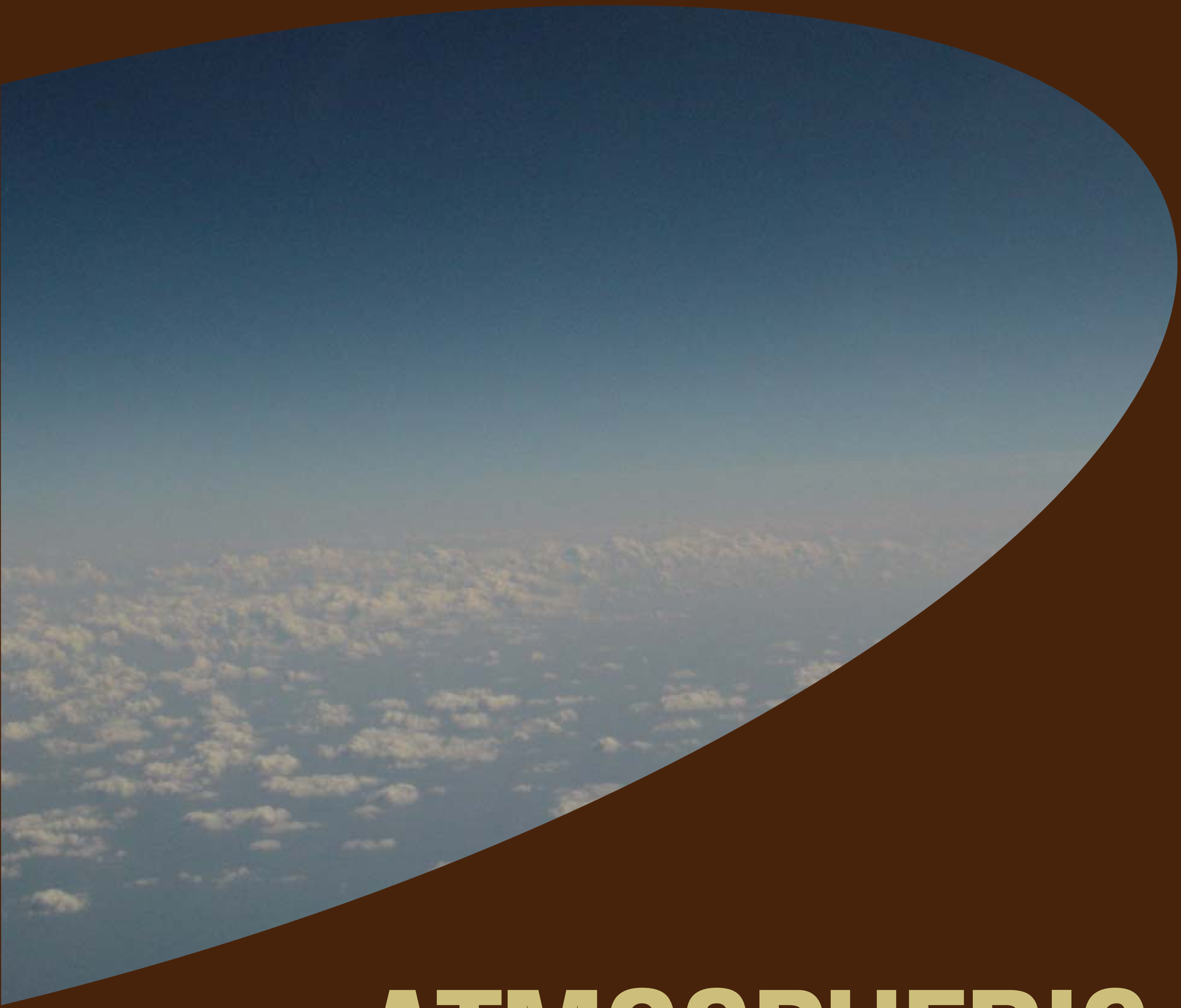
SUMMARY



ATMOSPHERIC BROWN CLOUDS

UNEP

REGIONAL ASSESSMENT REPORT WITH FOCUS ON ASIA

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ATMOSPHERIC BROWN CLOUDS

REGIONAL ASSESSMENT REPORT WITH FOCUS ON ASIA

SUMMARY

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SUMMARY FOR POLICY MAKERS

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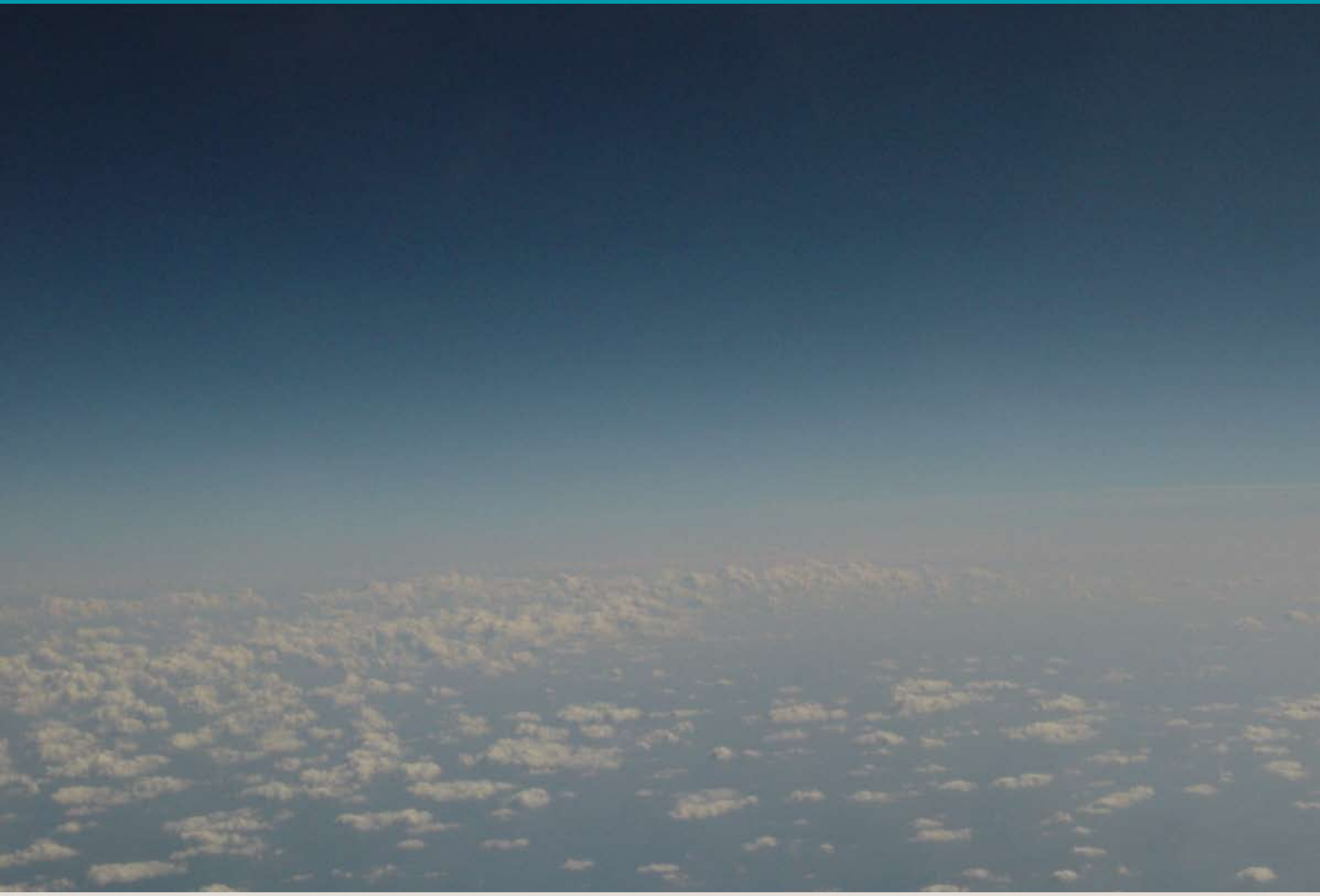


The build-up of greenhouse gases (GHGs) and the resulting global warming pose major environmental threats to Asia's water and food security. Carbon dioxide (CO_2), methane, nitrous oxide, halocarbons and ozone in the lower atmosphere (below about 15 km) are the major gases that are contributing to the increase in the greenhouse effect.

In a similar fashion, increasing amount of soot, sulphates and other aerosol components in atmospheric brown clouds (ABCs) are causing major threats to the water and food security of Asia and have resulted in surface dimming, atmospheric solar heating and soot deposition in the Hindu Kush-Himalayan-Tibetan (HKHT) glaciers and snow packs. These have given rise to major areas of concern, some of the most critical being observed decreases in the Indian summer monsoon rainfall, a north-south shift in rainfall patterns in eastern China, the accelerated retreat of the HKHT glaciers and decrease in snow packs, and the increase in surface ozone. All these have led to negative effects on water resources and crop yields. The emergence of the ABC problem is expected to further aggravate the recent dramatic escalation of food prices and the consequent challenge for survival among the world's most vulnerable populations. Lastly, the human fatalities from indoor and outdoor exposures to ABC-relevant pollutants have also become a source of grave concern.

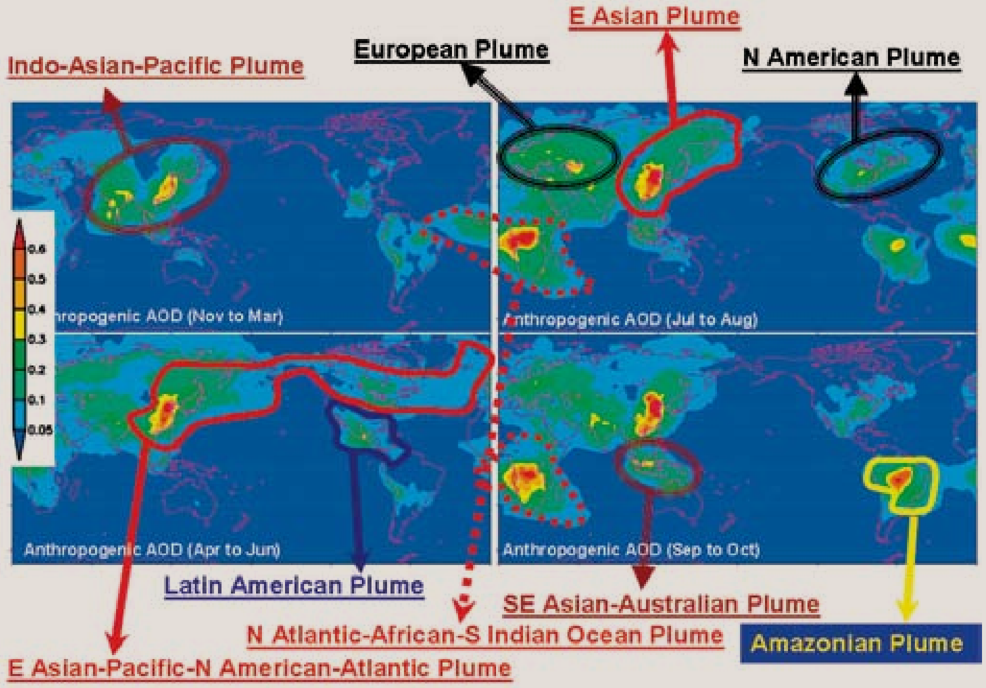
I. Atmospheric Brown Cloud Hotspots

ABCs start as indoor and outdoor air pollution consisting of particles (referred to as primary aerosols) and pollutant gases, such as nitrogen oxides (NO_x), carbon monoxide (CO), sulphur dioxide (SO_2), ammonia (NH_3), and hundreds of organic gases and acids. Widespread ABC plumes resulting from the combustion of biofuels from indoors; biomass burning outdoors and fossil fuels, are found in all densely inhabited regions and oceanic regions downwind of populated continents.

Five regional ABC hotspots around the world have been identified:

i) East Asia
ii) Indo-Gangetic Plain in South Asia
iii) Southeast Asia
iv) Southern Africa; and
v) the Amazon Basin.

