

# On the role of transport, emissions and chemistry on carbon monoxide modeling

## Comparison of emission inversions with AOD and CO data assimilation

B. Gaubert<sup>1</sup>, D. P. Edwards<sup>1</sup>, H. M. Worden<sup>1</sup>, L. K. Emmons<sup>1</sup>, W. Tang<sup>1</sup>, I. Ortega<sup>1</sup>, D. Fillmore<sup>1</sup>, K. Raeder<sup>2</sup>, J. L. Anderson<sup>2</sup>



(1) NCAR Atmospheric Chemistry Observations & Modeling Laboratory (ACOM)  
(2) NCAR Computational & Information Systems (CISL)



## Community Earth System Model (CESM)

- **Community**, fully-coupled, global climate model.
- Nominal 1x1 degree with full **gas phase chemistry** and **modal aerosol**.
- Simulation **ensemble** with perturbations in emission, initial conditions and global parameters.

## Observations

- **Terra/MOPITT CO**  
Daytime multispectral (TIR and NIR) retrieval profiles
- **Terra/Aqua MODIS AOD**, NRL QC Dark Target Deep Blue algorithm
- **Meteorological observations**

## Data Assimilation Research Testbed (DART)

DART is a **community** and **open source** software.

**Sequential** and **ensemble** DA technique.

DART provides advanced **localization** and inflation algorithms for efficient ensemble DA.

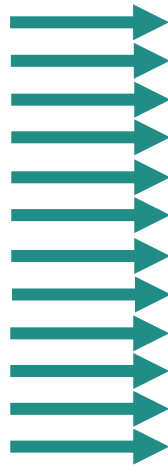
# Chemical Satellite Data Assimilation: CAM-chem/DART

## CAM-chem

- ❖  $0.9^\circ \times 1.25^\circ$  and 32 vertical layers
- ❖ Gas phase chemistry: MOZART-TS1 chemistry
- ❖ Aerosol scheme: MAM4 + VBS for SOA
- ❖ Perturbation in global aerosol and nudging parameters, initial conditions and emissions

*Daily ensemble*  
*CAMS-GLOB-ANT v5.1*  
Gases and aerosols

*Daily ensemble FINN2.2*  
Gases and aerosols



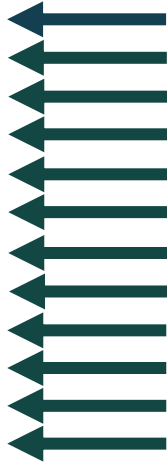
## Step 1: Forecast step

Ensemble: 30 member perturbed  
CAM-chem - 6-hour forecast

## Emission update

*Daily ensemble*  
**CAMS-GLOB-ANT v5.1**  
Gases and aerosols

*Daily ensemble* **FINN2.2**  
Gases and aerosols



## DART

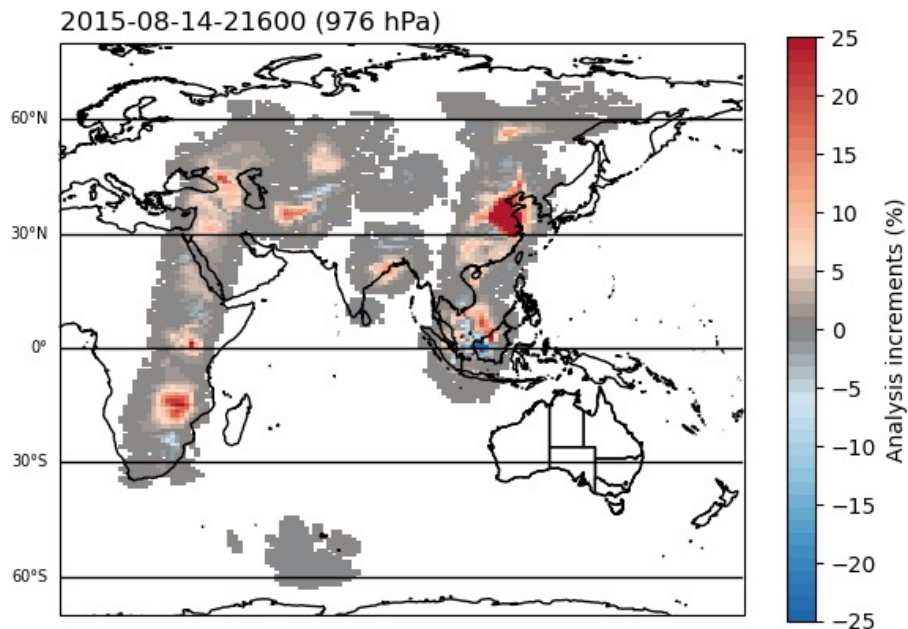
- ❖ EAKF analysis update
- ❖ Spatially and temporally varying adaptive multiplicative **covariance inflation** (El Gharamti, 2018)

### Case 1: Meteorology

- State vector: Ps, T, U, V, Q, CLOUD

### Case 2: Case 1 + Terra/MOPITT V9J CO profile

- State vector:
  - ✓ CO IC
  - ✓ CO anthro emiss.
  - ✓ CO FINN emiss.



# Chemical Satellite Data Assimilation: CAM-chem/DART

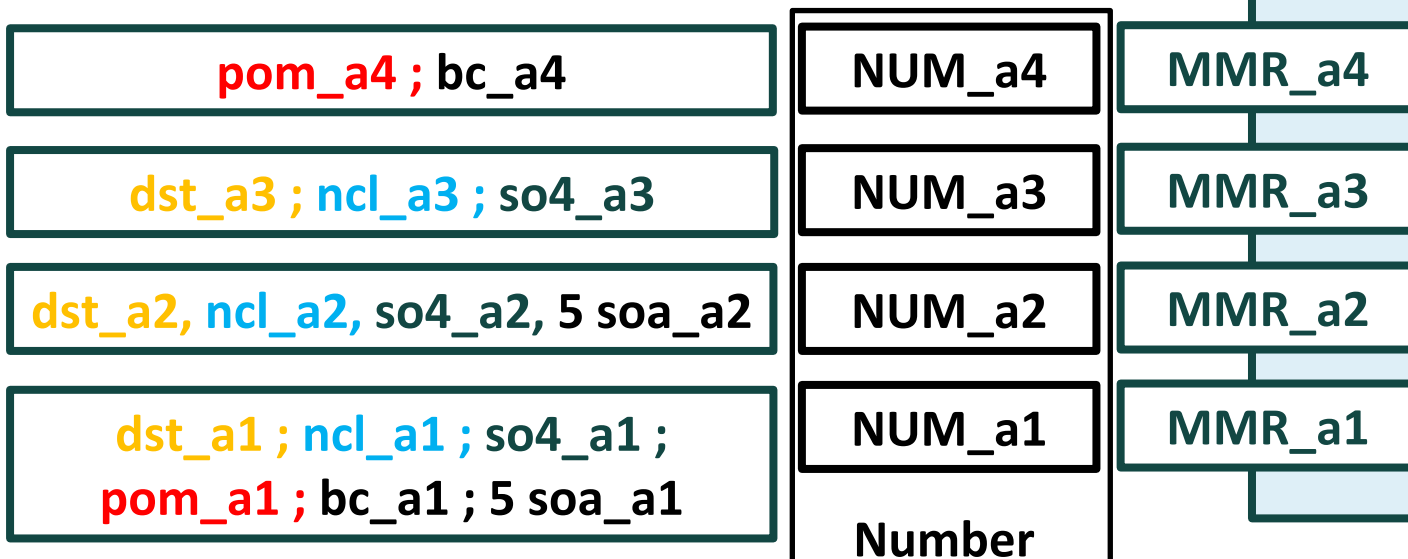
## DART

- ❖ EAKF analysis update
- ❖ Spatially and temporally varying adaptive multiplicative **covariance inflation** (El Gharamti, 2018)

### Case 1: Meteorology

- Ps, T, U, V, Q, CLOUD

- Case 3: Aerosol Optical Depth (AOD)  
Case 1 + Terra/Aqua MODIS C6.1 AOD
- 4 Mass Mixing Ratio bins (MAM4)



