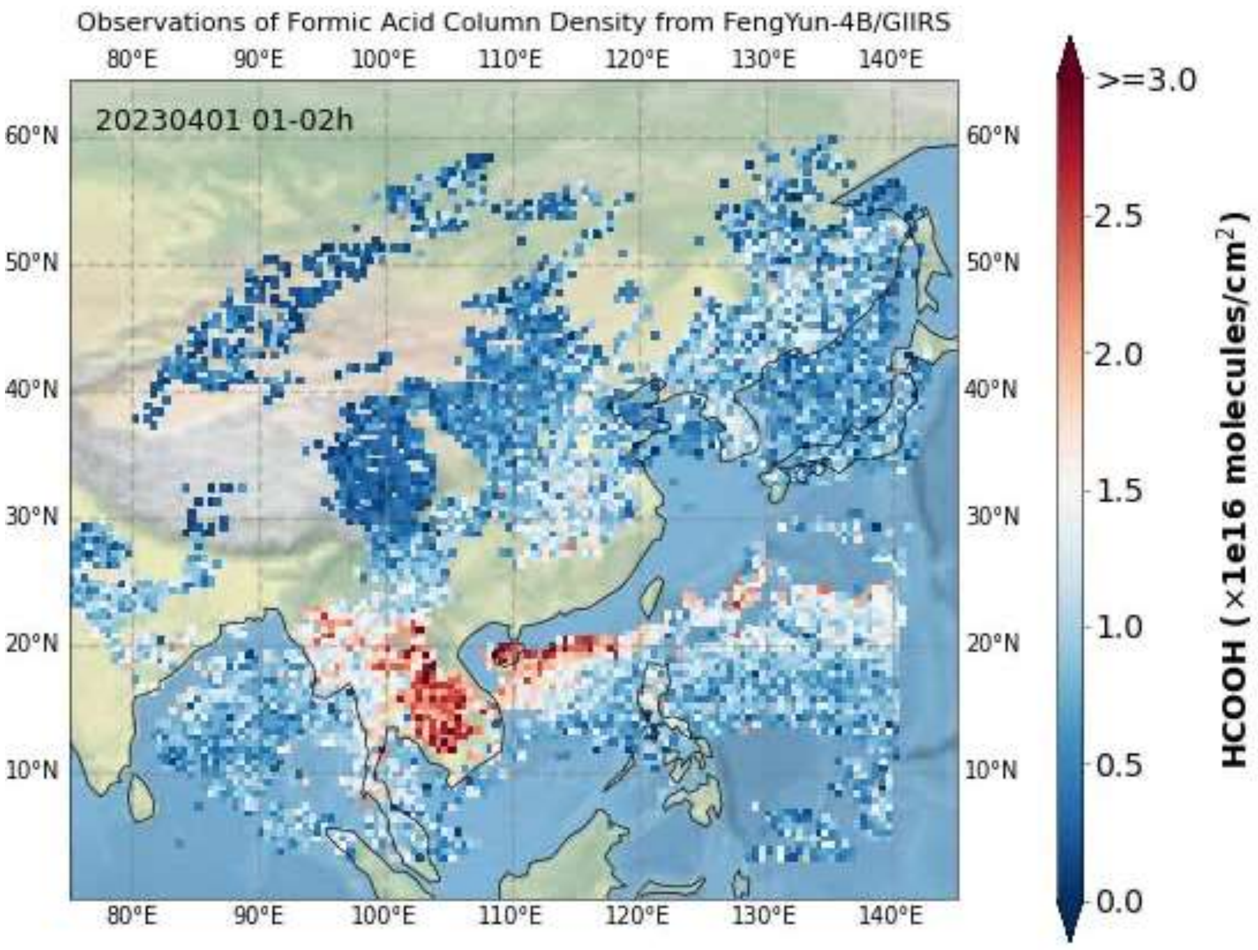
2-hour averages over the SE Asia land



(1) Strong CO emissions transported toward the South China Sea and the Pacific;
(2) The diel cycle represents typical fire emissions caused by changes in temperature/humidity/agricultural activities
(3) Observation sensitivity changes (indicated from AK matrix)

