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Developing an Aerosol Database for Understanding Aerosols' Effects on Atmospheric Processes and for HEL Research and Applications

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Developing an Aerosol Database for Understanding Aerosols' Effects on Atmospheric Processes and for HEL Research and Applications

by

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Prospectus

Statement of the Problem and Purpose for My Research

Atmospheric aerosols are tiny liquid or solid particles that are suspended in the atmosphere (Steiner et al. 2013), such as sulfate, black carbon, organic carbon, dust, and sea salt. Even though aerosols are quite tiny, they play a vital role in modulating atmospheric processes such as radiative transfer and cloud formation. Depending on size and composition, aerosols can either scatter or absorb incoming solar radiation (Steiner et al. 2013). Aerosols with a diameter size less than or equal to 2.5 µm, such as sulfate, typically scatter incoming solar radiation which results in atmospheric cooling while black carbon and organic carbon typically absorb incoming solar radiation which results in atmospheric warming (Steiner et al. 2013). Aerosols can also contribute to warming by trapping outgoing longwave radiation.

Aerosols can also function as cloud condensation nuclei, or seed locations for water vapor to condense and form cloud droplets. Cloud formation in the atmosphere is affected by the amount and type of aerosols present in the atmosphere. For example, as noted by Charlson et al. (2001), "*an increase in atmospheric aerosols from anthropogenic emissions would lead to smaller cloud droplets because the same amount of cloud liquid water is distributed among more condensation nuclei*" which leads to the formation of a cloud that can reflect more solar energy (Charlson et al. 2001) and thus has a cooling effect on the climate.

In addition to affecting natural atmospheric processes, aerosols can also impact the functioning of human-engineered systems. This includes high-energy lasers (HEL) weapon systems being developed for defense applications. Aerosols can affect laser beams through scattering or absorption of energy. Scattering is the process where the interaction between radiation and aerosols leads to the deflection of some of the radiation away from the original direction of propagation, whereas absorption results in the loss of radiative energy and conversion to heat (Brown and Smith 1975). Both of these processes lead to energy loss when a laser beam propagates through atmospheric aerosols (Duan and Song 2017).

Because of the impact that atmospheric aerosols have on important processes for natural and human-engineered systems, a near-real-time global aerosol database is important. Existing global aerosol datasets, especially those utilized for HEL applications, are of coarse resolution and were constructed two decades ago when there was a lack of observationally constrained aerosol datasets. My research is aimed at addressing these drawbacks by developing the methodology for creating a near-real-time global aerosol database that takes advantage of aerosol observational and modeling advances in recent decades.

Literature Review

Chin et al. (2002) conducted research into developing "*a global simulation of aerosol optical thickness, τ, from the Georgia Institute of Technology—Goddard Global Ozone Chemistry Aerosol Radiation and Transport (GOCART) model*." This simulation model addresses all five of the main aerosols: sulfate, black carbon, organic carbon, dust, and sea salt, and some of their emission sources, primarily their anthropogenic sources. Through using this GOCART model, Chin et al. (2002) found that the "*physically and observationally-based aerosol emissions, along with the use of assimilated meteorological fields, have made the [GOCART] model suitable for comparisons with observations conducted at a wide range of spatial and temporal scales.*"

Duan and Song (2017) conducted research into how aerosol backscattering can affect a laser beam in fog in their paper *Influence of Atmospheric Aerosol Backscattering on Incoherent Frequency Modulation Continuous-wave Laser Ranging in the Fog*. In their research they used a frequency modulation continuous-wave "*laser ranging system… that operates with a static and cooperative target for distance from 1m to 15m*" (Duan and Song 2017). Through running this frequency modulation continuous-wave laser ranging system and using extensive mathematical calculations, Duan and Song (2017) were able to determine that "*the amplitude of backscattering signal [increases] as the visibility reduces from 100m to 15m.*"

Furthermore, Ahn et al. used "*linear regression analysis to estimate the CCN.*" The aerosol optical depth data that was used in Ahn et al.'s study was taken from ground-based observations, NASA's Moderate Resolution Imaging Spectroradiometer (MODIS), and NASA's second Modern-Era Retrospective analysis for Research and Applications (MERRA-2), which does not provide information on fine aerosols. Ahn et al. specifically focused on data from these three sources for the Antarctic region. Using these different aerosol optical depth data from these different sources, Ahn et al. determined that cloud condensation nuclei "*concentrations considerably depends on light-absorbing aerosols, demonstrating similar monthly variations with… [black carbon aerosol] concentrations.*"

Therefore, the literature demonstrates the importance of understanding the effects of aerosols on atmospheric processes and lasers and demonstrates the necessity for an aerosol database to help develop a deeper understanding of those effects.

Research Methods

My research methods include a literature survey on understating the state-of-the-art aerosol datasets available for HEL applications. I will utilize findings from this literature survey to develop a data fusion methodology for creating a new near-real-time aerosol database. This data fusion methodology combines model data and satellite observations to improve the spatial and temporal resolutions of the database. I will use NASA's Goddard Earth Observatory Composition Forecasting (GEOS-CF) and GEOS Forward Processing (GEOS-FP) model aerosol data and determine the aerosol extinction coefficients at each point in the model horizontal grid and then interpolate it to the existing HEL grid. Then I will scale the vertical profile of the resulting dataset using satellite observation data. The results can then be verified by comparing them to ceilometer observations.

Anticipated Challenges

One of the anticipated challenges for my research is storage. Since I am creating an aerosol climatological database, I am pulling a lot of data from MERRA-2 files and storing them in my own files. Large amounts of data require a large amount of storage, and so storage could be a potential challenge that I will face.

Another anticipated challenge is speed. Handling large amounts of data could potentially lead to my code needing more time to run.

Anticipated Results

One of the anticipated results for my research is a deeper understanding of aerosols and their effects on atmospheric processes, especially their effect on HEL systems. Another anticipated result of my research is the creation of a data fusion methodology for developing an aerosol database.

