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India: Impact of Climate Change to 2030
A Commissioned Research Report

THE NATIONAL INTELLIGENCE COUNCIL SPONSORS WORKSHOPS AND RESEARCH WITH NONGOVERNMENTAL EXPERTS TO GAIN KNOWLEDGE AND INSIGHT AND TO SHARPEN DEBATE ON CRITICAL ISSUES. THE VIEWS EXPRESSED IN THIS REPORT DO NOT REFLECT OFFICIAL US GOVERNMENT POSITIONS.

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India: The Impact of Climate Change to 2030

A Commissioned Research Report

Prepared By
Joint Global Change Research Institute and
Battelle Memorial Institute, Pacific Northwest Division

The National Intelligence Council sponsors workshops and research with nongovernmental experts to gain knowledge and insight and to sharpen debate on critical issues. The views expressed in this report do not reflect official US Government positions.

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Scope Note

Following the publication in 2008 of the National Intelligence Assessment on the National Security Implications of Global Climate Change to 2030, the National Intelligence Council (NIC) embarked on a research effort to explore in greater detail the national security implications of climate change in six countries/regions of the world: India, China, Russia, North Africa, Mexico and the Caribbean, and Southeast Asia and the Pacific Island States. For each country/region we are adopting a three-phase approach.

- In the first phase, contracted research—such as this publication —explores the latest scientific findings on the impact of climate change in the specific region/country.
- In the second phase, a workshop or conference composed of experts from outside the Intelligence Community (IC) will determine if anticipated changes from the effects of climate change will force inter- and intra-state migrations, cause economic hardship, or result in increased social tensions or state instability within the country/region.
- In the final phase, the NIC Long-Range Analysis Unit (LRAU) will lead an IC effort to identify and summarize for the policy community the anticipated impact on US national security.

The Joint Global Change Research Institute (JGCRI) and Battelle, Pacific Northwest Division (Battelle, PNWD), developed this assessment on the climate change impact on India through 2030 under a contract with SCITOR Corporation. The Central Intelligence Agency's Office of the Chief Scientist, serving as the Executive Agent for the DNI, supported and funded the contract.

This assessment identifies and summarizes the latest peer-reviewed research related to the impact of climate change on India, drawing on both the literature summarized in the latest Intergovernmental Panel on Climate Change (IPCC) assessment reports and on other peer-reviewed research literature and relevant reporting. It includes such impact as sea level rise, water availability, agricultural shifts, ecological disruptions and species extinctions, infrastructure at risk from extreme weather events (severity and frequency), and disease patterns. This paper addresses the extent to which regions within India are vulnerable to climate change impact. The targeted time frame is to 2030, although various studies referenced in this report have diverse time frames. The research does not draw inferences about the potential for internal or interstate conflict arising out of changes, e.g., in water supply or in likely migration from Bangladesh; such analyses will be conducted in the subsequent efforts described above.

This assessment also identifies (Annex B) deficiencies in climate change data that would enhance the IC understanding of potential impact on India and other countries/regions.

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Executive Summary

India is both a major greenhouse gas emitter and one of the most vulnerable countries in the world to projected climate change. The country is already experiencing changes in climate and the impacts of climate change, including water stress, heat waves and drought, severe storms and flooding, and associated negative consequences on health and livelihoods. With a 1.2 billion but growing population and dependence on agriculture, India probably will be severely impacted by continuing climate change. Global climate projections, given inherent uncertainties, indicate several changes in India's future climate:

- ***Global observations of melting glaciers suggest that climate change is well under way in the region, with glaciers receding at an average rate of 10–15 meters per year.*** If the rate increases, flooding is likely in river valleys fed by these glaciers, followed by diminished flows, resulting in water scarcity for drinking and irrigation.
- All models show a trend of general warming in mean annual temperature as well as decreased range of diurnal temperature and enhanced precipitation over the Indian subcontinent. ***A warming of 0.5^{o}C is likely over all India by the year 2030 (approximately equal to the warming over the 20th century) and a warming of 2-4^{o}C by the end of this century, with the maximum increase over northern India.*** Increased warming is likely to lead to higher levels of tropospheric ozone pollution and other air pollution in the major cities.
- ***Increased precipitation—including monsoonal rains—is likely to come in the form of fewer rainy days but more days of extreme rainfall events, with increasing amounts of rain in each event, leading to significant flooding.*** Drizzle-type precipitation that replenishes soil moisture is likely to decrease. Most global models suggest that the Indian summer monsoons will intensify. The timing may also shift, causing a drying during the late summer growing season. Climate models also predict an earlier snowmelt, which could have a significant adverse effect on agricultural production. Growing emissions of aerosols from energy production and other sources may suppress rainfall, leading to drier conditions with more dust and smoke from the burning of drier vegetation, affecting both regional and global hydrological cycles and agricultural production.

Uncertainties about monsoonal changes will affect farmers' choices about which crops to plant and the timing of planting, reducing productivities. In addition, earlier seasonal snowmelt and depleting glaciers will reduce river flow needed for irrigation. ***The large segment of poor people (including smallholder farmers and landless agricultural workers) may be hardest hit, requiring government relief programs on a massive scale. Finally, migration, especially from Bangladesh, may strain resources and India-Bangladesh relations.***

The most important impacts of climate change will likely include the following:

- ***Agriculture.*** High-input, high-output agriculture will be negatively affected even as demands for food and other agricultural products rise because of an increasing population and expectations for an improved standard of living. Millions of subsistence and smallholder farmers will experience hardship and hunger through being less able to predict climate conditions.[1] To a certain extent, trade may compensate for these deficits.

- ***Water:*** Glacier melt may yield more runoff in the short term but less in the medium and long terms. More severe storms (especially cyclones) will cause more damage to infrastructure and livelihoods and exacerbate salt water intrusion in storm surges. Changes in the timing and amount of monsoon rains will make the production of food and other agricultural products more uncertain, so that, even in good-weather years, farmers will be more likely to make decisions leading to lower-productivity.
- ***Exacerbation of Inequality:*** The welfare of those who are affected by climate change and who have limited means to adapt may act as a force that can change governments, strain public budgets, and foster unrest. About one-third of Indians are extremely poor, and 60 percent depend upon agriculture for their livelihoods.
- ***Energy:*** As India searches for additional sources of energy to meet rising demand, climate change mitigation efforts may constrain its use of indigenous and imported coal, oil, and gas, while development of nuclear energy will be slow at best and likely to encounter opposition. Other non-emitting technologies will require technology transfer and capacity-building.
- ***Migration:*** India receives immigrants from a number of countries. Under climate change conditions, it may be flooded with many more, particularly from Bangladesh. Such migration may exacerbate tension between the two countries as well as putting a strain on Indian central and state governments.

Adaptive capacity in India varies by state, geographical region, and socioeconomic status. Studies point to influential factors such as water availability, food security, human and social capital, and the ability of government (state and national levels) to buffer its people during tough times. ***Where adaptive capacity is low, the potential is greater for impacts to result in displaced people; deaths and damage from heat, floods, and storms; and conflicts over natural resources and assets.***

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[1] The current accuracy of even current forecasts is in doubt. For example, the Indian Medium Range Weather Forecasting Center is not allowed to issue such forecasts in public media–that is the responsibility of the Indian Meteorological Department.

Contents

Annexes

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Introduction and Background

Global climate projections, given inherent uncertainties, indicate several changes in India's future climate:

- Global observations of melting glaciers suggest that climate change is well under way in the region, with glaciers receding at an average rate of 10–15 meters per year.[i]
- If the rate of glacial melt increases, flooding is likely in the river valleys fed by these glaciers, followed by a diminished flow, resulting in a scarcity of water for drinking and agricultural irrigation.
- All models show a trend of general warming in mean annual temperature as well as decreased range of diurnal temperature and enhanced precipitation over the Indian subcontinent.[ii]
- A warming of 0.5^{o}C is likely over all India by the year 2030 (approximately equal to the warming over the 20th century) and a warming of 2-4^{o}C by the end of this century, with the maximum increase over northern India.[iii]
- Increased precipitation is likely to come in the form of fewer rainy days but more days of extreme rainfall events, with increasing amounts of rain in each event, leading to significant flooding.[iv] Fine precipitation (drizzle-type) that replenishes soil moisture is likely to decrease.
- Increased warming is likely to lead to higher levels of tropospheric ozone pollution and other air pollution in India's major cities.[v]
- Most global models suggest that the Indian summer monsoons will intensify with a warming climate. The timing may also shift, causing a drying during the late summer growing season.[vi]
- Climate models also predict an earlier snowmelt, which could have significant adverse effects on agricultural production, both irrigated and non-irrigated.[vii]
- Growing emissions of aerosols from energy production and other sources may suppress rainfall, leading to drier conditions with more dust and smoke from the burning of drier vegetation, affecting both regional and global hydrological cycles and agricultural production.[viii]

In both its greenhouse gas emissions and its vulnerability to climate change, India is one of the most significant countries in the world. With a large and growing population, India's emissions of greenhouse gases are increasing. Moreover, potential climate impacts in India are severe: sea level rise, changes in the monsoon, increased severe storms and flooding, more drought, and severe water stress. Recently, climate variability in the form of floods and cyclones has resulted in destruction of crops, property and infrastructure, as well as in negative impacts on human health and well-being. All of these impacts set back general socio-economic development. Rural dwellers' continuing dependence upon agriculture for food and livelihood (17.5 percent of gross domestic product (GDP) and more than 60 percent of the labor force)[ix] makes the Indian people particularly vulnerable to climate variability and change. Nowhere is this more evident than in the linkage of the annual monsoon cycle and agricultural production, commonly referred to as, “Indian agriculture gambles with monsoon.”

The diversity and extremes of India’s climate and geography are characteristic of its society as well. Religious and cultural diversity is a major feature of Indian life. The strong Hindu traditions have been synthesized with and challenged by other religions, notably Islam, Christianity, and Sikhism. India has at least 300 known languages, 24 of which have at least one million speakers each. There are differences, sometimes amounting to estrangement, between the North, with its history of grand-scale invasions, and the relatively stable South. Religious divisions became geographical divides when Muslim Pakistan (1947), then Bangladesh (1971), were created, and ethnic and caste-related strife continues among groups. However, the connectedness of the extended family is a core feature of Indian life. Together with a sense of civil society’s claims on individuals and families, the extended family knits the society together and emphasizes interdependence.[x]

Diversity and extremes are evident in India’s patterns of economic development as well. In this sphere, two themes stand in contrast: modernist, democratic, and technical development, intensified by the economic liberalization beginning in the early 1990s; and persistent poverty, subsistence agriculture, and caste-based discrimination. Various models of development have been advanced. Das[xi] characterizes the country-level model thus: “Rather than adopting the classic Asian strategy—exporting labor-intensive, low-priced manufactured goods to the West—India has relied on its domestic market more than exports, consumption more than investment, services more than industry, and high-tech more than low-skilled manufacturing.” Kerala’s model of human development emphasizes education, health services, and equality; however, slow economic development has somewhat tarnished this model, as incomes remain low and the contributions of Keralans working abroad continue to be very much needed.[xii] The Karnataka model focuses on technology, centered in Bangalore, and historically participatory local governance by *Panchayat.* Yet Karnataka also has “enduring gender inequity and regional disparities, and a visibly increasing gap between urban and rural areas.”[xiii]

Despite substantial economic and general development progress, poverty, malnutrition, illiteracy, and inequality[xiv] continue to plague India, as well as serious environmental issues. India has not only several Silicon Valleys but also several Nigerias.[xv] In addition, the ongoing dispute with Pakistan over Kashmir and ethnic strife (e.g., in Assam) claim national attention. Conflict with Pakistan has lessened by confidence-building measures since 2002, when nuclear war was hinted at, but such hints arose again after the recent terrorist attack in Mumbai, although the response so far has been relatively temperate.

India’s broad spectrum of highly articulated national policies includes inclusive growth goals in the areas of economic development, human development, and environmental protection. National goals are, of course, differentially implemented in each of India’s states, which exhibit widely varying degrees of social and economic development. Limited growth has occurred in the areas of fiscal policy, privatization, small-scale industry, agriculture, and labor law.[xvi]

At the national level, India’s climate change policies are subsumed in its economic-industrial and human development policies, which come first. Local policies have had some success in limiting significant urban air pollution problems. Substantial improvements in local air quality in Delhi, for example, have resulted from recent government programs to improve the quality of petrol and diesel fuels, introduction of emissions standards for vehicles, and conversion of buses and three-wheelers to compressed natural gas (CNG) fuel—but Kolkata and other metropolitan centers experience worsening air quality, with increasing combustion of fossil fuels contributing to carbon dioxide emissions. Generally speaking, climate change policy has been reactive rather than proactive and focused largely on the energy sector. According to reports from the Organization for Economic Cooperation and Development (OECD) and the Pew Center,[xvii] India, through normal policy developments, is "making significant progress in limiting greenhouse emissions" (i.e., from what emissions might have been) through energy efficiency improvements and environmentally friendly energy development. Also, India is participating in the Clean Development Mechanism of the United Nations Framework Convention on Climate Change (UNFCCC) and actively participating in the development of a proposed UNFCCC mechanism called Reducing Emissions from Deforestation and forest Degradation (REDD). The National Clean Development Mechanism Authority (NCDMA) is housed in the Ministry of Environment and Forests (MoEF); CDM India has operated since December 2003 as the Designated National Authority (DNA). More aggressive measures, India feels, should be financed by developed nations as they lead by reducing their own emissions and engaging in clean technology transfer, in accordance with the 1992 UNFCCC (ratified by 192 countries).

