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Southeast Asia and Pacific Islands: The Impact of Climate Change to 2030

A Commissioned Research Report

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Southeast Asia and Pacific Islands: The Impact of Climate Change to 2030

A Commissioned Research Report

Jointly prepared by: Joint Global Change Research Institute Battelle Memorial Institute, Pacific Northwest Division Scitor Corporation

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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, experts from outside the Intelligence Community (IC) will meet at a workshop or conference to 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 U.S. national security.

To support research by the National Intelligence Council (NIC) on the National Security Impacts of Global Climate Change, this assessment of the impact of Climate Change on Southeast Asia and Pacific Islands through 2030 is being delivered under the Global Climate Change Research Program contract with the Central Intelligence Agency's Office of the Chief Scientist.

This research identifies and summarizes the latest peer-reviewed research related to the effects of climate change on Southeast Asia and Pacific Islands, drawing on both the literature summarized in the latest Intergovernmental Panel on Climate Change (IPCC) assessment reports and on other peer-reviewed research literature. It includes such impacts as sea-level rise, water supply and demand, agricultural shifts, ecological disruptions and species extinctions, infrastructure at risk from extreme weather events (severity and frequency), and disease patterns. The research addresses the extent to which Southeast Asia and Pacific Islands are vulnerable to climate change impacts. The timeframe of this analysis extends through 2030, although various studies referenced in this report have diverse timeframes and extend through the 21st century.

The research also identifies (Annex B) deficiencies in climate change data that would enhance the IC understanding of potential impacts on Southeast Asia and Pacific Islands and other countries/regions of interest.

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Executive Summary

Southeast Asia and Pacific Islands are at risk from the impact of climate change in the next 20 years due to the region's large and growing population, long coastlines, abundant low-lying areas, reliance on the agricultural sector, and dependence upon natural resources. This report focuses on the nations of Thailand, Cambodia, Laos, Vietnam, the Philippines, Malaysia, Singapore, and Indonesia. These countries have a diverse range of governments, populations, religions, economic growth, development, and allocation of natural resources, but they all have a similar tropical maritime climate and face similar threats from climate change.

The effects of climate change have already begun in the Southeast Asia and Pacific Islands region:

- Average annual surface temperatures in the region increased by 0.5-1.1 °C during the period 1901-2005.ⁱ
- Precipitation patterns are changing regionally, with increases in some locations and decreases in others. For example, annual rainfall decreased across most of the southern regions of Indonesia (Java, Lampung, South Sumatra, South Sulawesi, and Nusa Tenggara) and increased across most of the northern regions of the country (Kalimantan and North Sulawesi) during the period 1931-1990.ⁱⁱ
- Sea level is rising, and the magnitude varies regionally. During the period 1993-2001, the largest increases in sea level (15-25 mm per year) in the region occurred near Indonesia and the Philippines, while only moderate changes (0-10 mm per year) occurred along the coasts of Thailand, Cambodia, and Vietnam.ⁱⁱⁱ

Global circulation model projections indicate that climate change will continue to occur in the region over the course of the 21st century:

- Climate model simulations clearly indicate that average annual temperatures are likely to increase across the region by approximately 1°C through 2030, and they will keep increasing through the remainder of the 21st century.
- The magnitude, location, and trends of future precipitation changes are much less certain due to the inherent difficulty of modeling such changes. Furthermore, future precipitation changes due solely to climate change are difficult to resolve because they are superimposed on significant interannual variations that occur naturally in the region. Climate model simulations suggest that net precipitation rates will increase across the region in the next 20 years, but there will likely be local decreases that will vary geographically and temporally.
- It is difficult to project future changes in monsoon patterns and the effects of El Niño-Southern Oscillation (ENSO) on precipitation in the region, due to the difficulty of modeling these phenomena. Climate model results suggest that the onset of the monsoon in Thailand, Laos, Cambodia, and Vietnam may be delayed by 10-15 days for the period 2030-2070, but the duration of the monsoon will not change.^{iv} There is no evidence from climate model simulations that ENSO events will become more frequent due to climate change, but it is possible that their intensity may increase.^v

• Sea level will continue to rise, although rates will vary across the region. By the end of the 21st century, sea level is projected to have risen by approximately 30-40 cm.^{vi}

There is overwhelming evidence that climate change will impact a variety of sectors in Southeast Asia and Pacific Islands through 2030. All of the major effects of climate change on the region are interrelated, so it is impossible to assess one impact independently of the others. The most high-risk impacts of climate change in the region are related to fresh water and ocean water resources, and include the following:

Sea Level Rise. Throughout the region, rising sea level causes a number of devastating effects in the region, including saltwater intrusion into estuaries and aquifers, coastal erosion, displacement of wetlands and lowlands, degradation of coastal agricultural areas, and increased susceptibility to coastal storms. These effects are interrelated with impacts on agriculture, natural disasters, river deltas, water resources, coastal ecosystems, human livelihoods and infrastructure, and national security. Sea level rise has overarching socioeconomic impacts as well, due to loss in income associated with degradation of agricultural areas and loss of housing associated with coastal inundation, for example.

Water Resources. Future changes in regional water resources are closely tied to changes in precipitation. Individual areas under severe water stress in the region are projected to increase dramatically in the next few decades, although model results suggest that the region as a whole will not be at risk for water shortages. Fresh water resources on all island nations in the region are especially vulnerable to any variability in precipitation because many rely on rainwater collection for their supply of fresh water. The management of water issues is one of the most challenging climate-related issues in the region, as it is central to health and sustainable development. The impacts of climate change on water resources are interrelated with impacts on agriculture, river deltas, forests, coastal ecosystems, diseases and human health, and national security.

Agriculture. Assessment of the specific impacts of climate change on agriculture is challenging because it is difficult to reliably simulate the complicated effects of future variations in temperatures, precipitation, and atmospheric CO₂ concentrations on crop growth. Temperature increases associated with climate change could result in a northward expansion of growing areas and a lengthening of the growing season. Rising atmospheric CO₂ levels are expected to stimulate plant photosynthesis, which would result in higher crop yields. Studies show that the beneficial effects of CO₂ on plants may be offset by average temperature increases of more than 2° C, however. Overall, it is likely that future crop yields will vary by region and by crop, with yield increases in some locations but decreases in others. Management of the agricultural sector by regional nations is critical to their economic growth and national security. The impacts of climate change on agriculture are interrelated with impacts on sea level, river deltas, natural disasters, water resources, and national security.

Coastal Regions. Coastal regions are some of the most at-risk areas for the impacts of climate change in the region due to their prevalence and high population density.

Mangroves and coral reefs across the region are two key coastal ecosystems that are expected to be significantly impacted by climate change. Many coastal areas are already degraded by pollution, sediment-laden runoff, and destructive fishing practices. Climate change-related destruction and degradation of mangroves and coral reefs will only exacerbate these effects, and result in long-term economic repercussions, since these ecosystems are central to the tourism,

agriculture, fishing, and aquaculture industries. The area's coastal regions are also susceptible to inundation associated with sea level rise and destruction of infrastructure from flooding and storm surges, which are likely to increase as a result of future climate change. Careful management and safeguarding of coastal regions by regional governments is therefore essential in the next 20 years, as the effects of climate change manifest themselves. Impacts on coastal regions are interrelated with sea level, river deltas, natural disasters, water resources, agriculture, forests, and human livelihoods and infrastructure.

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Introduction and Background

The Southeast Asia and Pacific Islands region is one of the most vulnerable areas in the world to climate change, due to its large and growing population, its long coastlines and low-lying areas, the economic importance of its agricultural sector, and its high dependence upon natural resources for development.^{vii} This report summarizes the latest peer-reviewed research on projected climate change in Southeast Asia and Pacific Islands and the associated impacts on human and ecological systems across the region. Literature sources include the latest Intergovernmental Panel on Climate Change (IPCC) assessments, peer-reviewed journal articles, and reports generated by governments and scientific organizations.

The nations that constitute the focus of this assessment are Thailand, Cambodia, Laos, Vietnam, the Philippines, Malaysia, Singapore, and Indonesia. For convenience, these countries are referred to as "Southeast Asia" in this report, unless otherwise noted. The geographic scope of this report includes the region of approximately 23.5 °N to 10 °S latitude and 97 °E to 141 °E longitude. A map of the region, including the countries and their capitals, is given in Figure 1.

Specific information about the geography, economy, and society of the countries of interest is summarized below.^{viii}

Thailand: Thailand is a coastal nation that borders Burma, Cambodia, Laos, Malaysia, the Andaman Sea, and the Gulf of Thailand. The total area of Thailand is 514,000 km², composed of 511,770 km² of land and 2,230 km² of water, and it has 3,219 km of coastline. The topography of Thailand includes a central plain, the Khorat Plateau in the east, and mountainous regions. It is subject to droughts nationwide and land subsidence in the Bangkok area resulting from depletion of the water table. Environmental issues in Thailand include air pollution from vehicle emissions, water pollution from organic and factory wastes, deforestation, soil erosion, and wildlife populations threatened by illegal hunting. The estimated population in 2009 is approximately 66 million, with an annual growth rate of 0.6 percent. The urban population constitutes 33 percent of the total population. Life expectancy is approximately 73 years. The Thai population is overwhelmingly Buddhist, with approximately 5 percent Muslims.

Thailand has a well-developed infrastructure, a free-enterprise economy, and generally proinvestment policies, which permitted annual real Gross Domestic Product (GDP) growth of more than 6 percent for the period 2002-04. Overall economic growth fell sharply in 2005-2007, however, because persistent political crises stalled infrastructure mega-projects, eroded investor and consumer confidence, and damaged the country's international image. The GDP (purchasing power parity) for 2008 was \$553 billion. The labor force includes 43 percent in agriculture, 20 percent in industry, and 37 percent in services.



This Map is **UNCLASSIFIED**

Figure 1. Map of the geographic region of interest for this report. Colored areas indicate the eight nations of focus.

Laos: Laos is a landlocked nation that borders Burma, Cambodia, Thailand, China, and Vietnam. Laos' total area is 236,800 km,² composed of 230,800 km² of land and 6,000 km² of water. Laos is subject to droughts and floods. Current environmental issues include deforestation and soil erosion; most of the population does not have easy access to potable water. Laos' estimated 2009 population is about 6.8 million, with a 2.3 percent annual growth rate. The urban population makes up 31 percent of the total population. Life expectancy is approximately 57 years. The religious make-up of the population is approximately 67 percent Buddhist, 1.5 percent Christian, and other unspecified religions.

Laos is one of the few remaining one-party Communist states. It has an underdeveloped infrastructure, particularly in rural areas: the nation has no railroads, a rudimentary road system, and limited external and internal telecommunications. Subsistence agriculture, dominated by rice, accounts for about 40 percent of GDP and provides 80 percent of total employment. The GDP (purchasing power parity) for 2008 was \$14 billion. The labor force includes 80 percent in agriculture and 20 percent in industry and services.

Cambodia: Cambodia is a coastal nation that borders Thailand, Laos, Vietnam, and the Gulf of Thailand. Cambodia's total area is 181,040 km,² composed of 176,520 km² of land and 4,520 km² of water. Its terrain is mostly low, flat plains, with mountains in the southwest and north. Cambodia is subject to flooding and occasional droughts. Current environmental issues include soil erosion, lack of potable water in rural areas, and declining fish stocks due to illegal fishing and overfishing. In addition, illegal logging activities throughout the country and strip mining for gems in the western region along the border with Thailand have resulted in habitat loss and declining biodiversity. In addition, destruction of mangrove swamps threatens natural fisheries. Cambodia's 2009 population is estimated at 14.5 million, with a 1.8 percent annual growth rate. The urban population makes up 22 percent of the total population. Life expectancy is approximately 62 years, and 95 percent of the population is Theravada Buddhist.

Cambodia's economy grew about 10 percent per year during 2004-2008, driven mainly by construction, agriculture, tourism, and an expanding garment industry. As of 2008, the garment industry employed more than 320,000 people and accounted for more than 85 percent of Cambodia's exports. The global financial crisis is weakening demand for Cambodian exports, however. Tourism has grown rapidly in recent years, with more than 2 million foreign visitors per year during 2007-2008. The GDP (purchasing power parity) for 2008 was approximately \$28 billion. The labor force includes 75 percent in agriculture, with the remaining 25 percent in unspecified areas.

Vietnam: Vietnam is a coastal nation that borders China, Laos, Cambodia, the Gulf of Thailand, the Gulf of Tonkin, and the South China Sea. Vietnam's total area is 329,560 km,² composed of 325,360 km² of land and 4,200 km² of water. Vietnam is subject to occasional typhoons from May to January that can cause extensive flooding, especially in the Mekong River delta. Current environmental issues include deforestation and soil degradation due to logging and slash-and-burn agricultural practices, water pollution, over-fishing, limited potable water supply due to groundwater contamination, growing urban industrialization, and increasing population migration to Hanoi and Ho Chi Minh City. Vietnam's estimated 2009 population is about 87 million, with a 0.9 percent annual growth rate. The urban population makes up 28 percent of the total population. Life expectancy is approximately 72 years. The distribution of religions includes 9.3 percent Buddhist, 6.7 percent Catholic, 1.5 percent Hoa Hao, 1.1 percent Cao Dai, 0.5 percent Protestant, and 0.1 percent Muslim, with 80 percent reporting no religion.

