Applications of theoretical optical parameters from a transport model to the quantification and qualification of aerosol populations of a lidar in space data retrieval

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ABSTRACT

The Lidar In space Technology Experiment (LITE) provided for the first time highly detailed vertical profiles of aerosol and clouds from the Earth's surface to the middle stratosphere.

Validated theoretical results from a Model of Atmospheric Transport and Chemistry (MATCH) can help quantify and qualify the aerosol population as well as identify some consistent patterns of aerosol components for a certain region.

The goal of this work is to estimate the degree of confidence on MATCH's theoretical results, comparing them to the data set retrieved by LITE, in order to improve the lidar aerosol extinction-to-backscatter ratio retrieval algorithm to be applied to the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO), NASA's next mission that will be orbiting a Lidar around the Earth.

Keywords : Aerosols, CALIPSO, chemical and transport model, climate, lidar.

1. LITE MISSION DESCRIPTION

In 1994 LITE designed by NASA Langley Research Center flew on Discovery as part of the STS-64 mission. LITE was the first experiment that orbited a Lidar around the Earth. LITE's mission main goals were to validate the viability of space borne Lidar applications, as well as to study the potential applications of this new technology to climate studies.

LITE provided for the first time a highly detailed global view of the vertical structure of clouds and aerosols of the Earth's atmosphere (surface to mid-stratosphere) from Space. LITE's technology will be applied to NASA's next mission, CALIPSO, scheduled for launching at the end of 2004. CALIPSO will help the scientific community to have a better understanding of the effect of aerosols and clouds on the planet's climate.

The lidar equation (1) can be written as

$$P(r)= J\,(c/2)\,(A/r^2)\,\beta(r)T_{opt}\,T^2(r) \qquad (1)$$

where P(r) is the instantaneous received power at time t returned from a sample volume at range r, c is the speed of light, J is the laser pulse energy, A is the receiver area, β is the backscatter cross section, T_{opt} is the transmission of the lidar optics and T2(r) is the two-way transmittance between the lidar and the sample volume (1).

In order to solve the lidar equation we need to combine the extinction and the backscatter cross-sections in a single variable. The variable that represents the ratio between extinction and backscatter is called the lidar ratio (S_A). The lidar ratio is not a function of the number density of the population, but rather of their physical and optical properties. These properties depend primarily on the source of the aerosol and such factors as mixing, transport, and water content for hygroscopic aerosols (2). To properly identify the aerosol population is a key factor to guesstimate the initial value of the lidar ratio.

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The CALIPSO selection algorithm defines a minimum number of aerosol types based on observational data, knowledge of emission sources, and aerosol depolarization and color ratio measurements.

The scenario selection routine can be greatly beneficiated from the theoretical results of a chemistry and transport model such as MATCH from the point of view that if MATCH's quantitative results lay within our range of confidence compared to LITE's measurements, then MATCH's qualitative forecasting will be used to identify aerosol type patterns.

2. ATMOSPHERIC TRANSPORT AND CHEMISTRY MODEL (MATCH)

MATCH stands for Model of Atmospheric Transport and Chemistry. It was developed by the National Center of Atmospheric Research (NCAR) and the Center for Clouds, Chemistry and Climate (C^4).

MATCH uses a prescribed meteorological specification to drive the transport, production and removal of aerosols. MATCH establishes seven different aerosols species. Most of these aerosol species are parallel to the ones defined by the Optical Properties of Aerosols and Clouds (OPAC) software. Hence, MATCH distinguishes between Sultafe (SO_4) which OPAC identifies as sulfate droplets (suso); Sea Salt which is taken as an external mixture of the two OPAC sea salt modes (1 / 7 ssam + 6 / 7 sscm with ssam corresponding to acc. OPAC sea salt mode and sscm corresponding to OPAC'S coarse mode); hydrophilic and hydrophobic organic carbon (CPHI and CPHO) which correspond to OPAC's water soluble aerosol with 0% relative humidity in the case of the hydrophobic organic carbon); hydrophilic and hydrophobic black carbon (BCPHI and BCPHO) which corresponds to OPAC's soot. Finally, MATCH's dust module is an early version of the Dust Entrainment And Deposition (DEAD) model (3). There are four dust radius size bins ranging from 0.005 to 5.0 microns.

