Towards a remote sensing solution to quantify N_2O emissions by integrating shortwave and longwave infrared bands

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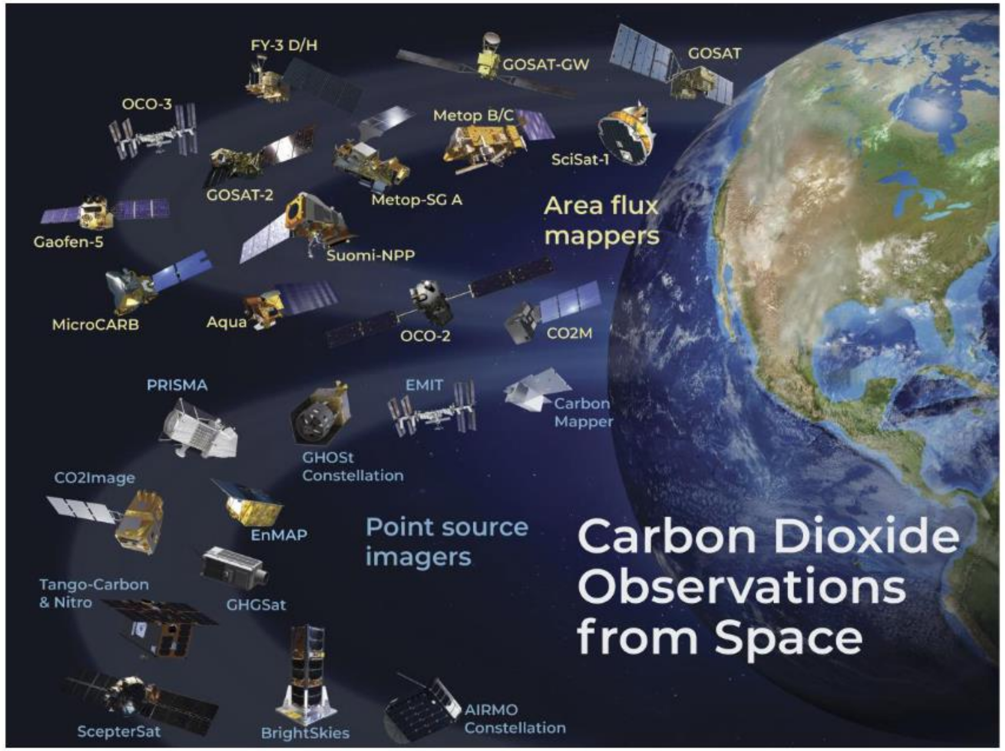
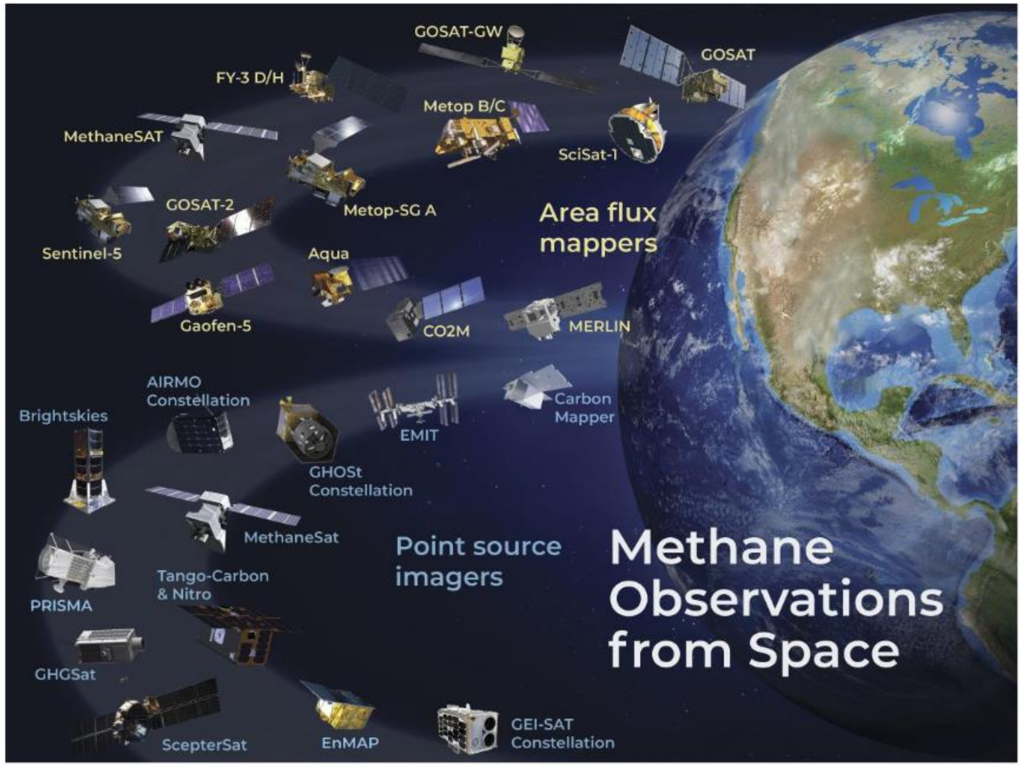
IWGGMS-21
21ST INTERNATIONAL WORKSHOP ON GREENHOUSE GAS MEASUREMENTS FROM SPACE