Abstract

Atmospheric aerosols play a vital role in the earth-atmosphere system, affecting cloud formation and radiative transfer. Aerosols also affect the propagation of radiation from anthropogenic sources, such as high-energy laser (HEL) weapon systems. Aerosol attenuates laser beams, and at times, the heat created leads to thermal blooming distorting the beam. Therefore, to design and operate HEL systems, information on the optical properties of atmospheric aerosol is crucial. Atmospheric aerosol information is available from multiple sources, including in situ, remote sensing observations, and chemical transport models. This research investigates combining information from two such sources (GEOS-CF, and GEOS-FP chemical transport models) and aerosol optical depth from GOES-16 satellite observations to develop a database for high-energy laser applications. This research also examines the utilization of Vaisala CL61 laser ceilometer observations from the Persistent Data Collection Site (PDCS) to evaluate such a product.

Introduction

Atmospheric aerosols are liquid or solid particles that are suspended in the air (Steiner et al. 2013) and "*range in size from about* 10^{-4} *μm to tens of micrometers and can be found in concentrations ranging from about* 10^{7} *to* 10^{-6} cm^{-3}" (Wallace and Hobbs 1977). Atmospheric aerosols can be categorized into two groups: primary aerosols and secondary aerosols (d'Almeida et al. 1991). Primary atmospheric aerosols are emitted directly into the atmosphere and can be from natural or anthropogenic sources (d'Almeida et al. 1991) (see Table 1). Some examples of natural primary sources include mineral dust, sea salt, biologically produced aerosols such as pollen, and volcanic aerosols such as ash and dust (Box and Box 2016) (see Table 1). Additionally, natural sources of secondary aerosols include gas-to-particle conversion of volcanic and biogenic gaseous sulfate emissions, natural NOx emissions and biogenic

Sources	Emissions (Tg/yr)	Lifetime (days)	Column Burden (mg/m^2)	Extinction Efficiency (m^2/g)	Optical Depth
Natural Primary					
Mineral	1500	4	32.2	0.7	0.023
Sea Salt	1300	1	7	0.4	0.003
Biological	50	4	1.1	2	0.002
Volcanic	33	4	0.7	2	0.001
Natural Secondary					
Sulphates from biogenic gases	90	5	2.4	5.1	0.013
Sulphates from volcanic SO_2	12	5	0.3	5.1	0.001
Organics from biogenic NMHC	55	7	2.1	5.1	0.011
Nitrates from NOx	22	4	0.5	2	0.001
Total Natural	**3060**		**46**		**0.055**
Anthropogenic Primary					
Industrial dust	100	4	2.1	2	0.004
Black carbon (soot, etc.)	20	6	0.6	10	0.006
Anthropogenic Secondary					
Sulphates from SO_2	140	5	3.8	5.1	0.019
Biomass burning (not black carbo	80	8	3.4	8	0.028
Nitrates from NOx	36	4	0.8	2	0.002
Organics from anthrop. NMHC	10	7	0.4	5.1	0.002
Total Anthropogenic	**390**		**11.1**		**0.061**
TOTALS	**3450**		**57**		**0.115**
Anthropogenic fraction	**11%**		**19%**		**53%**

Table 1: Sources and Characteristics of Aerosols. Taken from Table 5.1 from Box and Box (2016) and adapted slightly for clarity.

emissions of non-methane hydrocarbons (NHMCS) (Box and Box 2016) (see Table 1). In addition to the natural primary and secondary sources, there are also anthropogenic sources. Some examples of anthropogenic primary sources of aerosols include industrial dust and soot (Box and Box 2016) (see Table 1). Additionally, anthropogenic secondary sources of aerosols including gas-to-particle conversion of anthropogenic sulfate emissions, non-black carbon biomass burning, anthropogenic NOx emissions, and anthropogenic emissions of NHMCS (Box and Box 2016) (see Table 1). Furthermore, as can be seen in Table 1, there is variation in aerosol emissions–the amount of aerosol emitted into the atmosphere–and the aerosol lifetime–how long the aerosol stays in the atmosphere–depending on the type of aerosol.

Even though aerosols are quite tiny and constitute only a small fraction of the total mass of the atmosphere, they play a vital role in modulating atmospheric processes such as cloud formation and the propagation of radiation. Aerosols can function as cloud condensation nuclei, serving as sites for water to condense at a lower relative humidity than otherwise required by clean air (Wallace and Hobbs 1977). This leads to a higher probability of cloud formation when atmospheric aerosols are present. The amount of atmospheric aerosols can also affect the size distribution of cloud droplets. For example, as noted by Petzold and Kärcher (2012), the "*unperturbed cloud contains larger cloud drops as only natural aerosols are available as cloud condensation nuclei*." Perturbed clouds, or clouds affected by anthropogenically emitted aerosols, contain "*a greater number of smaller cloud drops as both natural and anthropogenic aerosols are available as cloud condensation nuclei*" (Petzold and Kärcher 2012). These clouds composed of a larger number of smaller cloud drops have "*a higher albedo than one with fewer, larger drops*" (Charlson et al. 2001) which means that they reflect more solar energy, indirectly affecting the energy received by the earth-atmosphere system. Additionally, the size distribution of cloud droplets influences the probability of rain formation. Due to the larger number of smaller cloud drops in heavily polluted clouds, it takes longer for the cloud drops to grow (Box and Box 2016), resulting in these clouds producing less rain. Therefore, aerosols play an important role in determining Earth's climate.

Additionally, aerosols also directly affect the propagation of radiation. Depending on size and composition, an aerosol can either scatter or absorb radiation (Steiner et al. 2013). Scattering is the deflection of radiation away from the beam path due to its interaction with an aerosol, while absorption is the removal of radiation from the beam due to its interaction with an aerosol. While these two processes are distinctly different, the net effect is a decrease in the amount of radiation reaching the target. The effectiveness of aerosols in scattering or absorbing radiation is dependent on both the composition and size of the aerosol relative to the wavelength of the radiation (see Figures 1 and 2). For example, sulfate typically scatters radiation, while black and

