Fate of Mountain Glaciers in the Anthropocene
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The Atmospheric Brown Cloud in the Himalayas

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Introduction

Research over the past decade has shown that changes in atmospheric composition directly affect numerous aspects of life. They influence climate, ultraviolet radiation levels, regional air quality and the deposition of chemicals onto the Earth. Such environmental issues in turn affect the basic prerequisites of human existence: human health, food production, ecosystem health and water resources.

Developing scientific knowledge on atmospheric composition change has brought with it the awareness of the imperative to understand the relationship between atmospheric composition and other components of the Earth System. For example, feedbacks between changing climate and anthropogenic emissions, and linkages between air quality and climate change are understood in a more quantitative way, and can be incorporated into models in a predictive capacity.

Local, regional and global air pollution scales are inherently linked by a common atmosphere. Emissions occur predominantly at local scales, leading to local, regional and global changes. Mitigation and adaptation to global changes occur at the local scale. Integration of scales has long been a key requisite for understanding the relationship between emissions and air pollution, and their cascade of effects. In this respect, the advance of remote sensing from space has enabled a view across the scales, but it must be properly backed-up by nested in-situ monitoring networks and experimental campaigns.

The Atmospheric Brown Clouds

Satellite measurements over the last few years have revealed the existence of Atmospheric Brown Clouds (ABC) downwind of nearly all densely populated regions of the world (Fig. 1). Each regional ABC has its distinct geographic, orographic and meteorological features, and is characterized by air pollutants due to specific source contributions (Ramanathan *et al.*, 2008).

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An ABC derives from a number of sources, including biomass burning, fossil fuel combustion and forest fires. It consists of copious amounts of tiny particles of soot, sulphates, nitrates, fly ash, and many other pollutants. Soot results from the incomplete combustion of fuels and consists of nano- to a few micro-meter size particles. Black carbon (i.e. light absorbing elemental and organic carbon particles) and many organic acids are the main constituents of soot. The brownish colour of ABCs is due to the absorption and scattering of solar radiation by these man-made products: anthropogenic black carbon, fly ash, soil dust particles, and nitrogen dioxide gas, sulphuric and nitric acids, sulphates and nitrates, organic chemicals, metals, soil and dust particles, micro-organisms, pollens and moulds. Current analyses indicate that ABCs consist of a mixture of light-scattering and light-absorbing aerosol particles and that they are a trans-boundary, trans-continental, and trans-oceanic phenomenon.

Five regional ABC hot spots, defined as regions where annual mean anthropogenic aerosol optical depths (AOD) exceeds 0.3 and the loading of absorbing aerosols exceeds 10%, have been identified around the world: i) East Asia; ii) Indo-Gangetic Plains; iii) Indonesia; iv) Southern Africa; v) the Amazon basin in South America. Substantial loadings of ABCs over eastern USA and Europe haves also been observed. However, in extra tropical regions, atmospheric concentrations of ABCs are high mainly during the summer season, since precipitation removes aerosols more efficiently during other seasons.

The ABC aerosols interfere with the distribution of the Sun's energy between the Earth's surface and the atmosphere, substantially influencing climate and the biosphere. In fact, aerosols in ABCs intercept the incoming solar energy before it reaches the Earth's surface, thus perturbing temperature, precipitation and biomass production.

ABCs intercept sunlight by both absorbing and reflecting it back to space. Absorption enhances the solar heating of the atmosphere; at the same time, both absorption and reflection of solar radiation reduce the amount of solar energy absorbed at the Earth's surface which affects the climate system, the ecosystem behaviour and, ultimately, life itself. ABC aerosols also affect the microphysical properties of clouds. In regions with high aerosol loading the competition for water between cloud nucleating aerosol particles causes cloud droplet size to decrease, increasing the reflection of solar radiation. Furthermore, reducing cloud droplet size inhibits precipitation formation (Rosenfeld *et al.*, 2009). Overall, ABC-affected regions are on average cloudier and with more reflective clouds, leading to a decreased amount of solar energy reaching the Earth's surface and thus to a cooling.

