Retrieval algorithms for remote spectroscopic mapping of Earth's mineral dust sources

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Abstract

In order to better characterize the mineralogical composition of atmospheric dust, NASA's Earth Surface Mineral Dust Source Investigation (EMIT) mission is currently developing a spectrometer for deployment on the International Space Station. Professor Natalie Mahowald, of the Cornell Department of Earth and Atmospheric Sciences, is a member of the mission's science team. Since the fall of 2017 I have been working under Professor Mahowald on dust-related projects. This summer, I will travel to the Jet Propulsion Laboratory in Pasadena, California to work with Dr. David Thompson, another member of the science team, on error propagation in EMIT data.

Specifically, we will investigate algorithms for atmospheric correction and mineral identification with particular emphasis on the errors they incur. We will be interested in ensuring that algorithms are robust and numerically sound. In addition, we will study the propagation of measurement and numerical errors through future modeling applications of the data retrieved, and characterize how these errors will effect downstream computations of dust radiative forcings performed based on these data.

Biographical Information

I am a junior hailing from Lawrenceville, New Jersey, majoring in mathematics with an outside concentration in computer science. Before I came to college, I wrestled a great deal with the decision between a more theoretical course of study in mathematics and a more applied trajectory in engineering. Ultimately, I settled on the former, but I retain a serious interest in applied mathematics. In particular, since arriving at Cornell I have developed an enthusiasm for numerical and scientific computing, disciplines based on profound theoretical notions but also relevant to myriad fascinating applications.

One such application is the simulation of Earth's climate. In the fall of my sophomore year, I began working under Professor Natalie Mahowald, whose research is in computational climate modeling. Learning the scientific and methodological ropes of our work as well as of academic research in general has been an invaluable experience. I also appreciate the broader impact of work in climate science – the field uses the mathematical and scientific concepts about which I am passionate to address issues of the utmost importance. Subsequent to the start of my work with Professor Mahowald, I decided to pursue a minor in atmospheric science.

Outside my technical undertakings, I am an active trumpet player and pianist in a number of jazz groups at Cornell, including the Cornell Jazz Ensemble and the Original Cornell Syncopators. I am the publicity chair for Jazz+, the student organization devoted to arranging jazz concerts and performance opportunities around campus. I also have an amateur interest in languages and linguistics, and I am completing a minor in French.

Statement of Purpose

Suspended throughout Earth's atmosphere is particulate matter referred to by atmospheric scientists as aerosols. Aerosols vary greatly in size and chemical composition and originate from both natural and anthropogenic sources. Typical aerosol species include desert dust, sea salt, sulfates, and carbon from organic matter and combustion. Aerosols influence climate behavior far more than what might be expected, given that they constitute only a small proportion of the mass of the atmosphere [1]. For this reason there is a large body of scientific research on the role aerosols play in the Earth system.

Of particular concern are the radiative forcings caused by aerosols – that is, the effects they have on incoming and outgoing radiation in the atmosphere. These forcings are often complex and can involve intricate environmental feedbacks, and there is uncertainty in estimates of their magnitudes and sometimes even of their signs – whether the net effect is one that cools or warms the atmosphere [2]. Aerosol radiative forcings may be direct, wherein the particulate absorbs or scatters radiation in a manner that affects the energy balance. Aerosols can also affect the formation of clouds as well as their microphysical properties, thereby causing indirect effects. Soot induces yet another type of forcing by darkening snow and ice and reducing the reflectivity of snow-covered regions [2].

It is worth noting that many of the radiative effects caused by aerosols cool rather than warm the atmosphere, and such forcings could partially mitigate the increase in global temperatures due to anthropogenic climate change [2], especially given that aerosol effects are likely on the same order as the warming induced by carbon dioxide [1]. However, some aerosol species are harmful to human health and the environment. In the future there will therefore likely be initiatives to reduce emissions of these species, potentially elevating global temperatures. Still other aerosol forcings have a warming effect outright. It follows that better quantifying aerosol radiative effects will be critical to understanding of and responses to global warming.

