The Vertical Distribution of Aerosols Over the Atmospheric Radiation Measurement Southern Great Plains Site Measured versus Modeled

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Abstract

Aerosol extinction profiles measured by the Department of Energy Atmospheric Radiation Measurement (ARM) Climate Research Facility Raman lidar are used to evaluate aerosol extinction profiles and aerosol optical thickness (AOT) simulated by aerosol models as part of the Aerosol module inter-Comparison in global models (AEROCOM) (http://nansen.ipsl.jussieu.fr/AEROCOM/aerocomhome.html) project. This project seeks to diagnose aerosol modules of global models and subsequently identify and eliminate weak components in aerosol modules used for global modeling; AEROCOM activities also include assembling data sets to be used in the evaluations. The AEROCOM average aerosol extinction profiles typically show good agreement with the Raman lidar profiles for altitudes above about 2 km; below 2 km the average model profiles are significantly (30-50%) lower than the Raman lidar profiles. The vertical variability in the average aerosol extinction profiles simulated by these models is less than the variability in the corresponding Raman lidar profiles. The measurements also show a much larger diurnal variability than the Interaction with Chemistry and Aerosols (INCA) model, particularly near the surface where there is a high correlation between aerosol extinction and relative humidity.

Introduction

Global models have been increasingly used to assess climate change scenarios. Since some of the largest uncertainties in model simulations of climate change are associated with aerosols, evaluating how these models portray aerosol characteristics is vital for determining uncertainties in simulations of aerosol radiative forcing and climate change. Assessments of aerosol models have to date focused primarily on comparing estimates of column integrated aerosol optical thickness (AOT) with satellite retrievals and/or ground-based measurements of AOT. However, AOT alone does not provide enough information to resolve several specific model deficiencies. One problem common to all models becomes particularly apparent when comparing the vertical distributions of aerosols. A model intercomparison performed as part of the Third Intergovernmental Panel on Climate Change, Climate Change (IPCC) Assessment of aerosol effects found that the vertical distribution of aerosol concentrations differs by a factor of two or more from one model to the next, especially for components other than sulfate (IPCC 2001). The lack of a climatological database to characterize the vertical distributions of aerosols has hampered efforts to evaluate and consequently improve such models.

Lidar measurements can provide one means of characterizing the vertical distribution of aerosols. Through its design as a turnkey, automated system for unattended, around-the-clock profiling of water vapor and aerosols, the U.S. Department of Energy Atmospheric Radiation Measurement (ARM) Climate Research Facility Raman lidar has begun to provide a climatological database of aerosol and water vapor profiles (Turner et al. 2001). Climate Research Facility Raman lidar profiles were used to evaluate the aerosol optical thickness and aerosol extinction profiles simulated by the Goddard Global Ozone Chemistry Aerosol Radiation and Transport (GOCART) global aerosol model (Ferrare et al. 2002). The GOCART and Climate Research Facility Raman lidar aerosol extinction profiles often show significant disagreement throughout the lower troposphere and indicate that good agreement between measured and modeled AOT (355 nm) does not necessarily mean that the model correctly represents the vertical distribution of aerosols (Ferrare et al. 2002). Here we describe how the Climate Research Facility Raman lidar aerosol extinction profiles are used to evaluate aerosol extinction profiles and AOT simulated by various global aerosol models from the AEROCOM project for the year 2000.

Climate Research Facility Raman Lidar

Climate Research Facility Raman lidar autonomously measures profiles of aerosols, clouds and water vapor in the low to mid troposphere throughout the diurnal cycle (Goldsmith et al. 1998). A tripled Nd:YAG laser, operating at 30 Hz with 350-400 millijoule pulses, is used to transmit light at 355 nm. A telescope collects the light backscattered by molecules and aerosols at the laser wavelength and the Raman scattered light from water vapor (408 nm) and nitrogen (387 nm) molecules. Profiles of water vapor mixing ratio, relative humidity, aerosol backscattering, and aerosol extinction are derived routinely using a set of automated algorithms (Turner et al. 2002). Water vapor mixing ratio profiles are computed using the ratio of the Raman water vapor signal to the Raman nitrogen signal. Relative humidity profiles are computed using these profiles and the temperature profiles from a collocated Atmospheric Emitted Radiance Interferometer (AERI). The water vapor mixing ratio profiles are integrated with altitude to derive precipitable water vapor (PWV). Profiles of aerosol scattering ratio are derived using the Raman nitrogen signal and the signal detected at the laser wavelength. Aerosol

volume backscattering cross section profiles are then computed using the aerosol scattering ratio and molecular scattering cross section profiles derived from atmospheric density data. Aerosol extinction profiles are computed from the derivative of the logarithm of the Raman nitrogen signal with respect to range. AOT is derived by integration of the aerosol extinction profile with altitude.

