Understanding Global CO_2 Fluxes and Concentrations using Multi-Model Simulations and Satellite Observations

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MOTIVATION

- Significant discrepancies exist among atmospheric inversion systems, particularly over mid- to high-latitude and tropical regions.
- It is critical to quantify whether uncertainties in derived carbon fluxes arise from inconsistencies across observational platforms or from structural errors in the transport model.

SCIENTIFIC QUESTIONS

How do regional differences compare between MIROC4-ACTM XCO_2 simulations and observations from four distinct satellite missions?

How does the inter-model spread in CO_2 transport compare to inter-satellite mismatches, and which regions exhibit the highest flux uncertainty?

DATA & METHODS

▸ 4 Satellite Missions (2020)

Satellite	Product	Orbit / LSH
GOSAT	NIES v03.05	Sun-sync, ~12:50
GOSAT-2	NIES v02.20 (raw)	Sun-sync, ~12:55
OCO-2	ACOS v11.2	Sun-sync, ~13:36
OCO-3 (ISS)	ACOS v11	Non-sun-sync, varies

Path A · Eq. 1 · Rodgers (2000) convolution

$$XCO_2^{ACTM} = \Sigma_i \{ \Delta P_i (CAK_i \cdot CO_{2i}^{ACTM} + (1 - CAK_i) \cdot CO_{2i}^{prior})$$

MIROC4-ACTM convolved with each mission's CAK & AP → satellite vs model

▸ 4 Transport / Inversion Models (2016–2019)

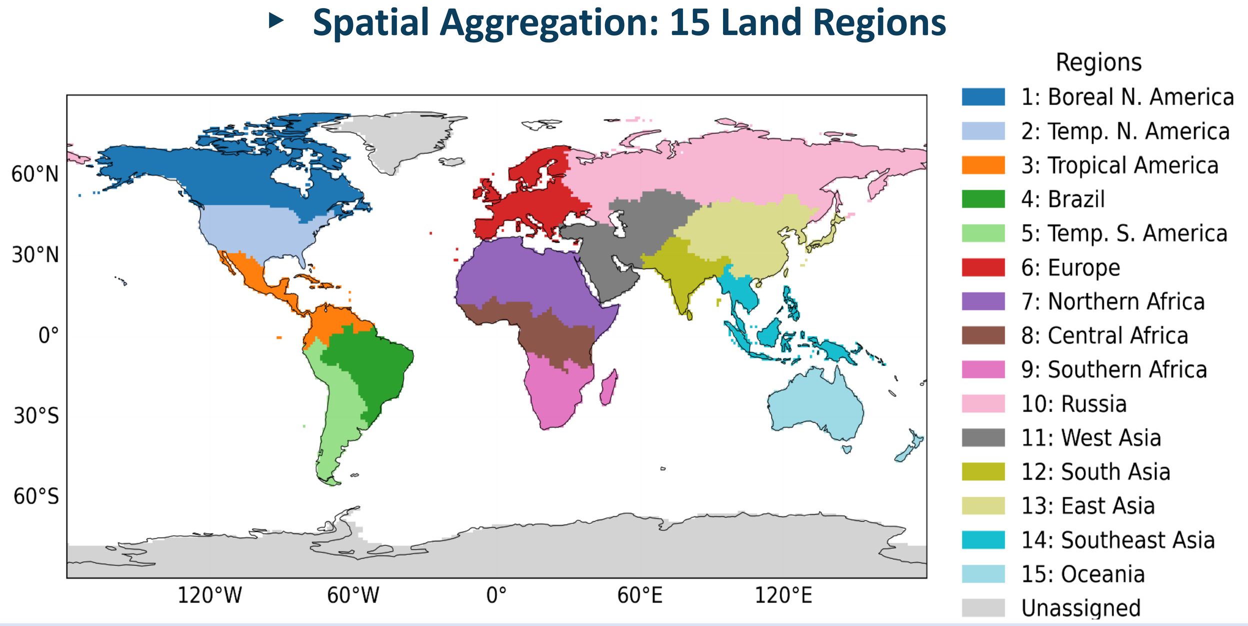
Inversion	Transport Core	Institute
MIROC4-ACTM	MIROC4.0 ACTM	JAMSTEC, Japan
COLA	GEOS-Chem	CMA, China
NISMON-CO_2	NICAM-TM (4D-Var)	NIES, Japan
GCASv2	MOZART-4	Nanjing Univ., China