Vietnam has an export-oriented economy, with 68 percent of GDP in 2007 coming from exports. The agriculture sector has shrunk from 25 percent of the nation's economic output in 2000 to less than 20 percent in 2008. The global financial crisis will constrain Vietnam's ability to reduce poverty and create jobs in coming years. The nation's GDP (purchasing power parity) for 2008 was \$242 billion. The labor force includes 56 percent in agriculture, 19 percent in industry, and 26 percent in services.

Philippines: The Philippines is an archipelago of 7,107 islands located east of Vietnam, between the Philippine Sea and the South China Sea. The total area of the Philippines is 300,000 km,² composed of 298,170 km² of land and 1,830 km² of water. The Philippines is mostly mountains with narrow to extensive coastal lowlands. It is subject to typhoons, landslides, active volcanoes, destructive earthquakes, and tsunamis. Environmental issues in the Philippines include uncontrolled deforestation (especially in watershed areas), soil erosion, air and water pollution in major urban centers, coral reef degradation, and increasing pollution of coastal mangrove swamps that are important fish breeding grounds. The estimated 2009 population is approximately 98 million, with an annual growth rate of 2 percent. The urban population constitutes 65 percent of the total population. Life expectancy is approximately 71 years. The Philippine population is overwhelmingly Catholic, with approximately 5 percent Muslims.

Economic growth in the Philippines has averaged 5 percent since 2001. The economy faces several long-term challenges, such as improving employment opportunities and alleviating poverty. In the coming years, the Philippines will need sustained economic growth to make progress in alleviating poverty, given the nation's high population growth and unequal distribution of income. The Philippine economy grew at its fastest pace in three decades in 2007 with real GDP growth exceeding 7 percent, but growth slowed to 4.5 percent in 2008 as a result of the world financial crisis. The GDP (purchasing power parity) for 2008 was \$320.6 billion. The labor force includes 35 percent in agriculture, 15 percent in industry, and 50 percent in services.

Malaysia: Malaysia occupies the southern portion of the Malay Peninsula and the northern onethird of the island of Borneo. Malaysia borders Indonesia, Brunei, and Thailand. Malaysia's total area is 329,750 km,² composed of 328,550 km² of land and 1,200 km² of water. Malaysia is subject to flooding, landslides, and forest fires. Current environmental issues include air pollution from industrial and vehicular emissions, water pollution from raw sewage, deforestation, and smoke and haze from Indonesian forest fires. Malaysia's estimated 2009 population is about 26 million, with a 1.8 percent annual growth rate. The urban population makes up 70 percent of the total population. Life expectancy is approximately 73 years. The religious make-up of the population is approximately 60 percent Muslim, 19 percent Buddhist, 9 percent Christian, 9 percent Hindu, and other less populous religions.

Malaysia is a middle-income country that has transformed from a producer of raw materials into an emerging multi-sector economy. It has recently attracted investments in high technology industries, medical technology, and pharmaceuticals. As an oil and gas exporter, Malaysia has profited from higher world energy prices, although the rising cost of domestic gasoline and diesel fuel forced Kuala Lumpur to reduce government subsidies. Real GDP growth has averaged about 6 percent per year over the past few years, although regions outside of Kuala Lumpur and the manufacturing hub of Penang are growing less robustly. Decreasing worldwide demand for consumer goods is expected to hurt economic growth. The GDP (purchasing power parity) for 2008 was \$387 billion. The labor force includes 10 percent in agriculture, 45 percent in industry, and 45 percent in services.

Singapore: Singapore is a small city-state that borders Malaysia on the southern tip of the Malay Peninsula. Singapore's total area is 692.7 km,² composed of 682.7 km² of land and 10 km² of water. Singapore's terrain includes lowlands and a gently undulating central plateau that contains a nature preserve. Current environmental issues include industrial pollution, limited

natural fresh water resources, limited land availability that causes waste disposal problems, and seasonal smoke and haze from forest fires in Indonesia. Singapore's estimated 2009 population is about 4.7 million, with a 1 percent annual growth rate. The population is 100 percent urban. Life expectancy is approximately 82 years. The distribution of religions includes 42.5 percent Buddhist, 14.9 percent Muslim, 8.5 percent Taoist, 4 percent Hindu, and 4.8 percent Catholic.

Singapore has a free-market economy that features a per capita GDP equal to that of the four largest West European countries. Singapore's economy depends primarily on exports, particularly consumer electronics, information technology products, pharmaceuticals, and a growing service sector. Real GDP growth for the period 2004-2007 averaged 7 percent, but it dropped to 1.2 percent in 2008 due to the global financial crisis. The nation's GDP (purchasing power parity) for 2008 was \$240 billion. The labor force includes 33 percent in industry and 67 percent in services.

Indonesia: Indonesia is an archipelago between the Indian Ocean and the Pacific Ocean. Indonesia's total area is 1,919,440 km,² composed of 1,826,440 km² of land and 93,000 km² of water. Its terrain is mostly coastal lowlands, although larger islands have interior mountains. Indonesia is subject to occasional floods, severe droughts, tsunamis, earthquakes, volcanoes, and forest fires. Current environmental issues include deforestation, water pollution from industrial wastes and sewage, air pollution in urban areas, and smoke and haze from forest and agricultural fires. Indonesia's estimated 2009 population is about 240 million, with a 1.1 percent annual growth rate. The urban population makes up 52 percent of the total population. Life expectancy is approximately 71 years. About 86 percent of the population is Muslim, with smaller Christian and Hindu populations.

Indonesia has made significant economic advances in recent years, but the nation faces challenges stemming from the global financial crisis and world economic downturn. Indonesia's debt-to-GDP ratio in recent years has declined steadily because of increasingly robust GDP growth and sound fiscal stewardship. Indonesia still struggles with poverty and unemployment, inadequate infrastructure, corruption, a complex regulatory environment, and unequal resource distribution among regions. As global demand slows and prices for Indonesia's commodity exports fall, Indonesia faces the prospect of growth significantly below the 6-plus percent recorded in 2007 and 2008. The GDP (purchasing power parity) for 2008 was \$916 billion. The labor force includes 42 percent in agriculture, 19 percent in industry, and 39 percent in services.

Projected Regional Climate Change

Current Climatology of Southeast Asia

Southeast Asia has a tropical maritime climate featuring relatively high temperatures, high relative humidity, and abundant precipitation. Figures 2-4 shows the monthly average daily minimum temperatures, monthly average daily maximum temperatures, and rainfall amounts for the capital cities of the Southeast Asian countries that are the focus of this report. There are three basic seasons in Southeast Asia: the rainy season, winter, and summer, although the characteristics, duration, and timing of the seasons vary widely based on latitude and geography.

Thailand has a rainy, warm, and cloudy southwest monsoon season from mid-May to September, a dry, cool winter northeast monsoon season from October to mid-March, and a warm and relatively dry summer season from mid-March to mid-May; Thailand's southern isthmus on the Malay Peninsula is generally hot and humid year-round.^{ix}

Laos and *Cambodia* both have two main seasons: the rainy season from May to November and the dry season from December to April.^x

Vietnam has a hot, rainy season under the influence of the monsoon from May to September and a warm, dry season from October to March.^{xi}

The Philippines has a northeast monsoon season from November to April and a southwest monsoon season from May to October.^{xii}

Malaysia has a southwest monsoon season from April to October and a more rainy northeast monsoon season from October to February.^{xiii}

Singapore has a southwest monsoon season from June to September and a more rainy northeast monsoon from December to March; during the inter-monsoon period, afternoon and early evening thunderstorms are common.^{xiv}

Indonesia's climate is hot and humid year-round, although it is more moderate in the highlands.^{xv}

The general pattern of rainy, winter, and summer seasons is typical except during El Niño-Southern Oscillation (ENSO) events. ENSO is a global climate phenomenon that recurs irregularly every 2-7 years and is associated with changes in sea surface temperature and prevailing winds. During a period of El Niño, the Northeast Trade Winds slacken, which increases the length of the dry season and creates drought conditions. La Niña is the complementary phenomenon; La Niña events are marked by a strengthening of the Northeast Trade Winds and a concomitant increase in the length of the rainy season. La Niña years are characterized by widespread flooding, landslides, and surface runoff from higher than average rainfall.

There is a great deal of natural climate variability in Southeast Asia. The regular pattern of seasonal monsoons can cause extreme weather events, such as floods and droughts. Overlaid on the monsoon variability is the periodic shift in global climate caused by ENSO, which can create or intensify existing floods and droughts.

Drought in El Niño years can have wide-reaching impacts on countries in Southeast Asia. For example, during the 1992 El Niño episode, total inflow to the Angat Reservoir in the Philippines, a major source of domestic and irrigation water supplies, was 69 percent less than average for the first six months of the year. As a result, there was a 20 percent reduction in the domestic water supply for the Manila metropolitan region, which necessitated water rationing in many areas. The cropping season was also delayed due to water shortages in June and July, and there were negative impacts on the national rice yield due to lack of irrigation water.^{xvi}



The Chart is UNCLASSIFIED

Figure 2. Monthly averaged daily minimum temperatures for the capital cities of the Southeast Asian countries that are the focus of this report. Climatology values for Bangkok, Thailand are averaged over the period 1961-1990; values for Phnom Penh, Cambodia are averaged over the period 1997-2001; values for Vientiane, Laos are averaged over the period 1951-2000; values for Hanoi, Vietnam are averaged over the period 1898-1990; values for Manila, Philippines are averaged over the period 1971-2000; values for Singapore are averaged values over the period 1961-1990; and values for Jakarta, Indonesia are averaged over the period 1994-1990. Source: World Meteorological Organization, *World Weather Information Service*, http://www.worldweather.org/ (accessed April 15, 2009).

Tropical cyclones, called typhoons in the Pacific, also bring a great deal of precipitation to regions of Southeast Asia north of approximately 10° latitude. Tropical cyclones do not occur near the equator because Coriolis force is required to impart rotation to developing systems; thus Indonesia, Malaysia, Singapore, and southern portions of the Philippines are generally spared from their devastating effects. Typhoons usually form in the Central Pacific and move in a westerly direction across Southeast Asia. The typhoon season typically runs from April to December, with the peak number of typhoons generally occurring in September and October.

Climate Predictions (Modeling)

General circulation models (GCMs) are the main tool used by scientists to project future climate change. These models simulate atmospheric and oceanic circulations, as well as processes that occur on land. As a result, GCMs are very complex models, and they tend to have rather low





Figure 3. Monthly averaged daily maximum temperatures for the capital cities of the Southeast Asian countries that are the focus of this report. Climatology values for Bangkok, Thailand are averaged over the period 1961-1990; values for Phnom Penh, Cambodia are averaged over the period 1997-2001; values for Vientiane, Laos are averaged over the period 1951-2000; values for Hanoi, Vietnam are averaged over the period 1898-1990; values for Manila, Philippines are averaged over the period 1971-2000; values for Kuala Lumpur, Malaysia are averaged values over the period 1971-2000; values for Singapore are averaged values over the period 1961-1990; and values for Jakarta, Indonesia are averaged over the period 1994-1990. Source: World Meteorological Organization, *World Weather Information Service*, http://www.worldweather.org/ (accessed April 15, 2009).

spatial resolutions, on the order of 400 to 125 km. To obtain model information on the local and regional scales, such as for Southeast Asia, at higher resolutions than native GCM grid sizes, "downscaling" is used. There are two main downscaling methods, dynamical and statistical. Dynamical downscaling involves the use of high-resolution climate models with observed or simulated data as boundary conditions. This approach has high credibility, but it is computationally expensive. In contrast, statistical downscaling, which involves application of established relationships between observed data to modeled data, is computationally inexpensive, and it can replicate finer scales than dynamical downscaling. Statistical downscaling methods do not accurately simulate regional feedback effects, however.^{xvii}

In general, GCM predictions of temperature changes for a given region are consistent, but predictions of precipitation changes can vary widely due to the difficulty in simulating the myriad of factors that influence precipitation frequency, duration, and intensity. An additional



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Figure 4. Monthly averaged total precipitation values for the capital cities of the Southeast Asian countries that are the focus of this report. Climatology values for Bangkok, Thailand are averaged over the period 1961-1990; values for Phnom Penh, Cambodia are averaged over the period 1997-2001; values for Vientiane, Laos are averaged over the period 1951-2000; values for Hanoi, Vietnam are averaged over the period 1898-1990; values for Manila, Philippines are averaged over the period 1971-2000; values for Kuala Lumpur, Malaysia are averaged values over the period 1971-2000; values for Singapore are averaged values over the period 1961-1990; and values for Jakarta, Indonesia are averaged over the period 1994-1990. Source: World Meteorological Organization, *World Weather Information Service*, http://www.worldweather.org/ (accessed April 15, 2009).

complication for Southeast Asia is the fact that precipitation varies naturally on an interannual time scale due to ENSO and other natural variability. Any precipitation changes associated with future climate change in model simulations are overlaid on this natural variability, and it can be very difficult for GCMs to resolve the natural and anthropogenic contributions. A more detailed discussion of the ability of GCMs to project regional climate changes is given in Annex A.

