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Melting of Major Glaciers in Himalayas: Role of Desert Dust and Anthropogenic Aerosols

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1. Introduction

The Himalayan and Tibet Glaciers, that are among the largest bodies of ice and fresh water resource outside of the polar ice caps, face a significant threat of accelerated meltdown in coming decades due to climate variability and change (Hasnain et al., 2002; Lau et al., 2010; Shrestha et al., 2011; Scherler et al., 2011). The rate of retreat of these glaciers and changes in their terminus (frontal dynamics) is highly variable across the Himalayan range (Raina, 2010; Scherler et al., 2011). These large freshwater sources are critical to human activities for food production, human consumption and a whole host of other applications, especially over the Indo-Gangetic (IG) plains. They are also situated in a geo-politically sensitive area surrounded by China, India, Pakistan, Nepal and Bhutan where more than a billion people depend on them. The major rivers of the Asian continent such as the Ganga (also known as Ganges), Brahmaputra, Indus, Yamuna, Sutluj etc., originate and pass through these regions (Kulkarni et al., 2010; Kehrwald et al., 2008; Bookhagen & Burbank, 2010; Immerzeel et al., 2009, 2010) and they have greater importance due to their multi-use downstream: hydro power, agriculture, aquaculture, flood control, and as a freshwater resource. Recent studies over the Himalayan Glaciers using ground-based and space-based observations, and computer models indicate a long-term trend of climate variability and change that may accelerate melting of the Himalayan Glaciers (Lau et al., 2010; Prasad et al., 2009). Other studies also suggest a decreasing trend in snowfall, which has historically served as a main source of precipitation for maintaining the glaciers and fresh water resources in this region. Short-term studies of terminus and mass balance of the Himalayan Glaciers, based on in situ observations, show an accelerated rate of melting (Berthier et al., 2007; Das et al, 2010; Raina, 2010). However, several studies report the rate of melting and the corresponding change in temperature is found to vary across the entire Himalayan range (Naz et al., 2011a; Raina, 2010; UNEP, 2008). Observations from space-based lasers altimeters (such as GLASS/ICESat), show glacial thickening in certain areas such as the Karakoram (Naz et al., 2011b, personal communication) but increased melting in its surrounding regions. The recent increase in the lake water level over the Tibetan Plateau using ICESat altimetry data (2003-2009) emphasize the effect of global warming on the glaciers (Zhang et al., 2011).

The major research objectives (and organization of sections of the chapter) of the present study are:

1. Brief overview of the source and influence of desert dust and anthropogenic aerosols on the atmosphere, regional temperature change, evidences from ice-core studies, and retreat pattern of Himalayan and Tibet glaciers. The results from recent studies on these aspects are briefly discussed in section 2.
2. Study of the aerial extent of major Himalayan and Tibetan Plateau snow cover and glaciers. We have used space-based sensors to study the several indicators of glacier dynamics such as glacier front, glacier lakes (melt-water lakes), and indicators of changes in the temperature of glaciers etc. We have used a combination of Landsat (since 1970s) and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) observations (2000-2010). The findings from the current study are discussed in section 3.
3. Source and transport of desert dust aerosols and anthropogenic pollutants over the Indian sub-continent. The inter-annual variability in the aerosol loading over the Indian sub-continent and the surrounding regions, such as Arabian Sea, have been studied using Moderate Resolution Imaging Spectroradiometer (MODIS) observations during the last decade. The role played by increasing anthropogenic activity, especially thermal power plants, industries, and vehicular emissions (since 1980) in changing the regional atmospheric (tropospheric) chemistry have been discussed. The influence of dense networks of coal-fired thermal power plants along the pathways of transport of desert dust has been discussed using observations from OMI Aura tropospheric NO_2. The results from MODIS AOD (2000-2008) and OMI NO_2 observations are discussed in section 4. The increasing awareness about the impact of dust storms due to daily observations from multiple environmental satellites and dissemination of news by media (print and television) since the last decade is also discussed briefly in section 4.
4. Whether the major dust storms are capable of reaching up to high-altitude Himalayas (~4-6 km above the mean sea level - msl). What is the height of vertical mix-up of aerosols during the dust storms over the IG plains, Himalayan and Tibet regions and its vertical range from the start of pre-monsoon season (April), through May month, and prior to the arrival of monsoon rainfall (late June or early July). Further, the variation of vertical mix-up across the western, central, and eastern regions is not well known.

To answers these questions, several case studies showing evidence of dust storms that can reach up to high altitude Himalayas (~4-6 km above msl) have been presented using MODIS Terra, and Aqua observations during the pre-monsoon season (please see section 5.1). The MODIS Terra and Aqua (deep-blue and deep-target aerosol optical depth - AOD) observations showing high AOD over Himalayan cryosphere regions is illustrated in section 5.1. The significance of band 3 (blue band) in aerosol retrieval over land is also discussed in this section.

The results from several Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) observations (night-time) that show the vertical structure of major dust storms across the IG plains, Himalayas and Tibet Plateau is shown in this article (please see section 5.2). The selected case studies of dust storms from CALIPSO observations for year 2010 not only cover the western, central, and eastern IG plains and Himalayas but also the entire pre-monsoon season (April to June) (section 5.2). The impact of dust storms on the western, central and eastern Himalayas and IG plains has been discussed using multiple parameters specifically developed for the detection of aerosols and cloud from CALIPSO observations.

5. Impact of the entrainment of anthropogenic aerosols with the desert dust, during the long-range transport that leads to the complex climate forcing scenarios is discussed in section 6.

2. Aerosols, temperature change, and retreat of glaciers

2.1 Mid-latitude westerlies and dust over the Himalayas and IG plains

The dust storms originating from Africa (Sahara desert), Arabia, Middle East, Afghanistan, and the Thar desert regions are transported by wind over to the IG plains and Himalayas (also called as Himalaya) due to the dominant westerly wind during the pre-monsoon season (Kayetha et al., 2007; Prasad et al., 2006b; Prasad and Singh, 2007a; Singh et al., 2004). The western and central part of Himalayas and IG plains are affected more than the eastern part as they are closer to the source of dust storms (Prasad and Singh, 2007a, 2007b). The glacier retreat pattern is different over the western and eastern Himalayas and Tibet plateau (He et al., 2003). The observed differences in the warming trends and glacial retreat of the western and eastern Himalayan range is very important in view of this contrast in aerosol loading over the region. A combination of the desert dust and aerosols resulting from anthropogenic sources (i.e. industrial, automobiles and crop, wood and animal waste burning) further complicates the interactions between the atmosphere and dynamics of glaciers in Himalayas (Ramnathan et al. 2005).

2.2 Ice-cores: Evidence of dust and anthropogenic aerosols

The influence of dust storms and anthropogenic activities on glacier dynamic has also been documented in the analysis of ice-cores from Tibet and Himalayan region (Duan, et al., 2007; Kang et al., 2000; Lee et al., 2008; Xu et al., 2007). The paleoclimatic records indicate that the South Asian monsoon and the mid-latitude westerlies affect the Himalayan glacier dynamics (Benn and Owen, 1998). The analysis of ice cores for multiple trace elements from the northeastern slope of Mt. Everest (central Himalayas) indicate high crustal enrichment factors that are attributed to the transport of anthropogenic aerosols to the high altitude region (Lee et al., 2008). The ice-cores from central Himalayas (Dasuopu glacier, 1988-1997) show seasonal variation of oxygen isotope and major ion concentrations (Ca^{2+}, Mg^{2+}, NH_4^+, SO_4^{2-} and NO_3^-) that coincide with the pre-monsoon dust storm period (Kang et al., 2000). The increasing effect of anthropogenic aerosols due to increased burning of fossil fuel in the last decade is reflected in some Himalayan ice-core analysis. For instance, the sulfate record (1000-1997) from ice cores of Dasuopu glacier show increased anthropogenic influence since the 1930s. Moreover, the doubling of sulfate concentration since 1970 coincides with the increased anthropogenic activities such as growth of coal-fired power plants in and around the IG plains. Thus, the transport of anthropogenic aerosols together with dust storm is evident based on the analysis of ice-cores in the Himalayan range (Duan et al., 2007).

2.3 Temperature change over Himalayan-Tibet glaciers

Recent studies show an increasing temperature trend over the Himalayas, Tibetan Plateau and IG plains (Shrestha et al., 1999; Liu & Chen, 2000; Rikiishi & Nakasato, 2006; Arora et al., 2005; Prasad et al., 2009). The Nepal Himalayas show a warming trend ranging between 0.068 to 0.128 °C (1971-1994) (Shrestha et al., 1999). The Tibetan Plateau also show a warming trend of 0.16°C/decade for the annual mean during period 1955-1996 (Liu & Chen, 2000). A significant increase in the maximum temperature over the Kashmir region (+0.04 to 0.05 °C/year) and the minimum temperature over the Jammu region (+0.03 to +0.08 °C/year) have been observed for period 1976-2007 (Jaswal & Rao, 2010). The northwestern Himalayan region shows significant rise in the air temperature by 1.6 °C during the last century based on data from three stations (Shimla in Himachal Pradesh, Srinagar and Leh in Jammu and Kashmir) (Bhutiyani et al., 2007). The inequality of tropospheric warming trend between the western and eastern IG plains and Himalayas has been observed from Microwave Sounding Unit (MSU) (Prasad et al., 2009). The western Himalayas show annual mean Temperature Middle Troposphere (TMT) warming of 0.48 °K (0.016±0.005 °K/year) during 1979-2008 compared to 0.33 °K (0.011±0.005 °K/year) over the eastern Himalayas. Similarly, the annual mean TMT trend (0.018±0.005 °K/year) is higher over the western IG plains compared to the eastern IG plains (0.013±0.004 °K/year). Over the IG plains, the warming trend is prominent and statistically significant (>0.030 °K/year) during the months of December, February, March and May. The warming trend is also generally positive during period December-May with higher values over the western side compared to the eastern side. In general, the warming trend over the northern India (the IG plains) during the winter months has been found to be positive and significant (maximum temperature trend at +0.29 °C/decade and minimum temperature trend at +0.38 °C/decade during February) compared to the southern parts of India (Jaswal, 2010). The ground stations based winter-time warming trend over the north-western Himalayas (Bhutiyani et al., 2007) is also corroborated by the MSU tropospheric temperature trends (Prasad et al., 2009) implying that the warming trend is also significant at the elevated levels of the atmosphere. Recently, Kulkarni et al. (2010) have found significant changes in the snow cover over western and central Himalayan river basins especially during the winter season. The warming trend is usually 2-3 times higher over the individual months (December-May). The maxima of the mean monthly warming TMT trend is around 0.48 and 0.51 °K/decade (or 0.048±0.026 and 0.051±0.024 °K/year) over the Himalayas and IG plains, respectively (Prasad et al., 2009). In contrast to the western side (Jammu and Kashmir region), the temperature trends have been found to be trendless over the stations of northeastern India (Jhajharia & Singh, 2010).

2.4 Retreat of glaciers

The Himalayan glaciers are among of the fastest receding glaciers of the world. The increasing rate of retreat of glaciers, that varies with the region, has a potentially detrimental effect on the available freshwater (river) resources especially in India, Pakistan, Bangladesh, and China (Kulkarni, 2007; Kulkarni & Bahuguna, 2002; Kulkarni et al., 2005; Krishna, 2005; Winiger et al., 2005; Rees & Collins, 2006; Kehrwald, et al., 2008). Recent studies document the alarming retreat of Parbati Glacier and Chenab, Parbati and Baspa basins since 1962 (Kulkarni & Bahuguna, 2002; Kulkarni & Alex, 2003; Kulkarini et al., 2005). The Rongbuk Glacier (Mount Everest, central Himalayas) shows a retreat of 170-270 m in 30 years (1966-1997) that is equivalent to a retreat speed of 5.5-8.7 m a^{-1} (Qin et al., 2000). Based on geological record, the Siachen Glacier in the western Himalayas, a 74 km long valley glacier which is also the largest glacier in the Karakoram and second largest glacier known outside the polar and sub-polar region, has receded by approximately 76 km compared to the past inter-glacial period (Raina & Sangewar, 2007; Upadhyay, 2009). In the last century, the Siachen glacier has receded during the period 1929 to 1958 compared to 1862 data, but it does not show any retreat since 1958 (Raina & Sangewar, 2007). The rate of retreat of several glaciers over the Himalayan and Tibetan Plateau has been updated and discussed by several recent studies (Prasad et al., 2009; Raina, 2010; Scherler et al., 2011). The degradation of a glacier is accompanied by the debris cover around the glacier termini and the formation of lakes (Ageta et al., 2000). An 8 % loss of glacier area has been observed between 1963-1993 over Bhutan (eastern Himalaya) (Karma et al., 2003).

3. Glaciers and snow cover regions: Landsat and ASTER

The monitoring of Himalayan glaciers started in India (1st phase: early 2000 - 1950 by the Geological Survey of India, GSI) with approximately 20 glaciers from Jammu and Kashmir in the west to Sikkim in the east. This was followed by a more systematic 2nd phase from the year 1957 (International Geophysical Year) to 1970. The third phase started with the Induction of the International Hydrological Programme (1970) that covered a number of major glaciers: Siachen, Mamostang, Kumdan, Machoi in J&K, Barashigri, Sonapanii, Guglu in Himachal Pradesh, Gangotri, Arwa, Poting, Milam, Pindari, Shankalpa, Kalganga, Bamlas, Safed, Bhilmagwar, Pachu, Burphu in Uttarakhand and Zemu in Sikkim (Raina, 2010). All the glaciers under observation by Indian agencies (particularly GSI) show negative mass balance during 1970-2000. The decline in glacial mass is found to be highest in the western Himalayas (Jammu and Kashmir) compared to the eastern Himalayas (Sikkim), with a declining trend from west to east. However, some glaciers, such as Siachen in the western Himalayas, do not show appreciable change since 1970 (Raina, 2010; Raina & Sangewar, 2007).

Himalayan snow cover and glaciers are a major source of water for major rivers of Asia, such as Indus, Ganga (or Ganges), Brahmaputra, Sutluj, Yamuna etc. Among them, the major rivers of Asia, such as Indus, Ganga and Brahmaputra, originate at the border region of India, Nepal and China (Prasad et al., 2009; Prasad & Singh, 2007b) (Figure 1, 2a). The point of origin of some of these rivers is shown in Figure 1. The surface reflectance (true color) images of a part of this region, based on the Landsat observations (since 1972) and ASTER (since 2000) show a conspicuous decline in the snow cover and the formation of numerous new lakes especially at the terminus of receding glaciers (Figure 2a). The Landsat images from 1972, 1989, 2000 and 2006 and ASTER images of 2000 show a gradual decline in the snow cover compared to the earliest image from 1972 (Figure 1b). The ASTER image obtained in 2008 show, however, an increased snow cover compared to year 2000 due to an increased snowfall over the region during 2008 which is corroborated with the maximum snow cover extent product derived from MODIS Terra at 500m resolution. The Landsat and ASTER images over the western Himalayas (Figure 2b) and central Himalayas (Figure 2c) also show significant change in the snow cover since 1972. The monitoring of the Bara Shigri shows the glacier frontal retreat as well as vertical shrinkage since 1950 (Raina, 2010). The photographs over the western Himalayas (nearby Bara Shigri Glacier region, Himachal Pradesh, Figure 2b) show contamination of glaciers and their discoloring (yellowish layer over the white snow) (Figure 2d). The nature of material as seen over the peak Himalayan region is not known and needs further investigation. Figure 2c show the glaciers situated in the Tibet region that is ~85 km north of Kathmandu, Nepal (near the Nepal and Tibet border). These glaciers south of Lake Paiku Tso (Tibet) show the retreat pattern as well as the formation of numerous new glacial lakes (at their terminus) due to the melting of snow and glaciers. The change in color (light blue to deep blue) in the satellite images indicates the melting of snow (ice phase) to water phase that usually appears as deep blue to black in true color images. The eastern Himalayas, border of Arunachal Pradesh (India) and Tibet (China) also show a decline in the snow cover as seen in the Landsat images taken during year 1988 and 2001 (Figure 2e). The major glaciers of the eastern Himalayas are showing signs of melting and formation of new lakes in the region.