Internationally, India has played a key role in climate negotiations at several points. India broke the impasse at the first Conference of the Parties by leading the development of a common statement that became the basis for the Berlin Mandate. More recently, India hosted the eighth Conference of the Parties to the Framework Convention on Climate Change in 2002. India, bolstered by nongovernmental organizations such as the Tata Energy Research Institute (TERI) and the Centre for Science and Environment (CSE), focuses on per capita emissions (low in India and high in most developed countries) and on cumulative emissions (also low in developing countries and high in developed countries), as the indicators that developed countries should undertake mitigation first. Government officials press developed nations to establish and conform to emissions reduction goals and to engage in technology transfer to developing countries.

CSE rebutted the second World Resources Report,[xviii] making the distinction between "subsistence emissions" of the poor (mostly in developing countries) and the "luxury emissions" of the rich (mostly in developed countries). CSE has also characterized "green" policies dictated by the North (e.g., debt-for-nature swaps) as unwarranted interference in other nations, as exacerbating inequality among nations, and as likely to foster unsustainable management.

Projected Regional Climate Change

The current climate of India is highly diverse, ranging from the subfreezing Himalayan winters to the tropical climate of the south. The states of Assam and West Bengal experience extremely damp, rainy, and humid conditions, while the regions of Rajasthan and Gujarat make up part of the arid Great Indian Desert. Based on precipitation and temperature, India can be divided into six climatic regions: the Himalayas, Assam and West Bengal, the Indo-Gangetic Plain, the Western Ghats and coast, the Deccan (the interior of the Peninsula south of the Narmada River), and the Eastern Ghats and coast.[xix]

The Indian Meteorological Service divides the year into four seasons, two of which are characterized by monsoon conditions. Winter occurs from December through February, when conditions are generally relatively dry and cool. March through May is considered to be summer, as the conditions are usually hot and dry. During this period temperatures throughout non-Himalayan India reach the upper 30s°C and can reach as high as 48°C during the day in the pre-monsoon months.

The southwest monsoon season occurs from June through September, when the predominating southwest maritime winds bring rains to most of the country. One branch of the southwest monsoon, known as the Arabian Sea monsoon, generally breaks on the west coast early in the season and spreads across South Asia by early July. The other, known as the Bay of Bengal monsoon, spreads over Assam during June and travels along the Indo-Gangetic Plain toward New Delhi, merging with the Arabian branch to bring rains farther north. The southwest monsoon provides almost 80 percent of the annual rainfall to most of the country. It is critically important to agricultural production; predictions of its timing are used by agronomists and farmers to determine optimal dates for plantings.

The northeast monsoon occurs in October and November as the southwest monsoon retreats. The states of Tamil Nadu, Karnataka, and Kerala receive most of their rainfall from the northeast monsoon during November and December. (See Figure 1 for a map of Indian states and http://en.wikipedia.org/wiki/File:India_climatic_zone_map_en.svg for climate regions.)

Interannual climate variability is linked to a global-scale, naturally occurring phenomenon known as the El Niño/Southern Oscillation (ENSO) cycle.[2] ENSO can explain some of the inter-annual rainfall variability over the subcontinent of India and can affect the location and activity of tropical storms. Analysis of observational data shows a significant correlation between ENSO and tropical circulation and precipitation such that there is a tendency for less Indian summer monsoon rainfall in El Niño years and above-normal rainfall in La Niña years. However, the effect is not linear. The ability to accurately predict the timing and occurrence of the ENSO phenomenon is extremely important to agricultural production.

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[2] The terms El Niño and La Niña represent opposite extremes of the ENSO cycle. El Niño refers to the above-average sea-surface temperatures that periodically develop across the east-central equatorial Pacific. It represents the warm phase of the ENSO cycle and is sometimes referred to as a Pacific warm episode. La Niña refers to the periodic cooling of sea-surface temperatures across the east-central equatorial Pacific. It represents the cold phase of the ENSO cycle, and is sometimes referred to as a Pacific cold episode.

Figure 1. Indian States.

Climate Observations

Global observations suggest that climate change is well under way. At continental, regional, and ocean basin scales, numerous long-term changes in climate have been observed, including widespread changes in precipitation amounts; ocean salinity; wind patterns; and aspects of extreme weather including droughts, heavy precipitation, heat waves, and the intensity of tropical cyclones. Studies of the tropical Indo-Pacific region show unusual warmth in the 20th century, and many isotope records show a trend toward warmer conditions in the tropical Indian Ocean. In most multi-centennial coral series, the late 20th century is shown to be warmer than any time in the past 100 to 300 years.

Some studies have suggested that the South Asian (Indian) monsoon, in the drier areas of its influence (northwest India), has recently reversed its millennia-long orbitally driven, low-frequency trend toward less rainfall. This recent reversal in monsoon rainfall also appears to coincide with a synchronous increase in inferred monsoon winds over the western Arabian Sea, a change that could be related to increased summer heating over and around the Tibetan Plateau.

Globally, estimates of the potential destructiveness of tropical storms and hurricanes show a substantial upward trend since the mid-1970s, with a trend toward longer storm duration and greater storm intensity. Storm activity is generally correlated with tropical sea surface temperature.

The distributions of global minimum and maximum temperatures have shifted to higher values, consistent with overall warming.[xx] More warm extremes imply an increased frequency of heat waves. However, cold extremes have warmed more than the warm extremes over the past 50 years. Further indications include the observed trend toward fewer frost days associated with the average warming in most mid-latitude regions. A prominent indication of a change in extremes is the evidence of increases in heavy precipitation events over the mid-latitudes in the past 50 years, even in places where mean precipitation amounts are not increasing. For very heavy precipitation events, increases are reported as well, but results are available for only a few areas.

Recent warming in sea surface temperatures (SSTs) is strongly evident at all latitudes, although there are inter-hemispheric differences. Much of the surface of the Indian Ocean has warmed since 1955, with the major exception of the 5°S to 20°S latitude belt. The Southern Ocean (south of 35°S) in the Atlantic, Indian, and Pacific sectors has generally warmed. The regions that exhibit cooling are mainly in the shallow equatorial areas and in some high-latitude regions. In the Indian Ocean, cooling occurs at subsurface depths centered on 12°S (South Equatorial Current) at 150 m depth and in the Pacific centered on the equator and 150 m depth. In the tropical and eastern subtropical Indian Ocean (north of 10°S), warming in the upper 100 m is consistent with the significant warming of the sea surface from 1900 to 1999. The surface warming trend during the 1900 to 1970 period was relatively weak but increased significantly in the 1970 to 1999 period, with some regions exceeding 0.2°C per decade. Models suggest that upper-ocean warming in the South Indian Ocean can be attributed to a reduction in the strength of the southeast trade winds and associated decrease in the southward transport of heat from the tropics to the subtropics.

Local and regional changes in the character of precipitation also depend a great deal on atmospheric circulation patterns determined by El Niño, the North Atlantic Oscillation (NAO),[xxi] and other patterns of variability. India’s rainfall features show strong variability but little in the way of a century-scale trend, even as the linear trends of rainfall decreases for 1900 to 2005 were 7.5 percent in western Africa and a similar decrease was observed when averaged over the broader southern Asia region as a whole. Over much of northwestern India, the 1901 to 2005 period shows precipitation increases of more than 20 percent per century, but the same area shows a strong decrease in annual precipitation in the 1979 to 2005 period.

Very dry land areas across the globe have more than doubled in area since the 1970s, an observation that has been associated with precipitation decreases related to ENSO and with subsequent increases primarily due to surface warming. The tendency of the warming to be more pronounced in winter is a conspicuous feature of the observed temperature trends over India, one that is likely to continue.

Climate Predictions (Modeling)

While Global Circulation (or Climate) Models (GCMs) can be used to infer climate changes in specific regions, it is far preferable to develop models that have a high resolution sufficient to resolve local and regional scale changes. There are many challenges in reliably simulating and attributing observed temperature changes at regional and local scales. At these scales, natural climate variability can be relatively greater, making it harder to distinguish long-term changes expected due to external radiative forcings.[3]

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[3] Radiative forcings are changes in the net irradiance at the tropopause resulting from a change in an external driver of climate change, such as carbon dioxide or the output of the Sun. These changes in net irradiance are expressed as watts per meter squared (Wm^2).

The procedure of estimating the response at local scales based on results predicted at larger scales is known as "downscaling." The two main methods for deriving information about the local climate are (1) dynamical downscaling (also referred to as "nested modeling" using "regional climate models" or "limited area models") and (2) statistical downscaling (also referred to as "empirical" or "statistical-empirical" downscaling).[xxii] Chemical composition models include the emission of gases and particles as inputs and the simulation of their chemical interactions; global transport by the winds; and removal by rain, snow and deposition to the earth's surface.

Downscaled regional scale climate models rely on global models to provide boundary conditions for the region to be modeled. There are three primary approaches to numerical downscaling: (1) limited-area models, (2) stretched-grid models, and (3) uniformly high resolution atmospheric GCMs (AGCMs).

Regional Climate Model (RCM) projections for climate change in India were compared for eight models using several different IPCC scenarios at time intervals of 20 years. All models show positive trends of widespread warming (Figure 2), with warming more pronounced during winter and post-monsoon months compared to the rest of the year (i.e., seasonal changes) consistent with recent observations.

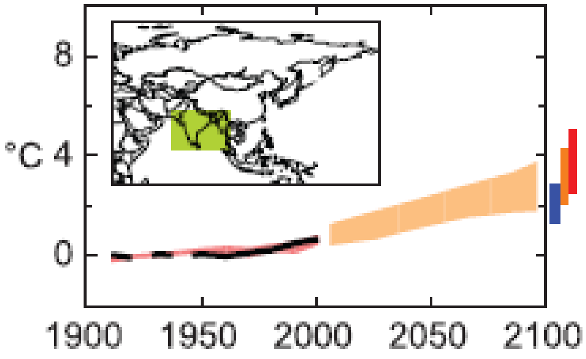

Figure 2. Temperature anomalies with respect to 1901-1950 for six Asian land regions 1906-2005 (black line) and as simulated (red envelope) by multi-model dataset (MMD) models. *Source:* Intergovernmental Panel on Climate Change (IPCC), *Climate Change 2007: the Physical Science Basis*, eds. S. Solomon, D. Qin, M. Manning, M. Marquis, K. Averyt, M.M.B. Tignor, H.L. Miller Jr. and Z. Chen (Cambridge: Cambridge University Press 2007): 882.

Although some models show a slight decrease in precipitation over all India during the first few decades of the study, all models show increased precipitation during the monsoon season by the year 2100, especially over the northwestern parts of India, an area that is currently very dry. One model projects that by 2050 there will be an overall decrease in the number of rainy days over all India but an increase in the number of one-day extreme rainfall events. The magnitudes and patterns of the projected rainfall changes differ significantly between models, probably due to their coarse resolution.

The Atlantic and Pacific Oceans are strongly influenced by natural variability occurring on decadal scales, but the Indian Ocean appears to be exhibiting a steady warming. Natural variability (from ENSO, for example) in ocean-atmosphere dynamics can lead to important differences in regional rates of surface-ocean warming that affect the atmospheric circulation and hence warming over land surfaces. New modeling efforts have shown improvements in climate forecasts in the southern hemisphere when the incidence of the Indian Ocean Dipole (IOD) is included.[xxiii] The IOD occurs periodically when there is a cold water upwelling in the eastern Indian Ocean, during which the eastern half of the ocean becomes much cooler than the western half.

The recent IPCC assessment report suggests that, in the future, circulation associated with the monsoon may slow down, but the moisture in the air may increase. However, the representation of the observed monsoon maximum rainfall along the west coast of India, northern parts of Bay of Bengal, and north India is poor in many models.