# Chemical Satellite Data Assimilation: CAM-chem/DART

## Emission update

*Daily ensemble*  
**CAMS-GLOB-ANT v5.1**  
Gases and aerosols

*Daily ensemble FINN2.2*  
Gases and aerosols



**pom\_a4 ; bc\_a4**

**dst\_a3 ; ncl\_a3 ; so4\_a3**

**dst\_a2, ncl\_a2, so4\_a2, 5 soa\_a2**

**dst\_a1 ; ncl\_a1 ; so4\_a1 ;  
pom\_a1 ; bc\_a1 ; 5 soa\_a1**

NUM\_a4

NUM\_a3

NUM\_a2

NUM\_a1

Number

MMR\_a4

MMR\_a3

MMR\_a2

MMR\_a1

## DART

- ❖ EAKF analysis update
- ❖ Spatially and temporally varying adaptive multiplicative **covariance inflation** (El Gharamti, 2018)

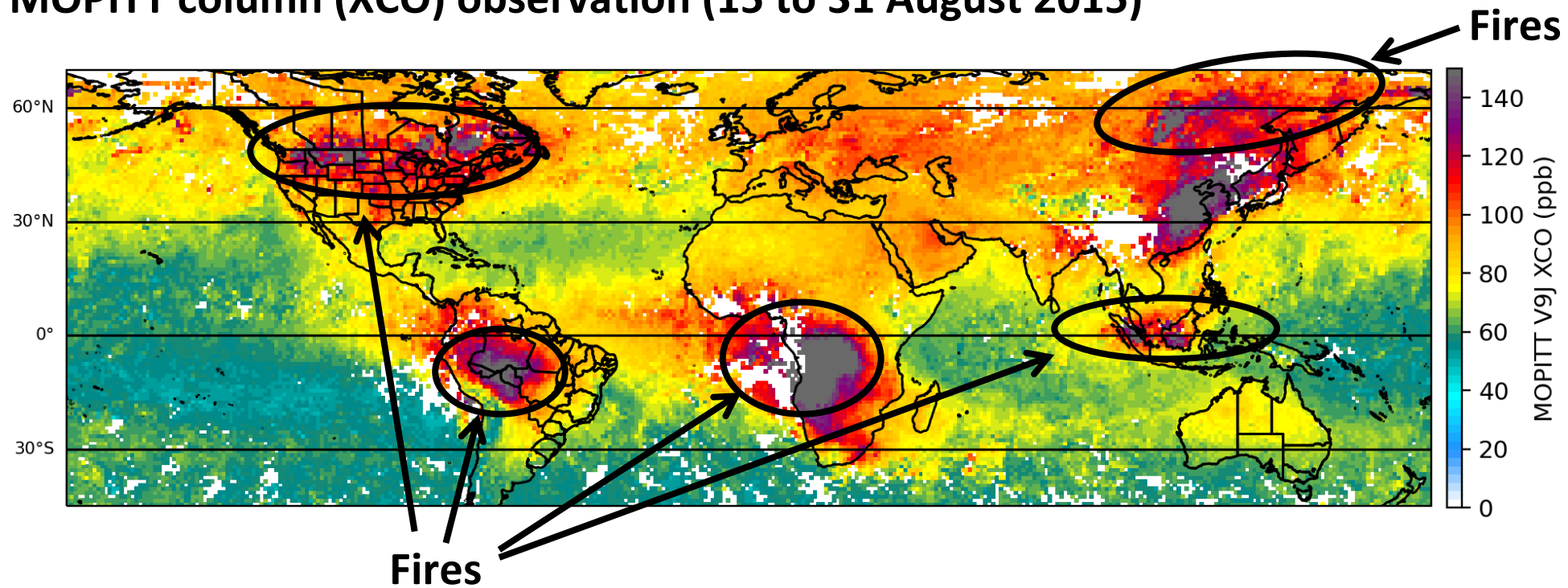
### Case 1: Meteorology

- Ps, T, U, V, Q, CLOUD

### Case 3: Aerosol Optical Depth (AOD) Case 1 + Terra/Aqua MODIS C6.1 AOD

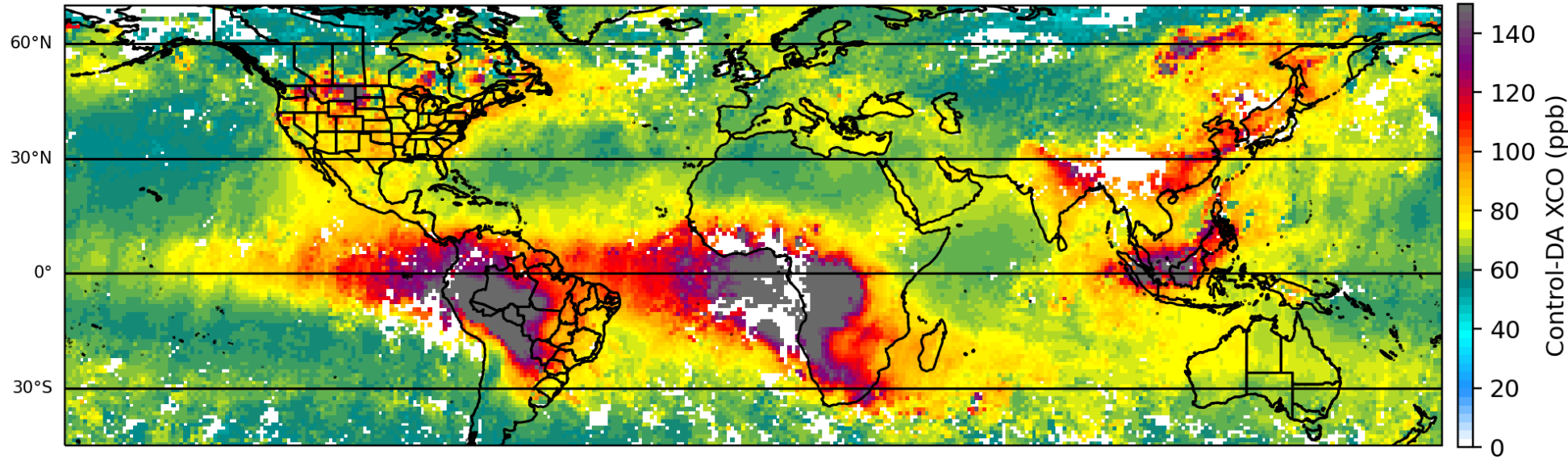
- 4 Mass Mixing Ratio bins (MAM4)
- Black carbon (bc\_a4) emissions
- Primary Organic Matter (pom\_a4) emissions

