CATS Near Real Time Data Products: Applications for Assimilation into the NASA GEOS-5 AGCM

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1. Introduction

From February 2015 through October 2017, the NASA Cloud-Aerosol Transport System (CATS) backscatter lidar operated on the International Space Station (ISS) as a technology demonstration for future Earth Science Missions, providing vertical measurements of cloud and aerosols properties. Owing to its location on the ISS, a cornerstone technology demonstration of CATS was the capability to acquire, process, and disseminate near-real time (NRT) data within 6 hours of observation time. CATS NRT data has several applications, including providing notification of hazardous events for air traffic control and air quality advisories, field campaign flight planning, as well as for constraining cloud and aerosol distributions in via data assimilation in aerosol transport models.

Recent developments in aerosol data assimilation techniques have permitted the assimilation of aerosol optical thickness (AOT), a 2-dimensional column integrated quantity that is reflective of the simulated aerosol loading in aerosol transport models. While this capability has greatly improved simulated AOT forecasts, the vertical position, a key control on aerosol transport, is often not impacted when 2-D AOT is assimilated. Here, we present preliminary efforts to assimilate CATS aerosol observations into the NASA Goddard Earth Observing System version 5 (GEOS-5) atmospheric general circulation model and assimilation system using a 1-D Variational (1-D VAR) ensemble approach, demonstrating the utility of CATS for future Earth Science Missions.

2. The CATS Instrument

From February – March 2015, CATS operated in Mode 1, providing backscatter and depolarization measurements at 532 and 1064 nm from 2 fields of view. CATS began operation in Mode 2 in March 2015, providing backscatter and depolarization measurements at 1064 nm from one field of view operated in this mode through October 2017. CATS level 2 products are derived from these measurements, including feature detection, cloud – aerosol discrimination, cloud and aerosol typing, and optical properties of cloud and aerosol layers. In the recently released CATS version 2 level 2 products, an improved cloud–aerosol discrimination algorithm has been implemented and modifications to algorithm thresholds have been made to reduce the misclassification of water clouds as aerosol.

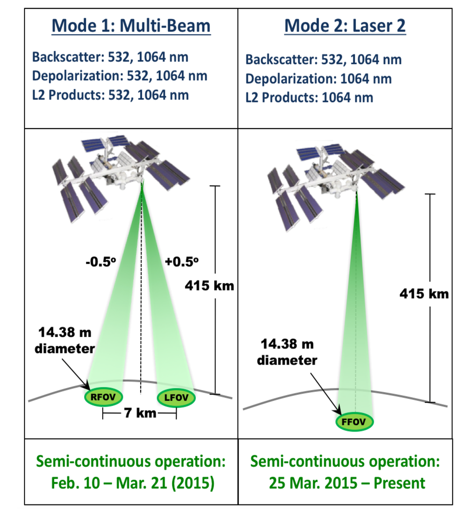

Figure 1. CATS operational fields of view

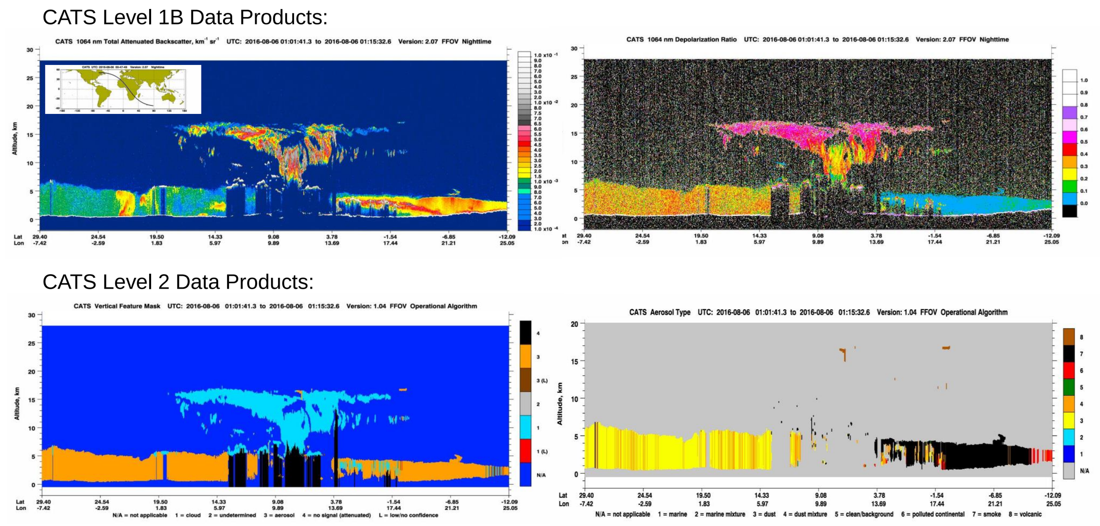

Figure 2. Example of CATS level 1B (top) and level 2 (bottom) data products

Figure 3. Field campaigns that have utilized CATS NRT data products for flight planning