A comparison of four different GCM models applied to the Indian subcontinent[xxiv] found a significant spread in the summer monsoon precipitation anomalies. Soil moisture was determined to be an important parameter in model projections. Most models project increased precipitation during the monsoon season, particularly over the northwestern parts of India, with differences in the magnitudes of the increase from one model to the other. West central India shows maximum overall increase in rainfall. Extremes in both temperature and precipitation events are likely to increase out to 2030.

Including sulfate aerosols in the models reduces the regional climate sensitivity, but the greenhouse warming still dominates the changes at the larger scale and longer time scale. Models that include emissions of short-lived radiatively active gases and particles suggest that future climate changes could significantly increase maximum ozone levels in already polluted regions. Projected growth of emissions of radiatively active gases and particles in the models suggest that they may significantly influence the climate, even out to year 2100.[xxv] Atmospheric brown clouds, plumes of polluted air moving from the Asian continent out over the Pacific and Indian Ocean, may cause changes in the monsoon circulation and reduce summer monsoon precipitation in parts of South and East Asia.

Global models that are unable to include small-scale spatial geographical features and distortions of albedo feedbacks are also unable to project precipitation over the Himalayas. It is expected that the net effect of a warming climate will be an increase in the rainfall associated with the monsoon. Several models suggest that throughout Asia there will be an overall decrease in the December-February precipitation, an increase in the remaining months, and more intense rainfall over larger areas in the future.

Stabilization emissions scenarios assume future emissions based on an internally consistent set of assumptions about driving forces (such as population, socioeconomic development, and technological change) and their key relationships. These emissions are constrained so that the resulting atmospheric concentrations of the substance level off at a predetermined value in the future. For example, if one assumes the global CO_2 concentrations are stabilized at 450 parts per million (ppm) (the current value is about 380 ppm), the climate models can simulate the climate consistent with the emissions of greenhouse gases and short-lived species of this scenario. The climate model predictions can be used to assess specific regional impacts at this stabilization level.

A recent study of models from the Coupled Model Intercomparison Project showed that the models' response to a +1 percent/yr increase in CO_2 includes a substantial warming of tropical storm basin SSTs, enhanced upper-tropospheric warming relative to the surface warming, and little change in lower-tropospheric relative humidity. The study included climate change scenarios from nine different global coupled climate models as inputs to an idealized hurricane model. The results demonstrate that there is a significant sensitivity in the models to the choice of climate model and convective parameterization.

A more detailed discussion of the ability of the models to project regional climate changes can be found in Annex A.[xxvi]

Projections of Future Temperature and Precipitation

Current projections of climate change from the latest IPCC Assessment[xxvii] suggest increases in temperatures, precipitation rates, and the intensity of tropical storms over the Indian Ocean.

Most models either assume a doubling of CO_2 and their results can be compared using this assumption, or the models are run to the year 2100 and the results of the climate projections are assessed for that date. The IPCC has not included numerical model results specifically for the year 2030. Kumar et al.[xxviii] have modeled climate changes on the Indian subcontinent for intermediate scenarios at 2020 and 2050; however, only the results for the final scenario for 2080 have been published. An earlier study[xxix] used eight global models to project temperature and precipitation changes over all India per decade for three different emission scenarios. Although the tables presented in this reference are useful, the uncertainties, especially in the prediction of precipitation changes, are great.

Most AGCMS predict general warming and enhanced rainfall over India, with these changes becoming particularly significant by 2040.[xxx] Kumar et al. use the model Providing Regional Climates for Impacts Studies (PRECIS), developed by the Hadley Centre for Climate Prediction and Research, to yield projections for climate change during intermediate time scales (every 10 years until 2100); these projections can be averaged over model results to estimate climate change in 2030.[xxxi] The models project an average temperature increase over all India by the year 2030 of around 0.5°C, an increase comparable with that that has occurred over the globe during the 20th century. The maximum temperature increase (i.e., annual mean temperature change) is expected to occur over northern India, with a secondary maximum over the eastern peninsula. By the year 2100, the temperature increase could be on the order of 2-4°C, with a maximum increase in the northern region of 4°C.

A regional model recently developed at the Indian Institute of Tropical Meteorology (IITM) projected that, averaged over the country, India could face a temperature increase of 4°C by 2100. However, the model predicts that, because of the longer time scales for system-wide changes in atmosphere-ocean interactions, a delay in the increase in monsoon rainfall will occur,[xxxii] resulting in drought in some areas.

Seasonal Weather Patterns (Monsoons)

Monsoon rains account for most of India's annual rainfall. Monsoons are generally defined as tropical and subtropical seasonal reversals in both the surface winds and associated precipitation. The strongest monsoons occur over the tropics of southern and eastern Asia and northern Australia as well as parts of western and central Africa. Rainfall is the most important monsoon variable because the associated latent heat release drives atmospheric circulations and because rainfall plays a critical role in the global hydrological cycle and is vital to socioeconomic impacts.

Most global models suggest that the Indian monsoons will intensify with a warming climate.[xxxiii] Since the continental-scale land-sea thermal contrast is expected to become larger in summer and smaller in winter, one would expect that in the future the summer monsoon will be stronger and the winter monsoon will be weaker than they are presently. However, some models predict that a pronounced warming over the tropics will result in a weakening of the Asian summer monsoon circulations due to a reduction in the meridional thermal gradients between the Asian continent and adjacent oceans.

The global monsoon system embraces an overturning circulation that is intimately associated with the seasonal variation of monsoon precipitation over all major continents and adjacent oceans. The Asian monsoon can be divided into the East Asian and the South Asian or Indian monsoon systems. Although the Indian monsoons recur each year, their irregularity at a range of time scales from weeks to years depends on feedback from the ocean in ways that are not fully understood. Intra-seasonal variability is associated with the Monsoon Intra-Seasonal Oscillation (MISO) and the Madden-Julian Oscillation (MJO), which are long-lasting weather patterns that evolve in a systematic way for periods of four to eight weeks. On an interannual and decadal scale, statistical methods have shown that, while there are periods of high correlation between ENSO and monsoon variation, there are decades in which little or no association is apparent. The influence of ENSO on the position and strength of the subtropical high in the North Pacific influences both typhoons and other damaging heavy rainfall events and has been implicated in observed inter-decadal variations in typhoon tracks. This suggests that the spatial structure of warming in the Pacific will be relevant for changes.

For South Asia, the monsoon depressions and tropical cyclones generated over the Indian seas modulate the monsoon anomalies. For East Asia, the monsoonal circulations are strengthened by extratropical cyclones energized in the lee of the Tibetan Plateau and by the strong temperature gradient along the East Coast.

Although attention is often focused on the frequency or number of storms, the intensity, size, and duration are much more important. From an observational perspective, then, key issues are the tropical storm formation regions; the frequency, intensity, duration, and tracks of tropical storms; and associated precipitation. All of these can be influenced by climate teleconnections,[xxxiv] especially those such as the Indian dipole oscillation (IOD) and the Southern Annular Mode (SAM) Index. Annular modes are hemispheric scale patterns of climate variability.[xxxv] SAM is linked to variations in temperatures over Antarctica, sea-surface temperatures throughout the Southern Ocean, and the distribution of sea-ice around the perimeter of Antarctica.

New evidence indicates that increased aerosol loading[4] in the atmosphere may also have strong impacts on monsoon evolution through changes in local heating of the atmosphere and land surface. Polluted air can also have an effect on local circulation patterns. Heating of a lofted dust layer in the Tibetan Plateau could act as an elevated heat pump to strengthen the Asian summer monsoon circulation and cause a local increase in precipitation, despite the global reduction of evaporation that accompanies the aerosol-induced reduction in shortwave radiation

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[4] Aerosols are very small particles that influence the climate in several ways. They are both emitted (e.g., via dust storms or from smokestacks) and form in the atmosphere.

at the surface. The dust-induced thermal contrast changes between the Eurasian continent and the surrounding oceans are postulated to trigger or modulate a rapidly varying or unstable Asian winter monsoon circulation, with a feedback to reduce the dust emission from its sources.

Sea Level Changes

A significant fraction of sea level rise is due to thermal expansion of a warmed ocean (as much as 0.3 to 0.8 m over the past century, according to the 2007 IPCC report). Geographic patterns of sea level rise are due mainly to changes in the distribution of heat and salinity in the ocean, resulting in changes in ocean circulation. Precise satellite measurements since 1993 show that the largest sea level rise since 1992 has taken place in the western Pacific and eastern Indian Oceans, with the potential for significant impacts on the east coast of India. The 2004 Indian National Communication to the UNFCCC states that sea level rise is highest in the Gulf of Kutch (Gujarat) and on the coast of West Bengal.[xxxvi] There is a large interannual variability in sea level rise associated with patterns of coupled ocean-atmosphere variability, including ENSO and the NAO.

Projected patterns of sea level rise display more similarity across models than in past assessments. Common features include a narrow band of pronounced sea level rise stretching across the southern Atlantic and Indian Oceans. Sea level is projected to rise between the present (1980-1999) and the end of this century (2090-2099) by 0.35 m (0.23 to 0.47 m). Due to ocean density and circulation changes, the distribution will not be uniform.

Agricultural Growing Periods

Many regions of India already face water scarcity. Productive agricultural regions in the North depend on the spring snowmelt to replenish regional water supplies. Climate models predict an earlier snowmelt, which could have a significant effect on agricultural production, especially if the levels of moisture in the soils are reduced during the growing season.

The retreat of snow and ice cover in and around the Himalayas is already having a drying effect on these regions. A recent study of the melting Naimona'ny glacier in the Himalayas, which provides water to the Indus, and Brahmaputra Rivers shows that the glacier has melted so much that the exposed surface of the glacier dated to 1944.[xxxvii]

A study of glaciers in the region shows that they are now receding at an average rate of 10-15 meters per year.[xxxviii] Himalayan glaciers collect water during the monsoon season and release it during the dry season, providing irrigation water for crops. If the rate of glacial melt increases, flooding is likely to occur in the river valleys fed by the glaciers. Later, as the river flows decrease to below previous rates, many people may be left without sufficient drinking water or water for irrigating crops.

Decreasing trends in evapotranspiration during recent decades are evident in records, even though such records are sparse. This is likely due to decreased sunshine duration related to increases in air pollution, atmospheric aerosols, and increases in cloud cover. An accelerating trend in sulfate deposition has been observed in Himalayan glaciers and is probably due to increased sulfur dioxide emissions from the increasing energy demand throughout Asia. The concentration of sulfate deposited in the glaciers in the past 50 years exceeded that for any prior 50-year period in the last millennium.[xxxix]

A model to predict changes in river flows due to future glacial melt from climate change was developed by the Centre for Ecology and Hydrology in the United Kingdom. Under different climate scenarios, the model predicts that in the upper Indus there will be an initial increase of between +14 percent and +90 percent in mean flows (compared to baseline) over the first few decades of the 100-year incremental scenario runs. By decade 10, river flows will decrease between –30 percent and –90 percent of baseline.[xl]

During the Indian Ocean Experiment[xli] that focused on emissions of human-generated aerosols from the Indian sub-continent, local forcing at the surface was observed to be significantly stronger than that at the top of the atmosphere. These results indicate that absorption of solar radiation by aerosols, primarily black carbon in the atmospheric column, is of great significance. It has been suggested that absorbing aerosols may have masked up to 50 percent of the surface warming in South Asia from the global increase in greenhouse gases. In cases where aerosols act to suppress rainfall (the second aerosol indirect effect), drier conditions tend to induce more dust and smoke due to the burning of drier vegetation, affecting both regional and global hydrological cycles and agricultural production. However, more research is needed to understand the combined effects of aerosols and dusts, which may influence the monsoon circulation and hydrological cycle in different ways.

Climatic Events

Extremes are the infrequent events at the high and low end of the range of values of a particular variable. The probability of occurrence of values in this range is called a probability distribution function (PDF) that for some variables is shaped similarly to a “Normal” or “Gaussian” curve (the familiar bell-shaped curve).

People affected by an extreme weather event (e.g., the heavy rainfall in Mumbai in July 2005) wonder whether climate changes due to human influences are responsible. It is difficult to attribute any individual event to a change in the climate. In most regions, instrumental records of variability typically extend only over about 150 years, so there is limited information to characterize how extreme rare climatic events could be. Further, several factors usually need to combine to produce an extreme event, so linking a particular extreme event to a single, specific cause is problematic. In some cases, it may be possible to estimate the anthropogenic contribution to such changes in the probability of occurrence of extremes.

As the climate changes and SSTs continue to increase, the conditions that cause tropical storms to form are no longer the same. Higher SSTs are generally accompanied by increased water vapor in the lower troposphere; thus, the moist static energy that fuels convection and thunderstorms is also increased. Hurricanes and typhoons currently form from pre-existing disturbances only where SSTs exceed about 26°C; so, as SSTs have increased, the areas over which such storms can form are potentially expanded. However, many other environmental factors also influence the generation and tracks of disturbances.