ABC hotspots are defined as regions where the annual mean anthropogenic aerosol optical depth (AOD) exceeds 0.3 and the percentage of contribution by absorbing aerosols exceeds 10 per cent (absorbing AOD > 0.03). Substantial loadings of ABCs over Eastern USA and Europe have also been observed. However, in these extra-tropical regions, the atmospheric concentrations of ABCs are large mainly during the summer season since precipitation removes the aerosols efficiently during other seasons. Furthermore, the soot concentrations are lower and hence these extra tropical regions are not included in the hotspots category. In Asia, new aircraft and satellite data have revealed that ABC plumes, measuring 1 - 3 km thick, surround the Hindu Kush-Himalayan-Tibetan glaciers, both from the South Asian and the East Asian sides. Between 1950 and 2002, soot emissions increased three-fold in India and five-fold in China, while sulphur emissions have increased ten-fold in China and seven-fold in India.



The integrated satellite data shows anthropogenic aerosol optical depth (AOD) in the period 2001-2003 for four seasons. AOD is an index for the fraction of sunlight intercepted by particles and total aerosol concentration in the vertical column. The ABCs over South Asia peaked during the months of November-March. For July-August ABCs and dust reached peak values over Africa and Middle East. During the boreal spring, the ABCs and dust extended from East Asia across the North Pacific and further into Atlantic. The Amazonian Plume peaked during September to October. (Source: Ramanathan and others 2007a). (Adopted from Figure 2.5 of Part I)

II. ABCs Radiative Forcing

The absorption of solar radiation by the surface and the atmosphere is the fundamental driver for the physical climate system, the biogeochemical cycles, and for all life on the planet. ABCs have significantly altered this radiative forcing over Asia, as summarized below.

It is certain that ABCs have caused dimming at the surface.

It is certain that soot in ABCs has increased solar heating of the atmosphere.

It is virtually certain that India and China are dimmer (at the surface) today by at least 6 per cent, compared with the pre-industrial values. Absorbed solar radiation at the surface in China and India are lower today by 15 W m^{-2} or more, compared with the pre-industrial values.

It is highly likely that black carbon (BC) in ABCs has increased the vertically averaged annual mean solar absorption in the troposphere (from the surface up to 14 km in altitude) by about 15 per cent (about 14 W m^{-2}) and the solar heating at elevated levels (1 - 4 km) over India and China by as much as 20 - 50 per cent (6 - 20 W m^{-2}).

III. Vulnerability of the Asian Monsoon System

Rainfall over the northern half of India has decreased, while the rainfall pattern in China has shifted. The southern parts of Eastern China have been receiving more rainfall since the 1950s, while the northern parts are experiencing a negative trend. The number of rainy days for all India is also decreasing, although the frequency of intense rainfall is increasing, leading to more frequent floods. The heavily populated Indo-Gangetic Plain is especially vulnerable. Rainfall over the Indo-Gangetic Plain has decreased by about 20 per cent since the 1980s.

ABC-induced dimming is considered as the major causal factor for the rainfall decrease in India and for the north to south shift of the summer monsoon in Eastern China. However, many uncertainties in modelling regional climate remain.

IV. Stability of the Hindu Kush-Himalayan-Tibetan (HKHT) Glaciers and Snow Packs

The acceleration of the retreat of the HKHT glaciers since the 1970s, in conjunction with the decrease in the summer monsoon rainfall in the Indo-Gangetic Plain region, is a major environmental problem facing Asia, threatening both the water and the food security of South and East Asia. Glaciers and snow packs provide the head-waters for Asia's major river systems, including the Indus, the Ganges, the Brahmaputra, the Mekong and the Yangtze.

Widespread deglaciation is occurring in the HKHT region. This includes a 21 per cent decrease in the area of 466 glaciers that were studied in the Indian Himalayas. About 80 per cent of the Western Tibetan glaciers are retreating.

The receding and thinning are primarily attributed in IPCC reports and other studies to global warming due to increases in greenhouse gases. The present report adds that soot in ABCs is another major cause of the retreat of HKHT glaciers and snow packs. The warming of the elevated atmospheric layers due to greenhouse warming is amplified by the solar heating by soot at elevated levels and an increase in solar absorption by snow and ice contaminated by the deposition of soot. New data shown in this report reveal substantial soot concentrations in the Himalayan region even at the altitude of 5 km.

If the current rate of retreat continues unabated, these glaciers and snow packs are expected to shrink by as much as 75 per cent before the year 2050, posing grave danger to the region's water security. This potential threat should be viewed in the context of the low per-capita water availability in South and East Asia, around 2000 - 3000 m^3/cap/year, far less than the world average of 8549 m^3/cap/year.

Projections show that most parts of South and East Asia will suffer from water stress by 2050. Water stress occurs when the demand for water exceeds the available supply during a certain period, or when poor quality restricts its use. It should be noted that the above projections, as well as similar projections in IPCC reports, do not yet account fully for ABC effects on the monsoon and the HKHT glaciers. As a result, the actual water stress situation is expected to be much worse than the projections in the available reports.

Geography of Asia, the Hindu Kush-Himalayan-Tibetan glaciers and their river basins.
(Figure 3.18 of Part I)

V. Food Security

Throughout Asia, the annual growth rate of rice harvest has decreased from 3.5 per cent (1961-1984) to 1.3 per cent (1985 - 1998). Similar decreases in growth rates have occurred for wheat, maize and sorghum. Multiple stresses, such as limited availability of water and air pollution concentrations, are increasing the crops' sensitivity to climate change and reducing resilience in the agricultural sector. The negative impacts of climate change will be felt most acutely in developing countries, particularly in Asia.

Without a decrease in monsoon rainfall due to ABCs and an increase in surface warming due to GHGs, the average annual rice output for nine states studied in India during 1985 - 1998 would have been about 6.2 million tonnes higher [which is equal to the total annual consumption of 72 million people].

In addition, elevated concentrations of ground level ozone have been found to have large effects on crop yields. Experimental evidence suggests that growing season mean ozone concentrations of 30 - 45 ppb could see crop yield losses of 10 - 40 per cent for sensitive varieties of wheat, rice and legumes. A recent study translated such impacts on yield into economic losses estimating that for four key crops (wheat, rice, corn and soybean) annual losses in the region of US$ 5 billion may occur across Japan, the Republic of Korea, and China. These studies used dose-response relationships derived from Europe and North America, recently collated scientific evidence suggests that some important Asian grown crop cultivars may actually be more sensitive to ozone than European or North American varieties. Concern for a worsening situation in the future is highlighted by projections which suggest that the annual surface mean ozone concentrations in parts of South Asia will grow faster than anywhere else in the world and exceed 50 ppb by 2030.

VI. Health

A large fraction of the aerosol particles that make up ABCs originate from emissions at the Earth's surface caused by the incomplete combustion of fossil fuels and biofuels. Humans are exposed to these particles both indoors and outdoors. The adverse health effects of such air-borne particles have been documented in many parts of the world. Some studies have been carried out in Asia, mostly in connection with indoor cooking with biofuels, wildfires and dust storm events.

The most serious health impacts of particles associated with the ABC include cardiovascular and pulmonary effects leading to chronic respiratory problems, hospital admissions and deaths. Review of the available evidence indicates that there are likely to be very significant public health impacts from the ABC.

In order to estimate the magnitude of the potential effects of ABCs on mortality in China and India, increases in anthropogenic $PM_{2.5}$ concentrations of 20 $\mu g/m^3$ were used, based on other studies and supported by calculations carried out using a regional aerosol chemistry model with assimilated satellite aerosol data. Using concentration-response relationships from the existing literature, it is inferred that 337,000 excess deaths per year, with a 95 per cent confidence interval of 181 000 - 492 000, can result due to inhalation of ABCs outdoors in India and China. This would be in addition to a WHO publication estimate of 380 700 total deaths for China and 407 100 total deaths in India from indoor air pollution attributable to solid fuel use.

The economic loss resulting from deaths due to outdoor exposure to ABC-related $PM_{2.5}$ has been crudely estimated to be 3.6 per cent of the GDP in China and 2.2 per cent in India, using mid-range mortality cost estimates. However, these numbers should be interpreted with caution at this early stage. With more research data, some of the uncertainties inherent in the health impact assessment should be reduced, leading to greater precision in the estimates.

TECHNICAL SUMMARY

Atmospheric Brown Clouds and Regional Climate Change

1. Five regional ABC hotspots around the world have been identified:
i) East Asia
ii) Indo-Gangetic Plain in South Asia
iii) Southeast Asia
iv) Southern Africa; and
v) the Amazon Basin.

By integrating and assimilating ABC surface observations with new satellite observations and chemistry transport model (CTM), the ABC Science Team produced global maps of ABC hotspots. ABC hotspots are defined as regions where the annual mean anthropogenic aerosol optical depth (AOD) exceeds 0.3 and the percentage of absorbing aerosols exceeds 10 per cent. Substantial loadings of ABCs over Eastern USA and Europe have also been observed. However, in these extra-tropical regions, the atmospheric concentrations of ABCs are large mainly during the summer season since precipitation removes the aerosols efficiently during other seasons.

BOX TS.1 WHAT ARE ABCs?

Atmospheric brown clouds (ABCs) are regional scale plumes of air pollution that consist of copious amounts of tiny particles of soot, sulphates, nitrates, fly ash and many other pollutants.

Basically, ABCs are the same as the aerosols that are mentioned in reports by the Intergovernmental Panel on Climate Change (IPCC). In principle, tropospheric ozone should be part of ABCs, but ozone effects are treated separately in this report. Soot results from the incomplete combustion of fuels and consists of nano- to a few micro-metre (millionth of a metre) size particles. Black carbon (that is, 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 anthropogenic black carbon, fly ash, soil dust particles, and nitrogen dioxide gas. Typical background concentrations of aerosols are in the range 100 - 300 cm^{-3}, whereas in polluted continental regions the concentrations are in the range 1 000 - 10 000 cm^{-3}.

ABCs start as indoor and outdoor air pollution consisting of particles (referred to as primary aerosols) and pollutant gases, such as nitrogen oxides (NO_x), carbon monoxide (CO), sulphur dioxide (SO_2), ammonia (NH_3), and hundreds of organic gases and acids.

These pollutants are emitted from anthropogenic sources, such as fossil fuel combustion, biofuel cooking and biomass burning. Gases, such as NO_x, CO and many volatile organic compounds (VOCs), are referred to as ozone precursors since they lead to the production of ozone which is both a pollutant and a strong greenhouse gas. Gases, such as SO_2, NH_3, NO_x and organics, are referred to as aerosol precursor gases, and these gases - over a period of a day or more - are converted to aerosols through the so-called gas to particle conversion process. Aerosols that are formed from gases through chemical changes (oxidation) in the air are referred to as secondary aerosols.

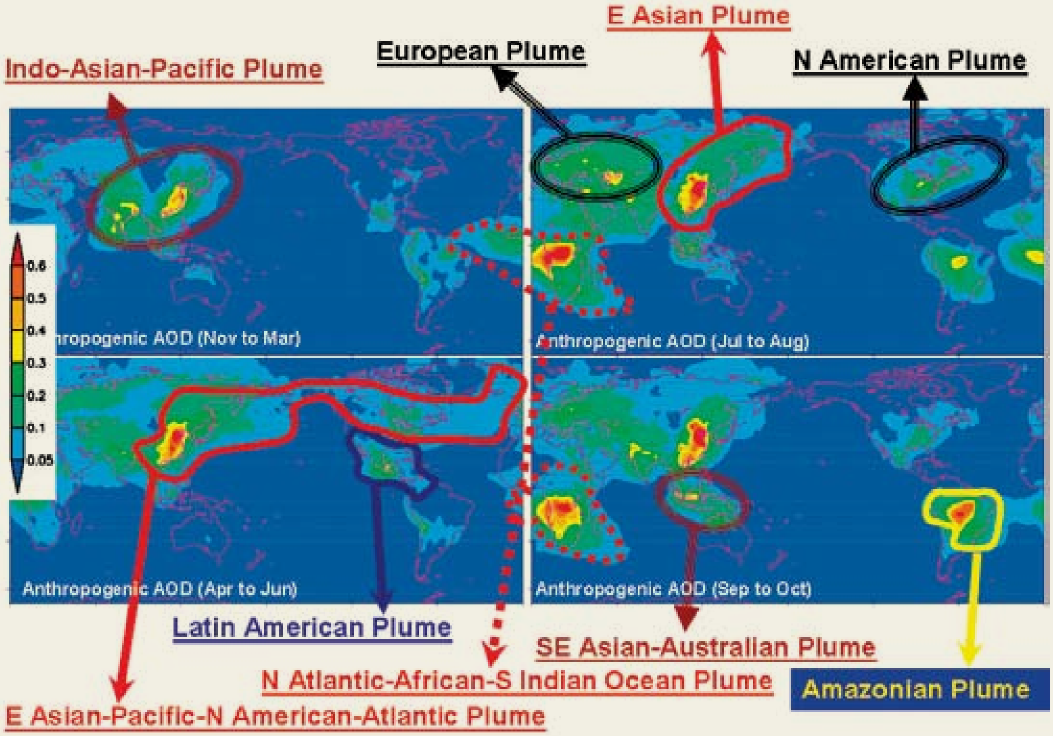


Figure TS1.1 *The integrated satellite data shows anthropogenic aerosol optical depth (AOD) in the period 2001-2003 for four seasons. AOD is an index for the fraction of sunlight intercepted by particles and total aerosol concentration in the vertical column. The ABCs over South Asia peaked during the months of November-March. For July-August ABCs and dust reached peak values over Africa and Middle East. During the boreal spring, the ABCs and dust extended from East Asia across the North Pacific and further into Atlantic. The Amazonian Plume peaked during September to October. (Source: Ramanathan and others 2007a). (Adopted from Figure 2.5 of Part I)*

2. The following 13 mega-city ABC hotspots in Asia have been identified: Bangkok, Beijing, Cairo, Dhaka, Karachi, Kolkata, Lagos, Mumbai, New Delhi, Seoul, Shanghai, Shenzhen and Tehran.

