On Comparisons and Evaluation of CO Multi-sensor Data: Role of Radiance Data Assimilation Schemes

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Radiances and Retrievals, as a primary and transformed data

- ***Advantage of retrievals*: estimated CO can be compared against in situ and simulated CO *projected onto retrieval space*.**

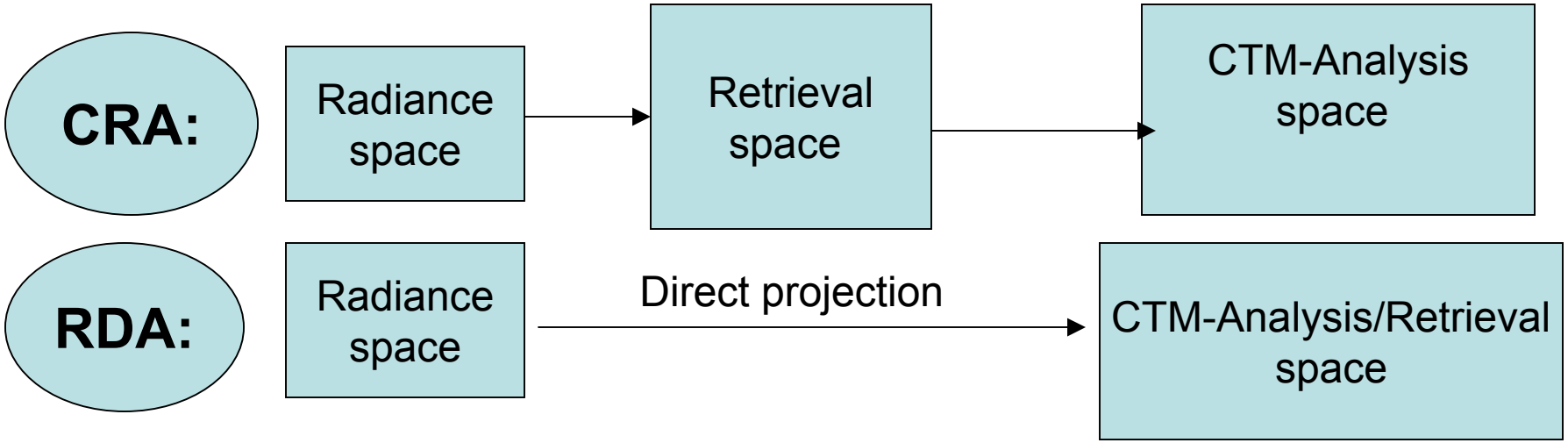
- ***Complexity of retrieval errors*: radiance errors + inverse algorithm errors + assignment (modeling) of initial errors for a priori uncertainties.**

- ***For data fusion*:**

  ***Second transform* is needed for projection of retrievals onto the CTM grid. *(Projection between spaces are not simple interpolation)*.**

  ***Single direct transform* (inversion) is needed for radiance data to project them onto the CTM grid.**

Assimilation schemes in the CTM: Retrievals vs Radiance Data



Benefits of RDA schemes or Direct Projection:

1) Avoid intermediate projection of the primary data on the "climatological/demonstrative" retrieval space;

2) Provide the scale-consistent solution of CO inverse and avoid assimilation of the potentially biased and scale-inconsistent smoothed CO retrievals;

3) Use the best knowledge for the instantaneous CO as a priori including CO uncertainties (with ensemble CO forecasting).

Role of Assimilation in Evaluation of CO Data

- **First long-term global estimations of CO from radiances**:

  MOPITT => NASA/Terra
  TES => NASA/Aura
  AIRS => NASA/Aqua
  MLS => NASA/Aura
  SCIMACHY => ESA/Envisat.....(others, ACE/ODIN/IASI*..)*

- **Assimilation of subset of CO data is a way to demonstrate consistency *of information from multi-sensors in the CTM space.***

- **Assimilation of MOPITT & TES CO retrievals produces different CO adjustment vector** *(while CO Jacobians of TES and MOPITT are rather similar in their vertical structures).*

- **In situ CO data can be used to evaluate retrievals and (or) assimilation of retrievals** ***[****flight (MOZAIC), campaign and surface (CMDL) CO].*

Comparing satellite CO data with in situ observations and models (3 types)

- **Fast look in the retrieval space** => **transform in situ data (model) with Averaging Kernels** *(smooth/convert the tracer data to scales of instrument sensitivity).*

- **Analysis look in the radiance space** => compute corresponding radiances with the in situ CO data (model) and **compare simulated (with in situ data) and measured radiances**.

- **Data fusion look in the CTM space is to assimilate validated radiances:**

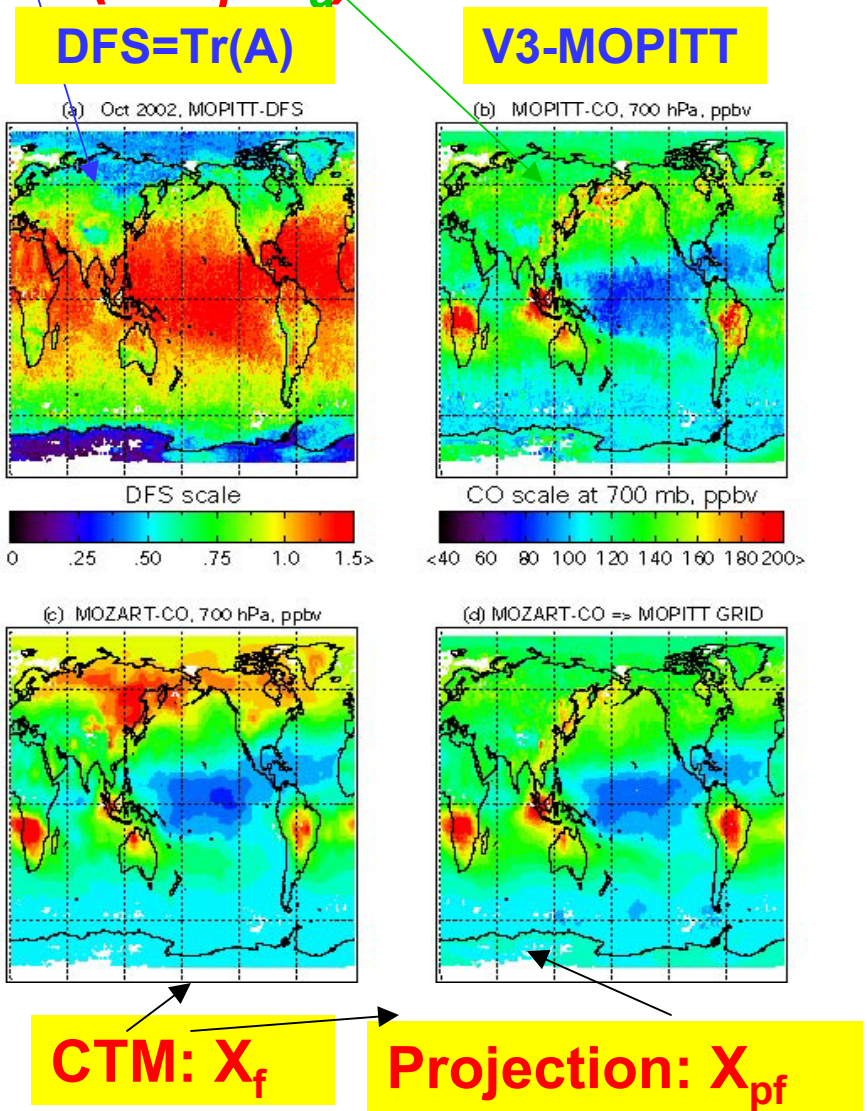
  1) evaluate radiances with in situ data (Analysis look);