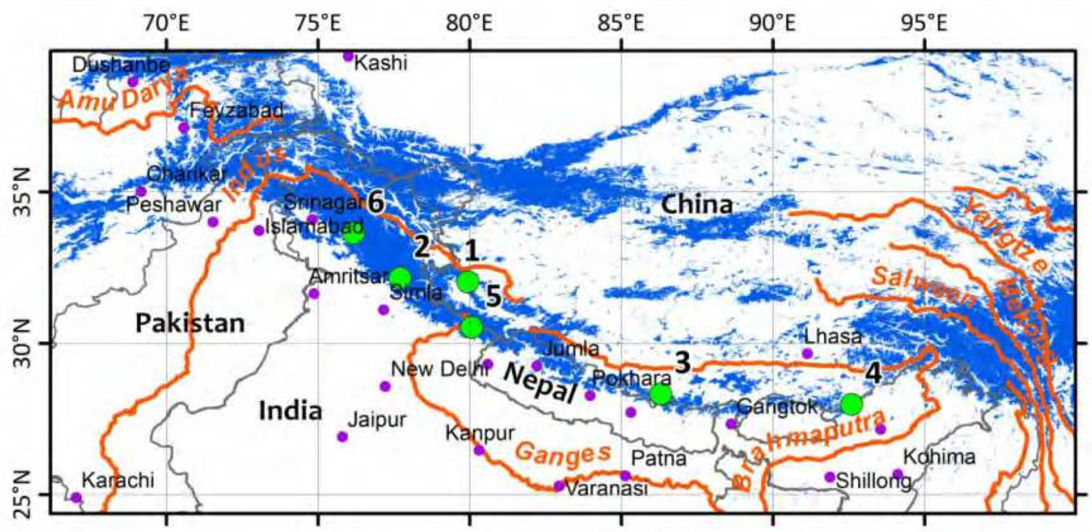

Fig. 1. The point of origin and pathways of flow of major rivers of Asia (marked as orange lines) are shown against the background of maximum snow cover extent from MODIS Terra (marked as blue color). The violet dots represent major cities in the region and the green dot (or circle) represents the location of major glaciers that are covered in Figures 2a-f.

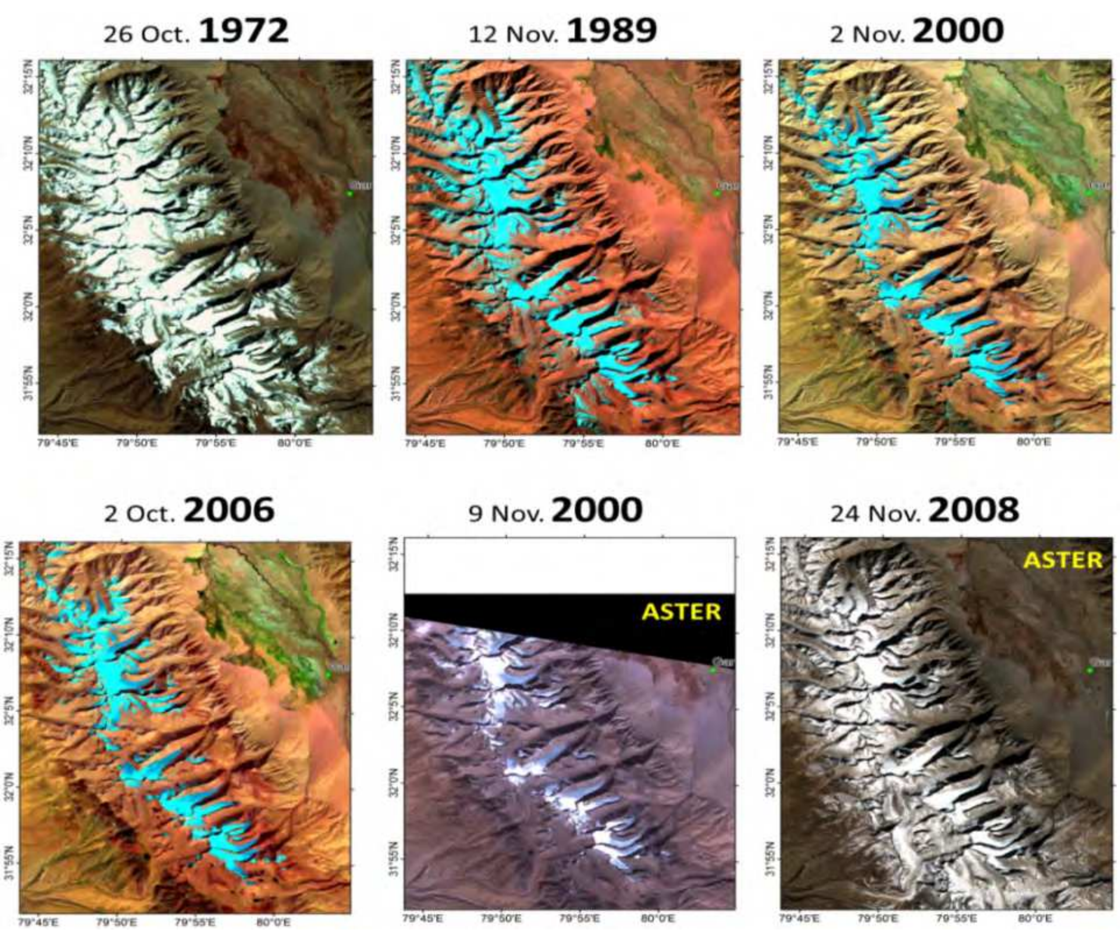

Fig. 2a. The true color images of Himalayan snow cover and glaciers, near the source of origin of three major rivers of Asia (Indus, Ganga and Brahmaputra), from the Landsat series (1972, 1989, 2000, 2006) and ASTER (2000, 2008). (*Location 1, in Figure 1*).

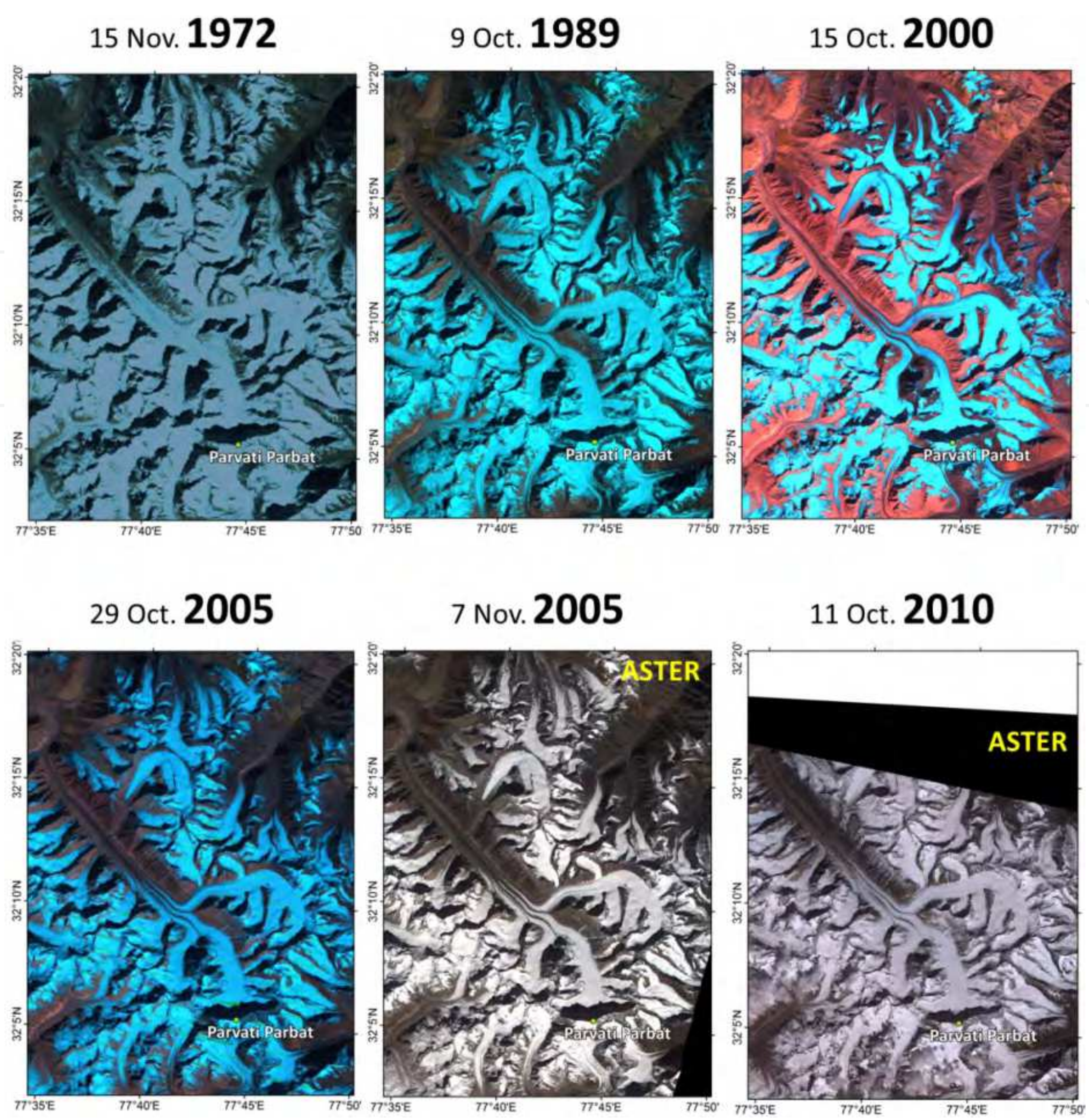

Fig. 2b. The true color images of western Himalayan glaciers (Bara Shigri Glacier, Spiti Valley, Himachal Pradesh, near Parvati Parbat) and surrounding regions from the Landsat series (1972, 1989, 2000, 2005) and ASTER (2005, 2010). (*Location 2, in Figure 1*).

The Goriganga river originates from the Milam Glacier at an altitude of ~3600 m and joins the Kali (Sharda) river downstream (after approximately 90 km) which finally merges into the Ganga river. The Landsat images from 1976, 1990, and 1999 depict changes in the snow cover and glacier over this region (Figure 2f). The Milam glacier is located NNE of Nanda Devi (7816 m, second highest mountain in India), a part of Garhwal Himalayas in the Uttarakhand State, India. Nanda Devi, means Bliss-Giving Goddess, is also regarded as the patron-goddess of the Uttarakhand Himalayas. The snow cover changes in numerous tributaries such as Goriganga and Kali River are important as they eventually feed into the main river Ganga. Moreover, small hydroelectric projects such as the Karmoli Lumti Tulli Hydroelectric project (55 MW) are proposed on the river Goriganga. The glaciers in the western Himalayas (near Doda, Jammu and Kashmir) show a decline in the snow cover along with the retreat of glaciers (Figure 2g). A significant trend in the warming of atmosphere (near-ground air temperature) has been observed over Jammu and Kashmir for period 1976-2007 (Jaswal & Rao, 2010).

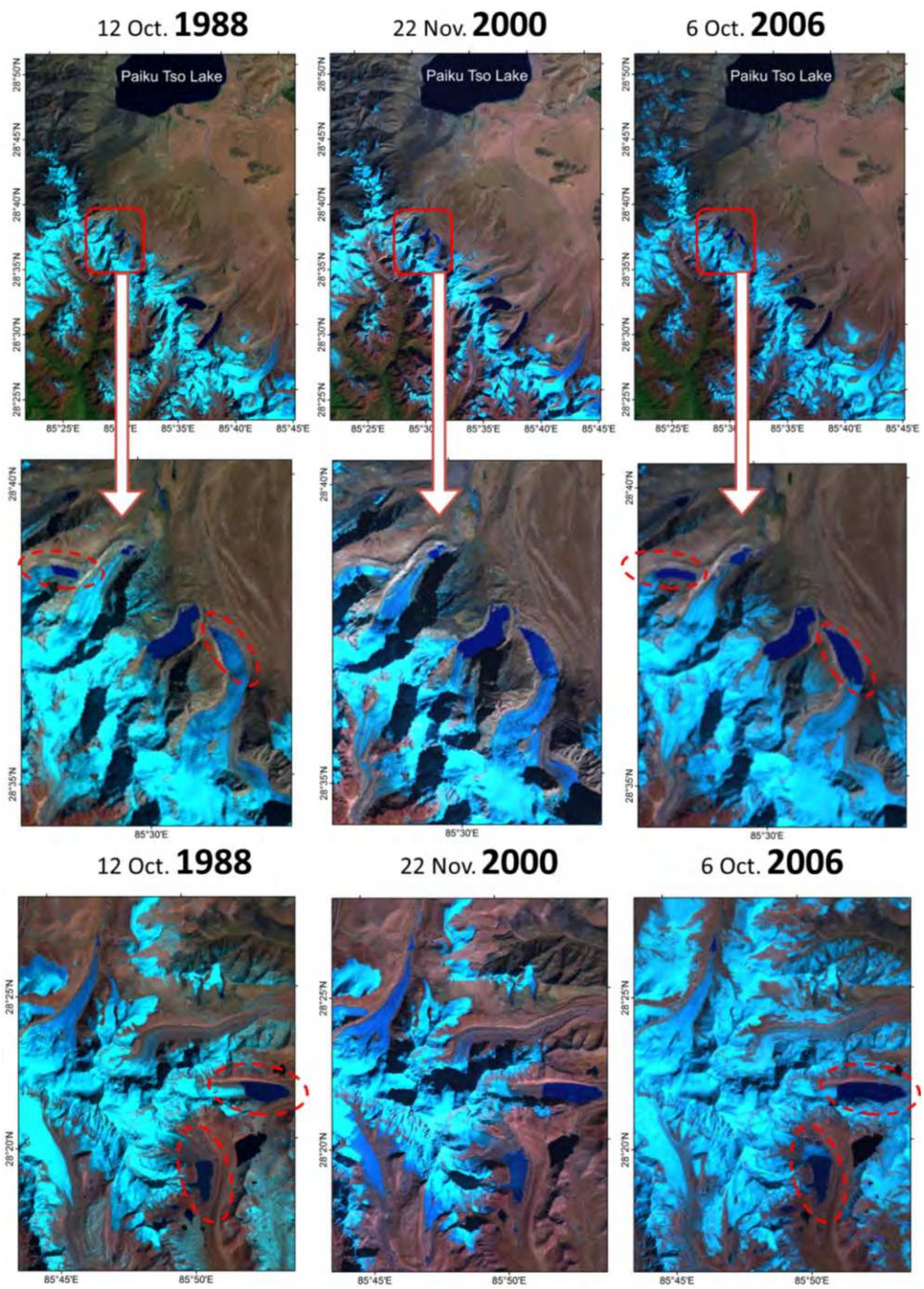

Fig. 2c. The true color images of central Himalayan glaciers (near Shisha Pangma which is the 14th highest mountain in the world – 8013m) from the Landsat series (1988, 2000, 2006) show the melting and formation of new lakes in the region during 2000 and 2006 compared with 1988. (*Location 3, in Figure 1*).

Fig. 2d. The photographs over the western Himalayan region (approximately around the Parvati Parbat, Bara Shigri Glacier region, Himachal Pradesh, Figure 2b) show contaminated glaciers with a yellowish layer over the white snow and glacier. Photo Courtesy: Alexander Naumov. Date of the photographs: 28 Aug. 2010.

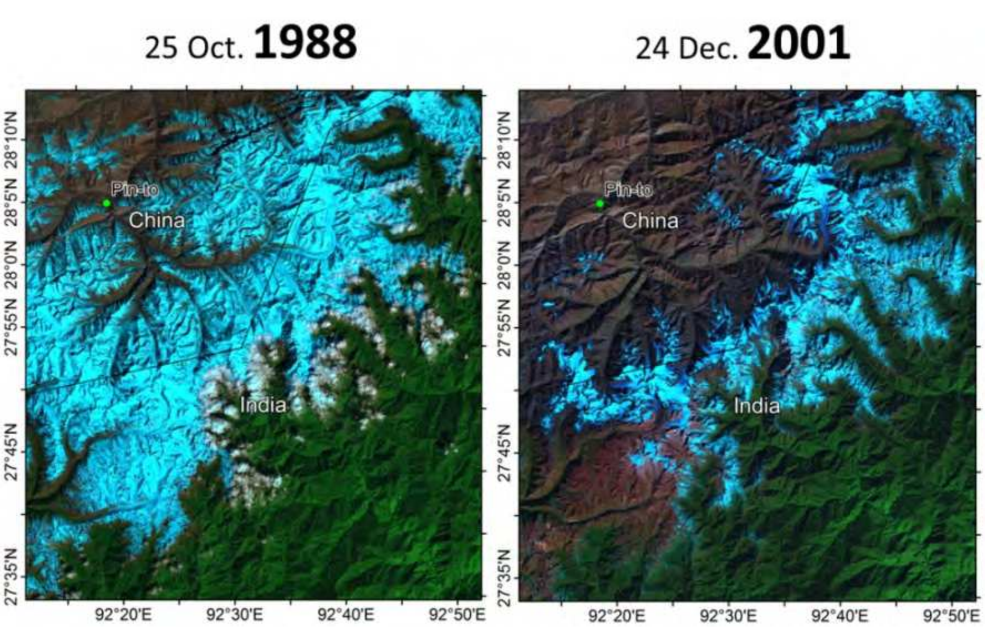

Fig. 2e. The Landsat images during year 1988 and 2001 show a sharp decline in the snow cover and enhanced melting of glaciers in the eastern Himalayas near the state of Arunachal Pradesh (India) and Tibet (China) border. (*Location 4, in Figure 1*).