## MOPITT column (XCO) observation (15 to 31 August 2015)

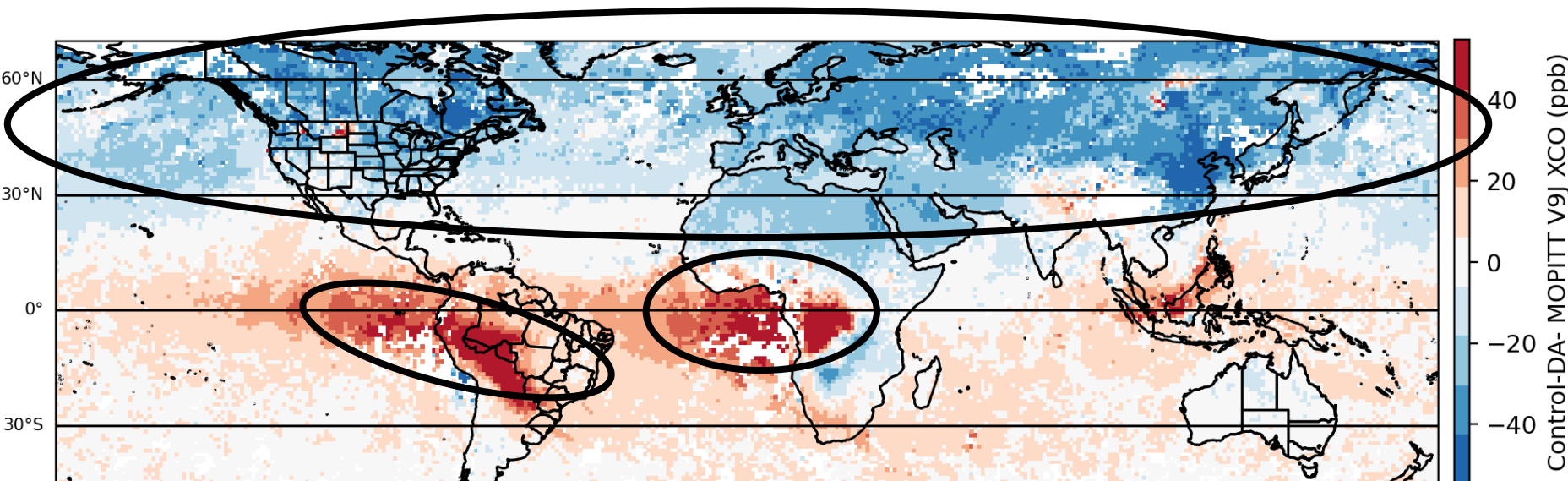


# Control-DA results (15 to 31 August 2015)

## CAM-chem Control (met. DA) column (XCO)



**Northern  
Extratropics  
CO background  
underestimated**



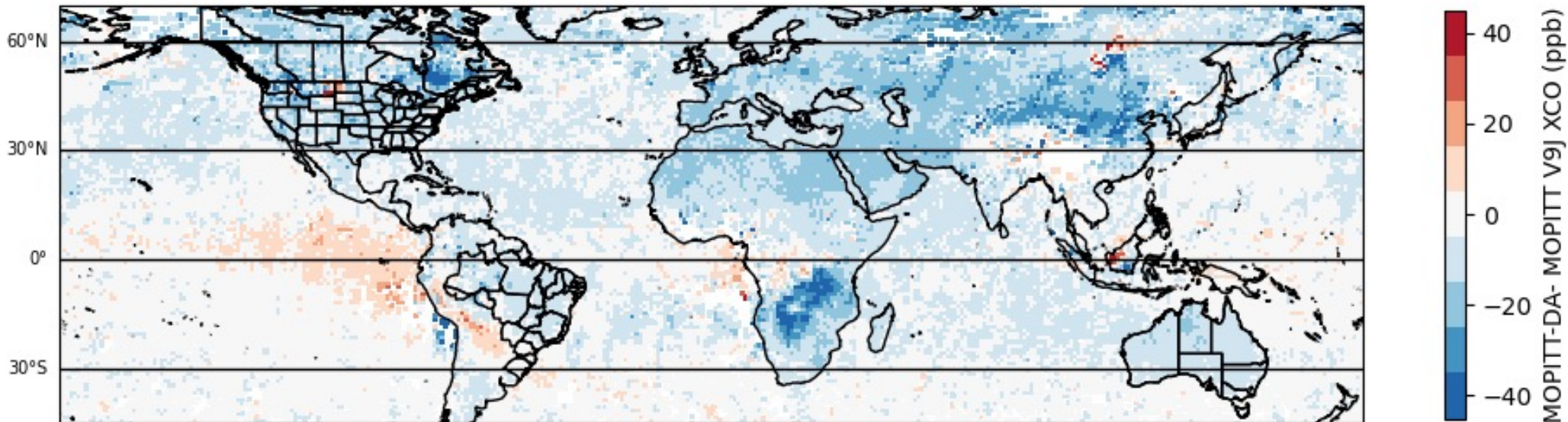
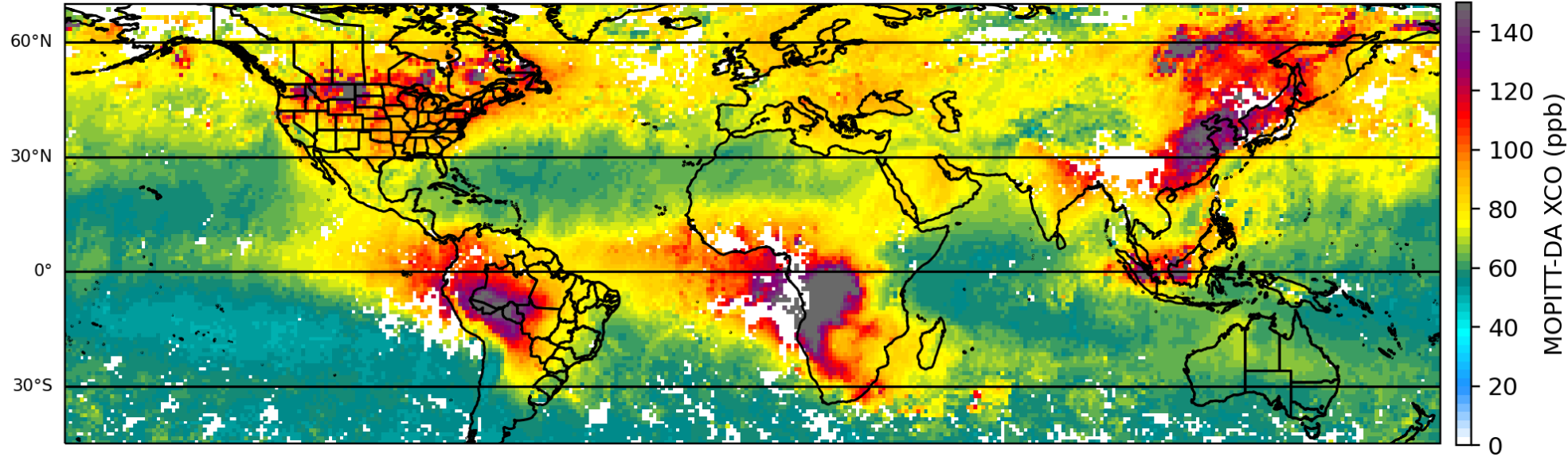
**Northern Extratropics  
fire CO underestimated**

**Tropical fire  
CO overestimated**



# MOPITT-DA results (15 to 31 August 2015)

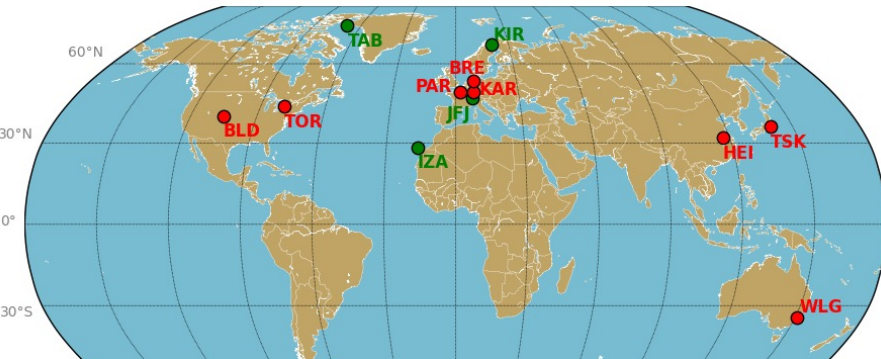
## MOPITT-DA column (XCO)



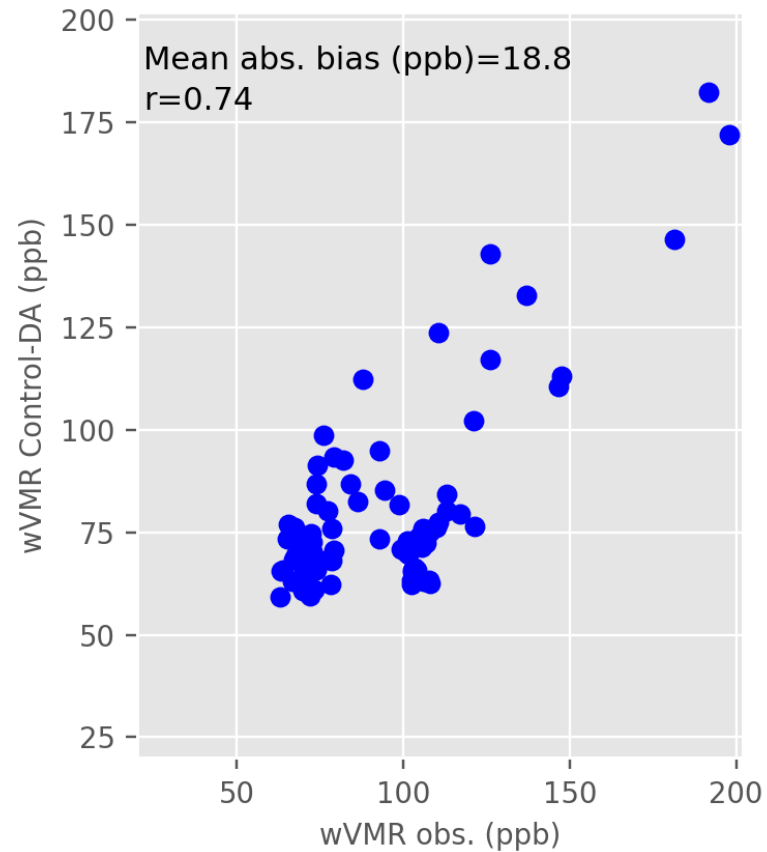
## MOPITT-DA- MOPITT column (XCO)