Aerosol Comparisons

Figure 1 shows the vertical distribution of aerosol extinction (355 nm) for the year 2000 as represented by several AEROCOM models, and as measured by Climate Research Facility Raman lidar. These distributions were comprised of monthly averages. Approximately 3700 10-min lidar profiles were used to construct the Climate Research Facility Raman lidar averages. Note the wide range in how the models represent the aerosol extinction profiles over the ARM Southern Great Plains (SGP) site. Models A, D, E, F, G, and the Climate Research Facility Raman lidar measurements are for cloud-free conditions; Models B, C, H, I are for all sky (clear+cloudy conditions).

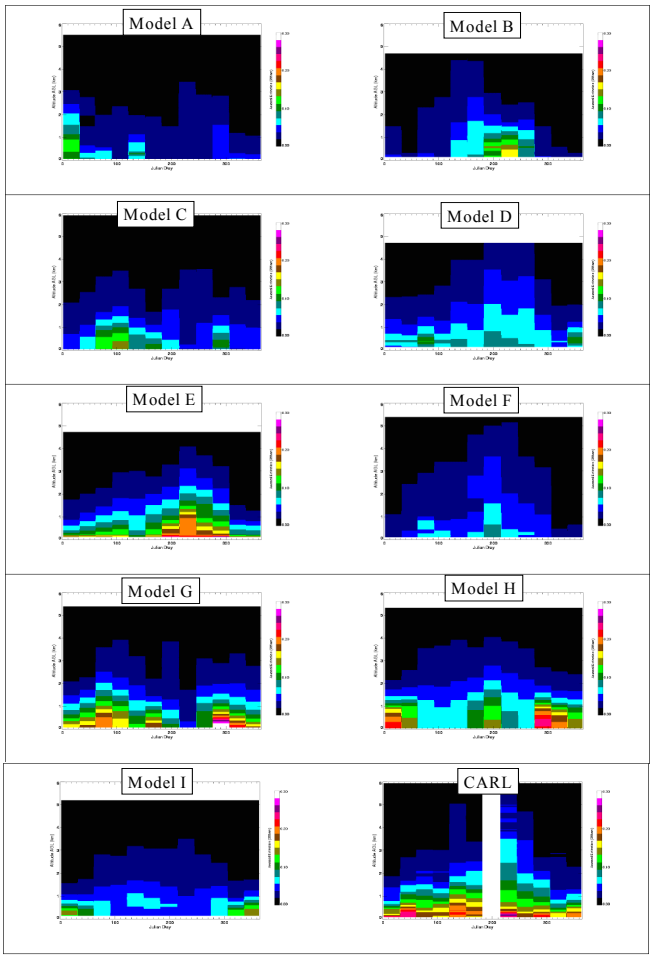

Figure 1. Vertical distribution of aerosol extinction (355 nm) for the year 2000 as represented by several AEROCOM models, and as measured by the ARM CRF Raman Lidar.

Figure 2 shows the average annual AOT (355 nm) from the various models, as well as annual averages derived from Climate Research Facility Raman lidar and AERONET Cimel Sun photometer (Holben et al. 1998) located at the SGP site. Averages were computed from the monthly averages; error bars represent standard deviations. Note how the average annual AOT represented by the various models and measured by Climate Research Facility Raman lidar and the Sun photometer are in general agreement, at least within the standard deviations of the averages.