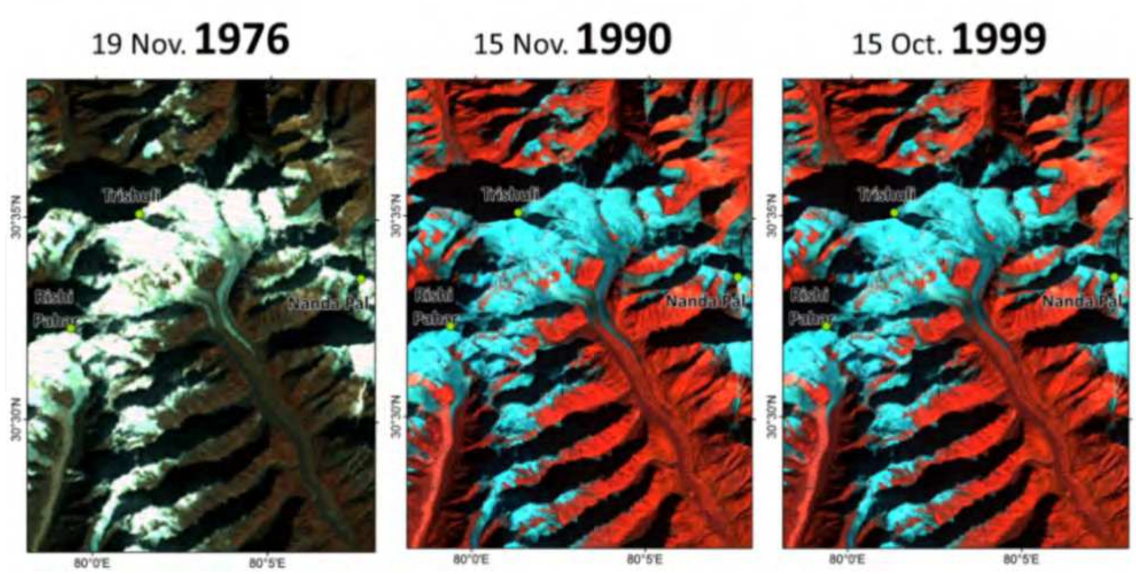

Fig. 2f. The Landsat images for year 1976, 1990 and 1999 over the Milam Glacier (Goriganga basin) in the central Himalayas (Uttarakhand State). (*Location 5, in Figure 1*).

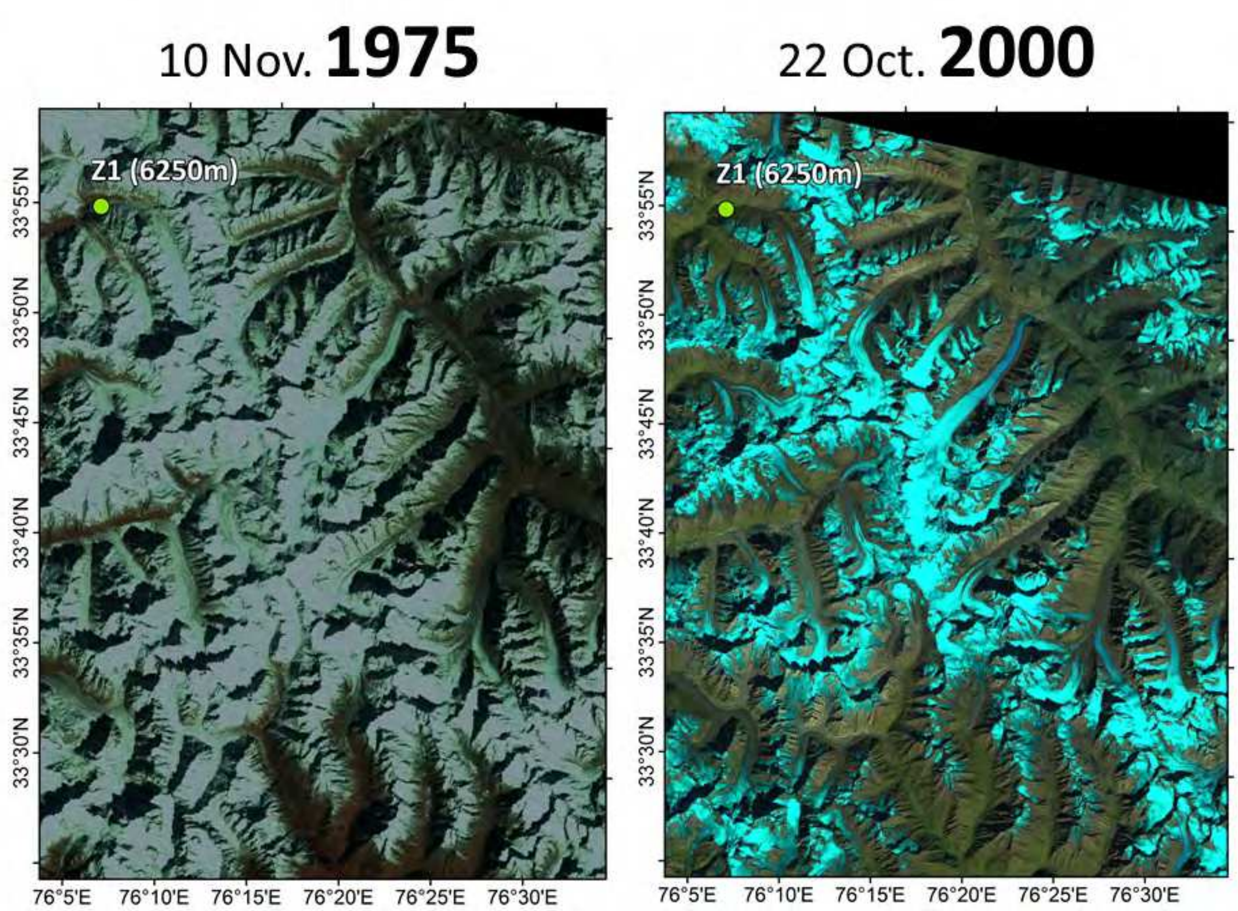

Fig. 2g. A comparison of the Landsat images from year 1975 and 2000 show a decline in the snow cover and enhanced melting of the western Himalayan glacier in between Doda (6573 m) and Z1 peak (6250 m) in the State of Jammu and Kashmir (India). (*Location 6, in Figure 1*).

4. Journey of dust storm over the Indian sub-continent

The first retrieval of aerosol loading over the land using POLDER (POLarization and Directionality of the Earth's Reflectances) data showed a dense concentration of aerosols over the Indo-Gangetic (IG) plains. A number of planned space-based sensors (MODIS Terra, MODIS Aqua, AIRS, PARASOL, ENVISAT, CALIPSO) and ground observations (AErosol RObotic NETwork - AERONET, Multi-wavelength radiometer – MWR, Microtops) have led to a better understanding of the amount, type and changes in aerosols over the Indian sub-continent and also the discovery of major aerosol "hot spots" over other regions of the globe. The desert dust, mixed with black carbon, is found to be one of the major sources of aerosols that affect the regional climate and precipitation patterns worldwide (Gautam et al., 2009; Lau & Kim, 2006; Lau et al., 2006, 2008, 2010; Ramanathan et al., 2005; UNEP, 2009).

4.1 Aerosol loading (dust and pollution) over the Indian sub-continent

The Intergovernmental Panel on Climate Change (IPCC) report of 2001 (IPCC, 2001) outlined a low level of understanding on the aerosols and their potential impact on the regional vegetation and climate. Since 2000, the availability of daily global data on the aerosols and associated variables from MODIS Terra (since 2000) and Aqua (since 2002) have greatly improved understanding of the aerosols, major sources, intra- and inter-annual variability over the Indian sub-continent (Bhattacharjee, 2007; Prasad & Singh, 2007a, 2007c; Prasad et al. 2006a, 2006b). Further, the ground-based observations from stations such as Delhi (Microtops) and Kanpur (AERONET) since 2001 have been used extensively to understand the physical and optical characteristics of aerosols over the western and central IG plains respectively (Prasad & Singh, 2007a; Prasad et al., 2007; Srivastava et al., 2011).

4.1.1 Pre-monsoon season: Dominance of desert dust

The vast agricultural land, plains of Indus and Ganga river, suffer from high concentration of desert dust and anthropogenic aerosols. Figure 3 show very high aerosol loading (appear as orange to red color, AOD > 0.5) over the IG plains during the summer and winter seasons (mean of 2000-2008). This belt of high AOD is observed to be running parallel to the Himalayan Mountain range (Figure 3a). The retrieval of AOD, as shown in figures 3a,b is based on the dark-target (DT) algorithm which is more sensitive to the ocean or lake water and dense vegetation covered regions over the land. The seasonal distribution of aerosols shows a striking contrast between the summer and winter aerosol loadings over the IG plains. The winter season, which is largely devoid of the transported desert dust, show mostly fine anthropogenic aerosols while the summer season is dominated by the coarse desert dust aerosols that get mixed with the local anthropogenic aerosols (Prasad et al., 2006a, 2006b). The long range transport of desert dust from the western sources gradually raises the aerosols loading over the IG plains during the period April to June. The AERONET data show that the mean AOD rises from 0.4-0.5 to 0.6-0.7 (>0.8-0.9 over the western side) from April to June months respectively due to the influence of these episodic dust storms (Prasad & Singh, 2007a). These pre-monsoon dust storms have been found to reach up to high altitude over Himalayas (Prasad & Singh, 2007b). The pre-monsoon dust storms are thereby affecting the regional atmospheric temperature and snow cover and hence glaciers dynamics over the Himalayas and Tibetan Plateau, especially the western and central regions (Lau et al., 2010; Prasad et al., 2009).

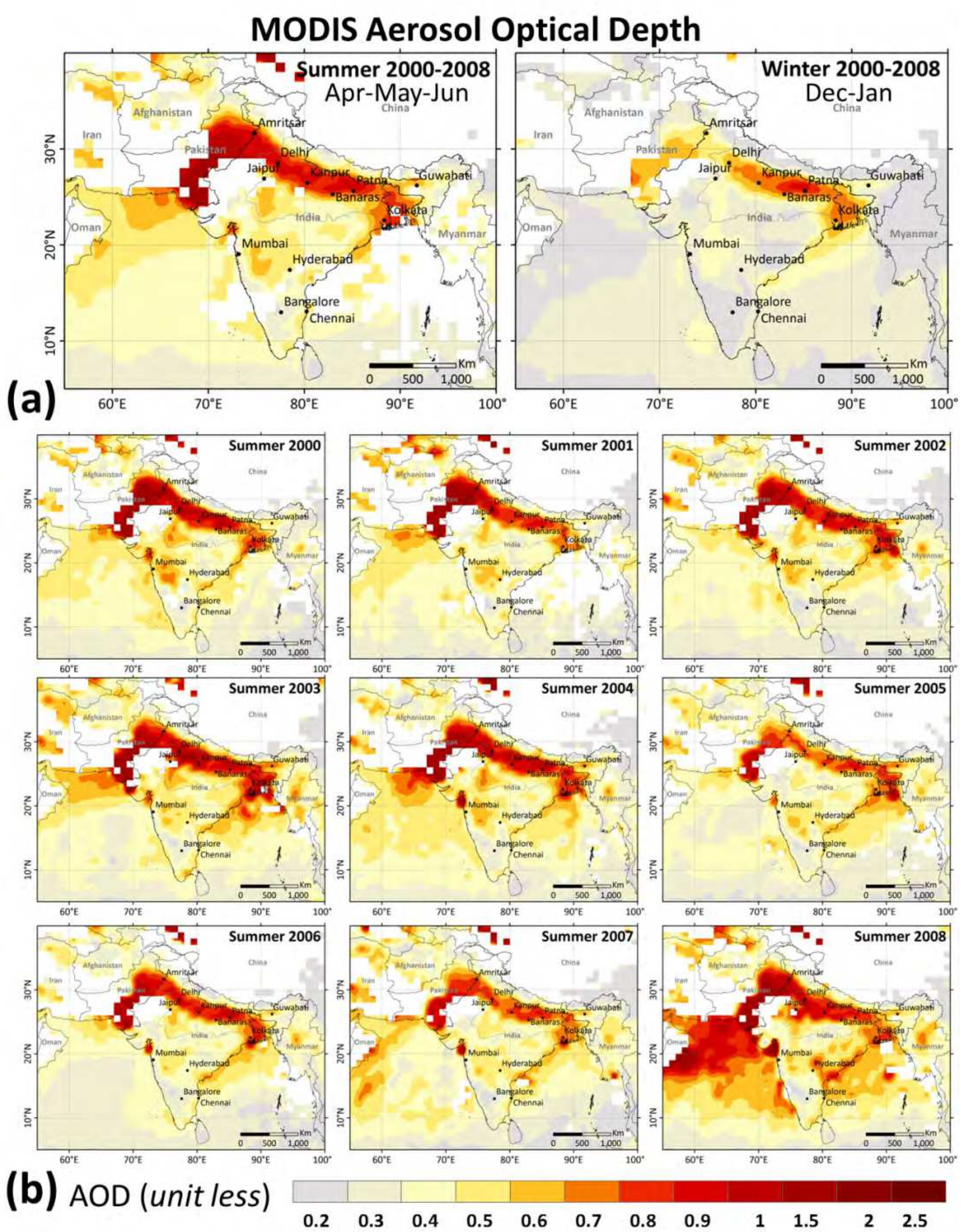

Fig. 3. (a) Mean MODIS Terra derived dark-target (DT) AOD (summer and winter season) over the Indian sub-continent and surrounding regions (Arabian Sea) during 2000-2008. (b) Inter-annual variability (2000 to 2008) of aerosol loading over the Arabian Sea and IG plains during the pre-monsoon season (April to June).

Figure 3b shows strong inter-annual variation of aerosol loading over the Indian sub-continent and its surroundings. For instance, the year 2008 shows the highest aerosol loading over the Arabian Sea which is situated between the major dust sources and sink regions. This anomaly indicates that the emission as well as the transport of dust varies greatly every year. Thus the effect of desert dust on the regional climate of the IG plains varies year-to-year with the variation of influx of transported aerosols.

Figure 4 show a simplified map of the location of major sources of dust over the IG plains. The satellite aerosol data as well as the dust transport model (HYbrid Single-Particle Lagrangian Integrated Trajectory - HYSPLIT) leads to the identification of these major sources. The HYSPLIT back-trajectory shows that the dust storm reaches over India in 2-5 days depending upon the distance of the source of desert dust (Prasad & Singh, 2007a). The dust storm from the arid regions of Afghanistan, Pakistan, Thar Desert (India) usually passes over land (land route) while the dust storm from Iran, other parts of Middle East and Sahara usually passes over the Arabian Sea (sea route) before reaching the IG plains (Figure 4). Thus the moisture associated with these dust storms varies with their route (Prasad & Singh, 2007a).