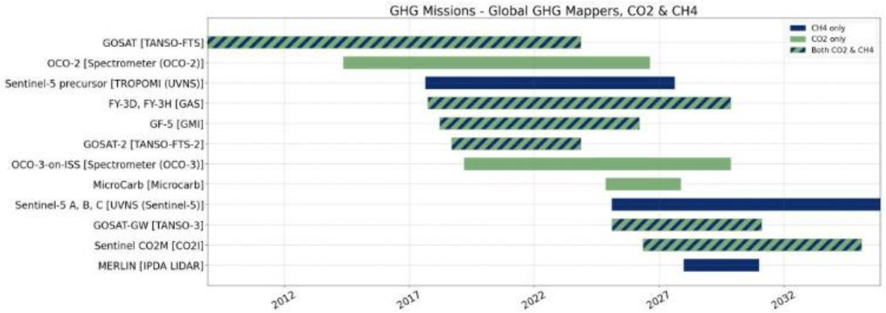
Environmental Defense Fund

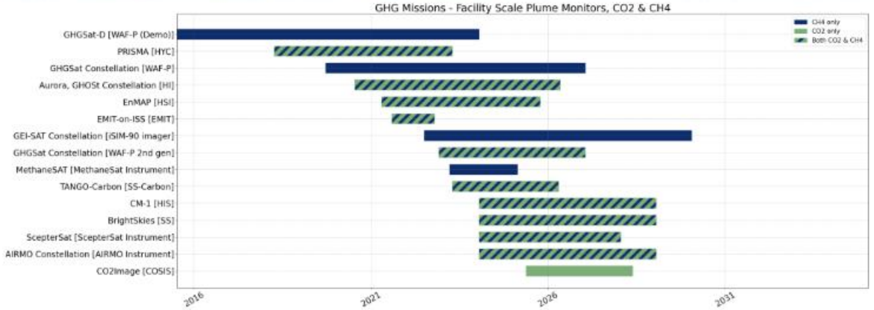
BAE SYSTEMS

N_2O: a key greenhouse gas overlooked from space



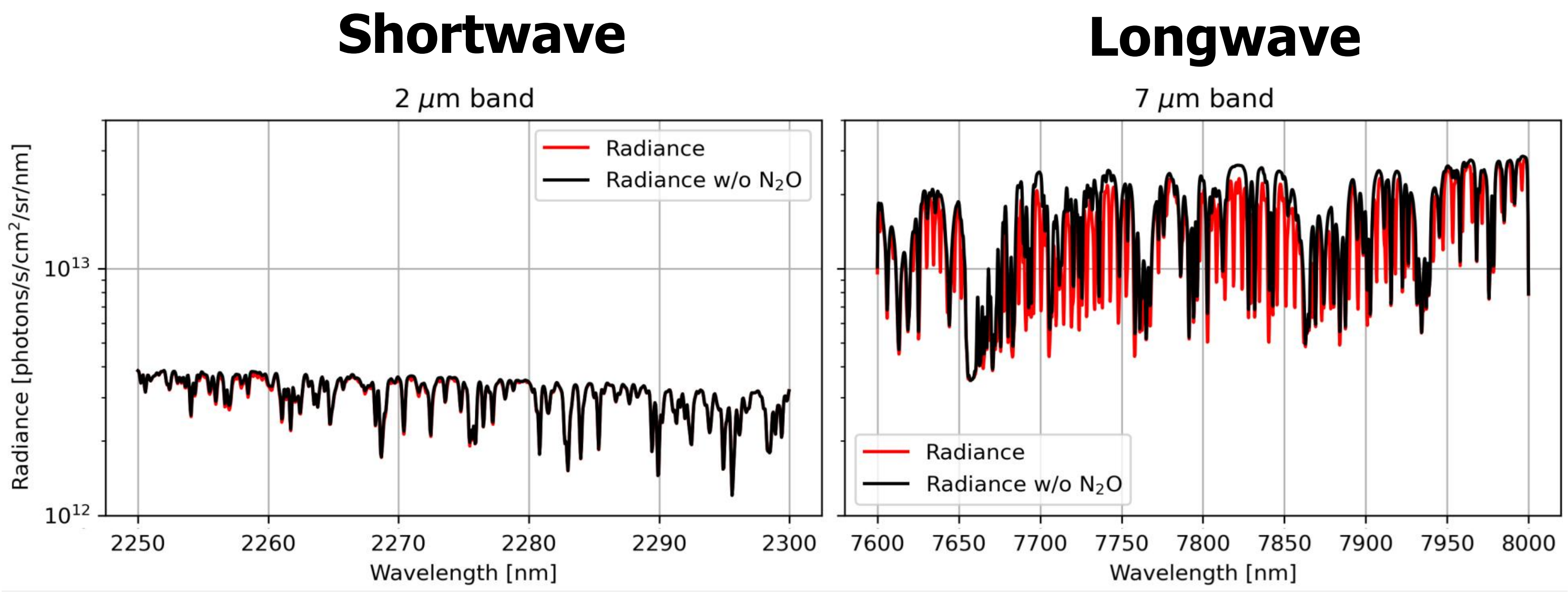






https://cpaess.ucar.edu/sites/default/files/2024-iwggms/Crisp-David.pdf

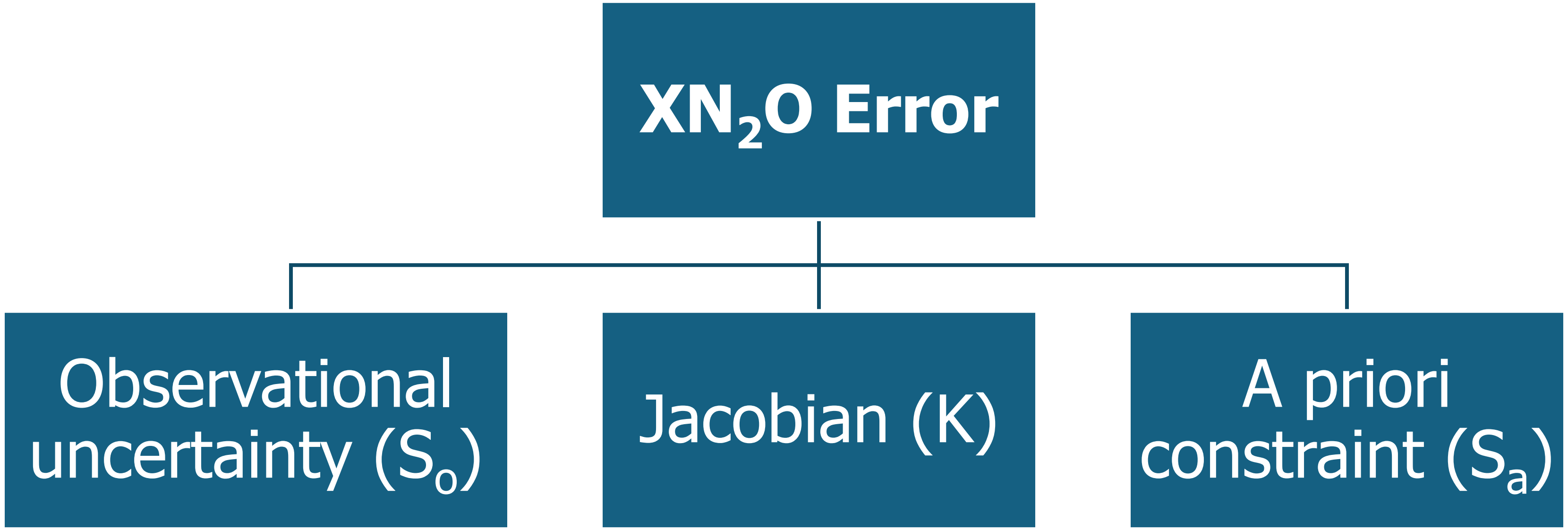
The challenge of N_2O remote sensing



- 2 μm: consistent vertical sensitivity but very weak N_2O absorption
- 7 μm: strong absorption and radiance level but weak near-surface sensitivity
- Integrate 2 μm and 7 μm to combine the strengths of short and longwave bands

How precisely can we observe XN_2O?