3. APPLICATIONS FOR CALIPSO

Theoretical model uncertainties in aerosol prediction can be ascertained comparing the results between two different chemistry and transport models. Another possibility is to compare the model predictions with observational data. In this paper, we compare where does MATCH predict aerosol population to the data retrieved by LITE over the same period of time. This exercise will benefit both. On the one hand, we will be able to discover the uncertainties on the model predictions. And on the other hand, if the level of agreement between theoretical and experimental aerosol population lies within our confidence range, the model results can be used to qualify the aerosol population retrieved by the instrument and identify aerosol type patterns. These patterns will be used to develop the selection algorithm for the Caliop aerosol extinction-to-backscatter ratio used with CALIPSO.

Initially, MATCH aerosol mass mixing ratio data are interpolated for each of the LITE satellite ground tracks. MATCH calculates the optical and physical properties of the aerosol population for a 3-dimensional grid, with 192 longitude grid points and 94 latitude grid points. Vertically, MATCH estimates the aerosol population corresponding to 28 so-called sigma-pressure-levels. Each of these levels has a constant pressure, therefore its altitude depends on the surface pressure, hence location. MATCH's values are interpolated by means of a bilinear interpolation algorithm to the corresponding LITE ground track. MATCH's vertical values are then interpolated for a fix set of 30 altitude levels, correcting the aerosol concentration to be zero below the surface level. We graphed MATCH results in a similar contour plot as the LITE profile map to get a preliminary visual effect of the accurateness of MATCH's theoretical estimations.

To illustrate this procedure we present here the results for LITE's orbit 117 (Figure 1) on the 16th of September, 1994, crossing over the East coast of the United States and over the Atlantic Ocean. Figure 2 shows the contour plots corresponding to LITE Level 1 data profiles retrieved (2a) and MATCH aerosol mass mixing ratio values in Kg/Kg (2b). The white points in LITE's plot correspond to spots where the return signal saturated the receiver.