Path B · Eq. 2 · pressure-weighted column

$$XCO_2^{mod} = \Sigma C_i \Delta P_i / \Sigma \Delta P_i$$

All 4 models · pure pressure-weighted average → model vs model

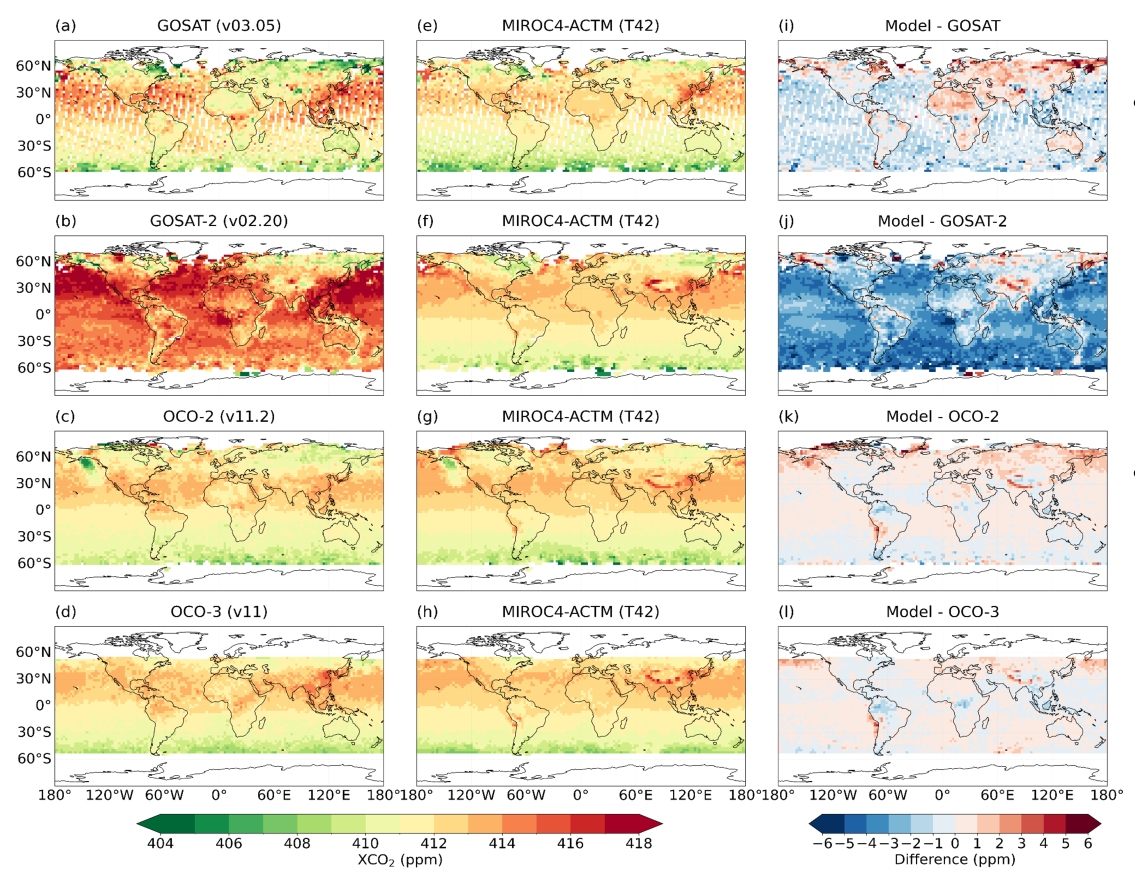
▸ Spatial Aggregation: 15 Land Regions



TAKE-HOME MESSAGES

- **OCO-2 & OCO-3:** Consistent (<1 ppm difference); ready for joint data assimilation.
- **GOSAT-2:** Requires empirical bias-correction (-1.32 ppm global offset) prior to joint use.
- **Inter-model XCO_2** spread (0.6–0.8 ppm) is comparable to **inter-satellite differences** within the OCO pair.