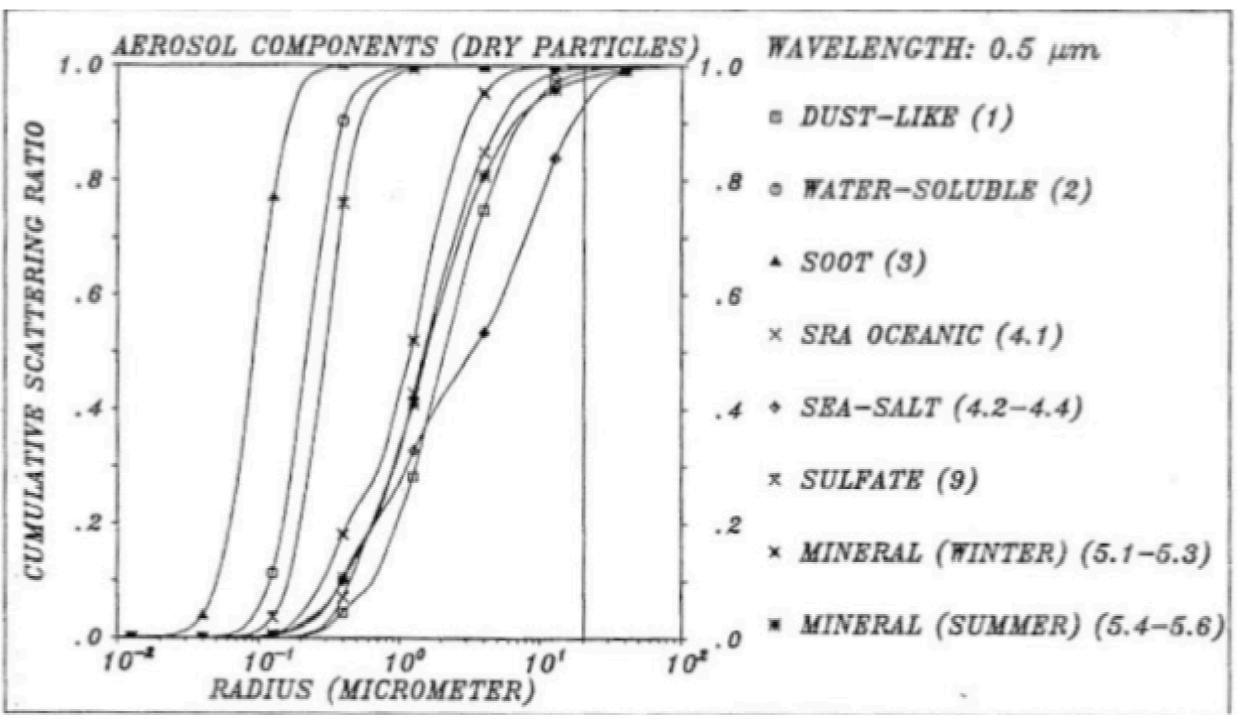

Figure 1: "*Cumulative scattering ratio of the aerosol components as a function of the particle radius for 0.500 µm wavelength*" (d'Almeida et al. 1991). This figure was taken from d'Almeida et al. (1991).

organic carbon typically absorb radiation (Steiner et al. 2013). Coefficients that quantify the

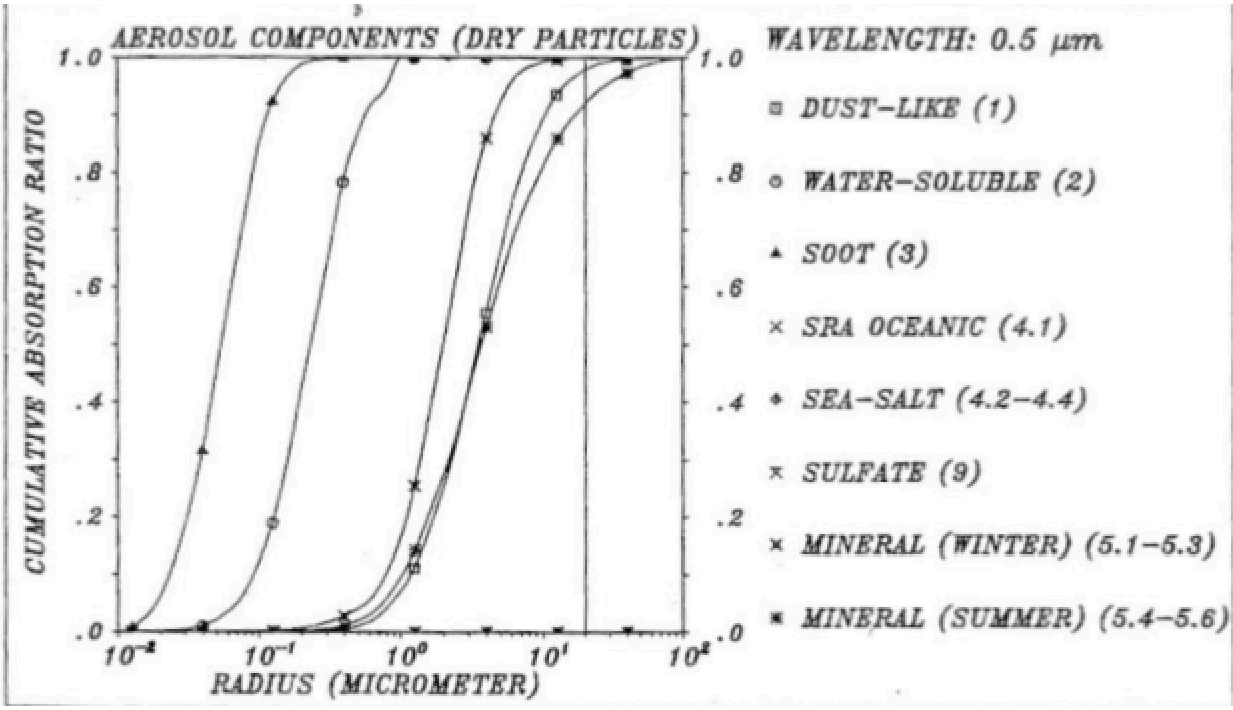

Figure 2: "*Cumulative absorption ratio of the aerosol components as a function of the particle radius for 0.500 µm wavelength*" (d'Almeida et al. 1991). This figure was taken from d'Almeida et al. (1991).

absorption and scattering effects of aerosols on radiation can be understood using Beer-Bouguer-Lambert's law.