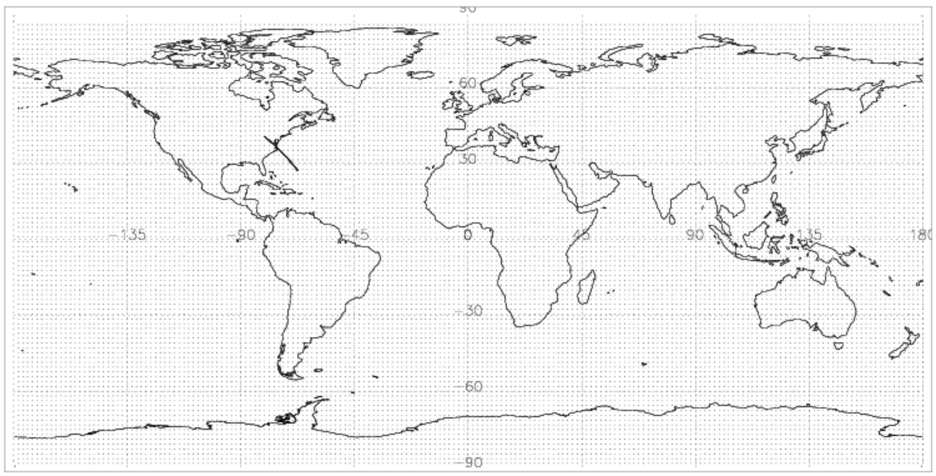

Figure 1. Orbit 117_56b ground track

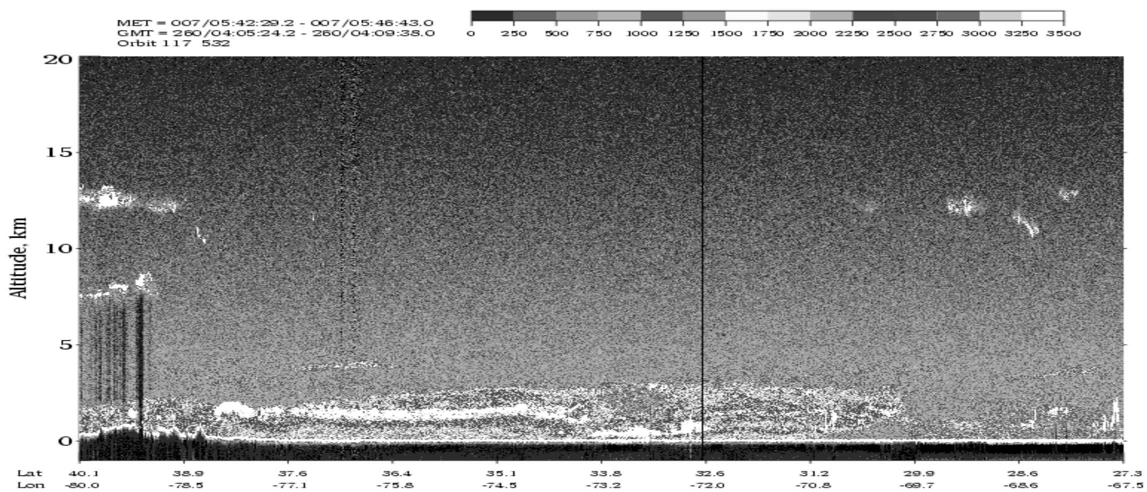

Figure 2a. LITE level 1 photo for orbit 117

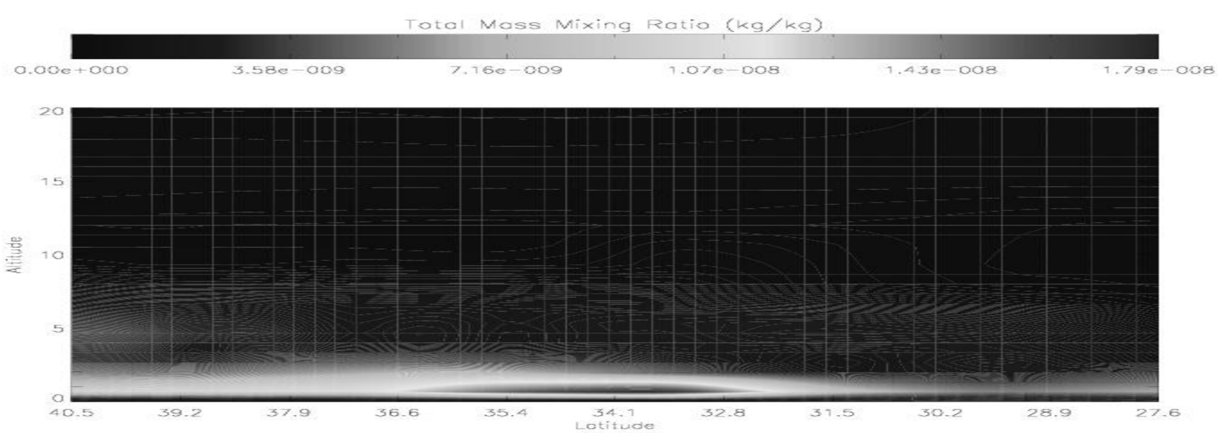

Figure 2b. MATCH interpolated data

Despite the obvious roughness of MATCH's prediction, the accuracy of the model to forecast the aerosol population in the area is remarkable. MATCH is able to locate the peak of the aerosol mass concentration around 34˚ North latitude which agrees with LITE's retrieved signal. Likewise, MATCH accurately previews the height of the aerosol cloud (around 8 km) and is able to anticipate the decay of the aerosol population south of 30˚ and north of 40˚ latitude. Orbit 117 is a fine example of how MATCH's aerosol population forecasting despite rough is basically correct. Some orbits, mainly the ones dealing with dessert dust, do present some inaccuracies and some vertical transport of dust that is not reflected on the satellite images. However, we will assume that MATCH's uncertainties are within our range of confidence.

