Chapter 98
Modeling of Air Pollution over the Ganges Basin and North-West Bay of Bengal in the Early Post-monsoon Season Using the NASA GEOS-5 Model

Pavel Kishcha, Arlindo M. da Silva, Boris Starobinets, and Pinhas Alpert

Abstract The NASA GEOS-5 model was used to extend the MERRA reanalysis with five atmospheric aerosol components (sulfates, organic carbon, black carbon, desert dust, and sea-salt). The obtained eight-year (2002–2009) MERRA-driven aerosol reanalysis (MERRAero) dataset was applied to the study of aerosol optical thickness (AOT) trends over the Ganges basin and north-west Bay of Bengal (BoB) in the early post-monsoon season. In October, in the absence of aerosol sources in north-west Bay of Bengal (BoB), MERRAero showed increasing AOT trends over north-west BoB exceeding those over the east of the Ganges basin. Various aerosol components showed strong increasing AOT trends over north-west BoB. Our analysis showed that the AOT trends over north-west BoB were reproduced by GEOS-5, not because of MODIS AOT assimilation, but because of the model capability of reproducing meteorological factors contributing to AOT trends. The following factors contributed to the increasing AOT trend over the area in question in October: an increasing number of days when prevailing winds blew from land to sea, resulting in a drier environment and an increase in air pollution over north-west BoB; wind convergence was observed over north-west BoB causing the accumulation of aerosol particles over that region, when prevailing winds blew from land to sea.

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98.1 Introduction

The Ganges basin is characterized by a significant population growth accompanied by developing industry and increasing transportation. This has resulted in increased anthropogenic emissions and declining air quality. The early post-monsoon season over the study region is characterized by aerosol transport from the Ganges basin to north-west BoB by prevailing winds; and still significant rainfall of over 150 mm/month over the east of the Ganges basin and north-west BoB. It would be reasonable to consider that AOT trends over sea areas in BoB were created by changes in aerosol sources on the land in the Indian subcontinent. In our previous study [3], we found that it was not always the case. Specifically, we found that, in October, MODIS showed strong increasing aerosol optical thickness (AOT) trends over north-west Bay of Bengal (BoB) in the absence of AOT trends over the east of the Indian subcontinent. It was interesting to determine whether existing aerosol data-assimilated systems were capable of reproducing the aforementioned observed AOT trends over north-west BoB. The NASA Goddard Earth Observing System (GEOS-5) was used to extend the NASA Modern Era-Retrospective Analysis for Research and Applications (MERRA) reanalysis by adding five atmospheric aerosol components (sulfates, organic carbon, black carbon, desert dust, and sea-salt). The obtained eight-year (2002–2009) assimilated aerosol dataset (so-called MERRAero) was applied to the study of AOT and its trends over the Ganges basin and north-west Bay of Bengal (BoB) in the post-monsoon season. Using an assimilated aerosol dataset over north-west BoB provided us with an opportunity to estimate the contribution of different aerosol components to AOT and its trends.

98.2 GEOS-5 and the MERRA Aerosol Reanalysis (MERRAERO)

GEOS-5 is the latest version of the NASA Global Modeling and Assimilation Office (GMAO) Earth system model. GEOS-5 contains components for atmospheric circulation and composition (including atmospheric data assimilation), ocean circulation and biogeochemistry, and land surface processes. GEOS-5 includes a module representing atmospheric aerosols [2]. This aerosol module is based on a version of the Goddard Chemistry, Aerosol, Radiation, and Transport (GOCART) model [1]. GOCART treats the sources, sinks, and chemistry of dust; sulfate; sea salt; and black and organic carbon aerosols. Aerosol species are assumed to be external mixtures. Total mass of sulfate and carbonaceous aerosols are tracked, while for dust and sea salt the particle size distribution is explicitly resolved across five non-interacting size bins for each. Both dust and sea salt have wind-speed dependent emission functions, while sulfate and carbonaceous species have emissions principally from fossil fuel combustion, biomass burning, and bio-fuel consumption, with additional biogenic sources of organic carbon. Sulfate has additional chemical production from oxidation of SO_2 and dimethylsulfide (DMS), as well as a database of volcanic SO_2 emissions and injection heights. GEOS-5 also includes assimilation of AOT observations from the MODIS sensor on both Terra and Aqua satellites.

