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Mapping aerosol intrusion in Himalayan valleys using the Moderate Resolution Imaging Spectroradiometer (MODIS) and Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO)

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ABSTRACT

Mapping the spatial and temporal distribution of aerosols along mountain ranges is an important step toward elucidating orographic aerosol–cloud–rainfall interactions. This requires high spatial resolution aerosol observations over complex topography, which are not currently available either from ground-based observing systems or from remote-sensing products. Here, a novel approach is presented that relies on visible channels from MODIS Rapid Response data at 250 m spatial resolution to extract the daytime aerosol run-up (intrusion length and height) from the Indo-Gangetic Plains to the High Himalaya. Intrusion length and height are determined from the intersection of topography with the MODIS-derived aerosol plume using an adaptive object-classification algorithm. The methodology is demonstrated for a case study of the Arun River in eastern Nepal. Results of run-up extraction are examined along with the Total Attenuated Backscatter (Level 1B at 532 nm) from CALIPSO to investigate the regional variability of aerosol. During the pre-monsoon season, CALIPSO nighttime profiles show the presence of a slanted dust layer following the envelope topography. This is consistent with upper level transport of aerosol by north-westerly winds associated with high-frequency dust storms. In the winter, the signal is weaker, and the nighttime elevated aerosol layer is flat and remains below the envelope orography consistent with blocking conditions. For both seasons, the daytime aerosol layer detected from MODIS observations is always below the ridges. This suggests that in addition to seasonal variability governed by synoptic conditions, there is a distinct diurnal cycle in the North–South transport of aerosol between the Himalayas and the IGP.

1. Introduction

Aerosol concentrations produced by human activities have been steadily increasing since the beginning of the industrial era. Aerosols impact the Earth's radiative forcing, and consequently its climate, by modifying the scattering and absorption behavior of the atmosphere (IPCC, 2007; Ramanathan et al., 2001). Beside this direct effect, aerosols can modify the cloud coverage (and consequently the Earth's albedo), and have an impact on cloud physical properties and precipitation initiation through their role as cloud condensation nuclei (CCN) (e.g. Rosenfeld et al., 2008). Even if there is no definite consensus regarding the sign of aerosol–cloud-precipitation feedbacks (Kaufman and Koren, 2006), previous studies using rain gauge observations linked significant decreasing trends in orographic precipitation downwind of urban areas due to air pollution (Rosenfeld et al., 2007). In the Indian subcontinent, the strong seasonal cycle of aerosol and rainfall in the northeastern region of the Indo-Gangetic plains (IGP) and the foothills of the Himalayas suggest the possibility of strong interactions among aerosols, clouds and rainfall processes (e.g. Lau and Kim, 2006; Gautam et al., 2010; Shrestha and Barros, 2010; Shrestha et al., 2010). The aerosol plume extending from the IGP to the Himalayan foothills has also been shown to impact the radiative budget regionally, and consequently the regional surface energy and water budgets (Ramana et al., 2004; Ramanathan and Ramana, 2005; Marcq et al., 2010). Therefore, the direct and indirect effects of aerosol can significantly alter the hydrological cycle in this region.

Previous regional studies based on ground point measurements of aerosol at high elevations in Nepal suggest a significant contribution of long-range dust transport, especially in the pre-monsoon season (e.g. Gogoi et al., 2011; Gobbi et al., 2010; Gautam et al., 2009; Carrico et al., 2003; Shrestha et al., 2000). In the winter, aerosol characteristics at lower elevations are dominated by the fine fraction, which can be explained in terms of local sources and low level intrusion from the IGP (e.g. Chatterjee et al., 2010).

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The low level aerosol concentration variations over the IGP are driven by Planetary Boundary Layer (PBL) diurnal dynamics, modulated by changes in local emissions (Nair et al., 2007). Recently, Shrestha et al. (2010) reported on simultaneous ground measurements of aerosol size distribution and chemical composition of aerosols during the Joint Aerosol Monsoon Experiment (JAMEX, May–June 2009) at two locations in the Middle Himalaya, in Central Nepal. They found that day-to-day variability observed in the time series of aerosol composition (i.e. increases in mean volume and mass aerosol concentrations) could be explained by the intrusion of synoptic scale aerosol that extended from the IGP to the sampling region during periods without precipitation (dry weather periods). The particle size measured during JAMEX in Central Nepal ranged between 10 and 340 nm, which is in line with the predominance of fine-mode aerosol particles (defined in this manuscript as particle with diameter lower than 0.7 μm) also found by Dey and Di Girolamo (2010) in the Himalayan foothills using MISR (Multi Imaging Spectro-Radiometer) data.

