**SUMMARY: Black Carbon and Climate Change in the Himalayan Region**
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The Hindu Kush-Himalayan-Tibetan (HKHT) region – the "Third Pole" – extends 3,500 km from Afghanistan to Burma/Myanmar and includes western China, northern India, and the entirety of Bhutan and Nepal. It is characterized by mountains and high broad plateaus; fourteen mountain ranges run in parallel from east to west, including the Altay, Tien Shan, Pamirs, Kunlun Shan, Karakoram, and Himalaya. The later three surround the Tibetan Plateau (TP) on three sides: the Kunlun Shan of Central Asia in the north, the Karakoram range (Western Himalaya) in the west and the Central Himalayas in the south. The TP, also known as the "Roof of the World," is a vast region of 2.5 million $km^2$, with an average elevation of 4500 meters above sea level (masl).

Global warming is having dramatic effects on the climate system in this region: temperatures increasing faster than the global average, a weakening monsoon system; and reduced precipitation in some areas, including over the HKHT mountains. As a result, the majority of the glaciers in the region are retreating, and the monsoon rains are becoming less predictable.

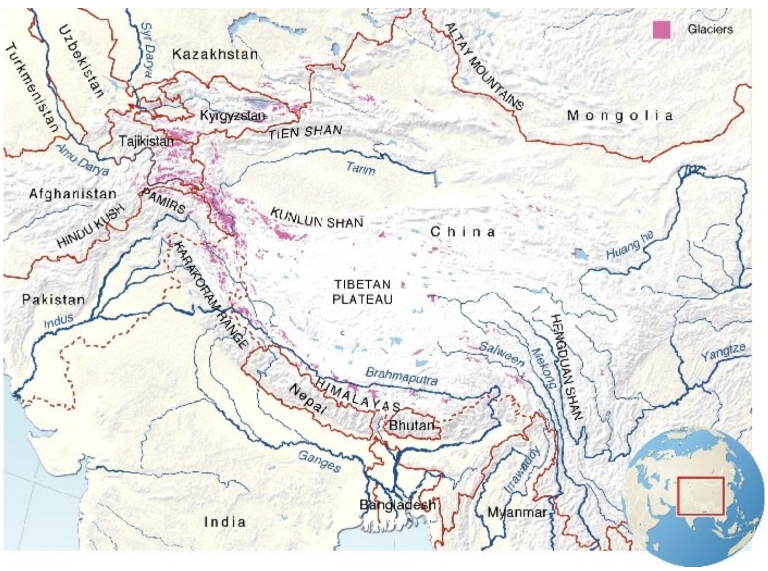


*Figure 1. Map of the Hindu-Kush-Himalayan-Tibetan (HKHT) Region, showing the locations of major mountain ranges and glaciers.*

For the purposes of this report, the vast and heterogeneous HKHT region is broken down into two major subregions:

- Western China, which includes the Tibetan Plateau (TP), the Qilian Mountains in the east, the Kunlun Shan, which forms the northern border of the TP, and the Tien Shan in the far north, along the China-Kazakhstan/China-Kyrgyzstan border.
- The Himalaya, which can be divided into the Western Himalaya/Karakoram range, where India, China, and Pakistan meet; the Central Himalaya, which includes Nepal and northern India; and the Eastern Himalaya. The northernmost Himalaya spill onto the Tibetan plateau.

**Temperatures in this region are increasing faster than globally**

Over the last 120 years, average temperature in the HKHT has increased by 1.2 °C, twice the global average. Over the last 50 years, regional temperatures have increased by 0.16°C per decade, with winter temperatures increasing 0.32 °C per decade. Warming over parts of the Tibetan Plateau have been in the range of 0.2 – 0.6 °C per decade between 1951 and 2000. Nepal in the Central Himalaya is warming even faster: 0.6 °C per decade between 1977 and 2000.

**Glaciers are retreating, although glacier behavior is not uniform across the region**

The mass balance of a glacier is determined by the difference between accumulation (via precipitation) and ablation (loss of ice through melting, evaporation, wind scouring). Changes in mass balance control a glacier's long term behavior and are the most sensitive climate indicators on a glacier. High-altitude alpine glaciers generally accumulate more snow in the winter than they lose in the summer, leading to a positive mass balance. However, some glaciers accumulate snow in the summer, such as those in the Central and Eastern Himalaya. When ablation exceeds accumulation, a glacier has a negative mass balance. If the negative balance is sustained over time, the glacier will retreat.