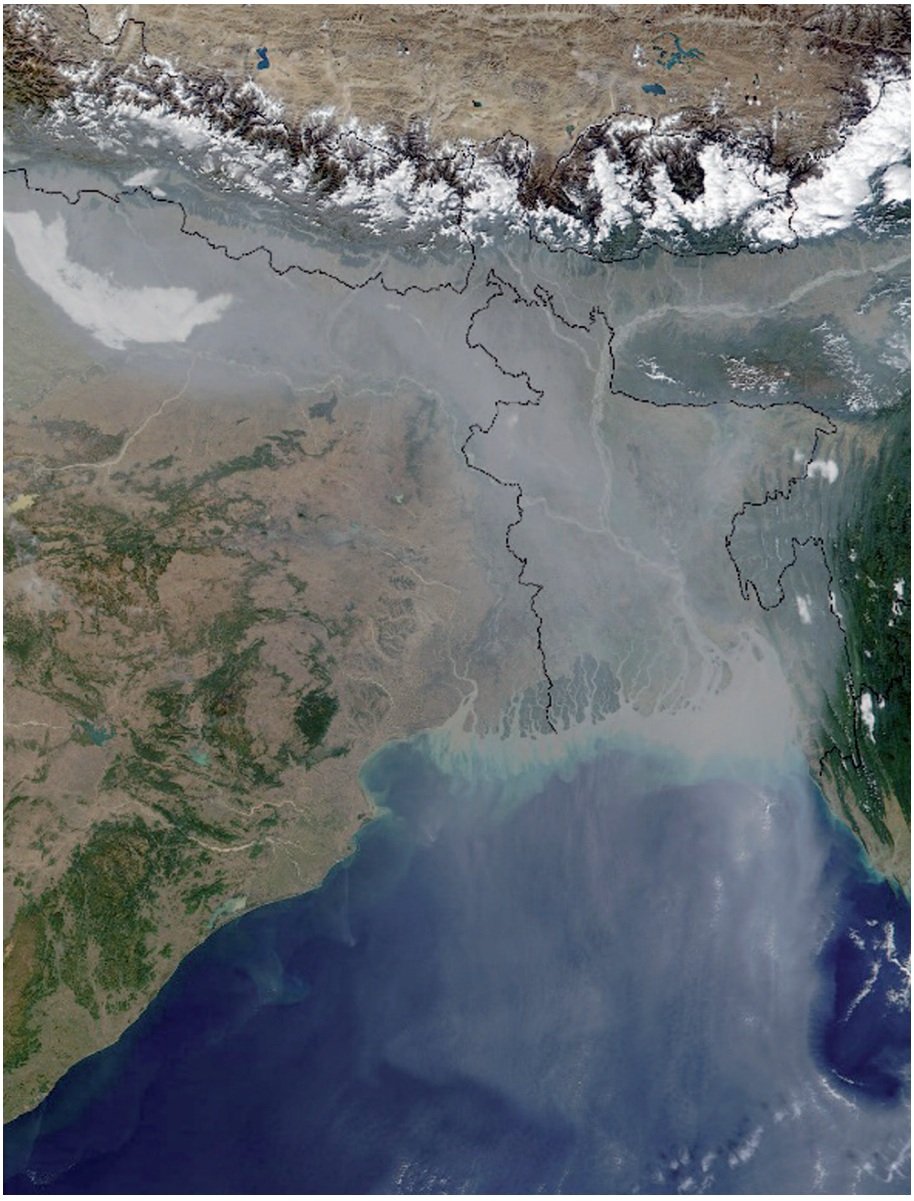

Figure 1. The Atmospheric Brown Cloud extending over the Gangetic Plain and into the Indian Ocean.

In order to improve knowledge on the brown cloud phenomenon and its influence on regional and global climate, air quality, public health and food security, the United Nations Environment Programme (UNEP) established in 2003 the "Atmospheric Brown Cloud" (ABC) project (www.abc-asa.uscd.edu).