3. The GEOS-5 AGCM

The GEOS-5 atmospheric general circulation model and data assimilation system developed by the NASA Global Modeling and Assimilation Office (GMAO) provides high resolution global simulations of weather and climate. Aerosols in GEOS-5 are treated with an online version of the Goddard Chemistry, Aerosol, Radiation, and Transport (GOCART) model, which simulates dust, seasalt, sulfate, and organic carbon. Pre-computed look-up tables of aerosol optical properties are used to convert simulated mass mixing ratios to aerosol optical quantities (e.g. total attenuated backscatter).

In addition to the assimilation of traditional meteorological quantities (e.g. winds) GEOS-5 assimilates 2-D AOT from both spaceborne MODIS Aqua/Terra sensors. Research forecasts are run 4x per day at 0z, 6z, 12, and 18z, with the following output resolution:

- Ensemble Mean:
  - ~12.5 km horizontal resolution, output at 25 km
  - 72 hybrid-sigma levels in the vertical
- Ensemble Members:
  - 32 members
  - ~50 km horizontal resolution
  - 72 hybrid-sigma levels in the vertical

Utilizing GEOS-5 ensembles, we are developing a 1-D VAR ensemble approach to assimilate NRT CATS observations of aerosol total attenuated backscatter into GEOS-5

4. 1-D VAR Ensemble Approach

Step 1: Use CATS level 2 observations to mask out profiles containing clouds and any profiles affected by attenuated beneath clouds. Then, regrid GEOS-5 ensemble mean and members to CATS grid.