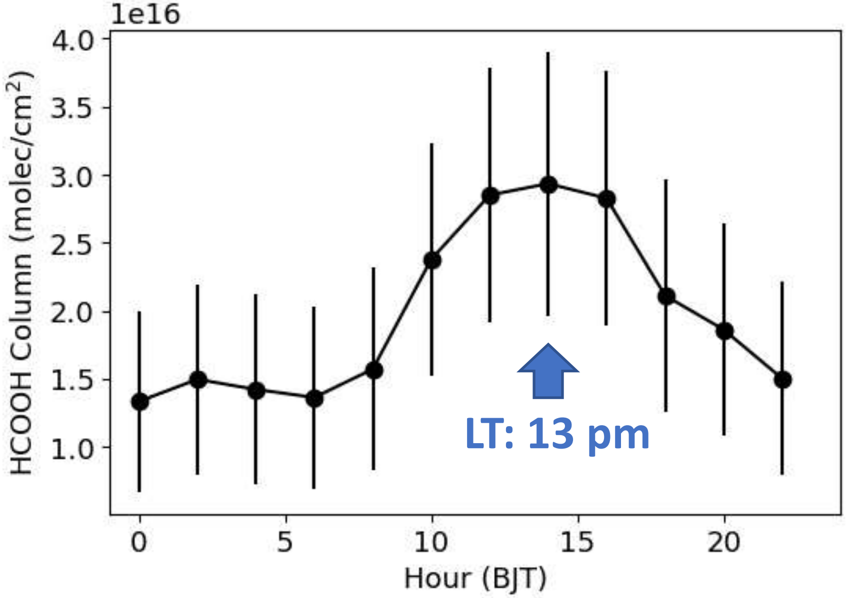
Diel cycle of wildfire HCOOH columns from Southeast Asia

Maps of HCOOH columns every 2-hour in Apr 2023



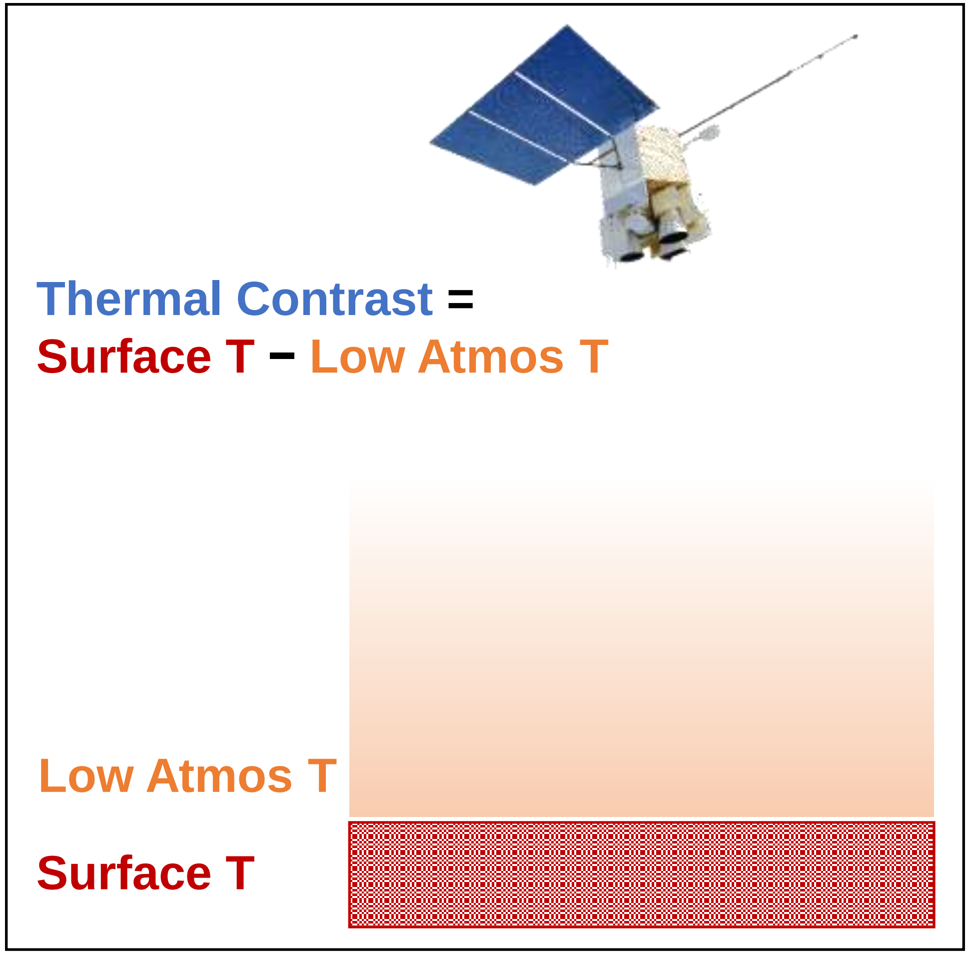
Credit: Peking University and National Satellite Meteorological Center