The 2007 IPCC assessment concluded that there was a risk of increased temperature extremes in India, with more extreme heat episodes in a future climate. This result has been confirmed and expanded in more recent studies. Future increases in temperature extremes are projected to follow increases in mean temperature over most of the world except where surface properties (e.g., snow cover or soil moisture) change. There is still much debate over whether there is likely to be an increase in tropical cyclone intensity.

Changes in tropical storm and hurricane frequency and intensity are often masked by large natural variability. ENSO greatly affects the location and activity of tropical storms around the world. Globally, estimates of the potential destructiveness of hurricanes show a substantial upward trend since the mid-1970s, with a trend toward longer storm duration and greater storm intensity, and this activity is strongly correlated with tropical SSTs. One study found a large increase in numbers and proportion of hurricanes reaching categories four and five globally since 1970, even as the total number of cyclones and cyclone days decreased slightly in most basins. The largest increase was in the North Pacific, Indian and Southwest Pacific Oceans.

Improved models, ones that prescribed convection constraints based on the relative humidity, were able to simulate the variability and extremes of rainfall quite well over most of India when compared to satellite-derived rainfall but had a tendency to overestimate heavy rainfall events in central India.

Several recent studies have addressed possible future changes in heat waves and found that in a future climate, heat waves are expected to be more intense, longer-lasting and more frequent. Based on an eight-member multi-model ensemble, heat waves are simulated to have increased for the latter part of the 20th century and are projected to increase globally and over most regions.

Impacts of Climate Change on Natural Ecosystems

Observed Changes

An analysis of seasonal and annual surface air temperatures for India, using data for 1881–2001 for 25 or more stations, shows a significant annual mean warming of 0.68°C per hundred years. Most of the warming occurs in the post-monsoon and winter seasons. The monsoon temperatures do not show a significant trend in most parts of the country except for a significant negative trend over northwest India. Maximum daytime temperatures show more of a trend than minimum nighttime temperatures,[xlii] in contrast to general expectation.

Water supply is changing. Almost 67 percent of the glaciers in the Himalayan mountain ranges, the source of major rivers in India, have retreated in the past decade.[xliii]

For India, the IPCC[xliv] reports increased frequency of hot days and multiple-day heat waves in the past century, with more deaths attributable to heat stress in recent years. Consecutive droughts in 1999 and 2000 led to a sharp decline in water tables in the northwest, and 2000-2002 droughts caused crop failures, leading to mass starvation and impacts on ~11 million people in Orissa.

Management decisions about natural hazards can cause conflicts. In 2002, under drought conditions in Andhra Pradesh, the state released dam water for electricity generation but not for irrigation. Poor farmers responded to such policies by smashing the pumps of their richer neighbors. Quarrels over water rights between states can be bitter, too. Tamil Nadu claimed that its neighboring state, Karnataka, violated agreements about sharing water from the Cauvery River.[xlv] Bangalore is facing acute water scarcity as it attempts to meet the drinking water needs of 7 million people in the city.[xlvi]

Public health is affected by currently experienced climate variability and change in the forms of heat and flooding. Between 1980 and 1998, 18 heat waves were reported in India; one in 1988 affected ten states and caused 1,300 deaths. Heat waves in Orissa, in the 1998-2000 period caused an estimated 2,120 deaths, and heat waves in 2003 in Andhra Pradesh caused more than 3,000 deaths.[xlvii] Flood-related increases in diarrheal disease have also been reported in India.[xlviii]

Observed trends in the mean sea level along the Indian coast indicate a rising trend of about 1 cm per decade, which is close to that recorded in other parts of the globe. Today, coastal regions in India and Bangladesh are subjected to stronger wind and flood damage than in the past because of stronger storm surges associated with tropical storms.[xlix]

Projected Changes: The Example of Forests

Based on the IPCC's *Special Report on Emission Scenarios*, a study by Ravindranath et al. (2006)[l] investigated the impacts of climate change on Indian forests into the year 2085 under two emission scenarios: A2 (740 ppm CO_2) and B2 (575 ppm CO_2). Globally, A2 is the more extreme scenario, representing a growing human population and slower and inequitable economic development whereby atmospheric CO_2 concentration is projected to double by 2050 and is likely to increase to 740 ppm by 2085. B2 represents moderate population growth, intermediate levels of economic development, adoption of environmentally sound technologies, and greater social equity.

Using the B2 scenario projections and Forest Service of India's categories of forests, a pattern emerges: colder forests are subject to a larger increase of about 3°C, while the Western Ghat evergreen forests become warmer by only about 2.4°C on average—compared to the national average of 2.9°C. For the A2 scenario, the magnitudes of the impacts are larger. Most of the forests show an increase of about 4°C with the northern temperate forests undergoing a temperature increase of around 4.6°C. Western Ghats evergreen, semi-evergreen, and mangrove forest types show the least impacts under both A2 and B2 scenarios.

Even with a conservative temperature increase of 1–2°C, most ecosystems and landscapes will be impacted through changes in species composition, productivity and biodiversity. Impacts to nearly 200,000 forest villages—naturally heavily dependant on forest resources—will be innumerable. Impacts to the country as a whole are also projected by way of economically important forest types, such as *Tectona grandis*, *Shorea robusta*, bamboo, upland hardwoods and pine. A clear possibility of a large-scale shift in forest types in India is projected for the period 2070 to 2100, with adverse implications for biodiversity and a nearly 70 percent increase in net primary productivity of forest types, with implications for biomass production and timber markets.

India's forests are already changing because of socioeconomic pressures; virgin forest areas are less dense and monocultures and plantations are preferred to native species. These conditions will be greatly exacerbated by climate change. Specifically, biodiversity is likely to be reduced under the projected climate scenarios representing changes or shifts in forest or vegetation types, forest dieback during the transient phase, and different response changes of species to climate changes even when there is no change in forest type.[li]

Impacts of Climate Change on Human Systems

Energy System

Primary energy demand in 2005 was roughly equivalent to that of Japan—but of course with many more people, India's per capita demand remains at about one-tenth of the OECD average. However, Indian demand is growing at a fast pace, 3.2 percent per year (2000-2005).[lii] The International Energy Agency (IEA)[liii] projects India's primary energy demand to more than double by 2030 in a reference scenario (i.e., no policies to slow demand); this projection is attributable largely to a projected annual growth rate for GDP of 6.3 percent. The primary energy demand growth areas will be industrial (mostly steel) and transport (although two- and three-wheelers will still be over half of vehicle stock). In this scenario, India will become the world's third-largest carbon dioxide emitter by 2030, although per-capita emissions will still be comparatively low.

Inequality is such an issue in the energy sector that the IEA devoted a chapter to it, "Focus on Energy Poverty." [liv] Approximately 412 million people are still without access to electricity in India. The use of fuelwood and dung for cooking and heating causes more than 400,000 premature deaths annually, mostly of women and children. Income disparities account for most of the energy access disparities, but other barriers include "unreliable energy service delivery, ineffective and regressive subsidies, gender discrimination in policy planning, inadequate information about the health impacts of current fuels and technologies, and administrative hurdles in getting connections." [lv] "Energy poverty" is one aspect of a concern in India that its booming economic conditions have benefited the "haves" but not the "have-nots."

India's current electrical system runs mostly on domestic coal: 82.7 percent fossil fuel, 14.5 percent hydropower, and 3.4 percent nuclear.[lvi] The transportation sector runs mostly on imported oil; domestic production is 785,000 bbl/day against a demand of 2.45 million bbl/day (2004 estimate).[lvii] OECD/IEA characterized the overall energy system as fueled "largely by coal and combined renewables and waste, with much smaller but growing shares of oil, gas, nuclear, and hydro."[lviii] Future increases in energy production will likely include the following:

- Domestic coal—although deposits are located at some distance from population centers and the coal is of low quality. (Higher quality coal is imported for steel making; India is the seventh-largest steel producer in the world.[lix]) Coal gasification could also be used to make diesel fuel.[lx] However, the use of coal contributes to anthropogenic climate change and bad air quality, so pressures to reduce greenhouse gas and other emissions could limit both options for coal use in India, unless carbon dioxide capture and storage technologies could be implemented.[lxi]
- Imported oil and gas—with associated issues of investing in oil fields, exploitation rights, and refineries in Myanmar, Sudan, Iraq, Russia, Vietnam, Venezuela, and Libya,[lxii] as well as raising the problematic prospect of a gas pipeline running through either Iran and Pakistan or Turkmenistan, Afghanistan, and Pakistan.
- Nuclear power—in part as a fruit of the 2005 "strategic partnership" with the United States, raising concerns about nuclear nonproliferation.
- Renewable sources—such as biomass fuels (waste and purpose-grown crops) and hydropower. Residential use of biomass (fuelwood, dung, and agricultural waste) is projected to change from a current 54 percent share to 12 percent in urban households, but a smaller 92-to-79 percent decline in rural households still means that the absolute amount of biomass used will increase. Biofuel crops, like other crops, will be affected by climate change;[lxiii] hydropower, like other water uses, will be subject to changes in precipitation under climate change.
- Domestic gas reserves—with 2002 and subsequent discoveries in the Krishna-Godavari basin (in Andhra Pradesh on the east coast) and more discoveries expected.[lxiv]

In all of these areas, advanced technologies will be essential to increasing production and meeting environmental regulations, including those related to climate change mitigation and adaptation. The Indian Government has introduced clean coal technologies like coal washing and the use of cleaner and less carbon-intensive fuels, e.g., liquefied petroleum gas (LPG) for automobiles and motor spirit-ethanol blending projects in selected states.[lxv]

Economic Growth and Development

Since 1990, India as a country has moved aggressively from a centrally planned economy to private ownership of businesses and trade liberalization. It has "developed a diversified industrial base and sophisticated financial sector. Its software subsector—one of the most dynamic in the world—has experienced a sustained and rapid growth."[lxvi] Over the past 25 years, the annual growth rate has been 6 percent, accelerating to a five-year annual average of 8.8 percent,[lxvii] investment at 30 percent of GDP, and booming foreign direct investment. India has made substantial strides in fostering human capital by reducing infant mortality, increasing life expectancy, and improving literacy. The central, democratic government provides stability and some curbs to unbridled free market-ism (or barriers to growth in an alternative characterization), and hordes of entrepreneurs provide the impetus for growth.

On the positive side, India's democracy results in equity slightly higher than the global average. The dependency ratio (the percentage of the population dependent on the percentage of the population in the work force) is relatively high, indicating that many people are available for the work force, supporting relatively few people other than themselves.

However, the poor condition of people engaged in agriculture and/or born into lower castes reduces the robustness of the overall economy. Climate change, adding to existing problems of the agricultural system, may worsen conditions for the large poor segment of the population enough to severely tax the economic and industrial resources of the central and state governments.

Thus, the impacts of climate change are likely to be felt first and foremost in the agricultural sector and associated water availability, with many people affected by lower food productivity (e.g., hunger, malnutrition, and its consequences for education and productive economic life) and burdens on the central and state governments in dealing with smallholders and landless workers who will require assistance. Educational and employment inequalities will exacerbate these conditions. Some (or many) of these workers will migrate to urban areas, placing stress on cities. The need to add to or replace infrastructure affected by climate change (e.g., in the energy and transportation sectors, as well as irrigation systems) will present additional economic costs. Finally, migrants, particularly from Bangladesh, will affect India's economy by providing competition for low cost labor.

Food Production and Drinking Water Supply

Agriculture and water are inseparable issues, as almost all the water use in India is for irrigation to support high productivity in agriculture. Thus, both the monsoon onset and active/break phase mean a great deal to the agriculture sector. Research indicates that the monsoon active/break phase is related to a tropical phenomenon called the Madden Julian Oscillation (MJO), which has a periodicity of 30-70 days, with a predictability of 20-30 days. Predicting the MJO has important implications to predicting subseasonal[5] rainfall variability. If farmers sow too early and the crop needs water when the monsoon break phase occurs, the whole crop is lost.

At the national level, India has abundant water resources for agriculture and drinking, as well as for cooking and sanitation uses. India withdraws 34 percent of its available water annually.[lxviii] However, at state and local levels, there are wide-ranging differences; overexploitation is already problematic and will likely become worse under climate change conditions.