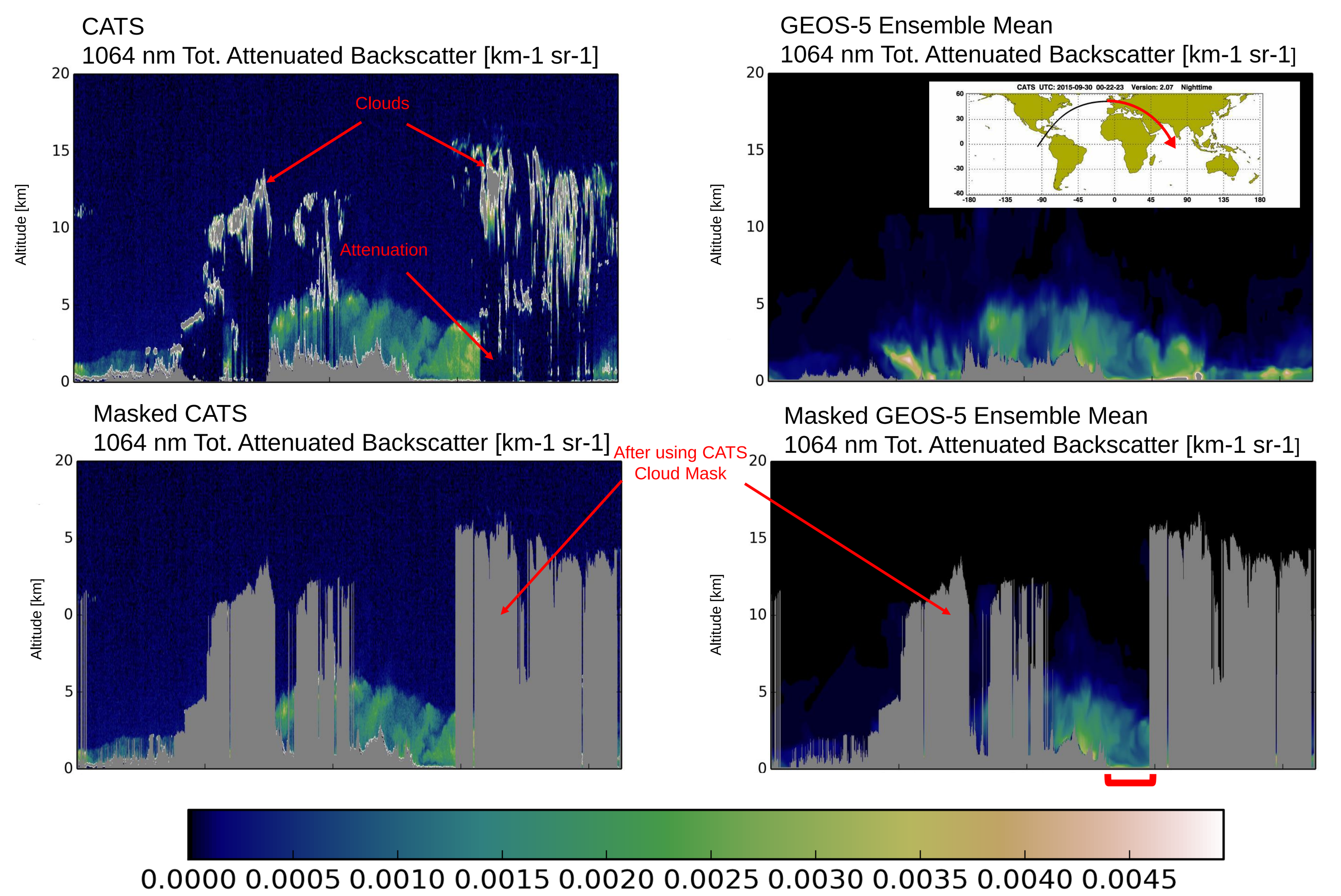

Figure 4. CATS (left) and GEOS-5 ensemble mean (right) profiles of 1064 nm total attenuated backscatter over the Arabian Peninsula and Arabian Sea before (top) and after (bottom) masking profiles affected by clouds

Step 2: Construct background error covariance [B] from GEOS-5 ensemble member total attenuated backscatter perturbations [γ'] with vertical localization [C] for reducing spurious correlation.

$$B = YY^T \circ C$$
where:
$$Y = [\gamma'(z)_1, \gamma'(z)_2, \ldots, \gamma'(z)_{nens}]$$

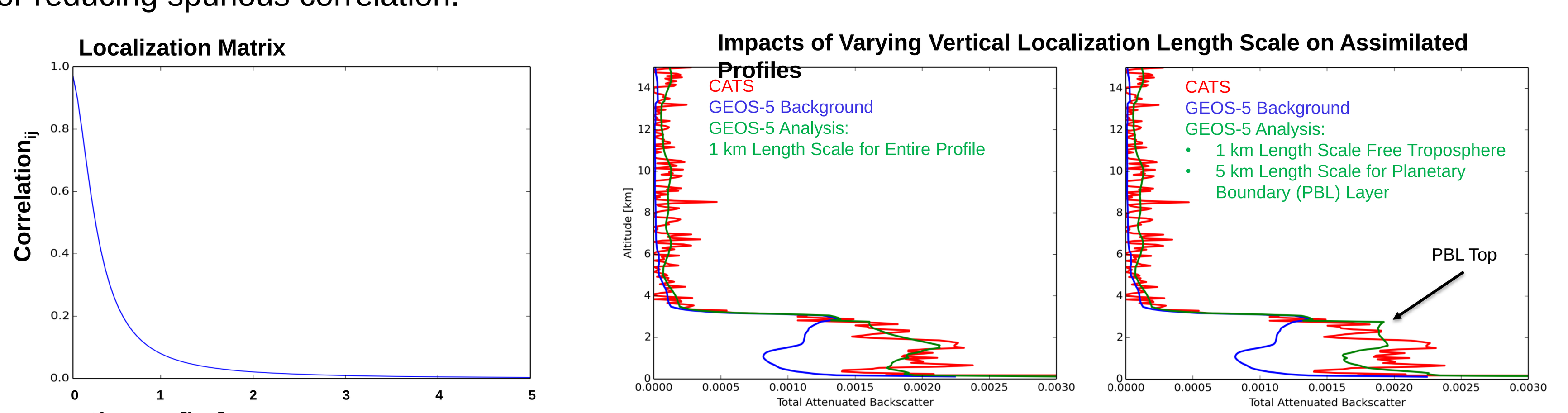

Figure 5. Example vertical localization matrix as a function of distance (left) and impacts of varying vertical localization length scale on an assimilated profile (center, right).

