FINAL REPORT

Period covered 2007-11

Title: Impact of Aerosols on the Arctic Hydrological Cycle

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Project Summary

This project is an interdisciplinary effort that integrates studies of aerosol, clouds, precipitation, atmospheric dynamics, surface energy balance, and surface snow characteristics. The goal is to develop an understanding of the interactions and feedbacks associated with aerosol forcing of the arctic hydrological cycle. This goal is accomplished through a synthesis of surface-based and suborbital observations and regional modeling activities being undertaken during the IPY in conjunction with A-Train observations. Specific objectives of the proposed research are:

1) Evaluation of A-Train data products associated with aerosols, clouds, precipitation, and surface energy balance using ground based measurements near Barrow, AK, and other sites in Canada, Europe, and Russia at which data will be available during the IPY period;

2) Integrated analysis of the relevant A-Train data with surface-based and suborbital data to address the overarching science question targeted by this proposal;

3) Evaluation of the regional modeling capability being developed under the PI's NASA MAP project for the different regions in the Arctic;

4) Implementation of sensitivity studies by perturbing aerosol characteristics for the different regions being studied to develop an improved understanding of the effects of variations in aerosol characteristics on the cryosphere.

Major Accomplishments and Results:

1) We have performed a comprehensive analysis of the impact of wildfires occurred in Northern America (Alaska and Canada) in the summer of 2007. In addition, selected cases of wildfires occurred in 2008 in Northern America and Siberia were analyzed to contrast smoke impacts on clouds in differing geographical and climatic regions. For this analysis a new methodology was developed to enable a comprehensive examination of smoke scenes through integration of multi-satellite, multi-sensor data products. The analysis included near-instantaneous, spatially collocated data from the NASA A-Train satellite constellation, including aerosol and cloud products from MODIS, CALIPSO lidar, and CloudSat. Smoke plume altitudes were constrained with the CALIPSO lidar, while MODIS aerosol products were used to determine aerosol optical depth and verify the spatial extent of the smoke plumes relative to the clouds. We examined aerosol optical depth, effective droplet radius (*Re*), liquid water/ice path (*LWP, IWP)*, and water content of smoke-polluted clouds. Our results reveal complex behavior and significant variations of *Re* and *LWP, IWP* values in analyzed data. We found significant differences between MODIS- and CloudSat- retrieved cloud products and between their behavior for both polluted and clean clouds. For both MODIS and CloudSat, more coherent (while still different) *Re* vs. *LWP* dependencies were found when data were stratified by cloud types and/or by cloud phase. MODIS retrievals show a narrower distribution and a shift of the *Re* vs. *LWP* dependencies toward larger sizes (17-35 μm) for clean deep convective clouds, while for polluted deep convective clouds the distributions were broader. Similarly in CloudSat retrievals, we observed larger *Re* values (up to 2 μm difference) for fixed *LWP* in clean altostratus clouds than in polluted ones, which is in agreement with the classical Twomey hypothesis. At the same time, opposite tendencies or the absence of obvious *Re* vs. *LWP* relationships were observed for the other cases (e.g., altocumulus clouds in CloudSat retrievals). A maximum of the *Re* distribution for the whole data set retrieved by MODIS was found to be at 8 μm for polluted clouds and close to 10 μm for clean clouds. The differences between “polluted” and “clean” distributions were much less pronounced in the CloudSat data. Overall, our results provide the empirical evidence for the effect of boreal wildfire smoke on clouds and precipitation but at the same time reveal significant sensor-dependent differences in quantitative assessment of the smoke impact.

2) We have completed a series of modeling experiments that were designed to assess the impact of smoke on cloud properties and precipitation during 2007 wildfires in Alaska and Canada. A coupled aerosol-cloud microphysics-meteorology model WRF-Chem-SMOKE was developed

under this project and was used in conjunction with satellite data. A new block emission was developed in WRF-Chem-SMOKE to compute hourly size- and composition-resolved smoke emission based on the satellite WF_ABBA burned area product. Smoke aerosol was considered as a mixture of organic carbon, black carbon, and sulfate particles. Smoke CCN were computed using the Abdul-Razzak and Ghan parameterization and coupled with the Morrison two-moment cloud microphysics scheme within WRF-Chem-SMOKE. Modeled 3D smoke fields and clouds were compared against the A-Train multi-satellite aerosol and cloud products. Comparisons with the MODIS aerosol optical depth, OMI aerosol index, and CALIPSO vertical feature mask reveal that the WRF-Chem-SMOKE model captures well both the horizontal and vertical spatial distribution of smoke plumes. However, modeled aerosol loading was much lower compared to observations (~ 10 times). We performed several modeling experiments by gradually increasing the emission amount and examined the effect it has on cloud and precipitation. Results demonstrate that precipitation is highly sensitive to smoke fields and varies non-linear with the increasing smoke load. Low smoke loadings provide a favorable condition for the collision-coalescence process, leading to either positive or negative changes in cloud water path (CWP) and causing the early onset of precipitation. However, when smoke emission is high, changes in CWP were positive. Domain-integrated increase in CWP was found to be proportional to smoke loading. In contrast, both positive and negative changes in rain water path (RWP) and snow water path (SWP) were found. Domain-integrated changes in RWP remain negative during the whole period. Domain-integrated changes in SWP changed dramatically from negative at high smoke load to positive for low smoke load. As a result, in the case of high smoke loads, precipitation was initially suppressed due to smoke-induced reduction of collision-coalescence and riming processes, followed by invigoration of precipitation.