Beer-Bouguer-Lambert's law describes how the intensity of a beam of radiation is modified when propagating a given distance through a medium (Liou 2002). Let $I_\lambda(0)$ be the initial intensity at the source and I_λ be the intensity after traveling through the medium over a distance s. Beer-Bouguer-Beer-Lambert's law is given by: $I_\lambda(s\ ) = I_\lambda(0) * exp(-\int_0^{s_1} k_\lambda \rho\, ds)$

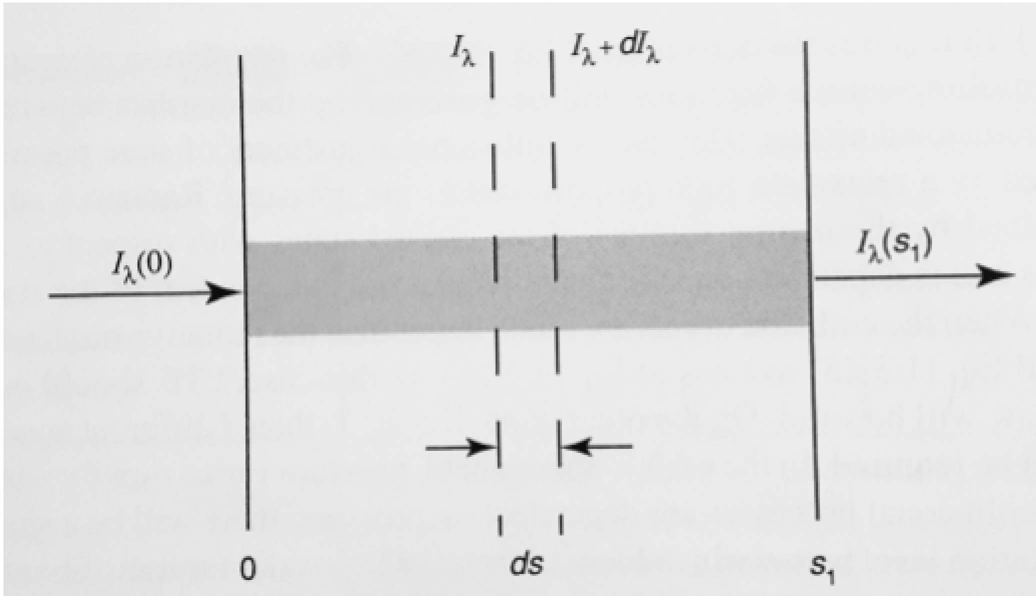

Figure 3: "*Depletion of the radiant intensity in traversing an extinction medium*" (Liou 2002). This figure was taken from Liou (2002).

where k_λ is the mass extinction cross section with units of m^2 kg^{-1} and ρ is the density of the medium (Liou 2002). This can be seen visually in Figure 3. Assuming uniform conditions over the propagation path, k_λ and ρ can be treated as constants. The integral term in the equation becomes $u = \int_0^{s_1} \rho \, ds = \rho s$ (Liou 2002), where u is the column burden associated with the medium and has units of kg m^{-2}. The product $k_\lambda * u$ is unitless and is usually called optical thickness or optical depth (τ). Beer-Bouguer-Lambert's equation, expressed in terms of optical depth becomes:

$$I_\lambda(s) = I_\lambda(0) * e^{-\tau}$$

Table 1 provides the typical values of mass extinction cross section, column burden and optical depth for the various types of aerosols.

Furthermore, the product of the mass extinction cross section and density results in the extinction coefficient, $\beta_{ext} = k_{\lambda}\rho$ which has units of m^{-1} (Liou 2002). Using this definition of β_{ext}, the Beer-Bouguer-Beer-Lambert equation can be written as:

$$I_{\lambda}(s) = I_{\lambda}(0) * e^{-\beta_{ext} s}$$

From the above equation, it can be seen that β_{ext} is a linear attenuation coefficient. Since change in intensity of the beam results from both scattering and absorption, β_{ext} can be expressed as a sum of the scattering and absorption extinction coefficients, β_{sct} and β_{abs} (Liou 2002).

Similar to how aerosols affect the propagation of solar and terrestrial radiation, they can also affect the propagation of man-made, active sources of radiation such as Lidars, optical communication systems, and directed-energy weapon systems (DEW). A DEW is a "*device that affects a target by focusing onto it a beam of electromagnetic energy or atomic particles*" (Karr and Trebes 2024). One type of DEW that is currently under development is the high energy lasers (HEL) systems. HEL weapons systems are DEWs whose "*emissions span a broad spectral range – from long-wave IR down to x rays or even gamma rays*" (Karr and Trebes 2024). Propagation of HEL is affected by atmospheric aerosols in the same way as other radiation propagation. And since a DEW "*requires pointing, tracking, beam control, and fire control*" (Karr and Trebes 2024), it is important to estimate the loss of energy from the beam caused by aerosol scattering and absorption. When absorbing aerosols are present, heating resulting from the absorption of energy can lead to the phenomenon of thermal blooming, which will further affect the propagation of the beam (Brown and Smith 1975). Thus, understanding the amount and speciation of atmospheric aerosols is crucial for research, development (R&D) and operational use of HEL systems. At present, the HEL system community relies on a coarse, climatological database for this purpose. Therefore, an aerosol database with near-real-time predictions of atmospheric aerosols is needed for HEL R&D and operations.

Currently, there are a variety of sources of information for aerosol properties. These include *in situ* measurement systems, ground- and space-based remote sensing sensor systems, and aerosol transport models. *In situ* measurements, which could be ground-based or airborne, quantify aerosol properties at a specific location or along a trajectory (Minikin et al. 2012). An example of an *in situ* system is, optical particle counters which "*have been designed to determine the concentration and size of aerosol particles which are optically active (at least approximately 0.1 µm in size)*" (Minikin et al. 2012). While *in situ* systems can provide detailed information about atmospheric aerosols, only a sparse network of these systems is currently available, and the majority of the measurements are made at the surface, and thus there is limited vertical information of the atmosphere from these systems. Remote sensing measurement techniques, which can be passive or active, are capable of inferring aerosol properties based on the sensing of electromagnetic radiation, acoustic waves, etc. with aerosols (Stephens 1994). Remote sensing is thus capable of inferring aerosol properties at locations far removed from the sensor system (Minikin et al. 2012). For example, the Geostationary Operational Environmental Satellite-16 (GOES-16) spectral measurements can be used to infer the aerosol optical depth (AOD) at a given geographical location (GOES-R Series Program Office). Satellites can only infer the total amount of aerosols present in an atmospheric column, and therefore there is a lack of information regarding how aerosols are vertically distributed. Furthermore, satellite sensor estimates of AOD are valid only under cloud-free conditions but are available at relatively high spatial and temporal resolutions (GOES-R Series Program Office). Chemical/aerosol transport models forecast atmospheric aerosols by incorporating natural and anthropogenic emission sources, secondary aerosol formation processes and transport and removal of aerosols due to atmospheric processes (Schmunk and Caims 2023). Models such as the NASA Modern-Era Retrospective analysis for Research and Applications-2 (MERRA-2) provide estimates of three-dimensional distribution of aerosols globally (Hendricks et al. 2012). However, spatial and temporal resolution model-derived aerosol properties are relatively coarse compared to the satellite-derived aerosol properties. They are also limited because of the assumptions regarding emissions and the errors in the prediction of atmospheric processes resulting from those assumptions.

