Project Proposal

Project Asian Brown Cloud

Air Pollution in the Indo-Asia-Pacific Region: Impact on Climate and the Environment

Integration of Science, Impact Assessment, Policymaking and Regional Capacity Building

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Center for Clouds, Chemistry & Climate

UNEP

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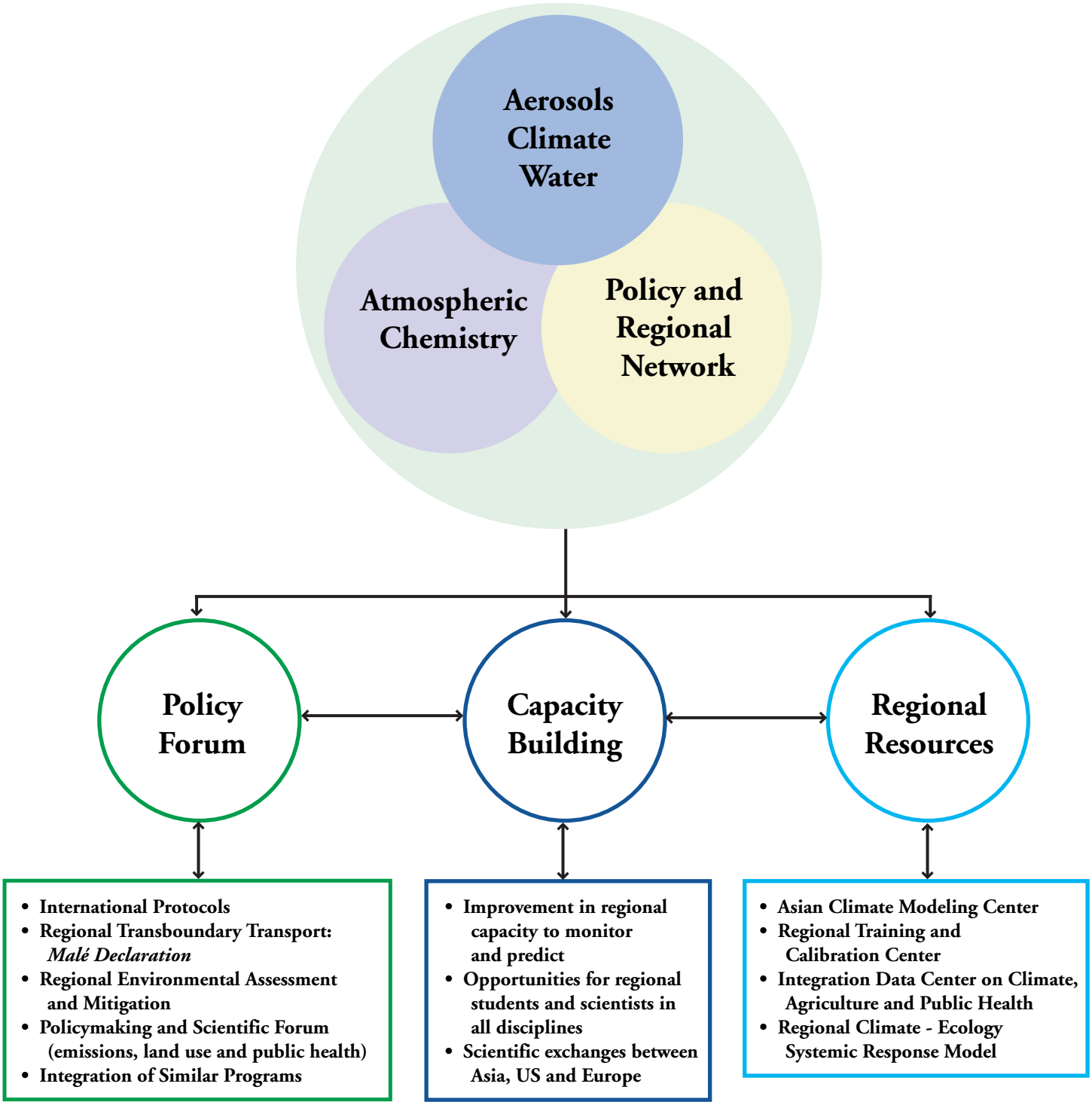

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Executive Summary

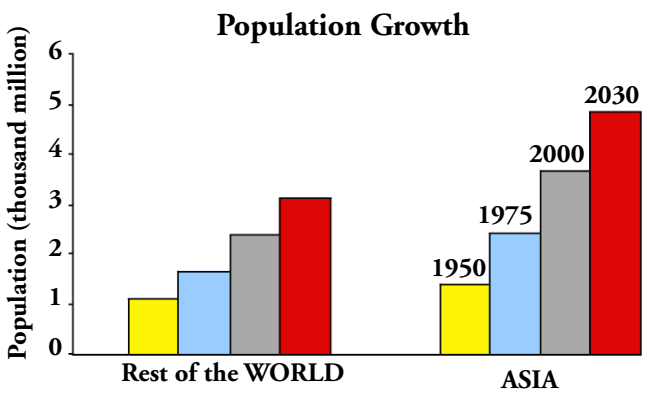
Project Asian Brown Cloud's (*ABC*) fundamental and ambitious goal is to avert further major environmental degradation and enable environmentally sustainable development in the Asia-Pacific region whose population is expected to reach 5 thousand million in the coming decades.

About 60% of the world's population of 6 thousand million live in Asia. Environmental consequences of the area's impressive economic development can be far reaching, especially with respect to air pollution at local and regional levels. Already, the United Nations Environment Programme (UNEP) has identified air pollution in the Asia-Pacific region as a major challenge for the 21st century (UNEP, 1999).

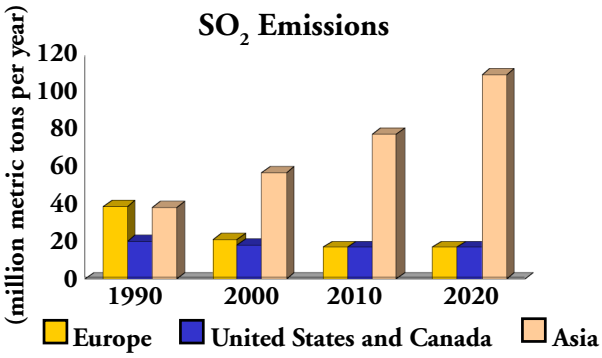
A recent international study, the Indian Ocean Experiment (INDOEX), documented the vast extent of the so-called Asian haze, a 3 km thick brownish pollution layer of pollutants hovering over most of the tropical Indian Ocean, South, Southeast and East Asia. The haze particles consist of sulfates, nitrates, organics, black carbon and fly ash amongst several other pollutants, which can be transported far beyond their source region, particularly during the dry season. Potential direct and indirect consequences of the haze involve regional and global climate, the water cycle, agriculture and human health, and include:

- *Direct effects*: Significant reduction in the solar radiation reaching the surface; a 50 to 100% increase in solar heating of the lower atmosphere; rainfall suppression; agricultural productivity decline; and adverse human health effects.
- *Potential indirect effects.* Cooling of the land surface; increase in frequency and strength of thermal inversions that trap more pollution; evaporation reduction; soil drying; and disruption of the monsoon rainfall patterns.

In spite of the advances by INDOEX, significant scientific uncertainties remain. We do not know the regional scale of the pollution layer, thus high quality data on the haze and the precursor pollutants are urgently needed to assess the long term trends. We also do not know the answers to basic questions such as: How does the solar



Source: World Population Prospects: The 2000 Revision; United Nations New York.



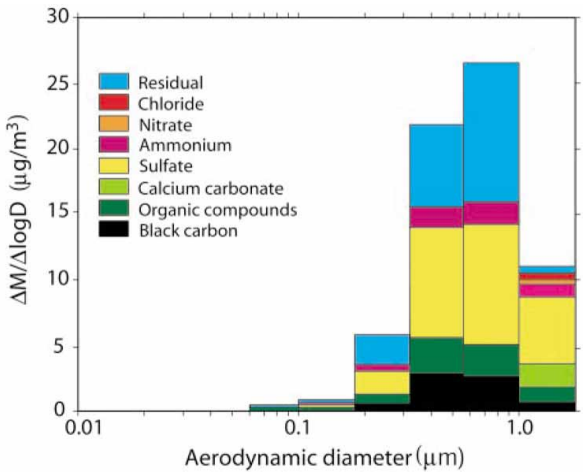
Source: Global Environmental Trends, World Resources Institute, *http://www.wri.org/wri/*, R. Downing, R. Ramankutty, and J. Shah, RAINS-ASIA: An Assessment Model for Acid Deposition in Asia (The World Bank, Washington, D.C. 1997, p. 11).

heating in the haze affect the monsoon rainfall? How does the reduction of solar energy to the surface affect the water budget and soil moisture? Does the haze amplify or ameliorate the warming due to greenhouse gases? How does air pollution from Asia affect the worldwide concentrations of ozone and other pollutants? On the policy side, the evidence of long range transport of the haze complicates potential prescriptions for dealing with the problem, as responses must be coordinated among sovereign nations.

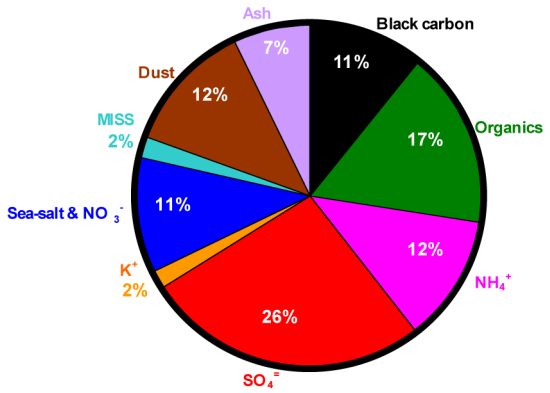
Project ABC articulates a strategy to understand air pollution in a broad context and to help policymakers arrive at informed decisions. We build on the strengths of the international, multi-disciplinary INDOEX science team of over 200 scientists and on our experience working with UNEP and other international bodies to translate scientific findings into policy options for action.