- XN_2O: Column-integrated mixing ratio of N_2O $\left(XN_2O = \frac{\Omega_{N2O}}{\Omega_A}\right)$



S_m: measurement error covariance matrix

$$S_m = GS_oG^T$$

$$G = S_aK^T\left(KS_aK^T + S_o\right)^{-1}$$

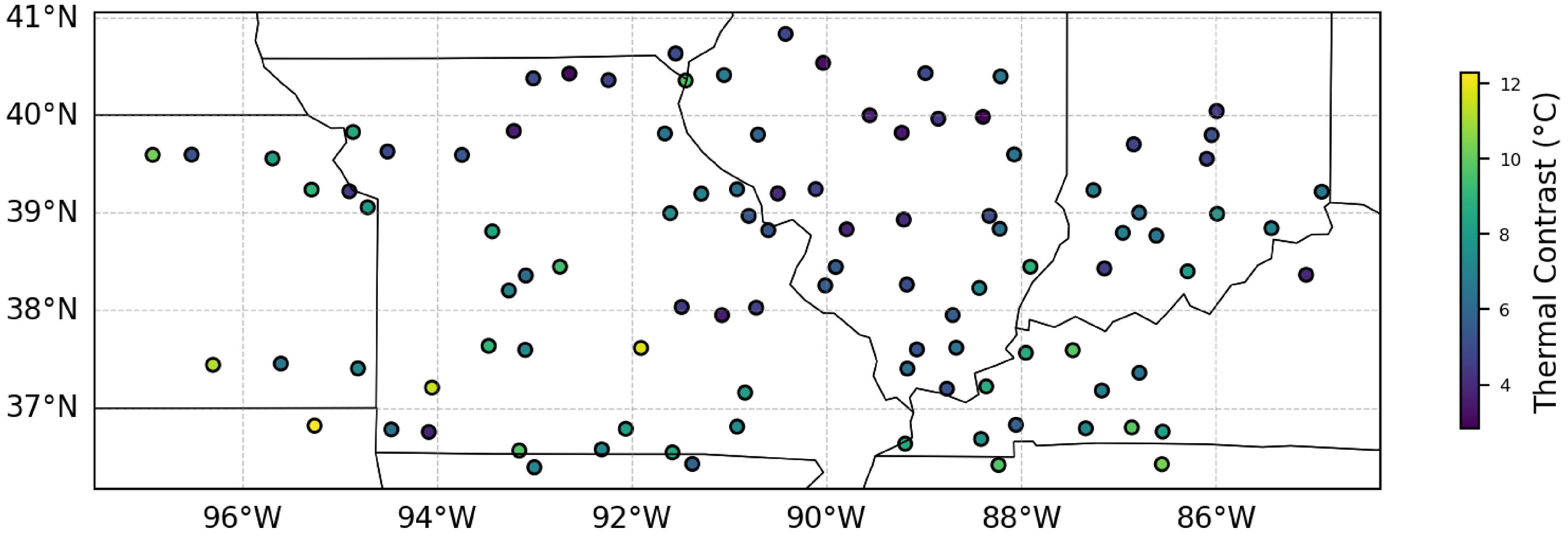
Measurement error of XN_2O

$$\sigma_{XN_2O(m)} = h^T S_m h$$

h: pressure weighing function

Atmospheric and surface states

- CrIS Level 2 files for N_2O, CH_4, H_2O, and temperature from the JPL MUSES algorithm
- Atmospheric profiles and surface conditions extracted from 100 CrIS pixels
- Area: US Midwest (Part of corn belt)
- Observation date: 23 August 2023