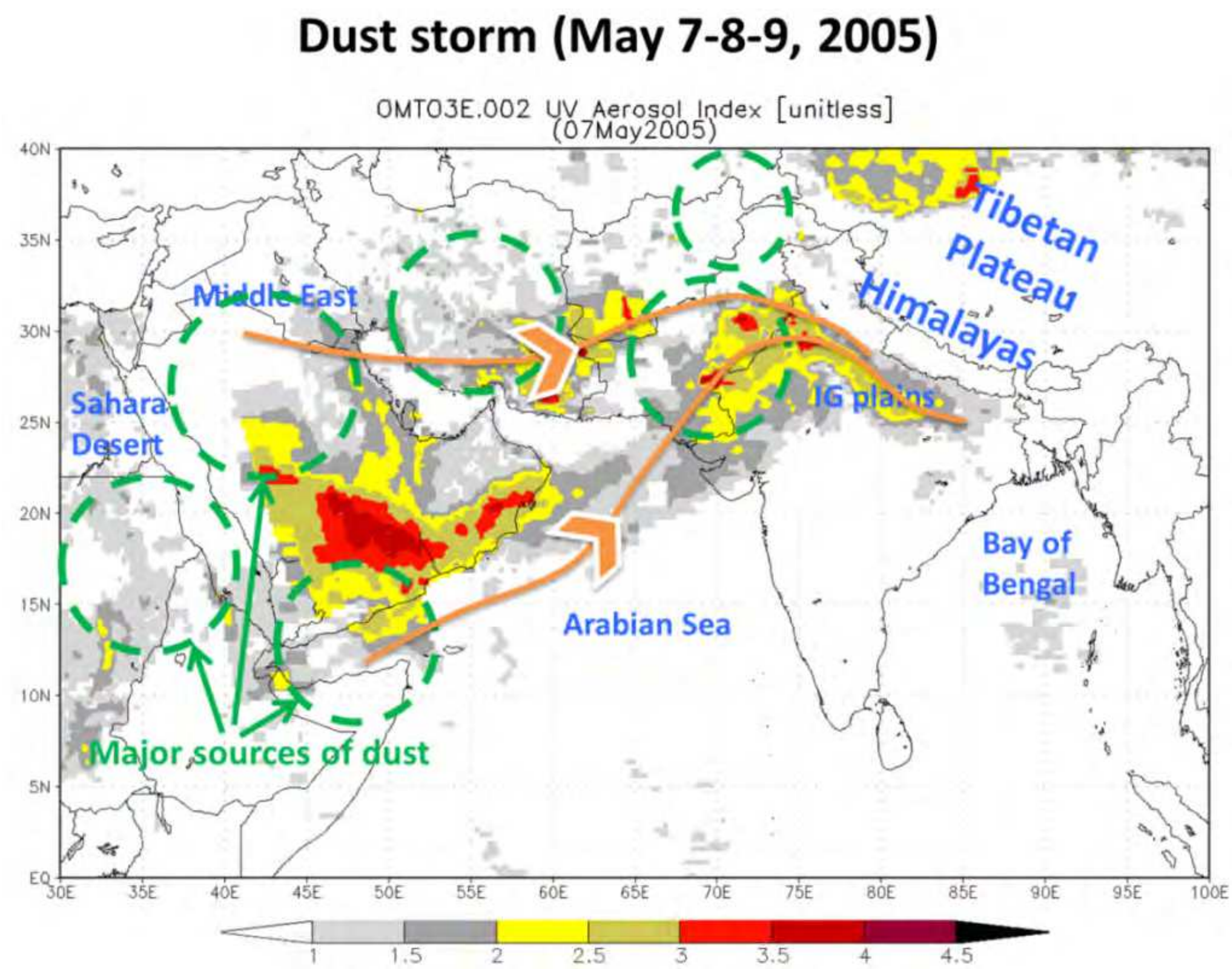

Fig. 4. The location of major sources of dust storms over the Indian sub-continent is marked as green broken circles (Prasad and Singh, 2007a). The two major pathways of dust storms, the sea route passing through the Arabian Sea and the land route, are marked by the orange line. The background show Aura derived UV aerosol index during a dust storm event (May 7, 2005) that illustrates the transport of dust aerosols through the Arabian Sea before reaching the IG plains.

The valley-like topography of the IG plains bounded by high altitude Himalayas (~ 4-6 km) in the north and Vindhyan mountain range (~700m) and Chotanagpur plateau in the south and Rajmahal hills in the southeast causes channelization of the dust storm as it moves from the west (Delhi and Jaipur) to the east (Kolkata and Dhaka) (see Figure 5a). This figure shows the three-dimensional topographical set-up of the study region (the Himalayas and IG plains). The west to east journey of the desert dust in the IG plains, capped by towering Himalayas in the north, not only affects the aerosol loading in the entire IG plains but also the Himalayas because a portion of the desert dust (mixed with local pollutants) also reaches the high altitude region over Himalayas. Because the dust storm is much stronger over the western and central IG plains as compared with the eastern zone, the direct and indirect effect of dust related loading is more prominent and frequent in the western and central Himalayas. However, some of the episodes of dust have been found to be reaching up to the Eastern Himalayas (East Nepal and Sikkim Himalayas). The evidence for transport of dust up to Himalayas is discussed in section 5.

4.1.2 Winter season: Dominance of anthropogenic emissions

The winter aerosol loading, mostly anthropogenic, is also high in the entire IG plains (valley region) (Figures 3a, 5a). During the winter season, fine aerosols emitted by the thermal power plants, industries, vehicles, coal-fired brick kilns, and bio-fuel burning stoves dominate the total aerosol loading over the IG plains (Di Girolamo et al., 2004; Prasad et al., 2006a; Ramanathan & Ramana, 2005). Although the dust storms are rare during this period, the satellite observations and overall assessment of aerosols indicate a dominant anthropogenic component exists over the IG plains. The bio-mass and bio-fuel burning and vehicular emission are traditionally considered to be one of the highest contributors to the winter aerosols (Di Girolamo et al., 2004; Garg et al., 2001; Gadi et al., 2003; Ramanathan & Ramana, 2005). Recent studies on the emissions from the major thermal power plants over India show that the coal fired power plants and similar industries, such as smelters, are one of the major contributors of gaseous (tropospheric NO_2) and particulate (black carbon, fly ash from coal) pollution (Ghude et al., 2008; Prasad 2007; Prasad et al., 2011) (Figure 5b). The NO_2 emissions (Ozone Monitoring Instrument, OMI Aura) from these coal based power plants situated in low populated regions such as Agori in the central India are found to be much higher than the largest city such as Delhi (with ~25 million human and ~5.6 million vehicular population) (Prasad et al., 2011). The presence of fine anthropogenic aerosols and gaseous pollutants such as ozone, NOx and SOx, very high humidity (>90%), near zero or calm wind, and near-ground (10-100 m) boundary layer leads to a severe problem of dense fog and high ozone during December and January (Di Girolamo et al., 2004; Prasad et al., 2006a; Ramanathan & Ramana, 2005). The development of dense fog with increasing intensity, duration, and frequency over the last two decades (1990-2010) is a relatively recent phenomena compared to the beginning of the Industrial (power utility) revolution in India (1970-1980) because most of the power plants were setup in the region since 1980 (Prasad et al., 2011) along with the gradual increase in the vehicular population. The disruption of air-traffic, ground-traffic and railways due to the dense fog during the winter season has increased the awareness to this problem among the public and media in recent years.

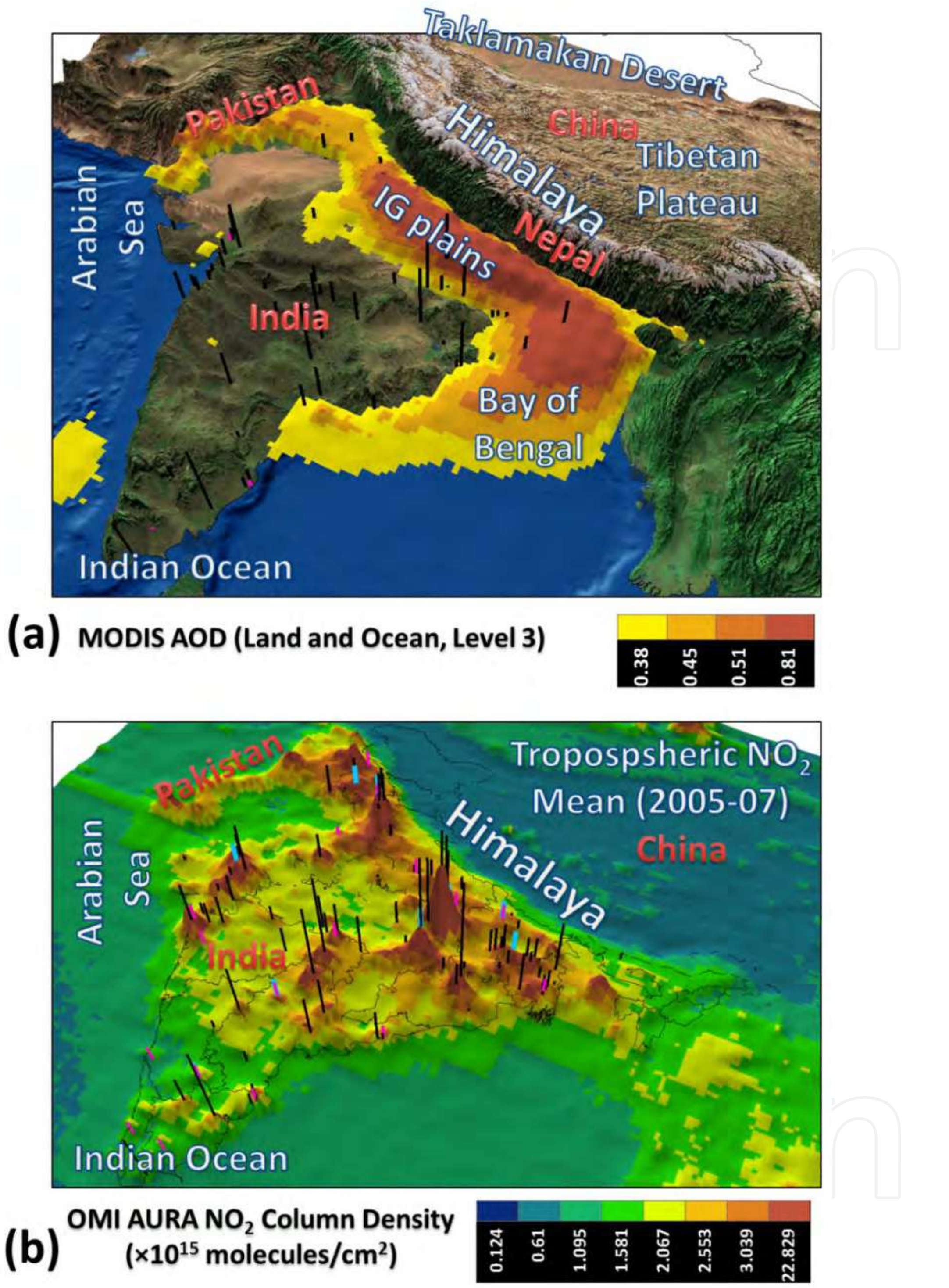

Fig. 5. (a) The three-dimensional image illustrates the valley type topography of vast alluvial IG plains that is bounded by the high altitude Himalayas in the north and Vindhyan mountain range in the south. The mean aerosol loading over the Indian sub-continent during the winter season (December and January, 2004-2008) illustrates high AOD over the entire IG plains. (b) The mean annual tropospheric NO_2 over the Indian sub-continent as measured by OMI Aura. The black lines or bar represent major (>100 MW) thermal power installations in the region where the length of bar is directly proportional to its capacity. The seasonal distribution of NO_2 is available at Prasad et al. (2011).

The recent advances made by the atmospheric aerosols science community through the space based multi-sensor monitoring, dust modeling and ground dust observations had led to an increased awareness among the public and media (newspapers, magazines, radio, and television). Figure 6 shows the arrival of a dust storm over the Delhi region on May 13, 2008 (using Total Ozone Monitoring Satellite - TOMS aerosol index) and its after-effect on the Delhi metropolitan area on May 13-14, 2008. Similar reports appeared in the print and television media from several cities west of Delhi (Lucknow and Kanpur, located in central IG plains) on the subsequent day. The reports of loss of life, property, respiratory problems, and air and ground traffic disruptions etc, in various media sources show the unpreparedness of the agencies and organizations affected or responsible for responding to such events. Though the awareness about the after-effects of dust storms are increasing in the region, an integrated approach (a decision support system) to tap the potential of forecasting dust storms using near real-time satellite observations, such as the MODIS direct, broadcast together with the dust transport models and ground based observations to warn the public and industrial sectors affected by these events is still lacking.

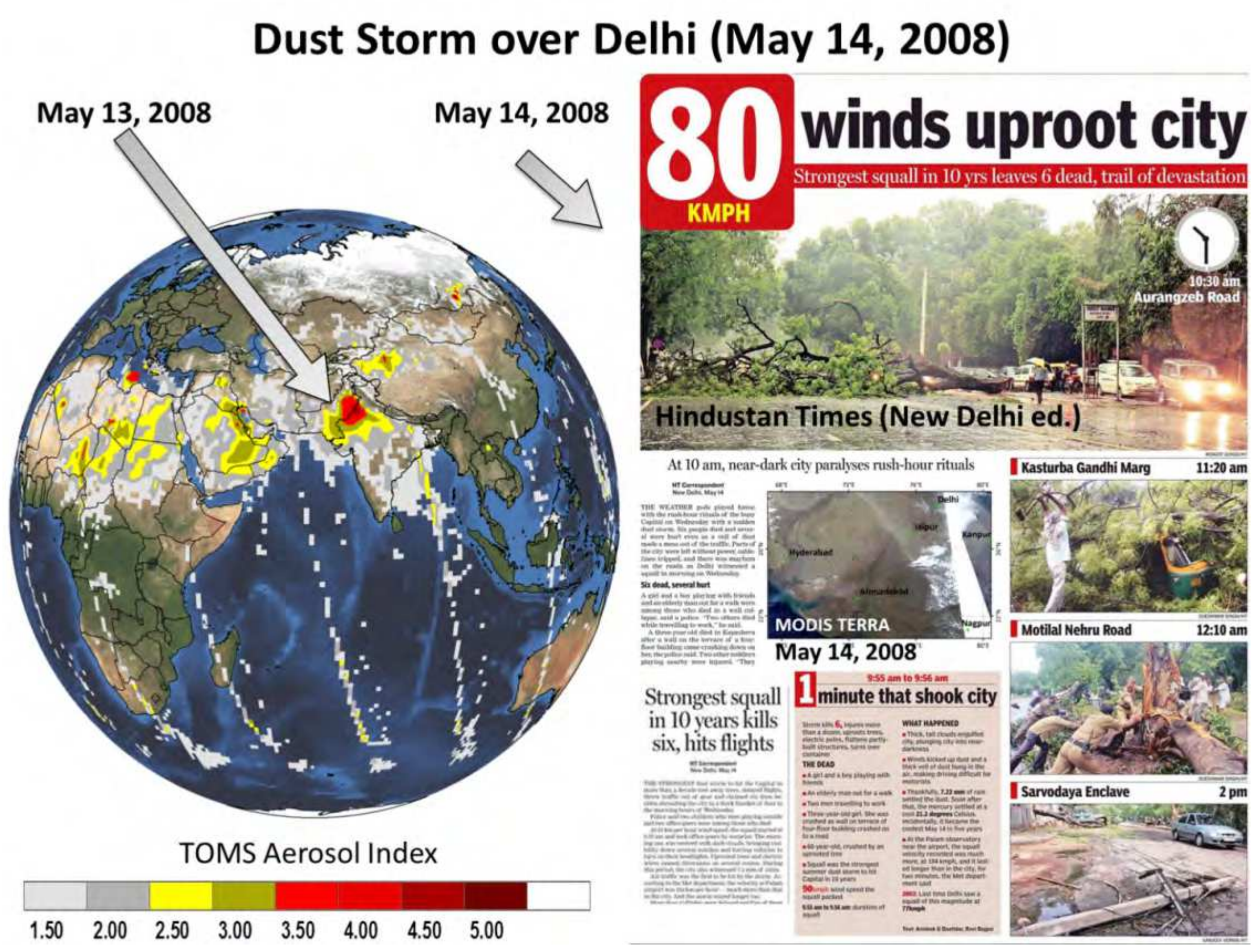

Fig. 6. The left panel shows arrival of the dust storm over Delhi region on May 13, 2008 using TOMS aerosol index (AI). The high values of TOMS AI (2.5-5) illustrate the aerosol loading associated with the dust storm. The right panel shows the after-effects of the dust storm over Delhi that was reported in several leading national newspapers (such as Hindustan Times, New Delhi edition on May 14, 2008).

5. Journey of dust to high altitudes over Himalayas and Tibetan Plateau

The episodes of dust storms are very frequent during the pre-monsoon season. The Figure 3 emphasizes the seasonal and inter-annual variation and distribution of aerosols over the land and oceans. Figure 3 also shows some notable blank regions in Pakistan, Iran, Afghanistan, Oman and Sahara. This is due to the fact that the traditional Dark Target (DT) AOD retrieval algorithms do not capture the aerosol loading over very bright arid or semi-arid desert surfaces that have sparse or negligible vegetation cover.

To overcome this limitation, incorporating the blue spectral band (Deep-Blue, DB algorithm) enhances the accuracy and frequency of the retrieval of AOD over such land surfaces as they are very sensitive to the dust (Hsu et al., 2006; Ginoux et al., 2010). For instance, a comparison of a true color image (composite of red, green, and blue – RGB: Band 1, 4, and 3), reflectance from the blue band (MODIS Band 3, 479 nm), MODIS Terra AOD (only DB), MODIS Terra AOD (both DT and DB) and AOD-like scale for values derived from the blue band (level 2, collection 5.1) is shown for a dust storm that affected the IG plains on June 7, 2003 (Figure 7). The area covered by the dust storm which is visible as a very bright surface in the true color image appears as a prominent region with very high reflectance in the band 3. The MODIS Terra AOD, based on the DB approach, retrieves the dust loading over bright surfaces, such as Thar desert, while a combination of both DT and DB approach gives better results (Figure 7). However, there is a scope for an improvement in the AOD retrieval procedure as both DB and DT misses the central median line of dust storm that appears as blank region bounded by very high AOD values. The scaling of values like AOD from the blue band (no other correction is applied) shows the continuity of dust storm and its perimeter. The band 3 by itself, presents scope for improvement in the aerosol retrieval along with other bands such as band 11 and 12 (used for cloud detection) that helps in distinguishing the dust aerosols from surroundings.