Science Strategy. We will research transboundary atmospheric pollution in Asia in two specific ways: 1) Establish an integrated network of surface climate observatories across the entire Asia-Pacific region to monitor air pollution's full extent, composition, impacts and transport. Priority will be placed on strengthening or complementing existing facilities of the East Asia Network (EANET) and the *Malé Declaration* sites in South Asia. Combined with satellites, the observatories will track the haze and plumes on regional scales. 2) Develop an integrated regional modeling approach that combines data assimilation techniques with predictive models to estimate the impact of air pollution on climate, atmospheric chemistry, agriculture, the water budget and public health.

Policy Forum. We will use *in-situ* observations and crop models to assess the effects of the haze, ozone and greenhouse gases on the water budget and agricultural productivity. We will also initiate epidemiological studies to assess the health impacts and the global climate impacts of the haze. Through UNEP, we will invite environmental economists to explore various policy options for the region.



Chemical composition of the INDOEX haze. Average mass (*M*) composition of fine aerosol on KCO (Maldives) as a function of the logarithm of the particle diameter (*D*) in February 1999. The residual includes mineral dust, fly ash, and unknown compounds (Lelieveld *et al.,* 2001). The chemical composition of aerosols can impact public health.



Aerosol contribution of the optical depth. Shows the relative contribution of the various chemical species to the aerosol optical properties, or ability to block sunlight, at visible wavelengths (Ramanathan *et al.*, 2001). Aerosol optical properties of the haze could potentially negatively impact agriculture.

Capacity Building and Regional Resources: We propose to advance the science and facilitate technology transfer through a) better observations, b) modeling using data collected with transfer to Asia within the project period, and c) a virtual school that will provide classes utilizing real-time video conference facilities. The climate observatories will also be critical components of this school by serving as regional education and training facilities for students, post-doctoral researchers and scientists. The Center for Clouds, Chemistry and Climate (C^4), a US National Science Foundation Science and Technology Center at the Scripps Institution of Oceanography (SIO) at the University of California at San Diego (UCSD), will collaborate with UNEP and other international organizations, such as SysTem for Analysis, Research and Training (START), to conduct this education outreach program.

Background

1. The Indian Ocean Experiment

Since 1995, scientists have been collecting data over the Indian Ocean as part of INDOEX. Led by C^4, INDOEX field experiments culminated in an Intensive Field Phase during January to April of 1999 with participation of over 200 scientists from about 60 institutions in 13 countries in Asia, Europe and the USA. In collaboration with the government of the Maldives, C^4 operated a surface observatory in the country to detect the long range transport of atmospheric pollution. For more information, see Attachment 3 - INDOEX Brochure, and visit the project's website <*www-indoex.ucsd.edu*>.

INDOEX results show widespread pollution over large sections of the region. In Spring 1999, scientists were surprised to find a dense brownish pollution haze layer about the size of the continental US over the Indian Ocean, South Asia, and Southeast Asia, and later through satellites, over China. INDOEX results indicate pollutants scatter and absorb incoming solar radiation and thus reduce up to 10% of the solar energy reaching the ocean and 10 to 20% over land surfaces. These findings have raised serious questions concerning the impact of atmospheric pollution of that magnitude on health, the regional monsoon hydrological cycle and wind systems, marine life, and especially the plant ecosystem and agriculture, which depend on sunlight for photosynthesis. If such a haze layer regularly covers agricultural areas, optimal crop yields could be reduced. More than half of the world's population is concentrated in the Asia-Pacific region, thus the effects of atmospheric pollution could be very large.

The long range transport of the haze was an important finding. For example, the persistent haze over the Bay of Bengal was traced to emissions from South and Southeast Asian countries. Cooperation across international boundaries is required for understanding the environmental impacts of the haze and for effective mitigation measures. In order to make this happen, we are proposing a synergistic cooperation and collaboration between the INDOEX scientists and UNEP, particularly UNEP RRC.AP.

The INDOEX group is entering the next phase of examining the impacts of this haze on the regional climate, monsoon, water cycle, agriculture and health. In parallel with this activity, the INDOEX group recognizes the scientific need and importance of dealing with the entire Asia-Pacific region (instead of only India and the tropical Indian Ocean) and has started to take steps to broaden the scope of its activity. Interaction with a regional body such as UNEP RRC.AP would significantly enhance the development of this next phase as well as provide a crucial link to the policy arena.

2. Malé Declaration on Control and Prevention of Air Pollution and Its Likely Transboundary Effects for South Asia

The UNEP RRC.AP, through its recent success in articulating the *Malé Declaration* is entering the stage of strengthening the monitoring network. We thus envision great possibilities for constructive interaction between science and policymaking at the working level, for the better management of the environment, and for ensuring the sustainability of the economic development of the region without a serious threat of environmental degradation. With accelerating urbanization and a high population growth rate, megacity air pollution is assured to become a major problem of the future in the Asia-Pacific region.

We excerpt the background information provided in the *Malé Declaration* (April 22, 1998), for it also provides an excellent background for this proposed activity:

> *"Air pollution is an emerging environmental issue in Asia. In particular, emissions of sulfur dioxide and nitrogen oxides have been rising steadily over the past few decades. Rapid growth of cities, together with expansion of industry and transport systems, has made the Asian region increasingly concerned with these emissions. Projections indicate that potentially large increases in emissions may occur during the next twenty to fifty years if the current trend persists. If this occurs, the impact which has been experienced in Europe will become apparent in large parts of Asia. These problems include reduction in crop yield by direct effects of gases; acidification of lakes; impacts on human health; impacts of corrosion on human-made structures, impact on soil fertility leading to damaging changes in natural ecosystems; and impacts on forest and crop growth in sensitive soils."* Visit <*www.rrcap.unep.org/issues/air/maledec*> for more information.

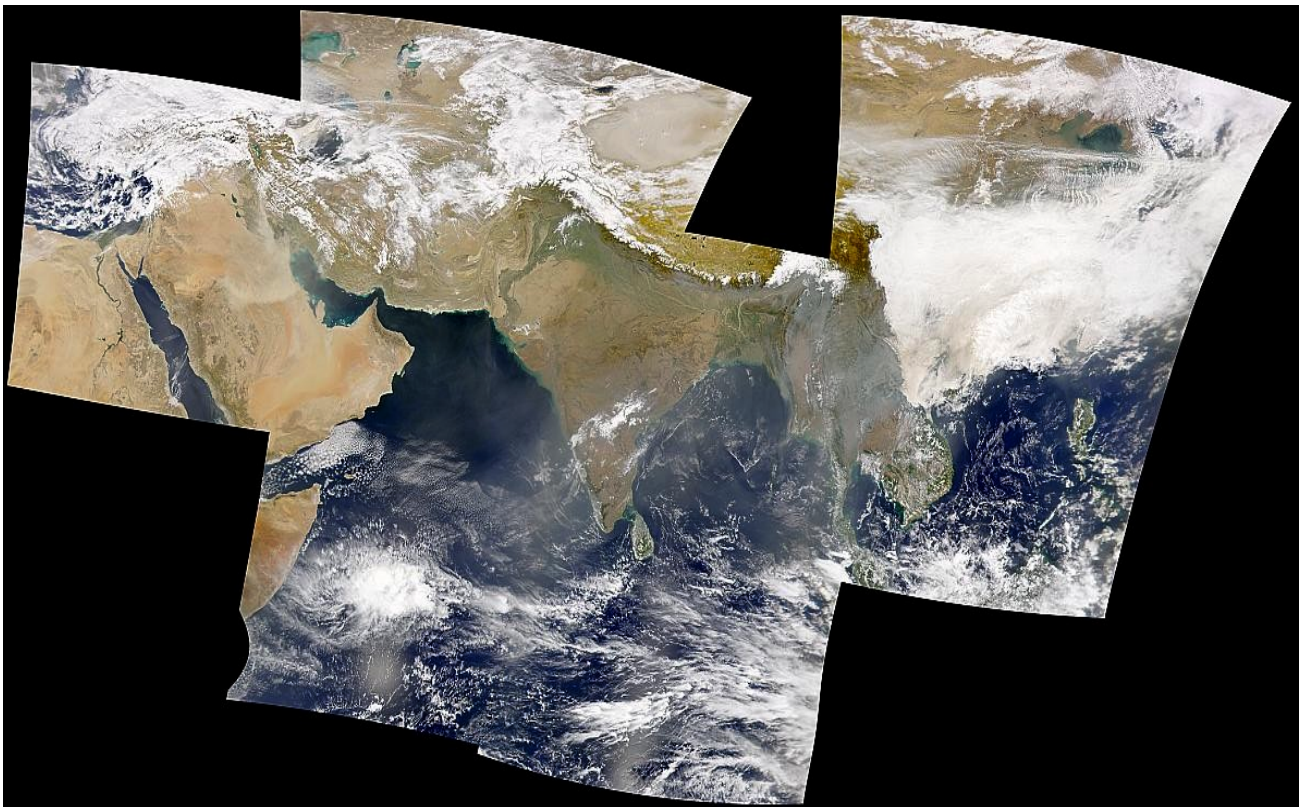
In fact, while the *Malé Declaration* only mentions urban and industrial pollution, the situation in Asia , and the other developing parts of the world as well, is even worse since rural biomass burning is another major source of pollution. We note that industrial pollution is mainly of urban origin while biomass burning is mainly of rural origin. It should also be noted that air pollution in or near cities would be much larger with contributions both from biomass burning and fossil fuel combustion. Likewise, policymakers in this declaration did not include the regional and global impact on climate, including most importantly, rainfall disturbances.