Over these hotspots, the annual AOD (natural+anthropogenic) exceeds 0.3 and the absorption optical depth is about 10 per cent of the AOD, indicative of the presence of strongly absorbing soot accounting for about 10 per cent of the amount of aerosols. The annual mean surface dimming and atmospheric solar heating by ABCs over some of the hotspots range from 10 - 25 per cent, such as in Karachi, Beijing, Shanghai and New Delhi.

3. Using satellite data and regional assimilation models, the chemical composition of aerosols in ABCs and how their chemistry contributes to the AOD have been characterized for the first time for China and India.

4. The TOA forcing due to the increase of GHGs from the pre-industrial period to the present is estimated by IPCC-AR4 (2007) at about 3 W m^{-2} (90 per cent confidence interval of 2.6 - 3.6 W m^{-2}). The same report estimates aerosol forcing (direct plus indirect) at -1.2 W m^{-2} (90 per cent confidence interval of -2.7 to -0.4 W m^{-2}).

5. The combined GHG and ABC forcing is 1.8 W m^{-2} with a 90 per cent confidence confidence interval of 0.6 - 2.4 W m^{-2}. By comparing this with only the GHG forcing of 3 W m^{-2} (90 per cent interval of 2.6-3.6 W m^{-2}), it is seen that aerosols in ABCs have masked 20 - 80 per cent of GHG forcing in the past century.

6. Air pollution laws can have major impacts on global warming this century. Thus, air pollution regulations can have large amplifying effects on global warming. For example, using climate sensitivity recommended in IPCC-AR4,

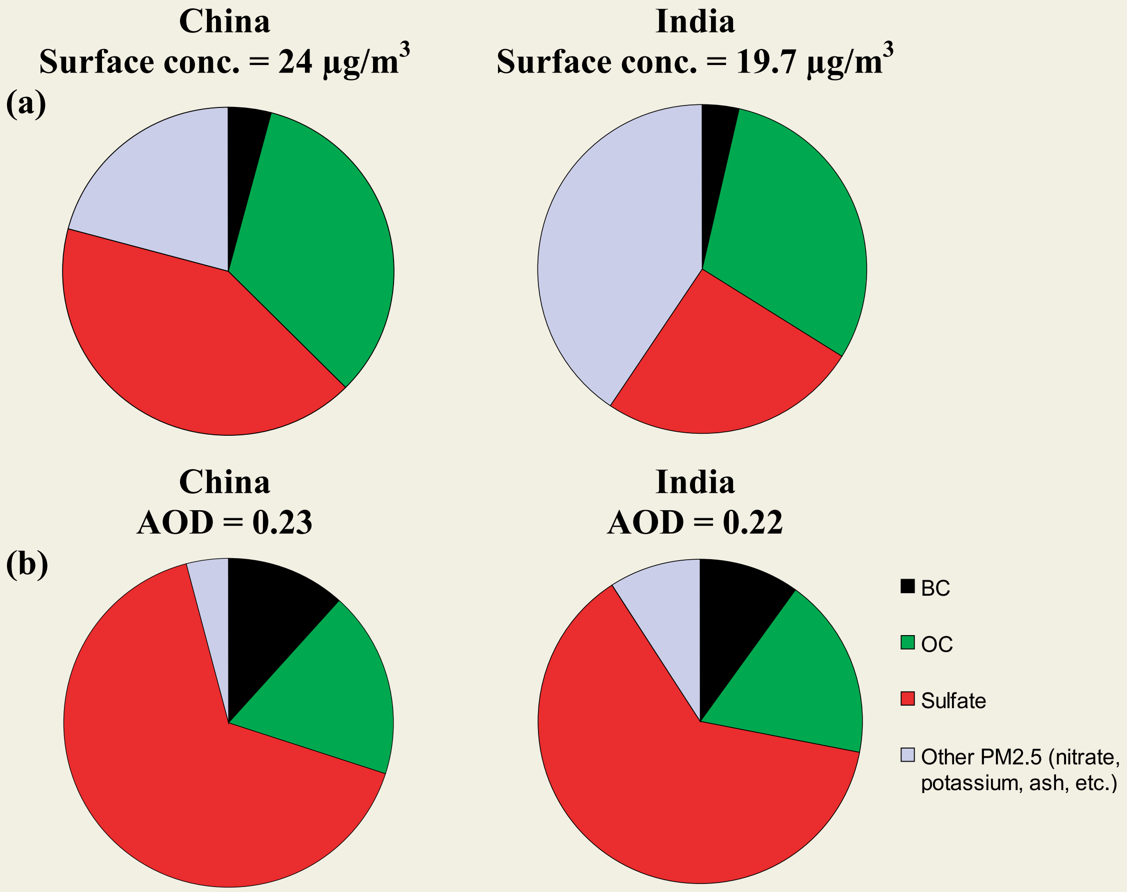


***Figure TS1.2** Annual and area average chemical speciation of (a) surface mass concentration for anthropogenic* $PM_{2.5}$ *aerosols in China and India, and (b) column integrated aerosol optical depth (AOD) for anthropogenic aerosols, i.e. ABCs (Source: Adhikary and others 2008; except that the average AOD values in (b) for China and India are from Chung and others 2005) (Figure 2.10 of Part I)*

elimination of aerosols in ABCs can lead to an additional warming of 0.3 - 2.2°C. The upper value of 2.2°C, when added to the 20th century warming of 0.75°C, could likely push the climate system over the 2°C threshold value for the so-called dangerous climate change.

ABC RADIATIVE FORCING OVER ASIA: CHINA AND INDIA

7. For regional climate change due to ABCs, the TOA forcing is not a sufficient metric for assessing the magnitude and sign of the climate change because surface forcing and atmospheric forcing have opposing signs. All three forcing components - TOA, surface and atmosphere - need to be evaluated to understand the magnitude and sign of regional temperature and precipitation changes.

BOX TS.2 RADIATIVE FORCING OF GREENHOUSE GASES AND ABCs

By interfering with the distribution of the sun's energy between the surface and the atmosphere, aerosols in ABCs influence climate and the biosphere in a fundamental way.

Greenhouse gases (GHGs) act like a blanket and trap some infra-red (IR) radiation. The addition of GHGs enhances this heat-trapping effect and reduces the outgoing IR, which leads to warming of the surface and the atmosphere. The GHGs add energy to both the atmosphere and the surface, unlike ABCs which add energy to the atmosphere and reduce it at the surface. When averaged over the entire planet over a long period, a decade or more, the net incoming solar energy (incoming minus reflected) is balanced by the outgoing infra-red radiation (also referred to as heat radiation) given off by the surface and the atmosphere.

Aerosols in ABCs intercept solar energy before it reaches the surface and thus perturb temperature, precipitation and biomass production. ABCs intercept sunlight by both absorbing it in the atmosphere and by reflecting it (also referred to as scattering) back to space. Absorption enhances the solar heating of the atmosphere. On the other hand, both absorption and reflection of solar radiation lead to dimming at the surface, that is, they reduce the amount of solar energy absorbed at the surface. Energy from the sun (also referred to as solar radiation or sunlight) is the fundamental forcing agent of the climate system, agriculture and life itself. Sunlight heats the surface and leads to the evaporation of water, which ultimately falls back as rainfall and snowfall. Sunlight is the energy source for photosynthesis.

The net effect of ABCs on the global mean climate is determined by the sum of their effects on the atmosphere (a heating effect) and on the surface (a cooling effect), and this sum is referred to as top of the atmosphere (TOA) forcing, which is described in the fourth assessment report of IPCC (IPCC 2007).

For global average climate change, the TOA forcing is the critical climate forcing term.

8. ABC-induced atmospheric solar heating and surface dimming are large over Asia in general and over India and China, in particular. The annual mean solar heating of the troposphere increased by 15 per cent or more over China and India. Heating increase in the lower atmosphere (surface to 3 km), where ABCs are located, is as much as 20 - 50 per cent (6 - 20 W m^{-2}) over China and India. Large increases in heating rates are also widespread over regions in the Northern Indian Ocean and the Western Pacific Ocean. Over China and India, the annual mean surface dimming due only to direct ABC forcing is about 14 - 16 W m^{-2} (about 6 per cent).

Regionally, TOA forcing by itself is an insufficient metric. Surface forcing (dimming) and atmospheric forcing (solar heating) are important terms as they are factors of 3 - 10 larger than TOA forcing. Dimming and solar heating have been estimated in numerous observational and modelling studies over China and India. Over the hotspots, the values are about twice as large. The above values are estimates for ABCs during the period 2000 - 2007. Direct radiative effects are major contributors (about 70 per cent) to dimming while indirect radiative effects dominate (>70 per cent) the TOA forcing.

BOX TS.3 AEROSOLS IN ABCs HAVE BOTH COOLING AND WARMING EFFECTS

For GHGs, the global mean forcing is positive, while for ABCs it is negative.
However, this does not mean that all aerosols in ABCs have a cooling effect. Some aerosols have a cooling effect and others have a heating effect, as described next.

Some aerosols, such as sulphates and nitrates, have a cooling effect. Others, such as black carbon (BC), have a warming effect on the surface-atmosphere system.

i. Cooling aerosols. These aerosols primarily scatter solar radiation back to space, leading to a reduction of solar radiation at the surface (known as surface dimming), which results in the cooling of the surface-atmosphere system. Major examples of this category are sulphates, nitrates and some organics.

ii. Heating aerosols. Major examples of this category are elemental carbon and some organic acids in soot. Together these aerosols are referred to as black carbon. The heating aerosols absorb solar radiation. Furthermore, the ratio of absorption to scattering exceeds 10 per cent. These absorbing aerosols add solar energy to the atmosphere and alter the distribution of energy in two different ways. First, by absorbing direct solar radiation, which would have otherwise reached the surface, the absorbing aerosols lead to dimming at the surface. This effect is a redistribution of the solar energy between the surface and the atmosphere, and has a significant influence on the stability of the atmosphere by warming the air above and cooling the surface below, suppressing cumulus clouds and cumulus precipitation. Furthermore, dimming will lead to reduced evaporation of water vapour from the surface, thereby impacting precipitation. Second, by absorbing solar radiation reflected by the surface, atmosphere and clouds, the absorbing aerosols reduce the amount of solar radiation that is reflected to space. This results in a net heating of the surface-atmosphere system and therefore constitutes a positive radiative forcing of the climate system and contributes to global warming. Thus, black carbon aerosols are major agents of regional and global warming.

In ABCs, the cooling aerosols and heating aerosols do not exist as separate entities (referred to as externally mixed), rather each aerosol particle contains a mix of cooling and heating aerosols (referred to as internally mixed). In the case of such internally mixed aerosols, the distinction between cooling and heating aerosols gets blurred, and the net effect can be highly variable depending on the region and the season. Thus far, we have summarized the forcing of the climate system by direct scattering and absorption of solar radiation. The above effects are referred to as direct radiative forcing.