Observational uncertainty

Parameter [unit]	2 μm band	7 μm band
Wavelength range [nm]	2240–2300	7600–8000
Spectral sampling [nm]	0.0575	0.25
Slit width [× spectral sampling][a]	3	3
Exposure time [s]	0.1	0.1
Detector pixel size [μm]	18	18
f-number	2	2
System efficiency	0.5	0.5
Readout noise [electrons]	60	60
Airborne observation altitude [km]	10	10
Spaceborne observation altitude [km]	600	600
Airborne along-track [m]	20	20
Spaceborne along-track [m]	701	701
Airborne across-track [m]	2.95	2.95
Spaceborne along track [m]	155	155
Airborne ground sampling distance [m]	7.7	7.7
Spaceborne ground sampling distance [m]	330	330

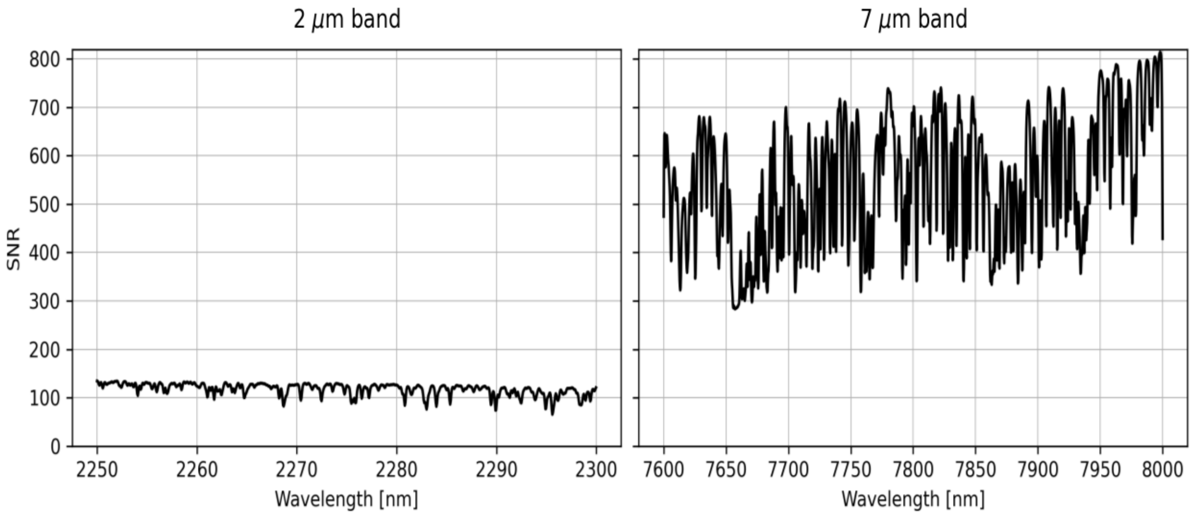
[a] Gaussian slit function (i.e., instrument spectral response function, ISRF) is assumed.

$$S = \frac{\pi}{4} \cdot \boxed{I} \cdot dp^2 \cdot \frac{1}{f^2} \cdot n_{\text{sample}} \cdot dt \cdot d\lambda \cdot \eta$$

$$N = \sqrt{S + N_r^2}$$

$$\text{SNR} = \frac{S}{N}$$

SPLAT-VLIDORT radiative transfer model is used to simulate radiance (I)