# Evaluation against NDACC FTS results (15 to 31 August 2015)

- ✓ NDACC FTS 15 sites
- ✓ 80 daily averages



## CAM-chem Control-DA

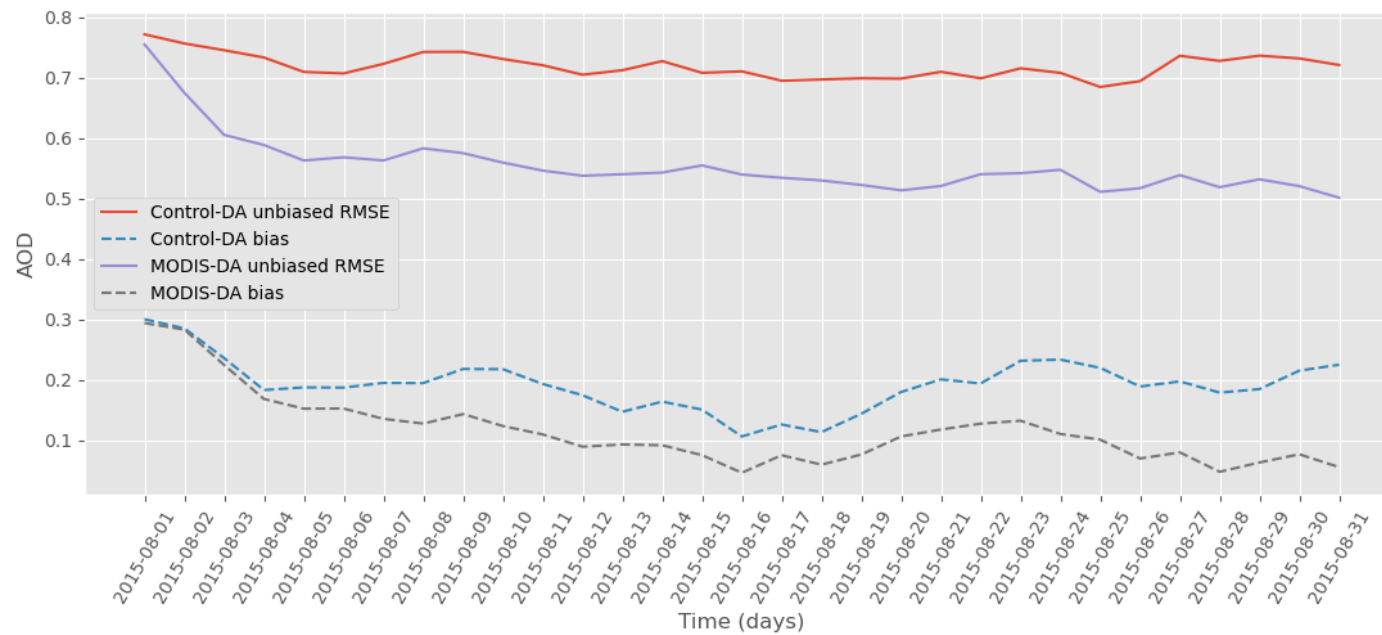


## MOPITT-DA

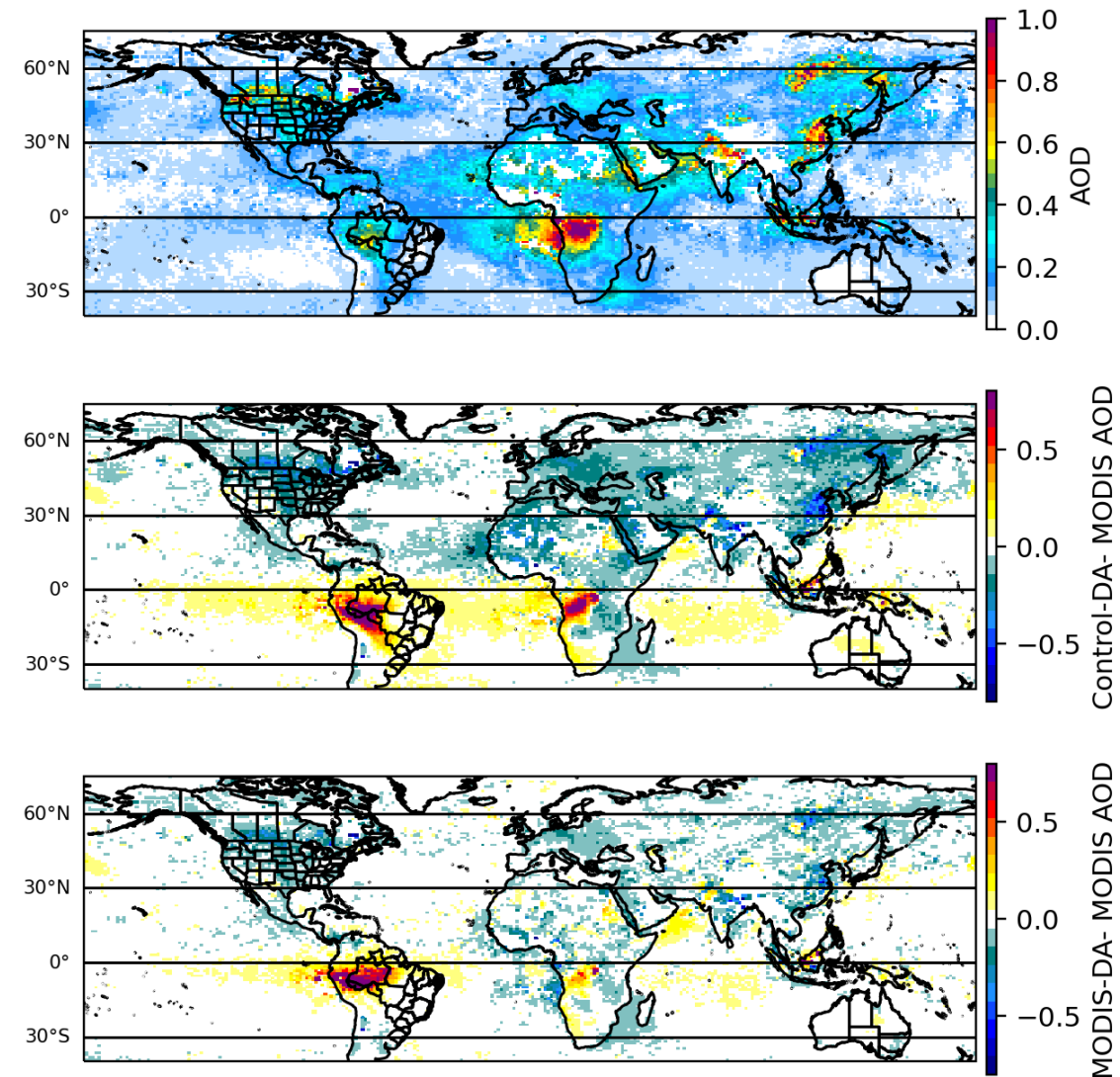


**Tropospheric weighted volume mixing ratio (wVMR)**

# MODIS AOD data assimilation results:

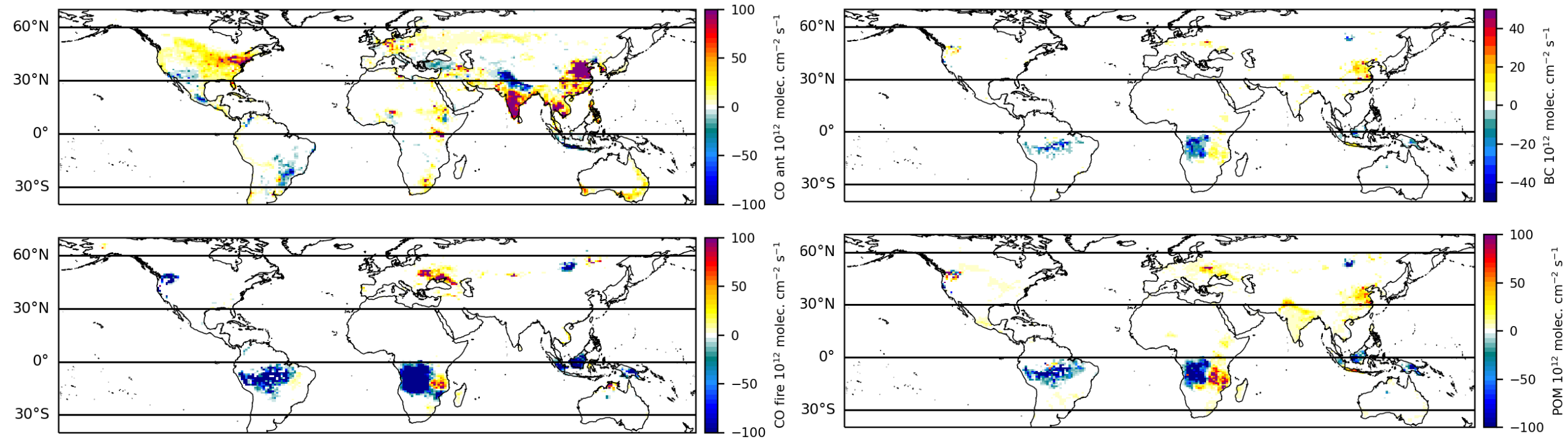