98.3 Method

We analyzed long-term variations of AOT over seven zones, each $3 \times 3°$, located in the Ganges basin and north-west BoB (Fig. 98.1). As mentioned, in the post-monsoon period, prevailing winds blow along the Ganges basin. The specified zones in the Ganges basin provide us with an opportunity for analyzing air pollution trends produced by local sources and aerosol transport. Figure 98.1a shows the spatial distribution of eight-year mean MERRAero AOT over the region under consideration in October, together with the location of zones $3° \times 3°$ in the Indian subcontinent (zone 1 to zone 5) and in the Bay of Bengal (zones 6 and 7). MERRAero monthly AOT data are available from the year 2002. To analyze AOT and its trends over the Indian subcontinent and north-west BoB, we used monthly MERRAero AOT data with horizontal resolution of approximately 50 km, during the eight-year period 2002–2009.

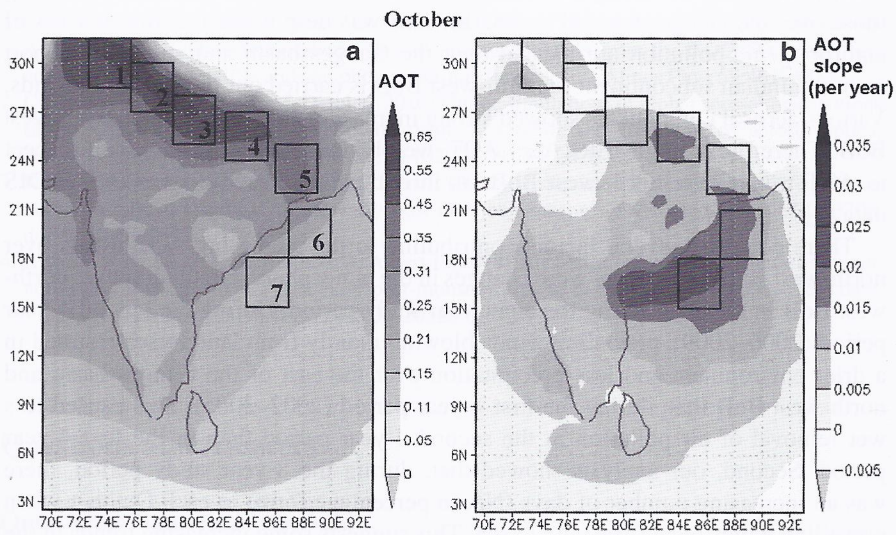

Fig. 98.1 Spatial distributions of (**a**) the eight year (2002–2009) mean MERRAero AOT and (**b**) its trends (characterized by AOT slopes) in October. The AOT trend values correspond to the slope of the linear regression (From Kishcha et al. [4])

98.4 Results and Discussion

In accordance with space distribution of eight-year mean AOT in the early post-monsoon season (October), MERRAero showed high AOT values over the Ganges basin with a maximum over the north-west part of the Ganges basin (Fig. 98.1a). Therefore, MERRAero data were able to reproduce the main structure of aerosol distribution over the Ganges basin. The Ganges basin is the most polluted part of the Indian subcontinent, where highly-populated areas and main industrial centers are located. The MERRAero AOT data set allowed us to determine aerosol species responsible for the AOT maximum over the north-west of the Ganges basin, which are both natural aerosols (dust particles) and anthropogenic aerosols (carbon aerosols from bio-mass burning and sulfates). In accordance with MERRAero data, most of dust particles fell out due to gravitational settling and wet deposition during dust transport from the north-west to the east of the Ganges basin. As a result, over the east of the Ganges basin and north-west BoB in the early post-monsoon season, aerosols were dominated by anthropogenic air pollution, such as sulfates and carbon aerosols. Our analysis showed that sea-salt aerosols did not contribute to the increasing AOT trends over north-west BoB: no sea-salt AOT trend was observed in year-to-year variations during the study period. Taking into account that anthropogenic aerosols are effective cloud condensation nuclei (CCN), these aerosols could influence the strength of typhoons crossing BoB in the early post-monsoon season.