BOX TS.4: ABCs ALSO INFLUENCE CLOUD PROPERTIES

Aerosols in ABCs nucleate cloud drops. The enhancement of the cloud drop population increases the reflection of solar radiation (making the clouds brighter) which leads to dimming and surface cooling. In regions with copious amounts of ABC aerosols, competition for water between nucleating aerosols causes cloud drop size to decrease, and this inhibits the formation of larger size drizzles and rain drops. The net effect is an extension of cloud lifetimes, that is, the polluted regions are cloudier with brighter clouds. This latter effect also leads to dimming and surface cooling. The radiative changes due to the two effects above are referred to as indirect radiative forcing.

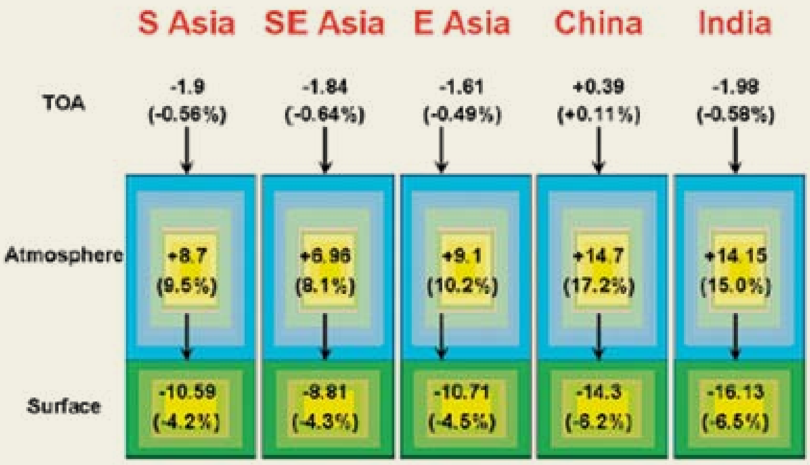


Figure TS1.3 *Regional and annual mean direct SW radiative forcing by ABCs over South Asia (0°N-4°N, 6°E-9°E), Southeast Asia (10°S-2°N, 9°E-13°E), East Asia (2°N-54°N, 75°E-145°E), China, and India. The forcings are for the all-sky condition with the unit W m^{-2}. The values inside the parentheses are the percentages of ABCs forcing relative to the background conditions (natural aerosols). (Figure 2.17 of Part I).*

9. Another important characteristic of ABC forcing in Asia is that it introduces large north-south asymmetries in the forcing and large land-sea contrasts. Since these are the driving forces for the monsoonal climate, ABCs have become major forcing terms for regional temperatures, circulation and precipitation.

For example, in the Indian Ocean surface dimming is negligible south of about 10°S (due to the absence of ABCs) and is concentrated north of 5°N. Similarly, negative forcing at the surface is much larger over the subcontinent than over the surrounding Arabian Sea and Bay of Bengal.

OBSERVED TRENDS IN ABC EMISSIONS

10. Emissions of various ABC precursor species increased rapidly after the 1950s. During the period 1950 - 2000, BC emissions increased five-fold in China and about three-fold in South Asia, including India, and Southeast Asia. SO$_2$ emissions increased about ten-fold in China and about six- to seven-fold in India.

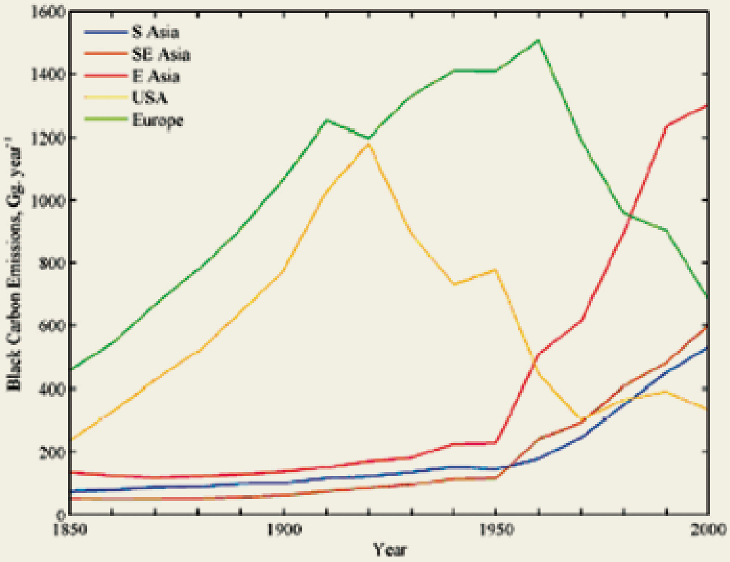


Figure TS1.4 *Black carbon emissions for 1850 - 2000. The estimate includes only fossil fuel and biofuel combustion sources. (Source: Bond and others 2007). (Figure 2.23 of Part I).*

OBSERVED TRENDS IN REGIONAL CLIMATE AND ATTRIBUTION: CHINA AND INDIA

11. **In China and India, large changes in solar radiation, surface and atmospheric temperatures and monsoon rainfall have been observed. These changes cannot be explained solely from the increase in GHGs. Global climate model (GCM) studies suggest that a combination of GHGs and ABCs, along with natural variables, is needed to properly simulate the observed trends.** It should be noted that understanding of the complex issues related to the simulation of regional climate change from regional and global forcing is in an early stage. For a more reliable estimate of regional climate changes, a combination of GCMs and regional climate models (RCMs) with a finer spatial resolution (about 50 km or less) than that adopted in GCMs (200 km or more), is required. The results and findings described here, based on GCMs, should be considered as indicative of the importance of the problem and should provide a strong motivation for further studies with RCMs.

SOLAR RADIATION

12. **Annual land-average solar radiation over India and China decreased significantly during the period 1950 - 2000.** For India, the observed surface dimming trend was -4.2 W m^{-2} per decade (about 2 per cent per decade) for the 1960 - 2000 period, while an accelerated trend of -8 W m^{-2} per decade was observed for the 1980 - 2004 period. Cumulatively, these decadal trends suggest a reduction of about 20 W m^{-2} from the 1970s up to the present, thus supporting the large dimming values inferred from modern satellite and field campaign data. In China, the observed dimming trend from the 1950s to the 1990s was about 3-4 per cent per decade, with larger trends after the 1970s. Cities like Guangzhou recorded more than 20 per cent reduction in sunlight since the 1970s.

13. **The dimming trend has been attributed by numerous studies largely to the rapid increase in ABC emissions since the 1950s.** Coupled Ocean-Atmosphere models that employ observed increases in SO_2 and BC emissions are able to account for the observed dimming trends solely from ABCs.

14. **In China and India, the dimming trend was accompanied by large decreases in pan evaporation.** However, this does not necessarily imply a decrease in actual evaporation or evapo-transpiration.

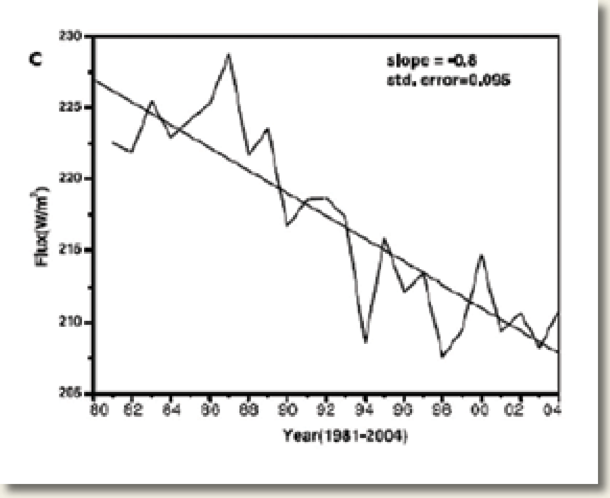


Figure TS1.5 All-India averaged annual mean surface reaching solar radiation. (Source: Kumari and others 2007). (Figure 3.1c of Part I)

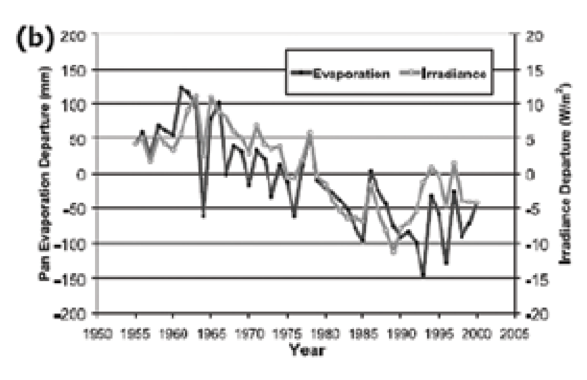


Figure TS1.6 Time-series of annual departures of pan evaporation and solar irradiance for the period 1995-2000, averaged over all stations in China (Source: Qian and others 2006). (Figure 3.2b of Part I)

SURFACE AND ATMOSPHERIC TEMPERATURES

15. **ABCs are intensifying the greenhouse warming of the atmosphere (at least during the dry season), while reducing surface warming due to GHGs.**

16. **Asia was subject to an annual mean warming trend of about 0.7 - 1°C from the pre-industrial period up to the present. The trend was not uniform over all seasons or over all regions.** In India, the warming trend from the early 1900s, during the dry season (January-May), was arrested after the 1950s, whereas the warming trend during the summer continued unabated into the 21st century. This is consistent with the stronger masking effect of ABCs during the dry season. Annual mean surface air temperature in Mainland China increased by 1.1°C during the past 50 years. Minimum night time temperatures were subject to a much larger warming trend than daytime maximum temperatures. However, the warming was not uniform throughout China. Regionally, North, Northeast and Northwest China, and the Tibetan Plateau experienced the most significant warming on an annual mean basis accompanied by a strong cooling trend (0.1 - 0.3 per decade) in Southwest China and in central East China.

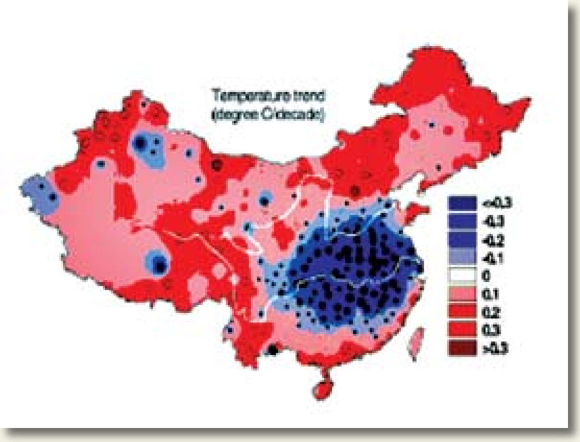


Figure TS1.7 *Geographical pattern of daily mean temperature changes in China in the past 50 years (Source: Xu and others 2006). (Figure 3.5b of Part I)*

17. **In India, the slowing down of the dry season warming after the 1950s and the larger positive trends in night time temperatures compared with daytime temperatures (when the dimming effect is present) are consistent with the masking effect of ABCs.**

18. **The combined effects of GHGs, ABCs and rapid urbanization are required to explain the complex pattern of warming and cooling trends in China.**

19. **In India, the atmosphere warms significantly more than the surface during the six month-long dry season.** Microwave satellite data for lower tropospheric average temperature trend, when compared with surface temperature trends, show that since the early 1980s, the atmosphere has been warming significantly more than the surface during the dry season. On the other hand, during the summer season, the atmosphere and the surface warm at about the same level (that is, the differential warming is very small). Reliable in-situ balloon data for atmospheric temperature trends are not available for Asia.

20. **Coupled Ocean-Atmosphere GCMs suggest that stronger atmospheric warming, preferentially during the Indian dry season, is due to the solar heating of the atmosphere by black carbon in ABCs.** This suggests the possibility of a positive feedback between an increase in ABCs and solar warming of the atmosphere, since a stable atmosphere increases the lifetime of ABCs.