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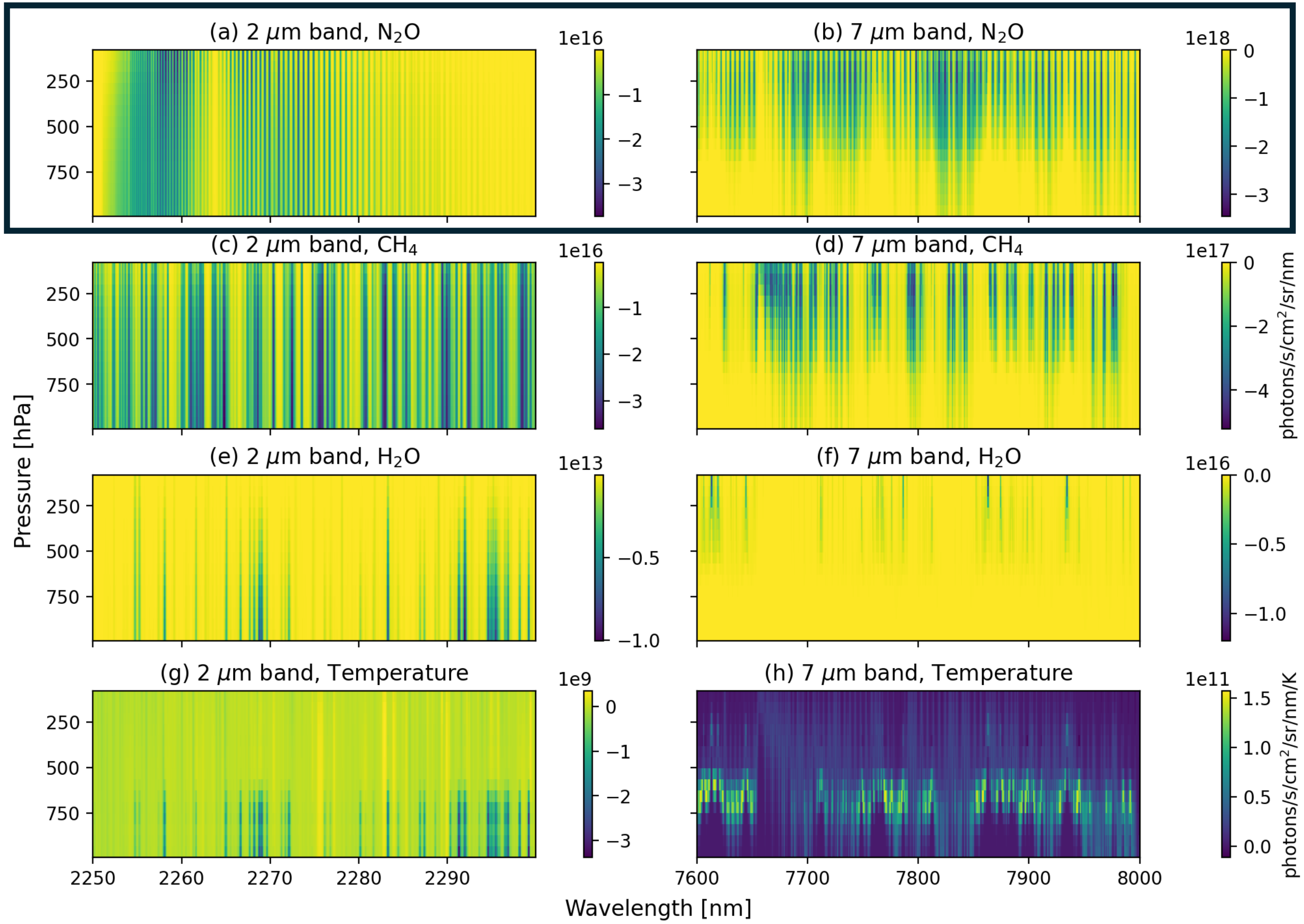
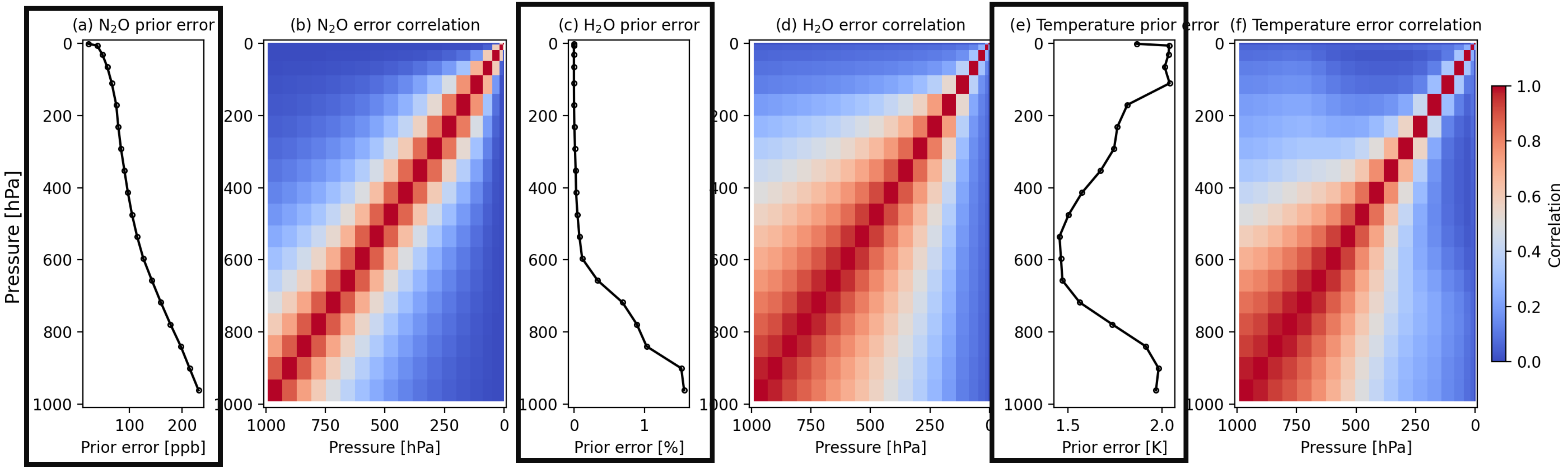
Radiance sensitivity to state vector (Jacobians)