SATELLITE vs MIROC4-ACTM XCO_2

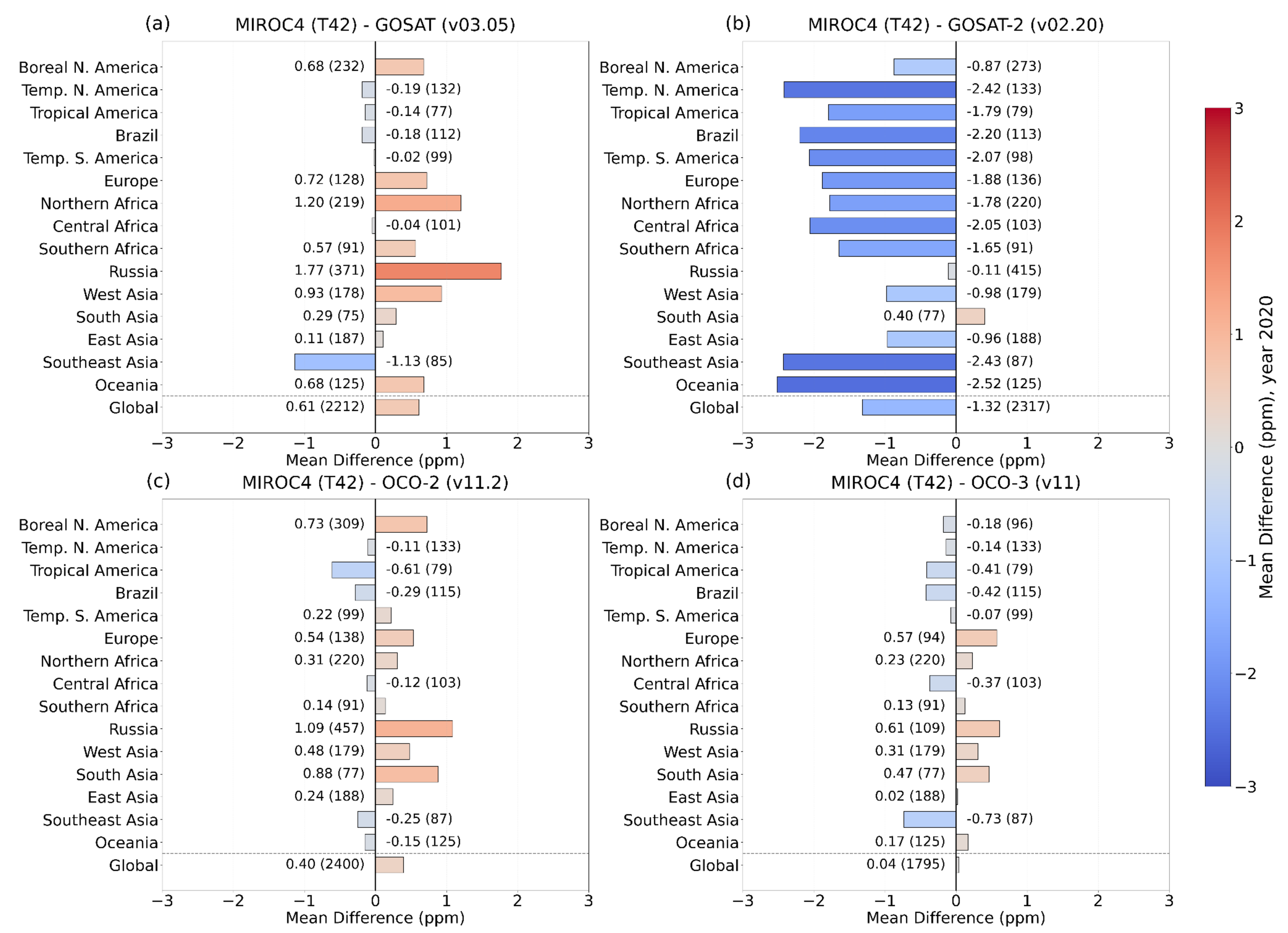


- GOSAT and the OCO pair show small, regionally confined residuals over high-latitude land, GOSAT-2 is systematically negative globally.
- All four missions capture consistent large-scale XCO_2 patterns — higher NH values, 3–4 ppm meridional gradient, and peak values over the West Pacific downwind of East Asian emissions.

GOSAT-2 shows the largest and most widespread negative differences (up to −4 ppm), while **OCO-2 and OCO-3** show comparatively small, spatially coherent differences (<1 ppm).

REGIONAL MODEL–SATELLITE BIAS

- Regional aggregation across 15 land regions: GOSAT-2 shows the largest negative difference (global mean −1.32 ppm).
- OCO-2 & OCO-3 are tightly distributed around zero (global means +0.40 & +0.04 ppm).