3. UNEP RRC.AP's Approach

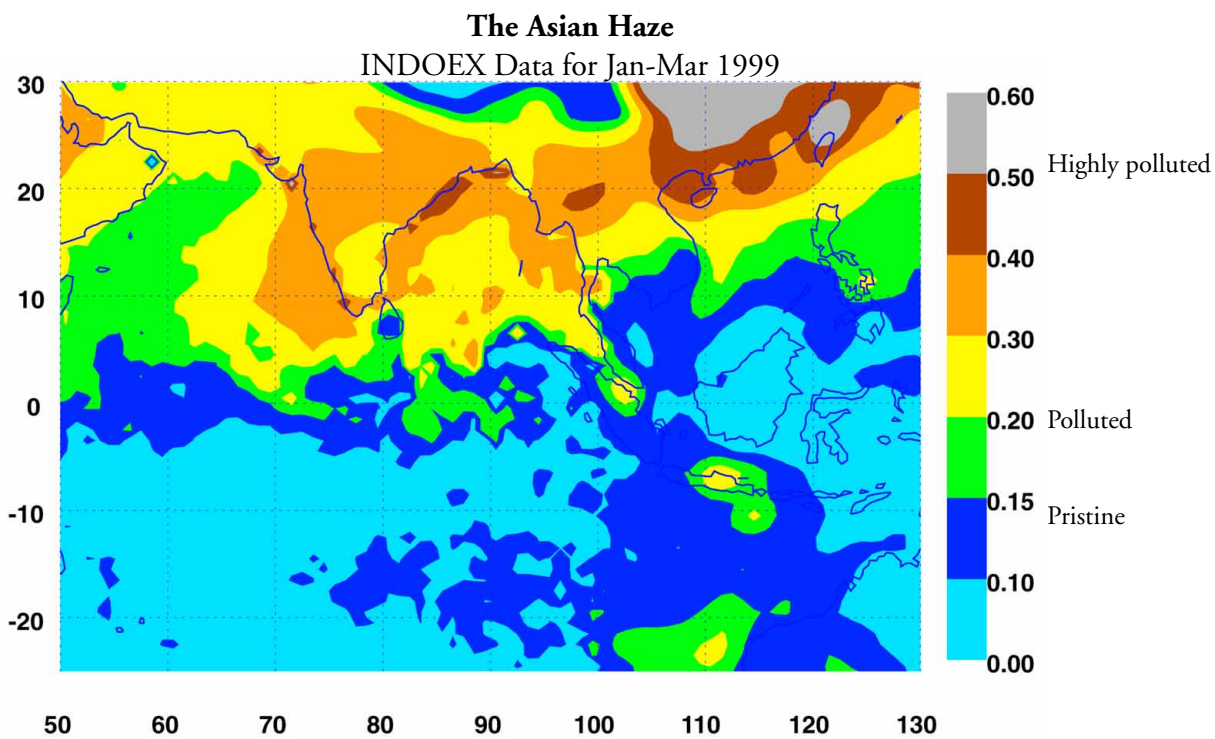
After consultations and study of the European and American experiences in coping with atmospheric pollution, the UNEP RRC.AP is following a three-stage approach to promote the policy cycle in the region. The program includes i) raise awareness amongst the policymakers and scientific community; ii) build a regional capacity for a network monitoring mechanism to collect and analyze data; and iii) take measures to reduce emissions through strongly improved energy use efficiency and economic and/or legal instruments. In South Asia, the adoption of the *Malé Declaration* was facilitated using this approach.

In Southeast Asia, UNEP is providing support to the Association of South East Asian Nations (ASEAN) secretariat in formulating a legal instrument to control the haze pollution in the region. Currently, the activities are directed towards formulating some legally binding agreements to deal with the transboundary air pollution, especially the haze pollution.

UNEP RRC.AP has been participating in the Acid Deposition Monitoring Network in East Asia (EANET) since its initial stages. EANET has designated UNEP RRC.AP as secretariat for the network starting 2002.



The Asian Haze. Satellite image on March 21, 1999 of the Asian haze during the Intensive Field Phase of INDOEX (Source: ORBIMAGE). Using observational data and aerosol model output, INDOEX scientists have recreated a composite image of the haze, as depicted in the next picture.

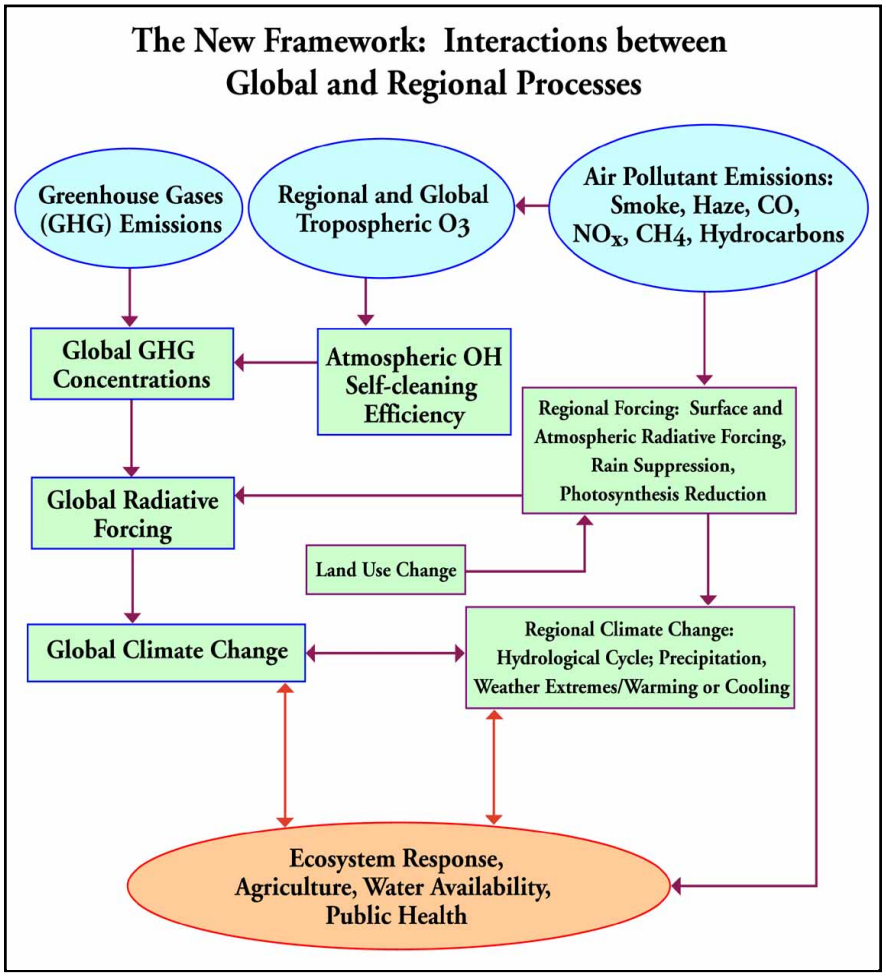


The regional map of aerosol column amount. The optical depth values over the ocean are retrieved from satellite data and over the land are estimated using a computer model (Ramanathan *et al.,* 2001).

Project Asian Brown Cloud (ABC): Intersecting Climate Issues with Ecosystem Response

1. The New Concept

A more complete picture of the roles and interactions of greenhouse gases, aerosols and ozone is urgently needed. Problems such as haze, smog, and acid deposition fall under the general category of air pollution. The aerosols and high level of ozone that result from rural and urban air pollution are part of the global warming issue since they could induce climate change by altering the radiative balance of the planet. Their presence can also have ecosystem impacts, notably on agriculture and public health. Thus, there is a need to assess the impacts under one common framework, which is the goal of the proposed strategy for *Project ABC*.



It is now undisputed that primary air pollutants and their chemical products could be transported over distances of many thousands of kilometers. Emissions in one country can cause damage in other countries through transboundary and even transcontinental transport. This transport of pollutants converts local issues into regional and global concerns. Thus this issue cannot be addressed by individual national efforts alone. Past experience has demonstrated that the most effective way of tackling air pollution is through international cooperation which is the essence of this proposed strategy. We should consider the effects on global as well as regional scales with emphasis on the following:

Impacts on the Regional and Global Physical Climate System

• both by direct back-scattering and absorption, the haze causes reduction of the solar radiation reaching the surface by more than 10% above large areas and adds significant heating to the atmosphere

• the resulting alterations of spatial gradients of atmospheric temperatures can shift the monsoon precipitation systems, drying out the northern and northwest sector of South Asia while increasing rainfall over the oceans

Impacts on Regional Watercycle and Agriculture

In turn, the haze could have potential impacts on agriculture by

• impeding plant growth and vitality due to ozone and deposition of pollutants

• reducing surface irradiance available for photosynthesis

• altering the regional winter monsoon hydrological cycle

Given the rapid increase in population with associated increased demands on wheat, rice and other cereals in South Asia, drastic changes in pollution control and land use are required in the near future to assure ample food supplies and limited environmental degradation due to air pollutions.

Impacts on Human Health

The health effects of outdoor air pollution have now been a topic of investigation for nearly half a century, with much of the original motivation for this research coming from the well-chronicled air pollution disasters - Donora, Pennsylvania 1948 and the London fog of 1952, for example. The resulting body of evidence from research application of toxicology, epidemiology, and exposure assessment is voluminous. It documents a wide array of adverse health effects of air pollution that extend from reduced well-being and increased symptoms of chronic diseases, and even premature death. Air pollution typically exists as a complex mixture, reflecting the multiplicity of sources and the many pollutants released by combustion processes, the principal source of pollutants generated by man's activities. Key components of combustion-related air pollution mixtures include particles, emitted as primary particles or formed secondarily from gaseous species, sulfur oxides (SO_x), nitrogen oxides (NO_x), carbon monoxide (CO), and numerous organic chemicals, including carcinogens, e.g., benzo(a)pyrene, and irritants, e.g., formaldehyde. In many urban areas of the world, pollution, especially the formation of ozone, is the result of photochemically-driven reactions involving hydrocarbons and nitrogen oxides emitted by vehicles and industry (*Project ABC* Assessment Report). In rural Asia, biomass burning is also a main contributor to emissions and degradation of air quality. *Project ABC* proposes to be one of the first systemic attempts to link a regional climatic phenomenon (pollution haze) to public health.

2. Intrinsic Synergy and Strategic Collaboration with UNEP

Scientific endeavors initiated by INDOEX have already produced a valuable scientific base for studying pollution impacts in the region. Since regional scientists are strongly involved in INDOEX, continuation of this initiative in close partnership with UNEP will further strengthen scientific knowledge as well as capacity building in the region. Scientific findings and developments need to be properly disseminated for policymakers to ensure informed decision-making. Currently, the communication gap between policymaking processes and scientific developments are wider in Asia than in Europe or North America. The development of the *Convention on Long-Range Transboundary Air Pollution* in Europe and the *Malé Declaration* are excellent examples of scientifically supported policy developments, which is also the essence of our proposed strategy.