All of the sources of atmospheric aerosol information discussed above have advantages and disadvantages. Data fusion, or the combining of different data sources to improve spatial and temporal resolution, could be used to incorporate the advantages offered by different sources of information. Therefore, this is the approach utilized for developing the aerosol database for HEL R&D and applications.

My capstone research includes: 1) gaining knowledge about atmospheric aerosols in the context of HEL R&D and applications and; 2) developing methodologies and software for implementing specific aspects of data fusion methodology used for developing the HEL aerosol database.

Data and Methods

The data fusion method is utilized to develop the aerosol database for HEL applications. Data fusion methodology combines outputs from multiple aerosol transport models with remote sensing observations such as satellite datasets to get higher spatial and temporal resolutions. One of the observational sources used to evaluate the aerosol database is a Laser ceilometer. Datasets relevant to this capstone research and an overview of the data fusion used are provided in the subsections below.

Aerosol Model Outputs

Aerosol transport models "compute aerosol distributions from source emissions using prescribed meteorological fields to calculate aerosol transport, mixing, transformation, and deposition" (Schmunk and Caims 2023). Several aerosol transport models that provide operational forecasts exist, which are listed in Table 2. The first two models highlighted in Table

Model	Horizontal grid spacing
NASA GEOS-CF	25 km x 25 km
NASA GEOS-FP	30 km x 30 km
NOAA GEFS-Chem	25 km x 25 km
NOAA GEFS-Chem	50 km x 50 km
FMI SILAM	35 km x 35 km
ECMWF CAMS-CF	40 km x 40 km
NAVY NAAPS	100 km x 100 km
NCAR WACCM	100 km x 100 km

Table 2: Different models and their spatial resolution. This table was taken from U. Nair et al. (2024, accepted presentation).

2 have the best horizontal spatial and temporal resolutions and will be used for the development of the initial version of the aerosol database. The NASA GEOS-CF (NASA Goddard Earth Observing System Composition Forecasting) model "*provides global near real-time estimates ('hindcasts') and forecasts of atmospheric composition such as ozone (O_3), carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and fine particulate matter ($PM_{2.5}$)*" (Keller

et al. 2021). This model has a spatial resolution of 25 km x 25 km (Table 2) and has "*15-minute and 1-hour temporal resolution*" (Knowland et al. 2020). Additionally, the NASA GEOS-FP (NASA GEOS Forward Processing) model has a spatial resolution of 30 km x 30 km (Table 2) and has 1-hour and 3-hour temporal resolution (Lucchesi 2018). The aerosol component of NASA's second Modern-Era Retrospective Analysis for Research and Applications (MERRA-2) uses the GEOS-5 model system, but generates offline reanalysis of aerosol fields (Bosilovich et al. 2016). As Randles and Da Silva (2020) note, MERRA-2 "*provides observationally-constrained aerosol optical depth from 1980 - present, with aerosol speciation determined from GOCART model.*" MERRA-2 aerosol reanalysis is on a 50 km x 50 km spatial resolution and 1-hour, 3-hour, and 6-hour temporal resolution (Bosilovich et al. 2016).

Satellite Observations

Additionally, we are also using the Geostationary Operational Environmental Satellites 16 (GOES-16) aerosol optical depth (AOD) product. This product "utilizes several spectral wavelengths of the ABI (Advanced Baseline Imager) to measure the reflectance properties of cloud-free pixels at the top of the atmosphere (TOA)" (GOES-R Series Program Office). The column aerosol amount is retrieved from the reflected top-of-the-atmosphere spectrum observed by the satellite sensor (GOES-R Series Program Office). This product has a 2 km x 2 km spatial resolution and a 5-minute temporal resolution (Fu et al. 2023)

Laser Ceilometer

In this study, we are using the Vaisala CL61 ceilometer hosted at the Persistent Data Collection Sites (PDCS). A laser ceilometer is a sensor that uses "*LIDAR (Light Detecting and Ranging) technology for the detection of clouds, precipitation and other obstructions to vision*"

(Wolfe 2011). The Vaisala ceilometer CL61 emits "*linearly-polarized laser pulses*" (Vaisala 2021), and some of that energy will be scattered back to the sensor due to its interaction with cloud drops and aerosols in the atmosphere (Vaisala 2021). The backscattered energy and the state of polarization is detected by the sensor (Vaisala 2021). Based on this information, the backscattering coefficient of the material (units of srad per mega kilo meter) and the nature of the scattering material (solid, liquid, ice, mixed phase) is retrieved.

Data Fusion Methodology

Our data fusion methodology is depicted in Figure 4. As Figure 4 shows, the general flow