Chinese researchers estimate that more than 82% of the glaciers in Western China have retreated and glacial area has decreased by 4.5% in the last 50 years, with the greatest percentage of retreat occurring on the north slope of the Himalaya. Glaciers in the central and northwestern Tibetan Plateau (TP) are relatively stable, while those in the mountains surrounding the TP have experienced extensive mass loss. Many Himalayan glaciers are retreating faster than world average and glacial retreat is accelerating across much of the region. Mass shrinkage of glaciers started to accelerate in the late 1970s and again in the 1990s. Evidence from ice cores from Naimona'nyi Glacier (6050 masl) in the Tibetan Himalaya suggest there has been no net accumulation of mass (ice) since at least 1950. The Gangotri Glacier, located on the southwestern edge of the TP, has shrunk over 30 km, at a rate of 23 meters/year. Some Chinese researchers have concluded that “strong warming and reduced precipitation are likely key drivers for the extensive ice-cover reduction in the eastern and southern parts of the TP.” Glacial behavior varies across the Himalaya. Glaciers in the Central and Eastern Himalaya, which are fed by precipitation from the summer monsoons, appear to be retreating. In the Western Himalaya and Karakoram Ranges, some glaciers may be advancing. These glaciers are fed by inter precipitation brought by westerlies, and are not as sensitive to changes in the South Asian Monsoon (below).

**The monsoon cycle is weakening**

Local records show a significant decreasing trend in monsoon precipitation from 1866 – 2006 in the West Himalaya. Ice core data also suggest a decrease in monsoon strength in the Central and Eastern Himalaya over at least the last 80 years. Since the 1980s, rainfall over the heavily-populated Indo-Gangetic plain has decreased by approximately 20% and the number of rainy days for all India is decreasing, although the frequency of intense rainfall is increasing, leading to more frequent floods. Sea surface temperatures (SSTs) in the equatorial Indian Ocean have warmed since the 1950s by about 0.6–0.8 °C, but there has been very little warming or even a slight cooling trend over the northern Indian Ocean. Summertime weakening in the SST gradient between these two ocean areas weakens the monsoon circulation, resulting in less monsoon rainfall over India. Model simulations suggest that warming from BC aerosols is a major contributor., as the water table is being depleted at a growing rate.

## IMPACTS OF CLIMATE CHANGE ON PEOPLE

The HKHT glaciers are considered to be a 'climate tipping element', much like the loss of Arctic summer ice or the Greenland ice sheet. This is due to the positive feedback that results when ice melts revealing darker land which leads to further warming and melting, as well as the catastrophic cascade of social and ecological impacts that would occur if such a large number of people were forced to look for resources elsewhere and sensitive ecosystems were permanently disrupted.

**Weakening Monsoon Means Less Water**

Throughout the region, the water table is being depleted and aquifers are drying out due to rapid population growth and increased water usage for drinking and irrigation. The monsoon rains are needed to replenish them. The Indian summer monsoon is the most significant source freshwater to the region: over 70% of the annual precipitation over India occurs during the summer monsoon (June – September). Reduction in rainfall is also of concern because, in South Asia, there is a strong positive correlation between the amount of precipitation and food production.

**Melting Glaciers Pose Short-Term Hazards and Long-Term Problems**

The melting of Himalayan glaciers poses hazards to people living downstream of the thousands of glacial meltwater lakes that have formed over the past few decades. Glacial lake outburst floods (GLOFs) threaten the lives and livelihoods of millions of people in the region and these events are becoming more frequent. In the longer-term, the loss of these glaciers will lead to a corresponding reduction in water availability. Snow and ice melt contribute 70% of the summer flow of the main Ganges Indus and Kabul rivers in the 'shoulder seasons' before and after the summer monsoons and the contribution to inner Asian rivers is even greater. The Gangotri Glacier, which is shrinking at the rate of 23 meters/year, is the main water source for the 500 million people living in the Ganges River Basin.