GCMs simulate changes in climate under scenarios of future greenhouse gas and aerosol emissions. The 2000 IPCC Special Report on Emission Scenarios (SRES)^{xviii} laid out the four basic scenario families used by IPCC scientists to predict future climate change; they are summarized in Table 1. This set of scenarios is designed to represent the range of possible future global conditions that will influence greenhouse gas emissions. The scenarios are based on consistent and reproducible assumptions about global forces that impact greenhouse gas emissions, including economic development, population, and technological change.

The following excerpt from the 2000 IPCC Special Report on Emission Scenarios (SRES) describes the emissions scenarios in more detail:

- A1. The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in the mid-21st century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil-intensive (A1FI), non-fossil energy sources (A1T) or a balance across all sources (A1B), where balance is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end use technologies.
- A2. The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than other storylines.
- **B1.** The B1 storyline and scenario family describes a convergent world with the same global population, that peaks in the mid-21st century and declines thereafter, as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.
- **B2.** The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels.

Climate researchers frequently use GCMs from the UK Met Office Hadley Centre for Climate Prediction and Research to investigate future changes in temperature and precipitation. These models are representative of many GCMs used to simulate the effects of climate change. The HadCM2 model has four different integrations that represent the climate effects of greenhouse gases and sulfate aerosols. Greenhouse gases, such as carbon dioxide, water vapor, ozone, methane, and nitrous oxide, absorb infrared radiation emitted from the Earth and subsequently emit it back into the atmosphere, which results in a net warming of the Earth's surface. HadCM2 includes the combined forcing of all greenhouse gases as an equivalent CO₂ concentration of 0.5 percent or 1 percent, depending on the integration. HadCM2 can also incorporate the negative direct forcing of sulfate aerosols by means of an increase in clear-sky albedo; sulfate forcing is 0.5 percent or 1 percent, depending on the model integration. The influence of sulfate aerosols is

Emission Scenario	Economic Development	Global Population	Technology Changes	Theme
A1	Very rapid	Peaks around mid- 21 st century and declines thereafter	Rapid introduction of new and more efficient technologies	Convergence among regions; increased cultural and social interactions
A2	Regionally-oriented	Continuously increasing	Slower and more fragmented than A1, B1, and B2	Self-reliance and preservation of local identities
B1	Rapid change toward service and information economy	Same as A1	Introduction of clean and resource-efficient technologies	Global solutions to economic, social, and environmental sustainability
B2	Intermediate levels of economic development	Continuously increasing, but not as fast as A2	Less rapid and more diverse changes than A1 and B1	Local solutions to economic, social, and environmental sustainability

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Table 1. Summary of IPCC emissions scenarios. Source: Intergovernmental Panel on Climate Change (IPCC), *Special Report on Emissions Scenarios (SRES)*, eds. Nebojsa Nakicenovic and Rob Swart (Cambridge: Cambridge University Press, 2000), http://www.ipcc.ch/ipccreports/sres/emission/index.htm.

important because they reflect incoming solar radiation; thus less reaches the surface of the Earth, which results in a net cooling of the Earth's surface. Each integration of HadCM2 has four ensembles, from which an ensemble mean can be calculated.^{xix} Ensembles are used to represent the range in uncertainty of model predictions. In this case, the same model, HadCM2, is run four times using different initial conditions. The average of a series of ensembles is always more accurate than any single model run.

HadCM3 is the successor to HadCM2. Its integrations are run under six different climatology scenarios of population growth, greenhouse gas emissions, and technology development through the 21st century. Both HadCM2 and HadCM3 have spatial resolutions of 2.5° latitude by 3.75° longitude. In general, this resolution is sufficient to resolve climate changes on a country-level scale in Southeast Asia, without the need for downscaling or temporal smoothing.^{xx} To simulate local climate changes, however, downscaling is required.

In contrast to the most recent GCMs, which are run under conditions matching the various IPCC emissions scenarios, many GCMs prior to approximately 2000 were run under more simplistic conditions. The most common method of simulating climate change in the older models was with an equivalent doubling of atmospheric CO₂ concentrations ($2 \times CO_2$), which represented the net radiative effect of increases in CO₂ and other greenhouse gases since pre-industrial times (typically equivalent to 560 ppm of CO₂). Models established a baseline using "current" CO₂ concentrations ($1 \times CO_2$), and the change between $1 \times CO_2$ and $2 \times CO_2$ " in model output was considered representative of future climate change. Under this type of scenario, researchers often neglected to frame the model results in terms of specific decadal changes, so the exact timeframe for projected climate changes was not specified.

Additional information on the GCMs mentioned in this report is available from the IPCC Data Distribution Centre (http://www.ipcc-data.org/).

Projections of Future Changes in Temperature and Precipitation

Rising concentrations of greenhouse gases in the global atmosphere during the 21st century are expected to cause a net warming of the Earth's surface. Higher surface temperatures will likely increase surface evaporation and thus global precipitation. To quantify regional future changes in temperature and precipitation, the IPCC uses a coordinated set of climate model simulations archived at the Program for Climate Model Diagnosis and Intercomparison (called the multimodel dataset, or MMD). Figure 5 shows the projected increase in temperature for Southeast Asia for the 21st century in the context of observed warming during the 20th century. This distinction is important because if GCMs cannot accurately reproduce observed climatic data, then they cannot be relied upon to simulate future climate changes. To obtain the temperature information shown in Figure 5, a subset of 58 simulations from 14 models of the MMD was used for the observed period and 47 simulations from 18 models for the future projections; the future projections were calculated for the A1B emissions scenario. The width of the shading and the bars in Figure 5 represent the 5-95 percent range of the model output. Results show that by the end of the 21st century, the annual mean temperature across Southeast Asia is expected to increase by a median value of 2.5°C, with little seasonal variation. This increase compares to a historical warming of 0.5-1.1°C in Southeast Asia for the period 1901-2005. The future temperature increase is expected to vary by location, with stronger warming in the interior of countries on the Asian mainland and less warming along coastal regions and in island nations.^{xxi}

IPCC also used the MMD models to estimate precipitation changes for the 21st century under the A1B scenario. In contrast to the temperature projections, which are consistent in predicting a temperature increase across Southeast Asia, future precipitation changes are less straightforward to quantify. Results from the MMD simulations show a net increase in precipitation across the region, with a median increase in average annual precipitation of 7 percent; these increases generally follow the location of the Intertropical Convergence Zone (ITCZ).^{xxii} The ITCZ is a region of low pressure and thus rising air near the equator that occurs where the Northeast Trade Winds meet the Southeast Trade Winds. As air rises, it cools and moisture condenses out, causing clouds and precipitation to form. Consequently, the ITCZ is marked by a band of heavy precipitation that moves northward and southward seasonally, following the warmest surface temperatures. The MMD models predict that the strongest and most consistent future increases in precipitation will follow the movement of the ITCZ, and thus will occur over Thailand, Cambodia, Laos, Thailand, the Philippines, Malaysia, Singapore, and northern Indonesia in June, July, and August; and will occur over southern Indonesia and Papua New Guinea in December, January, and February. During the times when these regions are not under the influence of the ITCZ, the models predict that concomitant decreases in precipitation will occur. The overall trend forecasted by the MMD models is for precipitation to increase during the rainy season and decrease during the dry season.^{xxiii}



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Figure 5. Temperature changes in °C predicted by the IPCC MMD models for Southeast Asia (SEA). Temperature anomalies for the region with respect to 1901-1950 are shown for 1906-2005 (black line), as simulated by the MMD models using known forcings (red envelope), and as projected for 2001-2100 by the MMD models for the A1B scenario (orange envelope). The colored horizontal bars on the right side of the figure represent the range of projected changes for 2091-2100 for the B1 scenario (blue), the A1B scenario (orange), and the A2 scenario (red). The width of the shading and the bars represent the 5-95 percent range of the model results. 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. Jr. Miller, and Z. Chen (Cambridge: Cambridge University Press, 2007), http://www.ipcc.ch/ipccreports/ar4-wg1.htm.

Variations in future regional precipitation are expected. Although a net increase in future precipitation is expected globally in a warmer world, regional precipitation rates in Southeast Asia will vary due to a variety of reasons, including shifts in the ITCZ, changes in the monsoons, variations in ENSO, local hydrological feedbacks, and alterations in atmospheric stability.^{xxiv} Future climate change-induced variations of regional precipitation will be superimposed on the natural interannual variations that occur in Southeast Asia. For example, analysis of monthly rainfall from 210 stations across Indonesia for the periods 1931-1960 and 1961-1990 showed that annual rainfall has decreased across most of the southern regions of Indonesia (Java, Lampung, South Sumatra, South Sulawesi, and Nusa Tenggara) and increased across most of the northern regions of the country (Kalimantan and North Sulawesi).^{xxv}

In addition to the global simulations of future temperature and precipitation changes executed by the IPCC, several other researchers have conducted localized simulations for the Southeast Asian region. Lal and Harasawa^{xxvi} used four GCMs to estimate the effect of climate change on temperature and precipitation in Asia for the periods 2049-2069 and 2070-2099. Their analysis of Southeast Asia included the region of 10° S – 20° N latitude and 95° E – 155° E longitude, which encompasses the countries that are the focus of this report, except for the northern-most sections of Laos and Vietnam. The authors ran the Japanese CCSR/NIES model, the Australian CSIRO model, the German ECHAM4 model, and HadCM2 under conditions of greenhouse gas forcing only and combined greenhouse gas and sulfate aerosol forcings. Ensemble results for the four GCMs showed a consistent increase in both temperature and precipitation across Southeast

Asia for both time periods. Due to increases in greenhouse gases only, the annual average temperature was predicted to increase by 2.15°C, the average "winter" season (December, January, and February) temperature was predicted to increase by 2.28°C, and the average "summer" season (June, July, and August) temperature was predicted to increase by 2.01°C for the 2049-2069 period. The inclusion of sulfate aerosol forcing in the GCMs caused a slight reduction in the magnitude of the expected temperature increases, to 1.72°C, 1.73°C, and 1.6°C for annual, winter, and summer average temperatures, respectively. In addition, the models predicted a uniform increase of 4.6 percent, 3.5 percent, and 3.4 percent in annual, winter, and summer average precipitation, respectively, for the period 2049-2069 due to increases in greenhouse gases. As with the temperature predictions, inclusion of sulfate aerosol forcing in the four GCMs resulted in a moderate reduction in the expected precipitation increase, to 1.0 percent, 2.9 percent, and 2.6 percent for annual, winter, and summer average precipitation, respectively. The temperature results of Lal and Harasawa are consistent with those of the IPCC MMD models, which also predicted little seasonal variation in the expected temperature increases across Southeast Asia. The seasonally uniform precipitation results of Lal and Harasawa are in contrast to those of the IPCC MMD models, however, which showed a variation in future precipitation changes for the rainy and dry seasons. The inconsistency of the precipitation estimates from these two studies underscores the difficulty in obtaining consistent precipitation forecasts from GCMs under conditions of future climate change.

Lal et al^{xxvii} continued their earlier work by simulating the temperature and precipitation effects resulting from climate change over small island states, including those of the Pacific Ocean, for the periods 2010-2029, 2049-2069, and 2070-2099. The authors ran the CCSR/NIES, CSIRO, ECHAM4, CCCma, and HadCM2 models under conditions of greenhouse gas forcing only and combined greenhouse gas and sulfate aerosol forcings. See M. Lal, H. Harasawa, and K. Takahashi, "Future climate change and its impacts over small island states," Clim. Res., 19 (2002):179–192 for results from the ensemble of five models for the Pacific Ocean Islands (the region $23^{\circ}S - 23^{\circ}N$ latitude and $120^{\circ}E - 145^{\circ}W$ longitude, which includes the Philippines and eastern Indonesia). Model results projected annual mean temperature increases of 0.93±0.12°C and 0.79±0.05°C due to increases in greenhouse gases and greenhouse gases plus sulfate aerosol, respectively, by 2010-2029. The models also predicted annual mean precipitation increases of 2.9±1.0 percent and 1.9±0.8 percent due to increases in greenhouse gases and greenhouse gases plus sulfate aerosol, respectively, by 2010-2029. Similar to the authors' earlier work in the Asia region, xxviii model results for the Pacific Ocean Islands showed a mostly uniform increase in both temperature and precipitation for the three simulated time periods of 2010-2029, 2049-2069, and 2070-2099 with little seasonal variation. The exception was slightly larger increases in precipitation during the summer season for the periods 2049-2069 and 2070-2099. The authors noted that regional precipitation is strongly dependent on local topography, particularly elevated terrain, which is typically not well represented in GCMs, and consequently there is significant uncertainty in their model projections of regional precipitation due to future climate change.

Although the IPCC MMD model results^{xxix} and the ensemble mean results of Lal and Harasawa^{xxx} and Lal et al^{xxxi} differed slightly from each other regarding the magnitude of projected seasonal precipitation in Southeast Asia, the models were generally internally consistent in the sense that they all predicted precipitation increases. Other researchers who have used a series of GCMs to estimate the future effects of climate change on precipitation in specific countries in Southeast Asia have obtained conflicting results.