2-hour averages over the SE Asia land



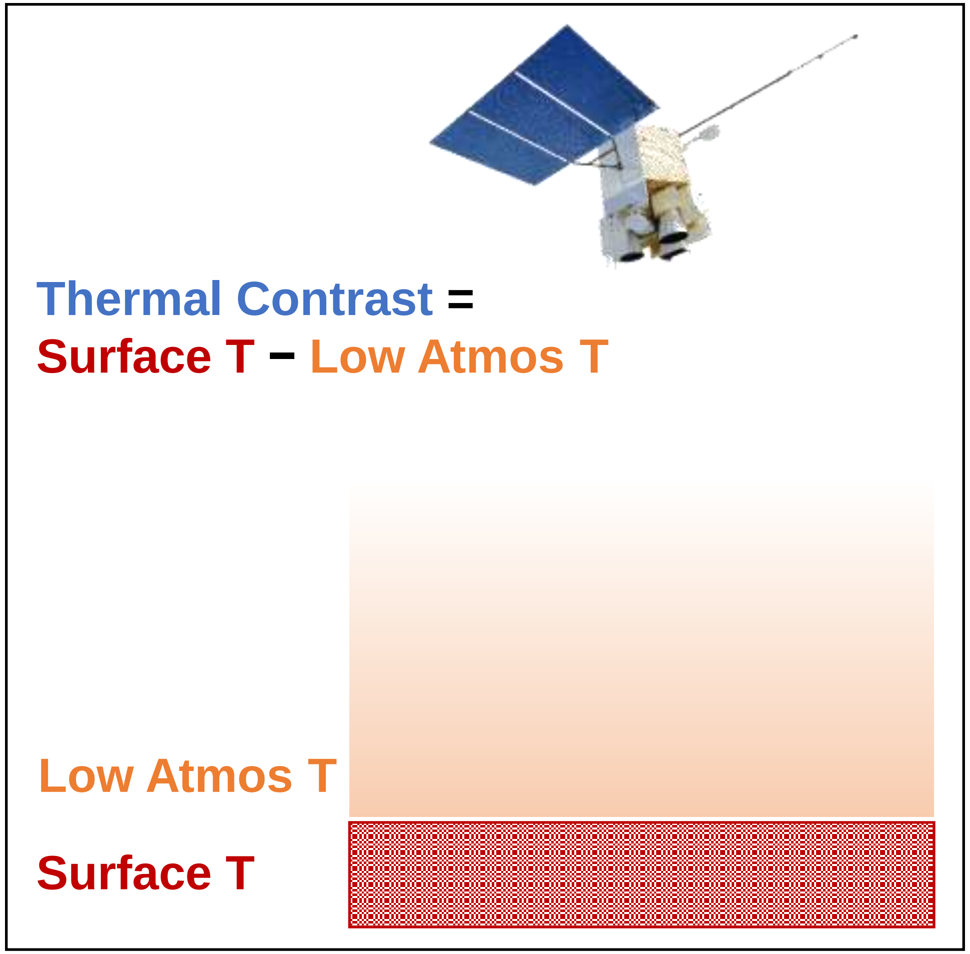
(1) Strong HCOOH emissions transported toward the South China Sea and the Pacific;
(2) The stronger diel cycle compared to CO;
(3) Most of the HCOOH enhancement comes from photochemical production (Franco et al., 2020; Millet et al., 2015, and others)