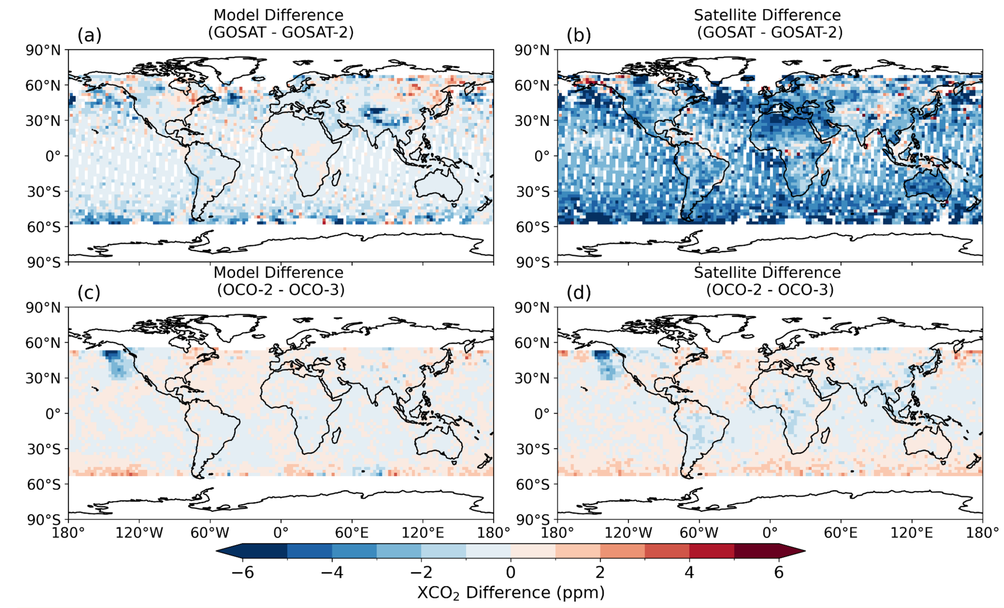


GOSAT-2 raw retrievals are systematically higher — empirical bias-correction needed before joint assimilation.

FUTURE DIRECTIONS

Targeted Validation: There is a critical need for enhanced in situ observations and ground-based satellite validation networks focused specifically on flux uncertainty "hotspots," such as boreal and tropical land regions.

INTER-SATELLITE DIFFERENCES



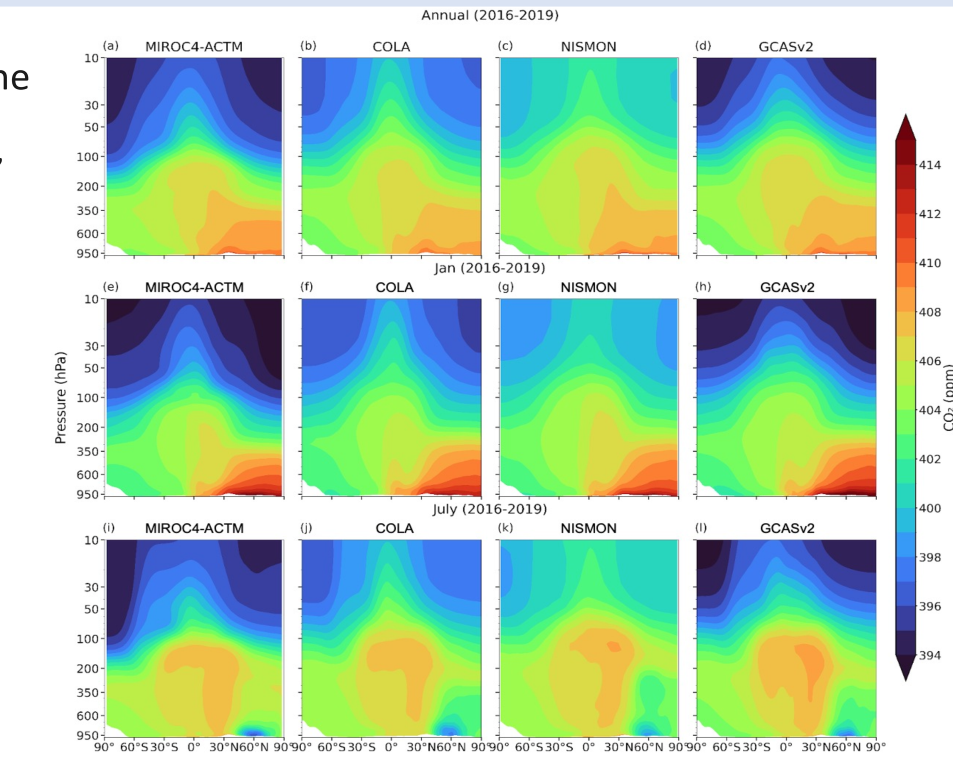
- OCO-2 ↔ OCO-3: model & satellite differences match — sampling-driven.
- GOSAT ↔ GOSAT-2: observed differences exceed model-sampled — retrieval-driven.