MONSOON RAINFALL

21. **Observed summer precipitation trends for the 1950 - 2000 period revealed the following: (a) a decrease in monsoon precipitation over India and Southeast Asia by about 5 - 7 per cent; and (b) a shift in rainfall in China with Northern China receiving less rainfall and Southern China receiving more rainfall.**

Table TS1.1 Changes and trends since the 1950s (Adopted from Table 3.1 of Part I)

Variables	South Asia and India	East Asia and China
Black carbon emissions	S Asia: Increased from under 170 Gg/yr in 1950 to about 550 Gg/Yr in 2000.	E Asia: Increased from about 250 Gg/yr in 1950 to about 1 300 Gg/yr in 2000.
SO_2 emissions	S Asia: Increased from about 1 Tg/yr in 1950 to about 7 Tg/yr in 2000.	E Asia: Increased from about 2 Tg/yr in 1950 to over 20 Tg/yr in 2000.
Dimming at surface: Solar radiation at surface	India: Trend of -4 W m^{-2} per decade from 1965 - 2000; Likely -8 W m^{-2} from 1980-2004. Total decrease of about 15 - 20 W m^{-2} since the 1960s.	China: Decrease of -20 W m^{-2} from 1960 - 1995; Reversal of trend after 1995, with a total increase of about 5 W m^{-2}.
Surface temperature	India: Wet season summer temperature trend is similar to global mean trend. During the dry season (January-May), there is a negligible trend in T_{max} after 1950. Since 1990, the warming trend in T_{min} (0.56 per decade) is twice as large as the trend in T_{max}.	China: T_{max} showed no trend (or even slight negative trend) from 1955-1990. From 1990-2000, the trend was about 0.5 per decade. But T_{min} showed a positive trend throughout the period from 1950, although the trend was twice as large since 1990. There is a strong regional pattern. The central and southern parts of Eastern China were subject to a strong cooling trend of about -0.1 to - 0.3°C per decade; the rest of China was subject to a warming trend.
Atmospheric temperature	India: Microwave satellite data reveal significantly larger atmospheric warming trend, compared with the surface. Data are available only from 1979. For the 1979 - 2003 period, the troposphere warmed more than the surface by about 0.5°C.	China: Data not available.
Monsoon rainfall	See table TS1.2	See Table TS1.2

Table TS1.2 Published studies on trends in Asian monsoons (Table 3.2).

Region	Surface winds	Surface temperature and gradient in land and sea surface temperatures
East Asian Monsoon Trends from 1969 - 2000; Observational study and model study	Annual mean wind speed decreased by 28%. Decrease in both winter and summer seasons.Windy days decreased by 58%.	A. Strong winter warming in Northern China attributed to weakening winter monsoon. B. Summer cooling in Southern China and warming over surrounding ocean attributed to weakening of summer monsoon.
East Asian Monsoon Observed trends and attribution using models		Surface cooling in South and central East China. Data show strong negative trends in surface solar radiation, supporting that the surface cooling is due to decreasing solar radiation.
East Asian Monsoon Change from pre-industrial to present; A modelling study with fixed SST on the role of black carbon		Cooled the surface over China.
East Asian Monsoon Trends in the past 25 years in surface temperature and precipitation		Cooling trend along the Yangtze River Valley and warming trend in Northern China.
Indian Summer Monsoon Observational study and coupled Ocean-Atmosphere modelling study of combined GHGs and ABCs. Trend from 1950 - 2000	Monsoon circulation weakened.	Warming due to greenhouse forcing but it was damped during the dry season. ABCs masked as much as 50% of the greenhouse forcing over land; decreased gradient in the Indian Ocean with more warming south of the equator and less north of the equator. Substantial warming at elevated levels of the atmosphere surrounding the Himalaya-Tibetan region.

	Precipitation	Reference and Comments
		Xu and others 2006. Wind speed correlated positively with declining solar radiation; Weakening is attributed to dimming from pollution.
	Southward movement of monsoon belt with "north drought and south flooding". Modeling studies suggest that air pollution-induced surface cooling leads to southward shift on monsoon belt.	Xu 2001. Concluded that air pollution, that is, ABCs, is the major reason for anomalies in monsoon rainfall.
	Summer precipitation increased in Southern China and decreased northwards.	Menon and others (2002). Concluded that the northern drought and southern flooding in China are due mainly to BC aerosols intensifying circulation over Southern China with subsidence in Northern China and Southeast Asia.
	More frequent floods along with cooler conditions over the Yangtze River Valley; accompanied by continuing droughts and longer hot spells in Northern China in the past 25 years.	Zhao and others (2005a) reviewed available papers on this topic. After considering natural variability, GHGs and sulphate and black carbon aerosols (ABCs), concluded that GHGs and brown clouds likely account for rainfall trends.
	Used station precipitation data to show that summer precipitation decreased over India by about 5%; model simulated this trend, but only if it included ABC effects. India averaged rainfall decreased by 4-8% since the 1950s. Predicted a doubling of drought frequency in the next few decades if ABC emissions increase at current rates.	Ramanathan and others (2005), Chung and others (2002, 2006). Showed that dimming decreased evaporation from the Indian Ocean; decreased SST gradient; atmospheric solar heating stabilized the column but also increased precipitation over land. The net effect of ABCs is to weaken the monsoon circulation and decrease monsoon rainfall.

Region	Surface winds	Surface temperature and gradient in land and sea surface temperatures
Indian Summer Monsoon Observational study of Central India rainfall trends from 1950 - 2000.		
Indian Summer Monsoon Rainfall trends from 1951 - 2003	Weakening of monsoon; and shrinking of the monsoon season.	Land-ocean temperature contrast is decreasing (<-0.3°C).
Indian Summer Monsoon Role of ABCs in monsoon circulation; modelling Studies		
Indian Summer Monsoon Role of black carbon; coupled Ocean-Atmosphere modelling study	Weakens in summer.	Warming of the atmosphere at elevated levels.
Indian Summer Monsoon Stability Modelling study	Monsoon is unstable to large changes in solar radiation.	

Precipitation	Reference & Comments
Significant increase in the frequency and magnitude of extreme rain events (>100 m/day); significant decreasing trends in frequency of moderate events (<100 mm/day). Frequency of very heavy events (>150 mm/day) nearly doubled.	Goswami and others (2006). Predicted a substantial increase in hazards due to heavy rainfall events in India.
Large (>25%) decrease in early and late season rainfall; and decrease in the number of rainy days (>25%). Concluded that the monsoon season is shrinking. Spatial coverage of rainfall is also shrinking.	Ramesh and Goswami (2007).
Elevated heating by black carbon and dust near the Indo-Tibetan region provides forcing for enhanced monsoon circulation and increased rainfall. This is referred to as Elevated Heat Pump (EHP) effect. This mechanism can add to monsoon variability.	Lau and others (2006). A review paper by Lau and others (2008) concluded that EHP can lead to increased rainfall during May-June; and the coupled Ocean-Atmosphere effects of dimming, SST gradients and reduced evaporation will take over during the monsoon period of July-August and decrease rainfall.
Increase in May to June rainfall supporting Lau and other's EHP hypothesis; accompanied by decrease in July-September rainfall supporting the findings of Ramanathan and others (2005) and Ramanathan and others (2007).	Meehl and others (2008).
	Lenton and others (2008). Used pedagogical models to suggest that the monsoon system is unstable to combined forcing due to GHGs, ABCs and land surface changes. Concluded that the Indian monsoon is one of the tipping elements of the climate system.

22. The Palmer Drought Severity Index shows an increase in drought-prone conditions, that is, a decrease in cumulative soil moisture in India and Northern China since the 1900s.

23. Intense rain events (>100 mm per day) have increased followed by a decrease in moderate events (<100 mm per day) in India as well as in China.

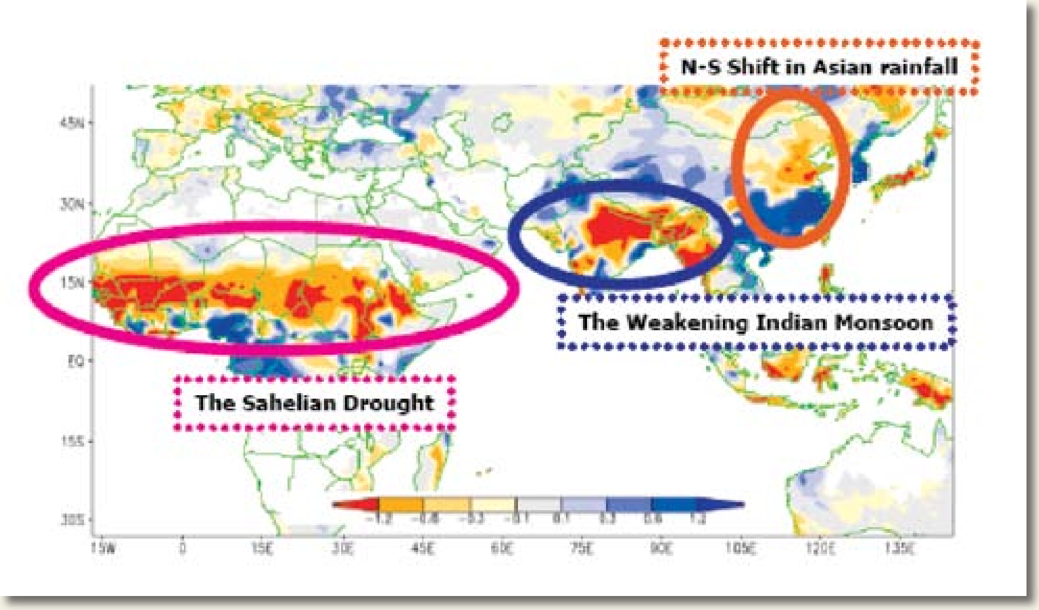


Figure TS1.8 *Observed trends in summer rainfall: 1950 - 2002. (Source: Chung and Ramanathan 2006). (Figure 3.8 of Part I)*

24. These observed trends in land average precipitation cannot be explained solely by increases in GHGs. The IPCC-AR4 GCMs with just the GHG increase are not able to simulate the decrease in zonal mean tropical land precipitation north of the equator, or the decrease in monsoon rainfall in India or the north-south shift in China's rainfall.

25. While the increase in intense rainfall can be accounted for by global warming due to GHGs and the solar heating of the atmosphere by black carbon in ABCs, dimming due to ABCs is required to account for the decrease in the Indian monsoon rainfall since the 1950s. Understanding rainfall trends at a regional scale is a science still at its infancy, although impressive progress has been made in identifying major drivers of regional changes in precipitation. Studies with GCMs suggest that four processes are involved in the ABC modification of rainfall. The first three tend to decrease rainfall while the fourth tends to increase rainfall. i) Dimming leads to a decrease in the evaporation of water vapour (that feeds rainfall) from the surrounding ocean and land surface; ii) Dimming decreases the land-sea contrast in the solar heating of the region, an important monsoon forcing agent; iii) The preferential dimming of the polluted Northern Indian Ocean, compared with the relatively cleaner Southern Indian Ocean, decreases the north-south gradient in sea surface temperatures, another important monsoon forcing term; and iv) The solar heating of the atmosphere strengthens the monsoonal flow into the subcontinent, increasing rainfall.

26. Numerous modelling studies have converged on the finding that regional ABC forcing is substantial enough to perturb the East Asian monsoon and alter the amount of precipitation as well as its regional patterns in China.

RETREAT OF HINDU KUSH-HIMALAYAN-TIBETAN GLACIERS AND SNOW PACK

The Hindu Kush-Himalayan-Tibetan glaciers are the water fountains of Asia

Figure TS1.9 *Geography of Asia, the Hindu Kush-Himalayan-Tibetan glaciers and their river basins. (Figure 3.18 of Part I).*

27. The observed retreat of the Hindu Kush-Himalayan-Tibetan (HKHT) glaciers is one of the most serious environmental problems facing Asia, since these glaciers and snow packs provide the head-waters for the major Asian river systems, including the Ganges, the Brahmaputra, the Mekong and the Yangtze. A glacier inventory by the Chinese Academy of Sciences has reported a 5 per cent shrinkage since the 1950s in the volume of China's 46 928 glaciers over the past 24 years, equivalent to the loss of over 3 000 km^2 of ice. About 82.2 per cent of the glacial area in Western China is shrinking. Many of the major glaciers in India (such as Siachen, Gangotri and Chhota Shigri) are also retreating at rates ranging from 10-25 m per year. The glacier retreat began in the mid-19th century. The retreat has accelerated since the 1970s.

28. Most of the studies, if not all, attribute the retreat of the Himalayan glaciers to rising air temperatures. Warming is much more pronounced at elevated levels of the Himalayan-Tibetan region. The warming trend at elevated regions (>3 km) is as much as 0.25°C per decade since the 1950s.