Increasing temperatures and increased seasonal variability will likely cause Himalayan glaciers to melt more and more quickly, also leading to increasing danger from floods as glacial lakes burst out of their natural bounds. Changes over decades will include less flow in rivers fed today by snow and ice, with impacts on hydropower, urban water supply, and agriculture.[lxix] Although there is clear evidence of de-glaciation across the Himalayas, the effect on river flows is likely to be substantially different in different areas. The extent of the changes is very uncertain because, as Sengupta puts it, “River flow data is so scant and recent that it is impossible for scientists to predict how the current rates of glacial retreat will affect river volume.”[lxx]

There are major regions, including many of the most highly productive agricultural and industrial regions of India, where water scarcity is already felt in day-to-day life. The retreats of snow and ice cover are important for several local climates, especially those near the Himalayas. The drying effect of an earlier spring snowmelt and, more generally, the earlier reduction in soil moisture is a continuing concern. Already 15 percent of aquifers are in critical condition, a figure that is projected to increase to a “frightening” 60 percent by the year 2030.[lxxi]

Especially in important agricultural areas that have benefited from the Green Revolution, irrigation has led to exploitation of groundwater resources—e.g., 94 percent in Punjab, 84 percent in Haryana, 60 percent in Tamil Nadu, and 51 percent in Rajasthan.[lxxii] Farmers who borrow to dig bore wells for crop irrigation may find that when groundwater tables decline, they cannot repay their loans; some probably will commit suicide. Groundwater depletion has been accelerated by the provision of free or subsidized electricity for agriculture: subsidized rates on irrigation pumps, some state-level free power policies, and supports for agricultural consumers.[lxxiii] In many places (northwest India as well as Pakistan) irrigation has resulted in not only overexploitation of water resources, but also increased soil salinity, waterlogging, and siltation of river basins. These problems have been intensified by declining soil fertility, increasing pest damage, and decreasing genetic diversity in crops.[lxxiv]

Environmental and economic leaders[lxxv] have called for a second Green Revolution as rates of growth in agricultural production have slowed. This would place more pressure on water resources for irrigation. To partially compensate for increased water demand, the efficiency of irrigation systems can be improved. And in recent years, Water Users Associations (WUAs) have formed to conduct participatory irrigation management; [lxxvi] these may promote conservation and water use efficiency.

Rainfed agriculture (65 percent of cropped land)[lxxvii] will experience climate change impacts, too. Without irrigation, smallholder farmers and landless agricultural workers will likely face household food shortages and loss of livelihoods, requiring government assistance or even international aid, as well as pressures on cities to accommodate migrants from rural areas.

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[5] “Subseasonal” refers to any timescale shorter than a season.

Cultural Willingness to Change

Even if scientists knew unequivocally how climate change will manifest itself, traditional knowledge and practices would need to be accounted for and integrated into responses. Change is never as simple as providing information that immediately alters people's worldviews and ways of doing things. Selvaraju et al. (2004) explored approaches to help smallholder farmers to benefit from seasonal forecasting. Traditional knowledge in Avinashi (southern India) includes such rules of thumb as, "If it rains on the 10th of Adi (July) … the rainfall in the succeeding season will be good" and, "If the breeze is towards the east during July, the winter monsoon will be good; if towards south, the summer monsoon will be successful."[lxxviii]

Researchers found that farmers could use their knowledge about on-farm conditions in combination with probabilistic forecasts of rainfall (derived from Southern Oscillation Index data) to better meet their production objectives. The most important, and potentially largest-yielding decisions involve crop choice, sowing season, and planting density. However, these decisions can be the riskiest, coming at the beginning of the growth cycle, and "communicating the risk and opportunities of alternative management options is a major challenge."[lxxix] The final decisions always rest with the farmers, so participatory approaches are essential for this kind of cultural shift.

The Indo-Gangetic Plain, the "bread basket" of the region, comprises both highly modernized and traditional agriculture. The western region (the Punjab in Pakistan and India) is characterized by high productivity, high investment in infrastructure, and widespread use of fertilizers and groundwater irrigation. The eastern region (northeastern India and Bangladesh) exhibits low productivity, with poor infrastructure and low inputs of fertilizer and water, high risk of flooding, and chronic poverty. Rising population and climate change will have acombined impact in each of these regions.[lxxx] Changes and uncertainties in water supply (especially monsoonal changes) will affect irrigated and rainfed crops alike.

During the "wheat panic" of 2007, India purchased nearly 800,000 tonnes of wheat to buffer its reserves of this essential grain.[lxxxi] India sees keeping a buffer stock as a necessity in a country that, although theoretically food sufficient, has historically experienced shortages. Climate is one of the key components influencing agricultural production in small Indian farming systems, accounting for two-thirds of the variation in production. ENSO can explain some of the inter-annual rainfall variability that affects overall production. ENSO-based climate forecasts may be used to aid vulnerable smallholder agriculture production systems in India (see box above). However, unless projections of future climate change are able to account for how ENSO may change in a warming climate, these forecasts may not be able to prevent the significant agricultural losses that are possible.

Over the longer term, most studies project decreased yields in non-irrigated wheat and in rice and a loss in farm-level net revenue between 9 and 25 percent for a temperature increase of 2.0–3.5°C.[lxxxii] Considering a range of equilibrium climate change scenarios which project a temperature rise of 2.5°C to 4.9°C for India, Kumar and Parikh (2001) estimated that the impacts of climate change on Indian agriculture would be significant across the scenarios.[lxxxiii] They estimated that, with a temperature change of +2°C and an accompanying precipitation change of

+7 percent, farm-level total net revenue would fall by 9 percent, whereas with a temperature increase of +3.5°C and precipitation change of +15 percent, the fall in farm-level total net revenue would be nearly 25 percent. Aggarwal et al. explored agricultural adaptations to global environmental change in the Indo-Gangetic Plan, concluding that "new information and tools are needed to analyze the trade-offs between the joint socioeconomic and environmental goals, and possible adaptation strategies."[lxxxiv]

Livestock, too, will be affected by climate change. India has the largest livestock population in the world,[lxxxv] with animals used as milk producers (especially cattle and buffalo), draft animals, nutrient recycling (manure) and seeding, and as household capital, particularly in landless households. Heat stress lowers production and reproduction, reduces feed and fodder, and increases conditions favorable to disease. For example, outbreaks of foot and mouth disease in cattle are explained 52 percent (in Andhra) and 84 percent (in Maharashtra) by temperature, humidity, and rainfall; mastitis increases in dairy animals during hot and humid weather, which also is associated with increases in flies and cattle ticks.[lxxxvi]

Water availability will be a crucial factor in the continued viability of both crops and livestock, but management is diffuse. Under the Indian constitution, water is the responsibility of the states, not the central government. Thus, water management institutions at the state level have the biggest say in planning and allocation. [lxxxvii] At the national level, at least five ministries (Water Resources, Environment and Forests, Rural Development, Power, and Urban Development and Poverty Alleviation) are concerned with water, but no organizational mechanism exists to coordinate water management among these ministries. Moreover, efforts to adapt to more variability in water flows by constructing dams and catchments may increase tensions with Bangladesh and Pakistan.

While freshwater resources will be affected, the marine environment is and will be changing too. Fisheries stocks may collapse or move in the already-contested waters of the Indian Ocean, potentially affecting livelihoods and food supply for millions of people. The international ocean management regimes will require renegotiation.[lxxxviii]

Human Health

Currently, India's public health care system produces relatively poor health outcomes.[lxxxix] For India, Healthy Life Expectancy (HALE), which includes adjustment for time spent in poor health, is 53 years for children born in 2003.[xc] Despite perceived strengths of the national-level public health system (good expertise, written guidelines and standards, and network of research and training institutions), implementation and monitoring of services are weak. [xci] Funding for control of communicable diseases has been deemphasized since the 1980s; several infectious diseases, such a tuberculosis and malaria, have reemerged as public health care concerns.[xcii] In India, unplanned urbanization has contributed to the spread of *Plasmodium vivax* malaria and dengue.[xciii]

Climate change impacts on health include an expected increase in communicable diseases, such as malaria. Malaria is projected to move to higher latitudes and altitudes in India.[xciv] An assessment in India projected shifts in the geographical range and duration of the transmission window for *Plasmodium falciparum* and *Pvivax* malaria.[xcv]

Coping Capabilities in Facing Natural Disasters

India is highly vulnerable to natural disasters, and people live on marginal lands or in coastal and delataic cities where they are at greater risk. Floods, regional droughts, cyclones, and earthquakes affect millions of Indians.[xcvi]

In the area of disaster mitigation, much has been done to document conditions leading to vulnerability. For example, a *Flood Atlas of India* and a *Vulnerability Atlas of India* (1997, revised 2006) have been produced; the latter assesses the vulnerability of housing and infrastructure to earthquakes, cyclones and floods to improve zoning and construction.

In India, as in the United States, the primary responsibility for responding to disasters lies at the state level. The Disaster Management Act of 2005 set up the Natural Disaster Management Division in the Ministry of Home Affairs and proclaimed a new emphasis on disaster prevention. The United Nations Development Program[xcvii] has developed a plan for disaster preparedness and response that attempts to integrate government and other activities.

Many Indian states have limited resources and lack their own disaster management plans. Because of these factors, India's disaster response record has been mixed, with delayed response, lack of early warning systems and resources to undertake measures like mass evacuation, inadequate coordination among various government departments, failure to keep essential stores (e.g., sandbags, medicines, and life-saving equipment) on hand, and inadequate coordination with the Army and other service organizations, as well as donors.

As an example of disaster response, in 2007 the *New York Times* reported[xcviii] a United Nations official as saying that about 2,800 people in India, Bangladesh, Nepal, and Pakistan had died in monsoonal floods ("the worst in living memory"), from drowning, waterborne illnesses, snakebites or hunger. For survivors, the land damage meant there would be no near-term agricultural work for millions of landless laborers, leaving them to rely on the sporadic support of aid agencies and government relief organizations. The condition of the 31 million people affected in India was covered internationally but was not featured either in New Delhi newspapers or on national news channels.

Infrastructure is affected by climate hazards as well. For instance, 14 percent of the annual repair and maintenance budget of the newly built 760 km Konkan Railway in India is spent repairing damage to track, bridges, and cuttings due to extreme weather events such as rain-induced landslides. In spite of preventive targeting of vulnerable stretches of the line, operations must be suspended for an average of seven days each rainy season because of such damage.[xcix]

Systematic disaster preparedness at the community level has helped reduce death tolls; for instance, new warning systems and evacuation procedures in Andhra Pradesh after 1977 reduced deaths from coastal tropical cyclones to 10 percent of the 1977 total by 1997.[c]

Climate Change in the Neighborhood

The most obvious regional climate change impacts will likely concern water. The Indo-Gangetic Plain stretches from Pakistan's coast across northern India to almost the whole of Bangladesh. The Indus River drains in Pakistan, the Ganges in India, and Bangladesh. Rivers fed by Himalayan snow and ice provide irrigation water for this important agricultural area. India has water agreements with both neighboring countries, and alleged violations of these agreements have caused international disputes.

Bangladesh, in particular, depends upon India to allow sufficient fresh water to flow into Bangladesh for every water use and for preventing salt water intrusion. Sea level rise and management decisions have reduced freshwater flows and increased salt-water intrusion in the Indus delta and Bangladesh. This adversely affects the Sundarbans, the largest mangrove forest in the world, which is shared by India and Bangladesh. In addition, flooding has displaced thousands to millions of Bangladeshis, who are subject to outbreaks of xenophobic violence if they resettle in India.

Also potentially important are changes in Arabian Sea (e.g., loss of fresh water input due to channeling of Indus river water to agriculture in Pakistan, leading to biogeochemical changes in the Western Arabian Sea); the impacts of aerosols (the "Atmospheric Brown Cloud"), which may diminish winter precipitation in western India and in Pakistan); and changes in the carbon cycle in the Bay of Bengal.

Adaptive Capacity

The impacts of climate change will be felt differentially, depending upon how well a society can cope with or adapt to climate change, that is, its adaptive capacity. Adaptive capacity is defined by the IPCC as, "The ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences."[ci] Thus, adaptive capacity is distinguished from both climate change impacts and the degree to which those impacts affect the systems that are in place (as discussed in the previous sections).

Although the specific determinants (or "drivers") of adaptive capacity are a matter of debate among researchers, there is broad agreement that economic, human, and environmental resources are essential elements. Some components of this adaptive capacity are near term, such as the ability to deliver aid swiftly to those affected by, e.g., flooding or droughts. Other components include a high enough level of education so that people can change livelihoods, a quantity of unmanaged land that can be brought into food production, and institutions that provide knowledge and assistance in times of change. For instance, Yohe and Tol[cii] identified eight qualitative "determinants of adaptive capacity," many of which are societal in character, although the scientists draw on an economic vocabulary and framing:

1. The range of available technological options for adaptation.
2. The availability of resources and their distribution across the population.
3. The structure of critical institutions, the derivative allocation of decision-making. authority, and the decision criteria that would be employed.
4. The stock of human capital, including education and personal security.
5. The stock of social capital, including the definition of property rights.
6. The system's access to risk-spreading processes.
7. The ability of decisionmakers to manage information, the processes by which these decisionmakers determine which information is credible, and the credibility of the decisionmakers themselves.
8. The public's perceived attribution of the source of stress and the significance of exposure to its local manifestations.