For example, Boer and Faqih^{xxxii} examined the potential changes in future temperature and precipitation in Indonesia through 2080 using the CCSR, CSIRO, ECJAM4, CGCM1, and HadCM3 GCMs under the A2 and B2 emissions scenarios. Results showed an expected uniform increase in average temperature across the country of approximately 0.0344°C per year for the A2 scenario and approximately 0.0211°C per year for the B2 scenario. Precipitation changes varied by model and emissions scenario, however, as CCSR and CSIRO predicted rainfall increases, ECHAM4 and CGCM1 predicted rainfall decreases, and HadCM3 varied depending on the emissions scenario. Based on these results, the authors concluded that it was not possible to determine the specific effects of climate change on precipitation across Indonesia.

Variations in the intensity and occurrence of tropical cyclones (typhoons) due to climate change will also impact precipitation changes in regions of Southeast Asia north of approximately 10 °N latitude. There is significant uncertainty in future changes in tropical cyclone occurrence and intensity, however, due to the fact that few GCMs have the spatial resolution necessary to simulate synoptic scale patterns. The IPCC reports that in general, higher-resolution models that can simulate tropical cyclone characteristics predict that mean and peak precipitation intensities will increase in future tropical cyclones.

Projections of Future Changes in Monsoons and ENSO

Regional precipitation in Southeast Asia will be affected by future variations in monsoons due to climate change. Giorgi et al^{xxxiii} analyzed the global effects of climate change for the period 2071-2100 relative to 1961-1990 using nine GCMs run under the A2 and B2 emissions scenarios. The model results predicted a consistent increase in summer monsoon precipitation across Southeast Asia relative to the global mean average precipitation. Overall precipitation across the region was not expected to change, however, which suggests that rainfall will decrease in some areas and/or during seasons that are not impacted by the monsoon.

Bhaskaran and Mitchell^{xxxiv} examined the changes in Southeast Asian monsoon precipitation due to climate change for the period 1990 to 2100 using the Hadley Centre HadCM2 global climate model. Two scenarios of HadCM2 were used: forcing only from greenhouse gases represented by a 1 percent per year increase in CO_2 concentration, and with the addition of sulfate aerosol forcing. Overall, the model simulations indicated that monsoon-related precipitation will increase as CO_2 concentration increases, and monsoon genesis and intensity are sensitive to sulfate aerosol forcing. Specific results for the region between 5 °N and 25 °N latitude and 90 °E and 105 °E (roughly including Thailand, Cambodia, Laos, and Vietnam) indicated an expected 10-15 day delay in the monsoon onset date, but with no extension of the monsoon season for the period 2030 to 2070. The model simulations also predicted an increase of approximately 3-6 mm day⁻¹ in total daily precipitation and a substantial increase in frequency of intensity of areal mean precipitation for the same period, which, if realized, could lead to an increase in monsoon-related flooding across the region.

As previously noted, natural variations in monsoon frequency and intensity are tied to ENSO, so any future enhancement of ENSO associated with climate change will likely affect monsoon characteristics. Future changes in ENSO are very uncertain, however, because GCMs cannot accurately simulate past observed ENSO variations and thus simulations of future changes are suspect.^{xxxv} Paeth et al^{xxxvi} studied potential variations in ENSO and monsoons in the 21st century using a suite of 12 GCMs under six IPCC emissions scenarios. Model results projected a substantial warming of the eastern tropical Pacific Ocean of more than 5°C, which represented a change in the background state of ENSO. There was no compelling evidence in the model

simulations for wholesale changes in the frequency of El Niño and La Niña events in the 21st century, although results suggested that the intensity of ENSO events may increase. The authors concluded that the intensity of summer monsoons in South Asia may increase as a result of changes in ENSO due to future climate change, with the caveat that model uncertainty in simulating ENSO makes it impossible to draw any definitive conclusions.

Projections of Future Changes in Water Resources

Changes in temperature and precipitation in Southeast Asia will affect water resources. Tao et al^{xxxvii} studied the impact of climate change on global water resources for the period 2021-2030 using two Hadley Centre models. HadCM2 was run with forcing from greenhouse gases represented by a 1 percent per year increase in CO₂ concentration and sulfate aerosols, and HadCM3 was run under the same conditions as HadCM2 but with the addition of ozone changes and the indirect forcing of sulfate aerosols. The model results projected that annual mean temperatures will increase uniformly by 0.5-1.5°C across Southeast Asia by 2021-2030. Precipitation projections across the region for the same period were not consistent due to variations between the models. The HadCM2 ensemble mean predicted that annual mean precipitation will increase by 0-100 mm in southern Philippines, western Malaysia, Singapore, and western Indonesia; increase by 0-50 mm in northern Vietnam, Thailand, and Laos; decrease by 0-50 mm in Cambodia; decrease by 0-100 mm in southern Vietnam and eastern Malaysia; and decrease by 100-150 mm in northern Philippines and eastern Indonesia. HadCM3 results were similar, with the exception of a projected increase in annual mean precipitation of greater than 150 mm for most of Indonesia. The models were consistent in predicting an increase in annual mean potential evapotranspiration¹ of 0-100 mm across Southeast Asia by 2021-2030, which suggests that climate change may cause a net decrease in ecosystem water demand across the region. Furthermore, model projections showed little change in annual soil moisture deficit across Southeast Asia by 2021-2030, indicating that the region as a whole may not be susceptible to water shortages or water stress on local vegetation due to climate change. The models indicated that net increases in precipitation across parts of Southeast Asia due to climate change are likely to lead to increased surface runoff, however, which in turn may cause increased erosion, flooding, and water pollution. Surface runoff occurs when soil moisture exceeds soil's water-holding capacity. Changes in annual surface runoff predicted by the GCMs mirrored the precipitation predictions, with variations across Southeast Asia and among the models. Areas with the largest predicted increases in surface runoff included parts of Thailand, Philippines, Malaysia, Vietnam, Laos, and Indonesia.

Arnell^{xxxviii} estimated the global effects of climate change on water resources using the Hadley Centre HadCM2 and HadCM3 global climate models. All simulations included forcing from greenhouse gases represented as a 1 percent per year increase in CO₂ concentration from 1990 to 2100, with no sulfate aerosol forcing. Analysis focused on surface runoff, and model projections showed that by 2040, annual surface runoff will increase by greater than 150 mm per year in Thailand, Malaysia, Singapore, and the Philippines and decrease by 50 to 150 mm per year in Laos, Cambodia, Vietnam, and Indonesia. See Nigel W. Arnell, "Climate change and global water resources," *Global Environmental Change* 9 (1999): S31-S49 for a graphic representation of the change in monthly average runoff for Thailand as predicted by the HadCM2 ensemble mean (thick black line) compared to baseline conditions (shaded region). The increases in runoff

¹ The combined process of water *evaporation* from the Earth's surface and *transpiration* from vegetation.

were predicted to occur during the rainy season, from June through October. The magnitude of the predicted changes in surface runoff generated in this study is consistent with that of Tao et al,^{xxxix} although the specific locations where increases and decreases in surface runoff were predicted varied among the two studies.

On a regional scale, Jose et al^{x1} investigated the effects of climate change on water resources in the Philippines using the CCCM, UKMO, and GFDL GCMs run under conditions of 2×CO₂. Analysis focused on two major reservoirs, Lake Angat and Lake Lanao, which provide water for domestic use, irrigation, and hydroelectric power in the Philippines. The models predicted a uniform increase in average annual temperature of approximately 2-3°C at both reservoir locations. Predictions of precipitation change were not consistent, however; CCCM estimated a slight decrease in annual average rainfall while the UKMO and GFDL models predicted a slight increase at both reservoirs. The authors used the temperature and precipitation simulations in conjunction with a hydrological model to estimate the changes in future rainfall runoff to the two reservoirs. For Lake Angat, the predicted changes in runoff were -12 percent, 5 percent, and 32 percent for the CCCM, UKMO, and GFDL models, respectively. Predicted changes at Lake Lanao were -2 percent, -12 percent, and 7 percent for the CCCM, UKMO, and GFDL models, respectively. As might be expected, projected changes in runoff roughly correlated with projected changes in precipitation. The variations in the model projections underscore the difficulty GCMs have in simulating precipitation changes, particularly on a local scale. Any areas that see an increase in runoff could experience an increase in flooding, while decreased runoff could lead to water shortages. These results are comparable to an earlier study by the same authors that focused only on the effect of climate change on water resources at Lake Angat.^{xli}

A study published as part of the Assessments of Impacts and Adaptations to Climate Change^{xlii} used the HadCM3, CCC, and CSIRO GCMs with downscaling to determine the effect of climate change in 2020, 2050, and 2080 for the Pantabangan-Carranglan Watershed (PCW) on the island of Luzon in the Philippines. Model results showed that by 2020, mean daily precipitation is expected to increase by an average of 6.7 percent and mean daily maximum temperature is expected to increase by an average of 1.6 percent, compared to observed daily values for the period 1960-1990. These changes are expected to result in an increase in stream flow during the rainy season and a decrease during the dry season. The authors concluded that there will be a higher likelihood of floods during the rainy season and water shortages during the dry season in the PCW Watershed associated with future climate change.

Projections of Future Changes in Sea Level

As the global ocean warms, its volume will increase, and as a result, sea level will increase. Net global sea level rose by approximately 17 cm in the 20th century.^{xliii} The rate of sea level rise varies regionally, however, principally due to local variations in the balance between the density and circulation of the oceans. Changes in local ocean momentum flux are also important in the tropical Pacific.^{xliv} Patterns of coupled ocean-atmosphere variability, such as ENSO, also influence local sea level rise. Recent analysis of tide gauge records and data from the TOPEX/Poseidon satellite altimeter indicate that changes in sea level have varied across the tropical Pacific for the period 1950-2001.^{xlv} See J.A. Church, N.J. White, and J.R. Hunter, "Sea level rise at tropical Pacific and Indian Ocean islands," *Global Planet. Change*, 53, no. 3 (2006): 155–168 for trends in sea level for 1993-2001 using a blend of the tide gauge and satellite data. The largest recent increases in sea level in Southeast Asia have been observed near Indonesia

and the Philippines, while only moderate changes have been observed along the coasts of Thailand, Cambodia, and Vietnam. These recent rates of change in sea level are characteristic of natural interannual climate variability and are consistent with the trend toward more frequent and intense ENSO events that have been observed in the past 20 years.

The IPCC^{xlvi} has estimated regional future changes in sea level due to ocean density and circulation changes for the 21st century using the ensemble mean of a subset of 14 models from the MMD. Results for the projected sea level change in Southeast Asia for the period 2080-2099 relative to 1980-1999 for the A1B emissions scenario are shown in Figure 6. The regional sea level projections are given in relation to the average global sea level increase of 35 cm expected over the same period by IPCC for the A1B emissions scenario. Thus, Figure 6 shows that most of the seas around Southeast Asia are expected to rise approximately 0-5 cm above the global average value by the end of the 21st century, for a net increase of 35-40 cm. A few areas, such as the Southern Philippines and parts of Indonesia, are expected to observe decreases in sea level of 0-5 cm below the global average value, for a net increase of 30-35 cm. Any increase in sea level represents a significant change for Southeast Asia, which is comprised of low-lying coastal and island nations that will be severely impacted by rising ocean waters.



Figure 6. Projected local sea level changes in meters during the 21st century relative to the global average. Sea level change is calculated as the difference between averages for 2080-2099 and 1980-1999 from the ensemble mean of 16 GCMs using the A1B emissions scenario. The local seal level changes shown are above/below the global average sea level rise of 35 cm expected in the 21st century under the A1B emissions scenario. Regional sea level changes are attributed to changes in ocean density and circulation. 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. Jr. Miller, and Z. Chen (Cambridge: Cambridge University Press, 2007), http://www.ipcc.ch/ipccreports/ar4-wg1.htm.

Projections of Future Changes in River Delta Flooding and Salinity Intrusion

Sea level rise resulting from climate change will affect flooding and salinity intrusion of major rivers and deltas across Southeast Asia. Several researchers have examined these effects on the Mekong River Delta in southern Vietnam. The health of the Mekong Delta is important because it supports agriculture, particularly rice production, in Vietnam and Cambodia. Since 1997, 50

percent of rice production in Vietnam has been supported by the Mekong Delta.^{xlvii} Flooding of the Mekong Delta can be devastating on rice crops, while salinity intrusion reduces the amount of fresh water available for crop irrigation.

Khang et al^{xlviii} studied the effect of sea level rise on salinity intrusion in the Mekong River Delta during the dry season (December to June) using a coupled hydro-dynamic and advection dispersion model. Salinity intrusion during the dry season is a problem because fresh water from the Delta permits a dry season rice crop via irrigation, and this contribution is essential to Vietnam's rice production and export. The authors ran the model under conditions of the B2 emissions scenario, specifically considering the effects of a 20 cm increase in sea level and a 15 percent decrease in Mekong River flow by the mid-2030s. The authors measured salinity intrusion by identifying the extent of water with a salinity concentration of 2.5 g/L, which is the threshold value for reduction in rice yield by approximately 25 percent. Results from the model showed that by the mid-2030s, the 2.5 g/L saline front is likely to shift upstream by 10 km in the main Mekong River and by 20 km in the rice paddy fields during the dry season. Consequently, due to the associated loss in fresh water from the river for irrigation, the total reduction in land area for dry season rice cropping was estimated at approximately 71,000 ha.