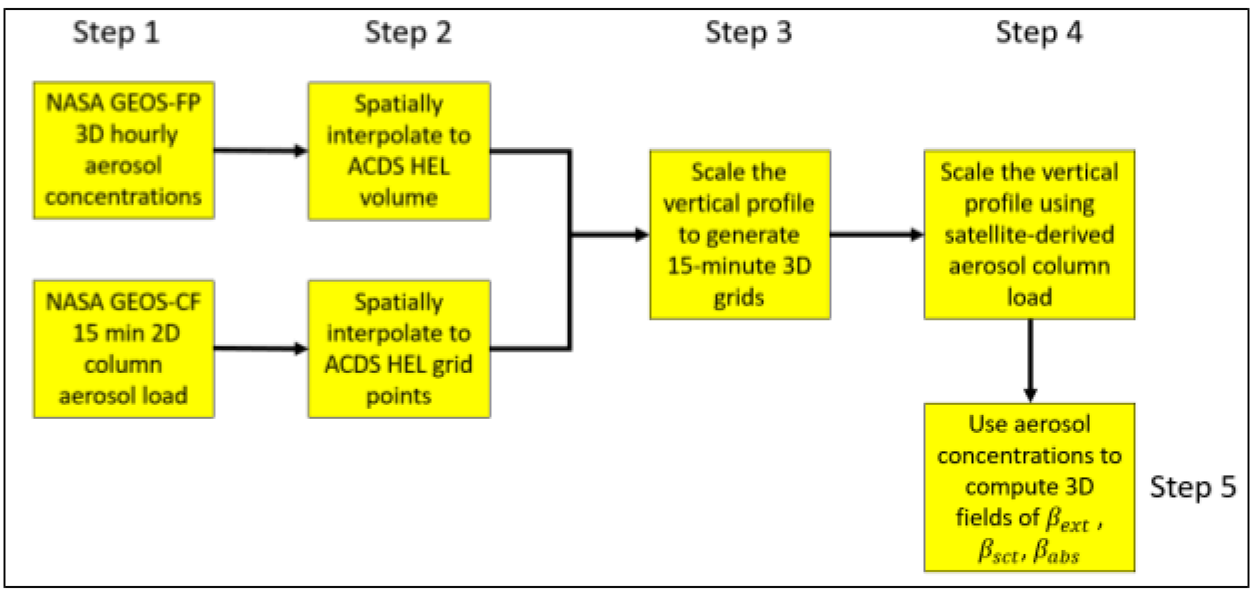

Figure 4: Data Fusion Methodology for combining different model datasets and satellite datasets. This figure was taken from U. Nair (2024, accepted presentation).

of our data fusion method is to first collect the model data, then interpolate that data to a pre-existing grid, then interpolate the data vertically, and then use the aerosol concentrations at each grid point and height to calculate β_{ext}, β_{sct}, and β_{abs}. My role in this data fusion process is primarily steps 2, 4, and 5.

Results

To create the aerosol database, the data fusion approach discussed in the previous section is used, and then ceilometer observations are used to validate these results. As discussed in the previous section, there are five steps to our data fusion methodology. My capstone research focused on: 1) developing an understanding of atmospheric aerosols; 2) developing a methodology for computing aerosol optical properties and interpolating them to a defined HEL engagement volume; 3) learning how to operationally access GOES aerosol datasets and process the data and; 4) learning how to access and process laser ceilometer data. The understanding I gained about atmospheric aerosols is documented in the introductory section. The following sections detail the results for the other objectives.

Implementing Spatial Interpolation of GEOS-CF and GEOS-FP Datasets Interpolation

We are interpolating the GEOS-CF and -FP horizontal grids to the HEL horizontal grid.

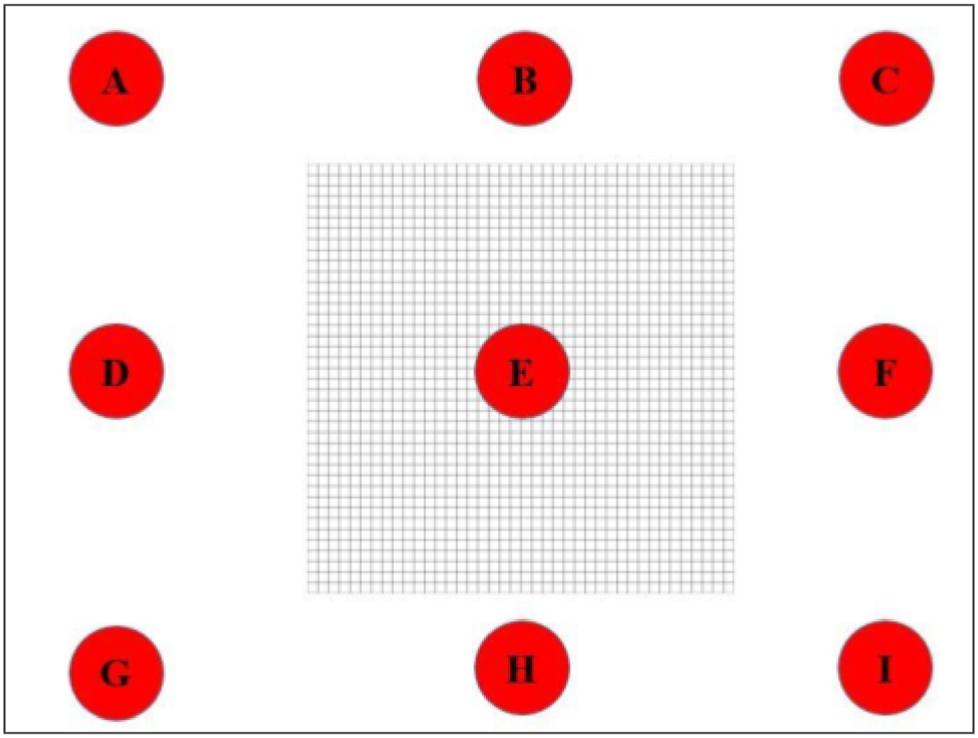

Figure 5: GEOS-FP grid points (red circles) overlaid on the HEL grid (center square grid). This was created by U. Nair (2024, personal communication).

To do this, a plot is made of the HEL grid with the GEOS-CF or GEOS-FP grid points overlaid on top (Figure 5). At any given point, the 20 km x 20 km HEL data grid will fit inside a three-point by three-point GEOS-FP grid with the center point (point E in Figure 5) corresponding to the point (i, j), where i is the row, and j is the column. The other GEOS-FP grid points can then be determined by adding or subtracting 1 from i or j. For example, point A is the point (i + 1, j), and point H is the point (i, j - 1). The values i and j relate to the longitude and latitude by the equations $i = \frac{\lambda_i + 180}{(\Delta\lambda)_n} + 1$ and $j = \frac{\varphi_j + 90}{(\Delta\varphi)_n} + 1$, respectively, where λ_i is the longitude, φ_j is the latitude, $(\Delta\lambda)_n = (5/16)°$, and $(\Delta\varphi)_n = (1/4)°$ (Lucchesi 2018). Once i and j are determined, we use a

Python code I wrote to pull the aerosol concentration and the relative humidity at each point. Using the relative humidity data and Figure 6, we can determine the mass absorption coefficient