Step 3: Perform analysis for each CATS profile.

$$x_{analysis} = x_{background} + BH^T[HBH^T + R]^{-1}(\gamma_o - Hx_{background})$$

where:
$x_{background}$ = Ensemble mean 1064 nm total attenuated backscatter
γ_o = CATS 1064 nm total attenuated backscatter
B = Background error covariance from ensemble perturbations w/vertical localization
R = CATS error covariance
H = Linear operator that regrids GEOS-5 to CATS vertical resolution

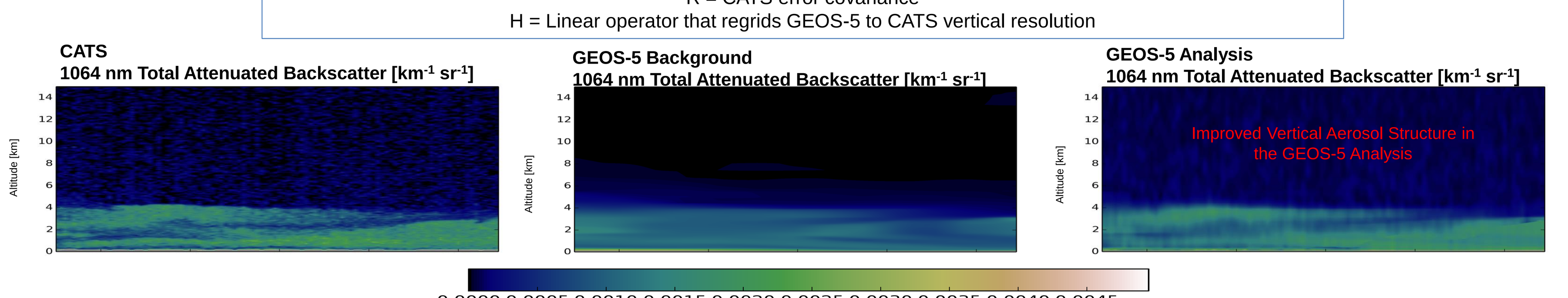

Figure 6. CATS total attenuated backscatter for a dust event over the Arabian Sea (left), GEOS-5 background simulated total attenuated backscatter (center), and GEOS-5 analysis total attenuated backscatter after implementing our 1-D VAR ensemble technique

5. Applications for Improved Aerosol Typing

For standard backscatter lidars, such as CATS, an aerosol typing algorithm is used to assign a extinction-to-backscatter or lidar ratio to an aerosol layer for converting observed backscatter to extinction products. Aerosol types are a function of observed quantities (e.g. depolarization ratio) and often other ancillary information such as surface type. Errors in defining an aerosol type can have dramatic implications for extinction, as lidar ratios can vary by as much as a factor of 3. By adapting our 1-D VAR assimilation technique to constrain the vertical distribution for each aerosol species simulated in GEOS-5, an aerosol vertical feature mask can be determined yielding a dynamic lidar ratio that is a function of the simulated mixture of aerosols.