- ✓ Reduced bias
- ✓ AOD errors reduced by 30 %



# Posterior emission increments

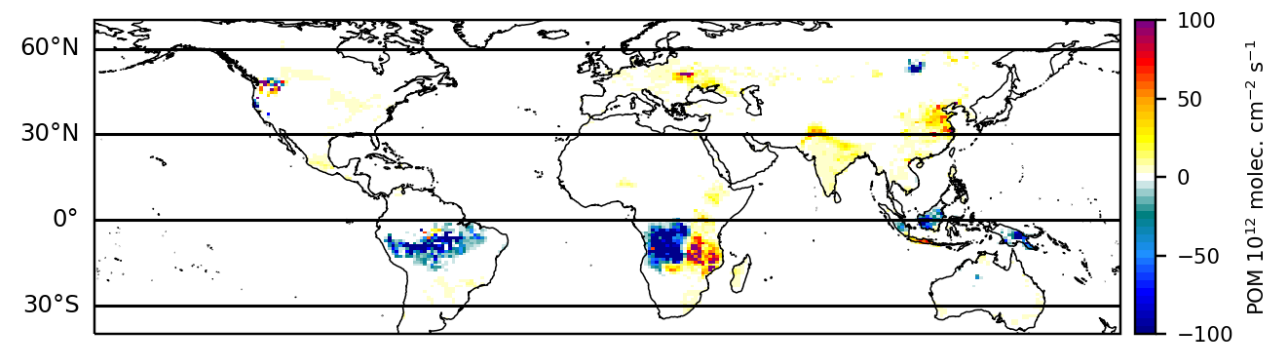
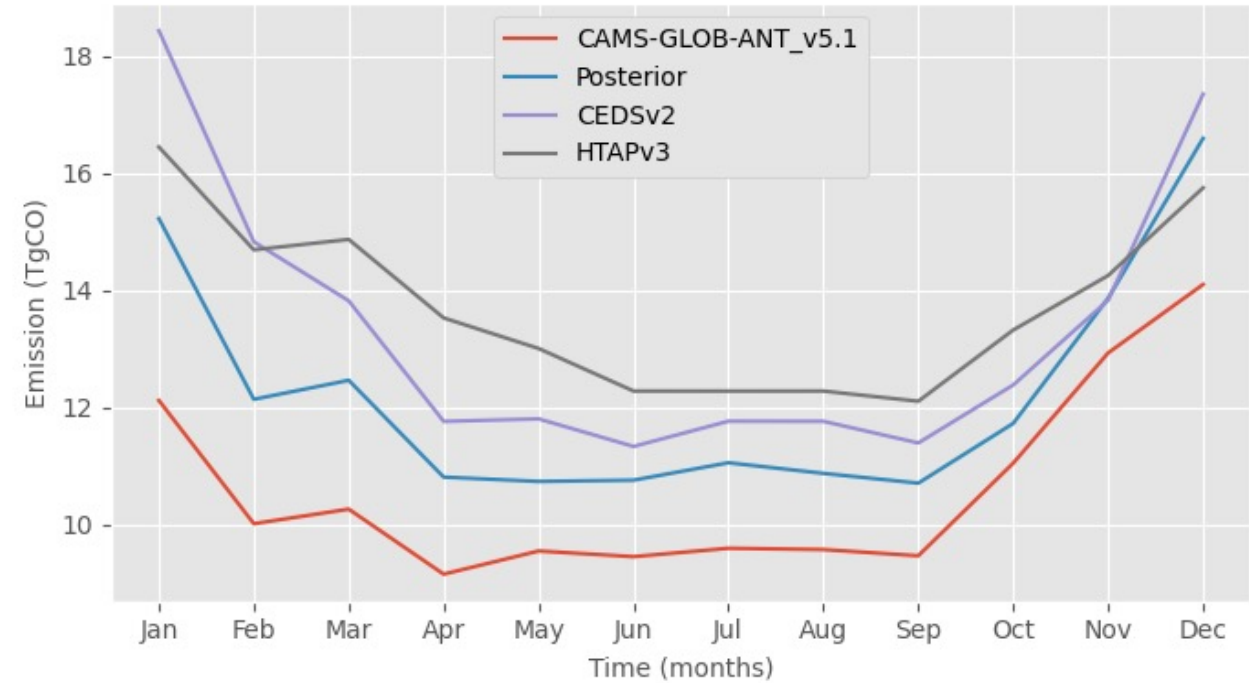
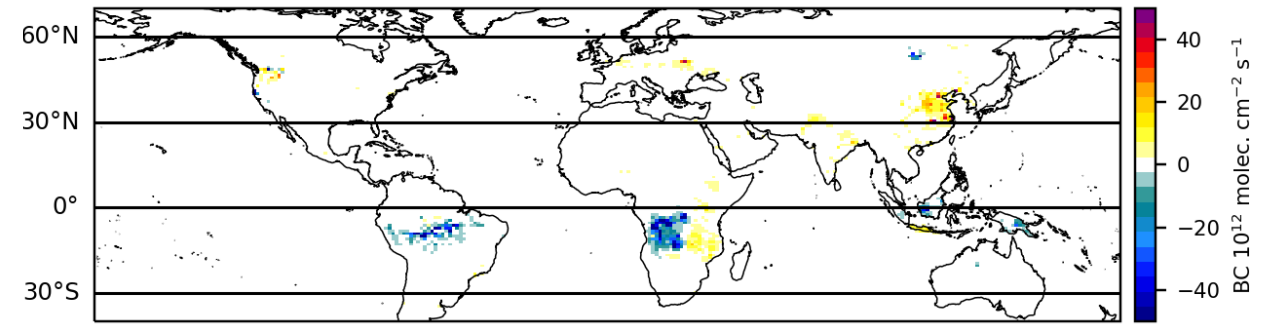
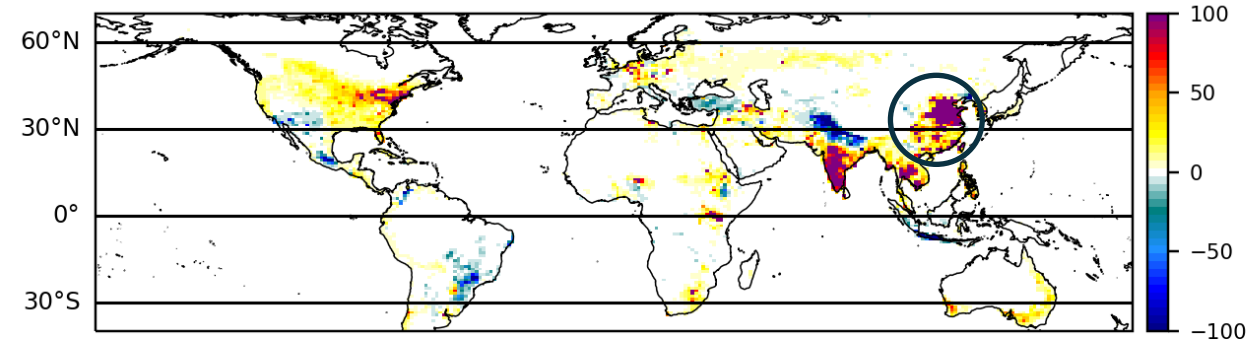
*Posterior CAMS-GLOB-ANT v5.1 CO emissions increments*



