Aerosol-Hydrologic Cycle Interaction: A New Challenge in Monsoon Climate Research

William K. M. Lau
Laboratory for Atmospheres
NASA/Goddard Space Flight Center

1. Introduction

Long recognized as a major environmental hazard, aerosol is now known to have strong impacts on both regional and global climate. It has been estimated that aerosol may reduce by up to 10% of the seasonal mean solar radiation reaching the earth surface, producing a global cooling effect that opposes global warming (Climate Change 2001). This means that the potential perils that humans have committed to global warming may be far greater than what we can detect at the present. As a key component of the Earth climate system, the water cycle is profoundly affected by the presence of aerosols in the atmosphere (Ramanathan et al. 2001, Rosenfeld 2000 and many others). Through the so-called "direct effect", aerosol scatters and/or absorbs solar radiation, thus cooling the earth surface and changing the horizontal and vertical radiational heating contrast in the atmosphere. The heating contrast drives anomalous atmospheric circulation, resulting in changes in convection, clouds, and rainfall. Another way aerosol can affect the water cycle is through the so-called "indirect effects", whereby aerosol increases the number of cloud condensation nuclei, prolongs life time of clouds, and inhibits the growth of cloud drops to raindrops. This leads to more clouds, and increased reflection of solar radiation, and further cooling at the earth surface.

In monsoon regions, the response of the water cycle to aerosol forcing is especially complex, not only because of presence of diverse mix of aerosol species with vastly different radiative properties, but also because the monsoon is strongly influenced by ocean and land surface processes, land use, land change, as well as regional and global greenhouse warming effects. Thus, sorting out the impacts of aerosol forcing, and interaction with the monsoon water cycle is a very challenging problem. Up to now, besides the general notion that since aerosols significantly alters radiative heating pattern, they *ought* to have an impact on the monsoon, there has been very little information regarding the specific signatures, and mechanisms of aerosol-monsoon water cycle interaction. This note offers some insights into how aerosols may impact the Asian monsoon based on preliminary results from the NASA climate model. It also discusses some future challenges that lie ahead in aerosol-water cycle dynamics research.

2. Results

To tease out possible signatures of aerosol direct forcing of in the water cycle variability in monsoon regions, we have conducted numerical experiments with the NASA finite-volume GCM (fvGCM) with Microphysics of clouds in relaxed Arakawa Schubert (McRAS) cumulus parameterization scheme (Sud and Walker 1999). In the control, the model is forced by three-dimensional aerosol forcing functions for all five major aerosol types, i.e., dust, black carbon, organic carbon, sulfate and sea salt , derived from outputs of the Goddard Chemistry Aerosol Radiation Transport (GOCART) model (Chin et al. 2002). In the anomaly runs, the initial and boundary conditions are identical, except that all or selected aerosol forcing were withheld. The results described here pertain to the Asian monsoon regions. Results for the monsoons of Australia, Americas, and Africa are being analyzed and will be reported in due course. Comparing the control and anomaly experiments for the Asian monsoon, we find that absorbing aerosols, consisting of dust transported from the North Africa/Middle East/Afghanistan region coupled with black carbon from local emission, over northern India can increase monsoon rainfall over northwestern India and the Bay of Bengal. The rainfall increase is spurred by an elevated heat source over the Tibetan Plateau, induced by shortwave absorption by dust and black carbon aerosols, which are lofted by orographically forced ascent against the southern slope of the Himalayas. The net atmospheric heating due to aerosol absorption acts as an "elevated heat pump" causing the air to warm and rise, increasing dynamic convergence which draws more warm and moist air from the low and mid-troposphere, providing a positive feedback to the aerosol heating.

Figure 1 shows that the anomalous warming in the upper troposphere over the Tibetan Plateau begins in March (Fig. 1a), becomes well established in April and May (Figs.1 b and c), which correspond to the pre-monsoon dry season with heavy atmospheric loading, and maximum residence time of dust and black carbon from industrial pollution and biomass burning. The warming forces an anomalous local meridional overturning with rising motion over northern India, and subsidence over southern India, which becomes very pronounced in May and June (Figs 1 c, and d). This overturning persists into July and August (not shown), resulting in an overall increase in rainfall over northern India, and suppressed rainfall in southern India and the northern Indian Ocean.

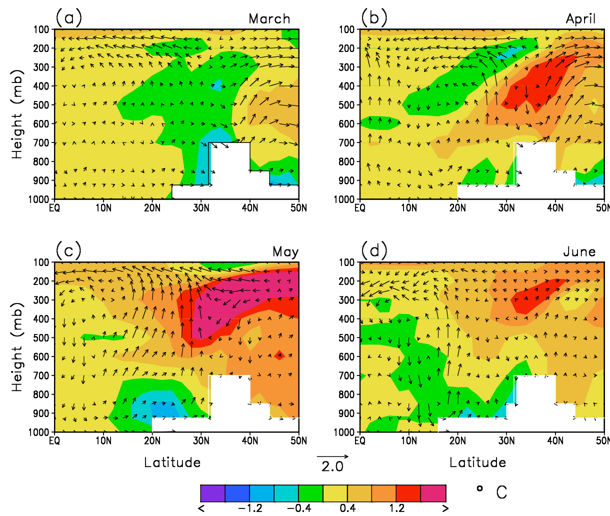

Fig. 1 Vertical cross-section of temperature and wind averaged over the Indian subcontinent in the fvGCM-GOCART simulations, showing the anomalous meridional overturning, and upper tropospheric temperature as a result of aerosol-induced heating.