Therefore, to identify and quantify the aerosol loading due to the major dust storms, we have utilized a combination of DT and DB algorithm to retrieve the AOD over land and ocean using the MODIS sensor on the Terra and Aqua. In this section, we present dust storm cases that highlight the journey of dust up to high altitudes over Himalayas using the MODIS (column AOD) and CALIPSO (vertical profile) observations.

5.1 Dust over Himalayas: Evidences from MODIS Terra and Aqua

A day to day analysis of aerosol data from MODIS during May 28 - June 15 show a number of dust storm events that affected the IG plains and Himalayas during the year 2003. The ground-based AERONET station at Kanpur also confirms these dust storms (Prasad & Singh, 2007a). Figure 8 shows a three day composite (maxima) of aerosol loading (Level 2, version 5.1, 10km grid) using both DT and DB algorithm to maximize the coverage over land and ocean. The composite of May 28-30 show very high AOD over the land and Arabian Sea. Similarly, a composite of June 6-8 also show very high AOD over the land and Arabian Sea. The path and source of the dust storm is emphasized by very high AOD over the western region that shows continuity up to the IG plains. During this period, the ground observed AOD (approximately every 15 minutes) from the Kanpur AERONET station (Prasad & Singh, 2007a) also showed arrival of a number of dust storms over the Kanpur city (central IG plains).

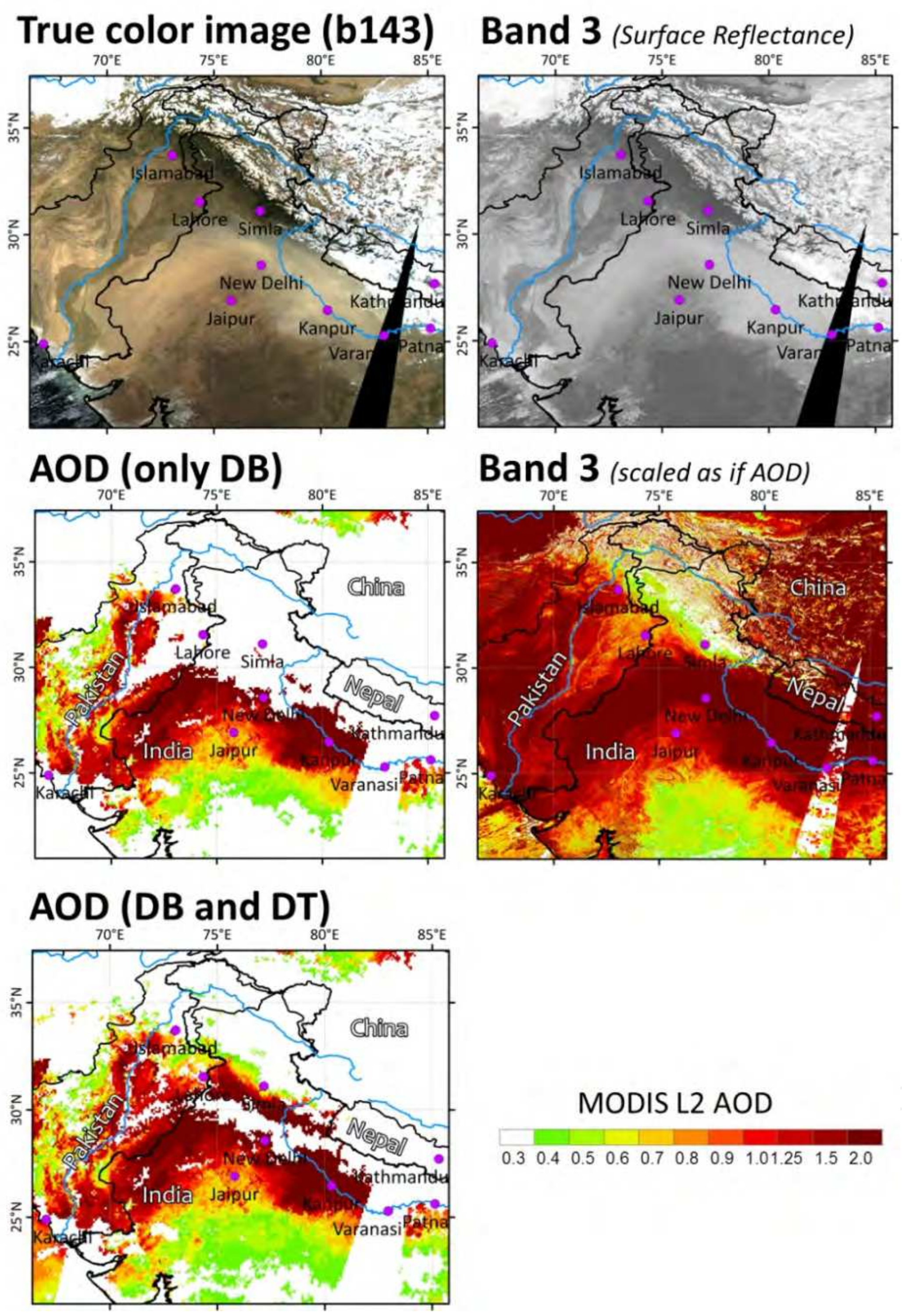

Fig. 7. The true color image (band combination: RGB: 1,4, and 3) based on the MODIS Terra observations during a dust storm event on June 7, 2003. The dust affected region is prominent in the band 3 (blue band: 479 nm). The AOD (only DB) and AOD (combination of DB and DT) from level 2 Terra (collection 5.1) show quantitative aerosol loading due to the dust storm (marked as green to deep red color). The MODIS AOD like scaling using only MODIS band 3 (blue band) without any other filtering for cloud etc., illustrates its usefulness in deriving AOD over bright (arid) and low vegetative surfaces.

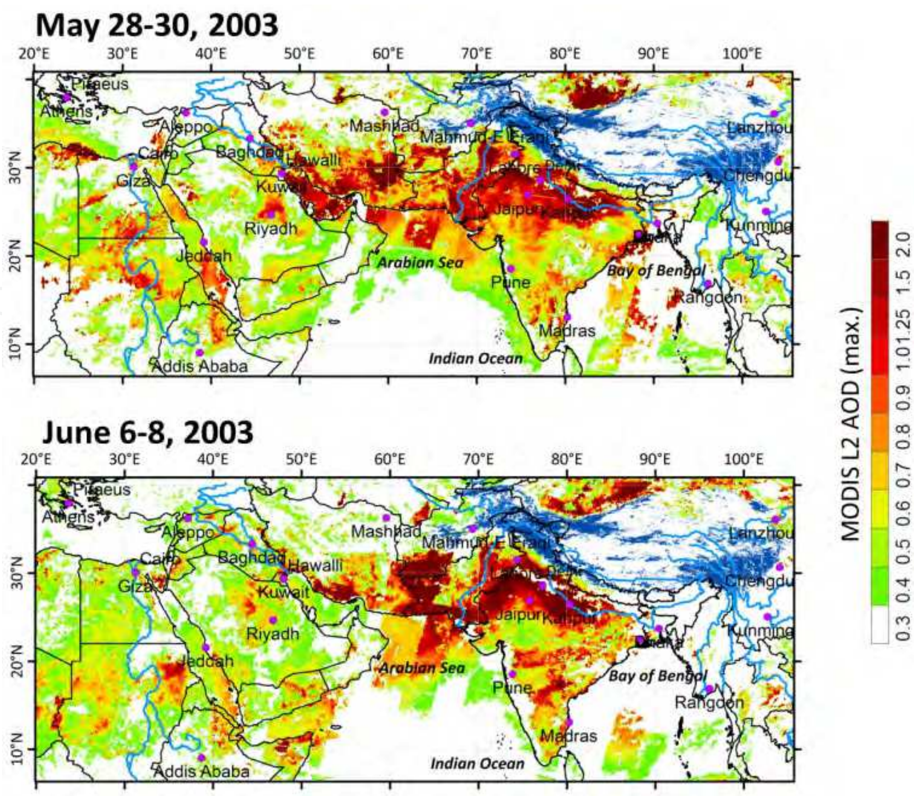

Fig. 8. Three day maxima of aerosol loading derived from MODIS Terra level 2 AOD (10 km grid, collection 5.1) during May 28-30 (top panel) and June 6-8 (bottom panel) illustrates source and path of transport of dust storms through the land and sea route as marked in Figure 4. The high aerosol loading over the IG plains (appear as deep red color) is primarily attributed to the desert dust brought by such dust storms.

5.1.1 Dust over the major rivers of Asia

A closer look at the daily aerosol retrieval (at 10 km grid resolution) using both DB and DT algorithm clearly shows a very high AOD over the high-altitude snow covered and glacier regions of Himalayas (Figure 9). The data used is a daily level 2 AOD, collection 5.1 from MODIS Terra and Aqua (Figure 9). The white color features in figure 9 represents the high altitude snow cover and Himalayan glaciers that are situated at an average height of ~4-6 km above the msl. Further, the region shown in these figures is interesting and valuable as three major rivers of Asia (Indus, Ganga – Brahmaputra) originate from here and depend on the snow cover and glacier melt for base river flow. Numerous other rivers such as Yamuna (passing through Delhi), Sutluj, and tributaries of river Ganga also originate from here. Very high AOD over the Himalayas is clearly visible during these dust storm events (May 31 to June 2, 2003 and June 12-13, 2003) (Figures 9a,b). Both Terra and Aqua (pre-noon and after-noon overpass) data show high AOD, visible as green-yellow-orange-red, over the Himalayan region. The MODIS AOD images also show that the dust storm also affects the Nepal Himalayas (both western and eastern Nepal) as it moves from the west to the east. The level-2 AOD is highly useful for such studies as it captures the dust storm and its reach in greater detail compared to the level 3 AOD at 100 km grid that has been found to be grossly missing the event of dust over Himalayas primarily due to its coarser resolution, incomplete retrieval over all pixels, and the binning method used to produce the level 3 data. The vertical profile of dust from CALIPSO is not available for these events as it was launched during the year 2006.

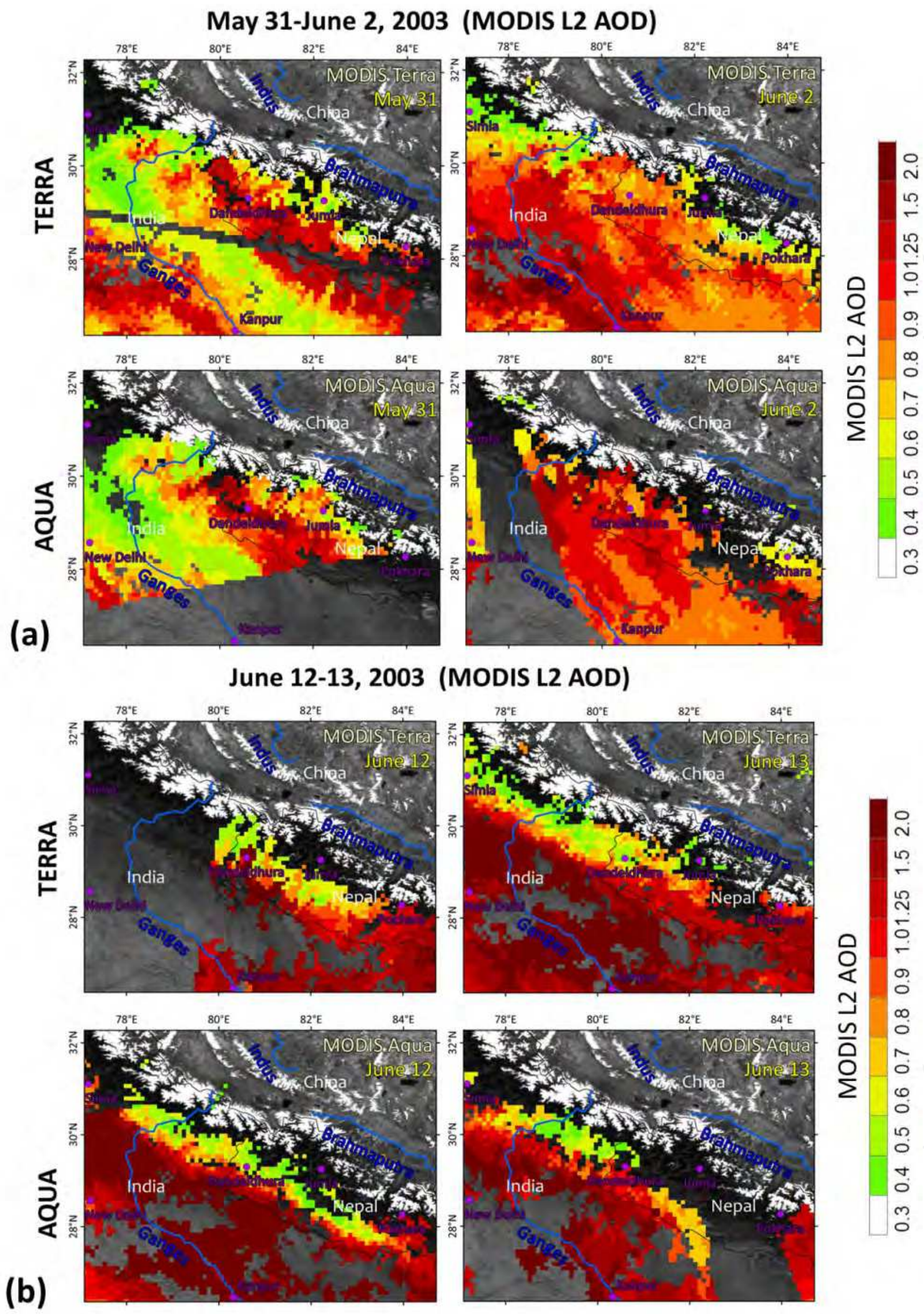

Fig. 9. The MODIS Terra and Aqua level 2 column AOD (collection 5.1) images during a dust storm episode on (a) May 31 and June 2, 2003 and (b) June 12-13, 2003, illustrates that the dust storm reaches up to the high-attitude Himalayan snow covered and glacier regions. The white color objects along the border of India, Nepal and China show the Himalayan snow cover and glaciers near the origin of three major rivers of Asia (Indus, Ganga, and Brahmaputra).

5.2 Dust over Himalayas: Evidences from CALIPSO vertical profiles

CALIPSO uses an active laser beam that provides unique information about the vertical structure of aerosols and clouds in the atmosphere. A number of parameters from CALIPSO such as the total attenuated backscatter at 532 nm, 1064 nm, their attenuated color ratio or c-ratio (1064/532nm), perpendicular backscatter at 532nm, and depolarization ratio or d-ratio provides critical information and identification of the dust (or clouds) and also its vertical structure. The aerosol related parameters from other sensors onboard Terra and Aqua (MODIS), CNES/Myriade (PARASOL), AURA, Earth Probe –EP (TOMS) etc., gives information only about the total column of atmosphere. To obtain evidence of dust storms reaching up to the high altitude Himalayas and Tibetan Plateau (~4-6 km), a vertical profile of the atmosphere when the major dust storms hits the region is vital. Further, such vertical profiles of the dust storms are needed over different regions (western, central and eastern) to assess the impact of dust. In this section, we present some evidence of dust reaching Himalayas in all three aforementioned regions during the entire pre-monsoon period (April, May and June) when the dust storm activity is highest over the IG plains. All the CALIPSO vertical profiles (0-20 km or 0-8 km) presented here depict the time of overpass (in UTC), and latitude-longitude (location) in the X-axis (bottom and top of x-axis respectively). The surface elevation along the path of CALIPSO is marked as a thick black line in Figures 10-15. The inset shows the path of CALIPSO overpass over the Globe (black line) and the study region (pink line) (Figures 10-15).