Wassmann et al^{xlix} investigated the effect of sea level rise on flooding of the Mekong Delta during the flood season (August to November) using a hydraulic model. Similar to the work of Khang et al,¹ the authors ran the model under a scenario of 20 cm increase in sea level by 2030. Results showed that in October, at the peak of the flood season, high water discharge into the Mekong River is expected to increase water levels in the Mekong Delta by 11.9 cm, leading to substantial aggravation of annual flooding in the Delta region. The authors concluded that increases in sea level due to climate change will cause excessive flooding in tidally inundated areas of the Mekong Delta and longer periods of flooding in the central portion of the Mekong Delta, both of which will negatively impact rice production.

Impacts of Climate Change on Human and Natural Systems

Southeast Asia is susceptible to climate change for a variety of reasons. It has major populations concentrated along low-lying coastal areas, including the poor who subsist as smallholder farmers and fishermen,^{li} and it contains fragile and unique ecosystems. The economy of much of the region is dependent on vulnerable industries, such as agriculture, aquaculture, fishing, and tourism. In addition, many nations in Southeast Asia are undergoing rapid economic development, which will likely exacerbate the effects of climate change on human and natural systems.

Although the precise extent and magnitude of future climate change in Southeast Asia is uncertain, it has already begun to impact the following human and natural systems:

- Sea level
- River deltas
- Natural disasters
- Water resources
- Agriculture
- Forests and biodiversity

- Coastal ecosystems
- Coral reefs
- Diseases and human health
- Electricity demand in urban areas
- Human livelihoods and infrastructure

Nearly all of these systems are interrelated. For example, rising sea level causes saltwater intrusion into river deltas, which limits available fresh water and in turn impacts agricultural irrigation, drinking water availability, and population patterns. Climate change impacts on natural and human systems also have socioeconomic consequences on both micro and macro scales, which will affect the economic vitality of individual countries and the region as a whole.

Impacts of Sea Level Rise

As documented in the Model Projections section, sea level rose in the Southeast Asia region at rates of up to 3 cm per year for the period 1993-2001,^{lii} and sea level is projected to rise up to 40 cm in the 21st century.^{liii} Increases in sea level associated with climate change are particularly problematic for Southeast Asia, which is comprised of low-lying coastal and island nations. In fact, approximately 20 percent of the world's population of low-lying coastal regions is in Southeast Asia.^{liv} The effects of rising sea level on island nations, including the Philippines, Malaysia, Singapore, and Indonesia, whose borders are mostly or entirely coastline, will be most pronounced.^{lv} Although limited studies exist, recent estimates indicate that Indonesia could lose 2,000 small islands to sea level rise by 2030.^{lvi} The primary impacts of sea level rise are saltwater intrusion into estuaries and aquifers, coastal erosion, displacement of wetlands and lowlands, degradation of coastal agricultural areas, and increased susceptibility to coastal storms.

Climate change-induced sea level rise in Southeast Asia will likely have significant economic effects as well. A recent study estimates that rising ocean waters could cause the loss of 40,000 km² of land in Vietnam, particularly rice paddies, and necessitate re-engineering of port facilities and transportation systems. Taken together, these impacts could result in economic losses of up to 80 percent of the yearly Vietnamese GDP.^{1vii} In addition, coastal inundation of Indonesian cities associated with potential sea level rise in the 21st century is estimated to cause total economic losses of 1.8-2.3 billion.^{1viii} Sea level rise is expected to inundate 38 km² of the total land area of Jakarta, Indonesia, by 2030, resulting in economic losses of US\$1 billion.^{lix}

Impacts on River Deltas

Increases in sea level due to climate change will impact river deltas in a variety of ways, particularly by increasing flooding, coastal erosion, and salinity intrusion. The Red River and Mekong River Deltas in Vietnam appear to be particularly vulnerable to the impacts of climate change. Saltwater intrusion into the Red River Delta is already occurring, and as outlined in the Model Projections section, saltwater intrusion is expected to move farther inland as a result of climate change. Saltwater intrusion is a serious problem for agricultural regions, particularly rice paddies, since fresh water from river deltas is a primary source of irrigation water in Vietnam. Saltwater intrusion also damages coastal ecosystems and modifies fish and wildlife habitats.^{1x}

A recent study^{lxi} of the impacts of sea level change on global river deltas found that by 2050 there will be serious challenges to human occupancy of delta regions in Vietnam and Indonesia. Table 2 shows that almost 2 million people will be at risk from the impacts of sea level rise on

the Mekong River Delta in Vietnam, which will constitute approximately 6.5 percent of the total population dependent on the delta. Furthermore, the Vietnam coast is an area of active economic development that is experiencing a rapid increase in population density, which will exacerbate future effects of climate change on the health of the Mekong and Red River Deltas.^{1xii}

River Delta	Country	Population at Risk	% of Delta Population at Risk	% Delta Area Potentially Lost
Chao Phraya	Thailand	12,300	0.01	0.34
Mahakam	Indonesia	64,800	7.06	6.29
Mekong	Vietnam	1,910,000	6.51	5.82
Red (Hong)	Vietnam	70,500	0.85	0.95

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Table 2. Impacts associated with climate change on Southeast Asian river deltas in 2050. Source: Jason P. Ericson, Charles J. Vorosmarty, S. Lawrence Dingman, Larry G. Ward, and Michel Meybeck, "Effective sea-level rise and deltas: Causes of change and human dimension implications." *Global and Planetary Change* 50 (2006): 63-82.

Impacts of Natural Disasters

Natural disasters, such as floods, droughts, and typhoons, can have far-reaching impacts on a variety of sectors in Southeast Asia, including agriculture, water resources, coastal ecosystems, and infrastructure. The Philippines appears to be particularly susceptible to impacts associated with climate change-induced increases in natural disasters. The nation experiences a wide range of climate-related hazards, including tropical cyclones, floods, droughts, and landslides.^{lxiii} As a result, flood-prone settlements, agricultural lands susceptible to drought, highly erodible and unstable areas on steep slopes, and grasslands and forests near settlements that are susceptible to fire have been identified as regions in the Philippines that are at risk from climate-change enhanced natural disasters.

Incidents of flooding have grown worse recently in the Philippine capital of Manila. Flooding in Manila is caused by a combination of climate-change induced sea level rise (1 to 3 mm per year), land subsidence (3 to >10 mm per year) associated with over-extraction of groundwater, and natural deltaic subsidence. Currently, even moderate rains can cause flooding in the Manila area, and some locations are left inundated for weeks or months at a time.^{lxv}

Impacts on Water Resources

Climate change is expected to impact the supply and quality of fresh water in Southeast Asia, which in turn will have far-reaching impacts on agriculture, coastal ecosystems, and population growth. Heavy seasonal monsoon rainfall in Southeast Asia provides abundant fresh water, but increases in agricultural use, inadequate planning and misuse, and deforestation have led to water shortages in recent years, particularly in dry seasons.^{lxvi} Climate change will likely exacerbate these effects. Recent observed increases in temperature have already contributed to increased evapotranspiration in water bodies, which results in decreased fresh water availability.

Much of Southeast Asia's water supply and water quality are sensitive to small changes in the frequency and distribution of precipitation. Recent changes in precipitation patterns have already been linked with increases in runoff, erosion, flooding, and associated impacts on surface water and groundwater in Southeast Asia.^{lxvii} Climate change-induced variations in precipitation patterns, such as delays in the onset of the monsoon or a shift toward heavier, less frequent precipitation events, are therefore expected to have significant impacts on water resources in the

region.^{xxxiv} Falling water levels in many constructed reservoirs, associated with changes in precipitation patterns and droughts in ENSO years, have already led to decreased water availability and decreased hydroelectric power production.^{lxviii}

Fresh water resources on island nations of Southeast Asia are especially vulnerable to any variability in precipitation because many island populations rely on rainwater collection for their supply of fresh water. Droughts that are associated with periodic ENSO events disrupt fresh water supplies, and any increase in frequency or intensity of droughts associated with future climate change could have severe impacts on water resources.^{lxix} Watersheds on the island of Java are more vulnerable to the effects of climate change than other islands in Indonesia.^{lxx} Although not an island, Singapore is also vulnerable to variability in precipitation patterns, because its water supply is based upon reservoirs which are significantly impacted by short-term decreases in precipitation.^{lxxi}

Impacts on Agriculture

Agriculture is a major component of the economy in many nations of Southeast Asia. Recent increases in population and incomes have changed demands for agricultural products, which has led to increases in production of domestic consumption crops, such as grains and animal feed, and industrial crops, such as palm oil and natural rubber. These changes have been accompanied by the conversion of huge areas of land for agricultural purposes.

Future climate change will have a significant impact on agriculture in the region, particularly rice and corn production. Rice is the most important food crop across Southeast Asia and accounts for more than 80 percent of total grain production in nearly every country in the region;^{lxxii} corn is also grown in some key locations, such as the Philippines. Rice and corn crops are very susceptible to climate variability, particularly due to flooding, tropical cyclones, El Niño-induced droughts, and the salinization of coastal waters.^{lxxiii} For example, for the period 1968-1990, 48 percent of the losses in rice and corn production in the Philippines were caused by tropical cyclones and floods, 33 percent were caused by drought, and 18 percent were caused by weather-related incidents of pests and diseases.^{lxxiv}

In theory, temperature increases associated with climate change should cause a northward expansion of growing areas and a lengthening of the growing season. Rising atmospheric CO_2 levels are expected to stimulate plant photosynthesis, which would result in higher crop yields. However, increased heat stress on plants in a warmer climate may negate the effects of higher CO_2 levels, since plants are very sensitive to air temperature. Many crops in the tropics are already grown in conditions near the maximum temperatures they can endure, and even small changes in temperature will decrease their productivity.^{1xxv} For example, Peng et al^{1xxvi} found that during the period 1979-2003, a 1°C increase in growing season minimum temperature during the dry cropping season (January – April) decreased rice yield by 10 percent at Laguna, Philippines. Higher minimum temperatures may benefit some crops, however, particularly those in upland regions and higher latitudes. Any increases in coastal or river delta flooding and salinity intrusion due to climate change will likely reduce future crop yields.

In an attempt to quantify the effects of climate change on crop yield in Southeast Asia, several researchers have used GCM climate simulations in conjunction with crop models. Matthews et al^{lxxvii} investigated the possible changes on rice production in Asia caused by increases in atmospheric CO₂ and temperature due to climate change using the GFDL, GISS, and UKMO GCMs. The models were run using 300 ppm (GFDL, GISS) and 323 ppm (UKMO) of CO₂ as a

baseline concentration $(1 \times CO_2)$, and future climate change was simulated as $2 \times CO_2$. Changes in rice crop production were estimated using two rice crop simulation models in conjunction with the GCMs. The crop models were calibrated for the *indica* rice ecotype that is prevalent in Indonesia, Malaysia, the Philippines, and Thailand. Overall, results indicated that rice yields across Asia are directly correlated with atmospheric CO_2 concentrations but indirectly correlated with temperature. In Southeast Asia, the models predicted clear increases in total rice production of up to 25 percent for Indonesia and Malaysia, compared to 1993 production levels. Model predictions were split for the Philippines and Thailand, however, with a modest increase in rice production of approximately 6-14 percent predicted by the GFDL model and a decrease in rice production of approximately 1-12 percent predicted by the GISS and UKMO models. These results suggest that the enhancing effect of increasing atmospheric CO_2 concentrations on rice growth is likely to be more important in Indonesia and Malaysia, while the negative effect of increasing temperatures on rice growth is likely to dominate in the Philippines and Thailand.

Buan et al^{lxxviii} studied the potential effects of climate change on rice and corn crops in the Philippines using the CCCM, GFDL, GISS, and UKMO GCMs in conjunction with rice and corn crop models. The GCMs simulated changes in total rainfall, solar radiation, and maximum and minimum temperature for the first and second cropping seasons at six locations in the Philippines based on $2 \times CO_2$. The six sites used in the study represented the major rice and corn growing areas in the Philippines, with a range in elevation of 22-302 meters above sea level. The GCMs predicted an increase in temperature at all six sites for both cropping seasons, but estimations of rainfall and solar radiation varied by model, location, and cropping season. Model results projected consistent decreases in corn yield of approximately 11-15 percent at all locations for both cropping seasons, but the predictions of changes in rice production were very inconsistent, with increases at some locations and decreases at others.