**CAUSES OF CLIMATE CHANGE AT THE THIRD POLE**

While $CO_2$ is the primary culprit, recent studies suggest that black carbon (BC) may play as large a role in warming the HKHT region. Increasing amounts of soot in atmospheric brown clouds (ABCs) have been shown to cause atmospheric solar heating, surface dimming, and BC deposition to the HKHT glaciers and snow packs. Studies conducted by Chinese researchers on the Tibetan Plateau demonstrate increased soot concentrations and their potential radiative effects on accelerated snowmelt. There is a need for similar quantitative studies on the Indian side of the Himalayas.

**Atmospheric Black Carbon (Aerosols)**

Black carbon, a component of soot, is a by-product of incomplete combustion. Unlike most aerosols, black carbon absorbs solar radiation. Atmospheric BC alters radiative forcing in a number of complex ways. BC mixes with other aerosols, some of which reflect solar radiation, such as sulfates, nitrates, and organic carbon (OC). Together, these anthropogenic aerosols contribute to Atmospheric Brown Clouds (ABCs), large plumes of particles that can stretch over whole continents or ocean basins. Determining the effects of ABCs is challenging due to the cooling effects of sulfate and other aerosols that are mixed with BC. Overall, ABCs intercept solar radiation by absorbing as well as reflecting it, leading to a warming of the lower atmosphere and simultaneous a reduction of sunlight at the Earth's surface (surface dimming).

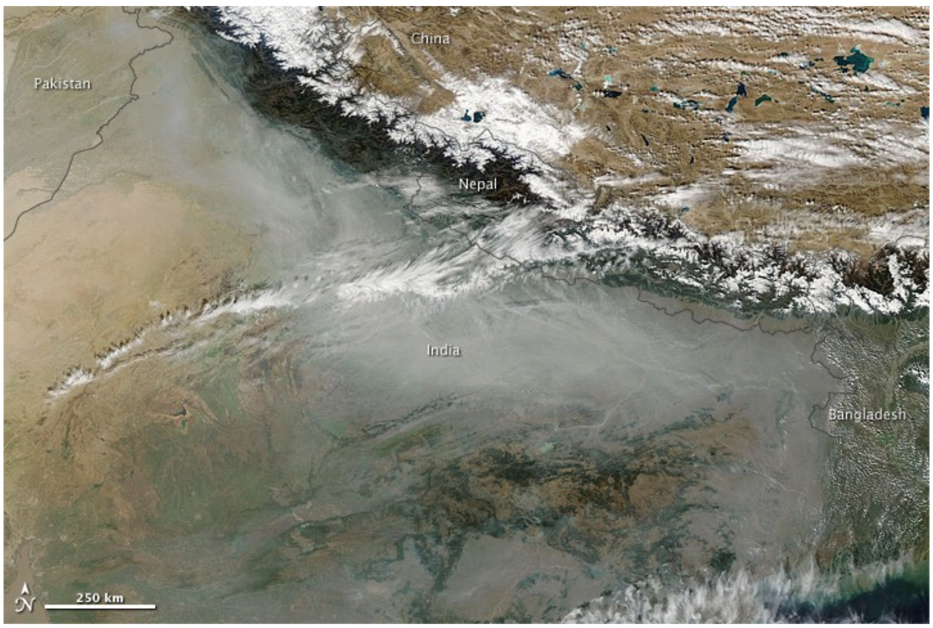

*Figure 2. Winter haze hugs the southern face of the Himalayas, causing health problems and warming the atmosphere. December 2, 2009, NASA.*

The Tibetan Plateau is at the crossroads of influence between maritime air masses from the Indian Oceans (monsoons) and continental air masses from central Asia (westerlies). During the winter and pre-monsoon season (October to April), large-scale circulation patterns (predominantly westerlies) transport air masses to the Plateau. Westerlies do not bring large quantities of pollutants with them, as they travel a long way from populated areas before they reach the region. In the summer (June to September), low pressure over the plateau induces a supply of moist, warm air from the Indian Oceans to the continent (summer monsoon). These masses bring considerable pollution from South Asia, some as far away as the Indian plains.