The increased rainfall over northern India, and reduction in southern India is only a part of a large-scale response of the entire Asian monsoon to aerosol induced forcing featuring extensive rainfall reduction in southern China, the East China Sea, an east-west oriented band of enhanced rainfall along 30- 35^{o} N in central China, southern Korea and Japan, and reduced rainfall over northeastern China (Fig. 2a). The suppression of rainfall over southern China is due to surface cooling spurred by industrial pollution mainly from sulfate and black carbon. In contrast to the Indian monsoon region, the absorption heating due to black carbon over southern China remains largely within the lower troposphere due to the lack of orographic forced ascent, and consequentially is not efficient as an atmospheric heat source to initiate new convection. As a result, the stabilizing influence due to semi-direct effect of aerosols prevails, as evident in the widespread suppression of rainfall over southern China.

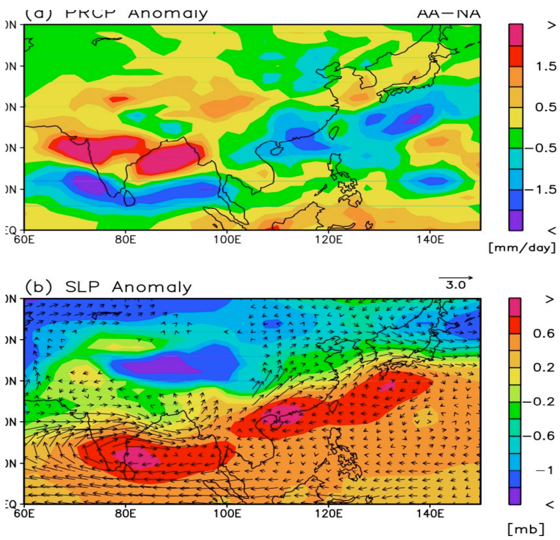

Fig. 2 Spatial pattern of aerosol-induced seasonal mean (JJA) anomalies of a) rainfall, and b) sea level pressure and 850 mb wind, based on the experiments with the NASA fvGCM-GOCART model

Fig. 2b shows that the aerosol induced rainfall anomaly is associated with the development of a large scale surface pressure and wind anomaly pattern, represented by an eastward extension and strengthening of the western subtropical high, which appears to be connected to a large scale anticyclonic circulation anomaly over southern India and the Indian Ocean. The increase low level westerlies over northern India and the Bay of Bengal indicates a strengthening of the Indian monsoon. The climatological southwesterly flow over the northern South China Sea is replaced by low level easterlies. Anomalous southwesterlies are found over central China, South Korea and Japan, signally a northward shift and weakening of the *Mei-Yu* rainfall regime over East Asia.

Analyses of further experiments with various combination of aerosol forcing (not shown), suggest that the anomaly patterns are due to the combined effects of dust and black carbon aerosols, with dust playing a primary role in instigating these patterns.

3. Concluding Remarks

Our results suggest a plausible and testable hypothesis regarding the different impacts of aerosols on the Asian monsoon that needs to be validated with further model experiments and observations. However, the validation process will be challenging for a number of reasons. First, state-of-the-art climate models either do not include aerosol-cloud interaction processes, or include them in simple, empirical parameterizations. Our present experiments deal with direct effects only. In the real world, both direct and indirect effects are likely to be important. Second, the present bootstrapping strategy of using dynamics for aerosol chemistry transport, and then separately using chemistry transport model to force dynamics, has its obvious inconsistencies and limitations. Ultimately, coupled chemistry-dynamic models have to be developed to simulate the full feedback between dynamics and aerosol forcing. Third, the lack of long-term global observations of aerosol emission, composition, and distribution makes it very difficult to define aerosol forcing functions, and to validate model results. At present, satellite observations from satellites, e.g., TOMS, MODIS, POLDER, MISR, and TRMM have providing tantalizing signals of the direct and indirect effects on water cycle. The Aerosol Robotic Network (AERONET) has provided valuable aerosol data for characterization and calibration of satellite observations (Holben et al. 1998). However, these observations still fall short of the requirement of global, coincident observations of aerosols, clouds and rain with high temporal and spatial (horizontal and vertical) resolutions. Current efforts in assembling and integrated multi-platform local and global data for model validation such as the Coordinated Enhanced Observing Period (CEOP) must be supported, while new field campaigns, and monitoring programs are being planned and incorporated into the global integrated data base. Observational and model efforts on monsoon and water cycle dynamics research should be coordinated, to improve physical parameterization in models.

An organized international effort on aerosol-monsoon water cycle process study jointly sponsored by GEWEX and CLIVAR, under the auspices of the WCRP emerging banner Coordinated Observations and Prediction of the Earth System (COPES) will go a long way in meeting these requirements and challenges.

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