Amien et al^{lxxix} studied the effects of climate change on rice yields in Java, Indonesia, through 2050 using the GISS GCM in conjunction with a rice crop growth simulation model. Rice is a staple food in Indonesia, and approximately 60 percent of rice grown in the country comes from the fertile volcanic ash soils on Java.^{lxxx} Analysis focused on Ngawi in East Java, an inland location on the flood plain of the Bengawan Solo River, and Sukamandi in West Java, a lowland coastal location. These sites are two principal rice production areas in Indonesia. Climate change was represented in the GCM by $2 \times CO_2$ equal to 555 ppm. The GISS simulations predict that in the 2030s decade, monthly rainfall at Sukamandi and Ngawi will increase by 10.3 percent and 6.2 percent, respectively; maximum temperature will increase by 7.2 percent and 6.9 percent, respectively; and solar radiation will increase by 1.1 percent at both locations. Based on these projected changes in meteorological conditions, rice yield at Sukamandi is expected to decrease by 18 percent in normal years and remain unchanged in El Niño years; at Ngawi, rice yield is expected to decrease by 17 percent and 11 percent in normal years and El Niño years, respectively.

In a follow-up study, Amien et al^{lxxxi} continued their analysis of rice yields in Java, Indonesia, using the GFDL and UKMO GCMs in addition to the GISS GCM. Analysis shifted to Mojosari in East Java, an inland site on the flood plain of the Brantas River, and Pusakanegara in West Java, a lowland coastal site. As in their previous study, climate change was represented in the GCMs by $2 \times CO_2$ equal to 555 ppm. Climate projections from the GCMs were incorporated into a crop growth simulation model to determine the effects on crop yield. Rice yield results were similar to the earlier study, with reductions in yield predicted in both East and West Java due to

climate change, although higher yield reductions were projected due to natural interannual climate variability, such as that associated with ENSO. The authors concluded that adoption of heat-tolerant rice varieties by farmers in Indonesia could compensate for expected yield losses due to climate change.

Most recently, Naylor et al^{lxxxii} investigated the potential effect of climate change on rice agriculture in Indonesia through 2050 using a suite of GCMs and a risk assessment model. Analysis focused on the regions of West/Central Java and East Java/Bali, which account for approximately 55 percent of Indonesia's annual rice production. The authors examined the impact of climate change on natural climate variability, particularly ENSO. El Niño events typically cause a delay of up to 2 months in the onset of the monsoon in Indonesia, which delays planting of the rice crop. As a result, a 30-day delay in monsoon onset was selected as a critical threshold in the study.

Analysis of observed data for 1983-2004 showed that the probability of a 30-day delay in monsoon onset was 18.2 percent for West/Central Java and 9.1 percent for East Java/Bali, which corresponded to 11 percent and 6.5 percent reductions in rice production, respectively. The authors used a set of 20 empirically downscaled CCMs from the IPCC MMD to simulate future changes in precipitation under the A2 and B2 emissions scenarios through 2050. Results showed that, in most cases, a delay in monsoon onset is likely to occur more frequently in 2050 than it has for the past 30 years. For example, under the A2 scenario, the probability of a 30-day delay in monsoon onset in 2050 is expected to be 23-33 percent for West/Central Java and 19.8-40 percent for East Java/Bali. Model projections also suggested that there will be about a 10 percent increase in precipitation later in the crop year (April – June) and a large decrease of up to 75 percent in precipitation later in the dry season (July – September), which could have serious negative consequences for rice agriculture in Indonesia.

As these modeling studies demonstrate, crops in Southeast Asia are very susceptible to drought, flooding, and storms associated with natural interannual climate variability caused by ENSO. In recent years, delayed onset of the rainy season, by up to a month in ENSO years, has been observed to cut rice yields by up to 11 percent in parts of Indonesia.^{lxxxiii} Potential increases in the frequency and severity of climate extremes under future climate change are expected to cause greater losses, which will be exacerbated if extremes occur during critical stages of crop growth. In order to address these issues, Lansigan et al^{lxxxiv} investigated the potential impacts of climate extremes on agriculture by comparing crop-sowing yields for El Niño and non-El Niño vears in the Philippines. Results indicated that during El Niño years, the variability in weather patterns moved the sowing date for rice (normally near Julian day 173) to as early as Julian day 137 (mid-May) or as late as Julian date 229 (mid-August), representing a major change in the cycle of planting and harvest. Results also showed that the variability of precipitation in El Niño years reduced crop yield. Typically, an El Niño year was marked by a shorter, more intense wet season, which decreased crop growing time, subjected crops to stress from excess water, and consequently caused a crop loss of 52-81 percent. High temperatures also significantly decreased rice production, particularly if they occurred during early phases of development.

Crop water requirements were significantly altered under El Niño regimes, because changes in temperature and precipitation altered rates of plant evapotranspiration. In the Philippines, results showed that El Niño was associated with a 20-50 percent reduction in rainfall, requiring increased crop irrigation. These results are consistent with the modeling simulations of Amien et al^{lxxxv} that projected similar changes on rice yields in Java, Indonesia due to ENSO-related
climate variability. Thus, it is likely that natural climate variability will continue to cause significant impacts on Southeast Asian agriculture in coming decades, and any increases in the frequency or severity of climate variability due to climate change will serve to aggravate these natural effects.

On a more local scale, a recent study^{lxxxvi} found that water availability is the key parameter affecting mangosteen growth in Thailand. Higher mangosteen yields are associated with increased water available to plants during fruiting, which suggests that impacts on precipitation associated with future climate change will be important for the mangosteen industry.

Increases in temperature have also been related to increased outbreaks of agricultural pests and diseases, such as rice stem borers and twisting disease. Climate change is expected to exacerbate these outbreaks and necessitate the more frequent use of stronger pesticides to protect crops.^{lxxxvii}

Impacts on Forests and Biodiversity

In 2005, the biologically diverse forests of Southeast Asia represented 5.1 percent of the total forest area in the world, and they were a major source of global forest products, accounting for 50 percent of total forestry exports from Asia and the Pacific.^{lxxxviii} Degradation and unsustainable practices, such as illegal logging and conversion of native forests to palm oil plantations or agricultural lands, have made many Southeast Asian forests particularly vulnerable to climate change. Burning and clearing of forests has increased the likelihood that they will not be able to adapt to projected changes in temperature and precipitation. The combination of human stresses and climate change is expected to increase the incidence of forest fires and make recovery from fires more difficult.^{lxxxix} In addition, habitat destruction in Asian boundary forests is increasing. Individual plant and animal species are often located in narrow bands of suitable environmental conditions, and their ability to tolerate new conditions associated with climate change will determine their future survival.^{xc}

Teak wood is an important economic product in Indonesia and the Philippines, and the teak tree is known to be especially sensitive to increases in temperature and changes in precipitation. Such dependence of individual species on existing climate conditions is a major threat to forest health, as flora, fauna, and pests are expected to adapt at different rates, and with varying levels of success.^{xci} Overall, climate change is expected to transform the types and species of forest vegetation in Indonesia.^{xcii}

Although variations in temperature and precipitation due to future climate change will impact forests across Southeast Asia, only a few limited studies are available that project the potential effects on specific species and regions. Boonpragob and Santisirisomboon^{xciii} investigated the potential changes in forest type and distribution in Thailand due to climate change using the UK89, UKMO, and GISS GCMs. The models were run using 320 ppm of CO₂ as a baseline concentration $(1 \times CO_2)$, and future climate change was simulated as $2 \times CO_2$. Model projections indicated that increases in temperature and variations in precipitation in Thailand due to climate change will reduce areas of subtropical forest and subtropical wet forest, and increase the areas of tropical dry forest, tropical moist forest, and tropical wet forest. Overall, the model simulations suggested that climate change will likely cause the expansion of tropical dry forest into subtropical forest in the northern part of the country, and the cause replacement of subtropical forests with tropical forests in the southern part of the country.

Koskela^{xciv} examined the effects of predicted climate change on the growth rate of Merkus pine trees in Thailand. Merkus pines grow across Southeast Asia at elevations less than 1200 meters,

including parts of Thailand, Laos, Cambodia, Vietnam, and the Philippines. Koskela used a gasexchange model to estimate changes in trees' gross photosynthesis, transpiration, and stomatal conductance, and a carbon- and nitrogen-balance model to simulate the growth of young trees. The models were run under several climate change scenarios involving variations in temperature, precipitation, and atmospheric CO_2 . The models were used to simulate Merkus pine growth rate changes at two representative locations in Thailand: Ban Wat Chan, a high-altitude site in the northern highlands and Surin, a low-altitude site on the northeastern Khorat Plateau. Results showed that rising temperature and atmospheric CO_2 levels associated with climate change are expected to increase annual photosynthesis and transpiration rates in pine seedlings, and cause concurrent large increases in total tree biomass and height. These results suggest that future climate change could enhance growth of Merkus pine trees and shorten the seedling stage. The author noted that actual tree growth in the future will be dependent on rainfall variability, since prolonged periods of drought could offset any enhancement in tree growth due to higher atmospheric CO_2 levels.

Booth et al^{xcv} assessed the possible effects of climate change through 2050 on two tree species in Vietnam using a climatic mapping program model, a simple plant growth simulation model, and a process-based tree growth simulation model. Each model was run under a range of climate change scenarios involving variations in temperature, precipitation, evapotranspiration, and atmospheric CO_2 . The authors analyzed two tree species that they considered to be representative of those important for forestry in Vietnam: Styrax tonkinensis, a native species used for pulp and perfume ingredients, and Acacia mangium, an introduced species used for pulp and fuel. Results from the climatic mapping program indicated that areas in Vietnam which are climatically suitable for growing S. tonkinensis will likely decrease as a result of future climate change. The simulation models projected that increases of 1-2°C in mean annual temperature in the vicinity of Hanoi will decrease S. tonkinensis growth rate by approximately 5-22 percent, since the species is not well adapted to warmer growing conditions. The authors noted that it was not possible to identify which of the four variables modeled in their study-temperature, precipitation, evapotranspiration, or atmospheric CO₂—had the most dominant effect on plant growth under future climate change conditions. They concluded that climate change is likely to cause significant alterations in the Vietnamese forestry industry, and these effects will be related to shifts in suitable growing regions rather than variations in tree yield.

Changes in forestry and vegetation due to climate change will likely impact species biodiversity in Southeast Asia. To investigate the possible future changes in global biodiversity, Malcolm et al^{xcvi} calculated changes in habitat areas and associated extinctions of endemic plant and vertebrate species in 25 biodiversity "hotspots," including the Philippines. The authors used a suite of 14 GCMs run under conditions of $2\times CO_2$ in conjunction with two global vegetation models. Biodiversity hotspots were defined as regions that are home to a large number of the world's species per unit land area and have suffered significant natural habitat loss. Biomes (vegetation types) were used as proxies for natural habitats in the study. Modeled habitat loss for the Philippines was 3-32 percent and associated mean required migration rate was 59-736 meters per year, depending on the vegetation model and biome type. Although these changes in habitat area and migration rate are from one limited study for a specific area in Southeast Asia, the results suggest that climate change likely poses a threat to biodiversity in the region.

Impacts on Coastal Ecosystems

Rapid development of coastal megacities has led to highly concentrated population surges and

economic activity in recent years, with roughly 80 percent of the population of Southeast Asia living within 100 km of the coasts in 2005. Coastal regions are major contributors to the regional economy because they are central to tourism, fishing, and aquaculture.^{xcvii}

Mangroves are a key component of Southeast Asian coastal ecosystems that will be affected by future climate change. Mangroves are critical to the region because they provide habitats for fish, help maintain coastal water quality, protect shorelines from erosion and storm surges, and provide products and services for human communities. Because of their importance, mangroves are very valuable. For example, the value of Malaysian mangroves for storm protection and flood control is estimated at US\$300,000 per kilometer of coastline, based on the cost of replacing the mangroves with rock walls.^{xcviii}

There are several climate change-related effects that are expected to impact mangroves, both positively and negatively. Sea level rise will impact mangroves to some degree, depending on the rate of mangroves' ability to migrate landward to maintain their preferred hydroperiod. Increases in intensity and frequency of storms related to climate change may intensify damage to mangrove forests through defoliation, stress, and soil impacts. Increased precipitation in tropical areas due to climate change may increase mangrove range and biodiversity. In addition, mangroves are likely to experience increased growth rates in response to increased atmospheric CO_2 levels.^{xcix}

On Olango Island in the Philippines, climate change is expected to cause destruction of mangroves, deaths of coral reefs, and loss of feeding grounds for migratory birds.^c Other ecosystem impacts in the Philippines associated with future climate change include coral bleaching, seaweed and sea grass impacts, shoreline erosion, and aggravation of marine diseases. Ecosystem effects will be driven by changes in ocean circulation, marine biogeochemistry, and increasing sea surface temperatures.^{ci}

Along the Vietnam coast, climate change is expected to result in loss of habitats for many rare and endemic species; destruction of coral reefs, mangroves, and sea grass beds; and a resulting decrease in living resources for residents.^{cii}

Increases in temperature are also projected to negatively impact fishing and aquaculture, with decreased abundance of large predator fish and significant decreases in the viability of fish larvae in warmer waters.^{ciii}

Impacts on Coral Reefs

Sustainable fisheries and coral reef systems are critical to the livelihoods of millions of people across Southeast Asia. The region has more coral reefs than any other part of the world, with a total of over 100,000 km², equivalent to 34 percent of the world's total. The reefs have substantial economic importance—the value of the region's sustainable coral reef fisheries alone is estimated at US\$2.4 billion per year. Coral reefs are also important for food security, employment, tourism, pharmaceutical research, and shoreline protection.^{civ}

Increases in atmospheric CO_2 concentration associated with climate change affect ocean water chemistry and have a direct impact on the growth of corals. Silverman et al^{cv} studied these effects using a coupled climate/carbon cycle model. Coral reefs grow by precipitating calcium carbonate (CaCO₃) from ocean water, but the chemistry of the oceans is being changed by rising atmospheric CO_2 levels that are causing the oceans to become more acidic. Results from the model study show that most coral reefs are currently precipitating 20-40 percent less CaCO₃

compared to pre-industrial times, and reefs located in the warm water pool of the Western Pacific show the strongest response to changes in water chemistry and temperature associated with climate change. When atmospheric CO_2 concentrations reach 560 ppm, which represents a doubling of CO_2 levels since pre-industrial times, all coral reefs are expected to stop growing and begin to dissolve. Present atmospheric CO_2 concentrations are approximately 380 ppm, and if emissions continue at the current rate, atmospheric levels will reach 560 ppm by the mid-22nd century.^{cvi} The potential widespread reduction in the number and extent of coral communities due to the climate change-induced decline in coral skeleton growth rates will have devastating impacts on coastal marine ecosystems and the various industries that are dependent on coral reefs.