Vertical sensitivity from thermal infrared remote sensing

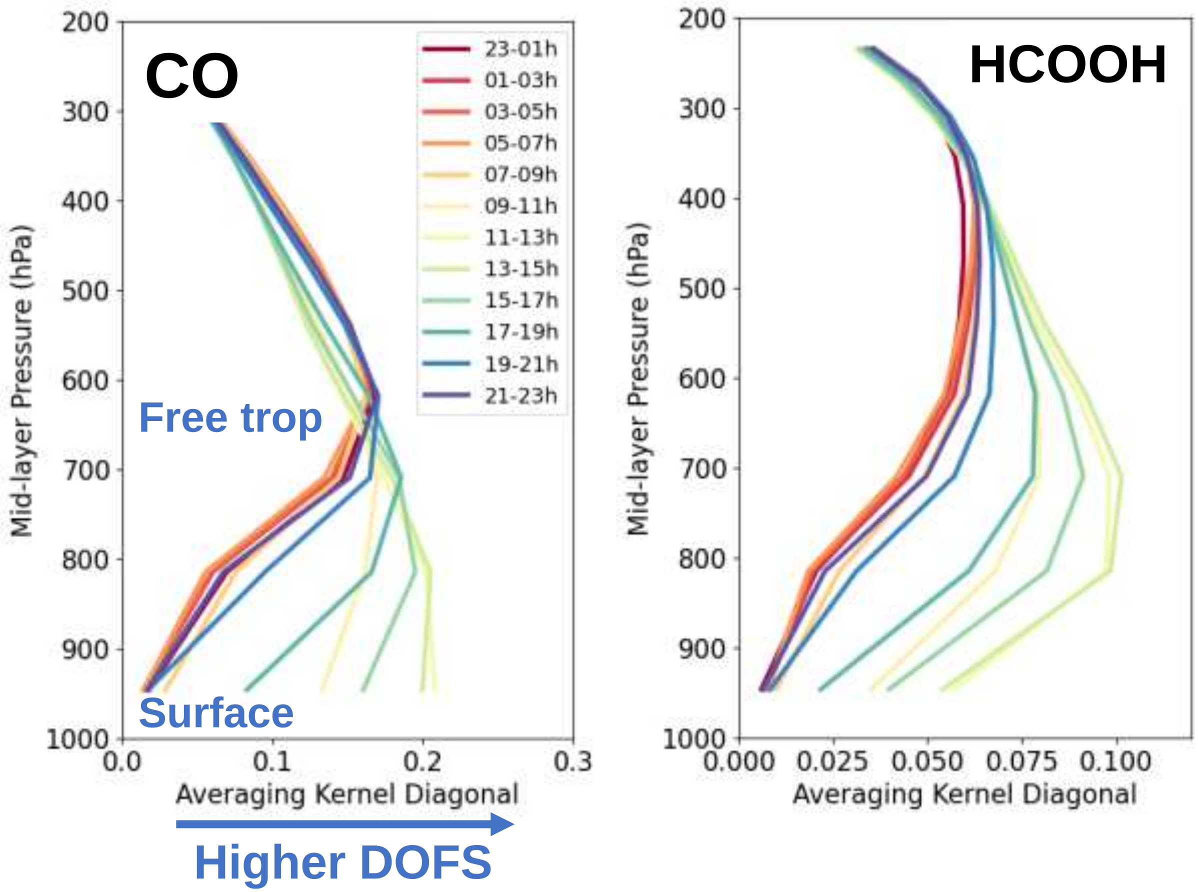


- **Degree of Freedom for Signal (DOFS)** represents the number of independent elements of information extracted from the spectra (The trace of the Averaging Kernel matrix)
- DOFS and thermal contrast are highly correlated.