Figure 3 represents MATCH's aerosol mass mixing values for each of the individual species and the percentage that each of these aerosol species represents with respect to the total aerosol mass.

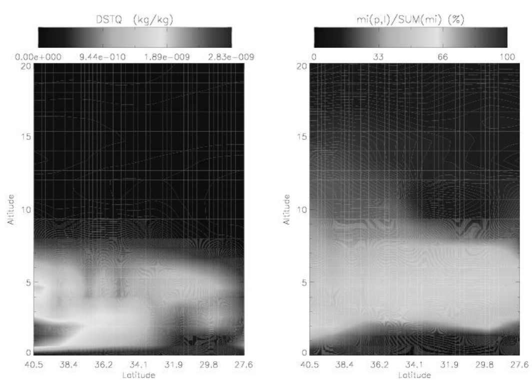

Figure 3a. Dust mass mixing ratio (MMR) (kg/kg)

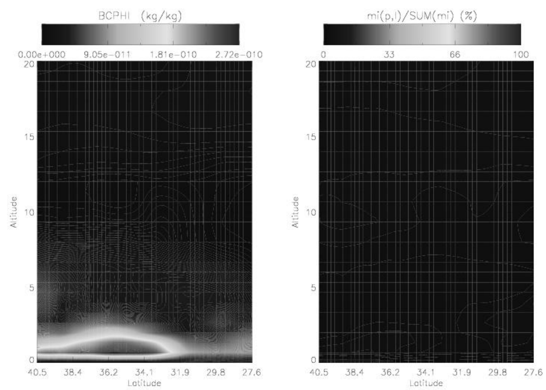

Figure 3b. Hydrophilic Black Carbon (BC) (kg/kg)

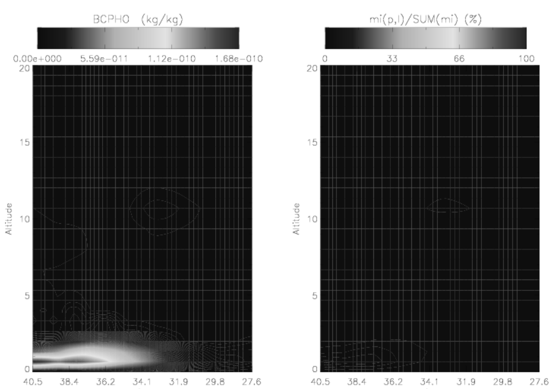

Figure 3c. Hydrophobic BC MMR (kg/kg)

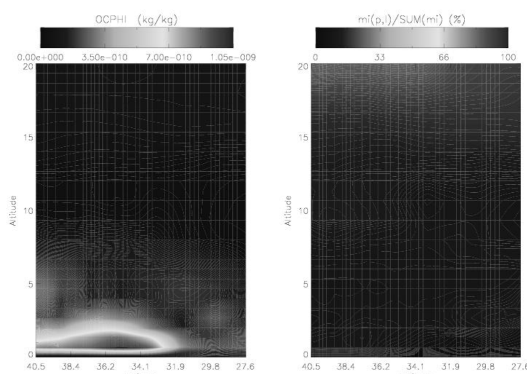

Figure 3d. Hydrophilic Organic Carbon (OC) MMR (kg/kg)