  2) ***use observed minus forecasted radiances to project the radiance misfit onto CO adjustment vector****.*

Fast Look in the Retrieval Space, Comparing Transformed Data: Retrievals and Forecasts

$$X_{pf} = PX_f = X_a + A(HX_f - X_a)$$

- **V3-MOPITT => Smoothed profiles** as the deviations from the single a priori **(X_a)**
- **V3 is the "demonstartive" product** that estimates CO **with variable DFS**.
- **Data fusion needs the best a priori for CO in the zones of low DFS** *(weak and intermediate sensitivity).*
- **CTM provides the comprehensive CO forecast comparing to the single CO** profile (**X_a**) or ?-CO climatology.
- **The best strategy with dynamical CO background => to assimilate radiance data in the CTM. It is ongoing NCAR/MOPITT project** (*similar to the direct assimilation of radiances in the NWP*).



MOPITT-TES as Characterized Retrievals

- *Rodgers and Connor [2003]*: **Simulating one profile retrieval with the other to examine consistency of instrument estimations in the same retrieval space.**

- ***Comparisons in the Retrieval Spaces:***

  a) Based on the post-retrieval diagnostics averaging kernels /A = KW/ and a priori /X_a/

  b) Projections between retrieval spaces

  (X_p => X_{pa}): $X_{pa} = X_a + A(HX_p - X_a)$

- ***Kernels/Grids*: TES => A_1[89,89]**

  MOPITT=> A_2[7, 7]

- ***Ranks of A => Upscaling and Directions for the Second Transform:***

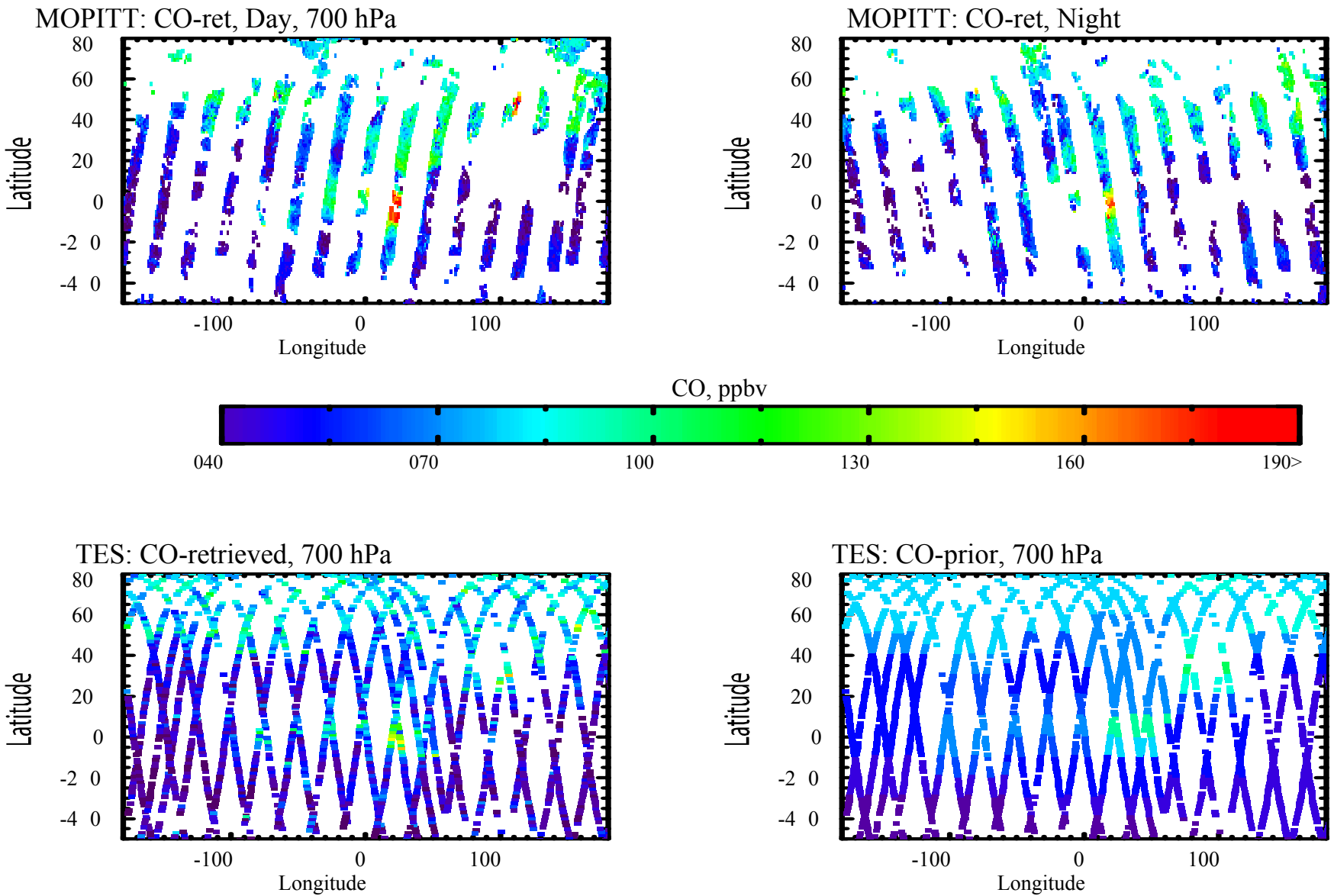
  rank(A_1) ~ rank(A_2) => scale-consistent retrievals