Vertical sensitivity from thermal infrared remote sensing



Averaged averaging kernel diagonal vectors in April 2023

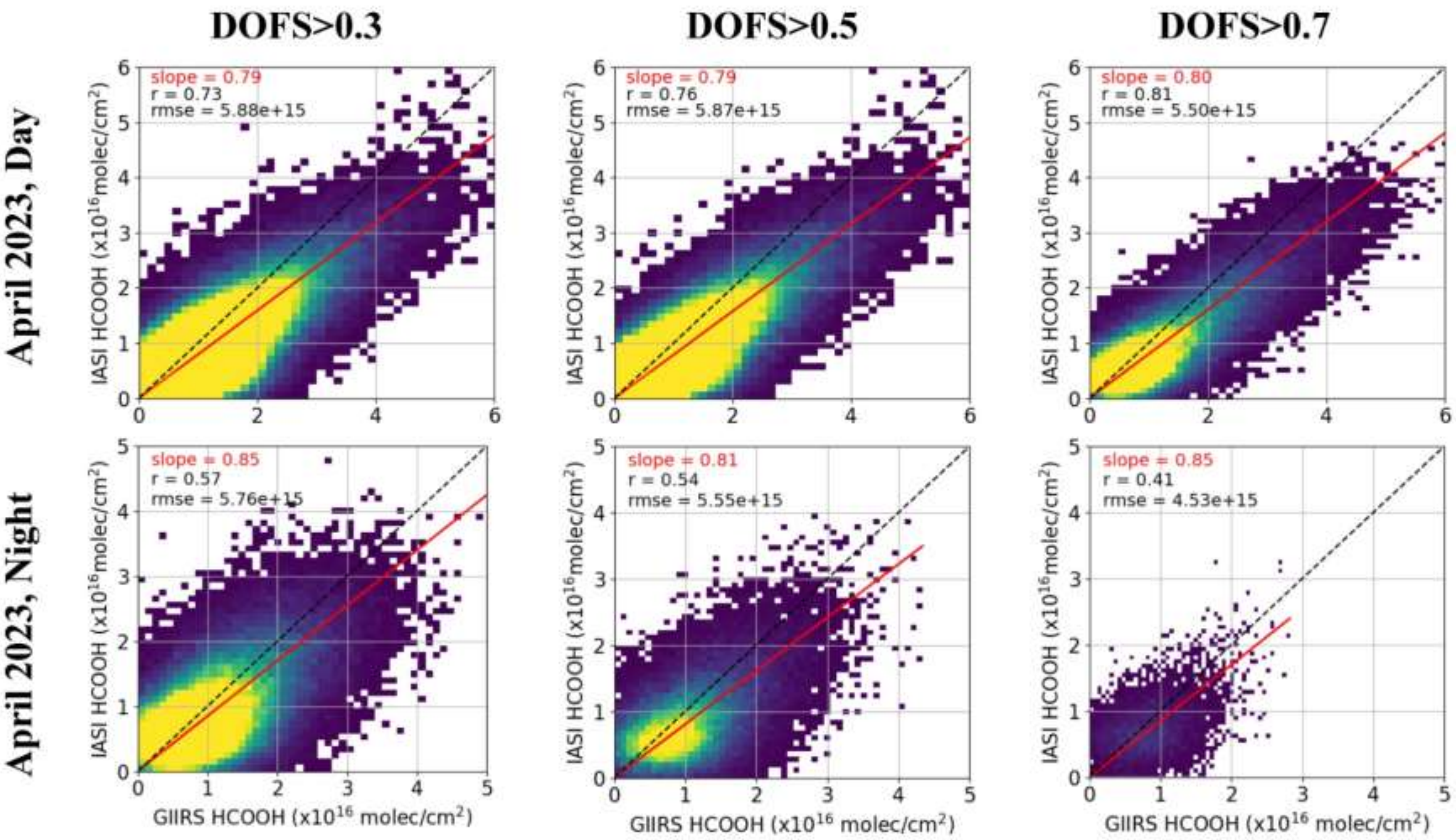


- **Degree of Freedom for Signal (DOFS)** represents the number of independent elements of information extracted from the spectra (The trace of the Averaging Kernel matrix)
- DOFS and thermal contrast are highly correlated.