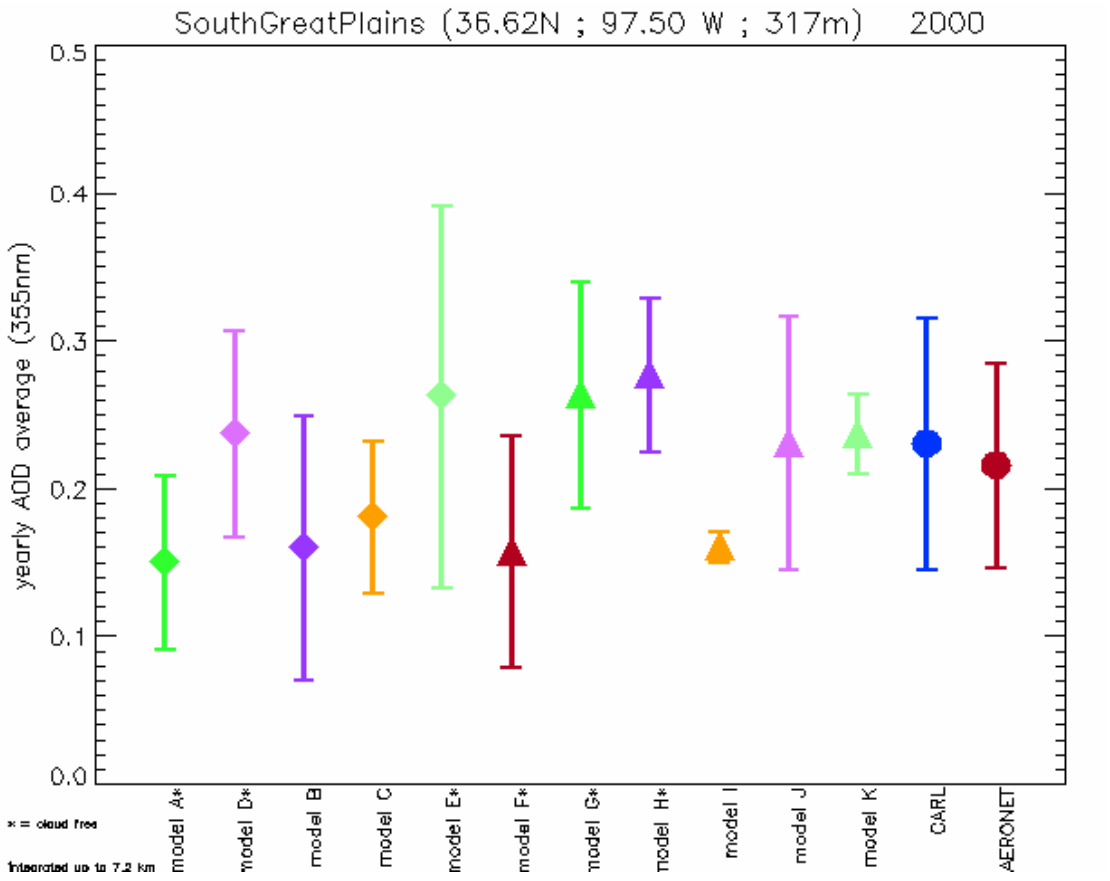

Figure 2. Average annual aerosol optical thickness (355 nm) from the various models, as well as annual averages derived from Climate Research Facility Raman lidar and the AERONET Sun photometer. Averages were computed from the monthly averages; error bars represent standard deviations.

Figure 3 shows the average annual extinction profiles from the various models and from the Climate Research Facility Raman lidar data. Note the differences in the average vertical distributions, even among models that have similar average aerosol optical thickness. Deviations between mean aerosol extinction profiles are generally small (~20-30%) for altitudes above 2 km, and grow considerably larger below 2 km. Similar results were found when comparing the aerosol extinction profiles derived from the EARLINET (Bösenberg et al. 2002) Raman lidar measurements for 2000 over Europe and the corresponding Interaction with Chemistry and Aerosols (INCA) (http://www.ipsl.jussieu.fr/~dhaer/inca/)