*Posterior FINN2.2*

# Posterior emission increments

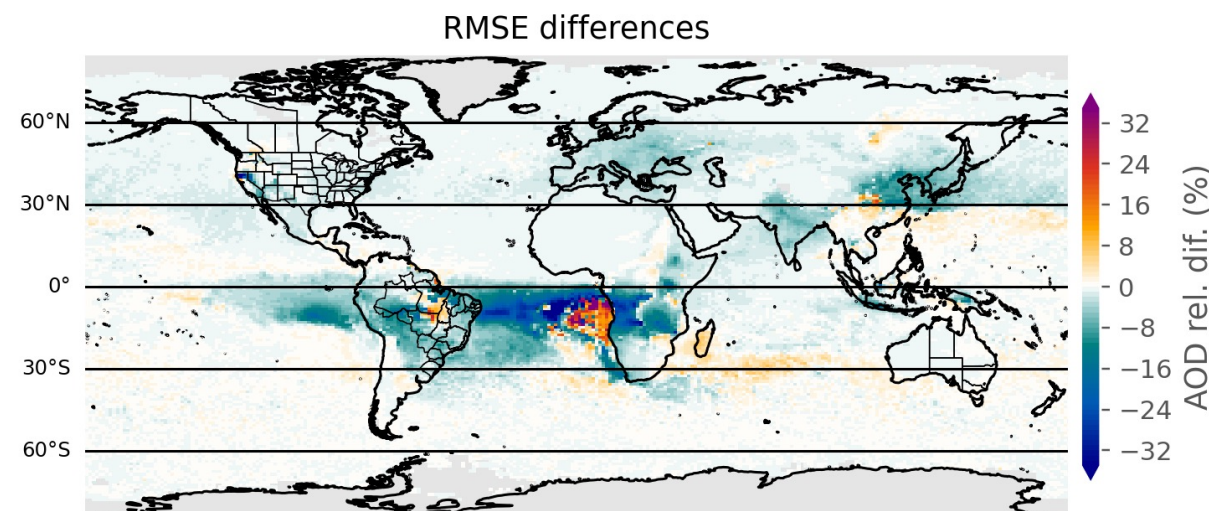
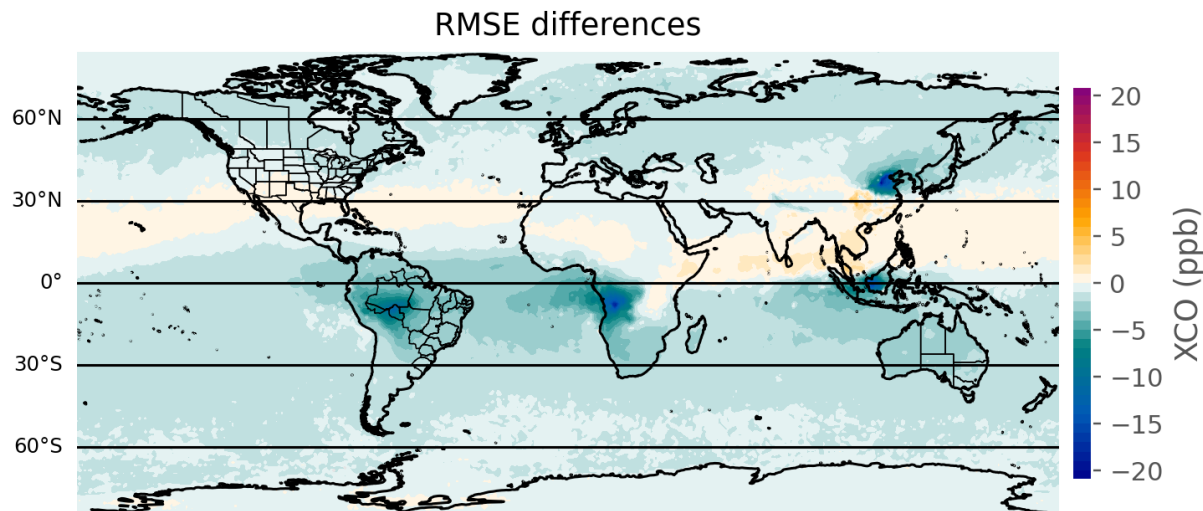
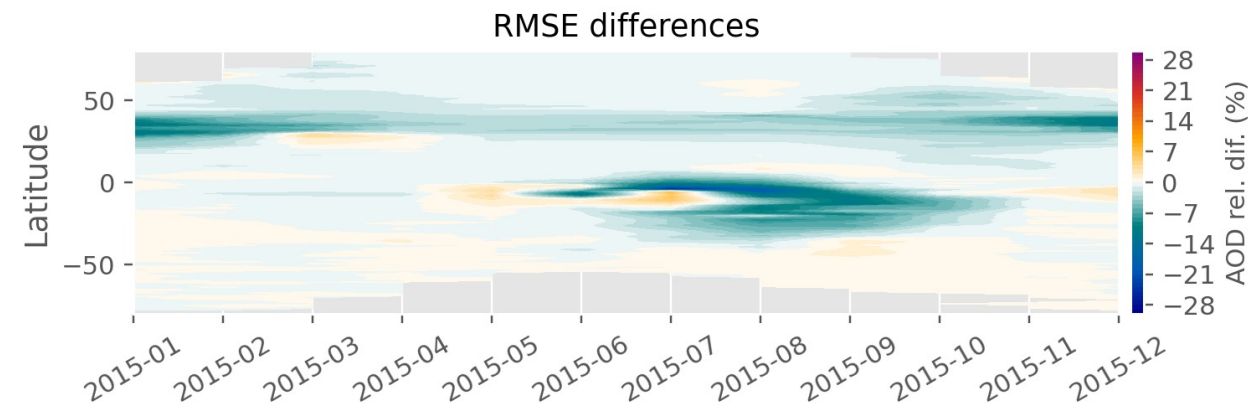
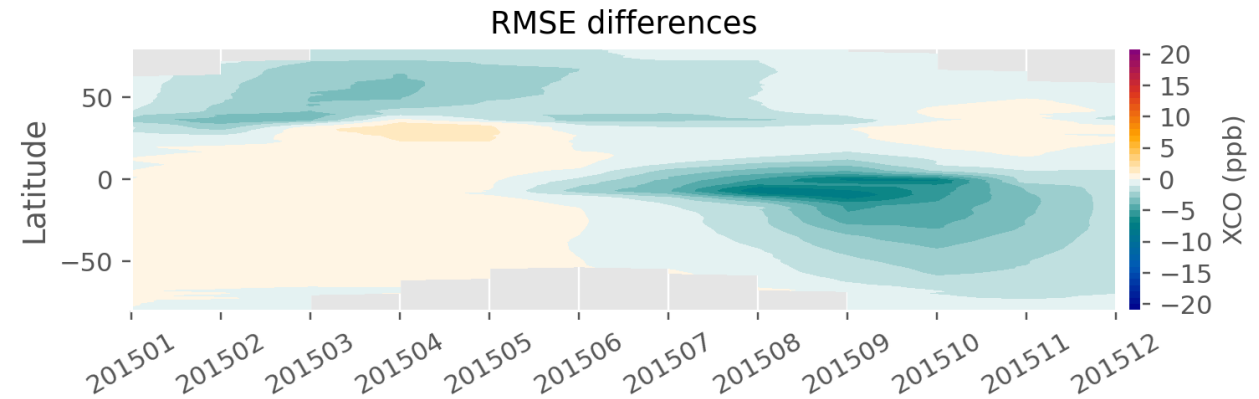
Posterior CAMS-GLOB-ANT v5.1 CO emissions increments