(1) Local noontime has the highest DOFS in the lower atmosphere;
(2) The distinctive difference in the lower tropospheric AK values demonstrates the importance of high TC in providing information to the lower tropospheric CO and HCOOH retrievals.

Cross-comparison with IASI: HCOOH as an example

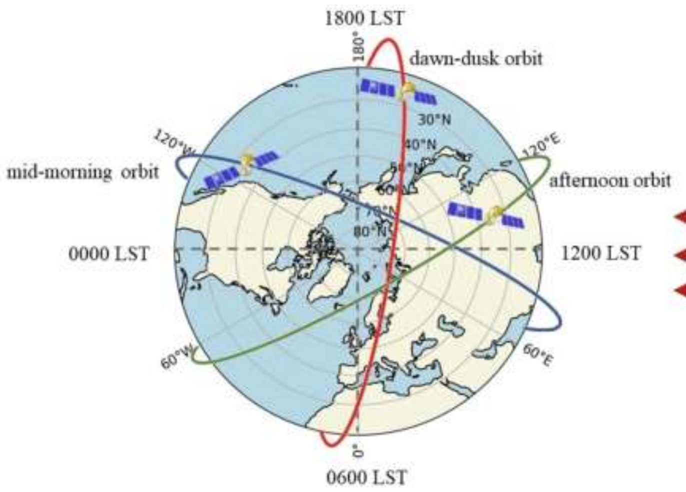
- Comparison of HCOOH columns between GIIRS and IASI retrievals in April 2023 and June 2023, separately for day and night.
- Collocated point pairs are defined as observation footprints that are less than 20 km apart in space and differ by less than 1 hr in observation time.