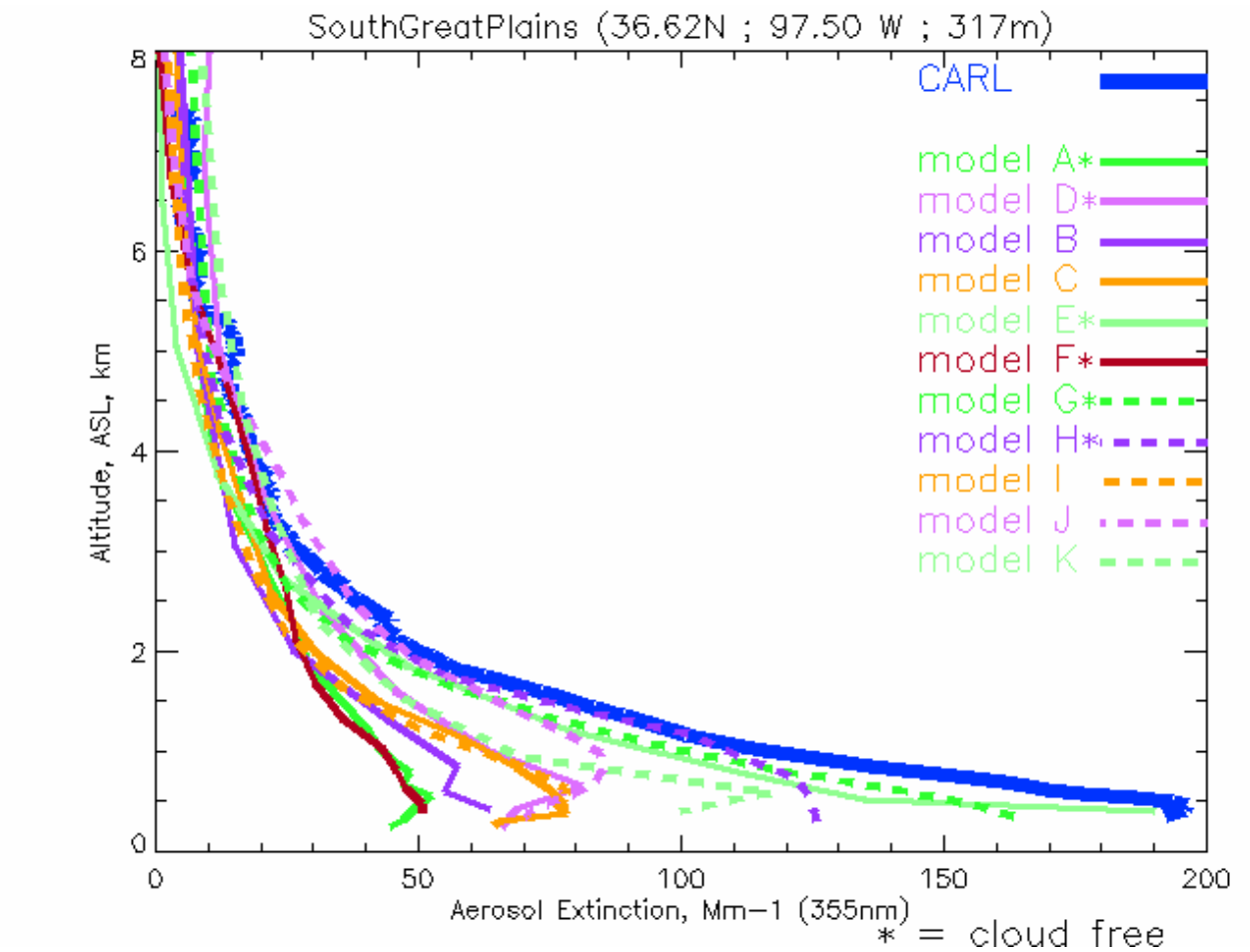

Figure 3. Average annual extinction profile from the various models and from the Climate Research Facility Raman lidar data. Note the differences in the average vertical distributions, even among models that have similar average aerosol optical thickness.

model results (Guibert et al. 2004). One possible explanation may be that there is no evolution of the planetary boundary layer in the model (Guibert, personal communication, 2004). Additional impacts of this limitation are also shown in Figure 4 where the average diurnal variations of aerosol extinction as measured by Climate Research Facility Raman lidar and represented by the INCA model are shown. Note how the largest values of aerosol extinction derived from the Climate Research Facility Raman lidar data are typically found near the surface around sunrise (10-12 UT). Since the highest average values of relative humidity are also normally found at this location and time, this maximum in the aerosol extinction is most likely due to the hygroscopic growth of the aerosol particles. In contrast, the INCA model shows minimum values of aerosol extinction at this location and time. Changes are already proposed to the INCA model to modify the parameterization of the convective boundary layer to better represent the diurnal cycle.