  rank(A_1) > rank(A_2) => upscaling TES => MOPITT

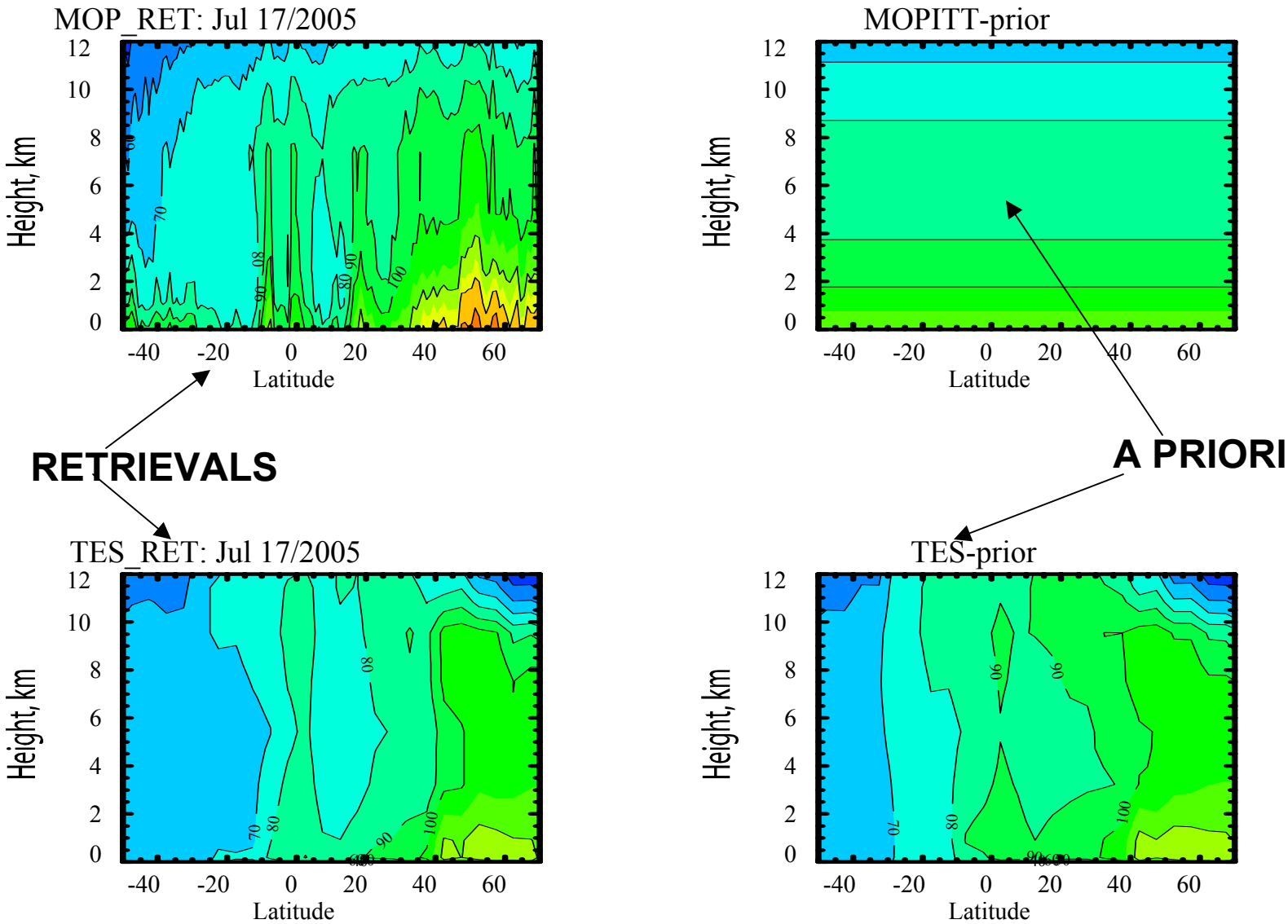
  rank(A_1) < rank(A_2) => upscaling MOPITT =>TES

July 17/2005: MOPITT (top)-TES (bottom) CO, 700 hPa.

(TES footprint increased for color illustrations.)