Strategic partnership between INDOEX and UNEP would create unprecedented synergy. It is recognized that UNEP has established a network of policymakers and experts in the field of air pollution in the region, thus it could play a major role in disseminating scientific findings, such as those from INDOEX, bridging the gap between science and the policymaking process.

3. Project ABC Conceptual Design

The underlying principles of Porject ABC include facilitating interaction between scientific and policymaking processes to promote regionally sustainable development and capacity building.

A comprehensive program will be developed and implemented for understanding the nature and scope of environmental issues facing Asia-Pacific, and develop a framework for assessing past and future impacts. This program will include integration of satellite data with regional surface data, global atmospheric chemistry and climate models in correlation with critical data from public health, agriculture, and marine and terrestrial ecology. Specifically, in the area of capacity building, it will include field experiments to facilitate active collaboration with regional scientists and practical training for regional students and post graduates.

The *ABC* Climate Observation Program

• *Surface Observatories: Sentinels for Asia-Pacific on the Regional and Transboundary Atmospheric Pollution*
Project ABC will establish an integrated network of surface climate observatories across the entire Asia-Pacific region. These strategically placed observatories will monitor the full extent, chemical composition, radiative effects and transport of transboundary atmospheric pollution. Because these surface sites will track the transport of pollution haze and plumes on a regional scale, synergistically, they will be key components of the implementation phase of the *Malé Declaration* and EANET. They will also provide critical information from a data sparse region of the world for calibration of satellite observations and baseline measurements for long-term analysis of changes in regional pollutant gases and aerosol characteristics. The network of stations, furthermore, will enhance regional capacity building.

Project ABC will establish 7 new regional air-quality and climate observatories at critical locations and contribute to 3 existing sites (see map) along the periphery and within the Asia-Pacific. Each surface observatory will be equipped with radiation, aerosol and chemistry instruments (Table 1). Locations of the new sites are preliminary and subject to change based on future studies, including trajectory analysis and site surveys. We will strive to include existing sites of the *Malé Declaration* and the EANET to promote international synergy in terms of ease of maintenance, training and technology transfer.

Eventually, pending feasibility and funding availability, we plan to operate all the sites with renewable power (wind and solar), only using electricity generated from fossil fuels as backup.

Short-Term: Marking the Four Corners of the Asia-Pacific
At a minimum, we will need the following four observatories initially to identify the extent of the Asia-Pacific plume.

1. Hanimaadhoo Island, Republic of Maldives.
The Maldives are sufficiently far from India and Sri Lanka to be truly representative of the remote marine environment of the northern Indian Ocean, yet they are strongly influenced by the northeast monsoon. The Hanimaadhoo Climate Observatory (HCO), 6.466°N, 73.110°E, is critical because it is the only observatory in the world which can measure two distinct types of air due to the monsoons: pristine air from the southern hemisphere during the southwest or wet monsoon, and polluted continental air from India, Indo-China and other regions of Southeast Asia during the northeast or dry monsoon. HCO will also document the transitional periods between the monsoons. Moreover, sampling southern pristine air will provide true background measurements for the region as well as the world. Sampling polluted air will support continued study of the influence of pollutants on the chemical composition and radiative properties of aerosols and clouds. Proof-of-concept for HCO was successfully carried out during 1998-1999 in INDOEX with the Kaashidhoo Climate Observatory (KCO) on Kaashidhoo Island which is about 160 km south of Hanimaadhoo.

2. Bidur, Nepal.
UNEP supports the development of a station in Nepal, tentatively in Bidur, to observe the haze pushing against the Himalayan mountains. It will also help monitor long range transboundary pollution from Europe.

3. Kosan Station, Cheju Island, Korea. Because the Kosan observatory (33.28°N, 126.17°E) already exists (it was used during ACE-Asia 2001), time until operation should be brief. This station, optimally located in the outflow of China, will help monitor the regional extent of the haze and desert and continental dust.

4. Mauna Loa Observatory, Hawaii.
We envision that the existing site at the Mauna Loa Observatory (155.58°W, 19.54°N) would become an important source of data for *Project ABC*, possibly complemented by additional instrumenation. This station will monitor the trans-Pacific transport of the Asian pollution plume.

5. We will also explore collaboration with Taiwan and Japan for their existing facilities and/or measurements.

6. In addition, another observatory will be established at La Jolla, California, to track the arrival of the Asia-Pacific plume to North America. This station will be established as part of existing long-term research program for C^4, but it will be operated within the *Project ABC* framework to provide scientific synergy in monitoring the global transport of pollution.

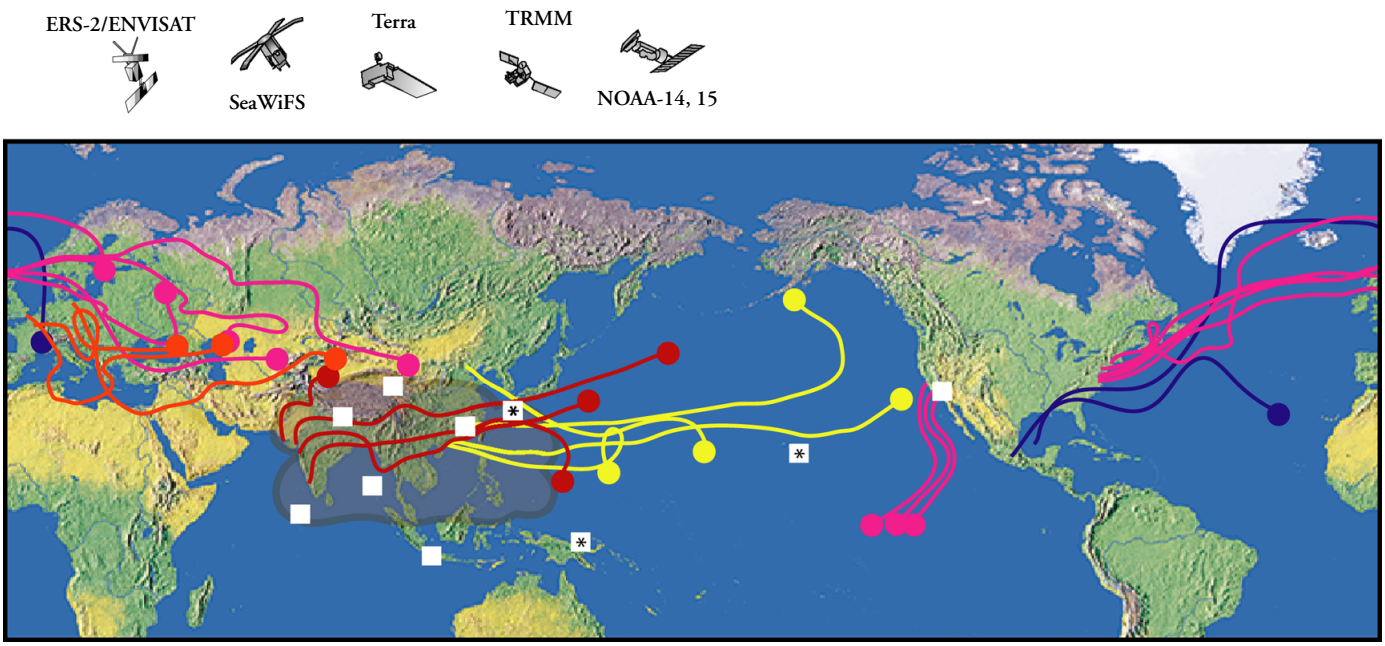
Long-Term: Encircling the Asia-Pacific Haze
Within the next 5-6 years, additional observatories will be built, tentatively including:

7. Bay of Bengal, to monitor the transport of the haze during the northeast monsoon.

8. and 9. Qinghai Hu and near Beijing, China. A station in the region of Qinghai Hu will facilitate measurements of desert aerosols, and possibly gauge the import of pollution from Europe. Another station is also proposed in the Beijing vicinity to monitor biomass burning, and urban and industrial plumes.

10. Malayia / Indonesia, to monitor emissions of recurrent forest fires.

11. Momote Station, Papua New Guinea. Along with the station in Indonesia, the Momote Station (2.058°S, 147.425°E), operated as a Western Pacific site in the US Department of Energy's (DOE) Atmospheric Radiation Measurement (ARM) Program, would provide a comprehensive picture of the path of pollution from biomass burning and forest fires.



Proposed Observation Network for Project *ABC*. Extensive usage of satellite data will be the hallmark of Project *ABC*. For the surface system, new surface sites (white squares) and existing sites with additional *ABC* instruments (white squares with asterisks) will be established to monitor regional and global transport.

• *Satellites Observation System*
Project ABC will take advantage of AVHRR data for trend analysis of the pollution haze, MODIS data on TERRA for classification of clouds, CERES for validation of the radiative forcing, SeaWiFS for aerosol global coverage over the ocean, GOME/SCIAMACHY for regional ozone, carbon monoxide and other gases, and MOPITT on TERRA for carbon monoxide.

• AVHRR - Advanced Very High Resolution Radiometer is onboard National Oceanic and Atmospheric Administration (NOAA) satellite series. The objective of the AVHRR instrument is to provide radiance data for investigation of clouds, land-water boundaries, snow and ice extent, ice or snow melt inception, day and night cloud distribution, temperatures of radiating surfaces, and sea surface temperature.

• MODIS - The Moderate-resolution Imaging Spectroradiometer (MODIS) is a key instrument onboard the National Aeronautic and Space Administration (NASA)'s Terra and Aqua satellites to monitor aerosols, atmospheric water vapor and rain water, physical and radiative properties of clouds, profiles of atmospheric temperature and moisture, atmospheric stability, and total ozone burden.

• CERES - The Clouds and the Earth's Radiant Energy System (CERES) experiment is one of the highest priority scientific satellite instruments developed for NASA's Earth Observation System. CERES products include both solar-reflected and Earth-emitted radiation from the top-of-the-atmosphere (TOA) to the Earth's surface. The instruments measure radiances, TOA and surface radiation fluxes, rain water, snow/ice, fire, aerosols, surface temperature, cloud physical and optical characteristics and liquid/ice water path.

