Final Report

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Title: Improving prediction of climate radiative forcing of atmospheric mineral dust using the CALIPSO space lidar data in conjunction with passive remote sensing and modeling

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Project Summary

The main goal of this project is to gain a better understanding of the properties and spatio-temporal distribution of atmospheric dust required for improved predictions of dust radiative forcing on climate by capitalizing on the new data provided by the CALIPSO, CloudSat, and solar and IR passive satellite sensors of the A-Train mission. Our strategy is to perform an in-depth study to explore the potential of the CALIPSO lidar and infrared imager in characterizing atmospheric dust and to develop a novel capability for integrating passive and active remote sensing observations of the A-Train mission in the dust-laden conditions enabling studies of dust radiative impacts as well as dust-cloud interactions. The objectives are as follows:

i) Develop new regional dust models by incorporating recent (new) data on region-dependent size-resolved composition (especially the new data on the iron oxide content) into optical modeling. New types of regional dust models that will predict dust optical properties from solar to IR wavelengths in a consistent fashion will be constructed.

ii) Perform extensive forward modeling to investigate the effects of dust particles on the scattering phase function, aerosol extinction-to-backscattering ratio, and lidar depolarization at the 532 and 1064 nm CALIPSO lidar wavelengths. Incorporate the regional dust models into the CALIPSO research retrieval algorithm and assist in the development and testing of the CALIPSO operational algorithm in the dust-laden atmospheric condition.

iii) Develop a methodological framework for merging the CALIPSO lidar and infrared imager data for discrimination of dust from clouds and retrieval of the effective dust particle size;

iv) Investigate how the distinct regional properties and vertical distribution of atmospheric dust affect its radiative impacts (such as top-of-the-atmosphere and surface radiative forcing, and radiative heating and cooling rates in cloud-free and cloudy atmospheric conditions) by analyzing CALIPSO lidar and infrared imager observations in conjunction with the newly developed regional coupled dust modeling system WRF-DuMo and selected data provided by the A-Train sensors. The study is focused on analyzing and contrasting Asian vs. Saharan dust.

Summary of Major Accomplishments:

1) Much effort has been devoted to improve the modeling capability for the prediction of optical properties and radiative effects of non-spherical, complex aerosol particles such as mineral dust. To aid in the interpretation of CALIPSO data, a detailed modeling of optical properties (lidar ratio, depolarization ratio, single scattering albedo, etc.) of non-spherical dust particles was performed using the most recent measurements of size distributions, mineralogical composition, and particle morphology. This modeling was performed by combining the T-Matrix code and an improved geometric optics method (IGOM) code (a newer version of IGOM was provided by Dr. Yang). The combination of these codes enables computation of dust optics for a broad range of particle sizes but under the assumption of spheroids. Using the DDA and T-Matrix/IGOM code, we have performed intensive optical modeling to examine the effects of fine and coarse modes, mineralogical composition, and types of the spheroid mixture on lidar variables (lidar ratio and particle depolarization). In particular, we examined the extent to which the selection of the spheroid mixtures for representing dust aerosols affect the optical characteristics that are used in lidar remote sensing and modeling the dust radiative impact (Choi and Sokolik, 2010). The dust mixtures were selected by considering different approaches that were either used by past studies or constrained by recent measurements of dust particle shapes. Our modeling results provided important insights on how dust particle properties and their changes can affect lidar remote sensing. For instance, we demonstrated that the lidar ratio, S, and particle linear depolarization ratio, LD, have very different sensitivity to the fine and coarse dust modes and the particle nonsphericity. For considered cases, the lidar ratio varied between 10 and 100 sr while LD shows little variability (from ~0.2 to 0.3). Therefore, the varying lidar ratio will need to be used instead of a current fix value for dust in the CALIPSO aerosol retrieval algorithm. Overall, the results of our optical modeling will contribute to improved retrievals of dust in the follow-up version of CALIPSO retrieval algorithms.

2) We have completed a comprehensive analysis of the CALIPSO data (both version 2 and version 3 for 2007-2010) to characterize the spatiotemporal dynamics of Asian dust and associated changes in dust radiative impacts. The focus was on determining the representative vertical distribution of Asian dust in the major dust sources (the Taklamakan region vs. the Gobi region), and during the mid- and long-range transport. The CALIPSO data were analyzed on a case-by-case basis that is all individual orbit segments in dust-laden conditions in the region of interest were pre-selected and then analyzed one-by-one in conjunction with A-Train satellite multi-sensor observations (OMI, MODIS, and MISR) as well as ground-based observations. We

used data from the WMO meteorological stations located in China, Mongolia, Korea, and Japan which report present weather types, including several dust weather types. Our analysis was targeted at two main goals: 1) examine the capability of the CALIPSO lidar (CALIOP) to discriminate between aerosols and clouds and identify dust among other aerosol types, and 2) characterize dynamics of the spatiotemporal distribution, properties and radiative impact of Asian dust.