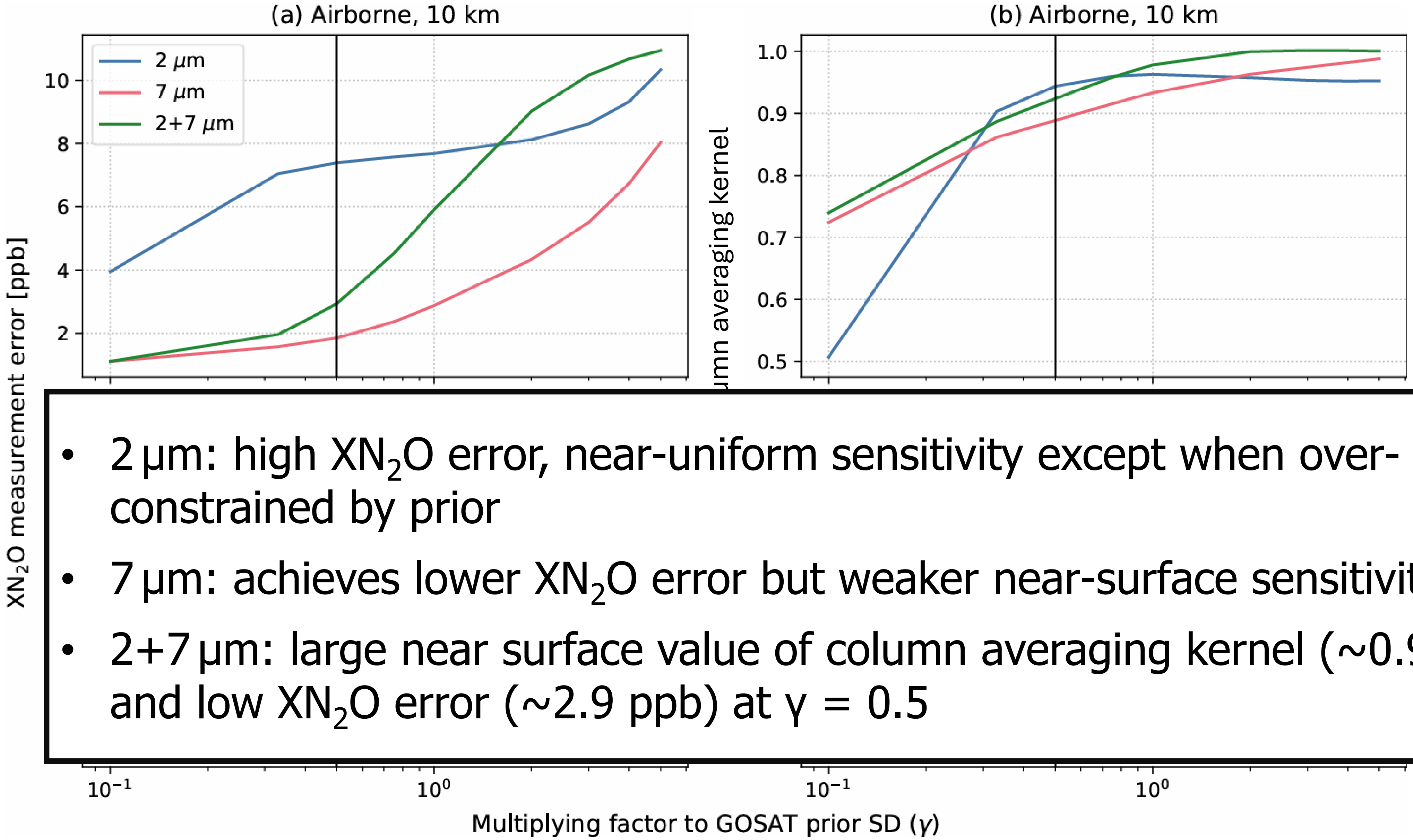
- State vector includes N_2O, CH_4, water vapor, temperature profiles, and surface temperature
- 2 µm: sensitivity to the whole column including near-surface
- 7 µm: stronger sensitivity to N_2O as compared to the 2 µm band, but less sensitive to near-surface layers

A priori constraint



- N_2O prior error is derived from University of Leicester GOSAT CH_4 retrieval, scaled by their background concentration ratio (330 ppb / 1900 ppb)
- H_2O and temperature priors are adopted from CrIS algorithm
- Scaling factor gamma (γ) is applied to N_2O prior standard deviation to tune prior constraint strength

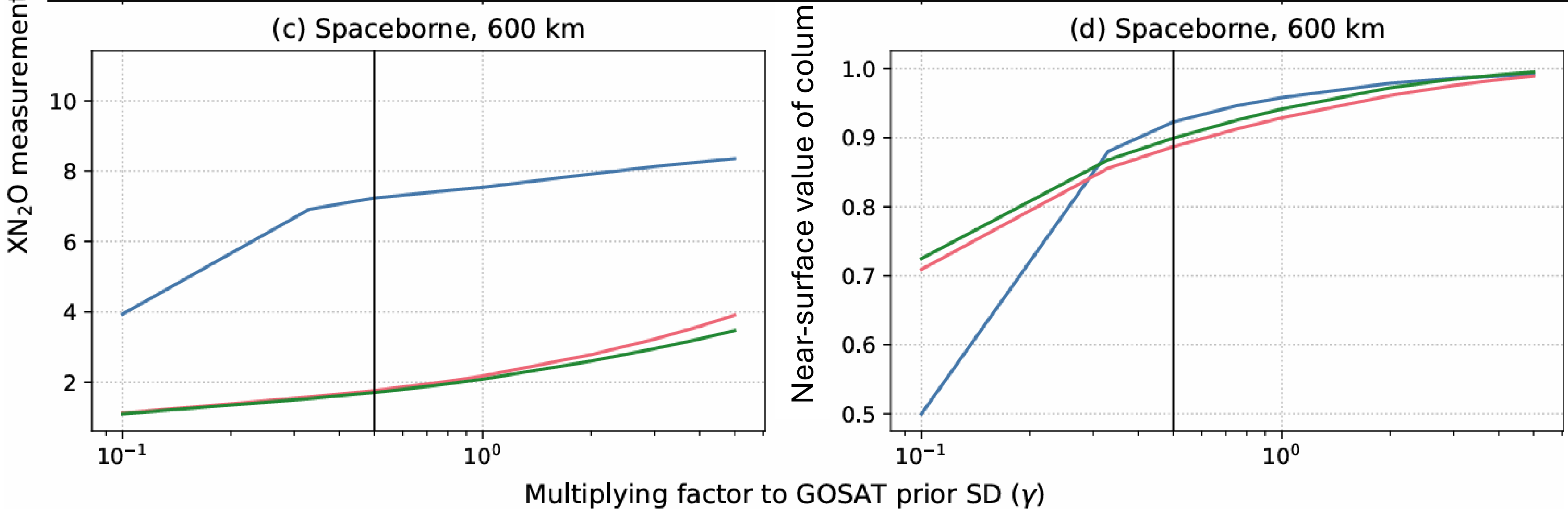
XN_2O precision



- 2 μm: high XN_2O error, near-uniform sensitivity except when over-constrained by prior
- 7 μm: achieves lower XN_2O error but weaker near-surface sensitivity
- 2+7 μm: large near surface value of column averaging kernel (~0.91) and low XN_2O error (~2.9 ppb) at γ = 0.5