• GOME and SCIAMACHY - The Global Ozone Monitoring Experiment (GOME) was launched in 1995 onboard the second European Remote Sensing Satellite (ERS-2). This instrument can measure a range of atmospheric trace constituents, with the emphasis on global ozone distributions. GOME is a nadir-viewing spectrometer that measures the solar radiation scattered by the atmosphere in the ultraviolet and visible spectral region (240 to 790 nm). Although GOME will continue to fly for some time, a substantially enhanced version,

Table 1. Instruments at KCO during INDOEX, Spring 1999

Aerosol and Radiometric Program
C^4/SIO/UCSD (V. Ramanathan):
- Pyranometer, clear dome, shaded
- Pyranometer, clear dome, unshaded
- Pyranometer, near IR, shaded + diffuse
- Pyranometer, near IR, unshaded + global
- Pyrheliometer, clear + direct
- Pyrheliometer, near-IR + direct
- Dual-channel spectroradiometer, direct and global
- 5-channel GUV-511c, global and diffuse
- Microtop handheld photometer
- Meteorological station (winds, temp., RH and pressure)
- Digital camera, whole sky imager


Kaashidhoo Climate Observatory

NASA-GSFC (B. Holben):
- CIMEL sun photometer

Univ. Miami, Florida
(J. Prospero, H. Maring and D. Savoie):
- Nephelometer, scattering coefficient
- Particle Soot Absorption Photometer (PSAP), extinction coefficient
- High Volume Aerosol Impactor, 3 stages <1, 1, >10 μm
- Anemometer

Atmospheric Chemistry Program
Univ. Maryland (R. Dickerson):
- Surface CO
- Surface Ozone

NOAA-CMDL (T. Conway and P. Tans)
- Whole Air Sampler (CO_2, CH_4, CO, H_2, N_2O, SF_6, and $^{13}C/^{12}C$ and $^{18}O/^{16}O$ of CO_2)

NOAA-CMDL (S. Oltmans)
- Columnar O_3 (sondes)

New instruments may include balloon sounding systems, an aerosol mass spectrometer, and surface lidar.

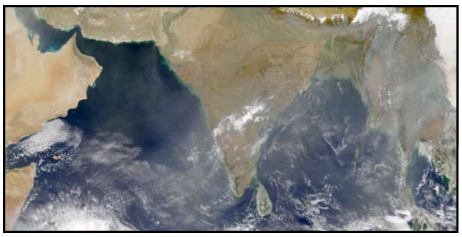
This set of instruments deployed at KCO during the Intensive Field Phase in Spring 1999 enabled the simultaneous measurements of aerosol characteristics and radiative fluxes reaching the Earth's surface. Measurement of solar radiative fluxes at the surface is very important for estimating the aerosol radiative forcing and hence its effect on climate.

Scanning Imaging Absorption SpectroMeter for Atmospheric CHartographY (SCIAMACHY), will be launched next year on ENVISAT by the European Space Agency.

• SeaWiFS - The purpose of the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) Project is to provide quantitative data on global ocean bio-optical properties. Subtle changes in ocean color signify various types and quantities of marine phytoplankton (microscopic marine plants), the knowledge of which has both scientific and practical applications, such as derived aerosol coverage.

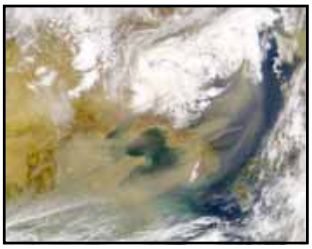
Satellite photographs document transboundary pollution. a) Indian Ocean haze; b) Chinese dust storm and Korean fires; c) Indonesia fires in 1997, and d) Asian dust reaches North America in Spring 2001.

a



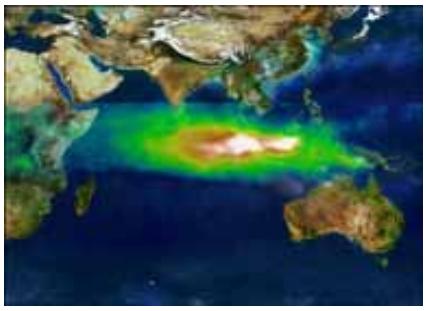
NASA/GSFC, SeaWiFS

b



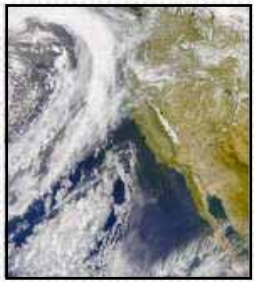
ORBIMAGE, NASA/GSFC, SeaWiFS, April 7, 2000

c



NASA/GSFC, Sci. Vis. Studio

d



ORBIMAGE, NASA/GSFC, SeaWiFS, April 15, 2001

The *ABC* Modeling Program

This program will consist of key components currently including:

• The US National Center for Atmospheric Research (NCAR) Climate System Model which is a global coupled ocean-atmosphere model.

• An Asia-Pacific regional climate model to complement our global climate modeling work. While the NCAR global climate model (GCM) covers the entire globe, its horizontal resolution is limited by the computing resources. Thus in a focused area such as the Asia Pacific region, we will use several regional models available to us in the US, in addition to the GCM, to simulate the monsoon hydrological cycle and the aerosol effect.

• Chemistry transport model will be run by our European colleagues to simulate transport of chemical species and ozone; while an aerosol transport model developed jointly by NCAR and C^4 will simulate aerosol transport.

• Various sophisticated agriculture models developed by the Indian Agriculture Research Institute (Wheat Growth Simulator and Crop Estimation through Resource and Environmental Synthesis) will be used in

conjunction with the above climate models and C[4]'s Monte Carlo Aerosol Cloud Radiation Model (MACR) to evaluate impacts on agriculture.

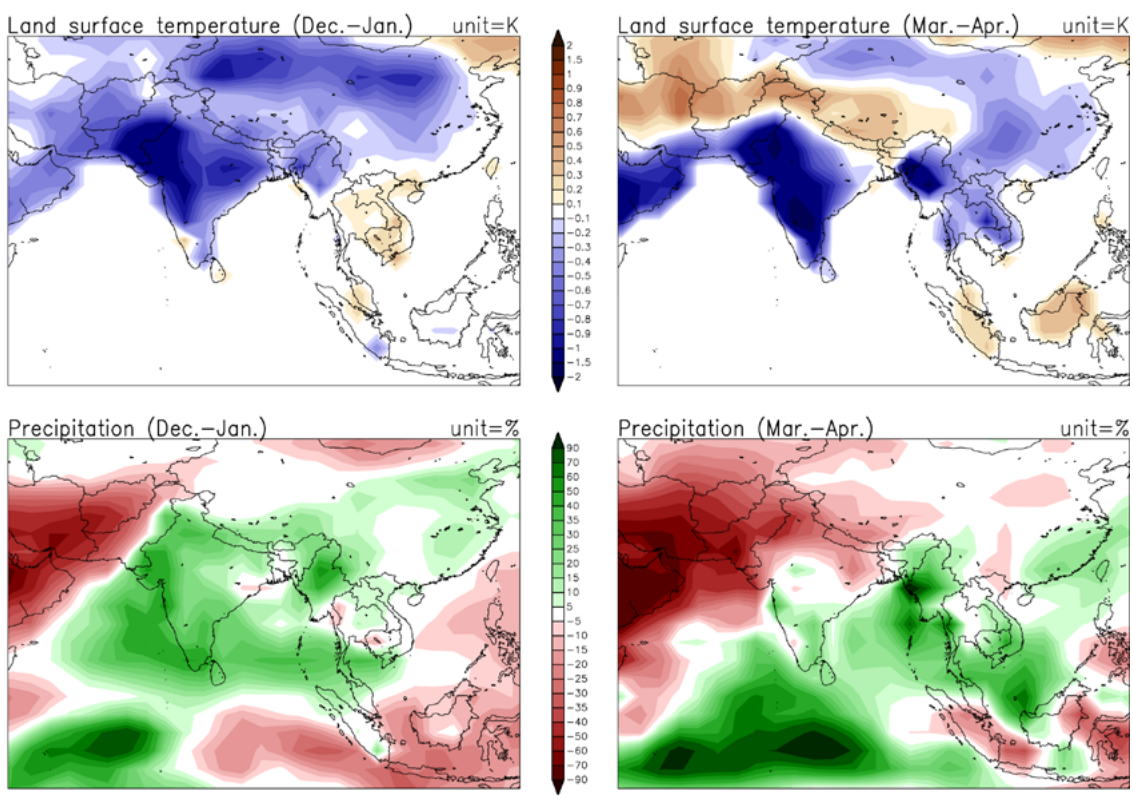
The goal for this modeling work is to create the Asia-Pacific Regional Climate Model (APRCM) to be available to regional researchers and students. Toward this goal, we will also initiate contact with the Frontier Research System for Global Change in Tokyo, Japan. APRCM will in turn be the first step toward the eventual establishment of an Asia-Pacific Climate Modeling Center (APCMC) to be located in a suitable location, such as Bangkok or Singapore.

The *ABC* Impact Assessment Program

- *Climate Impact*

A preliminary modeling assessment of the South Asian haze induced climate change was recently made by C[4] scientists using the National Center for Atmospheric Research-Community Climate Model Version-3 (CCM3).

Preliminary findings (Chung *et al.*2001; Kiehl *et al.*, 2001) show a cooling of the land surface, and warming of the atmosphere during the dry monsoon season. These temperature change features lead to the stabilization of boundary layer that results in a reduction of evaporation and sensible heat flux from the land. The rainfall disruption is surprisingly large, and is characterized mainly by increased precipitation over Bay of Bengal and drying of areas northwest of India. The figure (below) displays the surface temperature and



Regional climate change, as simulated by NCAR/CCM3. Upper panels display the land surface temperature variation (blue = cooling; yellow = warming). Lower panels show percentage precipitation change (green = wetting; red = drying). CCM3 was forced with the climatological seasonal cycle of observed SSTs. In the experiment being shown here, the ratio, "R", of the surface aerosol forcing to the atmosphere forcing is effectively -0.9 ("R[a]-0.9" experiment).

rainfall rate changes. There exists a 'positive feedback' between the aerosol forcing and deep convective precipitation, which greatly amplifies the initial dynamical response. The enhancement of the area-mean precipitation is as much as 20% over the haze area, and dries out the regions outside of the haze, notably Indonesia and the areas northwest of India (see figure, next page). Global mean precipitation decreases by 1%, consistent with a suppression of evaporation over the haze area.