5.2.1 Dust and anthropogenic aerosols over Central Himalayas and IG plains

The vertical profile of the atmosphere (0-20 km), as measured by CALIPSO, over passes through the central IG plains (State of Uttar Pradesh), Himalayas (State of Uttarakhand – formerly Uttaranchal, and western Nepal), Tibetan Plateau and Taklamakan desert is shown in Figure 10. The vertical profile from 41°-16° N (during 20:34 to 20:41 UTC or 2:04 to 2:11 am local India Standard Time – IST) show the vertical structure of a major dust storm passing through the central IG plains on April 22, 2010. Very high concentration of dust is observed from night-time CALIPSO backscatter (532nm) over the IG plains that are reaching up to the 4-5 km height near Himalayas and its foothill region. Dust is also observed over the Taklamakan desert. Other parameters from CALIPSO, such as perpendicular attenuated backscatter (532nm), total attenuated backscatter at 1064nm, c-ratio, and d-ratio, also support the presence of a major dust storm (Figure 12a). The cloud, with very high backscatter, at ~20° N latitude, blocks the backscatter from the atmosphere (appear as deep blue) below it. The perpendicular attenuated backscatter (532nm) show the scattering of laser beams by the dust particles which appear as colored dots against a blue background in Figure 12a.

5.2.2 Dust and anthropogenic aerosols over Western Himalayas and IG plains

During year 2010, one of the major dust storms is found to be reaching up to ~7 km over the western IG plains and western Himalayas on May 27 (Figure 11). The ceiling of the dust storm over the states of Punjab and Rajasthan (part of the western IG plains) is between 5-7 km. The height of dust (~7 km) is extending higher than the range of height of the Kashmir and Himachal Pradesh Himalayas (~2-5.5 km) as seen from the CALIPSO profile along with the surface elevation profile (Figure 11). This night-time profile was obtained during 21:05 to 21:11 UTC (or 2:35 to 2:41 am local time or IST).

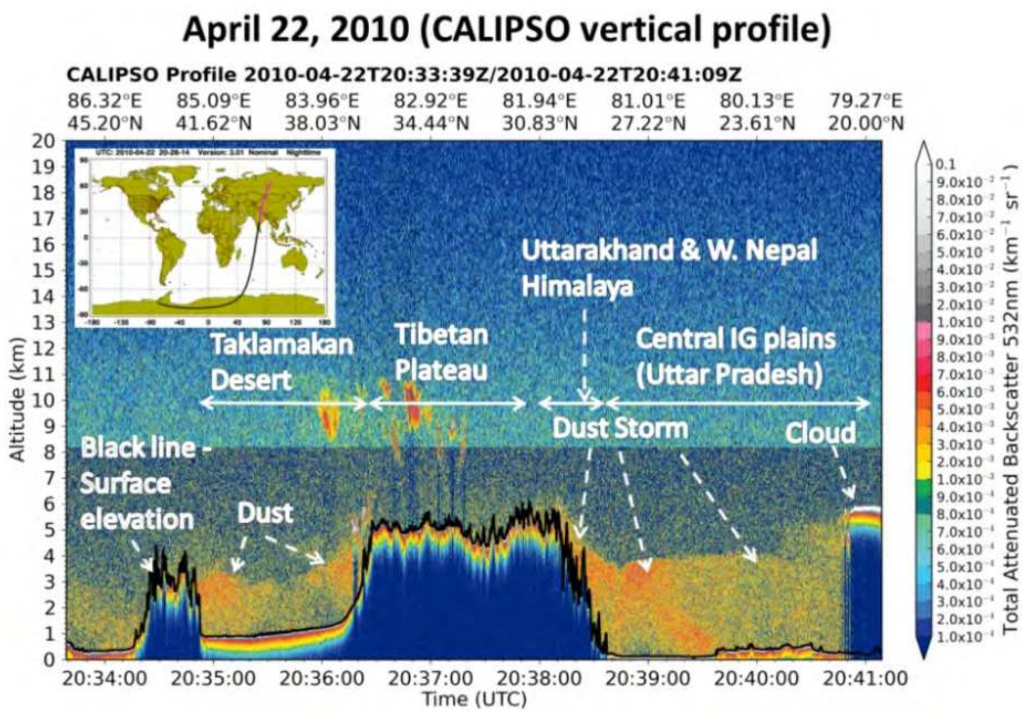

Fig. 10. The atmospheric profile (total attenuated backscatter at 532 nm, 0-20 km) of a dust storm event as measured by the night-time CALIPSO overpass over the central IG plain, Himalayas and Tibetan during April 22, 2010 (at 2:04 to 2:11 am IST).

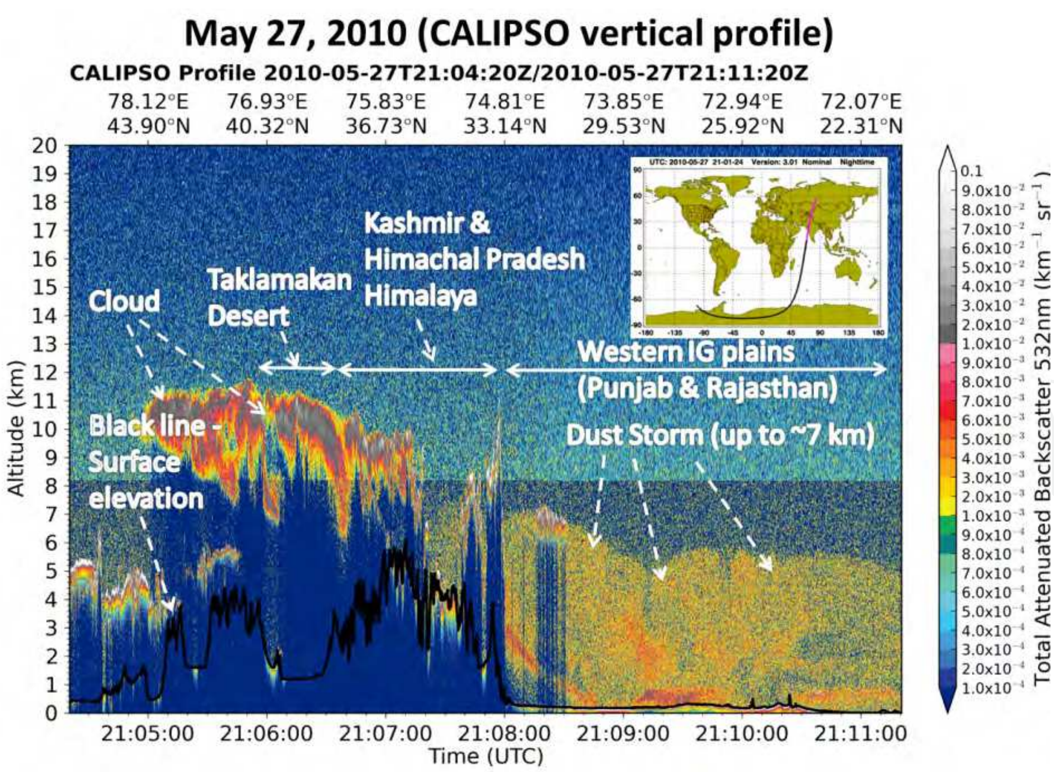

Fig. 11. The atmospheric profile (total attenuated backscatter at 532 nm, 0-20 km) of a dust storm event as measured by the night-time CALIPSO overpass over the western IG plain and western Himalayas during May 27, 2010 (at 2:35 to 2:41 am IST).

No dust is observed over the Taklamakan desert (near ground) during this overpass compared to the previous example (April 22, 2010, Figure 10). However, a thick layer of very high scattering particles (or cloud) is observed over the Himalayas and Taklamakan desert between altitudes 6-12 km that needs further investigation as the dust may get mixed with clouds that change the characteristics of aerosols and clouds (Figure 11). Other parameters from CALIPSO, shown in Figure 12b, mark the presence of various dense layers of dust between 26°-30° N (at 0-1 km height and from 1-8 km) that shows the state of vertical mix up of the dust in the atmosphere. Further, the dense layer of dust between 0-1 km show a gradual increase in the height to 0-4 km as it moves northwards between 30°-33.15° N.

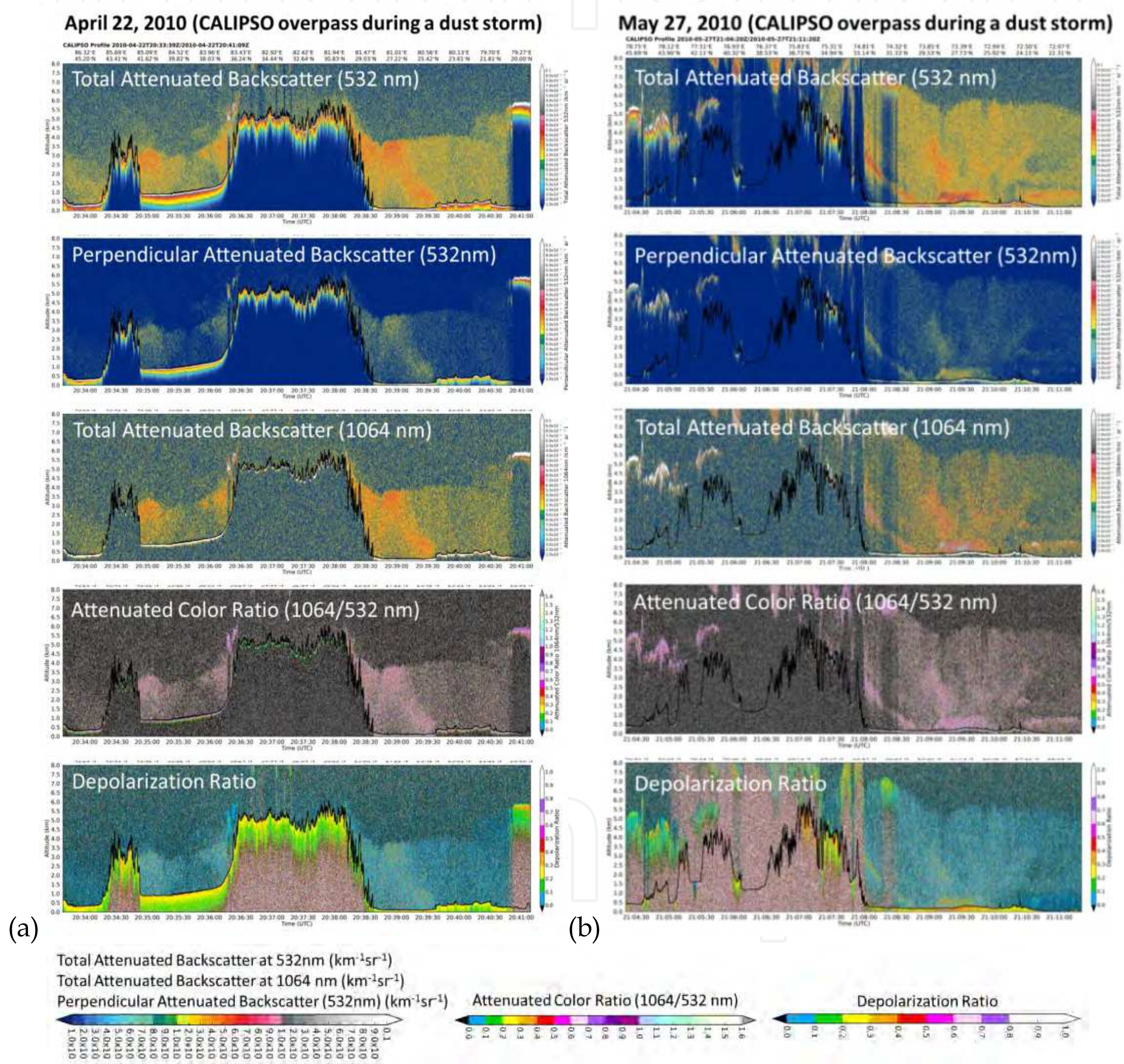

Fig. 12. The atmospheric profiles (0-8 km, y-axis) of a dust storm event using multiple parameters as measured by the night-time CALIPSO overpass over (a) the central IG plain and Himalayas during April 22, 2010 (at 2:04 to 2:11 am IST), and (b) the western IG plain and Himalayas during May 27, 2010 (at 2:35 to 2:41 am IST). The x-axis (top and bottom) of Figures 12(a) and 12(b) is same as that of Figures 10 and 11 respectively.

5.2.3 Dust and anthropogenic aerosols over Eastern Himalayas and IG plains

The night-time profile obtained from CALIPSO on the next day (May 28, 2010) shows the vertical structure of the same dust storm as it passes over the eastern IG plains (State of Bihar and Jharkhand) (Figure 13). The upper limit of dust storm in the eastern side of the IG plains is observed to be ~5 to 5.5 km while a dense layer of dust is observed at 2-3 km between 20°-26° N latitude. The vertical profile was obtained during the night-time over pass of CALIPSO (20:10 to 20:17 UTC or 1:40 to 1:47 am local time or IST). The dense layers of the dust storm are clearly visible in other parameters obtained from CALIPSO (Figure 15a). The CALIPSO profiles corroborate the transport of aerosols over the eastern Nepal Himalayas and its foothill region, as obtained from MODIS Terra and Aqua column AOD. High column AOD (at 10 km horizontal grid) from Terra and Aqua is observed over the snow and glacier cover regions during the episodes of major dust storms (May-June 2003) in the central and eastern Himalayas (Figure 3b, 3c). However, the dust over the eastern Himalayas (eastern Nepal and Sikkim) is relatively less prominent than the western Himalayas as the average height of the Himalayas is more in the eastern side and the dust storm gets weakened in strength (dust load, wind speed) and height as it moves to the eastern side which is approximately 1000-1500 km eastwards from the western end.

5.3 Dust storms during June (prior to the arrival of monsoon system)

The dust storms are also common during June which is followed by intense rains due to the arrival of monsoon over the IG plains. Figure 14 shows the vertical profile of one of the major dust storms hitting the western IG plains during the late June (June 28, 2010). The ceiling of the dust storm over the western IG plains is ~6 km. Thick dense layer of dust is observed between 0-2 km at 25°N latitude that gradually increases in height to 2-4 km at 32°N latitude. The density of dust changes with the height and latitude which is clearly visible in all the parameters shown in Figure 15b. Presence of dust is also observed in the atmosphere over the Taklamakan Desert (Figures 14, 15a).

6. The contribution by anthropogenic aerosols

The arrival of desert dust over the IG plains, either through the sea route (Arabian Sea) or land route (Rajasthan, Pakistan), leads to a mixing of coarse desert dust with the finer anthropogenic emissions (such as black carbon) from the major point sources. Figure 5b shows the presence of large networks of power plants around Gujarat (near Arabian Sea), north Pakistan, and the western IG plains (Punjab, Delhi). The passage of dust storms through these pockets of major point sources, before reaching the Himalayan range, increases the complexity of the physical (optical) and chemical nature of otherwise dust dominant aerosols.

Desert dust brought by the dust storms is rich in minerals such as quartz, feldspar, mica, alumino-silicates, calcite, carbonates, iron oxides etc. The anthropogenic emissions, emitted by burning of fossil fuel (coal and petroleum), biomass and biofuel burning, are mainly comprised of black carbon – BC (elemental and organic carbon), sulfate, and nitrate aerosols. The BC is widely known as a major climate forcing agent as it strongly absorbs the solar radiation which also varies with the nature, type, and source of black carbon aerosols (Lau et al., 2010; Yasunari et al., 2010).

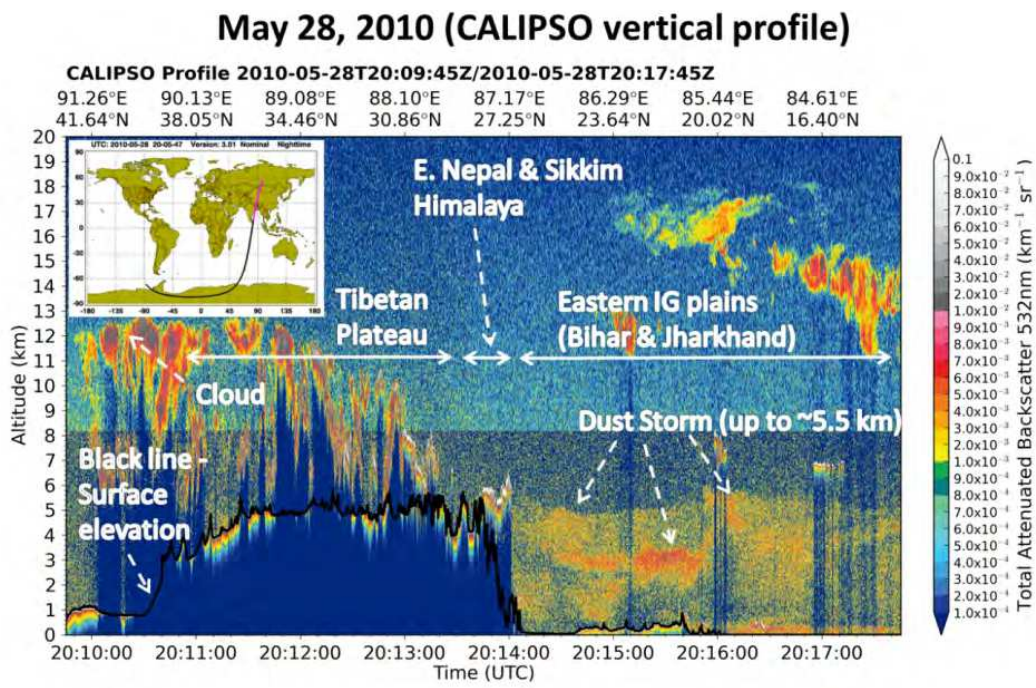

Fig. 13. The atmospheric profile (0-20 km) of a dust storm event as measured by the night-time CALIPSO overpass over the eastern IG plain, Himalayas and Tibetan Plateau during May 28, 2010 (at 1:40 to 1:47 am IST). The total attenuated backscatter (at 532 nm) shows the vertical structure of pre-dominantly dust aerosols up to ~5.5 km.