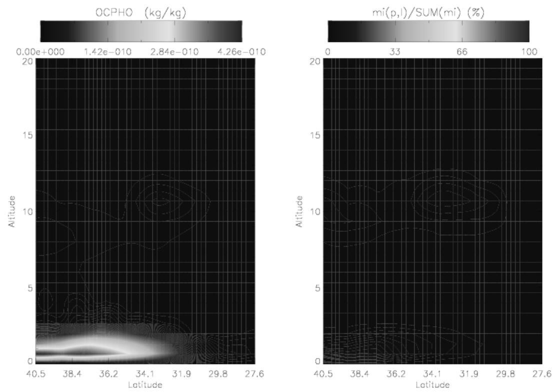

Figure 3e. Hydrophobic OC MMR (kg/kg)

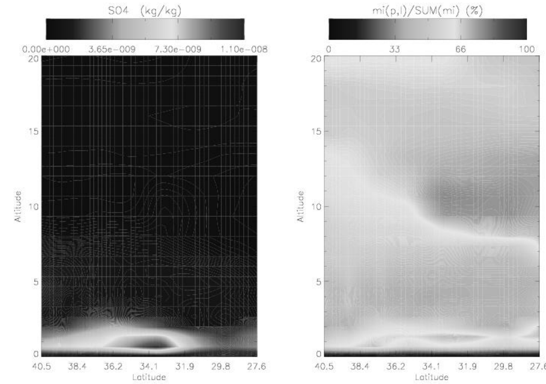

Figure 3f. Sulfate MMR (kg/kg)

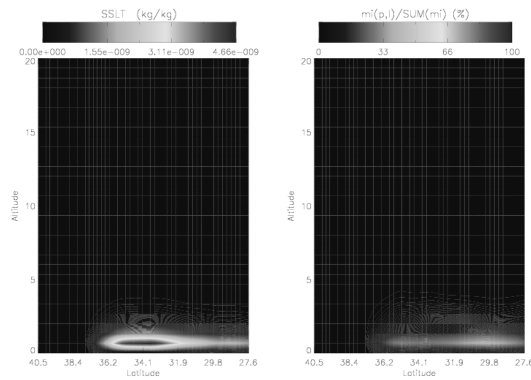

Figure 3g. Sea Salt MMR (kg/kg)

As it can be observed on each of the individual percentage plots (to the right of each figure) most of the aerosol population consist of sulfate and some dust for lower altitudes. There is no significant trace of organic or black hydrophobic carbon and as expected the sea salt is the major component right above the sea surface. It can also be observed how the dust is being transported from inland towards the water. As a conclusion, the aerosol population of this area is mainly formed by sulfate, water-soluble carbon components, and dust, which is archetypal of urban haze, typically located above industrialized areas such as the eastern coast of the United States. Some of the anthropogenic sources for these aerosols are industrial activities, traffic and non-dessert dust. We are unable to further characterize the dust aerosol composition with MATCH's information. From the literature, we can assume that it is mainly mineral dust and fly ashes (4). It should be pointed out that the accurateness of the Sea Salt concentration is biased. MATCH prediction module is controlled to determine an exponential decay of sea salt aerosol over maritime areas. A similar analysis has been applied to each one of the LITE's orbits.

In addition to the aerosol mass mixing ratio data, NCAR also made available the aerosol optical properties, providing their vertical extinction profiles. Since the color ratio is one of the most useful parameters to distinguish between clouds and aerosols, the theoretical values of the extinction coefficient can be used to calculate the two-way transmission and compare the results to the otherwise derived values from the Raleigh molecular model.

4. MATCH'S 5-YEAR CLIMATOLOGY APPLICATIONS

A 5-year climatology (1995-2000), courtesy from NCAR as well, propitiated the analysis of aerosol patterns (5). By studying the time evolution of the location of each of the aerosol species and some of their typical combinations we were able to determine some usual case scenarios.

We imposed the condition that the mass mixing ratio of the aerosol population under study were equal or higher than 90%. The aerosol location routine was applied to each of the sigma-pressure layers as well as to integrated aerosol concentration values for the total vertical column. The same analysis was conducted for a concentration equal or higher than 80% but that tolerance is too low and the aerosol coverage over the entire world would often been guesstimated as organic carbon and sulfate mixture.