Ultimately, more reliable estimates of the aerosol effect on climate call for more realistically designed forcing and less deficient climate models. Nevertheless, Chung *et al.* and Kiehl *et al.*'s studies implicate a large extent of the regional climate change. Regarding the domain of influence, the climatic effect may not necessarily be confined to the Indian sector. Through the modification of the Indian Walker circulation, the Pacific variability, including El Niño Southern Oscillation (ENSO), can also be impacted. The INDOEX aerosol climate forcing has significant implications to global climate, as it perturbs troposphere-wide temperature on a large spatial scale. The major inference from these modeling studies is that effects of manmade aerosols on regional climate can be quite large.

We propose to carry out detailed long term model studies for *Project ABC,* incorporating data collected in the region. Eventually, knowledge gained from these simulations will help design the APRCM.

• *Agriculture Impact*

Rice and wheat, main food staples throughout Asia-Pacific, are critical for the well-being of the region's 3.6 thousand million people. Although grain production has increased dramatically since the 1960's, yields may not continue to rise to help nourish the expanding population. Agricultural production is confronting growing constraints, such as decreased arable land quality and availability, and greater uncertainties due to aerosol impacts on climate, including: decreased surface radiation (Satheesh and Ramananthan, 2000) and potential impacts on the hydrological cycle, such as abbreviated or shifted monsoon cycles, more intense storms and flooding, and prolonged droughts.

The fine balance in the region's yearly grain production and world-wide pattern of grain imports could be easily impacted by climate change influenced by aerosols. When Asia produced 1,025.8 Mt of cereal (533.5 Mt rice, 261.7 Mt wheat) in 1999, only Thailand and Vietnam had 100% grain self-sufficiency (IPCC, 2001; FAO, 1999). Even in good harvest years, most countries in Asia expect to import cereals (IPCC, 2001; USDA, 1999) and all the countries are susceptible to crop losses due to potential adverse impacts of aerosols on climate. Regional crop models, coupled with *in-situ* field data, could help predict with greater confidence potential impacts on yield and growing conditions to promote better decision making for sustainable agriculture development and regional food security.

While the effect of rising levels of carbon dioxide on agricultural productivity has received significant attention in the past (e.g., Aggarwal and Kalra, 1994; Matthews *et al.*, 1995), the role of manmade aerosols in regulating crop yields in the Indo-Asia-Pacific region is yet to be addressed in detail. Although global warming could increase surface temperatures and extend growing seasons to enhance yield (IPCC, 2001; Rosenzweig and Hillel, 1998), aerosols could effectively shorten growing seasons by reducing solar energy reaching the Earth's surface.

As indicated by Chameides *et al.*, 1999 and the UNEP Assessment Report, reduction of solar energy at the Earth's surface by aerosols may have a significant effect on crop yields. *Project ABC* will conduct numerical experiments with a variety of highly sophisticated mathematical crop models using different scenarios with respect to water and nutrient intakes to build statistics of crop (initially rice, wheat and sugarcane) response

to atmospheric pollution. Output from the crop models will be used to quantify potential yields under different climate conditions. Modeling will be used in combination with *in-situ* and satellite observations to monitor crop health and water stress. The results will facilitate better strategies to help optimize resources, such as water and land, given complex feedback effects between atmospheric pollution and food production in the Asia-Pacific region in the context of rapidly increasing fossil fuel emissions on top of biomass burning.

Initial Agriculture Assessment in India

In order to link the effects of haze on surface radiation, regional monsoon winds and precipitation with agriculture, we plan to collaborate with the Indian Agricultural Research Institute (IARI) using dynamic crop models for rice, wheat and sugarcane:

- Crop Estimation through Resource and Environment Synthesis (CERES) - Rice model simulates the effects of weather, soil, water, cultivar, and nitrogen dynamics in the soil and the crop to predict rice growth and yield.
- Wheat Growth Simulator (WTGROWS) evaluates the effects of climatological variables (surface irradiance, temperature, etc.), genotype, agronomic management, water availability, and nitrogen use on crop growth and productivity of winter wheat in tropical and subtropical environments (Aggarwal and Kalra, 1994).
- CANEGRO module of the Decision Support System for Agrotechnology Transfer (DSSAT) program shell developed by the organizers of International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) project simulates sugarcane growth and yield.

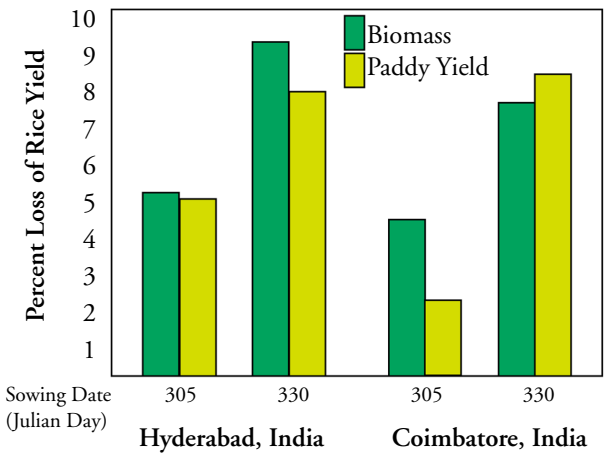
Model inputs include time series of a) surface radiative fluxes generated using C^4's MACR, b) NCAR's Aerosol Assimilation Model, and c) aerosol induced changes in regional rainfall and temperature patterns generated using the NCAR Community Climate Model (CCM).

Rice

The most important cereal crop in India, rice occupies nearly 35% of the total area under cultivation and contributes more than 40% of India's total food grain. It is mainly grown in the rainy summer and requires four months until harvest, enabling several crops each year. The CERES - Rice model run for two locations in India with two sowing times suggested that the presence of pollution aerosols could reduce rice yields by 2-8%. The effect was more pronounced for the second date of sowing.

Wheat

Wheat is grown during the winter (November to April) in the Indo-Gangetic alluvial plains and central India, mainly Madhya Pradesh (the study might be even more relevant to Pakistan and Afghanistan). WTGROWS run for different wheat growing areas under adequate irrigation, indicated that the presence of aerosols during INDOEX may have impacted wheat yields by 1.7 - 5.5%.



Potential Loss in Rice Yield Due to Aerosol Impact.
(*Project ABC* Assessment Report, 2001.)

Sugarcane

One of the most important cash crops in India, sugarcane covers around 4.1 million hectares, mainly in the Indo-Gangetic alluvial plains and southern India. Solar radiation reduction in the tilling and grand growth phase can cause considerable damage to final yield. Such findings

are observed in Poplar/sugarcane plantations where shade can decrease sugarcane yield by 10%. Using the CANEGRO module of DSSAT which incorporates agronomic management practices, sugarcane yield declined by approximately 1.5% because of aerosol impacts during important stages of growth.

Crop Assessment for the Entire Asia-Pacific Region

In the long-term, the *ABC* agriculture program will gradually expand to include other countries in the region, including China, Pakistan and particularly Indonesia, Thailand and Vietnam, the region's main rice producers. Of particular interest, to complement and validate modeling studies, strategic *in-situ* observations will be gathered to provide critical data input for the models. Agriculture models will continue to use climate data generated by the climate side of this program.

In addition to joint research with IARI, we will establish scientific collaboration with the Consultative Group on International Agricultural Research (CGIAR), the International Rice Research Institute (IRRI) in the Philippines; and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) to expand agricultural research to the entire Indo-Asia-Pacific region. Possible benefits include, for example, advances with IRRI to identify genetic strains that take advantage of increased CO_2 but tolerate air pollution and drought. Also, additional insights from regional crop models on the impacts of aerosols on agriculture could help agronomists and policymakers with economic planning (i.e. type of crop, timing of planting) to optimize yield.

- *Public Health Impact*

Recent studies in the US by the Health Effects Institute (HEI) in Cambridge, Massachusetts, found that death rate in the 90 largest US cities rise on average 0.5% with each 10 micrograms per cubic meter increase in PM_{10} loadings (aerosols less than 10 micrometers in diameter). The situation in urban areas of the developing regions could be worse. Several of the world's most polluted cities are found in South Asia: Calcutta, Delhi, Mumbai, Karachi, and Dhaka are examples of megacities that produce unacceptably high emissions of health endangering gaseous and particulate matter. SPM values are several times higher than those prescribed by National Air Quality standards: for the Delhi annual average for 1997 was 370 mg/m^3, 2.5 times larger than the standard value for the residential area. Though the values of SO_2 and NO_x generally remained within prescribed limits of 60-80 mg/m^3, there have been sharp increases in recent years: SO_2 by 109% from 1989 to 1996 and NO_x by 82% (White Paper on Pollution in Delhi, 2000).

There is distinct association between ambient air pollution and respiratory diseases, although estimates of mortality vary. Risk estimates for acute respiratory infections, chronic obstructive pulmonary disease and lung cancer, as well as tuberculosis and asthma (with less confidence) are available.

Air quality in 11 megacities

City	SO_2	SPM	Lead	CO
Bangkok	●	●●●	●●	●
Beijing	●●●	●●●	●	●
Calcutta	●	●●●	●	●
Delhi	●	●●●	●	●
Jakarta	●	●●●	●●	●●
Karachi	●	●●●	●●●	●
Manila	●	●●●	●●	●
Mumbai	●	●●●	●	●
Seoul	●●●	●●●	●	●
Shanghai	●●	●●●	●	●
Tokyo	●	●	●	●

●●● Serious problem. WHO guidelines exceeded by more than 100 per cent

●● Moderate to heavy pollution. WHO guidelines exceeded by up to 100 per cent

● Low pollution. WHO guidelines are normally met or may be exceeded from time to time by a small amount

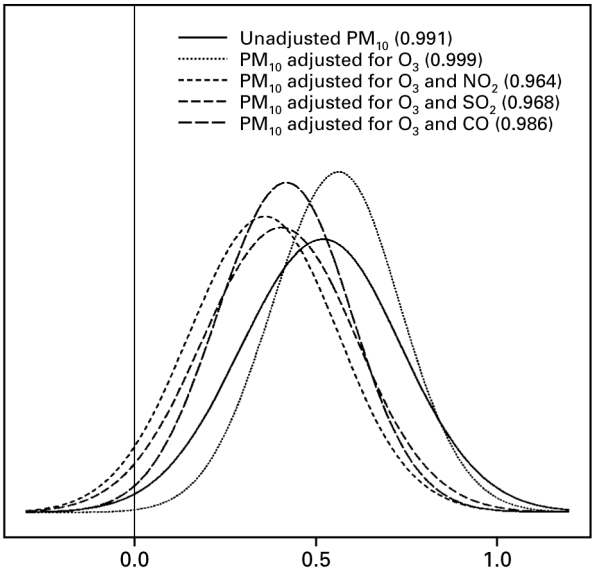
Air Quality in 11 Megacities (WHO and UNEP, 1992; UNEP, 1999).