Although ground-based field campaigns provide valuable information of local aerosol properties, they are often limited to a few sampling locations and for a specific period of time. By contrast, satellite based observations provide the means to investigate the spatial patterns of aerosol at regional scales, including long-range transport of aerosols, though temporal and spatial sampling is somewhat constrained by revisit times and the geometry of the satellite orbit and sensor characteristics. Regional climatologies obtained by integrating remote-sensing products over long periods of time provide a means to monitor the variability of the spatial patterns of aerosol on monthly time-scales (e.g. Jethva et al., 2005; Dey and Di Girolamo, 2010). However, the coarse spatial resolution of aerosol products from sensors on board of polar orbiting satellites (such MODIS, PARASOL – Polarization and Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar, OMI – Ozone Monitoring Instrument, MISR – Multi Imaging Spectro-Radiometer and AVHRR – Advanced Very High Resolution Radiometer) is a limitation for regional studies over complex terrain, where the characteristic spatial scales of ridge-valley features that control local circulations as well as cloudiness and rainfall patterns are in the 1–5 km range (Barros et al., 2004). For example, the MODIS aerosol products over land are obtained by aggregating observations from 3 channels (0.47 μm, 0.66 μm and 2.13 μm) into a nominal 10×10 km^2 box containing 20×20 pixels (Kaufman et al., 1997; Remer et al., 2005). This dark target approach is valid only for vegetated surfaces (green vegetation appears dark in red and blue channels). The Deep Blue Algorithm (DBA) (Hsu et al., 2004) has enabled the retrieval of aerosol properties over bright reflecting surfaces (e.g. deserts) at the same coarse resolution of 10×10 km^2. Recently, Jeong and Hsu (2008) retrieved the radiative effective aerosol layer height for biomass burning episodes over North America and Southeast Asia by merging measurements from MODIS, OMI and Cloud–Aerosol LIdar with Orthogonal Polarization (CALIOP), but the algorithm is constrained by the resolution of the source data, and does not provide the actual geophysical height of aerosol plumes. As a result, information relevant to capture the spatial heterogeneity of aerosols in complex terrain including the spatial gradients between river valleys and adjacent ridges is lacking. There is therefore great difficulty at present in assessing systematically the climatology of aerosol variability in mountainous regions, and the Himalayas in particular.

The 250 m resolution images from MODIS visible channels provide superior qualitative information to examine the spatial structure and potential transport patterns of aerosol, especially smoke and haze along the NS oriented river valleys in Nepal. Engel-Cox et al. (2004) conducted qualitative analysis of MODIS RGB (red–green–blue) images to study air quality at regional and urban scales, but they pointed out that the absence of information regarding the vertical extent and vertical structure of aerosol from the images was a major handicap. In this study, we present a methodology to extract the aerosol plume run-up including its spatial extent (intrusion length) and depth (difference between run-up height and the underlying terrain) using MODIS visible channels and digital elevation from the Shuttle Radar Topography Mission (SRTM). The approach relies on image processing algorithms and Geographical Information System (GIS) techniques to detect the aerosol run-up limits and penetration into the river valleys, where the aerosol plume is channelized by low level winds and intersects with the topography. The spatial aerosol intrusion mapped from MODIS provides a good estimate of the daytime scale height of aerosols at high spatial resolution in the narrow river valleys of the Himalayas. On the other hand, the CALIPSO overpass provides the corresponding nighttime profile of the aerosol plume. The methodology is demonstrated using a detailed illustrative case study for the North-South oriented Arun River valley in eastern Nepal (Fig.1). The Arun River is a major tributary to the Koshi River, which in turn is a major tributary of the Ganges. In addition, the nighttime CALIPSO overpass is closely aligned with the Arun river valley. Coordinated analysis of the MODIS and CALIPSO products provides a unique opportunity to investigate the diurnal cycle as well as the spatial structure of the intrusion of synoptic scale haze from the IGP along the Arun river valley from low to high elevations.

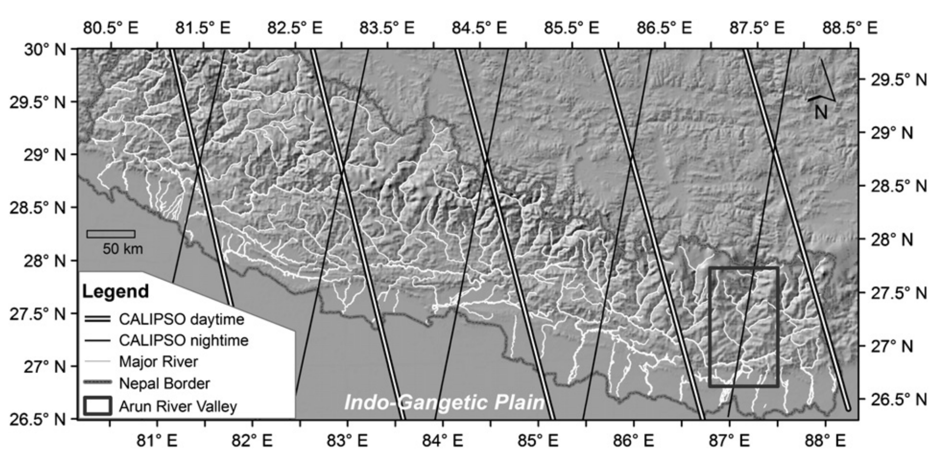

Fig. 1. Overview of CALIPSO tracks over Nepal. The daytime tracks are represented with double lines and the nighttime ones with simple lines. The Arun River valley is delimited by the rectangle.