Brown Clouds and High Elevation Glaciers in the Hindu Kush-Karakoram-Himalaya Region

The mountain region of the Hindu Kush, Karakoram and Himalaya holds the largest ice mass outside the Polar Regions, and is sometimes called the "third polar ice cap" of our planet. Glaciers in this area play the role of "water towers" in the hydrological balance of the region, and provide significant amounts of melt water, especially in the dry season, for agriculture, drinking purposes and power production. In particular, estimates indicate that more than 50% of the water flowing in the Indus river, which originates from the Karakoram, is due to snow and glacier melt. The climate in this area is changing rapidly: over the past thirty years, the large area at altitude above 4,000 m has warmed 0.3°C per decade, which is twice the rate of observed global warming (Immerzeel *et al.*, 2010).

The mechanisms by which climate change affects glaciers and snow-cover are complex, and are not univocally explained by the rising global temperatures. Glacier dynamics is certainly influenced by the large-scale atmospheric circulation, such as the South Asian summer monsoon for the Himalayan region, and the western weather patterns coming from the Mediterranean and Middle East for the Karakorum. However, local meteo-climatic conditions and the properties of individual glaciers also matter. In addition, black soot aerosols falling on the glaciers darken their surface, reducing snow albedo and favouring glacier melting (Ramanathan and Carmichael, 2008).

Many Himalayan glaciers are now retreating, while most Karakorum glaciers retreat much less or, in some cases, even advance. The presence of very high concentrations of anthropogenic aerosols in the most remote regions of the Hindu Kush and the Himalayas further complicates the picture, since aerosols can influence the regional energy budget, the atmospheric circulation and the water cycle.

As part of the UNEP ABC project, the Italian project SHARE (Stations at High Altitude for Research on the Environment) has been launched by the Ev-K2-CNR Committee with the aim of promoting continuous scientific observations in key high-mountain regions able to contribute to the knowledge on regional and global climate change.

The origin of the Ev-K2-CNR Committee, which dates back over 20 years, is a tale of chances and opportunities that is well worth telling. It all began in 1986, when an American expedition reported that the K2 mountain was higher than Everest. Ardito Desio, the famous geologist who had led in 1954 the expedition for the first ascent of K2 could not resist this challenge and, in 1987, together with the mountaineer Agostino Da Polenza, organized expeditions to re-measure both mountains using traditional survey techniques and innovative GPS (Global Positioning System) measurements. Not only did they confirm Everest's primacy but also set the standard for altitude measurements to come. Two years later, Da Polenza and Desio founded, in collaboration with the Italian National Research

Figure 2. The International Pyramid Laboratory.

Figure 3. Ardito Desio (1897-2001) geologist, explorer, cartographer. Head of the Italian expedition for the first ascent of K2 (8,611 m) in 1954. The picture in taken on the day of the inauguration of the Pyramid International Laboratory.

Council (CNR), the Ev-K2-CNR Committee to continue promoting technological and scientific research at high altitudes, particularly in the Hindu Kush-Karakorum-Himalaya region.

The Project benefited from important Italian Government support to build a permanent high altitude scientific laboratory-observatory as a logistic site for developing multidisciplinary research in the fields of geology, environment, medicine, ethnology. The planned location of the International Laboratory Pyramid, a prefabricated glass and aluminum pyramid-shaped structure energetically self-sufficient, stands on the Tibetan Plateau, an autonomous region of the Peoples Republic of China, in the Tingri Valley, at an height of 5300 m asl on the northern slopes of Mt. Everest.

When all materials for the construction of the Pyramid were ready to be shipped to Tibet, on 4 June, 1989, several hundred protesters were killed by the Chinese army in the so-called Tiananmen Square massacre. The re-

pression of the student movement was severely criticised by many countries, including Italy, making it impossible to continue the collaboration with the Chinese Academy of Sciences in establishing the Pyramid Laboratory. In order to avoid an indefinite delay of this major project, an agreement was then negotiated with the Nepalese Government and the whole project was transferred to the southern slopes of Mt. Everest. Eventually, the Pyramid laboratory was set up in the Khumbu Valley of Nepal at a height of 5050 m asl, not far from the Everest Base Camp (Fig. 2).