Researchers have only recently taken on the challenge of assessing adaptive capacity in a comparative, quantitative framework. A global comparative study[ciii] of resilience to climate change (including adaptive capacity) was conducted using the Vulnerability-Resilience Indicators Model (VRIM—see box below).

Adaptive capacity, as assessed in this study, consists of seven variables (in three sectors), chosen to represent societal characteristics important to a country's ability to cope with and adapt to climate change:

Methodological Description of the Vulnerability-Resilience Indicator Model (VRIM)

The VRIM is a hierarchical model with four levels. The vulnerability index (level 1) is derived from two indicators (level 2): sensitivity (how systems could be negatively affected by climate change) and adaptive capacity (the capability of a society to maintain, minimize loss of, or maximize gains in welfare). Sensitivity and adaptive capacity, in turn, are composed of sectors (level 3). For adaptive capacity these sectors are human resources, economic capacity, and environmental capacity. For sensitivity, the sectors are settlement/infrastructure, food security, ecosystems, human health, and water resources. Each of these sectors is composed of one to three proxies (level 4). The proxies under adaptive capacity are as follows: human resource proxies are the dependency ratio and literacy rate; economic capacity proxies are GDP (market) per capita and income equity; and environmental capacity proxies are population density, sulfur dioxide divided by state area, and percent of unmanaged land. Proxies in the sensitivity sectors are water availability, fertilizer use per agricultural land area, percent of managed land, life expectancy, birthrate, protein demand, cereal production per agricultural land area, sanitation access, access to safe drinking water, and population at risk due to sea level rise.

Each of the hierarchical level values is comprised of the geometric means of participating values. Proxy values are indexed by determining their location within the range of proxy values over all countries or states. The final calculation of resilience is the geometric mean of the adaptive capacity and sensitivity.

- Human and Civic Resources
  - *Dependency ratio:* proxy for social and economic resources available for adaptation after meeting basic needs.
  - *Literacy:* proxy for human capital generally, especially the ability to adapt by changing employment.
- Economic Capacity
  - *GDP (market) per capita:* proxy for economic well-being in general, especially access to markets, technology, and other resources useful for adaptation.
  - *Income equity:* proxy for the potential of all people in a country or state to participate in the economic benefits available.
- Environmental Capacity

— *Percent of land that is unmanaged:* proxy for potential for economic use or increased crop productivity and for ecosystem health (e.g., ability of plants and animals to migrate under climate change).

— *Sulfur dioxide per unit land area:* proxy for air quality and, through sulfur deposition, other stresses on ecosystems.

— *Population density:* proxy for population pressures on ecosystems (e.g., adequate food production for a given population).

Adaptive capacity for a sample of 11 countries from the 160-country study is shown in Figure 3 (base year of 2005). There is a wide range of adaptive capacity represented by these countries; India ranks low, both in the sample and overall:

- Russia ranks 32nd and Libya 34th (in the highest quartile).
- Indonesia ranks 45th, Belize 48th, Mexico 59th, and China 75th (in the second quartile).
- The Philippines ranks 91st and India 119th (in the third quartile).
- Morocco ranks 136th and Haiti 156th (in the lowest quartile).

Any country-level analysis must take into account the comparative ranking of the country.

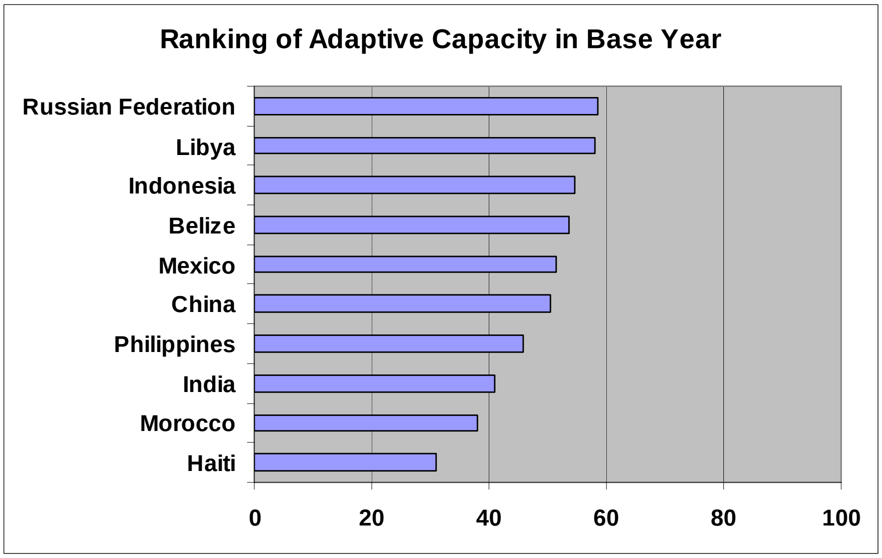


Figure 3. Sample of 11 countries' rankings of adaptive capacity (2005).

Figure 4 shows the contribution of each variable to the overall ranking (slight differences occurring because of the methodology (see box on page 25). India ranks low in comparison with Russia and China because of lower human resources (dependency ratio and literacy levels) than China, and both lower human resources and environmental capacity (non-managed land, emissions per total land area, and population density) than Russia.

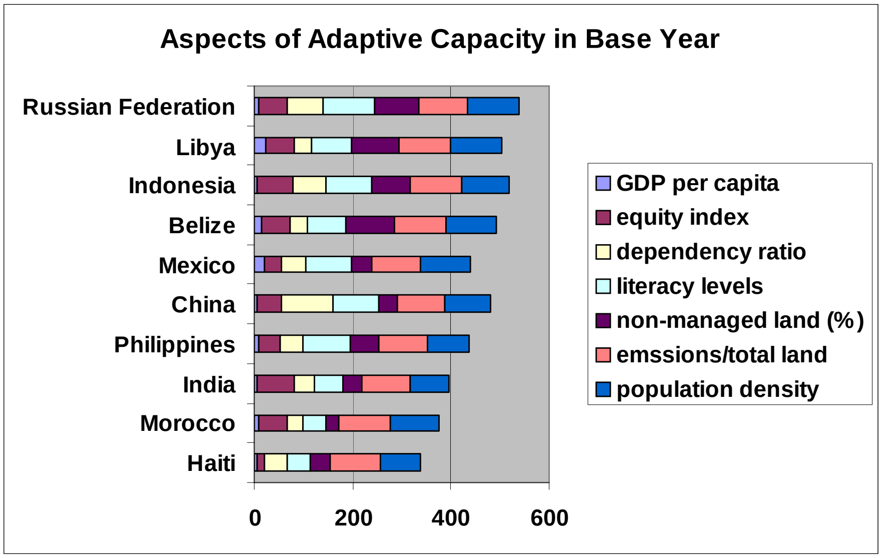


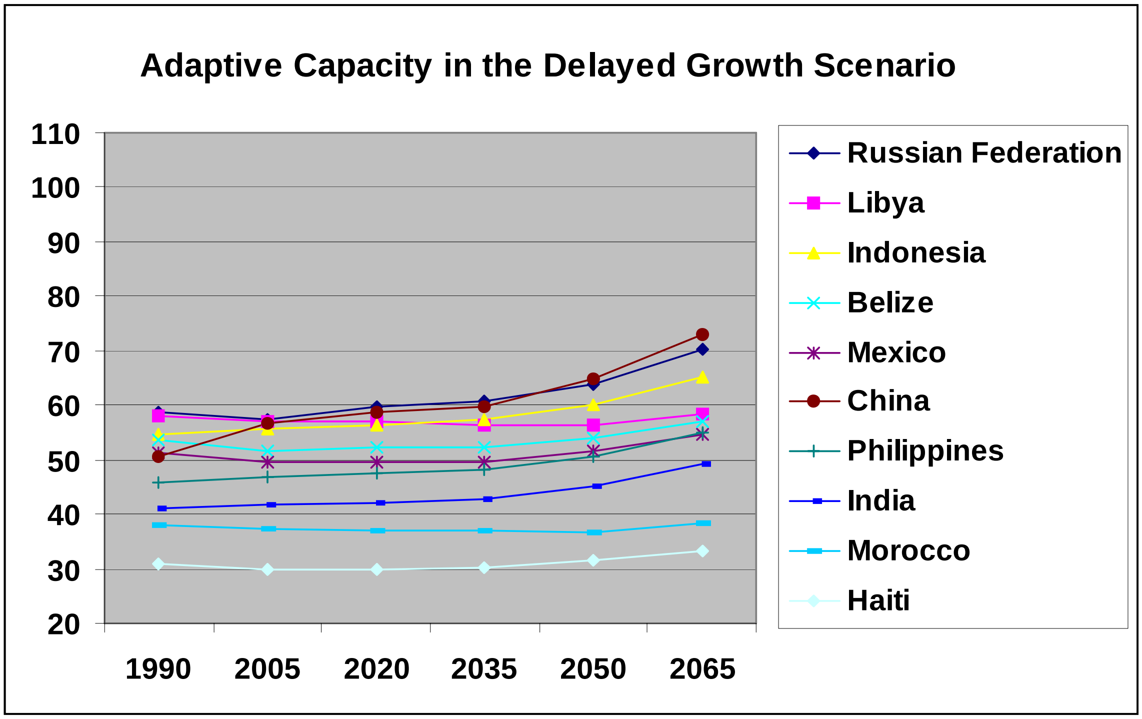
Figure 4. Variables' contributions to adaptive capacity rankings.

Figure 5 shows projected adaptive capacity growth over time for the 11-country sample. Projections are made for two scenarios; rates of growth are based on the IPCC's A1 scenario in its *Special Report on Emissions Scenarios*[civ]. Both scenarios feature moderate population growth and a tendency toward convergence in affluence (with market-based solutions, rapid technological progress, and improving human welfare). The scenarios used in this study differ in the rate of economic growth, one modeling high-and-fast economic growth, the other delayed growth. In the high-growth scenario, China overtakes Russia in adaptive capacity, but India retains its relatively low position throughout the entire period in both scenarios.

Strengths/Weaknesses in Adaptive Capacity Assessments

Even comparative measures of adaptive capacity only allow analysts to ask improved, more focused questions about area or local conditions that contribute to or reduce resilience. It is likely, for instance, that for particular places (e.g., states in India) important variables or domains are not included. For agricultural regions, this might include the extent of irrigation; for urban areas, better measures of education could be important. The measure of unmanaged land does not account for the potential usefulness of that land.

However, comparative measures such as these can be an important first step toward determining where to direct resources—for further analysis or additional factors.



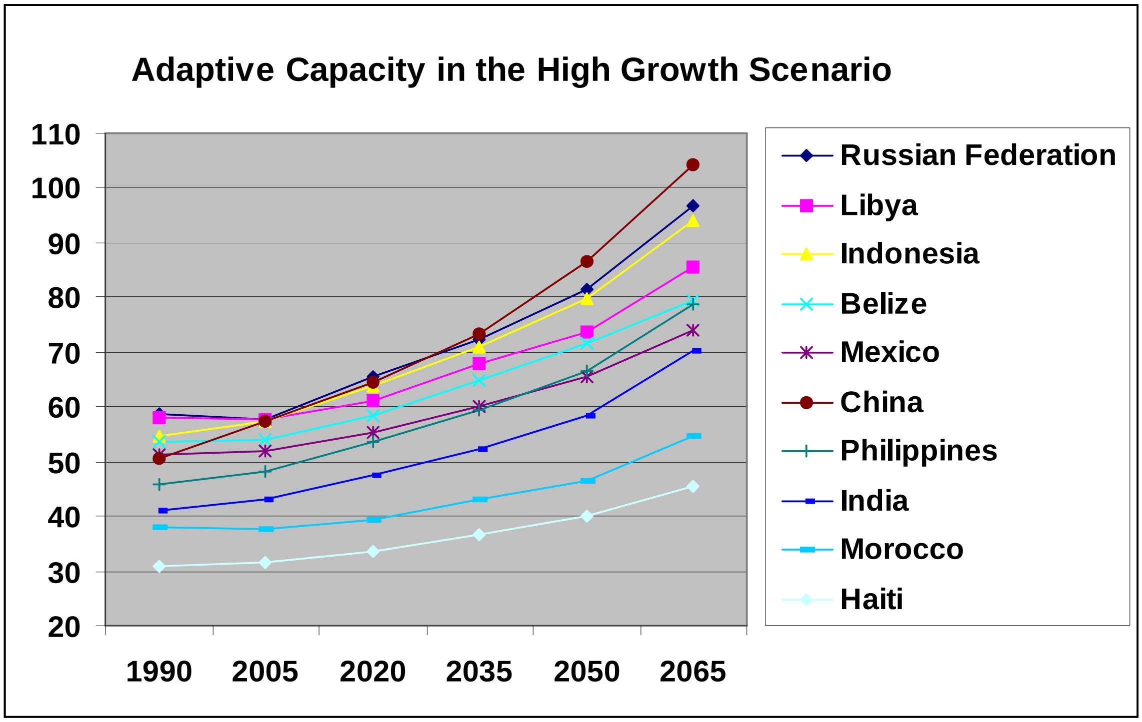


Figure 5. Projections of adaptive capacity for 11 countries.