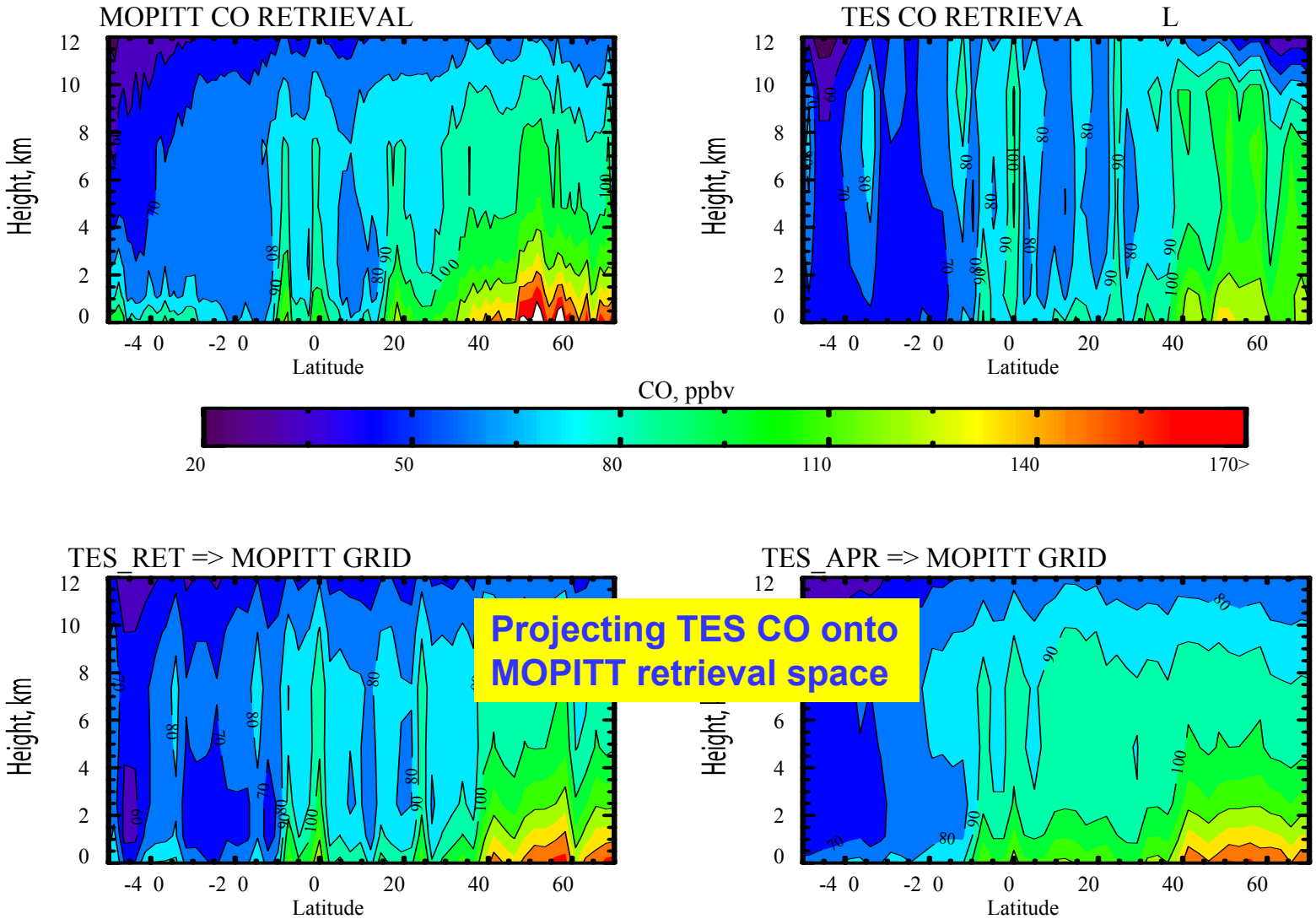


17/07/2005: MOPITT &TES CO retrievals



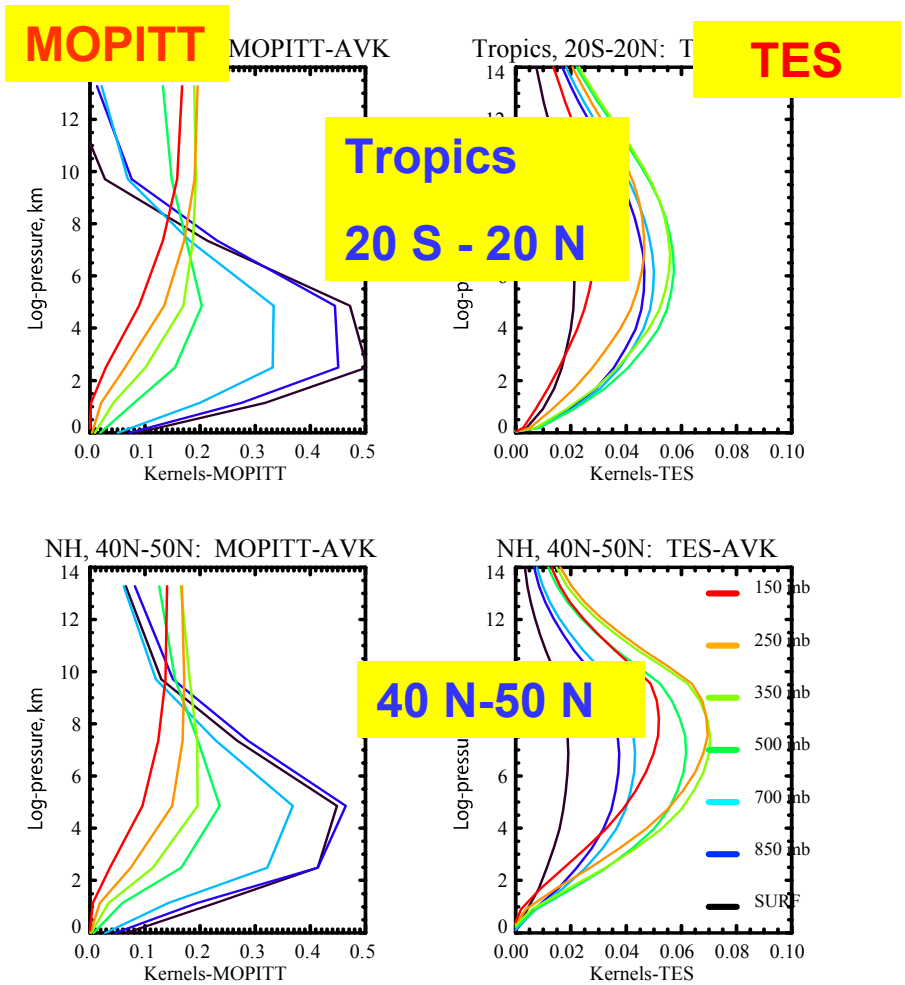
Mapping TES CO retrievals and TES a priori to MOPITT "space" with MOPITT a priori and averaging kernels