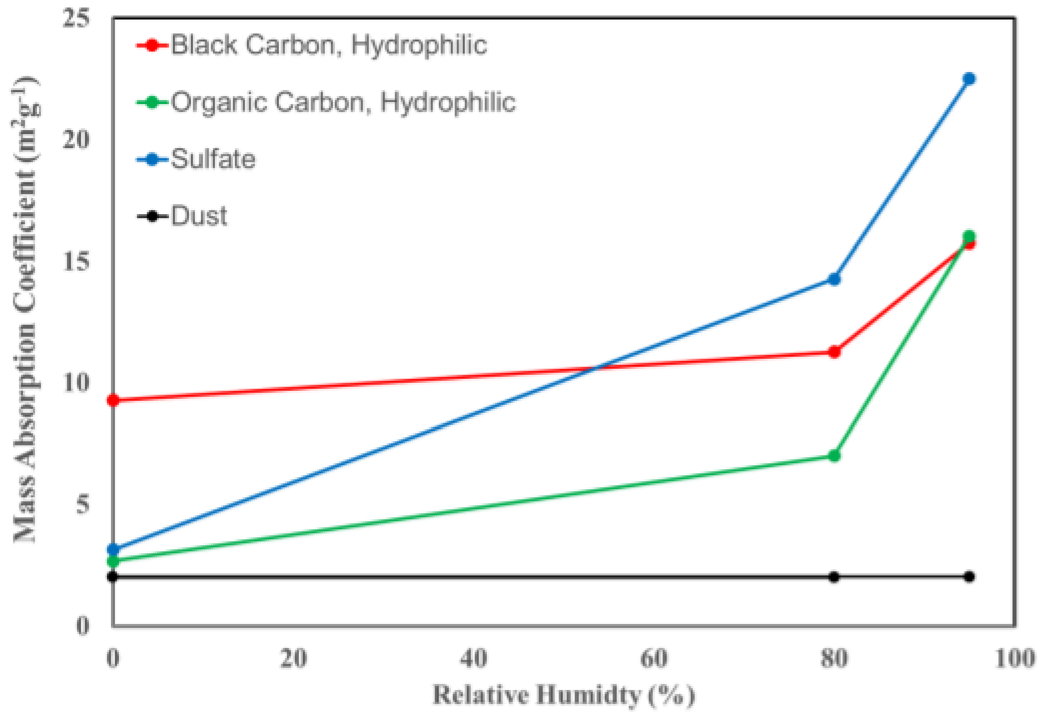

Figure 6: Mass absorption coefficient of different aerosols at different relative humidity values. This was taken from U. Nair et al. (2024, accepted presentation).

for any of the four listed aerosols. Then we can multiply that mass absorption coefficient by the aerosol concentration to calculate the β_{abs} at each point. The process is similar for calculating β_{ext} and β_{sct} as well. Once β_{abs}, β_{ext}, and β_{sct} have been found at each point, the data can then be interpolated onto the 20 km x 20 km HEL grid using the NumPy interpolation method. This horizontal interpolation process is then repeated at each vertical level in the GEOS-CF or GEOS-FP dataset.

After the data is horizontally interpolated at each vertical level in the GEOS-CF or GEOS-FP dataset, it is then vertically interpolated to specified height levels for the HEL volume.

Similar to how we calculated the horizontal interpolation, we are using the NumPy interpolation method to vertically interpolate the data as well.

An example of a curtain plot of an aerosol without any interpolation is shown in Figure 7.

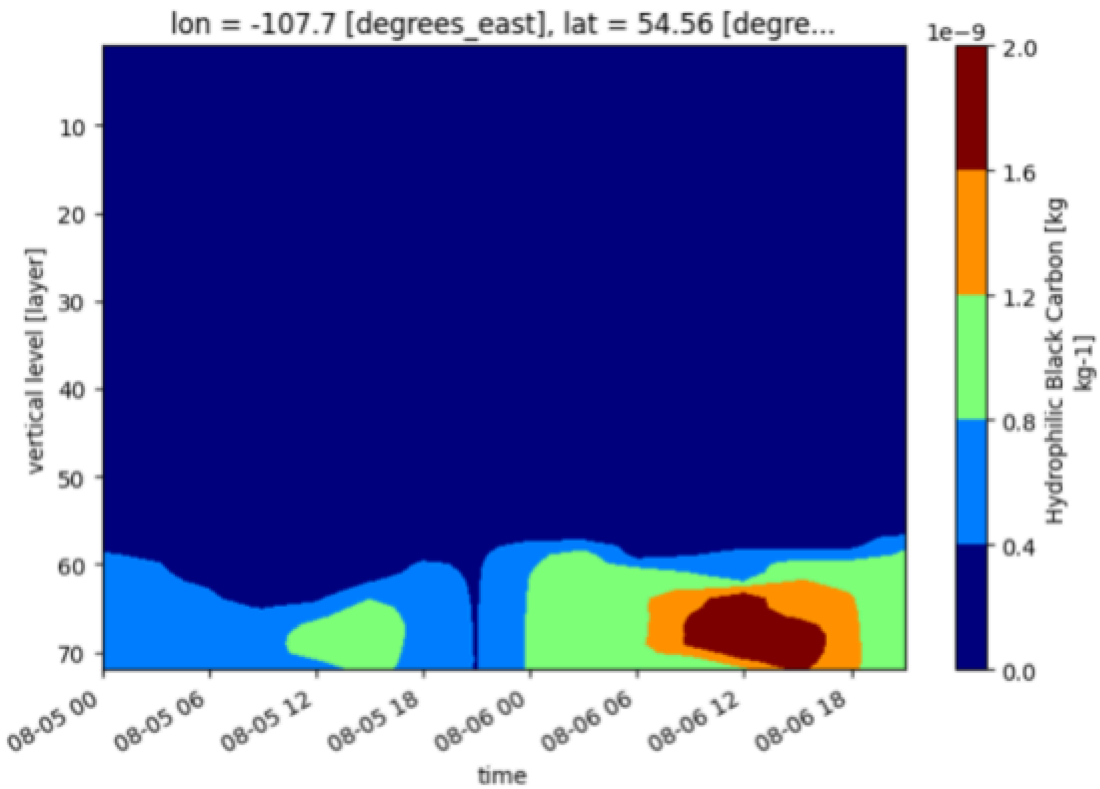

Figure 7: Curtain plot of hydrophilic black carbon mixing ratio before interpolation. Taken from U. Nair et al. (2024, accepted presentation).