Increasing sea surface temperatures associated with climate change are also a significant threat to the health of coral reefs in Southeast Asia. Elevated sea surface temperatures cause coral bleaching, which is the loss of color due to stress-induced expulsion of algae or loss of pigmentation of algae within the corals. The 1997-1998 ENSO caused the largest worldwide coral bleaching event ever recorded, damaging or destroying an estimated 18 percent of Southeast Asia's coral reefs. An increase in ocean water temperatures of only 1-2°C above the normal threshold temperature for a few weeks can cause a bleaching event, and extreme or prolonged temperature anomalies, such as those expected from future climate change, can cause significant coral mortality.^{cvii} Increased temperatures in recent years have significantly increased coral reef bleaching in the region, notably in the vast and diverse reefs of Indonesia, the Philippines, and Thailand.^{cviii}

Mass bleaching and mortality of corals has been widespread since the 1980s, but the magnitude varies significantly and is correlated with "hot spots" of sea surface temperature. Corals in accelerated warming regions will likely be impacted sooner than predicted by global climate change models. Impacts will be less severe and occur more slowly for corals in waters that are anomalously cooler than the global average, such as those around Indonesia.^{cix}

The reefs of Southeast Asia, particularly near Indonesia and the Philippines, are already degraded by pollution, sediment-laden runoff, destructive fishing practices, and other human impacts;^{cx} all of these effects will be compounded by climate change. Southeast Asian reefs do have several characteristics that make them more favorable for recovery compared to other ocean reefs, however, such as high levels of biodiversity, large-scale through-flow of Pacific Ocean water, and nearby reef systems to aid in reproduction. Impacts on humans as a result of coral damage and destruction due to climate change include lost or reduced tourism and fishery activities, and more difficult to quantify aspects such as shoreline damage.^{cxi}

Guinotte et al^{cxii} studied "marginal" coral reefs in the Pacific basin, which are those reefs considered to be living at the extremes of tolerable environmental limits. Results showed that corals in Southeast Asia that are most likely to become marginal due to increasing sea surface temperatures by 2069 are those in the Philippines, Gulf of Thailand, and Andaman Sea.

Recent country-specific impacts on coral reefs include the following:^{cxiii}

• Thailand has an estimated 1,800 km² of coral reefs in the Gulf of Thailand and the Andaman Sea. Sea surface temperature increases along Thailand's coasts have been particularly pronounced, such as near Phuket, where the sea surface temperature increased at a rate of more than 0.02°C per year between 1981 and 1999. As a result of the warming waters, coral reefs along Thailand's coasts have experienced significant bleaching episodes, especially in

the Gulf of Thailand. Existing pressures due to economic development, such as sedimentation and wastewater pollution associated with tourism, are expected to compound climate change pressures on reefs. Some coral reefs around small islands are currently under only minimal threat from existing pressures.

- The coral reefs of Cambodia and Vietnam are some of the most threatened in Southeast Asia; over 95 percent are threatened by existing pressures such as overfishing, land use changes, and high population density.
- There are over 350 species of coral in Malaysia. Over 85 percent of Malaysia's reefs are currently threatened by existing pressures such as shipping lanes, harmful fishing practices, and land use changes.
- Singapore has many fringing and patch reefs around both its main island and small offshore islands. Singapore's total coral reef area is estimated to be about 54 km² and includes more than 197 hard coral species. These reefs are also some of the most threatened in Southeast Asia, with over 95 percent threatened by existing pressures, including land reclamation and development.
- Indonesia has approximately 51,000 km² of coral reefs, and over 85 percent are currently threatened by existing pressures such as overfishing and land use changes. Indonesia's coral reefs provide annual economic benefits estimated at US\$1.6 billion per year. The greatest diversity of coral reef fish in the world is found in Indonesia, with more than 1,650 species in eastern Indonesia. Monitoring shows that the nation's reef conditions are currently declining. The 1997-1998 El Niño killed up to 95 percent of coral around certain Indonesian islands. Some areas have rebounded remarkably, possibly due to anomalously cooler waters in the area around Indonesia.
- The Philippines' coral reefs are severely threatened by existing pressures including overfishing, destructive fishing practices, agriculture, and aquaculture. The Philippines' approximately 26,000 km² of coral reefs contain extremely diverse species, and they provide annual economic benefits estimated at US\$1.1 billion per year. The first ever mass-bleaching event in the Philippines was reported in 1998-1999; it proceeded nearly clockwise around the Philippines and was correlated with anomalously high sea-surface temperatures.

Impacts on Diseases and Human Health

Climate-related health risks in Southeast Asia include increases in vector-borne disease, heat stress, food stress, and air pollution. Studies suggest that disease outbreaks in the region, including malaria, dengue, diarrhea, and cholera, are linked with climate events such as droughts and floods, which are in turn strongly related to ENSO events. Changes in temperature and precipitation patterns have already been linked to increases in dengue fever and malaria in Indonesia, Thailand, and Vietnam.^{cxiv}

Mosquito populations will be affected by variations in temperature and precipitation associated with future climate change, and thus the incidence of mosquito-borne diseases such as dengue fever and malaria are likely to be affected as well. Environmental conditions strongly influence the growth and survival of mosquitoes. The optimum temperature range for mosquito survival is 20-25°C, and rainfall is critical for mosquito reproduction because standing water is necessary for several of their life stages. Flooding due to excessive precipitation however, can disrupt mosquito larvae development.^{cxv}

Hopp and Foley^{cxvi} modeled the response of *Ae. aegypti*, the principal mosquito carrier of dengue fever, to observed climate variations for the period 1958-1995 in order to determine how future climate change may impact the incidence of worldwide dengue fever cases. They found that there was a strong relationship between mosquito larvae density and temperature, precipitation, and relative humidity. Results showed that for countries in Southeast Asia, cases of dengue fever are strongly dependent on climate-induced variations in mosquito densities. As a result, it is likely that increases in temperature and precipitation expected from future climate change in Southeast Asia will cause increased incidence of dengue fever across the region, in the absence of preventive measures to control the spread of the disease.

Martens et al^{cxvii} conducted a similar study that investigated the potential impact of global climate change on malaria risk. The authors predicted changes in malaria epidemic potential for the 21^{st} century by using temperature and precipitation output from the UKMO GCM run under two emissions scenarios in conjunction with an integrated linked-system model. Analysis focused on the *P. vivax* and *P. falciparum* mosquito species. The authors concluded that temperature and precipitation are the main climate variables that affect malaria transmission. Model results indicated that the incidence of malaria infection is sensitive to future climate change in Southeast Asia, and as a result, an increased rate of malaria infection is likely across the region in the 21^{st} century.

Projected increases in flooding due to changes in precipitation patterns and sea level rise are expected to increase the risk of water-borne disease such as dermatosis, amoebiasis, cholera, giardia, shigellosis, and typhoid. Residents of Southeast Asia already have higher risks of mortality and morbidity from water-borne diseases than in many other parts of the world, and climate change is expected to exacerbate these risks.^{cxviii}

Heat is also a public health threat, especially among the elderly and very young. Chronic exposure to excessive heat has been linked to increased incidence of cardiovascular and respiratory diseases. Researchers have noted that humans may be capable of adapting to heat associated with climate change, but the response time cannot be predicted.^{cxix}

A recent study^{cxx} found that human health impacts from climate change in the Philippines include blooms of toxic marine micro-organisms which can lead to dietary constraints and even poisoning, increases in heat stroke and vector-borne diseases, and population dislocation. Although this study was focused on the Philippines, the impacts are applicable across the Southeast Asian region.

Impacts on Electricity Demand in Urban Areas

Future increases in temperature and relative humidity associated with climate change will impact electricity demand across Southeast Asia, particularly in urban areas where air conditioning is more common. In order to determine the effect of climate change on temperature and associated electricity demand in Thailand through 2080, Parkpoom and Harrison^{cxxi} ran the HadCM3 general circulation model under four integrations that corresponded to the A1, A2, B1, and B2 emissions scenarios. These four scenarios were selected in order to represent the range of future socioeconomic developments in Thailand. Model analysis focused on the Bangkok metropolitan area, since 70 percent of Thailand's electricity demand is concentrated there. An initial linear regression analysis found that temperature is the most significant weather variable that affects electricity demand in Thailand. The model simulations were run to predict temperature increases due to climate change, and that information was fed into an electricity demand sensitivity model

in order to estimate the concomitant increases in electricity demand. Results showed that annual mean temperature is expected to increase by approximately 0.46-0.67°C in the 2020s (2011-2040) and 1.1-1.9°C in the 2050s (2041-2070) in Thailand under the four climatology scenarios. These temperature increases translate into an expected increase in peak electricity demand of 1.0-3.1 percent in the 2020s and 2.8-8.5 percent in the 2050s, with the highest demand during the summer season. Variations among model output corresponding to the four climatology scenarios became more pronounced as time increased. The authors concluded that the potential changes in electricity demand predicted by the model runs are significant and likely necessitate substantial investment in electrical power plant capacity to meet future demand. Nevertheless, these projected increases may only be a small portion of what is expected to occur over the next few decades due to economic development. For example, electricity consumption in Malaysia has been increasing on the order of 4-8 percent per year since 2001, and this rate is expected to continue.^{cxxii} Thus, a 1-8 percent increase in electricity demand in Thailand over the next 60 years associated with climate change may be only a small fraction of the total increase in demand due to general economic development, urbanization, and increases in manufacturing.

Impacts on Human Livelihoods and Infrastructure

Livelihoods in many parts of Southeast Asia, particularly in less urban areas, are heavily dependent on natural resources. Whether derived from fisheries, coral reefs, forests, agriculture, or tourism, residents are sensitive to impacts on these natural resources from climate change.^{cxxiii}

In the Philippines, climate change will heavily impact coastal-dwelling Filipinos, who are highly dependent on coastal resource related livelihoods, such as fishing, seaweed cultivation, aquaculture, shell collecting, and tourism.^{cxxiv} Population resettlement options in Manila are hindered by residents' strong cultural connections to lifelong homelands, particularly among impoverished populations.^{cxxv}

Climate-related increases in sea level and ecological perturbations related to extreme weather events will compound anthropogenic and climate change-related pressures, such as shortages in drinking water on small islands. These pressures could increase human migration to the mainland or larger islands.

Coastal erosion and inundation of coastal zones has increased across the region in recent years, damaging infrastructure and natural resources. Thailand's coastline is already observed to be eroding at a rate of 15-25 meters per year in some places.^{cxxvii} In Indonesia, adaptation to new livelihoods and resettlement as a result of increased coastal inundation associated with sea level rise will be particularly difficult for very low-income households with little social safety net and other cultural constraints. Impacts from inundation include physical damage to houses, and social damage such as interruption of school and commerce. In the city of Makassar, for example, the estimated damage to 4,000 houses from sea level rise in 2000-2002 was approximately US\$11 million. Entire sections of communities in coastal Indonesia are already being abandoned because of frequent inundation, often within "unplanned" housing communities containing highly impoverished residents. Climate change is expected to exacerbate these problems.^{cxxviii}

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. Adaptive capacity is defined by the IPCC^{exxix} 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." 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, for example, floods or droughts. Other components include a level of education sufficient for people to 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^{cxxx} 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.

The Adaptive Capacity of Southeast Asia in a Global Context

Researchers have only recently taken on the challenge of assessing adaptive capacity in a comparative, quantitative framework. A global comparative study^{cxxxi} of resilience to climate change (including adaptive capacity) was conducted using the Vulnerability-Resilience Indicators Model (VRIM – see box on page 44).

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:

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).

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.

The adaptive capacities for a sample of 10 countries from the 160-country study are shown in Figure 7 for the base year of 2005. These countries represent a wide range of adaptive capacity; of note for the Southeast Asian region, Indonesia ranks 45th (high in the second quartile) and the Philippines ranks 91st (high in the third quartile). Any country-level analysis must take into account the comparative ranking of the country in the 160-country group.