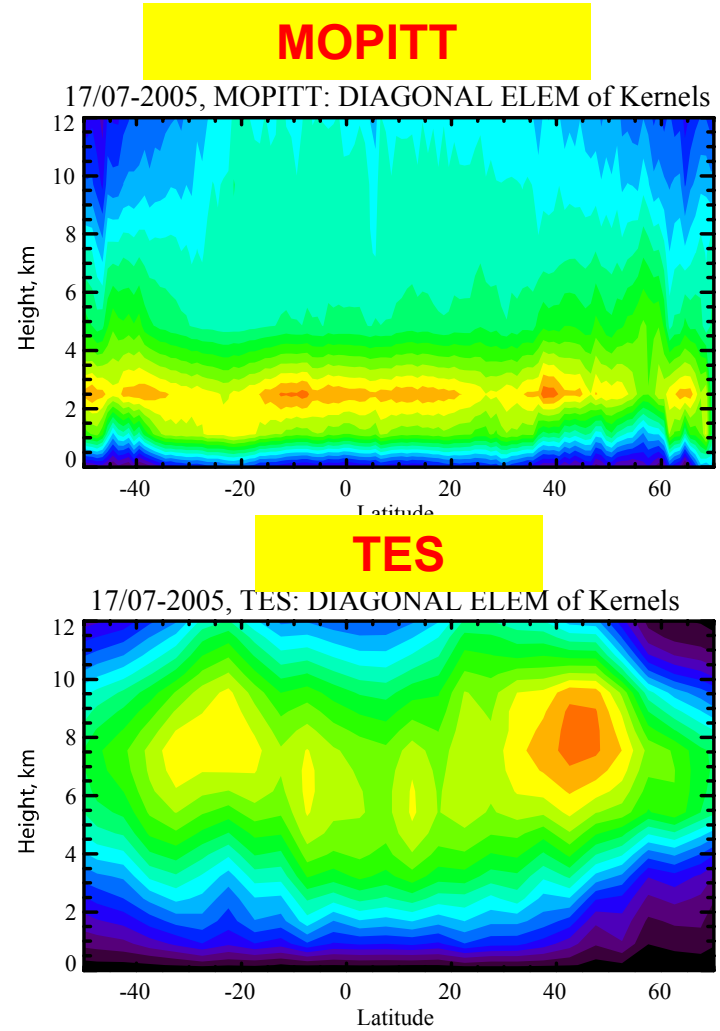
(*all quantities are the "zonal" means*).



MOPITT-TES: Averaging Kernel (Resolution) Matrices

(common feature: weak sensitivity near the surface)





Rows of A-matrix at 7 MOPITT levels

Diagonal elements of A-matrices

Limits for application of characterized retrievals in the data-data and model-data comparisons

- **General limits**: Application to the Linear (Moderate Nonlinear) Inverse Problems [Rodgers & Connor, 2003].

- **Limits for the Broad Width CO IR Channels (MOPITT, TES, AIRS....):**

  - optimal and scale-consistent retrievals of "broad" sub-columns with DFS <~ 1 can be compared/assimilated;

  - Jacobians of CO should satisfy linear characterization W =/= W(X) in the vicinity of a priori and retrieval.

  - It would difficult to expect consistency between retrievals with different leading kernels.

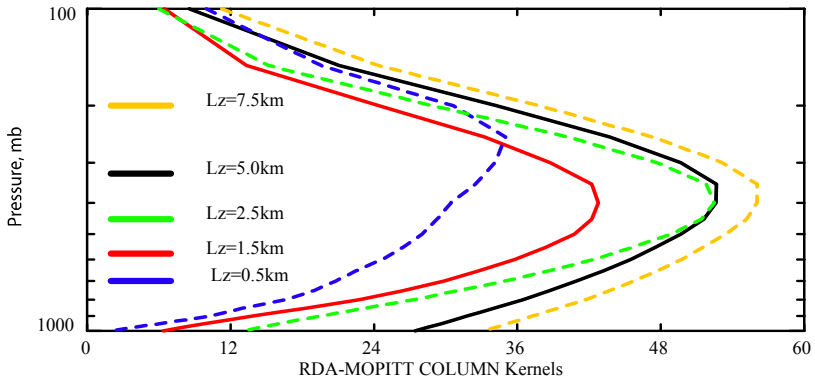
Scale-Consistency in CO estimation

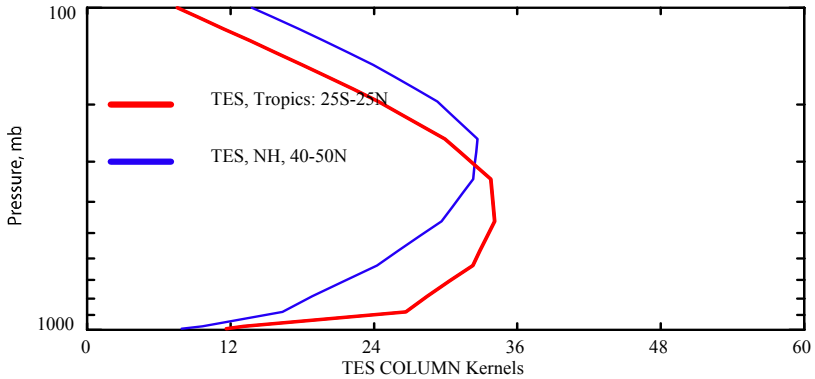
- **Widths of CO Jacobians (6-10 km) for thermal channels exceed the correlation lengths of in situ (model) CO (0.5-2 km).**

- **Consequence: the point-wise description of a priori covariance cannot be used directly in the CO inverse.**

- **For the scale-consistent CO estimations from IR radiances => UPSCALE the Inverse Problem to the width of CO Jacobians.**