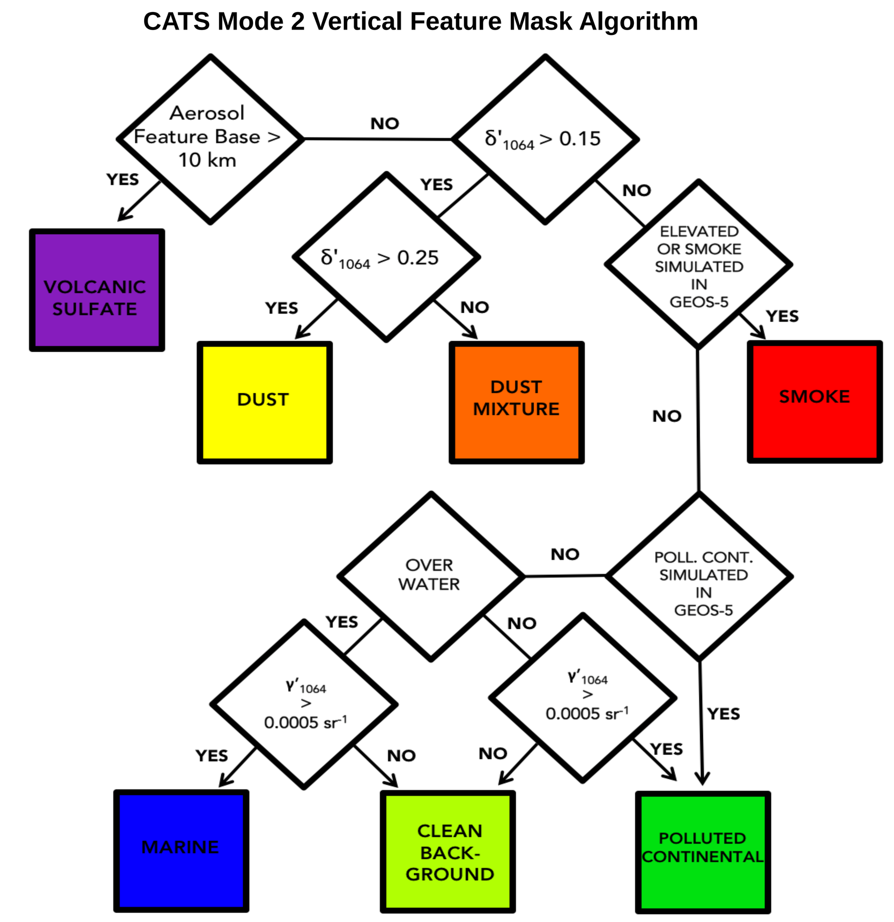

Figure 7. CATS Mode 2 aerosol typing algorithm

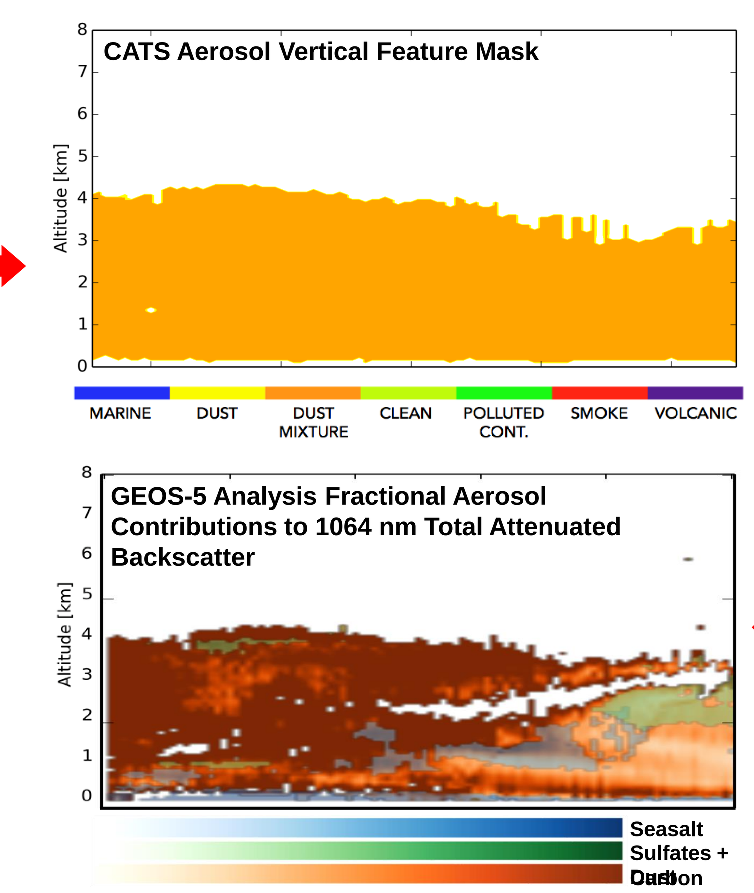

Figure 8. CATS and GEOS-5 analysis aerosol types

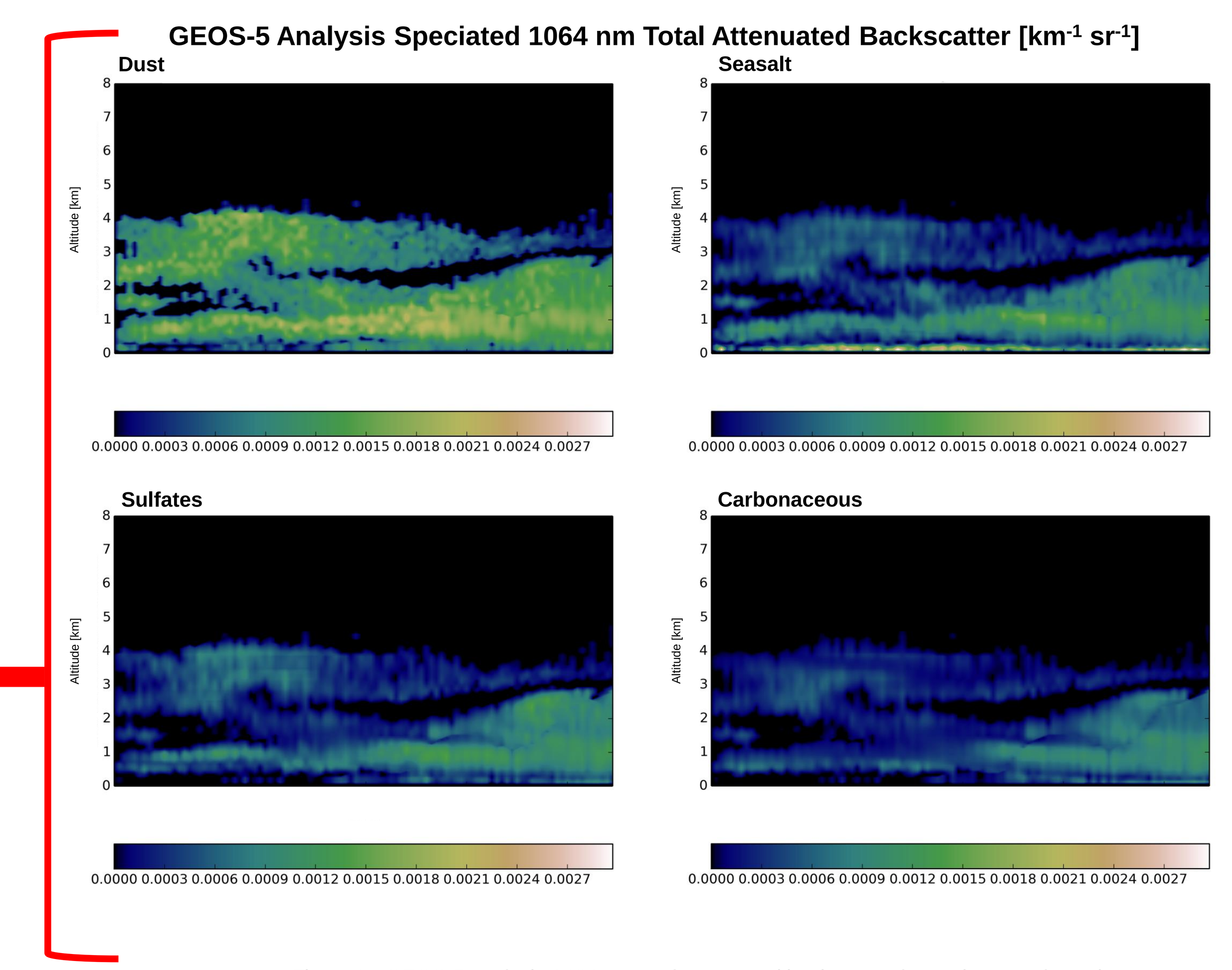

Figure 9. GEOS-5 analysis 1064 nm total attenuated backscatter for each aerosol species

6. Considerations for Extinction

A limitation of using total attenuated backscatter is that it is impacted by attenuation effects from above, which reduces the aerosol signal and has implications for computing the background error covariance with vertical localization. Here, we construct our background error covariance matrix using aerosol extinction perturbations from GEOS-5 ensemble members with vertical localization, avoiding the effects of attenuation. This method is a more appropriate way for constructing the background error covariance matrix and still yields improved vertical aerosol structure in the GEOS-5 analysis.

$$x_{analysis} = x_{background} + BH^T[HBH^T + R]^{-1}(\gamma_o - Hx_{background})$$

where:
$x_{background}$ = Ensemble mean 1064 nm total attenuated backscatter
γ_o = CATS 1064 nm total attenuated backscatter
B = Background error covariance from ensemble perturbations w/vertical localization
R = CATS error covariance
H = Regrids GEOS-5 to CATS vertical resolution & linear approximation of γ given x

$$B = XX^T \circ C$$
where:
X = Extinction Perturbations:
$$[x'(z)_1, x'(z)_2, \ldots, x'(z)_{nens}]$$