The Pyramid International Laboratory was officially inaugurated in October 1990, in the presence of Ardito Desio, who, at the age of 93, would not miss this historic occasion (Fig. 3).

The first results of the SHARE Project in the Hindu Kush-Karakoram-Himalaya region

SHARE is a scientific and technological research project focusing on mountains, areas that are particularly sensitive to climate changes. Within this project and in the framework of the UNEP ABC Project, the Nepal Climate Observatory-Pyramid (NCO-P) was installed in 2006 near the Pyramid at 5079 m a.s.l., to foster a better understanding of the atmospheric conditions in the Himalayas, the world highest mountain region, which is located between China and India, two of the most rapidly developing nations in the world, and primary sources of anthropogenic pollution (Fig. 4).

Since March 2006, at this station, also one of the 34 Global Stations of the Global Atmospheric Watch network established by the World Meteorological Organization, a wide range of measurements for aerosols and trace gases characterisation have been continuously running, together with meteorological and radiation measurements (Bonasoni *et al.*, 2010).

The Himalayan high-altitude climate is intensely characterised by its relationship with large-scale circulation, and strongly dominated by the diurnal cycle of thermal parameters. In fact, at NCO-P, the seasonal variation of atmospheric conditions is influenced both by the local mountain wind system (with a strong diurnal valley wind and a weak mountain night-breeze), and by the large-scale Asian monsoon circulation. Four seasonal periods were singled out, based on local meteorological observations: i) pre-monsoon (Mar-May); ii) monsoon (Jun-Sept); post-monsoon (Sep-Oct); winter (Nov-Feb).

The 5-day back-trajectories were calculated using the Lagrangian Analysis Tool (LAGRANTO) (Fig. 5) to study the large-scale air-mass flows specifically characterising the NCO-P region for each of the above seasons. The analysis showed that: (a) during the winter season NCO-P is mainly

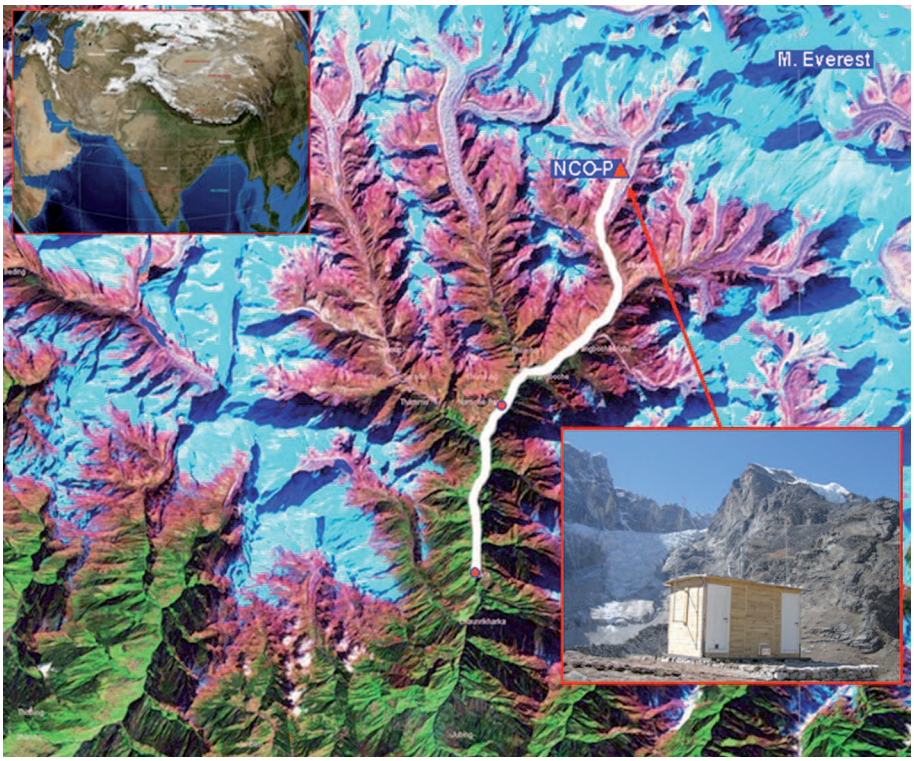

Figure 4. The location of the Nepal Climate Observatory-Pyramid (NCO-P). The measurement shelter is shown in the box on the right.