29. ABC solar heating (by black carbon) of the atmosphere is suggested to be as important as GHG warming in accounting for the anomalously large warming trend observed in the elevated regions.

Fast Retreat of Western Himalayan Glaciers

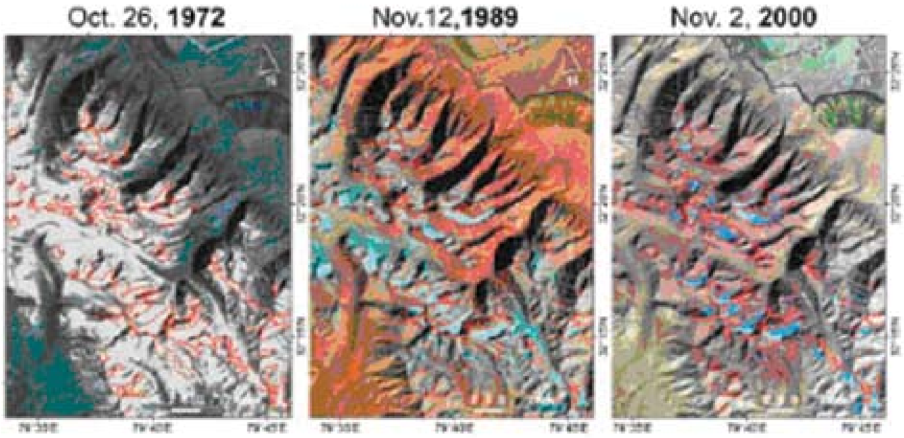


Figure TS1.10
Change in the snow and glacier cover in the Western Himalayan region as shown in Landsat multispectral scanner (1972), thematic mapper (1989), and Enhanced Thematic Mapper Plus (2000) images. (Source: Prasad and Singh 2007). (Figure 3.19 of Part I).

30. Decreased reflection of solar radiation by snow and ice due to black carbon deposition is emerging as another major contributor to the melting of snow packs and glaciers. Recent ice core observations reveal large depositions of sulphates and black carbon, with a large increasing trend during the past few decades. Furthermore, new atmospheric observations by Project ABC in elevated regions of the Himalayas (1 - 5 km) within 100 km of the Mt Everest region, suggest large black carbon concentrations ranging from a few hundred to a few thousand ng m^{-3}.

The Himalayan-Tibetan Region is surrounded by ABCs and dust

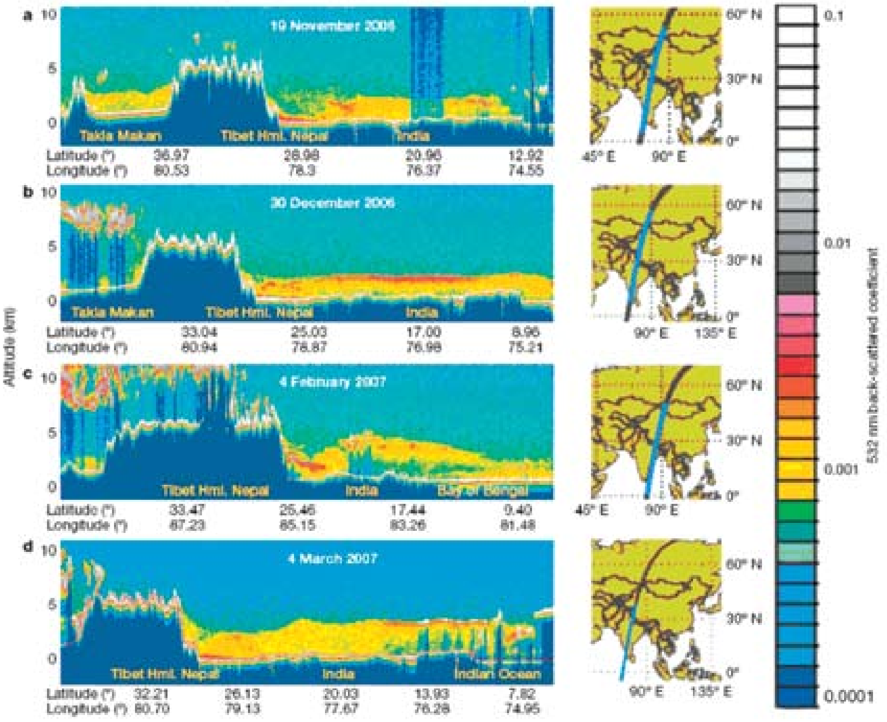


Figure TS1.11. *Colour-coded profiles of 532 nm backscatter return signal from the CALIPSO lidar showing the vertical distribution of ABCs. The panels on the right show the orbit track across Asia and on the left the vertical extent of the aerosol is shown for the blue-shaded portion of each track. This colour scale was chosen so that aerosol usually shows up in green, yellow and red (for low, medium and high loadings, respectively) and boundary layer clouds usually show up as grey or white. Cirrus usually ranges from yellow to grey. Sample profiles are shown for four months of the dry season (November-May). The Takla Makan desert is in Northwestern China between 37°N and 41°N and 77°E to 90°E. Hml., Himalayas. (Source: Ramanathan and others 2007b). (Figure 3.22 of Part I).*

Table TS1.3 Glacier retreat in India and China. (Table 3.3).

Tian Shan and Pamirs

“Glaciers in the mountains of Central Asia provide more than 70 per cent of the water in the Indus and Amu Darya rivers. Glacial area has dropped by 35-50 per cent since the 1930s and hundreds of small glaciers have already vanished. The Indus is critical to Pakistan’s food and water security -more than three-quarters of Pakistanis live in the Indus basin and its water irrigates 80 per cent of the nation’s cropland.” (Earth Policy Institute 2008).

Region	Area (km^2)	Period	Retreat	Reference and Comments
Tian Shan	15 417	1930-present	25-30%	Yablokov (2004, 2006) Kutuzov (2005)
Ürümqi glacier		1950-2000	4.5 m/yr	Li and others (2003, 2006)
Pamirs	12 260	1930-present	30-35%	Podrezov and others (2001) Chub (2000)

Hindu Kush-Himalayan

The Himalayan glaciers are retreating at rates ranging from 10-60 m per year and many small glaciers (<0.2 sq km) have already disappeared – vertical shifts as great as 100 m have been recorded during the past 50 years and retreat rates of 30 m per year are common. (Bajracharya and others 2007). The ice extent in the Himalayas is estimated to be about 33 050 km^2. Observations of individual glaciers indicate annual retreat rates varying from basin to basin (Zemp and Haeberli 2007). The Gangotri Glacier, which provides up to 70 per cent of water in the Ganges, is retreating more than 35 m per year, nearly twice as fast as 20 years ago. If it disappears, the Ganges will become seasonal, ceasing to flow during the dry season. The Ganges Basin is home to 407 million people and contains 40 per cent of India’s irrigated cropland (Earth Policy Institute 2008).

Region	Glacier	Period	Retreat	Reference & Comments
Bhutan		1963-1993		Karma and others (2003). 8% loss in area (146.87-134.94 km^2) of 66 glaciers
Dudhi-Koshi	Imja	1962-2006	1970 m	41 m/year during 1962-2001 and 74 m/year during 2001-2006 (Bajracharya and others 2007)
Himachal Pradesh	Chhota Shigri	1986-1995	6.7 m/yr	IPCC (2007)
		present	31 m/yr	Hasnain (2007)
	Bara Shigri	1890-1906	20 m/yr	Mayekwski and Jeschke (1979)
		1977-1995	36.1 m/yr	IPCC (2007)
	Triloknath	1969-1995	15.4 m/yr	IPCC (2007)
Saichen	Saichen		31.5 m/yr	Vohra (1981)
Uttaranchal	Gangotri	1935-1976	15 m/yr	Vohra (1981)
		1985-2001	23 m/yr	IPCC (2007)
		1780-2001	2000 m	Kargel (2005)
	Milam	1909-1984	13.2 m/yr	IPCC (2007)
	Pindari	1845-1966	23 m/yr	Vohra (1981)
	Dokriani	1992-2000	1.94 m thickness	Dobhal and others (2008)
	Pindari	1845-1966	135.2 m/yr	IPCC (2007)
	Ponting	1906-1957	5.1 m/yr	IPCC (2007)

Region	Glacier	Period	Retreat	Reference and Comments
Jammu & Kashmir	Kolhani	1857-1909	15 m/yr	Mayekwski and Jeschke (1979)
		1912-1961	16 m/yr	Mayekwski and Jeschke (1979)
	Machoi	1906-1957	8.1 m/yr	Tiwari (1972)
Sikkim	Zemu	1977-1984	27.7 m/yr	IPCC (2007)
Basin	**Glacier Numbers**	**Glacier Area 1962, 2001/04 (% loss)**	**Glacier Vol. 1962, 2001/04 (% loss)**	**Reference and Comments**
Chenab	359	1 414 1110 (21)	157.6, 105.03 (33.3)	Kulkarni (2007)
Parbati	88	488 379 (22)	58.5, 43 (26.5)	Kulkarni (2007)
Baspa	19	173 140 (19)	19.1, 14.7 (23)	Kulkarni (2007)

Tibetan

These glaciers that provide water to the Yangtze, Yellow, and Brahmaputra rivers are melting at an accelerating rate and two-thirds could be gone by 2060. This threatens China's massive rice harvest, more than half of which is irrigated by the Yangtze River (Earth Policy Institute 2008).

Region	Glacier Area (km^2)	Period	% Loss	Reference and Comments
Tibetan Plateau (surrounding areas)	59 400 (5 600)	1650-1900	20	Retreat rate has increased in the past century, especially in the past 10 years. About 90% of glaciers are retreating. (Yao and others 2000, Liu and others 2006a).
Tibetan Plateau	-	1986-2006	4.5	(CNCCC, 2007)
Tibetan Plateau (east slope of Xixiabangma Mountain) - Glacier 50191B0029	20.3 (18.8)	1977-2003	7.3	Lengths of two glaciers decreased by 1.22 km and 1.85 km, respectively, while the corresponding glacial lake areas increased by 1.79 km^2 and 1.97 km^2 (Mool and others 2004)
- Glacier 50191C0009	6.9 (5.3)	1977-2003	22.9	
Tibetan Plateau (Far East Rongbuk Glacier)	length	1966-1997		Length decreased by 230 m. Ice net-accumulation has decreased since 1959 with a sharp decline in the 1960s (Shugui and others 2000)
Central Tibetan Plateau	permafrost	1970-2000	Lower limit has risen by 71 m and sustained thickness decreased by 20 m	Permafrost areas are much larger than those covered by glaciers and perennial snow, especially in China (2.15 x 106 km^2) (Wu and others 2001, Jianchu and others 2007)
Western China		1950-2000	4.5% 82.2% of glaciers are shrinking	Temperature increased by 0.2K per decade (Liu and others 2006a)

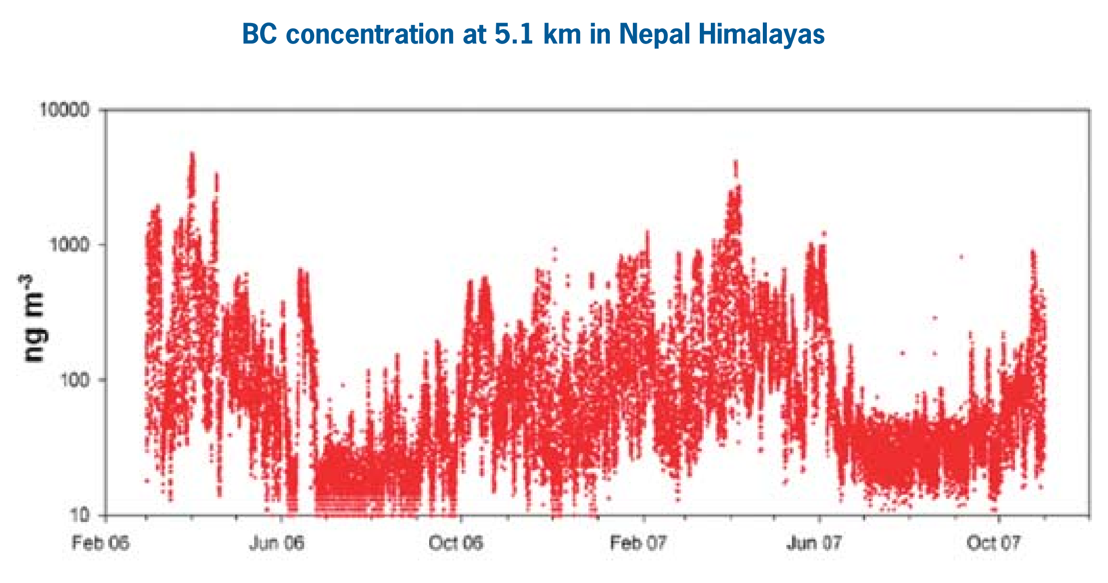


Figure TS1.12 Black carbon concentration measured at the Nepal Climate Observatory – Pyramid (5079 m asl) by EV-K2-CNR (February 2006-October 2007). (Source: Bonasoni and others 2008). (Figure 3.26 of Part I).