Conclusions: High Risk Impacts

Agriculture

There are impacts to high-input, high-output agriculture as a result of various changes in the Indian climate, which will affect productivities negatively even as demand for food and other agricultural products rises because of both rising population and standard of living. On the other hand, millions of subsistence and smallholder farmers will experience immediate hardship and hunger because they will be less able to predict climate well enough to make adequate decisions about when to sow, what to grow, and how to time inputs.

Water

Glacier melt may yield more runoff in the short term but less in the medium and long terms. More severe storms (especially cyclones) will cause more damage to infrastructure and livelihoods and exacerbate saltwater intrusion[6] in storm surges. Changes in the timing and amount of monsoon rain will make the production of food and other agricultural products more uncertain, so that, even in good-weather years, farmers will be more likely to make decisions resulting in lower-productivity outcomes.

Energy

As India searches for additional sources of energy to meet rising demand, climate change mitigation efforts may constrain its use of indigenous and imported coal, oil, and gas, while development of nuclear energy will be slow at best and likely to encounter opposition. Other non-emitting technologies will require technology transfer and capacity-building.

Exacerbation of Inequality

In a country so prone to natural hazards, the welfare of those who are affected and who have limited means to recover will loom large under climate change, as a force that can change governments, strain public budgets, and foster unrest. The proportions are significant: about a quarter of the population lives on less than $1 a day; at least one-third face poverty, discrimination (often scheduled castes or tribes and Muslims), and lack of educational opportunities; and 60 percent are dependent upon agriculture for their livelihoods. Those who lack financial resources and adequate education and who depend on agriculture for sustenance and livelihood will be disadvantaged under climate change because they have few choices but continued dependence on shrinking or uncertain resources. India is attempting to reduce inequality by using quotas in government jobs and educational institutions;[cv] the National Rural Employment Guarantee Act (2005) also guarantees that at least one member of a rural household will have 200 days of work per year; and India's 11th five-year plan adopts the policy of sectoral, spatial, and socioeconomic growth that includes all people.

Migration

India receives immigrants from a number of countries. For instance, since 1960 the government has hosted approximately 110,000 de facto refugees from Tibet. The government considers Tibetans and Sri Lankans to be refugees and provides assistance to them. However, the government regards most other groups, especially Bangladeshis, as economic migrants and does not provide them with aid.[cvi]

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[6] Saltwater intrusion is the process in which saltwater flows inland into fresh water because saltwater is denser.

Annex A:

Accuracy of Regional Models

This is an excerpt from IPCC (2007), Chapter 11, Regional models; see IPCC 2007 for references. [7]

11.4.2 Skill of Models in Simulating Present Climate

Regional mean temperature and precipitation in the multi-model dataset (MMD) models show biases when compared with observed climate (Table 1). The multi-model mean shows a cold and wet bias in all regions and in most seasons, and the bias of the annual average temperature ranges from –2.5°C over the Tibetan Plateau (TIB) to –1.4°C over South Asia (SAS). For most regions, there is a 6°C to 7°C range in the biases from individual models with a reduced bias range in Southeast Asia (SEA) of 3.6°C. The median bias in precipitation is small (less than 10 percent) in Southeast Asia, South Asia, and Central Asia (CAS), larger in northern Asia and East Asia (NAS and EAS, around +23 percent), and very large in the Tibetan Plateau (+110 percent). Annual biases in individual models are in the range of –50 to +60 percent across all regions except the Tibetan Plateau, where some models simulate annual precipitation 2.5 times that observed and even larger seasonal biases occur in winter and spring. These global models clearly have significant problems over Tibet, due to the difficulty in simulating the effects of the dramatic topographic relief, as well as the distorted albedo feedbacks due to extensive snow cover. However, with only limited observations available, predominantly in valleys, large errors in temperature and significant underestimates of precipitation are likely.

South Asia

Over South Asia, the summer is dominated by the southwest monsoon, which spans the four months from June to September and dominates the seasonal cycles of the climatic parameters. While most models simulate the general migration of seasonal tropical rain, the observed maximum rainfall during the monsoon season along the west coast of India, the north Bay of Bengal, and adjoining northeast India is poorly simulated by many models (Lal and Harasawa, 2001; Rupa Kumar and Ashrit, 2001; Rupa Kumar et al., 2002, 2003). This is likely linked to the coarse resolution of the models, as the heavy rainfall over these regions is generally associated with the steep orography. However, the simulated annual cycles in South Asian mean precipitation and surface air temperature are reasonably close to the observed. The MMD models capture the general regional features of the monsoon, such as the low rainfall amounts coupled with high variability over northwest India. However, there has not yet been sufficient analysis of whether finer details of regional significance are simulated more adequately in the MMD models.

Recent work indicates that time-slice experiments using an AGCM with prescribed SSTs, as opposed to a fully coupled system, are not able to accurately capture the South Asian monsoon response (Douville, 2005). Thus, neglecting the short-term SST feedback and variability seems to have a significant impact on the projected monsoon response to global warming, complicating the regional downscaling problem. However, May (2004a) notes that the high-resolution (about

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[7] Some references in this section have been changed to be internally consistent with this document and other references have been removed to avoid confusion.

1.5 degrees) European Centre-Hamburg (ECHAM4) GCM simulates the variability and extremes of daily rainfall (intensity as well as frequency of wet days) in good agreement with the observations (Global Precipitation Climatology Project, Huffman et al., 2001).

Three-member ensembles of baseline simulations (1961–1990) from an RCM (PRECIS) at 50 km resolution have confirmed that significant improvements in the representation of regional processes over South Asia can be achieved (Kumar, 2006). For example, the steep gradients in monsoon precipitation with a maximum along the western coast of India are well represented in PRECIS.

East Asia

Simulated temperatures in most MMD models are too low in all seasons over East Asia; the mean cold bias is largest in winter and smallest in summer. Zhou and Yu (2006) show that over China, the models perform reasonably in simulating the dominant variations of the mean temperature over China but not the spatial distributions. The annual precipitation over East Asia exceeds the observed estimates in almost all models and the rain band in the mid-latitudes is shifted northward in seasons other than summer. This bias in the placement of the rains in central China also occurred in earlier models (e.g., Zhou and Li, 2002; Gao et al., 2004). In winter, the area-mean precipitation is overestimated by more than 50 percent on average due to strengthening of the rain band associated with extratropical systems over South China. The bias and inter-model differences in precipitation are smallest in summer, but the northward shift of this rain band results in large discrepancies in summer rainfall distribution over Korea, Japan, and adjacent seas.

Kusunoki et al. (2006) find that the simulation of the Meiyu-Changma-Baiu rains in the East Asian monsoon is improved substantially with increasing horizontal resolution. Confirming the importance of resolution, RCMs simulate more realistic climatic characteristics over East Asia than AOGCMs, whether driven by re-analyses or by AOGCMs (e.g., Ding et al., 2003; Oh et al., 2004; Fu et al., 2005; Zhang et al., 2005a, Ding et al., 2006; Sasaki et al., 2006b). Several studies reproduce the fine-scale climatology of small areas using a multiply nested RCM (Im et al., 2006) and a very-high resolution (5 km) RCM (Yasunaga et al., 2006). Gao et al. (2006b) report that simulated East Asia large-scale precipitation patterns are significantly affected by resolution, particularly during the mid- to late-monsoon months, when smaller-scale convective processes dominate.

Southeast Asia

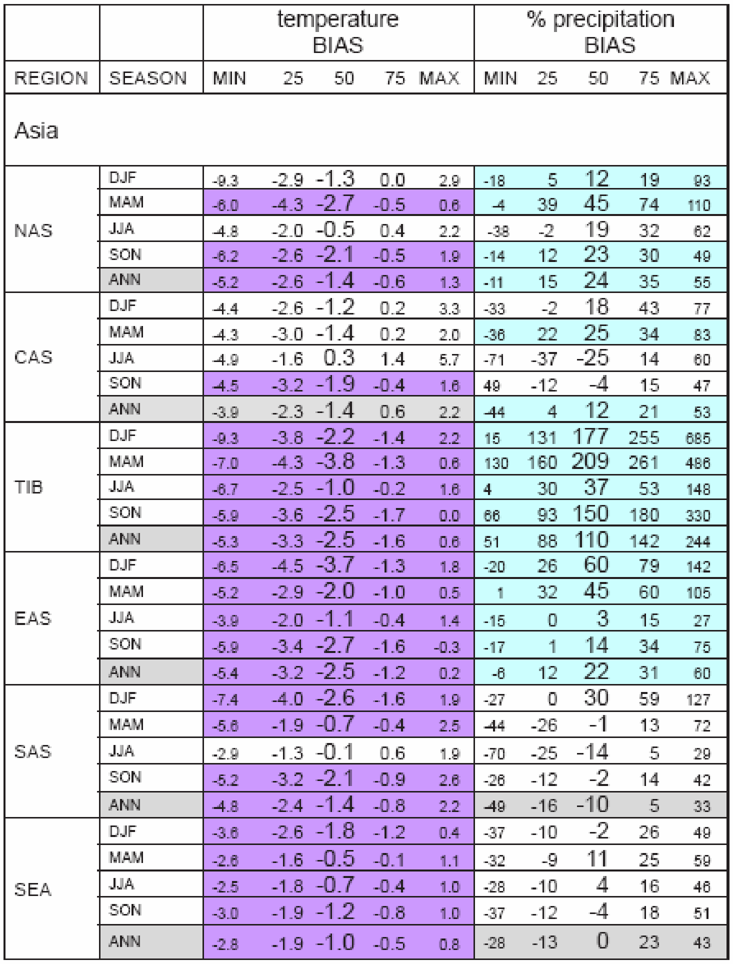
The broad-scale spatial distribution of temperature and precipitation in December, January, February (DJF) and June, July August (JJA) averaged across the MMD models compares well with observations. Rajendran et al. (2004) examine the simulation of current climate in the MRI coupled model. Large-scale features were well simulated, but errors in the timing of peak rainfall over Indochina were considered a major shortcoming. Collier et al. (2004) assess the performance of the CCSM3 model in simulating tropical precipitation forced by observed SST. Simulation was good over the maritime continent compared to the simulation for other tropical regions. Wang et al. (2004) assess the ability of 11 AGCMs in the Asian-Australian monsoon region simulation forced with observed SST variations. They found that the models' ability to simulate observed interannual rainfall variations was poorest in the Southeast Asian portion of the domain. Since current AOGCMs continue to have some significant shortcomings in representing ENSO variability, the difficulty of projecting changes in ENSO-related rainfall in this region is compounded.

Rainfall simulation across the region at finer scales has been examined in some studies. The Commonwealth Scientific and Industrial Research Organisation (CSIRO) stretched-grid Conformal-Cubic Atmospheric Model (CCAM) at 80-km resolution shows reasonable precipitation simulation in JJA, although Indochina tended to be drier than in the observations (McGregor and Nguyen, 2003). Aldrian et al. (2004a) conducted a number of simulations with the Max-Planck Institute (MPI) regional model for an Indonesian domain, forced by reanalyses and by the ECHAM4 GCM. The model was able to represent the spatial pattern of seasonal rainfall. It was found that a resolution of at least 50 km was required to simulate rainfall seasonality correctly over Sulawesi. The formulation of a coupled regional model improves regional rainfall simulation over the oceans (Aldrian et al., 2004b). Arakawa and Kitoh (2005) demonstrate an accurate simulation of the diurnal cycle of rainfall over Indonesia with an AGCM of 20-km horizontal resolution.

Central Asia and Tibet

Due to the complex topography and the associated mesoscale weather systems of the high-altitude and arid areas, GCMs typically perform poorly over the region. Importantly, the GCMs, and to a lesser extent RCMs, tend to overestimate the precipitation over arid and semi-arid areas in the north (e.g., Small et al., 1999; Gao et al., 2001; Elguindi and Giorgi, 2006).