With respect to the first goal, we demonstrated that CALIOP is capable of detecting mineral dust in the dust sources as well as downwind. However, various problems in the detection algorithm were found, especially in the case of heavy dust loadings (e.g., misclassification of dust as a cloud). Also, retrievals of aerosol optical depth, AOD, were found to be biased low in the Version 2 data. Biases found in Version 2 data products were reported to the CALIPSO team (Dr. Winker, the PI) and appropriate corrections were made in the newer Version 3 data. Still analyses of Version 3 products revealed some remaining problems with dust discrimination from clouds. Our results stress the importance of independent data that must be used to verify the detection of dust with CALIOP, especially in dust-cloud mixed conditions.

Our analyses of the dynamics of Asian dust and radiative impacts demonstrated that vertical and horizontal distributions of Asian dust optical properties in the source regions are highly variable compared to low variability found in the case of Saharan dust. However, in both cases large values (up to 0.35) of the particle linear depolarization ratio were measured by CALIPSO, confirming the significant effect of dust nonsphericity. We found that during mid-range transport the depolarization ratio of Asian dust can remain as high as in the source region (~0.35) or be much lower (~0.1), pointing to the existence of different mechanisms that control the aging of Asian dust during the mid- and long-range transport. The vertical profile of Asian dust was found to be more complicated and variable compared to transported Saharan dust that often forms well-defined layers in the atmosphere. Based on our computed dust optical characteristics and CALIPSO and other analyzed data, the range of dust radiative impact (including forcings at the top and bottom of the atmosphere, and heating/cooling rates) were computed for representative cases of 3D Asian dust fields. These results provide a better understanding of how Asian dust affects the radiation at the local to regional scales. They also provide important constraints for regional transport models and help to improve treatments of dust in GCMs. The results of this work were presented at several scientific meetings (e.g., Choi et al. 2007, 2008, 2010, Sokolik et al. 2008, 2009) and submitted for publication (Choi et al. 2010).

In addition, CALIPSO orbit segments over the world's arid and semi-arid regions were analyzed in conjunction with other satellite data to determine the similarities and regional specifics of dust spatiotemporal fields (Sokolik et al. 2010). We found some distinct regional features in the vertical profile of dust in different dust sources that might help to constrain the dust lifting height in the models leading to more realistic representation of dust transport. Our analyses also confirmed the existence of the region-specific IR dust signature based on data from the CALIPSO IR sensor and AIRS (Kalashnikova et al. 2008).

3) We have been working on development of new approaches for integrating CALIPSO lidar data with a regional transport model. The goal was to determine the extent to which CALIOP and passive remote sensing data can be used to improve representation of dust in the regional and global models. The modeling component involved the coupled regional dust modeling system WRF-Chem-DuMo (Sokolik et al. 2009, 2010). This model has the advanced capability for predicting the 3D dust fields and radiative properties in support of the A-Train observations. The WRF-DuMo model was driven by NCEP reanalysis data to reproduce actual dust events occurred in East Asia. We examined how the modeled 3D fields are affected by the choice of the dust emission scheme, initial dust size distribution, and entrainment heights. The modeled dust fields were compared against individual satellite products (OMI AI, MODIS AOD, and CALIPSO vertical AOD) as well as their combinations. To overcome the inherit limitations of satellite products and model biases, we have developed a new framework for the probabilistic characterization of the 3D dust fields (Darmenov et al. 2008, Sokolik et al. 2009, 2010). We introduced the notion of an ensemble 'modeled dust index' (MDI), which provides a new measure for probabilistic characterization of the spatiotemporal dust distribution predicted with a transport model. Modeled fields are then constrained against observations (including visibility, aerosol optical depth, and CALIPSO vertical profiles) to provide 3D dust fields with assigned confidence level. In particular, this approach was applied to test the predictions of air quality degradation caused by dust storms in which separation between dust loads in PBL from dust aloft is a major issue (Darmenov et al. 2010).

4) CALIPSO data along with other aerosol, cloud and precipitation satellite products were used to study the impact of dust on tropical cyclones (Zhang et al. 2010). In particular, the effect of Saharan dust acting as cloud condensation nuclei (CCN) and ice nuclei (IN) on the early development of Hurricane Helene (2006) was examined by performing numerical simulations with the Weather Research Forecast (WRF) model constrained by satellite data. Satellite data were also used to assess the model performance and aid in the model result interpretations. The results showed that the presence of dust tends to promote ice formation at lower altitudes in

strong updraft cores, increase the local latent heat release, and produce more low clouds and less high clouds. The inclusion of dust acting as CCN and IN modified the storm intensity, track, cloud top temperature, precipitation and latent heat distribution. However, no monotonic dependence of storm intensity, latent heating rate, and total precipitation on the dust concentration was found. This study suggests that a large amount of dust acting as CCN and IN has the potential to modify the early development of a tropical cyclone.

Publications and presentations resulted from full or partial support from this grant:

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