Such quantification is often performed using sophisticated computer models of the Earth and its atmosphere, like the Community Earth System Model (CESM). These models permit researchers to simulate climate behavior while changing properties of the aerosols involved – how much particulate there is, where the source regions are, and even whether certain species are present at all. Since climate models emulate the atmospheric radiation balance, the differences between simulations with differing aerosol properties can lead to conclusions about the radiative forcings that aerosols cause [3].

Of course, this approach is predicated on the accuracy of the models in simulating the climate response to changing aerosol conditions. Earth system models rely on high-quality observational data, among other factors, to perform well. The purpose of such data is twofold. First, models use observational datasets to initialize simulations – for example, the magnitude and frequency of carbon emissions might be passed into the model from a dataset. Second, model simulations must be validated against observed climate behavior, so that model parameters may be tuned to better reflect the natural world.

In particular, the quantification of the radiative forcings caused by desert dust aerosols necessitates data on its mineralogical composition, as studies have found that the interactions between dust and radiation are governed in large part by the mineral makeup of the dust involved [4]. These data may be obtained through a network of on-the-ground monitoring stations. However, this solution may be impractical in many dust source regions, often remote or lacking in requisite scientific infrastructure. An alternative method is the use of remote sensing equipment – instruments on satellites capable of determining this mineralogical information from space.

To this end, NASA's Earth Surface Mineral Dust Source Investigation (EMIT) mission is currently developing a spectrometer for deployment on the International Space Station. The goal of the mission is to characterize the composition of dust aerosols by spectroscopically determining the mineralogy of dust source regions. EMIT will take in light reflected by arid regions across a wide range of wavelengths, and use the differences between these images to make inferences about the minerals present. Similar instruments have been successfully employed from aircraft, but there remains significant uncertainty in extant dust mineralogy data. EMIT will combine fine spectral resolution – the capacity to make distinctions between wavelengths – with sufficient coverage of relevant regions to produce a comprehensive dust emission mineralogy dataset [5].

This summer, I will travel to Pasadena, California to work with Dr. David Thompson, a member of the EMIT science team and a researcher at the NASA Jet Propulsion Laboratory, on algorithms and error analysis for the EMIT mission. Broadly, we will seek to investigate and constrain the propagation of errors throughout the entire lifetime of the data EMIT will retrieve, taking into particular consideration algorithms for atmospheric correction and mineral identification.

Vegetation as well as gases and other atmospheric constituents interfere with the light reflected off of target minerals on the ground before it reaches the spectrometer. Atmospheric correction algorithms seek to account for this interference and recover the original signal [6]. A study by Thompson et al. (2018) demonstrates mathematically elegant and numerically sound methods of using prior knowledge in tandem with correction algorithms to produce statistical estimations of the error therein [6]. We will explore the use of this approach on the EMIT mission. After atmospheric correction, the recovered signal needs to be analyzed to identify spectral features characteristic of particular minerals. EMIT will likely use the Tetracorder identification system [7] or some adaptation thereof, so we will focus on pipelining atmospheric correction and mineral identification algorithms to yield a data product usable by climate models.

Our overarching goal in the study of these algorithms, and the ultimate objective of my work this summer, will be the analysis of error propagation throughout the system. In other words, we will seek to rigorously estimate and keep track of the error incurred at each step. Moreover, we will run simulations using a single column model – a reduced climate model that operates solely in the vertical dimension – to determine how much the error propagated through the EMIT system will ultimately affect our estimations of the dust radiative forcing.

We will thus gain a clearer view of how much measurement error is acceptable given the level of uncertainty we are willing to permit in our radiative forcing computations. In addition, we will be better equipped to understand and constrain the error in the dust radiative forcing simulations that will eventually be run using EMIT data.

I will begin familiarizing myself with use of the single column model this semester in Ithaca, and then over the summer at the Jet Propulsion Laboratory I will further develop an analysis of error propagation in light of the algorithmic techniques EMIT will use. I will therefore benefit from both Professor Mahowald's expertise in climate models and Dr. Thompson's background in spectroscopy. Under Professor Mahowald's guidance, I hope to present the work I do on the EMIT project in a senior thesis next year.

References

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