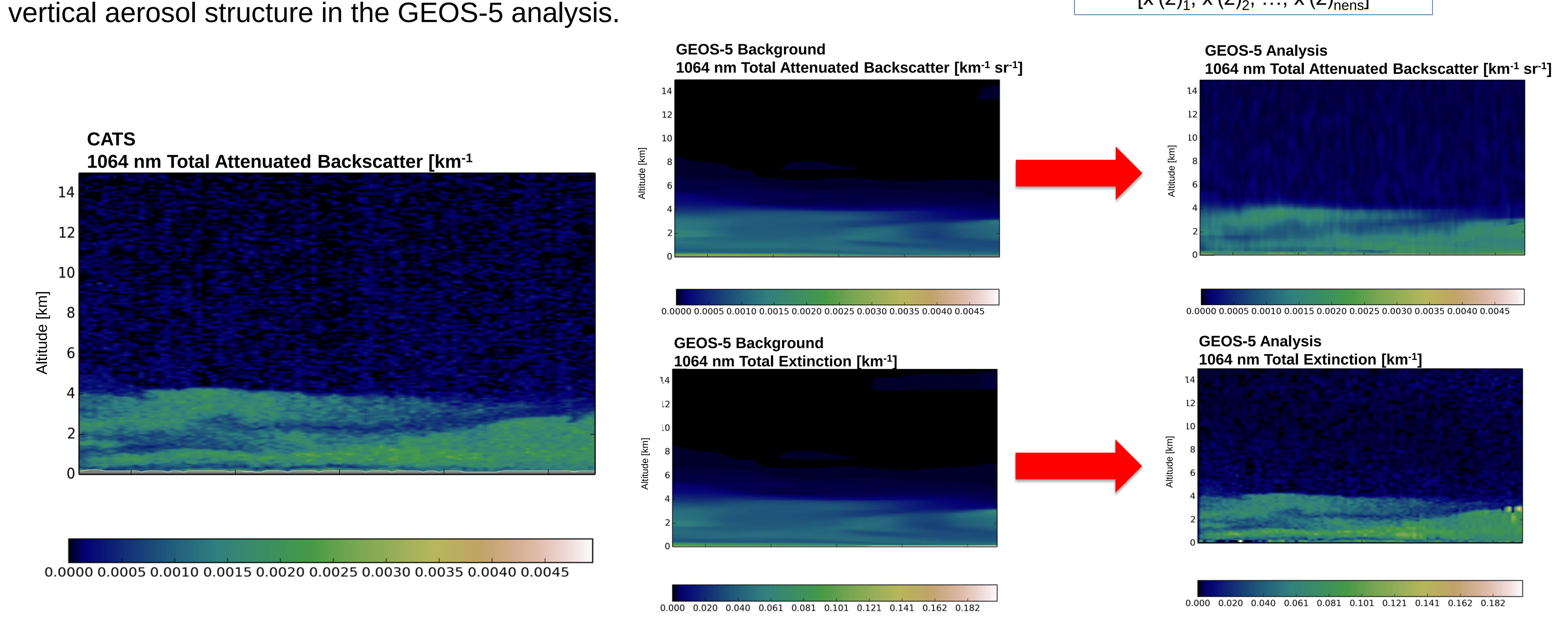

Figure 10. GEOS-5 background (left) and analysis (right) for 1064 nm total attenuated backscatter (top) and extinction (bottom)

7. Summary and Future Work

CATS NRT data downlinking capabilities have provided an opportunity for developing a 1-D VAR ensemble approach for assimilating spaceborne lidar profiles of total attenuated backscatter into NASA GEOS-5 aerosol forecasts:

- After performing a 1-D ensemble assimilation with vertical localization of a cloud-free profile, the GEOS-5 analysis drew to the observed total attenuated backscatter from CATS
- We explored the impacts of varying the vertical localization length scale for the well – mixed planetary boundary layer and the free troposphere
- After assimilating a segment of a CATS granule, the structure of an aerosol layer over the Arabian Sea was better resolved in the GEOS-5 analysis for both total attenuated backscatter and extinction
- Applying our assimilation technique to vertically constrain the individual species simulated in GEOS-5 yields an aerosol feature mask that produces a dynamic lidar ratio that evolves in conjunction with simulated aerosol mixtures

To do:

- Explore horizontal localization to enable assimilation in profiles impacted by clouds/attenuation
- Address "noisy" analysis increments in the free troposphere where both CATS and GEOS-5 aerosol loadings are low