Dependence of column kernels on correlation length of a priori CO

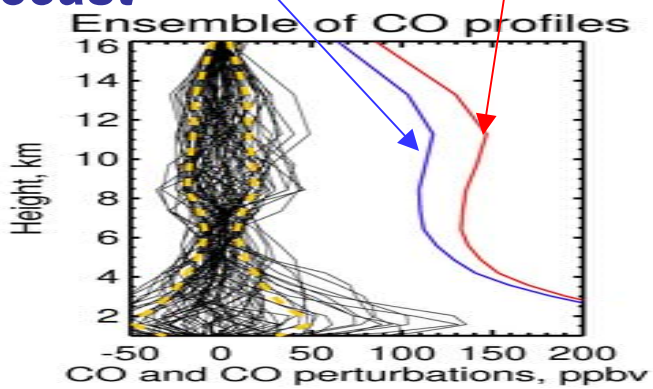


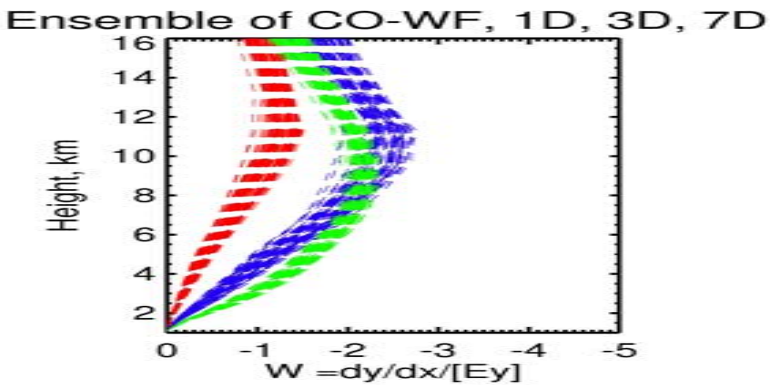


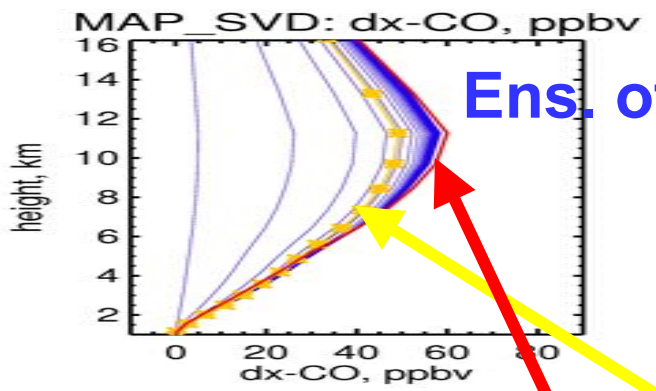
CO estimation by the ensemble schemes with rank-deficient and scale-consistent formulations (MOPITT IR Channels)

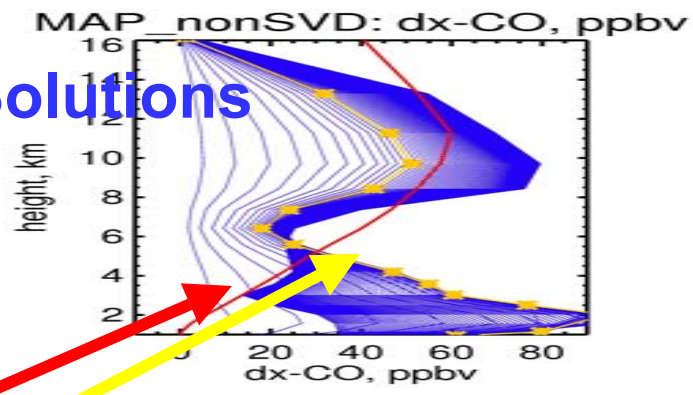
[*Tropical Biomass Burning Scene*]

Ens. mean CO forecast ***True CO*** **CO broad-width Jacobians**









Ens. of Solutions

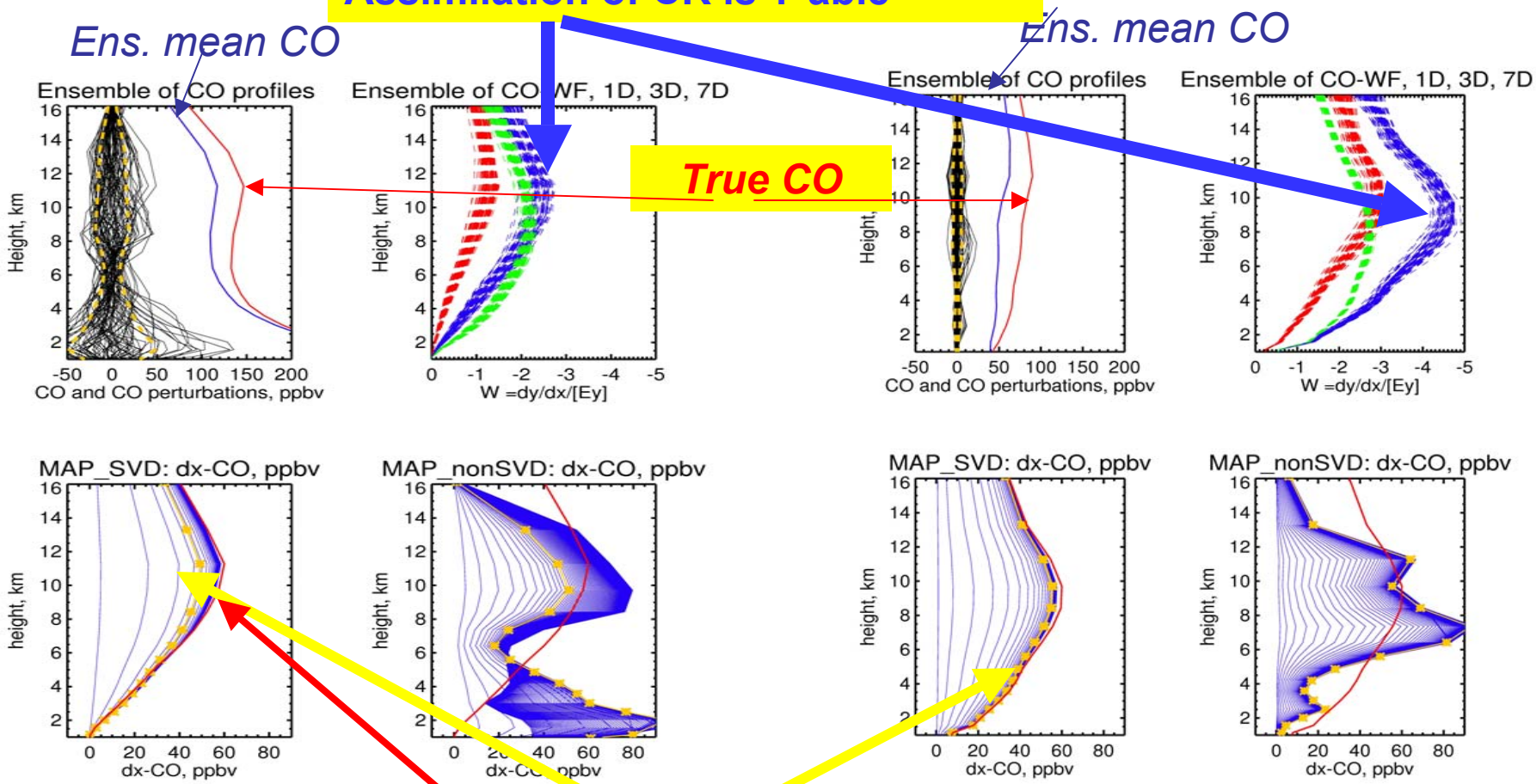
δX-CO True & Optimal

MOPITT: Ensemble-based schemes with SVD and rank-deficient formulations

Tropical Biomass Burning Scene

Wf-CO depends on CO loading, e.g. Nonlinear Characterization => Assimilation of CR is ?-able

SH ocean clean scene



True & Optimal δX-CO

Concluding remarks

- **In Remind: Measured Radiances are the primary data.**
  Estimated CO (retrievals) are transformed data.