GOES-16 AOD Plots

Since we want to scale the vertical profile of our database using GOES-16 data, I was tasked with writing a Python code for pulling the AOD observations from the level two full disk GOES-16 (ABI-L2-AODF) product. My Python code uses Amazon Web Services to pull this AOD data. I am then able to plot this AOD data as well (Figures 10 and 11).

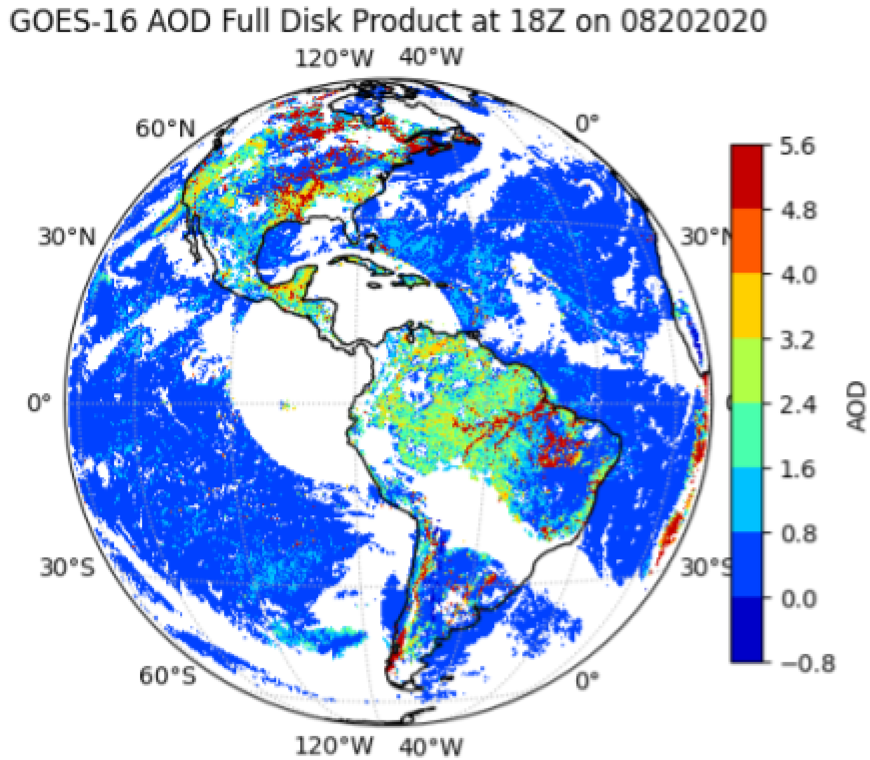

Figure 10: Plot of the GOES-16 full disk AOD product at 18Z on August 20th, 2020. The data to create this plot was pulled using Amazon Web Services in Python.

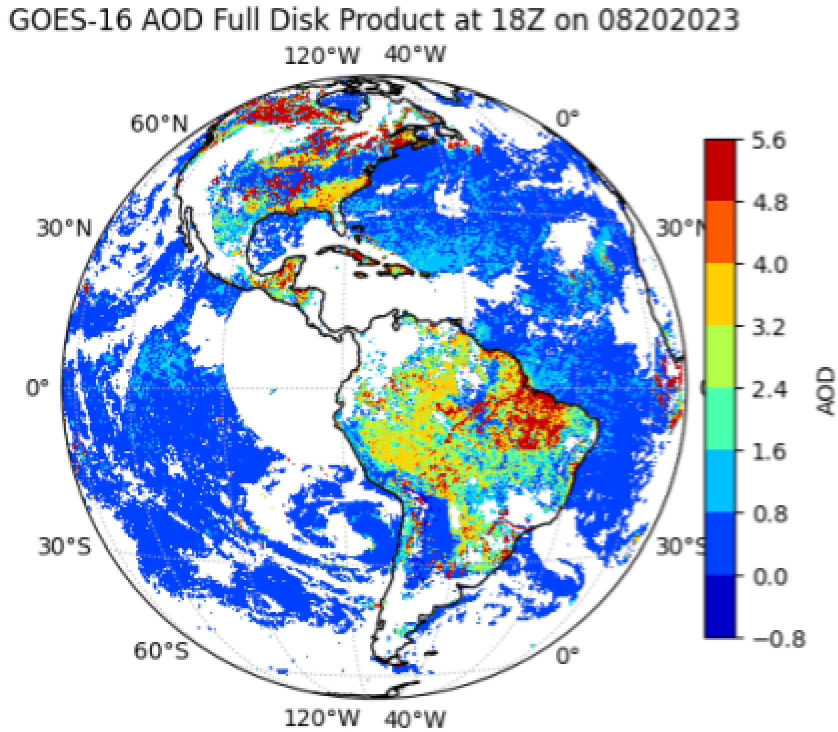

Figure 11: Plot of the GOES-16 full disk AOD product at 18Z on August 20th, 2020. The data to create this plot was pulled using Amazon Web Services in Python.

In these plots, the white spaces indicate clouds since the GOES-16 ABI-L2_AODF product measures cloud-free pixels (GOES-R Series Program Office). The perfect circle represents areas where aerosol retrieval cannot be conducted due to the presence of sun glint (Huff 2022).

Discussion

Using the methodology discussed in the previous section, we will be able to execute the horizontal and vertical interpolation of the MERRA-2-derived β_{ext}, β_{abs}, and β_{sct} onto the HEL grid. After interpolating the data, we will then need to scale the vertical profile of the database using satellite data from the GOES-16 ABI-L2-AODF product. Once we have completed these tasks, we can use observations, such as observations from the PDCS ceilometer, to verify our aerosol database results.

Conclusion

During this research, I have developed a deeper understanding of atmospheric aerosols, specifically how aerosols interact with radiation and the quantification of the attenuation effect. I have developed knowledge and skills to extract aerosol characteristics from global models and compute aerosol optical properties for HEL R&D and operational applications. I also developed programming skills (Python) for creating the collection of operational aerosol model datasets, computing aerosol optical properties, and interpolating it into a specified HEL engagement volume grid. I have also developed knowledge and skills for accessing and utilizing GOES-16 AOD data for scaling three-dimensional aerosol fields, such as aerosol extinction coefficient. Furthermore, I have developed an understanding of the working principles of a laser ceilometer, unpacking observations from the instrument and generating plots of the observations. My undergraduate research has given me a firm footing to continue working on aerosol research for HEL application.

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