OCO-2/OCO-3 differences are small and **spatially coherent** (<1 ppm), while GOSAT/GOSAT-2 differences are large and heterogeneous

STRATOSPHERE DRIVES XCO_2 SPREAD

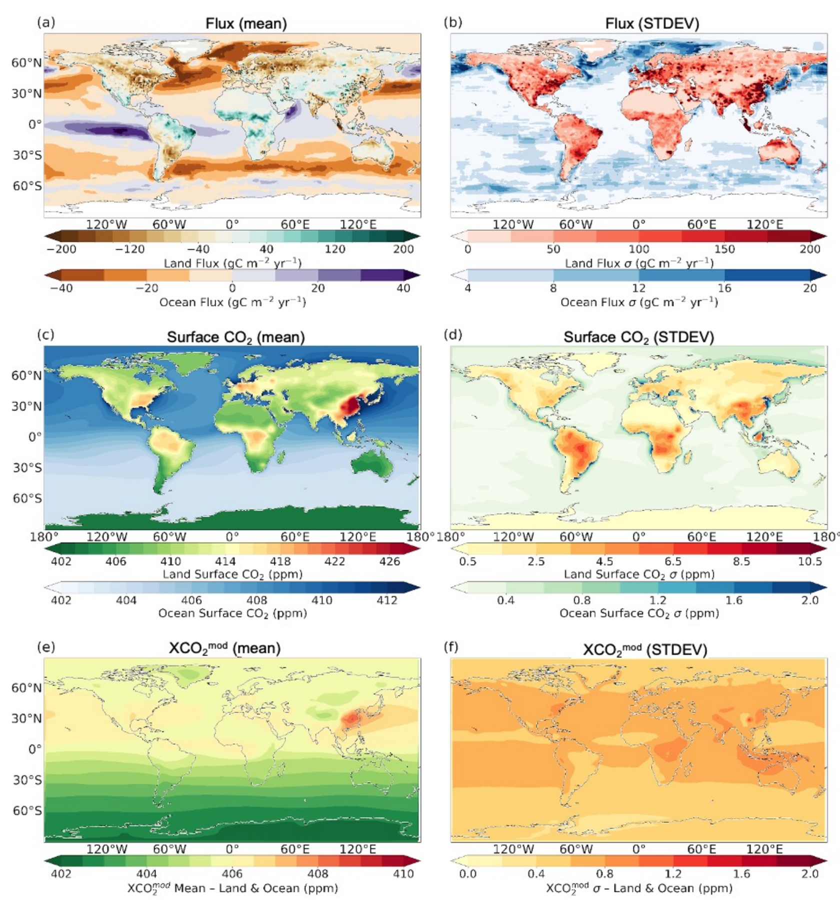
- Models broadly agree in the troposphere but diverge in the stratosphere (~6 ppm spread in the SH mid-stratosphere), reflecting differences in Brewer–Dobson representations.

Variable	Annual (2016-2019)	0-90° N/ 0-90° S
Total XCO_2^{mod}	0.49	0.53/0.45
Trop. XCO_2^{mod}	0.25	0.24/0.25
Strat. XCO_2^{mod}	0.56	0.59/0.53



Stratosphere spread **0.53–0.59 ppm** >2× troposphere (0.24–0.25 ppm), despite ≈ 20% of column mass.

MULTI-MODEL FLUX UNCERTAINTY



- Posterior flux spread reaches 130–150 gC m^{-2} yr^{-1} (~100% of mean) over boreal & tropical land.
- Surface CO_2 spread peaks at 8 ppm; XCO_2^{mod} spread damped to 0.6–1.3 ppm by vertical integration.

Model disagreement peaks over **major anthropogenic** and biospheric hotspots—like East Asia, Europe, and the tropics—where surface CO_2 spreads reach up to 8 ppm.

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