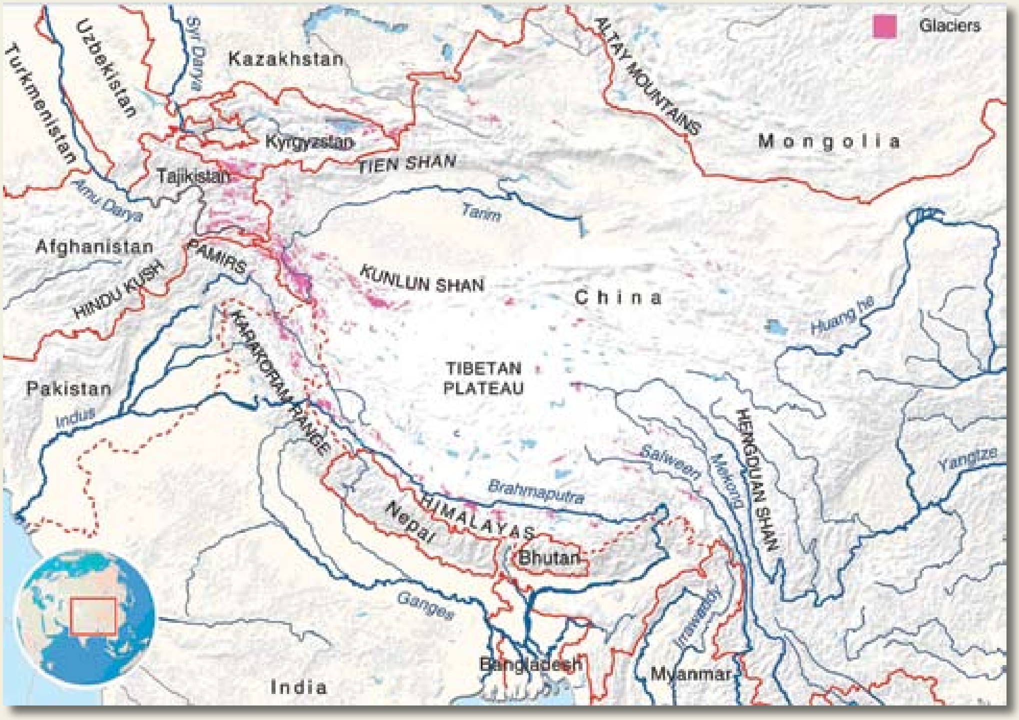


Figure TS1.13 Map of glacier regions in India and Asia. (Source: Zemp and Haeberli 2007).

Impacts of Atmospheric Brown Clouds on Agriculture

THE IMPACT OF THE GROUND LEVEL OZONE COMPONENT OF ABCs ON AGRICULTURE

1. **Ozone concentrations vary across Asia as a result of regional and local scale variations in precursor emissions and atmospheric circulation patterns.** Ozone concentrations across Asia appear to follow a well-defined annual profile with two ozone peaks (during spring and autumn, when ozone concentrations commonly reach monthly mean values of 50 and 40 ppb, respectively) and a mid-summer trough associated with the main monsoon season, when monthly mean ozone concentrations are reduced to approximately 30 ppb. However, these values vary considerably depending on geographical location and proximity to pollutant sources.

2. **There currently exist only a few unevenly distributed ozone monitoring sites across the whole of Asia, making it difficult to obtain a true picture of the current Asian ozone climate and how this varies by geographical characteristics (for example, sub-urban, rural, remote).** To aid future ozone-based risk assessments, a more evenly and densely populated monitoring network should be established.

3. **A large number of experimental studies using a variety of experimental techniques (fumigation, filtration, chemical protectant and transect studies) have been conducted on major crops in Asia. The studies suggest that growing season mean ozone concentrations in the range 30 - 45 ppb could see crop yield losses in the region of 10 - 40 per cent for sensitive cultivars of important Asian crops (that is, wheat, rice and legumes).** In comparison, IPCC (2007) projects decreases of 2.5-10 per cent in crop yield for parts of Asia in the 2020s and a 5-30 per cent decrease in the 2050s, compared with 1990 levels, without carbon dioxide (CO_2) effects.

4. **Pooling experimental data on the impact of ozone on crops in Asia allows comparison with European and North American dose-response relationships. These comparisons would suggest that Asian grown crop varieties are more sensitive to ozone.** This could be due to varietal differences, predisposing environmental conditions or pollutant exposure characteristics. However, these data should be interpreted with caution given the heterogeneity in the experimental methods used in the derivation of the Asian data.

5. **Given the annual variability in ozone concentrations, it is important to consider the growing seasons and developmental stages of the main Asian crops and to identify those that are likely to be exposed to higher ozone concentrations and therefore be more susceptible to ozone damage.** For example, the sensitive grain filling period for wheat occurs during February-March across much of Asia, coinciding with periods of high ozone concentration.

6. **Economic loss estimates due to ozone impacts on crops have only been recently conducted for East Asia using North American dose-response relationships**. A study estimated losses of four key crops (wheat, rice, corn and soybean) at US$ 5 billion in Japan, South Korea and China; these economic losses were attributed to percentage yield losses of up to 9 per cent for cereal crops and 23-27 per cent for soybean (Wang and Mauzerall 2004).

7. **Global ozone projections suggest that some of the largest increases in ozone concentration will occur in South and Southeast Asia from now until 2030. Such projections would see South Asia becoming the most ozone polluted region in the world, with annual surface mean concentrations reaching 52.2 ppb** (Dentener and others 2006).

8. **The impacts of current and projected ozone concentrations therefore need to be considered within the broader context of impacts on agriculture under climate change, as well as consideration of how climate change may influence crop sensitivity to ozone (through alterations in temperature, atmospheric humidity and soil moisture).** Atmospheric brown clouds (ABCs) will also influence radiation and precipitation patterns across the region. New flux-based risk assessment methods offer an opportunity to assess the interactions of these various environmental stresses and the consequent effects on crop productivity.

9. **Although many experimental studies have been conducted to assess the impacts of ozone on a variety of different crops and cultivars, these have not been performed according to common experimental protocols, making it difficult to construct dose-response relationships.** A coordinated pan-Asian experimental programme would add greatly to our understanding of the impact of ozone on crops and cultivars that are representative of the region.

CLIMATE-RELATED IMPACTS OF ABCs ON AGRICULTURE IN ASIA

10. **Growth of agricultural output in China and India has slowed down since the mid-1980s.** For example, while rice harvest in India increased annually by about 3.2 per cent between 1961 and 1984, it has grown by only 2.4 per cent annually since then. In China, the average annual growth rates changed from 5.4 to 0.2 per cent during the same period. For Asia as a whole, annual growth rates have decreased from 3.5 to 1.3 per cent.

11. **Research on the agricultural impacts of ABCS is very limited compared to research on the agricultural impacts of climate change caused by elevated greenhouse gas (GHG) concentrations.** Although not focused on ABCs, the latter research has generated results that provide insights into the likely impacts in Asia of ABC-induced drying (reduced rainfall) and cooling (reduced temperatures, especially at night). In the case of rice, which is the most important food crop in Asia, this research indicates that drying can be expected to reduce agricultural output, while cooling can be expected to raise it by partially offsetting GHG warming. Other research has found that ABC-induced dimming (reduced surface radiation) likely reduces agricultural output. The indirect (that is, climate-related) impacts of ABCs are thus complex and are distinct from, though inter-related with, those of GHGs.

12. **The impacts of drying, cooling and dimming on Asian agriculture must be analyzed jointly, not individually.** This follows from evidence that these impacts can be in different directions (that is, negative or positive). Focusing impact studies solely on a single impact of ABCs, such as dimming, results in biased impact estimates.

13. **Impact studies should consider the farmers' ability to adapt to worsening environmental conditions to prevent overestimating damages under given climate scenarios.** This is another implication of research on GHG impacts, which has relied mostly on statistical models of farmers' behaviour that are based on historical observations. Statistical models can account for farmers' decision-making in response to changes not only concerned with climate but also with economic conditions, enabling more realistic estimates of impacts and a more realistic portrayal of adaptation possibilities. Laboratory studies of plant responses to altered growing conditions cannot provide such information.

14. **There have been very few studies on the joint impacts of climate change on agriculture due to the build-up of GHGs and ABCs. The only published statistical study on this focused on wet-season rice in India. It found that reductions in ABCs would have resulted in significantly higher wet-season rice harvests in India during the period 1985 - 1998, suggesting that ABCs contributed to the well-known slowdown in agriculture in Asia.** The increase, nearly 11 per cent higher on average, would have been even larger (14 per cent) if GHGs were simultaneously reduced. Without ABCs and GHGs, the average annual rice output for these states during the period 1985 - 1998 would have been roughly 6.2 million tonnes higher, which is equal to the total annual consumption of 72 million people. The impact of drying outweighed the impacts of cooling and dimming, although the study might have underestimated the latter.The study also ignored direct pollution damage caused by pollutants linked to ABCs via common emission sources or chemical reactions in the atmosphere (such as ozone). Two-thirds of the harvest impact were related to farmer behaviour (that is, changes in area), with only one-third coming from changes in yields.

15. **Future studies should focus on understanding the impacts of ABCs in a larger number of locations. A major effort on data collection at the farm level is necessary to better understand the direct (pollution damage) and indirect (climate-related) impacts of ABCs in a field setting.** Farm level studies would allow for disentangling the direct and indirect impacts of ABCs, which is pertinent to policy responses related to pollution control measures. Such studies would advance the understanding of farmer responses. Data would need to be collected from a wide variety of sites over several years.

16. **Dynamic crop simulation models are effective tools to assess the impacts of ABC on crop yield.** The effects of ABC are mediated through increase in diffuse radiation, decrease in direct radiation and cooling effect. All these are important weather variables controlling crop growth and yield. Except diffuse radiation, other factors are included in simulation models and can be used to quantify single as well as interactive effects on yield. Incorporation of diffuse radiation as a separate model input needs to be achieved.

17. **Impacts of ABCs are likely to be crop-specific.** For wheat and rice, yield reductions up to 8 per cent were predicted in India when single effect of aerosols on radiation was considered by crop simulation models. However, when cooling effect was also incorporated in the model, it nullified the yield reductions due to enhanced crop duration effect. The effect of ABCs on sugar cane yield was non-significant as predicted by the sugarcane model.

Impacts of Atmospheric Brown Clouds on Human Health

ABCs are likely to impact human health

1. **ABCs have several characteristics that determine their impact on human health, including:** large geographical reach; long-range transport of aerosols across continents and oceans; consistent and persistent exposure of large populations, including high-risk populations; potential for physical, chemical and microbiological mixing and interactions of the aerosols, and for exacerbating local air pollution when aerosols transported over long distances transfer to the lower atmosphere. These characteristics, together with the potential for the aerosols to act as transport mechanisms for pathogens, pose important challenges for public health, well-being and welfare.

2. **The focus of the section on Impacts of ABCs on Human Health will be on the exposure, epidemiology, toxicology, associated diseases, preliminary estimations of numbers of premature deaths and economic costs, and the science and characteristics of ABCs, which are important considerations for policy options.**

3. **The Part III draws upon knowledge of ABCs, in particular aerosol particles, which have potentially significant health effects because of their size and composition.** Knowledge of the physical, chemical, and microbial characteristics of ABCs, and the potential for intermixing and inter-reactions of the anthropogenic aerosol mixture will be important in improving the assessment of health risks and effects, whether they are direct through exposure to toxic agents, or indirect through climate change and global warming and their influence on life support systems. This knowledge will be important for supporting decisions on what research to undertake, what policy responses to formulate, and what technical and management options to implement.