Over Tibet, the few available RCM simulations generally exhibit improved performance in the simulation of present-day climate compared to GCMs (e.g., Gao et al., 2003a,b; Zhang et al., 2005b). For example, the GCM simulation of Gao et al. (2003a) overestimated the precipitation over the northwestern Tibetan Plateau by a factor of five to six, while in an RCM nested in this model, the overestimate was less than a factor of two.



		temperature BIAS					% precipitation BIAS				
REGION	SEASON	MIN	25	50	75	MAX	MIN	25	50	75	MAX
Asia											
NAS	DJF	-9.3	-2.9	-1.3	0.0	2.9	-18	5	12	19	93
	MAM	-6.0	-4.3	-2.7	-0.5	0.6	-4	39	45	74	110
	JJA	-4.8	-2.0	-0.5	0.4	2.2	-38	-2	19	32	62
	SON	-6.2	-2.6	-2.1	-0.5	1.9	-14	12	23	30	49
	ANN	-5.2	-2.6	-1.4	-0.6	1.3	-11	15	24	35	55
CAS	DJF	-4.4	-2.6	-1.2	0.2	3.3	-33	-2	18	43	77
	MAM	-4.3	-3.0	-1.4	0.2	2.0	-36	22	25	34	83
	JJA	-4.9	-1.6	0.3	1.4	5.7	-71	-37	-25	14	60
	SON	-4.5	-3.2	-1.9	-0.4	1.6	49	-12	-4	15	47
	ANN	-3.9	-2.3	-1.4	0.6	2.2	-44	4	12	21	53
TIB	DJF	-9.3	-3.8	-2.2	-1.4	2.2	15	131	177	255	685
	MAM	-7.0	-4.3	-3.8	-1.3	0.6	130	160	209	261	486
	JJA	-6.7	-2.5	-1.0	-0.2	1.6	4	30	37	53	148
	SON	-5.9	-3.6	-2.5	-1.7	0.0	66	93	150	180	330
	ANN	-5.3	-3.3	-2.5	-1.6	0.6	51	88	110	142	244
EAS	DJF	-6.5	-4.5	-3.7	-1.3	1.8	-20	26	60	79	142
	MAM	-5.2	-2.9	-2.0	-1.0	0.5	1	32	45	60	105
	JJA	-3.9	-2.0	-1.1	-0.4	1.4	-15	0	3	15	27
	SON	-5.9	-3.4	-2.7	-1.6	-0.3	-17	1	14	34	75
	ANN	-5.4	-3.2	-2.5	-1.2	0.2	-6	12	22	31	60
SAS	DJF	-7.4	-4.0	-2.6	-1.6	1.9	-27	0	30	59	127
	MAM	-5.6	-1.9	-0.7	-0.4	2.5	-44	-26	-1	13	72
	JJA	-2.9	-1.3	-0.1	0.6	1.9	-70	-25	-14	5	29
	SON	-5.2	-3.2	-2.1	-0.9	2.6	-26	-12	-2	14	42
	ANN	-4.8	-2.4	-1.4	-0.8	2.2	-49	-16	-10	5	33
SEA	DJF	-3.6	-2.6	-1.8	-1.2	0.4	-37	-10	-2	26	49
	MAM	-2.6	-1.6	-0.5	-0.1	1.1	-32	-9	11	25	59
	JJA	-2.5	-1.8	-0.7	-0.4	1.0	-28	-10	4	16	46
	SON	-3.0	-1.9	-1.2	-0.8	1.0	-37	-12	-4	18	51
	ANN	-2.8	-1.9	-1.0	-0.5	0.8	-28	-13	0	23	43

Table 1. Biases in present-day (1980-1999) surface air temperature and precipitation in the MMD simulations. The simulated temperatures are compared with the HadCRUT2v (Jones, et al., 2001) data set and precipitation with the CMAP (update of Xie and Arkin, 1997) data set. Temperature biases are in °C and precipitation biases in percent. Shown are the minimum, median (50 percent) and maximum biases among the models, as well as the first (25 percent) and third (75 percent) quartile values. Colors indicate regions/seasons for which at least 75 percent of the models have the same sign of bias, with orange indicating positive and light violet negative temperature biases and light blue positive and light brown negative precipitation biases.

Annex B:

Knowledge Gaps That Preclude a Full Evaluation of Climate Change Impacts Affecting India and India's Adaptive Capacities

To increase the likelihood that this evaluation represents a reasonable assessment of India's projected climate changes and their impacts, and the country's adaptive capacity, the following gaps would need to be addressed:

- In physical science research, regional analyses will continue to be limited by the inability to model regional climates satisfactorily, including complexities arising from the interaction of global, regional, and local processes. One gap of particular interest is the lack of medium-term (20-30 years) projections that could be relied upon for planning purposes. Similarly, scientific projections of water supply and agricultural productivity are limited by inadequate understanding of various climate and physical factors affecting both areas. Research agendas in these areas can be found in, for instance, the synthesis and assessment reports of the US Climate Change Science Program (http://www.climatescience.gov) and the National Academy of Sciences (e.g., http://books.nap.edu/catalog.php?record_id=11175#toc). Similar types of issues exist for the biological and ecological systems that are affected.
- In social science research, scientists and analysts have only partial understandings of the important factors in vulnerability, resilience, and adaptive capacity – much less their interactions and evolution. Again, research agendas on vulnerability, adaptation, and decision-making abound (e.g., (http://books.nap.edu/ catalog.php?record_id=12545).
- Important factors are unaccounted for in research; scientists know what some of them are, but there are likely factors whose influence will be surprising. An example from earlier research on the carbon cycle illustrates this situation. The first carbon cycle models did not include carbon exchanges involving the terrestrial domain. Modelers assumed that the exchange was about equal, and the only factor modeled was deforestation. This assumption, of course, made the models inadequate for their purposes. In another example, ecosystems research models are only beginning to account for changes in pests, e.g., the pine bark beetle.
- Social models or parts of models in climate research have been developed to simulate consumption (with the assumption of well-functioning markets and rational actor behavior) and mitigation/adaptation policies (but without attention to the social feasibility of enacting or implementing such policies). As anthropogenic climate change is the result of human decisions, the lack of knowledge about motivation, intent, and behavior is a serious gap. Moreover, the long time scale of climate-related research introduces uncertainties about social behavior in the future as well as weaknesses in scientists' ability to predict the social conditions under which mitigation and adaptation will be undertaken.

Overall, research about climate change impacts on India has been undertaken piecemeal: discipline by discipline, sector by sector, with political implications considered separately from physical effects. This knowledge gap can be remedied by integrated research into energy-economic-environmental-political conditions and possibilities.

Annex C:

State/District Vulnerability and Adaptive Capacity in India

Note: The original source data used for derivation of state and district adaptive capacity was from 1990-1991 sources and may not reflect current circumstances.

Results from the Vulnerability-Resilience Indicators Model (VRIM)

The vulnerability of India and Indian states to climate change was assessed using the Vulnerability-Resilience Indicators Model (VRIM) (see box on page 25 for description).[cvii] Vulnerability here includes both adaptive capacity and climate sensitivity (i.e., potential negative impacts of climate change).

As in other quantitative rankings, India is ranked as more vulnerable than most countries to climate change; in a VRIM-assisted study of 160 countries,[cviii] India ranks low in the third quartile. The largest contributions to current vulnerability of India in the VRIM analysis are food security (as represented by total protein intake in the sensitivity aspect) and water availability (also in the sensitivity aspect). Rapid expansion in the use of groundwater, primarily for irrigation, has contributed significantly to agricultural and overall economic development in India, but in many arid and hard-rock zones, increases in overdraft areas and associated water-quality problems are emerging.

Specific comparative levels of adaptive capacity are shown in Figure 6. Adaptive capacity is lowest along the Indo-Gangetic Plain, higher in the northwest and south.

When sensitivity and adaptive capacity are combined into an overall comparative measure of vulnerability, small mountainous northern inland states tend to be ranked higher than coastal states, and only five states are ranked higher than the world average.

Interestingly, most of the variability in state-level sensitivity proxies (i.e., proxies that represent how large climate impacts are) results from variability in settlement and food sensitivity, i.e., social and economic factors. On the other hand, most of the variability in state-level proxies for coping and adaptive capacity results from environmental rather than economic or human resource factors. These results imply that social policies would be more likely to be effective in reducing sensitivity, while environmental protection policies would likely be more effective in increasing coping and adaptive capacity.

Many analyses attempt to measure these kinds of differences by using GDP per capita or some income measure as a summary proxy. However, this study shows no meaningful correlation between net domestic product (NDP) per capita in states and vulnerability of a state to climate impacts. Differences other than economic ones are of great importance. For example, literacy rates in the states range from 44 to 91 percent, life expectancy from 58 to 70 years. There are great disparities in natural resources and climate hazards among Indian states.

Figure 6. Coping and adaptive capacity comparative levels of India's states (average of four periods, 1990-2035). *Source:* based on Antoinette L. Brenkert and Elizabeth L. Malone, "Modeling vulnerability and resilience to climate change: a case study of India and Indian states," *Climatic Change* 72 (2005): 57-102.

Adaptive Capacity of Indian Districts

O'Brien et al.[cix] performed a detailed analysis of adaptive capacity at the district level in India; likely because of the focus on agriculture and the difference in variables measured, the results differ from the VRIM analysis. To measure adaptive capacity, the researchers used the following indicators:

- Biophysical indicators: soil conditions (the depth of the soil cover and severity of soil degradation) and groundwater availability (based on estimates of the total amount of replenishable groundwater available annually).
- Human and social capital: adult literacy rates, degree of gender equity in a district, and the presence of alternative economic activities (an indicator of the ability of farmers in a district to shift to other economic activities).
- Infrastructure: irrigation rates and quality of infrastructure (measured using the Infrastructure Development Index of the Center for Monitoring of Indian Economy).

The capacity index map shows higher degrees of adaptive capacity in districts located along the Indo-Gangetic Plains (except Bihar) and lower adaptive capacity in the interior portions of the country, particularly in the states of Bihar, Rajasthan, Madhya Pradesh, Maharashtra, Andhra Pradesh, and Karnataka.

O'Brien et al. measured sensitivity under exposure to climate change. They found the areas with high to very high climate sensitivity for agriculture to be located in the semi-arid regions of the country, including major parts of the states of Rajasthan, Gujarat, Punjab, Haryana, Madhya Pradesh, and Uttar Pradesh. Under the HadRM2 (the Hadley Centre's Regional Model) scenario, district climate sensitivity noticeably increased in Uttar Pradesh, Madhya Pradesh, and Maharashtra.

Vulnerability in India was assessed by summing a district-level index of adaptive capacity with an index of climate sensitivity under exposure. The districts with the highest/lowest sensitivity were not necessarily the most/least vulnerable. For example, most districts in southern Bihar exhibited only medium sensitivity to climate change, yet were still highly vulnerable as the result of low adaptive capacity. By contrast, most districts in northern Punjab showed very high sensitivity to climate change, yet were found to be only moderately vulnerable as the result of high adaptive capacity.

Last, the research team added factors representing exposure to globalization. Liberalization of agricultural trade may provide new opportunities for some Indian farmers to engage in production for export market, but also may expose many other farmers to competition from imported agricultural products. One example is the liberalization of trade in edible oils and oilseeds which led to a crash in domestic oilseed prices in the late 1990s due to imports of inexpensive Malaysian palm oil. For farmers in southern India, particularly in the state of Andhra Pradesh, this price crash, perhaps exacerbated by such factors as the inability to afford imported hybrid seeds, proved devastating and is associated with the beginning of a long wave of suicides by bankrupt farmers.

O'Brien et al. focused on exposure to import competition, with the result that high vulnerability was shown in most of Rajasthan and Karnataka, as well as in substantial portions of Bihar, Madhya Pradesh, Maharashtra, Gujarat, and Assam. Notable areas of low vulnerability occurred along the Indo-Gangetic plains. Districts, mostly concentrated in Rajasthan, Gujarat, Madhya Pradesh, as well as in southern Bihar and western Maharashtra, may be interpreted as areas of "double exposure," where globalization and climate change are likely to pose simultaneous challenges to the agricultural sector.

Several short case studies complement the broader-scale research. The case studies showed the effect that institutional barriers or support systems have on local-level vulnerability; this is not visible in the district-national profiles. In the cases of Jhalawar (Rajasthan) and Anatapur (Andhra Pradesh), institutional barriers leave farmers who are "double exposed" poorly equipped to adapt to either of the stressors, let alone both simultaneously. In Chitradurga (Karnataka), on the other hand, institutional support appears to facilitate adaptation to both climatic change and globalization. However, these supports tend to disproportionately benefit the district's larger farmers.

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SPECIAL REPORT

INDIA: IMPACT OF CLIMATE CHANGE TO 2030
A COMMISSIONED RESEARCH REPORT