XN_2O precision

- 2 μm: highest XN_2O error across all prior strengths
- 7 μm: comparable XN_2O error with dual-band approach but weaker near-surface sensitivity
- 2+7 μm: large near surface value of column averaging kernel (~0.9) and low XN_2O error (~1.7 ppb) at γ = 0.5



How precisely can we observe XN_2O?

Using 2 μm and 7 μm integration and at a moderate prior strength (γ = 0.5), we achieve:

- 2.9 ppb XN_2O error for airborne
- 1.7 ppb XN_2O error for spaceborne
- ~0.9 near surface value of column averaging kernel for both

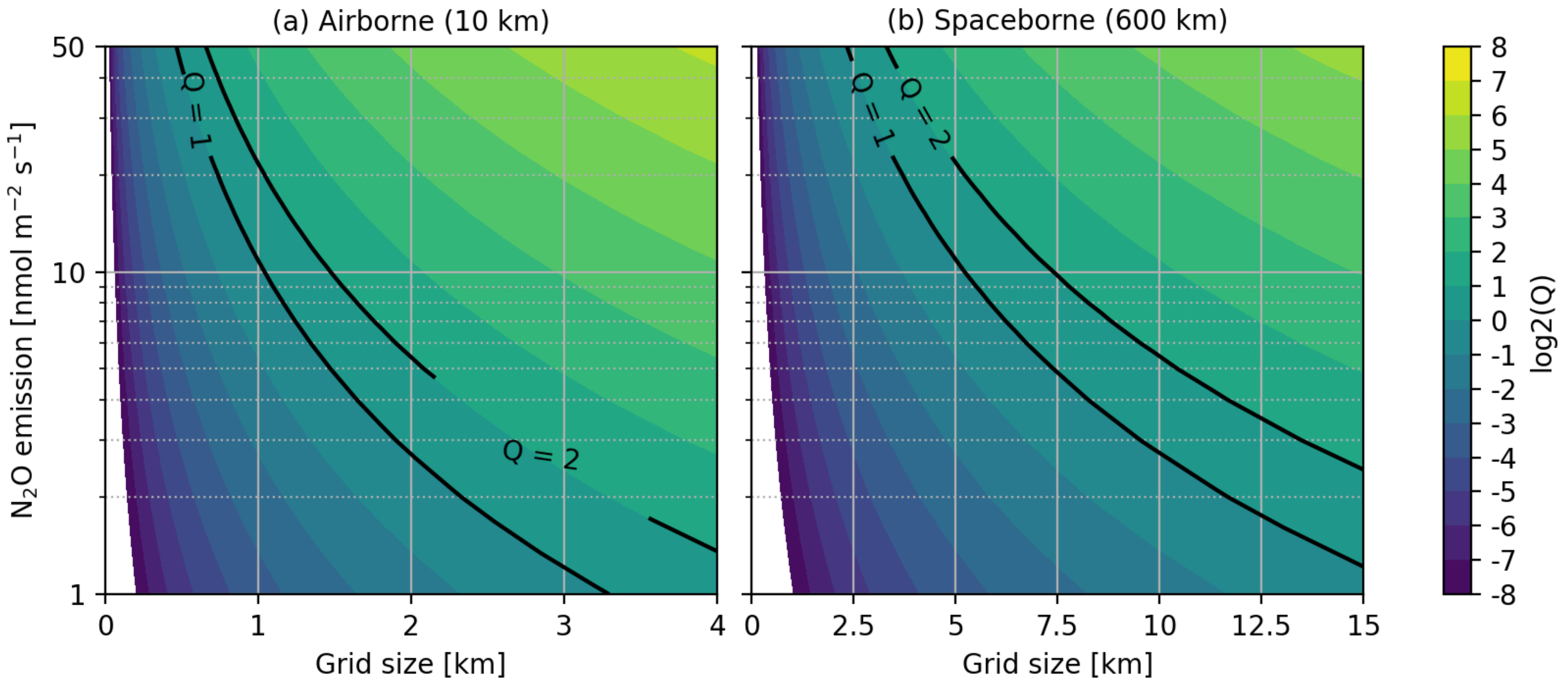
With those precisions, can we detect actual surface emissions, and at what spatial scale?