<u>Atmospheric BC Concentrations</u>

Modern atmospheric aerosols over the central Himalayas are dominated by anthropogenic sources which have increased at a rapidly accelerating rate since 1930 with the increase in energy demand and fossil fuel use. Studies of atmospheric aerosols have found that aerosol optical depths (AOD), which increase as the transparency of the air decreases, were low in the summer and during the monsoon, then increased through the late winter to peak during pre-monsoon season (May). This enhanced buildup of aerosols is dominated by dust transported by westerlies from the arid regions of India, the Middle East, and perhaps the Sahara Desert. During monsoon season, the aerosols are washed out, and build up again during the following dry winter season. Some studies have found that the abundance of carbonaceous aerosols or soot measured also exhibited a seasonal pattern: on Manora Peak in the outer Himalayas, carbonaceous aerosols were highest in the winter. On Mt. Qomolangma (Everest) the abundance of soot was higher in the non-monsoon period (25%) than during the monsoon period (14%). Backward trajectories suggest that northwestern India contributed to the atmospheric aerosols in these areas.

There are few modeling studies of the transport of BC to this region from China. Trajectory analysis suggests that emissions from Xinjiang Province and Central Asia transported by westerlies could be the most important sources for BC to the northern and western edges this region. However, up to 40% of these emissions could come from within the region: e.g., the high concentrations measured close to Lhasa and the Qinghai-Tibet Highway could reflect the influence of local anthropogenic activity. In the north, the highest BC concentrations were measured near the city of Urumqi in the Tienshan. In the central/southeast and southern TP (Himalayas), analysis indicated that BC concentrations are influenced by emissions from the Indo-Gangetic basin transported by westerlies and monsoons.

ABCs have been found to enhance lower atmosphere heating by about 50% over Asia and contribute as much to lower atmospheric warming trends as anthropogenic greenhouse gases. Unmanned aircraft flying through these ABCs over the Indian Ocean found that the zone atmosphere containing the clouds is warming by 0.25° C per decade as compared to 0.10° C at ground level. The Himalayas are located at the same altitude as that where the ABCs have been measured , suggesting that atmospheric heating due to BC in these ABCs may be as important as $CO_2$ in the melting of the Himalayan glaciers. Surface dimming reduces the amount of solar radiation reaching the surface. Modeling studies suggest that BC aerosols in ABCs play a role in both the recent increases in precipitation seen in the pre-monsoon season, as well as the reduction of precipitation during the monsoon itself.

**Black Carbon on Snow**

BC is removed from the atmosphere by snow, rainfall, and direct deposition onto surfaces. Clean snow is the most reflective natural surface on earth, with an albedo of almost 90%. Snow albedo can be reduced by very small amounts of impurities, like dust or black carbon. The atmosphere in the Himalayas has high levels of natural dust, resulting in the deposition of dust on Himalayan glaciers. However, BC is estimated to be fifty times more efficient than dust in reducing snow albedo; experimental results show that parts-per-billion of black carbon (BC) on the surface can reduce snow albedo by 1-2%.

Modeling suggests that the total warming impact of black carbon per meter may be greatest in the mid-latitudes of Central and East Asia because of the BC-snow forcing. This model further suggests that the greatest forcing is over the Tibetan Plateau, averaging 1.5 W m-2 over all land. During some spring months BC-snow forcing may exceed 10 W m-2 over parts of eastern China and 20 W m-2 over the Tibetan Plateau. The forcing is greatest over the Plateau because lower latitudes are exposed to more solar radiation, have less vegetation cover, and are closer to the sources of black carbon than higher latitudes. Climate experiments suggest that fossil fuel and biofuel emissions of black carbon plus organic matter induce almost as much springtime snow cover loss over Eurasia as anthropogenic $CO_2$ emissions. There are uncertainties associated with these models, due to the low resolution of the grid. Significant work is needed to develop realistic simulations of the effects of BC on snow in this varied and highly complex terrain.

