Abstract

Aerosol-cloud interaction continues to be one of the most uncertain components of climate change. This uncertainty is even more prominent at the regional level because of the heterogeneity in aerosol and cloud properties (IPCC, 2013), especially over the Indian monsoon region due to heterogeneity in aerosol and cloud properties. Ever since the role of aerosols in altering the cloud characteristics was demonstrated during the Indian Ocean Experiment, efforts have increased exponentially to advance understanding aerosol-cloud-precipitation interaction using in-situ observations in stationery and campaign mode, satellite data, and models.

Despite decades of research, climate models still struggle in representing aerosol and cloud characteristics over the South Asian monsoon region. Subsequent observations from the surface, aircraft, and ship campaigns (e.g., BoBMEX, ARMEX, ICARB, ISRO-GBP, CAIPEEX, and CTCZ) provided critical inputs to the modelling community and even to the satellite community to improve the model outputs and satellite products. Better observations led to the robust estimates of aerosol direct radiative forcing at a local and regional scale. However, key gaps exist, particularly in (1) year-round evidence of aerosol-cloud interaction and (2) observationally-constrained estimates of aerosol indirect radiative forcing in the South Asian monsoon region.

This thesis aims to fill these two critical gaps by analyzing fifteen years (Mar 2000-Feb 2015) of daily satellite data over the oceans adjacent to the Indian subcontinent. The focus of the thesis is on marine low water clouds, as different cloud types have contrasting dynamics that might have impacted the interpretation. The results are presented for the three oceanic regions - the Arabian Sea (AS), Bay of Bengal (BoB), and South Indian Ocean (SIO). First, a monthly climatology of cloud and aerosol parameters from various satellite products has been developed to understand the seasonality. Since the satellite products do not provide characteristics of natural and anthropogenic aerosols separately, a hybrid approach is proposed to first quantify the relative contributions of anthropogenic, dust, and maritime aerosols on total aerosol loading and use the data to understand the sensitivity of cloud characteristics to individual aerosol types. Anthropogenic aerosols contribute 31%, 29%, and 28%, and dust particles contribute 39%, 40%, and 24% to total aerosol optical depth over the AS, BoB, and SIO, with the remaining contributions from maritime aerosols.

Further, the dependency of cloud top pressure on cloud fraction in clean and polluted conditions is analyzed, which provided evidence of lifetime effect. Cloud cover has been found to increase with a decrease in cloud top pressure by a larger margin in the clean conditions than in the polluted condition for anthropogenic aerosols. The relationship is insensitive to marine aerosols. Evidence of semi-direct effect has been identified in three seasons except for the post-monsoon (Oct-Nov) season. In both AS and BOB, the aerosol-cloud interaction is strongly modulated by meteorology compared to the SIO, with a larger impact during the monsoon (Jun-Sep).

Previous studies in the Indian ocean provided evidence of aerosol impacts on cloud properties during the winter (Dec-Feb). This study confirms the presence of aerosol-cloud interaction throughout the year. The effective radius of clouds (*Reff*) has been found to increase with an increase in Liquid Water Path (*LWP)* in clean and polluted conditions suggesting the meteorological impact on the cloud dynamics. However, the segregation of the data into various aerosol bins has allowed isolating the aerosol signal. One critical result is that the aerosol-cloud interaction is the most prominent in the middle range of the liquid water path of 150–350 gm/m^2 in these regions. This study suggested that better and explicit representations of aerosol-cloud interaction in the regional and climate model are required to reduce uncertainty since such interaction is sensitive to the LWP and meteorology.

Next, a theoretical framework has been proposed to analytically estimate aerosol indirect radiative forcing. This framework relies on observationally-constrained estimates of the aerosol-induced changes in cloud albedo (albedo or first indirect effect) and cloud fraction (lifetime or second indirect effect). Cloud albedo (R_c) increases with an increase in *LWP* (macrophysical pathway) and a decrease in R_{eff} (microphysical pathway) due to aerosols. The analysis has been carried out for total aerosols (aerosol optical depth, τ_a) and anthropogenic aerosols (anthropogenic aerosol optical depth, τ_{an}). Look-up tables are generated to quantify the changes in cloud albedo per unit change in aerosol optical depth ($dR_c/d\tau_a$) for narrow bins of *LWP* and *Reff* by analyzing the MODIS cloud and aerosol products. In the theoretical construct, the macrophysical and microphysical pathways are separated. R_C response to an increase in τa is found to be the most sensitive in the range of *LWP* between 150-300 gm/m^2 for a range of R_{eff} varying from 8-24 μm.

Using this framework, aerosol first and second indirect radiative forcing is calculated for the three oceanic regions. The mean ($\pm 1\sigma$) annual total aerosol indirect radiative forcing over the AS, BoB, and SIO are estimated as -6.7 $\pm$ 2.7 W/m^2, -4.3 $\pm$ 1.1 W/m^2, -3.6 $\pm$ 1.4 W/m^2, respectively. The first aerosol indirect radiative forcing due to the microphysical pathway are estimated to be -3.4 ± 1.7 W/m^2, -4.15 ± 2.04 W/m^2, -4.72 ± 1.5 W/m^2 over the AS, BoB and SIO, respectively. In contrast, mean (±1σ) annual aerosol indirect radiative forcing due to anthropogenic aerosols over the AS, BoB, and SIO are estimated as -5.96 ± 2.4 W/m^2, -4.12 ± 1.7 W/m^2 w/m^2, -8.38 ± .4 W/m^2, respectively, out of which the contributions due to the microphysical pathways are -5.9 ± 3.4 W/m^2, -4.12 ± 2.1 W/m^2, -8.6 ± 5.04 W/m^2 respectively.

The mean (±1σ) annual aerosol indirect effect due to the lifetime effect over the AS, BoB, and SIO are estimated as -3.1± 1.4 W/m^2, -2.5 ± 0.92 W/m^2, and -0.75 ± 0.14 W/m^2 for total aerosols, respectively. In contrast, the annual aerosol indirect radiative forcing due to the lifetime effect over the AS, BoB, and SIO are estimated as -3.7 ± 1.63 W/m^2, -4.2± 3.4 W/m^2, and -0.5 ± 0.09 W/m^2 for the anthropogenic aerosols.

The results, particularly, the separation of the microphysical and macrophysical pathways in the albedo effect and the comparative assessment relative to the lifetime effect would be critical to modelers who can assess the model performance at a disaggregated level in the aerosol-cloud interaction module. The approach can be applied to estimate aerosol indirect radiative forcing over land and also for other types of clouds in future, and is universally applicable.