Space distributions of MERRAero AOT trends during the eight-year (2002–2009) study period showed strong increasing AOT trends over north-west BoB exceeding those over the Ganges basin (Fig. 98.1b). This was despite the fact that sources of anthropogenic pollution are located over the Ganges basin and aerosol transport from the Indian subcontinent to north-west BoB is carried out by prevailing winds. Various aerosol components showed strong increasing AOT trends over north-west BoB. Therefore, using MERRAero AOT, we obtained similar results with respect to AOT trends over north-west BoB, as in our previous study based on MODIS data [3].

There could be several factors contributing to the increasing AOT trends over north-west BoB. First, there were changes in the atmospheric circulation over north-west BoB in October during the eight-year study period. During the second 4-year period (2006–2009), prevailing winds blowing mainly from land to sea resulted in a drier environment and less precipitation over the east of the Ganges basin and north-west BoB than during the first 4-year period (2002–2005). This caused less wet removal of air pollution in the second 4-year period than in the first 4-year period. Second, our analysis showed that, during the 8-year study period, there was an increasing number of days (Np, in percentage form) in each October when prevailing winds blew from land to sea. This suggests some increasing trends in the transport of anthropogenic air pollution from their sources in the east of the Ganges basin to north-west BoB. Third, for Octobers when $Np > 50\ \%$, wind convergence was observed over north-west BoB causing the accumulation of aerosol particles over that region, in line with our previous study [3]. All the three factors contributed to the increasing AOT trend over north-west BoB in the early post-monsoon season.

We estimated the NASA GEOS-5 model performance over the study area analyzing model AOT increments. These AOT increments are the field differences between MODIS AOT and modeled AOT. AOT increments include a complex combination of all model errors in AOT simulations over each specific location. To analyze AOT increments, 3-h MERRAero AOT data were used. These 3-h data allowed us to distinguish between 3-h periods with and without MODIS AOT assimilation. A comparison was conducted between spatial distributions of eight-year (2002–2009) AOT trends at 6 UT with and without AOT assimilation. Here, the modeled AOT without MODIS assimilation was obtained as the field difference between MODIS AOT and AOT increments at 6 UT. Similar AOT trends were obtained using MERRAero AOT with and without MODIS AOT assimilation. This is evidence that the increasing AOT trends over north-west BoB were reproduced by the model not because MODIS AOT assimilation provided us with an opportunity to correct the uncertainty in aerosol emissions, but because the model was capable of reproducing changes in meteorological factors contributing to the AOT trends.

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Questions and Answers

Questioner Name: Antony Dore

Q: You mentioned a decrease in wet removal over the Bay of Bengal. Could this be caused by an increase in particle and cloud droplet numbers forming clouds with a smaller droplet size, which are less likely to grew to raindrop size? If so, has a decrease in rainfall been observed in the region?

A: In the early post-monsoon season (October), there are days when winds blow from land to sea. This is accompanied by a decrease in aerosol wet removal over north-west BoB. On the other hand, there are also days when winds blow from sea to land. In these days, aerosol wet removal increases. In our previous study [3], we analyzed long-term changes in accumulated rainfall over north-west BoB in October during the 10-year (2000–2009) period using TRMM rainfall data. No decreasing trend in accumulated rainfall was found.

Questioner Name: Roger Timmis

Q: Can the change in atmospheric circulation over north-west BoB in the early post-monsoon season between the first and second 4-year study periods be related to the phase of the El Nino South Oscillation (ENSO) cycle?

A: There could be different factors causing the change in atmospheric circulation over north-west BoB in the early post-monsoon season, such as monsoon variability, ENSO cycle, etc. To identify the causal factors, further research is needed using a much longer time record of wind data than the eight-year period selected for analysis in the current study.

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