- **Ranking these data for tropospheric chemistry studies:**
  - Primary data, IR radiances *bear information on CO sub-columns rather than smoothed profiles;*
  - Cautions on CO retrievals (demonstrative products). They can be biased *due to scale-inconsistent inverse solutions, reporting CO profiles instead of CO sub-columns (extra-sensitivity).*

- **For scale-consistent CO estimation from radiances:**
  CTM with ensemble forecasting provides the reasonable instantaneous CO background *(vertical CO shapes, PBL CO loading, and initial errors).*

- **Role Assimilation For Multi-Sensors:**
  Assimilation of radiances can *quantitatively* evaluate consistency of information from the primary data, e.g.
  MOPITT-TES-AIRS-SCIAMACHY.....

How to proceed in comparisons of retrievals => 1) benchmarks; 2) the real data

- **Compare information content from the radiance data** (Jacobians, SVD, SV, # of effective channels).
- **Use the same Retrieval Space** (CTM-grid), background CO and CO uncertainties **to compare retrieval schemes**.
- **Build the ensemble of CO estimation and post-retrieval diagnostics** (kernels, sub-columns or profiles) for the set of the forward model errors (*with fixed error metrics for non-retrieved parameters*).
- **Establish Synthetic Benchmark for CO estimations from the MOPITT, TES, and AIRS IR radiances.**
- **Proceed with the real radiance data *(overpasses),* assimilate measured radiances to show consistency of information from multi-sensors (full set of data, and subsets).**

Ensemble-based scheme for projecting information from radiances to CTM space

- **MOZART CTM with the NCEP analyses** => **Ensemble of CO profiles** /CO uncertainties as perturbations from the ensemble mean/.

- **MOPITT radiances minus the MOPFAS background radiances** => **Ensemble of the Residual Radiance Data**, δy

- **Linear Inverse step :** $\delta y = W\delta x$, $rank(\delta y) =/= rank(\delta x)$
  (W- CO broad Jacobians, estimates δx –CO adjustment vector, or profiles)

- **SVD scheme is a scale-dependent inversion for the amplitudes of the singular vectors** $\delta\alpha = V^t\delta x$ (*not for the point-wise CO*)

$$\delta y = US(V^t\delta x) = W_\alpha\delta\alpha\,, \quad rank(\delta y) = rank(\delta\alpha)$$

- **MAP estimation of $\delta\alpha$ constrains the partial CO columns** => **Backward transform $\delta x = V\delta\alpha$ => δx – estimation at the CTM grid.**

How valid the *KEY UNBIASED ASSUMPTION* *(compare MOPITT retrievals and in situ CO data)*?

- **MOPITT CO** against the flight CO data **at the clean CMDL sites** (overpasses) => **positive bias** ***(Emmons et al. 2003, limited #).***

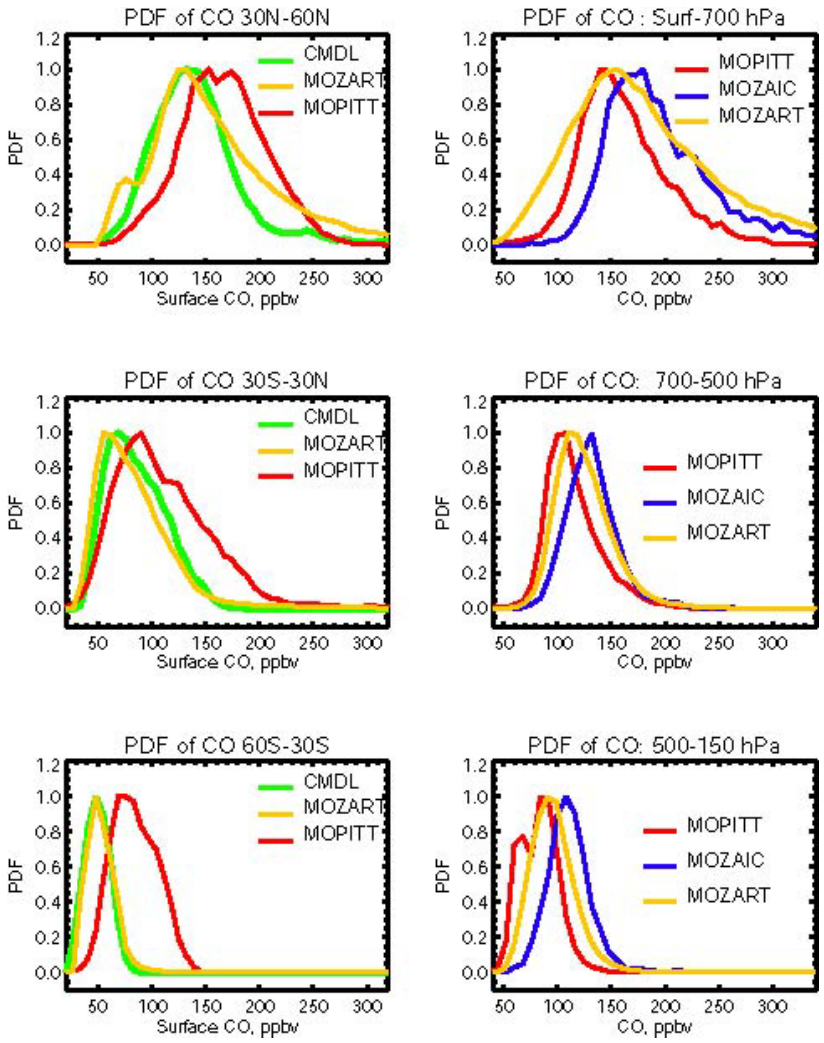
- **Two sources for the statistical multi-year 2001-2003 evaluation**: ***the CMDL surface CO and the flight MOZAIC CO (25º-55ºN).***

- **CO histograms:**
  MOPITT vs CMDL *for 3 lat-l bands*;
  MOPITT vs MOZAIC *for 3 vertical layers*.