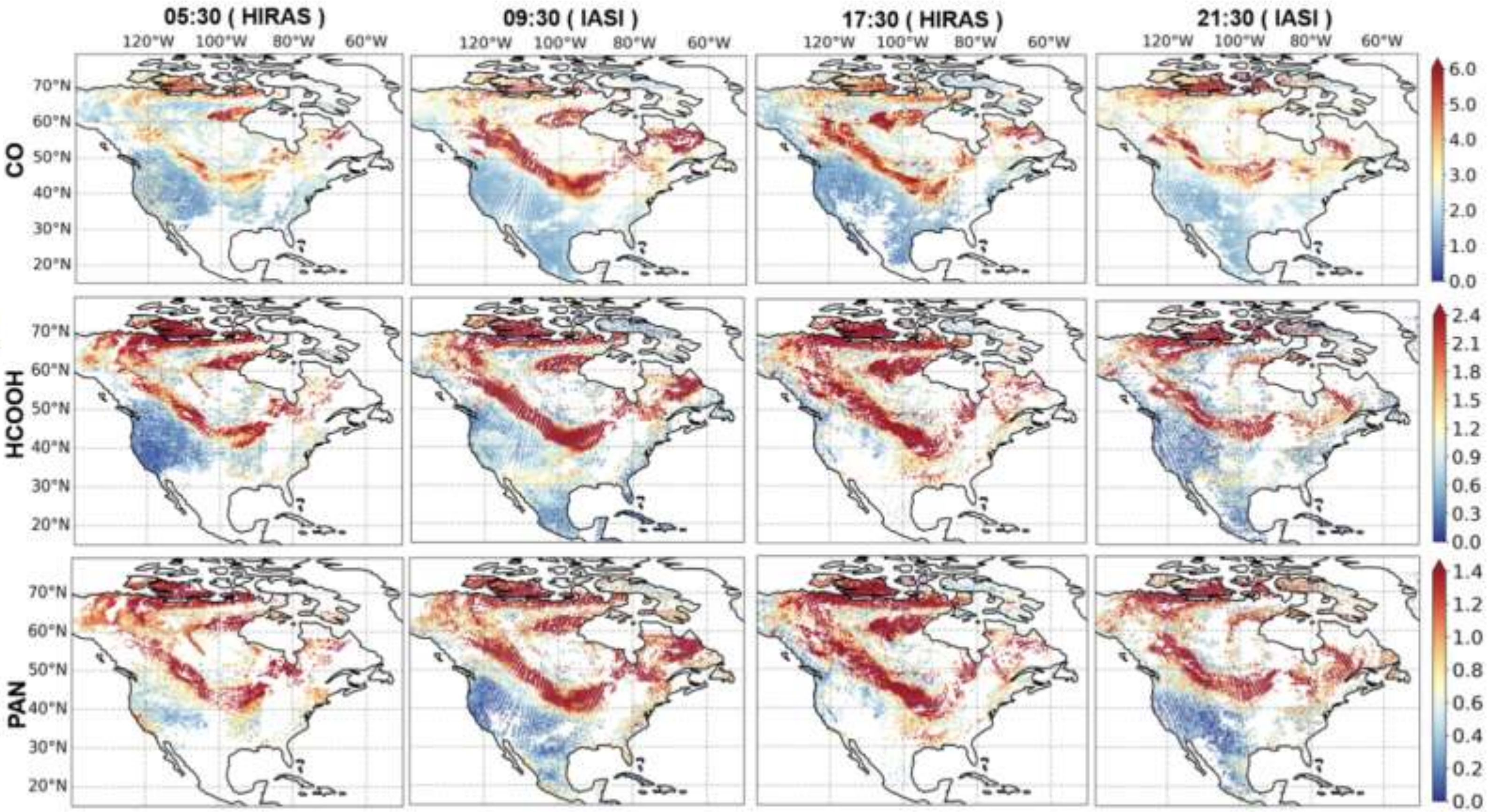
Zeng et al. 2024 JGR-Atmosphere

Observing CO and VOCs (PAN and HCOOH) from Canadian wildfires in 2023 from FengYun-3E/HIRAS-II in a dawn-dusk sun-synchronous orbit

FY-3E: equatorial overpass times at 5:30am/pm



unit: $\times 10^{18}$ molec/cm^2



Highly consistent; Slightly change from morning to afternoon; Combined with IASI and CrIS to form a global LEO IR constellation with 4-hour temporal resolution.

Hua et al., 2024, in review by RSE, preprint at ESSOA, http://dx.doi.org/10.22541/essoar.172675985.56629182/v1

Conclusions

- We demonstated that GIIRS retrievals tracks day-night cycle of the wildfire induced trace gases enhancements from Southeast Asia.
- Observing CO and VOCs (PAN and HCOOH) from Canadian wildfires in 2023 from FengYun-3E/HIRAS-II in a dawn-dusk sun-synchronous orbit
- Combining with atmospheric chemical transport models, these observations will offer important information to improve our understanding of the production, evolution, and loss processes of CO, NH_3, and HCOOH in the atmosphere.

Thank you for your attention!

Related Publications

- Zeng, Z.-C., et al., 2023a, Diurnal carbon monoxide observed from a geostationary infrared hyperspectral sounder: first result from GIIRS on board FengYun-4B, Atmos. Meas. Tech., **AMT Highlight paper**
- Zeng, Z.-C., et al., 2023b, Optimal estimation retrieval of tropospheric ammonia from the Geostationary Interferometric Infrared Sounder on board FengYun-4B, Atmos. Meas. Tech.
- Zeng, Z.-C., et al., 2024, Observing a Volatile Organic Compound from a Geostationary Infrared Sounder: HCOOH from FengYun-4B/GIIRS, JGR-Atmosphere.

Data availability:

- The GIIRS L1 spectra are publicly available from the National Satellite Meteorological Center: http://satellite.nsmc.org.cn/portalsite/.
- Early portion of CO, NH3, and HCOOH are publicly available online, links are in the paper; Full 2-year datasets are available (zczeng@pku.edu.cn)
- Encounter problems in accessing FengYun data? Account registration no response? user guide in Chinese only?

Acknowledgement: National Science Foundation of China; IASI portal (https://iasi.aeris-data.fr/); National Satellite Meteorological Center (https://nsmc.org.cn/); IASI data portal (https://iasi.aeris-data.fr/)