affected by a very fast westerly circulation related to the well-developed SJS along 30° N; (b) during the pre-monsoon and post-monsoon, slower but still westerly air-masses mainly affect the measurement site, with evident excursions related to SJS undulation and synoptic scale systems; (c) during the monsoon season NCO-P is strongly affected by air masses originating at lower latitude regions (i.e. Gulf of Bengal and Indian sub-continent). The analysis magnifies the different atmospheric circulation characterising the high Himalayas with respect to the South Asian plains during the winter and transitional seasons. While in the South Asian boundary layer, a north to north-easterly circulation usually prevails, in the middle and upper troposphere the mean flow turns to westerly, indicating a synoptic-scale decoupling of the middle troposphere circulation from the lower troposphere (Bonasoni *et al.*, 2008).

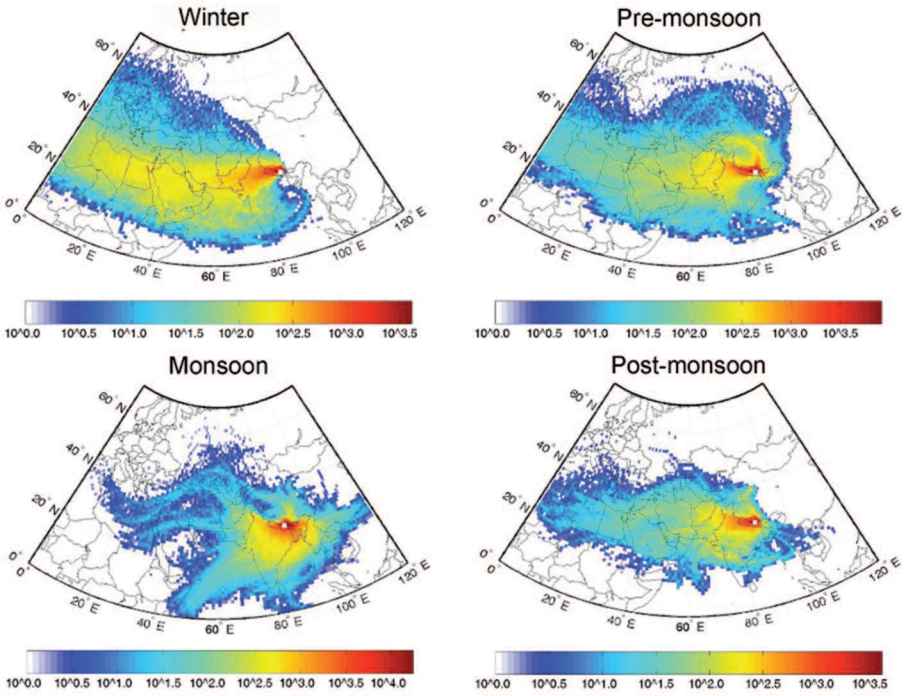

Figure 5. Field concentrations (expressed as the logarithm of the number of back-trajectory points passing over a 1° ×1° grid) of LAGRANTO back-trajectories for the four seasonal periods defined on the basis of current meteorological data at NCO-P.

Long-term observations at NCO-P allowed a first characterization of atmospheric composition over the southern Himalayas, also allowing the investigation of the possible influence of ABCs. The evolution of atmospheric composition at NCO-P is determined by the South Asia summer monsoon cycle, highlighted by the variation of the seasonal behaviours of BC, scattering coefficient, PM_1, coarse particles and O_3, as shown by their seasonal mean values in Table 1.