- **At the CMDL clean regions =>**
  MOPITT overestimates CO /positive bias due to crude a priori/. *Assimilated CO agree well with the CMDL CO (**value of CTM results as a good a priori**).*

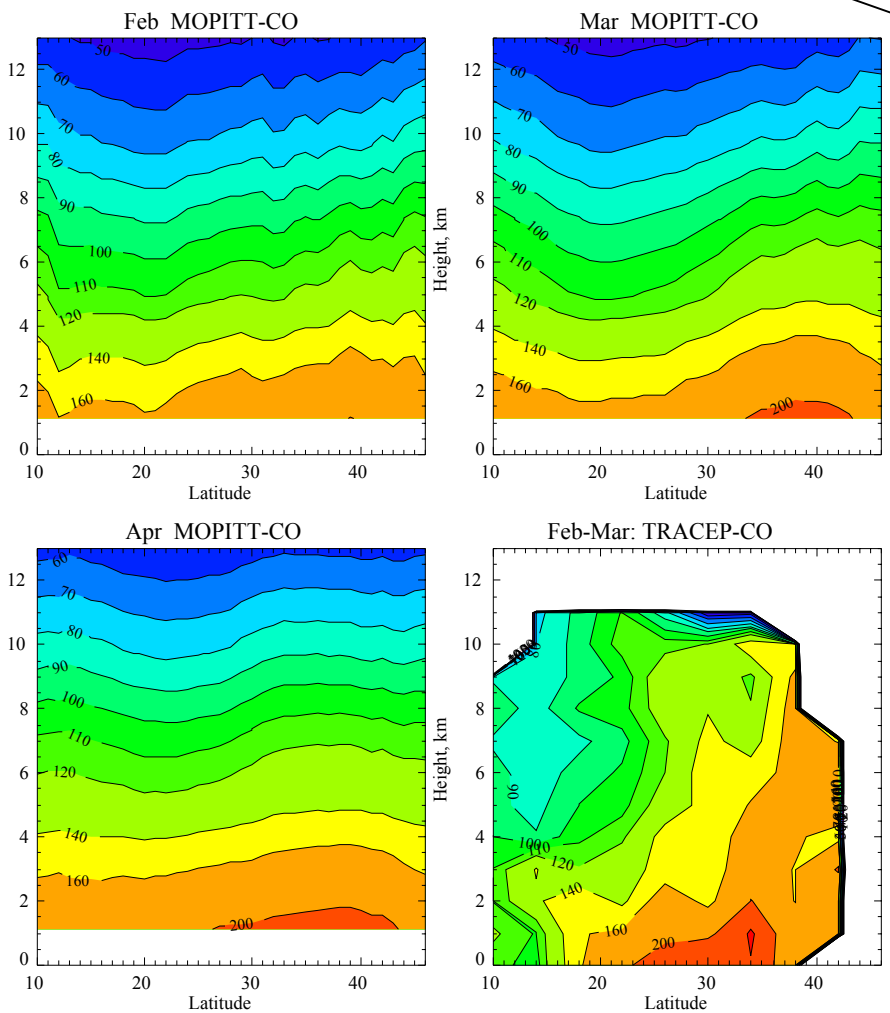
- **At the polluted regions (NH airports) =>**
  Retrievals underestimate (negative bias) CO.

- **The current goal => reduce these biases related with a priori crudeness and errors in the retrieval scheme (MOPITT-V4 ?).**

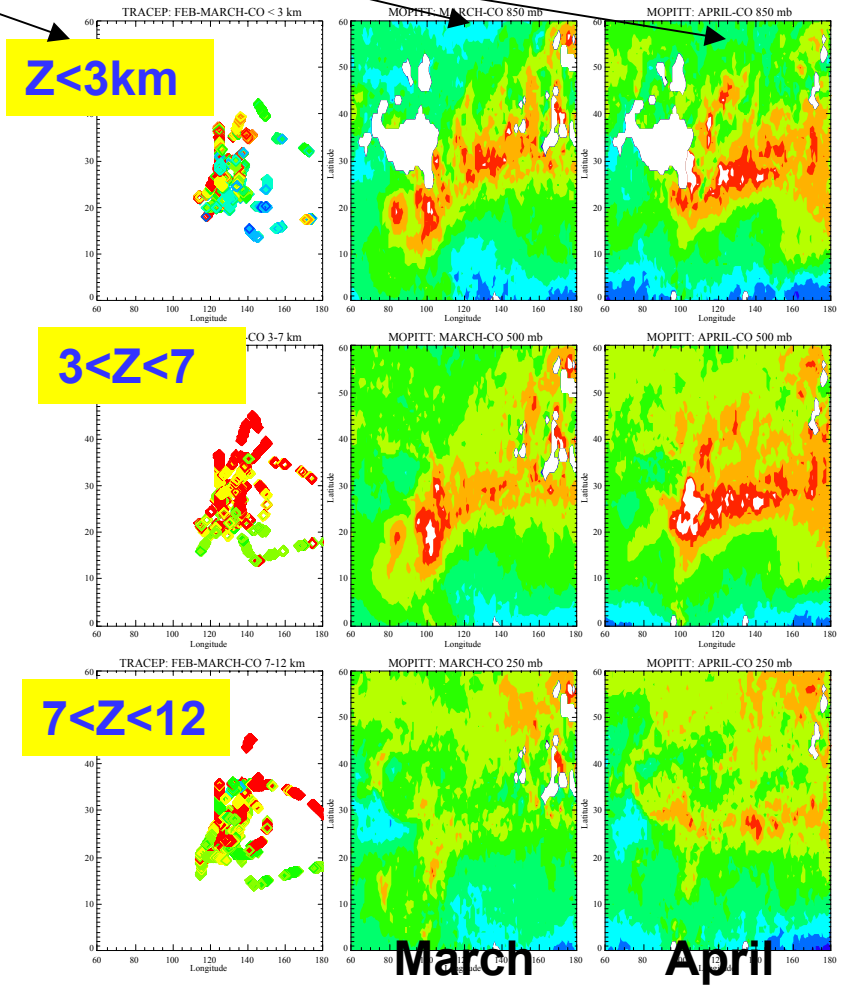


CMDL/NOAA sites **MOZAIC NH airports**

Feb-Mar, 2001 CO: TRACEP(flight) – MOPITT(retrievals)



Height-Latitude CO Composites



Lat-Lon CO composites