The climatology correctly guesstimates well-characterized aerosol mixtures such as the so-called artic haze. The climatology results also show an almost constant coverage of the Antarctica by organic carbon and sulfate slightly decreasing during the summer time. Figure 4 represents this aerosol population coverage and concentration values for the months of January and July.

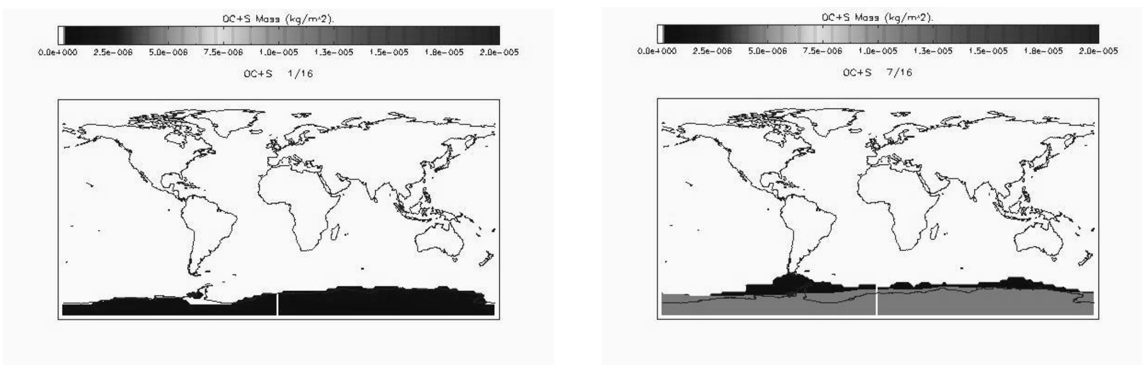

Figure 4. Organic carbon and sulfate dominate aerosol population for the months of January (left) and July (right)

It's interesting as well to observe the seasonal changes of other aerosols such as desert dust over the Sahara desert, which drastically decreases during winter. Figure 5 shows the dust mass mixing ratio values for the months of January and July.

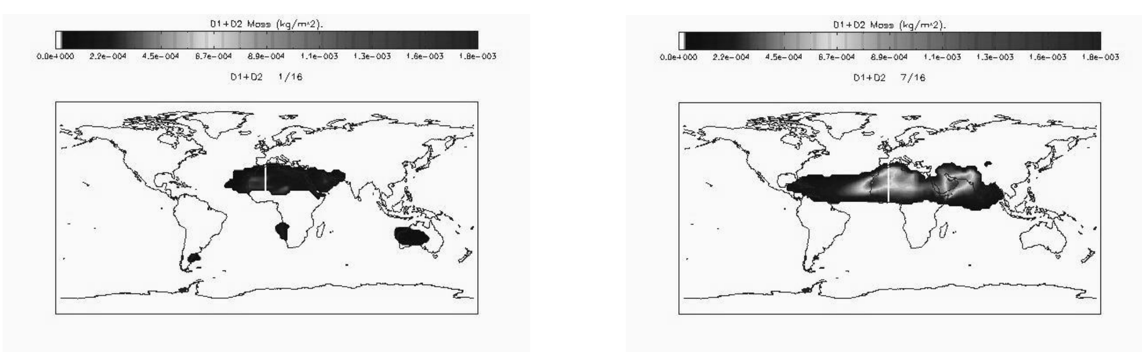

Figure 5. Dust (size bin 1 and size bin 2) dominates aerosol populations for the months of January (left) and July (right).

A very precise focus of black and organic carbon over the jungle of Brazil during the months of July and August, probably due to forest fires, can be appreciated on Figure 6.