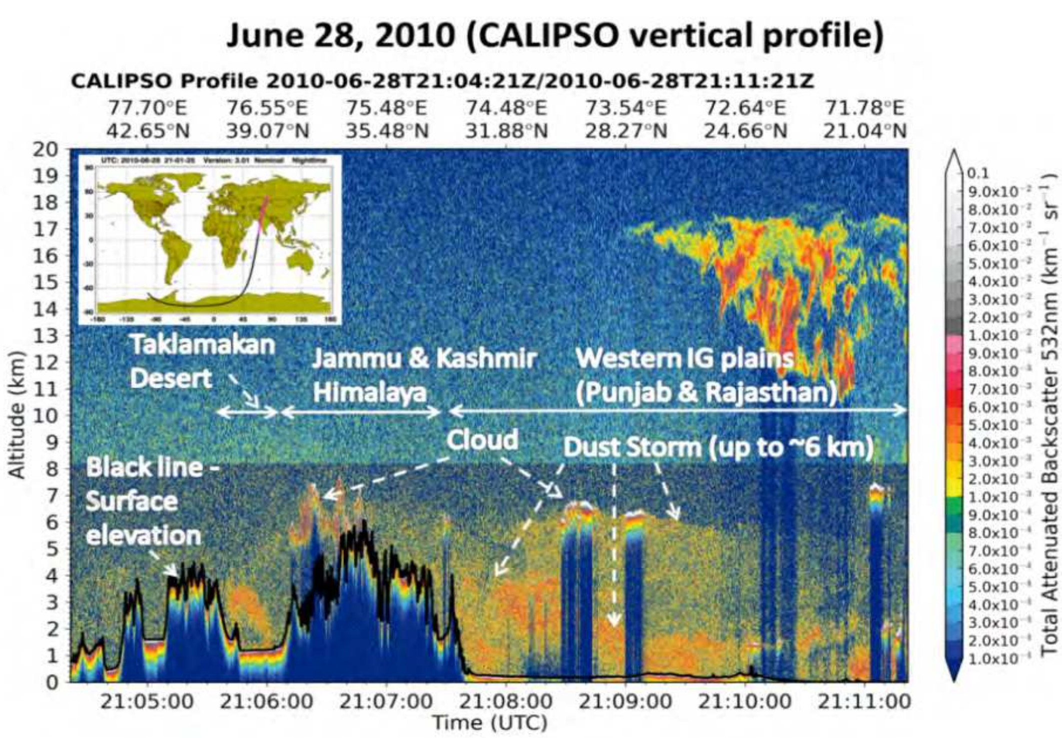

Fig. 14. The atmospheric profile (0-20 km) of a dust storm event as measured by the night-time CALIPSO overpass over the western IG plain, and Himalayas during June 28, 2010 (at 2:35 to 2:41 am IST). The total attenuated backscatter (at 532 nm) shows the vertical structure of pre-dominantly dust aerosols up to ~6 km.

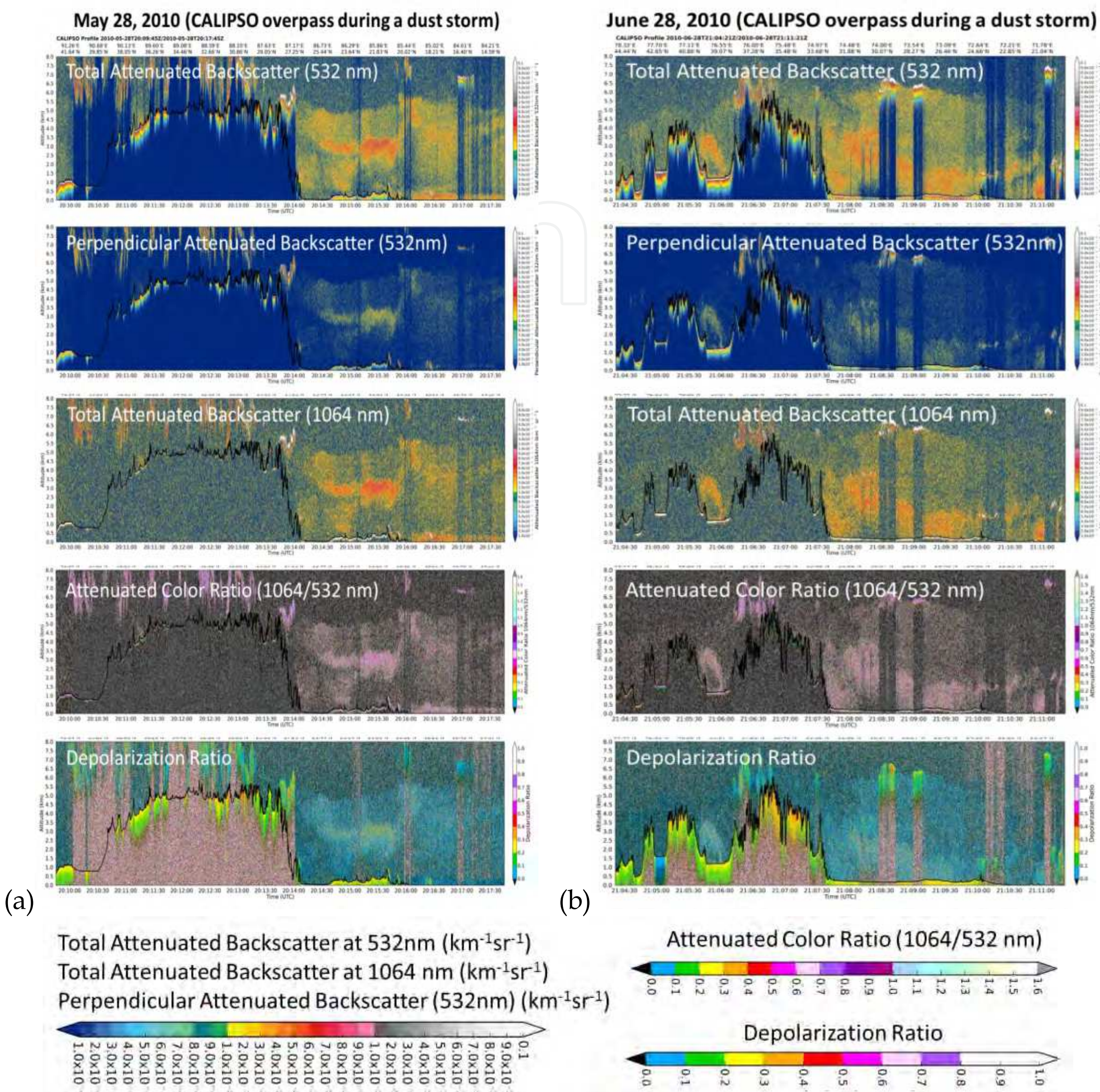

Fig. 15. The atmospheric profiles (0-8 km, y-axis) of a dust storm event using the multiple parameters as measured by the night-time CALIPSO overpass over (a) the eastern IG plain and Himalayas during May 28, 2010 (at 1:40 to 1:47 am IST), and (b) the western IG plain and Himalayas during June 28, 2010 (at 2:35 to 2:41 am IST). The x-axis (top and bottom) of Figures 15(a) and 15(b) is same as that of Figures 13 and 14 respectively.

The entrainment of anthropogenic aerosols with the desert dust, during the long-range transport, leads to the complex climate forcing scenarios because the radiative impact of the mixed aerosols depends on the chemical composition and optical characteristics of the fraction of individual components and also on the type of mixed state – internal (one or more of smaller aerosol particles are embedded in larger host particles), external (various aerosol species exists independently), and semi-external (aerosol aggregate - physical contact between two or more aerosol particles) mixed state. Recent studies involving the microscopic examination of the desert dust over polluted environments (anthropogenic) have found coating of desert dust with black carbon and other compounds of nitrate and sulfate that significantly alters the optical and radiative properties (such as single scattering albedo, extinction efficiency) of dust aerosols (Bauer et al., 2007; Buseck & Posfai, 1999; Chylek et al., 1995; Huang et al., 2010; Li & Shao, 2009; Yasunari et al., 2010). The desert dust also causes reduction in the albedo of contaminated snow over the Himalayas (Negi & Kokhanovsky, 2011).

Surface roughness of the snow increases due to the deposition of dust over the smooth snow surface. Over the years, the cycle of snow melting, dust deposition and snowfall leads to the formation of alternate layers of dust and snow. This may lead to increased melting as the presence of a very thin dust layer changes the friction within a snow pack. Thus, the snow pack in the desert dust affected region is more prone to melting than a dust-free region.

The vertical mixing (elevated layer, up to ~7 km) of dust with anthropogenic emissions have an impact on the radiation budget and precipitation over the IG plain and the high altitude Himalayan mountain range (Lau et al., 2006, 2008; Lau & Kim, 2006; Prasad & Singh, 2007; Prasad et al, 2009; Ramanathan et al., 2005). The deposition of desert dust and other pollutants as well as the changes in atmospheric temperatures (lower and middle tropospheric temperature) over the region due to the presence of mixed aerosols negatively impacts the snow cover and glaciers of Himalayas and Tibetan Plateau, particularly the western (Kashmir and Himachal Pradesh) and central (Uttarakhand, and west Nepal) Himalayas which are closer to the source and experience more frequent dust storms compared to the eastern Himalayas (eastern Nepal, Sikkim, Bhutan, and Arunachal Pradesh) (Das et al., 2010; Prasad & Singh, 2007b; Prasad et al., 2009; Yasunari et al., 2010).

7. Summary and conclusions

The Himalayan and Tibet Glaciers, source and origin of major rivers of Asia, are showing a variable rate of change of the snow cover and glacier retreat during the last several decades (since 1970) due to increasing effects of the climate variability and change, and ever increasing anthropogenic aerosols. The true color images from the earliest available satellite records from Landsat series (since 1972) and ASTER (since 2000) show substantial changes in the snow cover and glacial termini, with some spatial variability, over different regions of the Himalayas. The formation of numerous lakes, especially at the terminus of numerous glaciers, is a common feature compared to the 1970-1980 images. The ASTER images (2000-2010) also show inter-annual changes in the snow cover besides decadal changes since 1972.

The presence of dense networks of coal-fired power plants over the Indian sub-continent (emitting black carbon and various other aerosols) along the pathways of transport of desert dust leads to the mixing of dust and anthropogenic aerosols before reaching the Himalayan-Tibet region. As the anthropogenic activities, such as burning of fossil fuel, have tremendously increased during 1980-2010 over the IG plains, their adverse impact on the snow-cover and glaciers are discernible in space-based observations over the Himalayas, especially the western and central Himalayas. These observations are corroborated with independent measurement of concentrations of anthropogenic particles (aerosols) in the ice-cores that show an increase over the recent decades as compared with preceding decades.

The daily aerosol observations from MODIS Terra and Aqua show long-range transport of desert dust to high altitude Himalayas. This is also supported by air-mass transport models such as HYSPLIT. Models and satellite observations indicate that the arid and desert regions of Sahara, Middle East, Iran, Afghanistan, Pakistan and Thar-desert are the major sources of desert dust. The major pathways of transport of dust (land and sea route) show large inter-annual variability in the dust concentration. For instance, the aerosol loading during year 2008 was abnormally high compared to years 2000-2007 over the land and sea-route (Arabian Sea) and over the dust sink region (IG plains).

The long term aerosol observations from MODIS Terra and Aqua and the vertical profile of pre-monsoon (April-June) dust storms from CALIPSO show direct evidence of the transport of mixed dust and anthropogenic aerosols over the high altitude Himalayas (approximately 4-6 km above the msl). A combination of DT and DB AOD from MODIS Terra and Aqua satellites provides better results as compared with previous approaches to aerosol retrieval methods using the same observations (i.e. DT AOD method only). The current study shows that the elevated aerosol layer is visible up to ~7 km above the msl during the dust storm episodes. The vertical mixing of dust and pollutants also changes the radiation budget of the troposphere. The desert dust mixed with anthropogenic aerosols (black carbon) affects the atmospheric conditions (enhanced heating, change in the temperature gradient, and the monsoon circulation pattern), the reduction in snow albedo, and the roughness of layered snow deposits, leading to an increased melting of the snow pack. The melting of the cryosphere regions in the Himalayas is likely to accelerate due to growing anthropogenic aerosols from emissions in the IG plains. This, in turn, may result in the warming of the troposphere during December-May as indicated by atmospheric temperature trends derived from the Microwave Sounding Unit (MSU) during 1979-2008 (Prasad et al., 2009). Such changes would have profound socio-economic implications over the IG plains in the future.

8. Acknowledgements

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9. References

Ageta, Y. & Fujita, K. (1996). Characteristics of mass balance of summer-accumuation type glaciers in the Himalayas and Tibetan Plateau, *Zeitschrift für Gletscherkunde und Glazialgeologie*, 32 (2), pp. 61-65.

Arora, M.; Goel, N. K. & Singh, P. (2005). Evaluation of temperature trends over India, *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques,* 50(1), pp. 81-93.

Bauer, S. E.; Mishchenko, M. I.; Lacis, A. A.; Zhang, S.; Perlwitz, J. & Metzger, S. M. (2007). Do sulfate and nitrate coatings on mineral dust have important effects on radiative properties and climate modeling?, *Journal of Geophysical Research-Atmospheres,* 112(D6).

Berthier, E.; Arnaud, Y.; Kumar, R.; Ahmad, S.; Wagnon, P. & Chevallier, P. (2007). Remote sensing estimates of glacier mass balances in the Himachal Pradesh (Western Himalaya, India), *Remote Sensing of Environment*, 108(3), 327-338.

Bhattacharjee, P. S.; Prasad, A. K.; Kafatos, M. & Singh, R. P. (2007). Influence of a dust storm on carbon monoxide and water vapor over the Indo-Gangetic Plains, *Journal of Geophysical Research-Atmospheres,* 112(D18).

Bhutiyani, M. R.; Kale, V. S. & Pawar, N. J. (2007). Long-term trends in maximum, minimum and mean annual air temperatures across the Northwestern Himalaya during the twentieth century, *Climatic Change,* 85(1-2), 159-177.

Bookhagen, B. & Burbank, D. W. (2010). Toward a complete Himalayan hydrological budget: Spatiotemporal distribution of snowmelt and rainfall and their impact on river discharge, *Journal Of Geophysical Research-Earth Surface,* 115.

Buseck, P. R. & Posfai, M. (1999). Airborne minerals and related aerosol particles: Effects on climate and the environment, *Proceedings of the National Academy of Sciences of the United States of America,* 96(7), 3372-3379.

Chylek, P.; Videen, G.; Ngo, D.; Pinnick, R. G. & Klett, J. D. (1995). Effect of black carbon on the optical-properties and climate forcing of sulfate aerosols, *Journal of Geophysical Research-Atmospheres,* 100(D8), 16325-16332.

Das, S. K.; Dobhal, D. P. & Juyal, N. (2010). Variability of aerosol optical depth and recent recessional trend in Dokriani Glacier, Bhagirathi Valley, Garhwal Himalaya, *Current Science,* 99(12), 1816-1821.

Di Girolamo, L.; Bond, T. C.; Bramer, D.; Diner, D. J.; Fettinger, F.; Kahn, R. A.; Martonchik, J. V.; Ramana, M. V.; Ramanathan, V. & Rasch, P. J. (2004). Analysis of Multi-angle Imaging SpectroRadiometer (MISR) aerosol optical depths over greater India during winter 2001-2004, *Geophysical Research Letters,* 31(23).

Duan, K.; Thompson, L. G.; Yao, T.; Davis, M. E. & Mosley-Thompson, E. (2007). A 1000 year history of atmospheric sulfate concentrations in southern Asia as recorded by a Himalayan ice core, *Geophysical Research Letters,* 34(1).

Gadi, R.; Kulshrestha, U. C.; Sarkar, A. K.; Garg, S. C. & Parashar, D. C. (2003). Emissions of SO2 and NOx from biofuels in India, *Tellus Series B-Chemical And Physical Meteorology,* 55(3), pp. 787-795.