Studies in India in a number of locations (Delhi, Calcutta, Mumbai, Lucknow) also point to serious hazards from both indoor and outdoor pollution, although there are inherent uncertainties reflecting differences in pollution mixtures, gender, income levels and occupational patterns.

Selected Causes of Death in China

Cause	Approximate number per year, 1990-1995
Air-pollution-related lung and heart disease	1,100,000
Smoking-related lung disease, heart disease, and stroke	800,000
Stroke from hypertension	
Infectious diseases,	600,000
except pneumonia	500,000
Suicide	300,000
Liver cancer from hepatitis, microcystin, and aflatoxin	250,000
Falls and drowing	200,000
Motor vehicle accidents	135,000
Homicide	50,000
Fires and burns	24,000
Coal mining accidents	5,000
All causes, 1995	**8,000,000**

(Environmental Science & Technology, American Chemical Society; Hood and Sweet, 1999.)



Study of 20 US Cities, 1987-1994: 0.5% Increase in Deaths from All Causes for Each Increase in PM_{10} of 10 $\mu g/m^3$. Posterior distributions of the overall relative rate of increase in death from all causes for each increase in the PM_{10} level of 10 $\mu g/m^3$, before and after adjustment for the levels of O_3, NO_2, SO_2 and CO. Values in parentheses are the posterior probabilities that the overall effects are greater than zero. PM_{10} denotes particulate matter that is less than 10 μm in aerodynamic diameter (Samet *et al.*, 2000).

In rural Asia, due to burning of unprocessed solid biomass for cooking and heating, indoor air pollution is a major health issue. A study of the East West Center in Hawaii (Smith, 2000) estimates that about half a million women and children 5 years or younger in India die yearly due to indoor air pollution. A significant fraction of the air pollution, especially in rural areas, originated from indoor biomass burning.

In *Project ABC*, epidemiologists will be encouraged to work with pathologists in the field to make case studies of deaths caused by atmospheric pollution. Asian institutions, through UNEP RRC.AP and perhaps the World Health Organization (WHO), will be paired with those in the US, Europe and Japan for comparative studies and exchange programs. Physical and chemical property data on the haze, its seasonal spatial coverage and pollution events, will be used as environmental background for these studies.

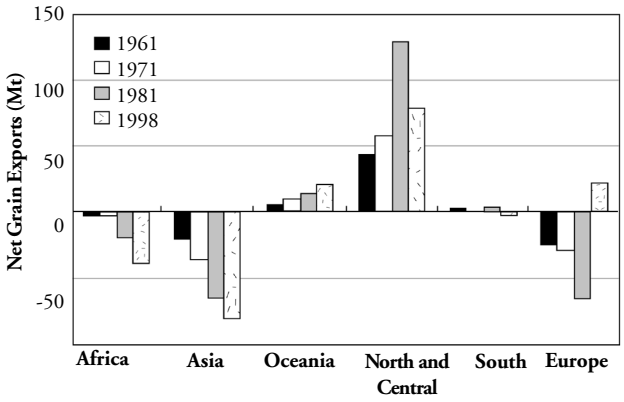
- *Economic Impacts and Policy Implications*

Throughout the life span of the *Project ABC*, in parallel with the research programs, UNEP RRC.AP will coordinate with economists in the US, Europe, Asia and the Asian Development Bank (ADB) to provide yearly assessments of economic impacts, taking into consideration the results of the climate, agriculture and public health impact studies, to include societal cost vs. benefits and trade-offs among policies and options. Examples are provided in the following tables.

Potential Health Benefits from Better Emission Controls

Health Outcome	*Best Estimates, Fewer Cases/Year*
Mortality	300
Emergency Room Visits (cardiovascular and respiratory)	2,000
Asthma Attacks	10,000

In a region covering Wisconsin, Illinois, Michigan and Indiana that is home to 33 million people, nine old coal-fired power plants upwind of Chicago, Illinois contribute about 0.6 $\mu g/m^3$ to the region's annual average $PM_{2.5}$ concentration of 15-20 $\mu g/m^3$. Above benefits could be realized if tighter regulations are adopted to reduce about 75% of emissions. (Levy and Spengler, 2000.)



Food Security. Worldwide pattern of production and export of grain. Even in a good harvest year, Asia-Pacific still has to import a significant quantity (IPCC, 2001)

CHINA: UNDP Urges Government to Reduce Smog Emissions
UNWire, November 26, 2001
http://www.unwire.org/

The **U.N. Development Program** issued a report today saying that China's air pollution is among the worst in the world and calling on the Chinese government to adopt strict economic measures to curb smog emissions in urban areas.

"China's major cities have been characterized by some of the highest levels of air pollution in the world, often with pollutant concentrations at multiples of the levels considered safe for human health and the environment," the report says. The study, produced in cooperation with Chinese institutes, also mentions the need for "market-oriented solutions based on the rule of law."

The UNDP based its recommendations on six agency-sponsored air pollution projects across China that aimed to reduce acid rain from coal burning and industrial and vehicle pollution. One of these projects in the southern province of Guizhou found that increasing energy efficiency and burning cleaner coal could reduce acid rain by as much as 30 percent. Acid rain in Guizhou is considered to be among the worst in the world, posing both a health hazard and an environmental risk by decreasing soil fertility.

China's own annual environmental report, which was published earlier this year, said that even though the country has made some strides in decreasing pollution, environmental degradation nationwide continues to be an extremely serious problem (Agence France-Presse, Nov. 26).

China: Possible Annual Avoided Deaths by 2020
Policy Implications between Economic and Environmental Benefits

Scenario	*Sector*	*Low Range*	*Mid Range*	*High Range*
Efficiency	Power	1,500	4,400	13,000
	Household	62,000	150,000	460,000
Fuel substitution least-cost GWP	Power	1,700	4,900	15,000
	Household	47,000	120,000	360,000
Fuel substitution least-cost dose	Power	1,800	5,200	16,000
	Household	70,000	180,000	530,000

The above scenarios are based on an estimated mortality/population in China in 2020: 14 million/1470 million. Numbers of avoided deaths are estimated for the three scenarios for both the power sector and household sector, relative to the business-as-usual (BAU) case by 2020:

- Efficiency = improved combustion to reduce GHG and particulates by 15% of BAU.
- Fuel substitution, least-cost per unit of Global Warming Potential (GWP) = cheapest substitutes are successively taken until exhausted, to achieve GHG target.
- Fuel substitution, least-cost dose = cheapest substitutes are successively taken until exhausted to achieve smallest exposure to air pollution

The wide range of the results shows urgent need to characterize relationship between indoor and outdoor emissions and exposures; and to prioritize the efficiency of or replacing solid and biomass fuels. Also, benefits from the electric power sector currently seem not to be sufficient to offset the incremental cost of introducing GHG and particulate strategies.

(Wang and Smith, 1999).

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ATTACHMENT 1 - Potential Collaborating Institutions

Project Asian Brown Cloud

A collaboration between the Center for Clouds, Chemistry and Climate and the UNEP Regional Resource Center for Asia and the Pacific

V. Ramanathan[1] and P.J. Crutzen[1,2]
Coordinator: H.V. Nguyen[1]
1. Scripps Institution of Oceanography, University of California, San Diego (UCSD), La Jolla, California, USA
2. Max-Planck Institute for Chemistry, Mainz, Germany

Potential Collaborating Institutions:

Florida State University, Tallahassee
Georgia Institute of Technology, Atlanta
Indian Agriculture Research Institute, New Delhi
Indian Institute of Science, Bangalore
International Centre for Integrated Mountain Development, Kathmandu
Institute of Earth Sciences, Academia Sinica, Taipei
Institute for Global Change Research, Yokohama
Laboratoire de Météorologie Dynamique, Paris
Max-Planck Institute for Chemistry, Mainz
Ministry of Home Affairs, Housing and Environment, Republic of Maldives
National Agricultural Research Centre, Islamabad, Pakistan
National Center for Atmospheric Research, Boulder
National Institute for Environmental Studies, Japan
National Physical Laboratory, New Delhi
Patel Chest Institute, New Delhi
Peking University, Beijing
Physical Research Laboratory, Ahmedabad
School of Medicine, University of California, San Diego
School of Public Health, Johns Hopkins University, Baltimore
Scripps Institution of Oceanography, UCSD
State Environmental Protection Agency, China
State Science and Technology Commission, China
Stockholm University, Stockholm
SysTem for Analysis, Research and Training (START)
United Nations Environmental Programme, Regional Resource Center for Asia and the Pacific, Bangkok
University of Maryland, College Park
University of Miami, Miami
University of Seoul, Seoul
University of Tokyo

Proposed Timelines and Estimated Budget, October 2001-September 2003

(in thousands US$)