It should also be noted that, in particular conditions during the pre-monsoon season, the levels of BC and PM concentration can greatly exceed the average values reported in Table 1. A particular case took place at the beginning of April 2010. The total number of daily hot spot fires obtained by the Moderate Resolution Imaging Spectroradiometer (MODIS) on board NASA's Aqua and Terra satellites showed widespread fire episodes

	Pre-Monsoon	Monsoon	Post-Monsoon	Winter
BC (ng m^{-3})	316.9 ± 342.9	49.6 ± 60.9	135.3 ± 78.5	118.4 ± 80.9
Scattering coefficient (Mm^{-1})	11.9 ± 10.5	2.2 ± 3.5	5.0 ± 2.9	3.4 ± 1.6
PM1 (μg m^{-3})	3.9 ± 4.0	0.6 ± 1.0	1.5 ± 0.8	1.3 ± 1.8
Coarse (cm^{-3})	0.37 ± 0.37	0.09 ± 0.02	0.07 ± 0.05	0.16 ± 0.14
O_3 (ppbv)	60.9 ± 8.4	38.9 ± 9.6	46.3 ± 5.0	51.2 ± 5.4

Table 1. Seasonal averages (mean ± standard deviation) of BC, aerosol scattering coefficient, PM1, coarse particle number and O_3 at NCO-P.

over South Asia from the beginning of April 2010. An analysis of atmospheric circulation indicated that valley winds transported these forest fires and biomass burning originated pollutants to the high Khumbu valley and to the Everest glaciers: the concentration of BC over the period 2-10 April 2010 increased more than 5 times with respect to the pre-monsoon seasonal average (Bonasoni *et al.*, 2010).

Black carbon effects on atmospheric radiative balance and on glaciers

Of particular interest is the time series of BC concentration at NCO-P over a period of five years (Fig. 6). It shows how at this remote high mountain site BC concentration regularly exceeds 4 g m^{-3} during the pre-monsoon season (Marinoni *et al.*, 2010), a concentration which could be found close to a busy road!

Transport of optically active material to the very sensitive regions of the Himalayas is therefore a key issue to improve the description of the BC effect on the Indian Summer Monsoon and, in particular, its impact on precipitation in the HKH regions and, hence, on frozen water storage. In fact, BC not only affects the energy budget of the atmosphere, but deposits to snow surfaces, absorbs light, thus decreasing the albedo of the snow and modifying the energy budget of snow surfaces Using actual aerosol optical depth (AOD) measurements, Marq *et al.* (2010) calculated the resulting direct local radiative forcing at NCO-P due to aerosols for selected air mass cases. It was found that the presence of absorbing particulate material can locally induce an additional top of the atmosphere (TOA) forcing of 10 to 20 W m^{-2} for the first atmospheric layer (500 m above surface). The TOA positive forcing depends

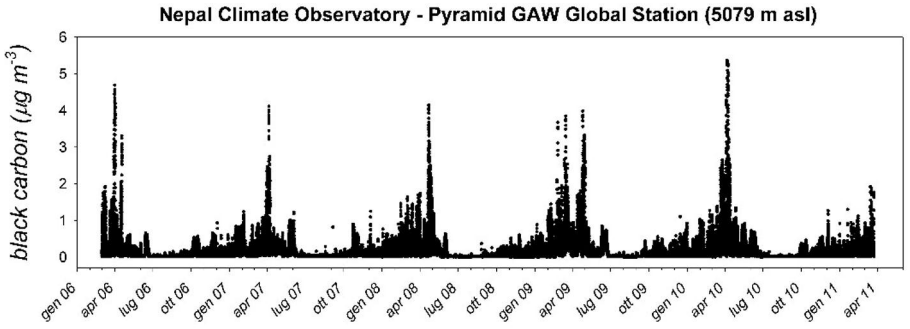

Figure 6. BC concentration trend at NCO-P during the period March 2006-March 2010. The concentration peaks regularly occur during the pre-monsoon season (March-May).

on the presence of surface snow, and takes place preferentially during episodes of regional pollution occurring on a very regular basis in the Himalayan valleys. Warming of the first atmospheric layer is paralleled by a substantial decrease in the amount of radiation reaching the surface. The surface forcing is estimated to range from -4 to -20 W m^{-2} for small-scale regional pollution events and large-scale pollution events, respectively. The calculated surface forcing is also closely dependent on surface albedo, with maximum values occurring over a snow-covered surface.