Garg, A.; Shukla, P. R.; Bhattacharya, S. & Dadhwal, V. K. (2001). Sub-region (district) and sector level SO2 and NOx emissions for India: assessment of inventories and mitigation flexibility, *Atmospheric Environment,* 35(4), pp. 703-713.

Gautam, R.; Hsu, N. C.; Lau, K. M.; Tsay, S. C. & Kafatos, M. (2009). Enhanced pre-monsoon warming over the Himalayan-Gangetic region from 1979 to 2007, *Geophysical Research Letters,* 36.

Ghude, S. D.; Fadnavis, S.; Beig, G.; Polade, S. D. & van der A, R. J. (2008). Detection of surface emission hot spots, trends, and seasonal cycle from satellite-retrieved NO(2) over India, *Journal Of Geophysical Research-Atmospheres,* 113(D20).

Ginoux, P.; Garbuzov, D. & Hsu, N. C. (2010). Identification of anthropogenic and natural dust sources using Moderate Resolution Imaging Spectroradiometer (MODIS) Deep Blue level 2 data, *Journal of Geophysical Research-Atmospheres,* 115.

Goloub, P.; Deuze, J. L.; Herman, M.; Marchand, A.; Tanre, D.; Chiapello, I.; Roger, B. & Singh, R. P. (). Aerosol remote sensing over land from the spaceborne polarimeter POLDER, *in* W. L. Smith & Y. M. Timofeyev, ed., IRS 2000: Current Problems in Atmospheric Radiation, A Deepak Publishing, pp. 113-116.

Hasnain, S. J. (2002). Himalayan glaciers meltdown: impact on south Asian rivers, *in* H. A. J. VanLanen & S. Demuth, ed., FRIEND 2002-Regional Hydrology: Bridging The Gap Between Research And Practice, Int Assoc Hydrological Sciences, pp. 417-423.

He, Y.Q., Z.L. Zhang, W.H. Theakstone, T. Chen, T.D. Yao, H.X. Pang (2003). Changing features of the climate and glaciers in China's monsoonal temperate glacier region, *Journal of Geophysical Research – Atmospheres*, 108(D17), article number 4530.

Hsu, N. C.; Tsay, S.-C.; King, M. D. & Herman, J. R. (2006). Deep blue retrievals of Asian aerosol properties during ACE-Asia, *IEEE Transactions on Geoscience and Remote Sensing,* 44(11, Part 1), 3180-3195.

Huang, K.; Zhuang, G.; Li, J.; Wang, Q.; Sun, Y.; Lin, Y. & Fu, J. S. (2010). Mixing of Asian dust with pollution aerosol and the transformation of aerosol components during the dust storm over China in spring 2007, *Journal of Geophysical Research-Atmospheres* 115.

Immerzeel, W. W.; Droogers, P.; de Jong, S. M. & Bierkens, M. F. P. (2009). Large-scale monitoring of snow cover and runoff simulation in Himalayan river basins using remote sensing, *Remote Sensing Of Environment,* 113(1), 40-49.

Immerzeel, W. W.; van Beek, L. P. H. & Bierkens, M. F. P. (2010). Climate Change Will Affect the Asian Water Towers, *Science,* 328(5984), 1382-1385.

IPCC (2001). Climate Change 2001: Impacts, Adaptation and Vulnerability - Contribution of Working Group II to the Third Assessment Report of Intergovernmental Panel on Climate Change, Cambridge University Press, UK. http://www.grida.no/climate/ipcc_tar/wg2/index.htm

Jaswal, A. K. & Rao, G. S. P. (2010). Recent trends in meteorological parameters over Jammu and Kashmir, *Mausam,* 61(3), pp. 369-382.

Jaswal, A. K. (2010). Recent winter warming over India - spatial and temporal characteristics of monthly maximum and minimum temperature trends for January to March, *Mausam,* 61(2), pp. 163-174.

Jhajharia, D. & Singh, V. P. (2010). Trends in temperature, diurnal temperature range and sunshine duration in Northeast India, *International Journal of Climatology*, DOI: 10.1002/joc.2164.

Kang, S. C.; Wake, C. P.; Qin, D. H.; Mayewski, P. A. & Yao, T. D. (2000). Monsoon and dust signals recorded in Dasuopu glacier, Tibetan Plateau, *Journal of Glaciology,* 46(153), 222-226.

Karma, Ageta, Y.; Naito, N.; Iwata, S. & Yabuki, H. (2003). Glacier distribution in the Himalayas and glacier shrinkage from 1963 to 1993 in the Bhutan Himalayas, 29-40.

Kayetha, V. K.; Senthilkumar, J.; Prasad, A. K.; Cervone, G. & Singh, R. P. (2007). Effect of dust storm on ocean color and snow parameters, *Photonirvachak-Journal of the Indian Society of Remote Sensing,* 35(1), 1-9.

Kehrwald, N. M.; Thompson, L. G.; Tandong, Y.; Mosley-Thompson, E.; Schotterer, U.; Alfimov, V.; Beer, J.; Eikenberg, J. & Davis, M. E. (2008). Mass loss on Himalayan glacier endangers water resources, *Geophysical Research Letters,* 35(22).

Krishna, A. P. (2005). Snow and glacier cover assessment in the high mountains of Sikkim Himalaya, *HYDROLOGICAL PROCESSES* 19(12), pp. 2375-2383.

Kulkarni, A. & Alex, S. (2003). Estimation of recent glacial variations in Baspa basin using remote sensing techniques, Photonirvachak-Journal of the Indian Society of Remote Sensing, 31, pp. 81-90.

Kulkarni, A. (2007). Effect of Global Warming on the Himalayan Cryosphere, *Jalvigyan Sameeksha*, 22, 93-108.

Kulkarni, A. V. & Bahuguna, I. M. (2002). Glacial retreat in the Baspa basin, Himalaya, monitored with satellite stereo data, *Journal of Glaciology,* 48(160), pp. 171-172.

Kulkarni, A. V.; Rathore, B. P.; Mahajan, S. & Mathur, P. (2005). Alarming retreat of Parbati Glacier, Beas basin, Himachal Pradesh, *Current Science,* 88(11), pp. 1844-1850.

Kulkarni, A. V.; Rathore, B. P.; Singh, S. K. & Ajai (2010). Distribution of seasonal snow cover in central and western Himalaya, *Annals of Glaciology,* 51(54), 123-128.

Lau, K. M. & Kim, K. M. (2006). Observational relationships between aerosol and Asian monsoon rainfall, and circulation, *Geophysical Research Letters,* 33(21).

Lau, K. M.; Kim, M. K. & Kim, K. M. (2006). Asian summer monsoon anomalies induced by aerosol direct forcing: the role of the Tibetan Plateau, *Climate Dynamics,* 26(7-8), pp. 855-864.

Lau, K. M.; Ramanathan, V.; Wu, G. X.; Li, Z.; Tsay, S. C.; Hsu, C.; Sikka, R.; Holben, B.; Lu, D.; Tartari, G.; Chin, M.; Koudelova, R.; Chen, H.; Ma, Y.; Huang, J.; Taniguchi, K. & Zhang, R. (2008). The Joint Aerosol-Monsoon Experiment - A new challenge for monsoon climate research, *Bulletin of the American Meteorological Society,* 89(3), 369-+.

Lau, W. K. M.; Kim, M.-K.; Kim, K.-M. & Lee, W.-S. (2010). Enhanced surface warming and accelerated snow melt in the Himalayas and Tibetan Plateau induced by absorbing aerosols, *Environmental Research Letters,* 5(2).

Lee, K.; Do Hur, S.; Hou, S.; Hong, S.; Qin, X.; Ren, J.; Liu, Y.; Rosman, K. J. R.; Barbante, C. & Boutron, C. F. (2008). Atmospheric pollution for trace elements in the remote high-altitude atmosphere in central Asia as recorded in snow from Mt. Qomolangma (Everest) of the Himalayas, *Science of the Total Environment,* 404(1), pp. 171-181.

Li, W. J. & Shao, L. Y. (2009). Observation of nitrate coatings on atmospheric mineral dust particles, *Atmospheric Chemistry and Physics,* 9(6), pp. 1863-1871.

Liu, X. D. & Chen, B. D. (2000). Climatic warming in the Tibetan Plateau during recent decades, *International Journal of Climatology,* 20(14), pp. 1729-1742.

Naz, S. B.; Bowling, L.C. & Crawford, M. M. (2011a). Spatial and temporal glacier changes in the Karakoram Himalaya derived from Landsat satellite data. Journal of Glaciology, (*Submitted,* December, 2010).

Naz, S. B.; Bowling, L.C. & Crawford, M. M. (2011b). Quantification of glacier changes using ICESat elevation data and the SRTM digital elevation model in the Upper Indus Basin, *(under preparation).*

Negi, H. S. & Kokhanovsky, A. (2011). Retrieval of snow albedo and grain size using reflectance measurements in Himalayan basin, *Cryosphere,* 5(1), 203-217.

Prasad, A. K. & Singh, R. P. (2007a). Changes in aerosol parameters during major dust storm events (2001-2005) over the Indo-Gangetic Plains using AERONET and MODIS data, *Journal of Geophysical Research-Atmospheres,* 112(D9).

Prasad, A. K. & Singh, R. P. (2007b). Changes in Himalayan Snow and Glacier Cover Between 1972 and 2000, *Eos Trans. AGU,* 88(33), 326.

Prasad, A. K. & Singh, R. P. (2007c). Comparison of MISR-MODIS aerosol optical depth over the Indo-Gangetic basin during the winter and summer seasons (2000-2005), *Remote Sensing of Environment,* 107(1-2), pp. 109-119.

Prasad, A. K. (2007). Multi-sensor appraisal of aerosols, vegetation and monsoon dynamics over Indian subcontinent. *Ph.D. Thesis*, Indian Institute of Technology Kanpur, pp. 1-238 *(Unpublished).*

Prasad, A. K.; Singh, R. P. & Kafatos, M. (2006a), Influence of coal based thermal power plants on aerosol optical properties in the Indo-Gangetic basin, *Geophysical Research Letters,* 33(5).

Prasad, A. K.; Singh, R. P. & Singh, A. (2006b), Seasonal climatology of aerosol optical depth over the Indian subcontinent: trend and departures in recent years, *International Journal of Remote Sensing,* 27(12), pp. 2323-2329.

Prasad, A. K.; Singh, S.; Chauhan, S. S.; Srivastava, M. K.; Singh, R. P. & Singh, R. (2007). Aerosol radiative forcing over the Indo-Gangetic plains during major dust storms, *Atmospheric Environment,* 41(29), pp. 6289-6301.

Prasad, A. K.; Yang, K. H. S.; El-Askary, H. M. & Kafatos, M. (2009). Melting of major Glaciers in the western Himalayas: evidence of climatic changes from long term MSU derived tropospheric temperature trend (1979-2008), *Annales Geophysicae,* 27(12), pp. 4505-4519.

Prasad, A.; Singh, R. & Kafatos, M. (2011). Influence of Coal Based Thermal Power Plants on the Spatial-Temporal Variability of Tropospheric NO2 Column over India, *Environmental Monitoring and Assessment*, DOI: 10.1007/s10661-011-2087-6 *(in press).*

Qin, D. H.; Mayewski, P. A.; Kang, S. C.; Ren, J. W.; Hou, S. G.; Yao, T. D.; Yang, Q. Z.; Jin, Z. F. & Mi, D. S.Steffen, K., ed., (2000). Evidence for recent climate change from ice cores in the central Himalaya, *Annals of Glaciology*, 31, pp. 153-158.

Raina, V. (2010). Himalayan Glaciers A State-of-Art Review of Glacial Studies, Glacial Retreat and Climate Change, Geological Survey of India. Retrieved January 10, 2010. Available at http://gbpihed.gov.in/MoEF%20Dissussion%20Paper%20on%20Himalayan%20Glaciers.pdf

Raina, V. K. & Sangewar, C. (2007). Siachen glacier of Karakoram Mountains, Ladakh its secular retreat, *Journal of the Geological Society of India,* 70(1), 11-16.

Ramanathan, V. & Ramana, M. V. (2005). Persistent, widespread, and strongly absorbing haze over the Himalayan foothills and the Indo-Gangetic Plains, *Pure and Applied Geophysics,* 162(8-9), pp. 1609-1626.

Ramanathan, V.; Chung, C.; Kim, D.; Bettge, T.; Buja, L.; Kiehl, J. T.; Washington, W. M.; Fu, Q.; Sikka, D. R. & Wild, M. (2005). Atmospheric brown clouds: Impacts on South Asian climate and hydrological cycle, *Proceedings of the National Academy of Sciences of the United States of America,* 102(15), pp. 5326-5333.

Rees, H. G. & Collins, D. N. (2006). Regional differences in response of flow in glacier-fed Himalayan rivers to climatic warming, *Hydrological Processes,* 20(10), pp. 2157-2169.

Rikiishi, K. & Nakasato, H. (2006). Height dependence of the tendency for reduction in seasonal snow cover in the Himalaya and the Tibetan Plateau region, 1966-2001, *Annals of Glaciology, 43,* pp. 369-377.

Scherler, D.; Bookhagen, B. & Strecker, M. R. (2011). Spatially variable response of Himalayan glaciers to climate change affected by debris cover, *Nature Geoscience,* 4(3), pp. 156-159.

Shrestha, A. B. & Aryal, R. (2011). Climate change in Nepal and its impact on Himalayan glaciers, *Regional Environmental Change,* 11, S65-S77.

Shrestha, A. B.; Wake, C. P.; Mayewski, P. A. & Dibb, J. E. (1999). Maximum temperature trends in the Himalaya and its vicinity: An analysis based on temperature records from Nepal for the period 1971-94, *Journal of Climate,* 12(9), pp. 2775-2786.

Singh, R. P.; Dey, S.; Tripathi, S. N.; Tare, V. & Holben, B. (2004). Variability of aerosol parameters over Kanpur, northern India, *Journal of Geophysical Research-Atmospheres,* 109(D23).

Srivastava, A. K.; Tiwari, S.; Devara, P. C. S.; Bisht, D. S.; Srivastava, M. K.; Tripathi, S. N.; Goloub, P. & Holben, B. N. (2011). Pre-monsoon aerosol characteristics over the Indo-Gangetic Basin: implications to climatic impact, *Annales Geophysicae,* 29, pp. 789-804.

UNEP (2008). U.N. Environmental Program and World Glacier Monitoring Service, Global Glacier Change: Facts and Figures UNEP Publ., http://www.grid.unep.ch/glaciers/ (2008).

UNEP (2009). Recent trends in melting glaciers, tropospheric temperatures over the Himalayas and summer monsoon rainfall over India. Available at http://www.unep.org/dewa/Portals/67/pdf/Himalayas.pdf

Upadhyay, R. (2009). The melting of the Siachen glacier, *Current Science,* 96(5), pp. 646-648.

Winiger, M.; Gumpert, M. & Yamout, H. (2005). Karakorum-Hindukush-western Himalaya: assessing high-altitude water resources, *Hydrological Processes,* 19(12), pp. 2329-2338.

Xu, J.; Hou, S.; Qin, D.; Kang, S.; Ren, J. & Ming, J. (2007). Dust storm activity over the Tibetan Plateau recorded by a shallow ice core from the north slope of Mt. Qomolangma (Everest), Tibet-Himal region, *Geophysical Research Letters,* 34(17).

Yasunari, T. J.; Bonasoni, P.; Laj, P.; Fujita, K.; Vuillermoz, E.; Marinoni, A.; Cristofanelli, P.; Duchi, R.; Tartari, G. & Lau, K. M. (2010). Estimated impact of black carbon deposition during pre-monsoon season from Nepal Climate Observatory - Pyramid data and snow albedo changes over Himalayan glaciers, *Atmospheric Chemistry and Physics,* 10(14), pp. 6603-6615.

Zhang, G.; Hongjie, X,; Kang, S.; Yi, D. & Stephen, F. A. (2011). Monitoring lake level changes on the Tibetan Plateau using ICESat altimetry data (2003-2009), *Remote Sensing of Environment* 115, pp. 1733-1742.

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The failure of the UN climate change summit in Copenhagen in December 2009 to effectively reach a global agreement on emission reduction targets, led many within the developing world to view this as a reversal of the Kyoto Protocol and an attempt by the developed nations to shirk out of their responsibility for climate change. The issue of global warming has been at the top of the political agenda for a number of years and has become even more pressing with the rapid industrialization taking place in China and India. This book looks at the effects of climate change throughout different regions of the world and discusses to what extent cleantech and environmental initiatives such as the destruction of fluorinated greenhouse gases, biofuels, and the role of plant breeding and biotechnology. The book concludes with an insight into the socio-religious impact that global warming has, citing Christianity and Islam.

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