Exposure assessment is essential

4. **Assessment of exposure is essential to the estimation of risk associated with exposure to air pollution, as it is not possible to determine risk without some reliable measure of exposure.** There is currently a lack of critical exposure information as it pertains to ABCs. The information that is available is generally about ambient levels of pollutants, which can be significantly different from levels that cross biological membranes, reach their target tissues, and exert their toxic effects.

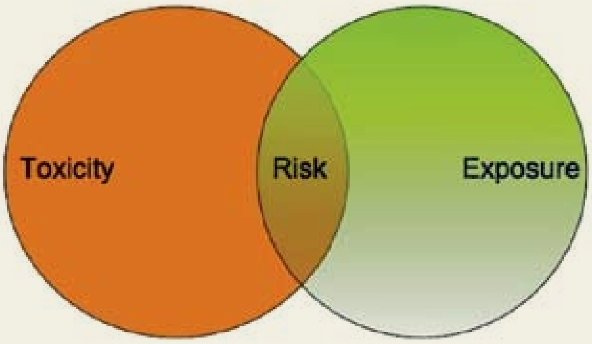


Figure TS3.1 Toxicity, exposure and risk. (Adopted from Figure 8.2 of part III).

5. **Molecular epidemiology is a potentially important tool for assessing exposure to ABCS, as well as the consequent effects from such exposure.** The field involves assessing, at the molecular level the contribution of environmental risk factors, with the influence of genetics, to the etiology of disease. One of the main aims is to gain mechanistic information from epidemiological studies. Another important

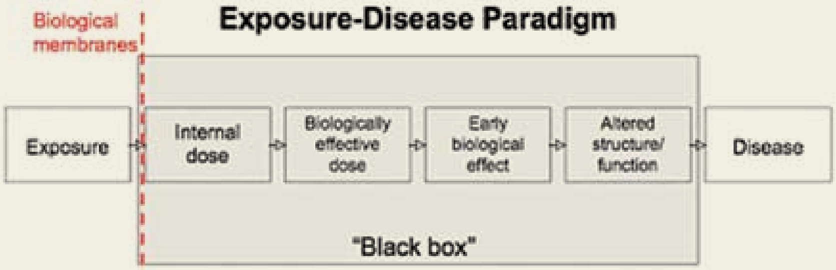


Figure TS3.2 *Exposure-disease paradigm. (Adopted from Figure 8.1 of Part III)*

aim is to correlate exposure and effects data that are relevant to the exposure and/ or disease. Exposure assessment includes environmental monitoring, exposure modelling, and bio-monitoring.

6. **Environmental monitoring studies should encompass ambient and personal monitoring of air pollutant exposures.**

7. **Bio-monitoring of exposures and effects will include ABC-relevant pollutants and air pollution-associated health effects,** such as asthma and cardiovascular effects. What ultimately need to be known are the ABC components to which human beings are being exposed, the magnitude and duration of these exposures, and factors that may differentiate exposure levels or susceptibility among the exposed populations.

ABCs and adverse health outcomes

8. **There are many epidemiology studies that have addressed the direct health effects of ABC-relevant pollution sources, such as wildfire, indoor biomass and coal smoke and dust events. These studies have documented a variety of acute and chronic health effects, including premature deaths, hospital admissions and chronic respiratory disease.** ABC-relevant pollutant studies reviewed from available literature include studies of health effects related to increased cardio-respiratory hospital admissions and mortalities in Malaysia, Indonesia, Singapore, Australia and Brazil from exposure to smoke from forest fires, bush fires, and agricultural burning; increased asthma and other respiratory effects, cardiovascular hospital admissions, and mortality in China and Republic of Korea related to dust storm events; increased acute respiratory infections, chronic obstructive pulmonary disease and lung cancer in Nepal, India and China, resulting from exposure to biomass and coal smoke; and reduced pulmonary function, bronchitis, wheezing, shortness of breath, increased hospital admissions and mortality in India and China associated with exposure to urban and industrial air pollution.

9. **Available information about adverse health effects of airborne fine particles from studies conducted in many areas of the world suggests that ABC exposure is very likely associated with significant adverse health effects.** Key studies have shown small but consistent effects of day to day variations in Particulate matter (PM) pollution and non-accidental, cardiovascular and respiratory mortality. People living in communities with elevated fine PM concentrations have a higher risk of dying over an associated follow-up period than subjects living in cleaner communities. Several studies have indicated that there is no threshold for development of health effects from exposure to PM. Exposure to PM induces serious cardiovascular effects, as is evident

from increased cardiovascular deaths from both short- and long-term exposures, as well as increased cardiovascular hospital admissions after high pollution days. The biological plausibility of the effects of PM on cardiovascular and respiratory health has been supported by various lines of in vivo and in vitro toxicological research, including increased plaque formation from long-term exposures to $PM_{2.5}$ in experimental mice and emerging human evidence of increased atherosclerosis from exposures to elevated ambient $PM_{2.5}$ levels.

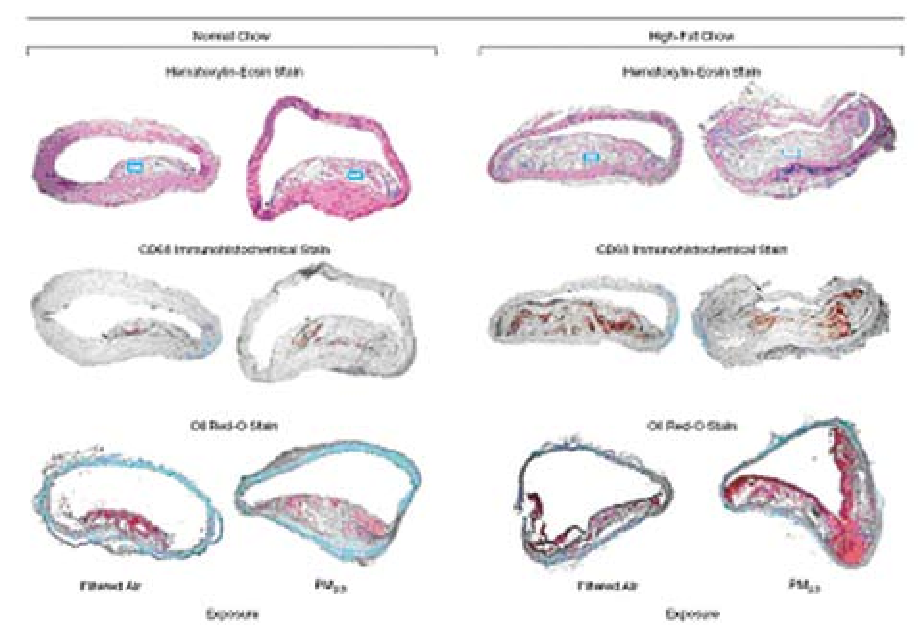


Figure TS3.3 *Plaque formation after long-term exposure to concentrated ambient $PM_{2.5}$ in sensitive mice fed normal and high fat diets. The figure shows that mice exposed to concentrated ambient PM developed greater plaque size (Hematoxylin-eosin and Oil Red-O stains) than air-exposed mice. CD68 staining, which identifies macrophage infiltration, indicates the inflammatory nature of the atherosclerotic plaques. (Adopted from Figure 9.11 of Part III)*

10. **Toxicity outcomes associated with individual ABC-relevant pollutants include cardiovascular and respiratory disease, cancer, and reproductive and/or developmental alterations.**

11. **Cardiovascular effects, including the up-regulation of cardiac factors associated with vascular remodelling, have been noted in mice exposed to gasoline emissions, while atherosclerotic lesions and other vascular changes were enhanced in animals with repeated exposure to concentrated particulate matter.** In addition, serious cardiac outcomes have been observed in controlled human and experimental studies examining the effects of biomass burning.

12. **Respiratory effects, such as pulmonary inflammation, have also been observed in response to ABC-relevant pollutants in controlled human studies, in response to inhaled diesel exhaust particles, as well as immune system alterations consistent with allergic asthma in exposed animals.** Exposure to wood smoke produces extensive lung damage along with diminished immunocompetence and increased susceptibility to pulmonary infection in exposed animal models.

13. **With regards to cancer outcomes, studies performed in vitro have demonstrated the carcinogenic potential of**

gasoline emissions and while the cancer-causing ability of wood smoke is still being debated, International Agency for Research on Cancer (IARC) has concluded that emissions from household combustion of biomass fuel are probably carcinogenic to humans.

14. **With regards to other health outcomes, reproductive effects are less well known but some ABC-relevant pollutants have been shown to reduce testicular cell and sperm number in male rodent offspring and produce preterm birth and low birthweight in offspring exposed prenatally.** In addition to these particular disease outcomes, exposure to many of the ABC-relevant pollutants can compromise host immunity, leading ultimately to increased susceptibility of the host to infectious disease and/or cancer.

15. **As large human populations are exposed to ABCs for extended durations, and since particles (either alone or with adsorbed gases) likely underlie the majority of observed effects, the main emphasis of the toxicological studies should be on long-term inhalation exposure studies of diesel and motor vehicle exhaust, ambient particulate matter with emphasis on fine and ultra fine particles, coal combustion products, particularly fly ash, biomass emissions and dust.**

16. **The health impacts associated with exposure to ambient air pollution can be quantified through concentration-response (CR) functions that relate predicted changes in air pollution to increases in mortality and morbidity.** The quantitative assessment is based on four components: (1) change in air pollution concentrations; (2) size and composition (for example, age profile) of the population groups exposed to the current levels of air pollution; (3) background incidence of mortality and morbidity, and (4) CR functions.

17. **There are certain model assumptions and inputs that are used in the quantification of health impacts associated with exposure to ambient air pollution.** Depending on the model, such as Adhikary and others (2008), Adhikary and others (2007), Ramanathan and others (2007a), and Mayol-Bracero and others (2002), data, and assumptions used, the number of deaths would change significantly. Changes in the exposure estimates used will have a proportional impact on the calculated excess mortalities.

18. **The “willingness to pay” and “human capital and/or cost of illness” approaches are considered as techniques available for conducting original economic valuation studies.** The “benefits transfer” alternative (that is, the use of health values estimated for one site and one particular policy context as a proxy for health values in another site and possibly another context) is a common approach in the analysis of health policies, projects and programmes and will likely be important in the evaluation of ABC control strategies.

19. **While there is a relatively large value of statistical life (VOSL) literature for North America and Europe, there is a huge lack of evidence on the costs of premature mortality for developing countries in general, and China and India in particular.** Because of this gap in knowledge, many studies seeking to evaluate the local health impacts of air pollution abatement strategies transfer estimates from developed countries for use in what are very different local conditions, after simple income adjustments. This can largely affect the precision and robustness of the values used and therefore compromise the analysis of policy efficiency.

20. **An illustrative calculation of the magnitude of the health costs of the predicted excess mortality from ABC-related $PM_{2.5}$ increases found the**

potential for very significant health costs associated with ABCs in both China and India that could amount to 3.6 and 2.2 per cent of the GDP, respectively, even when using mid-range mortality cost estimates, although these numbers should be interpreted with caution at this early stage. With more research data, some of the uncertainties inherent in the health impact assessment should be reduced, leading to greater precision in the estimates.

21. **The Report gives a brief review of typical values for air-pollution related morbidity impacts that may be relevant for evaluating ABC control policies.** Although value estimates abound for many relevant health outcomes in developed countries, country-specific evidence for developing countries is minimal. Despite the lack of ABC-specific morbidity data, previous evidence from other air pollution-related studies suggest that among all the health impacts potentially associated with ABCs, premature death is likely to play a dominant role in terms of total economic costs. Among the morbidity endpoints, chronic bronchitis is expected to have a large contribution.

Further studies on ABCs and human health

22. **Understanding the science and characteristics of ABCs is of significant importance to strategic and effective public policy on human health and welfare.** The ABC characteristics that merit attention include:
    - wide spatial distribution, hence exposing very large populations;
    - composition, which consists of fine and ultra fine particles that can reach target tissues, exerting their toxicological effects and increasing environmental health risks and influencing the etiology of diseases;
    - likelihood to transport bio-aerosols over long distances with significant consequences on human health and well-being, livestock and agricultural productivity and the quality of drinking water.
    - health outcomes are compounded by impacts on water, agriculture and ecosystems.

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