	2001 Jan-Sep	YEAR 1 O-N-D	2002 J-F-M A-M-J J-A-S	YEAR 2 O-N-D	2003 J-F-M A-M-J J-A-S	YEAR 3 O-N-D	
Immediate Term (Jan-Aug 2001)							
Impact Assessment I	50						already funded. Assessment Report due by Aug 31
Short Term (Year 1-2)							
Project Coordination		150		155			coordinator, editor, travels, teleconference
Surface Observation Program							
Construct+Equipt Hanimaadhoo, Maldives		400		100			costs includes construction and instruments
Solar Energy Program		200		50			solar energy will be the main power source
Calibration Program		30		50			to purchase radiation calibration instruments
Construct+Equipt station in Bidur, Nepal		250		150			
Construct+Equipt station in Bay of Bengal		100		250			
Solar Energy (Bidur and BOBengal)		200		300			
Data Analyses and Training		50		80			training provided at the surface observatories
Visitor and Exchange Program		50		70			between Asia/US/Europe
Transboundary Transport Assessement		20		20			Yearly Report
Regional Postdocs and Students		60		80			local personnel to operate the sites
Agriculture Program							
Numerical Experiments		30		40			initiate agriculture and climate model runs
Visitor and Exchange Program		40		60			between Asia/US/Europe
Climate-Agriculture Integration		0		70			training provided to A-P scientists/students
Impact Assessment		20		20			Yearly Report
Public Health							
Statistical Studies		40		90			epidemological studies for Asian mega cities
Visitor and Exchange Program		50		60			in conjunction with the above studies
Climate-Health Integration		0		70			initiation of first climate-health model
Impact Assessment		20		20			Yearly Report
Economics Impacts							
Quantification of pollution damages				80			policy-related studies coordinated by UNEP
Visitor and Exchange Program				50			between Asia/US/Europe
Impact Assessment				20			Yearly Report
TOTAL PROPOSED REQUEST*	50	1710		1885			

**additional Direct and Indirect Cost to partner universities are not included in the above proposed budget*

Proposed Timelines and Estimated Budget (Continued)

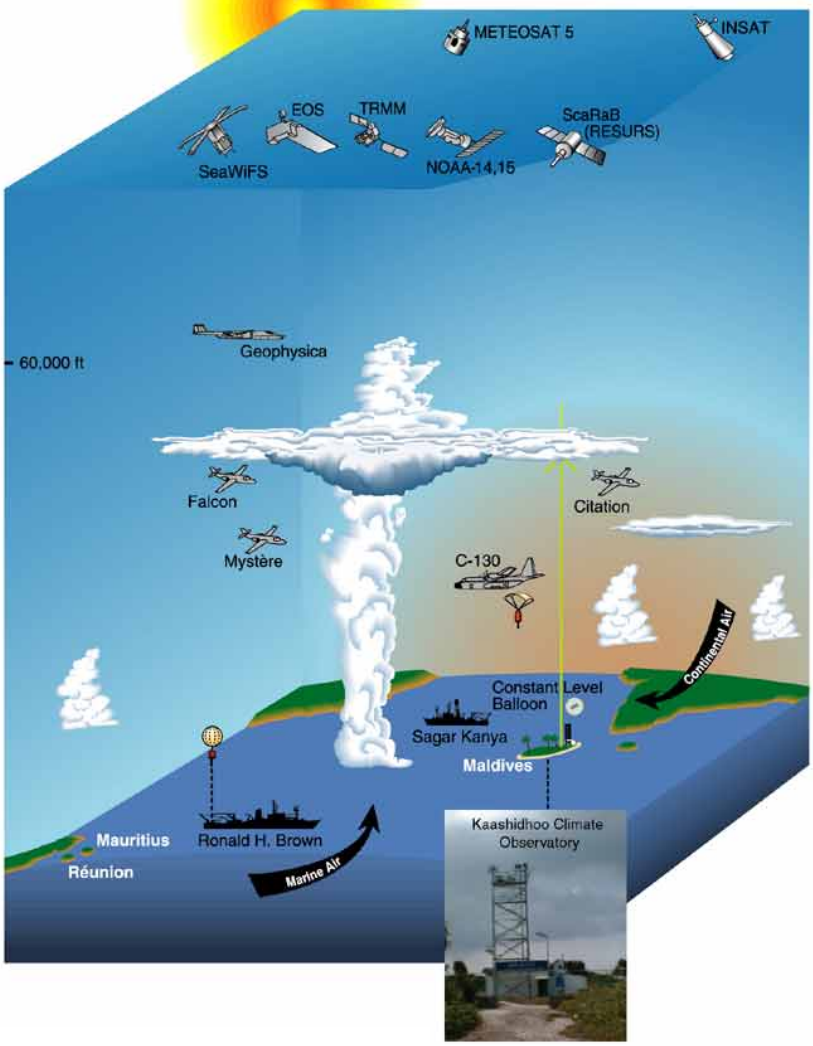
Proposed Timelines and Estimated Budget, October 2003-September 2006 and Beyond

(in thousands US$)	YEAR 3				YEAR 4				YEAR 5				YEAR 6	
	2003	2004				2005				2006				
	O-N-D	J-F-M	A-M-J	J-A-S	O-N-D	J-F-M	A-M-J	J-A-S	O-N-D	J-F-M	A-M-J	J-A-S	O-N-D	
Long Term Program (Year 3-5 and beyond)														
Project Coordination	160				165				170					coordinator, editor, travels, teleconference
Surface Observation Program														
Data Collection &Analyses	100				100				100					for the existing observatories
Operations and Maintenance	60				60				60					ops expenses, existing observatories
New Observatory in Pac Rim country 1	300				0				0					construction + instruments
New Observatory in Pac Rim country 2	200				100				0					construction + instruments
New Observatory in Pac Rim country 3	100				200				0					construction + instruments
Solar Energy Program	250				250				250					solar energy set up for new stations
Operations and Maintenance	60				60				60					operations expenses
Data Analyses, Calibration and Training	100				100				100					Asia/US/Europe or at the observatories
Visitor and Exchange Program	70				150				280					between Asia/US/Europe
Field Studies	100				200				300					dry monsoon experiments
Transboundary Transport Assessement	60				80				100					Yearly Report
Regional Postdocs and Students	200				250				300					local personnel to operate the sites
Agriculture Program														
Numerical Experiments	50				50				50					using climate data in agri. models
Expansion to Rice Producing Countries	50				100				100					Indonesia, Thailand and Viet-Nam
Visitor and Exchange Program	20				30				30					between Asia/US/Europe
Climate-Agriculture Integration	60				60				60					integration of climate and agr. models
Field Studies	150				150				150					to collect in-situ data to verify models
Impact Assessment	40				60				80					Yearly Report
Public Health														
Statistical Studies	200				200				200					expansion to other mega cities in Asia
Visitor and Exchange Program	20				40				50					between Asia/US/Europe
Climate-Health Integration	50				50				50					integration of health-climate models
Field Studies	150				150				150					to collect in-situ pathological data
Impact Assessment	40				40				40					Yearly Report
Economics Impacts														
Quantification of pollution damages	200				200				200					policy-related studies coordinated by UNEP
Visitor and Exchange Program	60				60				60					between Asia/US/Europe
Impact Assessment	40				40				40					Yearly Report
Data Access System														
Development and Testing	70				70				10					integration of surface, satellite and model
Operations and Training	0				0				80					testing with regional/national resources
Integrated Computer Model for Asia-Pacific Region														
Development and Testing	200				200				200					integration of climate-agriculture-health
Visitor and Exchange Program	50				50				50					between Asia/US/Europe
Student/Scientist Exchange Program	50				50				50					Inst. for Global Sustainability, exchange program
Planning for Asia-Pacific Experiment	50				50				50					To fund Asia-Pacific participants. The field program would start in the 6th year
TOTAL PROPOSED REQUEST*	3310				3365				3420					

**additional direct and indirect cost to partner universities are not included*

ATTACHMENT 3 - The Indian Ocean Experiment

The Indian Ocean Experiment (INDOEX), an international field experiment, has been collecting data since 1996, featuring an intensive field campaign conducted in Spring 1999. For details, see *http://www-indoex.ucsd.edu*.



Participating Institutions

Austria
Universität Innsbruck
Canada
York University, Toronto
Europe
Airborne Platform for Earth Observation (Geophysica, Falcon)
European Organisation for the Exploitation of Meteorological Satellites (Meteosat-5)
France
Laboratoire d'Optique Atmosphérique
Laboratoire de Météorologie Dynamique du CNRS
Laboratoire de Météorologie Physique, Université Blaise Pascal
Laboratoire des Sciences du Climat et de l'Environnement, CEA-CNRS
Laboratoire Interuniversitaire des Systèmes Atmosphériques
Service d'Aéronomie
Germany
Forschungszentrum Jülich
GKSS-Forschungszentrum Geesthacht
Institut für Troposphärenforschung
Max Planck Institut für Chemie
Max Planck Institut für Kernphysik
Max Planck Institut für Meteorologie
Meteorologisches Institut der Universität Hamburg
Universität Bremen
India
Antarctic Study Centre, Vasco-da-Gama
Indian Institute of Science, Bangalore
Indian Institute of Technology, New Delhi
Indian Institute of Tropical Meteorology, Pune
Indian Meteorological Department, New Delhi
Indian Space Research Organization, Bangalore
National Centre for Medium Range Weather Forecasting, New Delhi
National Institute of Oceanography, Goa
National Physical Laboratory, New Delhi
Physical Research Laboratory, Ahmedabad
Space Applications Centre, Ahmedabad
Space Physics Laboratory, Thiruvananthapuram
Israel
Tel-Aviv University
La Réunion
Université de La Réunion
Mauritius
Department of Meteorological Services, Mauritius
University of Mauritius, Reduit
Maldives
Department of Meteorology, Maldives
Ministry of Home Affairs, Housing and Environment
Netherlands
Koninklijk Nederlands Meteorologisch Instituut
Technische Universiteit Delft
Universiteit Utrecht
South Africa
University of Witwatersrand, Johannesburg
Sweden
Meteorologiska Institutionen, Stockholms Universitet
United Kingdom
Imperial College, London

United States
Center for Clouds, Chemistry and Climate
Arizona State University, Tempe
Atmospheric Research Laboratory
Colorado University, Boulder
Desert Research Institute
Florida State University, Tallahassee
NASA - Goddard Space Flight Center
National Center for Atmospheric Research
NOAA - Atlantic Oceanographic and Meteorological Laboratory
NOAA - Climate Monitoring and Diagnostics Lab
NOAA - Pacific Marine Environmental Laboratory
North Carolina State University, Raleigh
Oregon State University, Corvallis
Pennsylvania State University, University Park
Scripps Institution of Oceanography
SeaSpace Corporation
University Corporation for Atmospheric Research
University of Alaska, Fairbanks
University of California, Irvine
University of California, Riverside
University of California, San Diego
University of Hawaii, Manoa
University of Maryland, College Park
University of Miami
University of Washington, Seattle