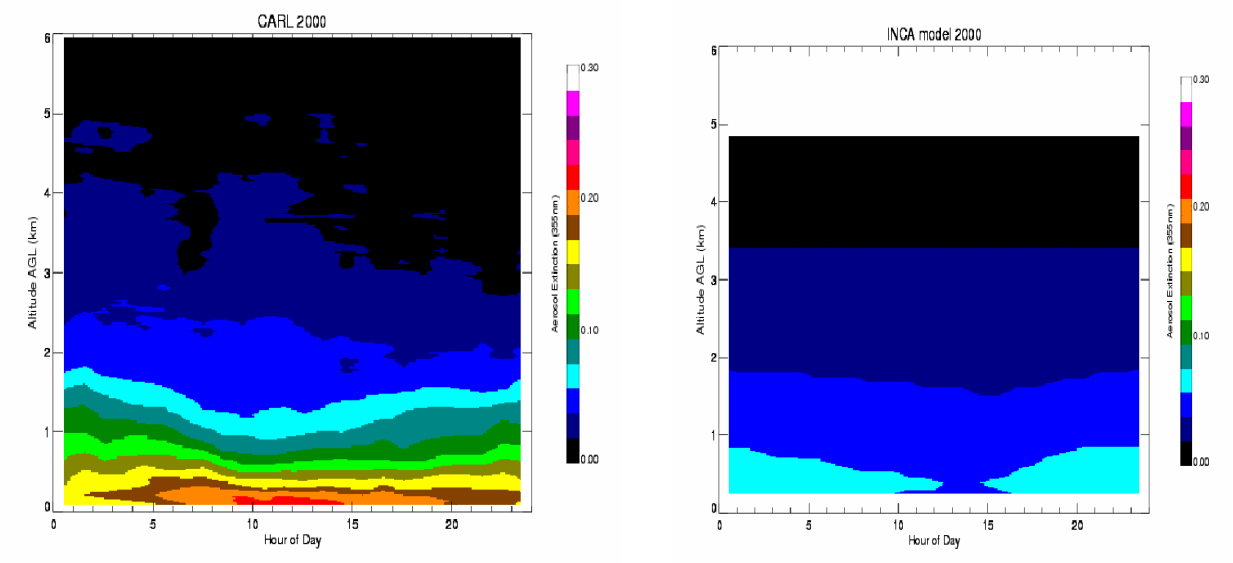

Figure 4. Average diurnal variation in vertical distribution of aerosol extinction measured by Climate Research Facility Raman lidar (left) and represented by the INCA model (right).

Some indication of potential reasons why the models have different average distributions can be seen in Figures 5 and 6. Figure 5 shows examples of the monthly AOT values from the various models, along with the corresponding values measured by Climate Research Facility Raman lidar and AERONET. The contributions to the total aerosol optical thickness made by the various aerosol components (sulfate, black carbon, sea salt, particulate organic matter, dust) as represented by the various models are also shown. Figure 6 shows the average aerosol extinction profiles for these models as well as the contributions made by the various aerosol components. Note how model C (top right) shows that sulfate decreases in the summer in contrast to models A (top left) and E (bottom left), which show increases in sulfate during the summer. This behavior may be responsible for the apparent deficit in total aerosol optical thickness during the summer as represented by model C. Model H (bottom right) shows a much higher concentration of dust throughout the year than any of the other models and, perhaps as a result, shows higher overall levels of aerosol extinction and optical thickness than the other models. These results indicate that there are differences in how the models represent the contributions made by the various aerosol components, and that these differences may help to explain some of the differences between the measured and modeled values of aerosol extinction and optical thickness.