Estimating N_2O emissions using errors

$$Q = \frac{Emission\ induced\ enhancement\ (\Delta\Omega)}{Column\ error\ (\sigma_\Omega)} = \frac{E\Delta x^2 M_{air} g}{|u|\sigma_{XN2O} x_0 P_{air}}$$

Parameter	Value [unit]
Emissions (E)	1-50 [nmol m^{-2} s^{-1}]
Airborne ground sampling distance (x_{0_air})	7.7 [m]
Spaceborne ground sampling distance (x_{0_space})	330 [m]
Airborne aggregation scale (Δx)	X_{0_air} to 4 [km]
Spaceborne aggregation scale (Δx)	X_{0_space} to 15 [km]
Molar mass of dry air (M_{air})	0.029 [kg mol^{-1}]
Acceleration due to gravity (g)	9.8 [m s^{-2}]
Wind speed ($|u|$)	1.389 [m s^{-1}]
Airborne σ_{XN2O}	2.9 [ppb]
Spaceborne σ_{XN2O}	1.7 [ppb]
Pressure (P_{air})	1e5 [Pa]

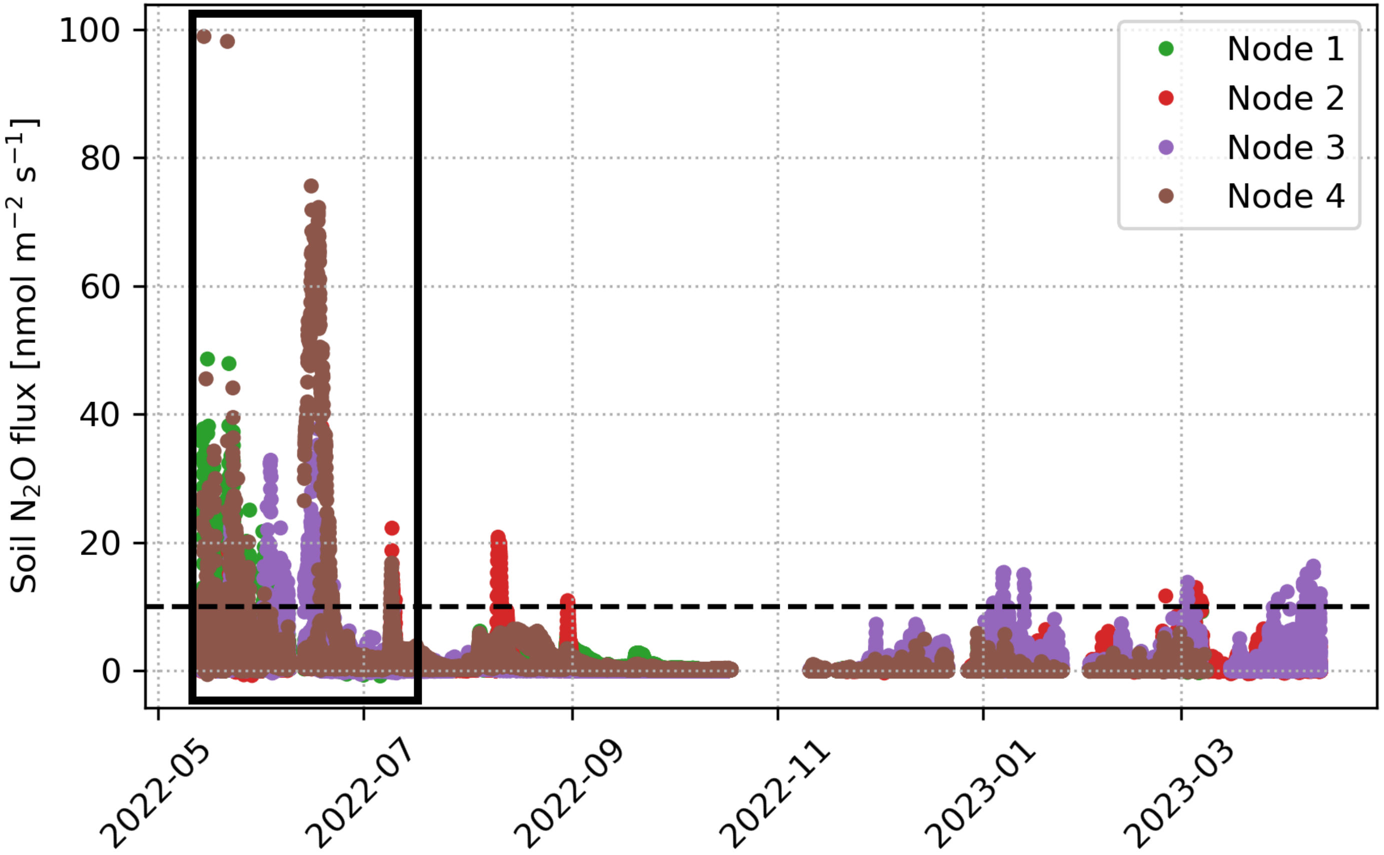
Estimating N_2O emissions using errors



- Airborne: 10 nmol m^{-2} s^{-1} emission flux is observable at unit signal-to-noise ratio (Q) at ~1 km
- Spaceborne: 10 nmol m^{-2} s^{-1} emission flux is observable at unit signal-to-noise ratio (Q) at ~5 km

N_2O chamber data from University of Illinois

Auto-chambers on conventionally tilled maize field in central Illinois, USA



- 4 Nodes, 5 chambers per node
- $5x10^4$ m^2 area of the field, with nodes 50–100 m distance apart
- 10 nmol m^{-2} s^{-1} or higher N_2O emission does occur in the real field especially during growing season
- N_2O flux correlated for nodes that are 100 m apart

Conclusion

- Evaluated remote sensing solutions for high-resolution mapping of N_2O flux variability in agricultural landscapes

- Integrating the shortwave and longwave bands deliver strong near-surface sensitivity (AVK ≈ 0.9) and low XN_2O error (≈ 2.9 ppb airborne; 1.7 ppb spaceborne)

- Emission flux of 10 nmol m^{-2} s^{-1} is observable at Q = 1 down to ~1 km for airborne and ~5 km for spaceborne