<u>Concentrations of BC in Snow</u>

Concentrations of BC in snow/ice have been reported from about 16 sites in Western China. Most of the work has been done along the southern and eastern margins of the area; little has been done in the interior. One study analyzed data from snow/ice core samples across the Tibetan Plateau. It includes samples along a north-south transect from the Tienshan mountains in Xinjiang Province, along the eastern margin of the Tibetan Plateau (TP), from the Qilian Mountains to Lhasa, to the Himalayas in the south. Other sites were samples along the western and southwestern edges. Other studies have sampled sites north of the TP in the Altay Mountains, the western edge of the TP in the Kunlun Mountains, and along the eastern edge. The highest concentrations of BC (67 – 114 ng/g) were found at the northern (MEG2 and HXR48) and southeastern (DK, LN, ZD) edges. These sites are close to regional population centers: Xinjiang Autonomous Region in the north > 19 million people and Lhasa and the Qinghai-Tibet Highway in the southeast. Sites along the eastern/central (LHG2, QY) and southwestern margin, and in the Himalayas (KW, ER, QIY) were low (18 – 35 ng/g) but still reflected significant anthropogenic influence. Even the lowest concentrations (4.3 and 6.6 ng/g) found in the remote eastern Qilian (J1) and western Himalayan Mountains (NM) exceeded the concentrations measured in relatively pristine Antarctic snow by an order of magnitude. Ice core records of the past 50 years from Mt. Qomolangma (Everest) revealed an apparent trend of increasing BC concentrations that started in the mid-1990's, with higher concentrations measured during the monsoon season.