Another study (Yasunari *et al.*, 2010) estimated the possible range of reduction in snow surface albedo due to dry deposition of BC during the pre-monsoon period, based on actual atmospheric observations at the NCO-P. A total BC deposition rate was estimated as 2.89 g m^{-2} day^{-1}, equal to a total deposition of 266 g m^{-2} for March-May at the site, based on a calculation with a minimal deposition velocity of 1.0×10-4 m s^{-1} with atmospheric data of equivalent BC concentration. The main BC particle size was estimated as 103.1-669.8 nm by correlation analyses between equivalent BC concentration and particulate size distributions measured at NCO-P. The BC deposition from the size distribution data was also estimated. It was found that 8.7% of the estimated dry deposition corresponds to the estimated BC deposition from equivalent BC concentration data. If all the BC is deposited uniformly on the top 2 cm of pure snow, the corresponding BC concentration is 26.0-68.2 g kg^{-1}, assuming snow density variations of 195-512 kg m^{-3} of the Yala Glacier, close to NCO-P site. Such a concentration of BC in snow could result in 2.0-5.2% albedo reductions. Assuming such albedo reductions continue throughout the year, and ap-

plying simple numerical experiments with a glacier mass balance model, this would lead to runoff increases of 70-204 mm of water. This runoff is the equivalent of 11.6-33.9% of the annual discharge of a typical Tibetan glacier. The estimates of BC concentration in the snow surface for the pre-monsoon season is comparable to those at similar altitudes in the Himalayan region, where glaciers and perpetual snow regions begin, in the vicinity of the NCO-P.

Outlook for the future of the SHARE Project

Given their influence on the mountain ecosystem and tropospheric background conditions, and their role in the radiative equilibrium of the atmosphere and Earth's surface, the determination of absorbing aerosol and trace gas concentrations, together with the investigation of processes influencing their variability, represent an urgent task for the Himalayan region. The continuous monitoring of atmospheric composition in this area is crucial for evaluating the Asian background conditions of the free troposphere, and for quantifying the region's pollution levels.

While the NCO-P site continues producing on a regular basis data on atmospheric composition in an area where these measurements are very rare, SHARE, jointly with the ABC UNEP project, promotes similar studies in the Karakoram region. The construction of a new climate observatory is planned in the Northern Areas of Pakistan. In this mountain range, based on the NCO-P experience, SHARE has launched, in collaboration with the French CNRS, the new project PAPRIKA (*CryosPheric responses to Anthropogenic PRessures in the HIndu Kush-Karakoram-HimalayA regions: impacts on water resources and Availability*). The project is devoted to determining the state of the glaciers and water reserves in the Hindu-Kush, Karakoram and Himalaya regions, and to estimating their future conditions in different climate change scenarios, with special emphasis on the role of atmospheric aerosols.

The ultimate goals of PAPRIKA are to:

- Obtain a quantitative assessment of i) the current state of the atmospheric properties and circulation; ii) aerosol loading, deposition and chemical properties; iii) glacier status, mass/energy balance and flow estimates; and iv) hydrologic characteristics, including water quantity and quality, in the two study areas;
- Provide an ensemble of integrated modelling tools, based and validated on field and remotely sensed data (satellites and airborne radars), to obtain quantitative estimates of water availability and climate change impacts on agriculture, environment and ecosystems in the coming decades (2010-2050);

– Develop strategies for capacity building, dissemination and information transfer to policy makers in the area.

Acknowledgements

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