3) High northern latitude eruptions have the potential to release volcanic aerosol into the Arctic environment, perturbing the Arctic's climate system. We have completed an integrative analysis of the radiative impact of volcanic aerosol volcanic aerosol from the 2009 eruption of Redoubt Volcano, Alaska. Quantitative assessments of shortwave (SW), longwave (LW) and net direct aerosol radiative forcings (DARFs) and atmospheric heating/cooling rates caused by volcanic aerosol was performed through performing radiative transfer modeling constrained by NASA A-Train satellite data. The Ozone Monitoring Instrument (OMI), the Moderate Resolution Imaging Spectroradiometer (MODIS), and the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model for volcanic ash were used to characterize aerosol across the region. A

representative range of aerosol optical depths (AODs) at 550 nm were obtained from MODIS, and the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) was used to determine the altitude and thickness of the plumes. The optical properties of volcanic aerosol were calculated using a compositionally resolved microphysical model developed for both ash and sulfates. Two compositions of volcanic aerosol were considered in order to examine a fresh, ash rich plume and an older, ash poor plume. Optical models were incorporated into a modified version of the Santa Barbara Disort Atmospheric Radiative Transfer (SBDART) model. Radiative transfer calculations were made for a range of surface albedos and solar zenith angles (SZA) representative of the region. We find that the total DARF caused by a fresh, thin plume (~2.5 – 7 km) at an AOD (550 nm) range of 0.16 - 0.58 and SZA = 55^{o} is - 46 Wm^{-2}AOD^{-1} at the top of the atmosphere (TOA), 110 Wm^{-2}AOD^{-1} in the aerosol layer, and – 150 Wm^{-2}AOD^{-1}at the surface over seawater. However, the total DARF for the same plume over snow and at the same SZA at TOA, in the layer, and at the surface is 170, 170, and -2 Wm^{-2}AOD^{-1}, respectively. We also see that the total DARF when SZA = 75^{o} for the same layer over snow is 35 Wm^{-2}AOD^{-1}at TOA, 64 Wm^{-2}AOD^{-1} in the layer, and 11 Wm^{-2}AOD^{-1} at the surface. These results indicate that environmental conditions, such as surface albedo and SZA, control the sign of the radiative forcing at TOA and at the surface and the magnitude of the forcing in the aerosol layer. An older plume over snow at SZA = 55^{o} would have total DARFs of 25, 31, and -5 Wm^{-2}AOD^{-1} at TOA, in the layer, and at the surface, respectively. Our results demonstrate that plume aging can alter the magnitude of the radiative forcing. We also compare results for the thin plume to those for a thick plume (~3 – 20 km) with an AOD (550 nm) range of 1 to 3. The fresh, thin plume with AOD = 0.58, over seawater, and SZA = 55 ^{o} will heat the atmosphere in the SW by ~ 2.5 Kday^{-1} and cool the atmosphere in the LW by ~ 0.3 Kday^{-1}. The fresh, thick plume with AOD = 3 under the same environmental conditions will produce SW heating in the atmosphere by ~ 31 Kday^{-1} and atmospheric LW cooling of ~6.7 Kday^{-1}. These calculations convey the importance of vertical plume structure in determining the magnitudes of the radiative effects. Our results demonstrate a potential for volcanic aerosol to provide a sizeable contribution to the radiative effects and even outshine other types of aerosol when significant proportions of volcanic ash are present, as in young volcanic plumes. Therefore, volcanic aerosol, although sporadically present, can have a significant radiative impact in the region. We recommend that volcanic aerosol be included in future assessments of the Arctic radiation budget. This will facilitate efforts to understand the radiative impacts of natural aerosols on the Arctic environment in order to create successful mitigation strategies for warming due to anthropogenic sources.

Publications/Presentations prepared with full or partial support from this grant:

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