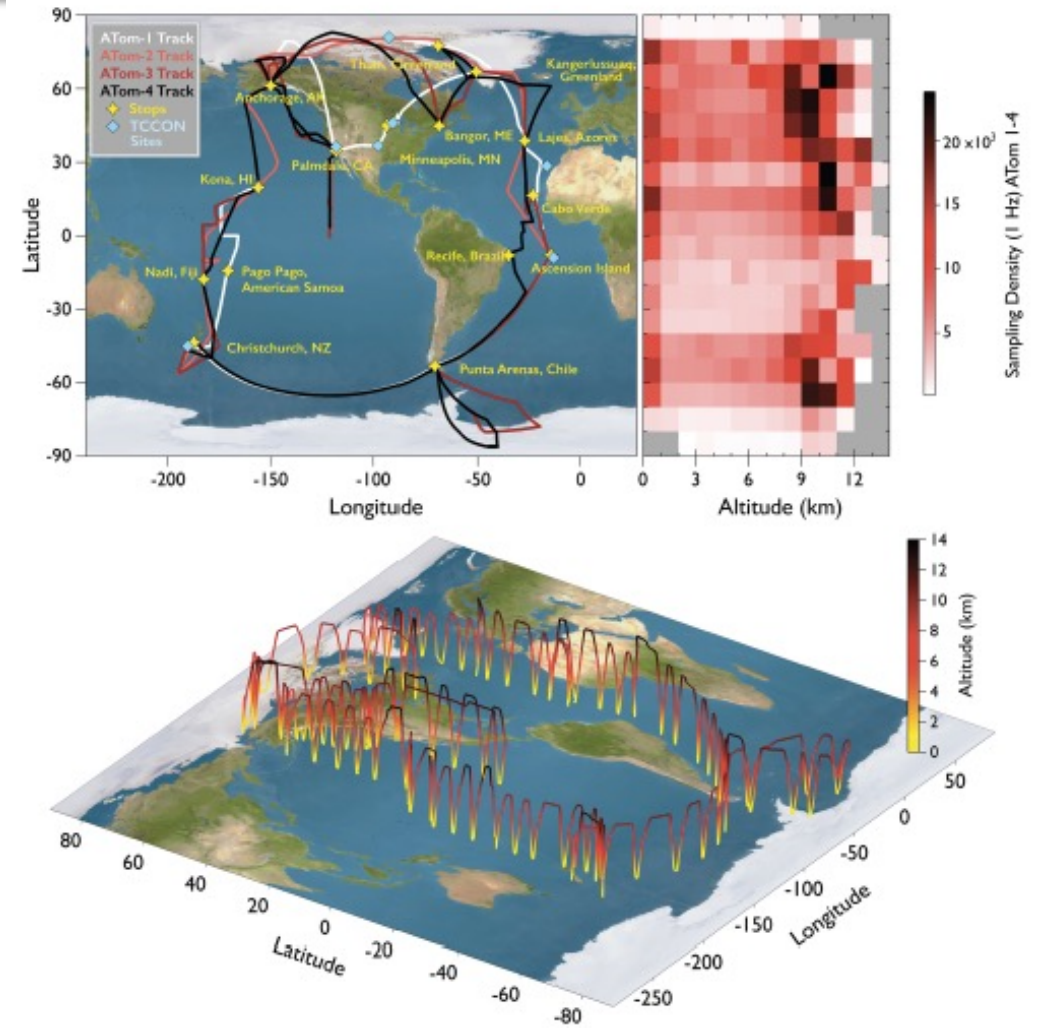
# CAM-chem simulations (2015 to 2018) comparison to L3 MOPITT and MODIS

## 2 CAM-chem simulations (nudged):

- ❖ CAM-chem-Ref (CAM5-GLOB-ANT v5.1 + FINN2.2)
- ❖ CAM-chem-Post same with updated emissions



# Comparison with NASA Atmospheric Tomography Mission (ATom)



- ATom-1: August 2016**
- ATom-2: February 2017**
- ATom-3: October 2017**
- ATom-4: May 2018**

- 3 CAM-chem simulations (nudged):**
- ❖ **CAM-chem-Ref (CAM5-GLOB-ANT v5.1 + FINN2.2)**
  - ❖ **CAM-chem-Post same with updated emissions**
  - ❖ **CAM-chem-O1D with 10 % reduction in JO<sup>1</sup>D**

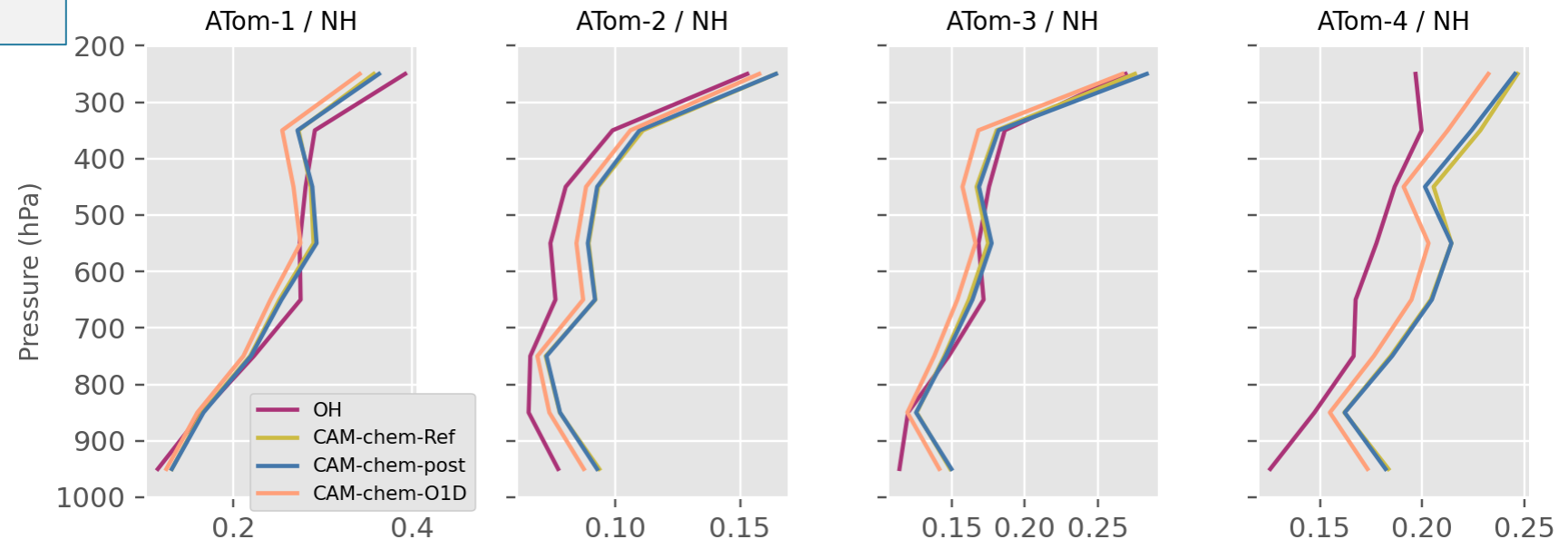
Thompson et al. BAMS, 2022

# Posterior Simulations: Comparison with NASA ATom OH and HO<sub>2</sub> observations

OH

ATom-1: August 2016  
ATom-2: February 2017  
ATom-3: October 2017  
ATom-4: May 2018