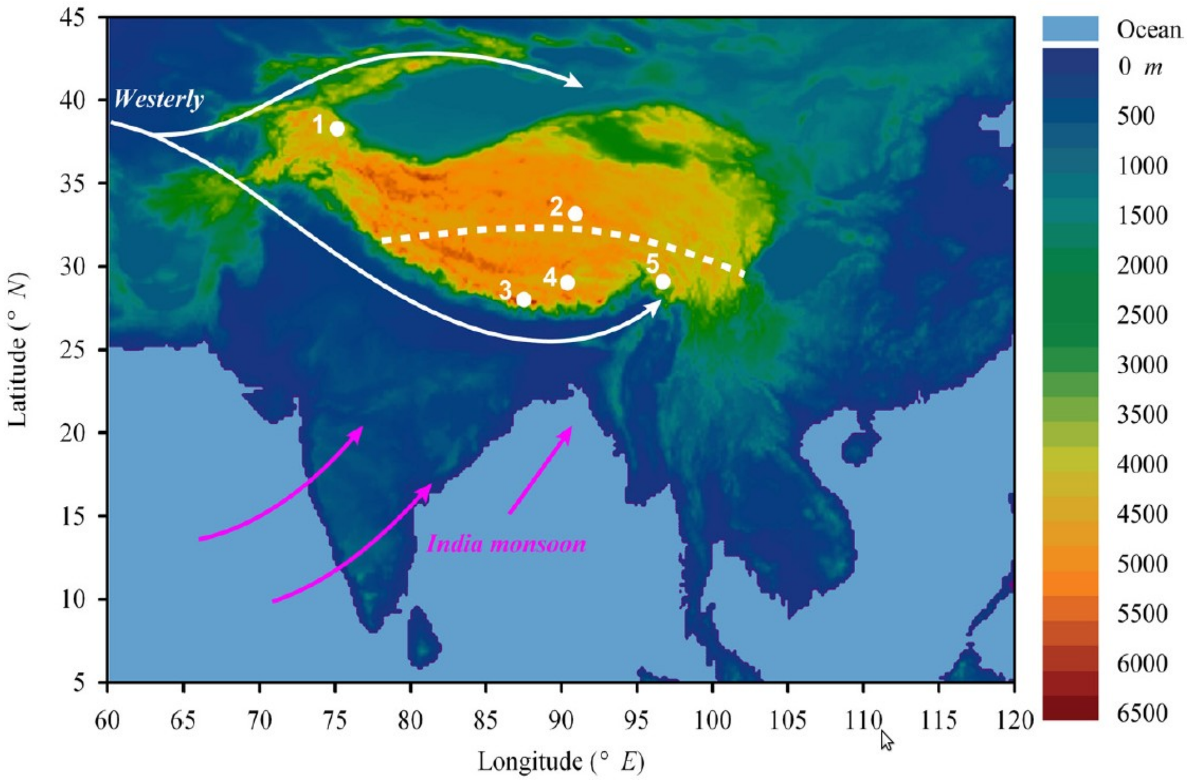


*Figure 3. The locations of five high-altitude ice cores extracted from the Himalayas and Tibetan Plateau: 1 - Mt. Muztagh Ata (6,300 m); 2 - Tanggula glacier (5,800 m); 3 - East Rongbuk glacier, Mt. Everest (6,500 m); 4 - Noijin Kangsang glacier (5,950 m); and 5 - Zuoqiupu glacier (5,600 m). Arrows indicate the direction and origin of the two major air currents that impact the region: the Westerly and the Indian Monsoon. The white dashed line is the estimated northern boundary of the India monsoon. From Xu et al., 2009*

**EMISSIONS AND SOURCES OF BC**

The HKHT region is bounded by two high BC-emitting neighbors: China and India. When determining BC emissions, there is a noticeable discrepancy between top-down studies that rely on measured ratios of BC to total carbon or other aerosol components, and bottom-up emissions inventories based upon fuel consumption and emissions factors. Measurements of elemental composition of ambient aerosols point at fossil fuels as the source of 50 – 90% of BC, whereas emission inventory models suggest biofuels as primary source of emissions, with fossil fuels responsible for only 10-30%.

**China**

A study of sites in the Central TP near Lhasa and the Qinghai-Tibet Highway (ZD and LN) reported that aerosols had local biogenic sources, such as burning of dung for heating and cooking. On the western edge of the TP, analysis attributed the BC measured there to fossil fuels. A high-resolution emission inventory of BC from China in 2000, based upon fuel consumption data (fossil and biomass) and socio-economic statistics, estimated total BC emissions of 1499.4 Gg, per year, mainly due to burning of coal and biomass. This is higher than previous estimates because burning by rural industries and residences were found to be higher than previously assumed. There was a strong seasonal pattern to emissions, with peaks in January and December, and lower emissions in July and August, due to changes in residential heating and open burning of crop residues.

**India**

A 2004 study estimated BC emissions from India to be 426 Gg/yr with a range of 156 – 1365 Gg/yr. Another study estimated 400 – 1400 Gg/yr. Both agreed that most of the BC comes from the burning of biomass for fuel. The Atmospheric Brown Cloud BC Radiocarbon Campaign (ABC-BC14) used radiocarbon measurements of winter monsoon aerosols to determine that both fossil fuel and biomass burning contribute significantly to the ABC over South Asia. Fossil fuel was found to be responsible for up to ½ and biomass for ½ – ⅔ of the BC in the ABC.

**SIGNIFICANT SCIENCE GAPS REMAIN**

There are significant gaps in all areas of the science on the effects and impacts of climate change in this region. The Third Pole is grossly under-monitored relative to the Arctic and Antarctic. Only a handful of stations are conducting in situ observations in high mountain regions. A 2008 workshop in the region noted the scarcity of observational data, including few actual measurements of aerosol deposition onto snow and ice. Little is known about the chemical composition, origin and transport pathways of aerosols arriving in Himalaya, air-to-snow transfer processes, and the fate of aerosols once they are deposited. Workshop participants noted the need for integrated field and modeling studies of ABC characteristics and deposition rates, the energy and mass balance of glaciers, and hydrologic fluxes of streams receiving inputs from glacial melt and/or snowmelt. They also indicated a need for studies on select basins to estimate socioeconomic impacts of glaciers and snowpack melting.

China and India recognize that the HKHT region is vulnerable to climate change, but view data from western sources with suspicion. While research is being conducted in both countries, more is needed. The majority of Chinese research comes out of the Tibetan Plateau Research Institute, Chinese Academy of Sciences. Much of India's research is conducted under the auspices of the Indian Network for Comprehensive Climate Assessment, which includes 127 research bodies, and the National Institute of Climate Institute. The Indian Space Research Organization (ISRO) is also involved in Himalayan BC research. There is growing interest in establishing joint research initiatives, although historical tensions between the two countries make that a challenge.