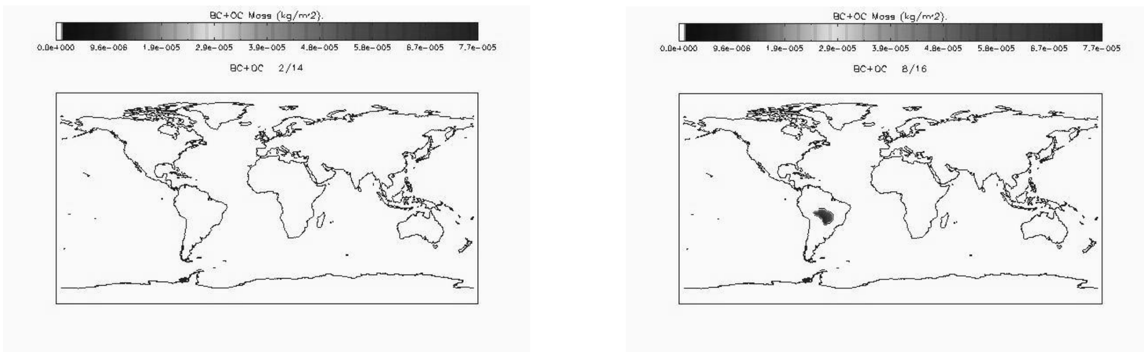

Figure 6. Organic and black carbon during the months of February (left) and August (right)

Interestingly enough, other aerosol mixtures typical of developed regions, such as the combination of black and organic carbon and sulfate, pass from being the dominant species over industrialized areas such as the east coast of North America, to be the principal aerosols over forestry regions like the Brazilian coast during the summer time, again, probably due to fires. Figure 7 illustrates this premise. All the results shown in Figures 4, 5, 6 and 7 correspond to the integrated mass mixing values for the total vertical column.

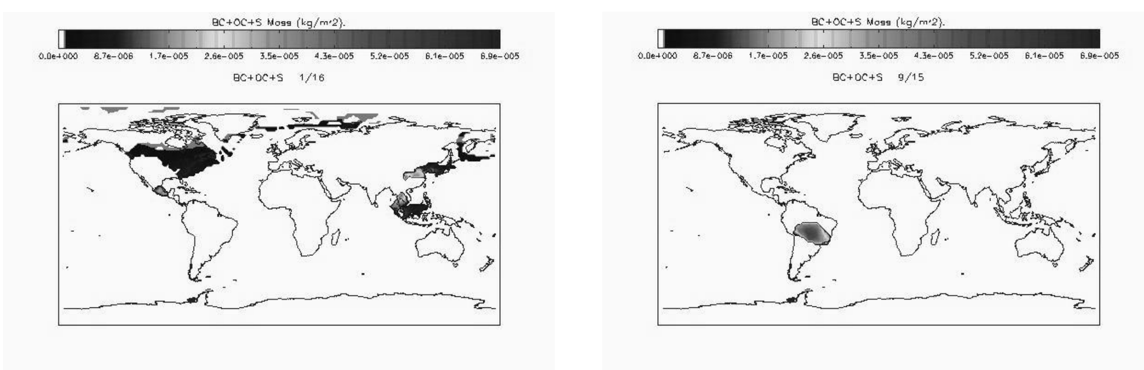

Figure 7. Organic carbon, black carbon and Sulfate aerosol dominant population during the months of January (left) and September (right)

5. CONCLUSION

This article describes the applications of theoretical optical parameters from a transport model to the quantification and qualification of aerosols by a lidar in space data retrieval. After validating the correctness of the model in locating the aerosol clouds, the theoretical optical values are used to guesstimate the color ratio and the lidar ratio parameters, in order to solve the lidar equation and typify the aerosol population. According to the climatology results provided by

NCAR some conclusions concerning aerosol patterns have been extracted. Further work needs to be done in this aspect; a deeper study on aerosol sampling by layer is on its way.

The conclusions extracted from this work will be used to improve the design of the CALIPSO selection algorithm. Likewise, the MATCH forecasting mode will benefit from the analysis of its uncertainties derived from this work.

6. ACKNOWLEDGMENTS

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7. REFERENCES

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