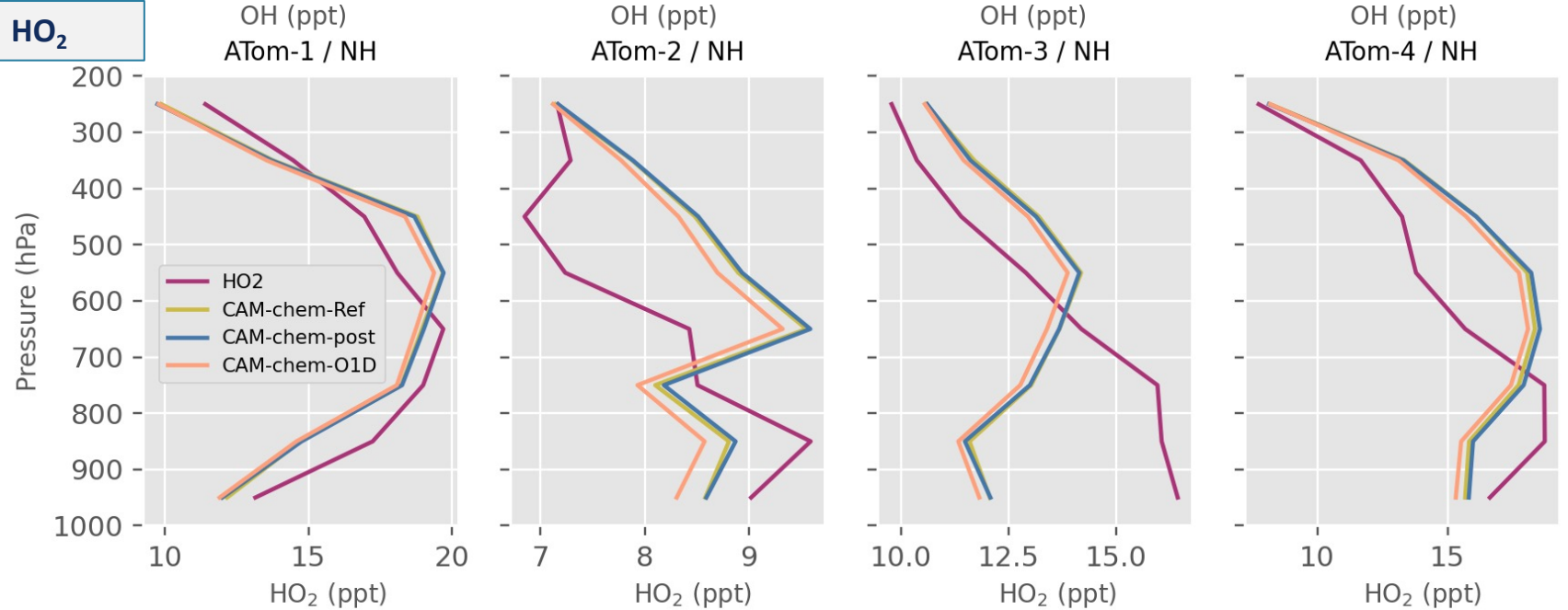
$\tau_{\text{CH}_4} = 7.9$  years



HO<sub>2</sub>

10 % reduction in JO<sup>1</sup>D

$\tau_{\text{CH}_4} = 8.3$  years

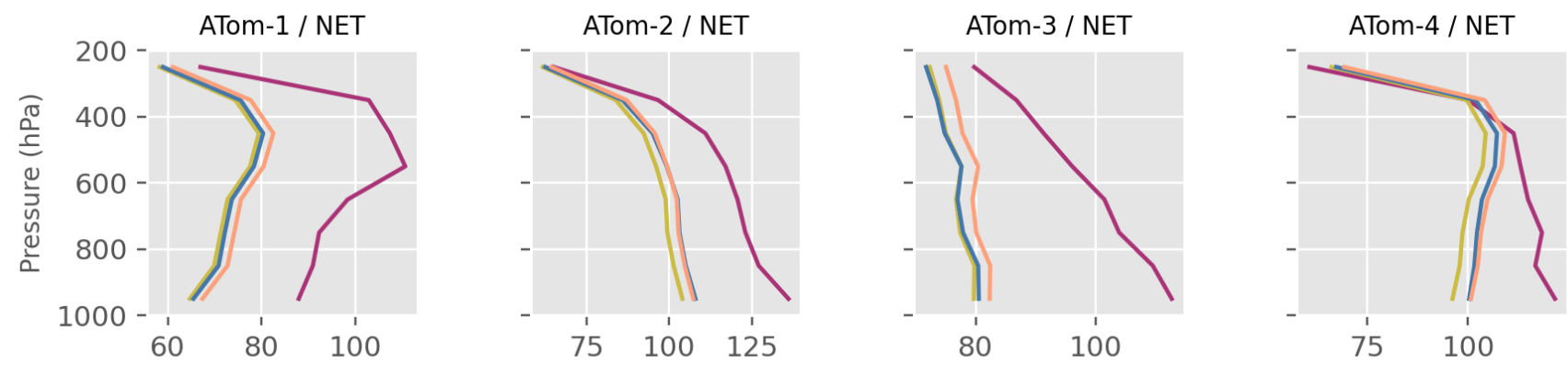




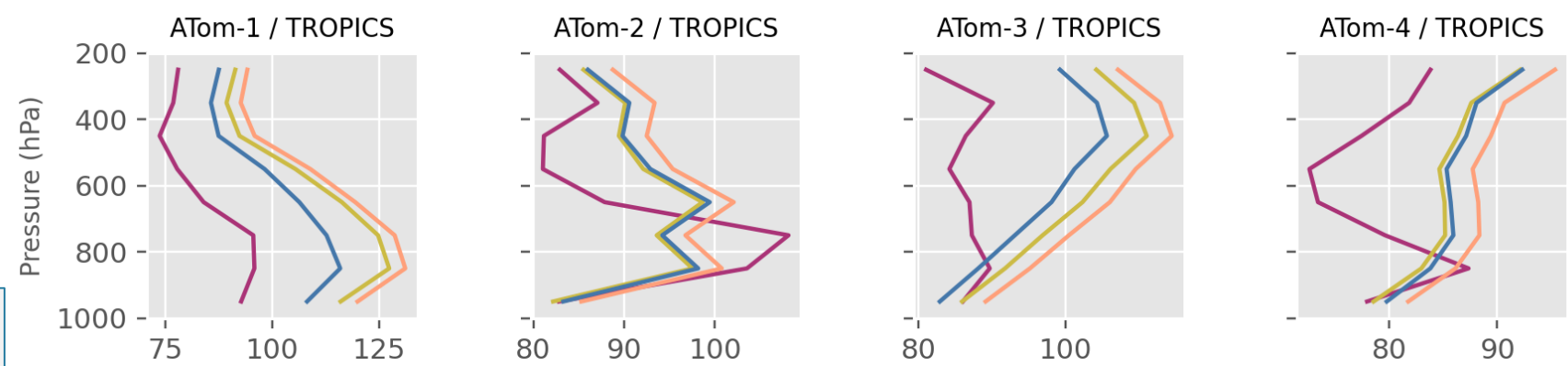


# Posterior Simulations: Comparison with NASA ATom

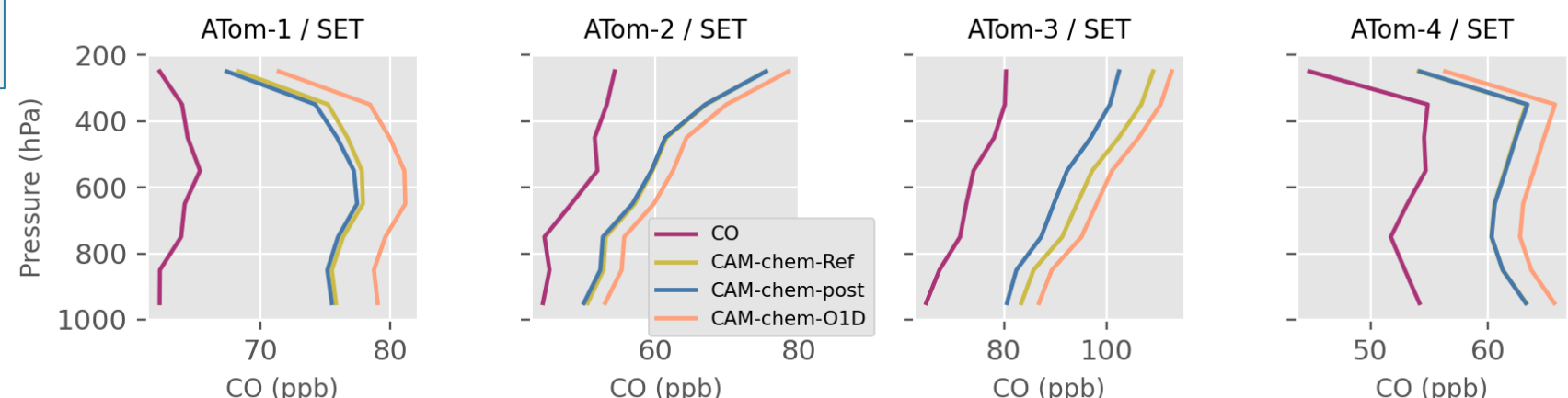
**CO underestimation**  
Post. Emi improves  
winter



**Northern  
extratropical  
hemisphere**



**Tropics**



**Southern  
Extratropical  
hemisphere**

**CO overestimation**  
Post. Emi  
improvements

- **DART/CAM-chem** system for ensemble assimilation of meteorology-aerosol-chemistry
- First successful ensemble assimilation of **AOD with CAM-chem (MAM4)**
- Emission updates allows for discrimination of **anthropogenic (CAM5-GLOB-ANT v5.1)** and **fire (FINN2.2)** emission fluxes
- Posterior emissions are consistent between MOPITT and MODIS based inversions
- Underestimation of CO and aerosols anthropogenic emissions in East Asia (**CAM5-GLOB-ANT v5.1**), and overestimation fire emissions in the tropics (**FINN2.2**)
- The sensitivity of remote CO to CO emission biases is small in CAM-chem, because of biases in CO loss term

- Comparison of assimilation of **Terra/MOPITT CO**, **NOAA20/CrIS CO** and **S5P/TROPOMI CO**
- **Joint assimilation of CO and CH<sub>4</sub> observations**
- Improved **analysis algorithm update for bounded quantities** with the Quantile Conserving Ensemble Filtering Framework (Anderson 2022)
- Assimilation in **variable resolution grid** (MUSICA), with refinements up to ~14 km
- **Coupled land-atmosphere** data assimilation for vegetation impact on biogenic emissions

# Posterior Simulations: Comparison with NASA ATom