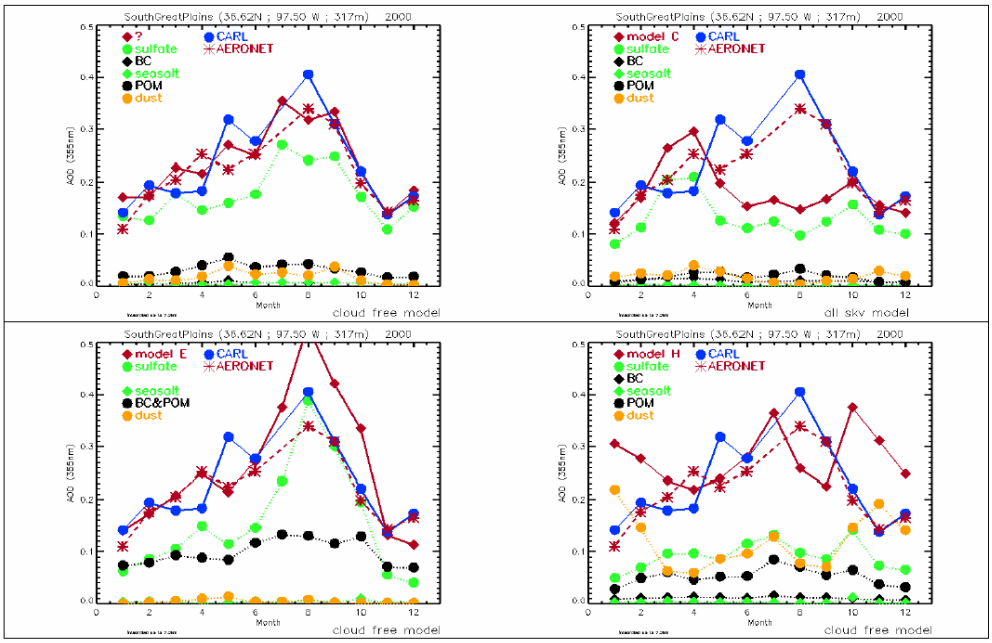

Figure 5. Monthly average aerosol optical thickness measured by Climate Research Facility Raman lidar and the Cimel Sun photometer, and represented by four different models. The contributions to the total aerosol optical thickness made by the various aerosol components (sulfate, black carbon, sea salt, particulate organic matter, dust) as represented by the various models are also shown.

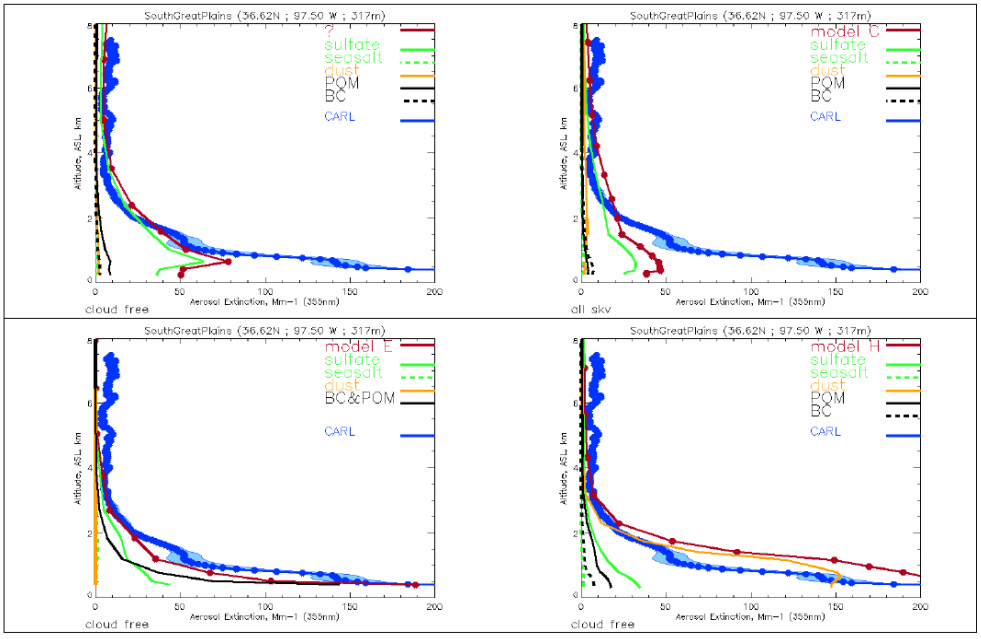

Figure 6. Average aerosol extinction profiles represented by four of the AEROCOM models, and derived from the Climate Research Facility Raman lidar measurements. The contributions to the total aerosol extinction profile made by the various aerosol components (sulfate, black carbon, sea salt, particulate organic matter, dust) as represented by the various models are also shown.

Acknowledgements

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