Figure 8 shows the contribution of each variable in the model to the overall ranking of adaptive capacity. Slight differences occur in the contribution of the variables among the countries due to the overall methodology, as described in the box below. Indonesia ranks third because of its relatively high rankings in most areas; the exceptions are a very low ranking in GDP per capita and a moderately low ranking in non-managed land. The lower overall rank of the Philippines stems principally from low rankings in the equity index and dependency ratio.

Figure 9 shows projected adaptive capacity growth over time for the 10-country sample. Projections are made for two scenarios, with rates of growth based on the A1 emissions scenario. Both modeled scenarios feature moderate population growth and a tendency toward convergence in affluence, featuring market-based solutions, rapid technological progress, and improving human welfare. The scenarios used in this study differ in the rate of economic growth: one models high-and-fast economic growth and the other models delayed growth. In the delayedgrowth scenario, Indonesia showed strong growth in adaptive capacity and is projected to





Figure 7. Adaptive capacity for a sample of 10 countries for the base year of 2005. Source: Based on E.L. Malone and A.L. Brenkert, "Vulnerability, sensitivity, and coping/adaptive capacity worldwide," *The Distributional Effects of Climate Change: Social and Economic Implications*, M. Ruth and M. Ibarraran, eds., Elsevier Science, Dordrecht (in press).

overtake Libya by 2035. The Philippines showed good growth in adaptive capacity and is projected to catch up with Mexico by 2065. In the high-growth scenario, Indonesia ranks in the top three countries; however, China is predicted to move past Indonesia by 2020. By 2065, the model projects that the Philippines will have moved past Mexico and caught up to Belize.

Strengths and Weaknesses in Adaptive Capacity Assessments

Comparative measures of adaptive capacity, such as the model results outlined in the previous section, only allow analysts to ask improved, more focused questions about area or local conditions that can contribute to or reduce resilience. It is likely, for instance, that important variables or domains for particular sub-national areas are not included. For agricultural regions, a key domain might be the extent of irrigation; for urban areas, it might be better measures of education. In addition, the measure of unmanaged land does not account for the potential usefulness of that land. Comparative measures are an important first step toward determining the allocation of resources, either for further analysis or to address additional factors.

Specific Adaptive Capacity Considerations for Southeast Asia

Climate change is expected to exacerbate the effects of natural disasters, such as floods, droughts, and typhoons. Community-based disaster preparedness focuses on building adaptive and coping capacities at the local level, such as construction of flood control infrastructure and emergency shelters, and providing community training. A community-based disaster preparedness pilot project in the Philippines in 1998-1999 demonstrated the promise of this approach to overcoming impacts associated with climate change, while also highlighting the need to simultaneously increase local capacity and responsibility.^{cxxxii} Expansion of this type of disaster preparedness program to other nations in Southeast Asia could help mitigate the expected impacts of climate change on the region.





Figure 8. The contributions of several variables to adaptive capacity rankings. Source: Based on E.L. Malone and A.L. Brenkert, "Vulnerability, sensitivity, and coping/adaptive capacity worldwide," *The Distributional Effects of Climate Change: Social and Economic Implications*, M. Ruth and M. Ibarraran, eds., Elsevier Science, Dordrecht (in press).

Many Southeast Asian countries are facing a water crisis due more to poor management than to water scarcity. Rapid industrialization and increases in population and wealth have led to dramatic increases in demands for water and energy in many Southeast Asian nations. With the additional stresses expected from climate change, Asian countries will need to consider new methods for water management to ensure sustainability of water resources for human and ecological requirements.^{cxxxiii}

- The recent sustained regional economic growth of Southeast Asian countries is energyintensive and has relied heavily on consumption of fossil fuels. International policy responses to global climate change in the next several decades may restrict use of fossil fuels,^{cxxxiv} which will necessitate that Southeast Asian governments invest in development of alternative energy sources, such as solar and wind power.
- Improvement in the coordination of policy and planning to address adaptive capacity in Southeast Asia is vital because climate change will have impacts far beyond the purview of a single governmental ministry or organization. To improve adaptive capacity, inter-agency and inter-ministry coordination is required and must include integration with national disaster risk management.^{cxxxv}
- A holistic approach to building adaptive capacity, which will include the needs of vulnerable groups and vulnerable locations, is recommended for Southeast Asia. Part of this holistic approach is the consideration of the potential impacts of adaptation measures. For example, a dam and reservoir may increase the adaptive capacity of one region, but it may negatively influence the adaptive capacity of downstream communities.^{cxxxvi}

Summary of Possible Adaptive Strategies for Climate Change in Southeast Asia

The following adaptive strategies were recently summarized in a review report on climate change in the Asia/Pacific region.^{cxxxvii} The effectiveness and suitability of these strategies will vary for the different countries in Southeast Asia, depending on national priorities and specific susceptibilities to the impacts of climate change, but all of these strategies are potentially relevant for the region.

Disasters and Emergency Management

- Diversify economic activity to reduce reliance upon climate-sensitive sectors
- Develop emergency management plans for climate hazards
- Develop early warning systems for extreme weather events (e.g., flood, cyclones, heat waves)
- Expand availability and use of risk-spreading institutions (e.g., insurance, government assistance)
- Identify critical activities and infrastructure for protection (e.g., health services, energy, transport, communication)





This chart is UNCLASSIFIED

Figure 9. Projections of adaptive capacity for 10 countries under a delayed growth scenario and a high growth scenario. Source: Based on E.L. Malone and A.L. Brenkert, "Vulnerability, sensitivity, and coping/adaptive capacity worldwide," *The Distributional Effects of Climate Change: Social and Economic Implications*, M. Ruth and M. Ibarraran, eds., Elsevier Science, Dordrecht (in press).

Water Resources

- Develop new water resources and storages (where possible)
- Invest in climate and catchment monitoring and research
- Rehabilitate existing water supply and transport systems
- Implement water management measures
- Increase recycling and reuse of waste water
- Invest in water saving technologies/methods

Agriculture

- Change farming practices
- Change timing of farm operations
- Use different crop varieties (i.e., heat resistant)
- Review governmental and institutional policies and programs
- Research new practices and technologies (e.g., land-use planning, biotechnology)
- Develop drought management and relief protocols

Forests and Biodiversity

- Establish conservation areas and networks
- Invest in natural resource management plans
- Manage land use to reduce environmental harm
- Identify at-risk ecosystems and species
- Develop aquaculture and plantation forestry instead of exploiting native resources

Coastal Communities

- Identify vulnerable areas, communities, and infrastructure
- Channel future development around "high," "moderate," and "low growth" areas
- Develop coastal zone management plans
- Construct new, or modify existing, coastal defenses
- Design infrastructure to accommodate sea-level rise
- Manage progressive retreat from the coastline

Public Health

- Develop early warning systems for extreme weather events (e.g., flood, cyclones, heat waves)
- Establish or bolster public health institutions

- Engage in research and development regarding disease transmission and prevention
- Improve access of individuals and communities to medical and public health agencies
- Provide education in disease prevention

Conclusions: High-Risk Impacts

There is overwhelming evidence that climate change will impact a variety of Southeast Asian sectors through 2030. The timing and magnitude of climate change impacts are difficult to quantify due to limitations in projections of future trends in temperature and precipitation in Southeast Asia. Studies using GCMs indicate that average annual temperatures across the region will rise by approximately 1°C through 2030, and they will keep rising through the remainder of the 21st century. The magnitude, location, and trends of future precipitation changes are much less certain, however, due to the inherent difficulty in modeling such changes. Future alterations in precipitation patterns associated with climate change are complicated by a strong natural variability in local climate, associated with ENSO, that routinely causes flooding and droughts across the region. Model simulations suggest that net precipitation rates will increase across Southeast Asia in the next 20 years, but there will likely be local decreases.

A recent study^{cxxxviii} found that the areas in Southeast Asia that are most vulnerable to climate change are:

- All regions of the Philippines
- The Mekong River Delta in Vietnam
- Most regions of Cambodia
- North and East Laos
- The Bangkok region of Thailand
- West Sumatra, South Sumatra, West Java, and East Java in Indonesia.

The most high-risk impacts of climate change in Southeast Asia are related to fresh water and ocean water resources, due to the region's heavy dependence on precipitation for supplies of fresh water and its close proximity to the ocean. All of the major effects of climate change on Southeast Asia are interrelated, so it is impossible to assess one impact independently of the others.

Sea Level Rise

- Sea level rose in the Southeast Asia region at rates up to 3 cm per year during 1993-2001, and GCM projections indicate that it will continue to rise up to 40 cm by the end of the 21st century.
- Since Southeast Asia is composed entirely of low-lying coastal and island nations, rising sea level causes a number of devastating effects, including saltwater intrusion into estuaries and aquifers, coastal erosion, displacement of wetlands and lowlands, degradation of coastal agricultural areas, and increased susceptibility to coastal storms.

- Impacts from sea level rise are interrelated with impacts on agriculture, natural disasters, river deltas, water resources, coastal ecosystems, human livelihoods and infrastructure, and national security.
- Sea level rise also has overarching socioeconomic impacts, due to loss in income associated with degradation of agricultural areas and loss of housing associated with coastal inundation, for example.

Water Resources

- Future changes in Southeast Asian water resources are closely tied to changes in precipitation.
- GCM results suggest that there will be a net increase in surface runoff across the region, but local trends will vary, with increases in some areas and decreases in others. Any areas that see an increase in runoff could experience an increase in erosion, flooding, and water pollution, while decreased runoff could lead to water shortages.
- Individual areas under severe water stress in Southeast Asia are projected to increase dramatically in the next few decades, although model results suggest that the region as a whole will not be at risk for water shortages.
- Fresh water resources on island nations of Southeast Asia are especially vulnerable to any variability in precipitation because many island populations rely on rainwater collection for their supply of fresh water.
- The management of water issues is one of the most challenging climate-related issues in Southeast Asia, as it is central to health and sustainable development.
- Water resource impacts are interrelated with impacts on agriculture, river deltas, forests, coastal ecosystems, diseases and human health, and national security.

Agriculture

- Agriculture is a major component of the economy in many nations of Southeast Asia, and there is no question that it will be significantly affected by climate change in the next 20 years.
- Assessment of specific agriculture impacts is challenging, because it is difficult for GCMs and crop models to reliably simulate the complicated effects of future variations in temperatures, precipitation, and atmospheric CO₂ concentrations on crop growth.
- Overall, it is likely that future crop yields will vary by region and by crop, with yield increases in some locations but decreases in others.
- Climate change-induced impacts on agriculture will be augmented by natural climate variability, especially due to ENSO, which is responsible for serious impacts on agriculture associated with droughts, floods, and severe storms.
- Management of the agricultural sector by Southeast Asian nations is critical to their economic growth and national security. Food shortages in the region, clearly associated with ENSO years in the past and projected to increase with changing climate, will stress poor populations across the region who are already susceptible to malnutrition.

• Agriculture impacts are interrelated with impacts on sea level, river deltas, natural disasters, and water resources.

Coastal Regions

- Coastal regions are some of the most at-risk areas for the impacts of climate change in Southeast Asia due to their prevalence and high population density.
- Many coastal areas in Southeast Asia are already degraded by pollution, sediment-laden runoff, and destructive fishing practices.
- Mangroves and coral reefs are two key coastal ecosystems that are expected to be significantly impacted by climate change. Destruction and degradation of mangroves and coral reefs will result in long-term economic repercussions for Southeast Asia, since these ecosystems are central to the tourism, agriculture, fishing, and aquaculture industries.
- Coastal regions obviously are susceptible to inundation associated with sea level rise and destruction of infrastructure from flooding and storm surges, which are likely to increase as a result of future climate change.
- Careful management and safeguarding of coastal regions by Southeast Asian governments is essential in the next 20 years, as the effects of climate change manifest themselves.
- Impacts on coastal regions are interrelated with impacts on sea level, river deltas, natural disasters, water resources, agriculture, forests, and human livelihoods and infrastructure.

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Annex A: Accuracy of Regional Models

This is an excerpt from IPCC Fourth Assessment Report, Working Group 1 Report, Chapter 11: Regional Climate Projections; see original text for references.²

11.4.2 Skill of Models in Simulating Present Climate

Regional mean temperature and precipitation in the MMD models show biases when compared with observed climate. 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.

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 sea surface temperature (SST). Simulation was good over the maritime continent compared to the simulation for other tropical regions. B. Wang et al (2004) assess the ability of 11 atmospheric general circulation models (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 atmosphere-ocean general circulation models (AOGCMs) continue to have some significant shortcomings in representing El Niño- Southern Oscillation (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 (2004) conducted a number of simulations with the Max-Planck Institute (MPI) regional model for an Indonesian domain, forced by reanalyses and

² Some references have been removed to avoid confusion.

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.

Annex B: Knowledge Deficiencies that Preclude a Full Evaluation of Climate Change Impacts in Southeast Asia and Southeast Asia's Adaptive Strategies

To increase the likelihood that this report represents a reasonable assessment of the projections and impacts of future climate change in Southeast Asia, as well as the region's adaptive capacity, the following general data gaps must be addressed:

- In physical science research, regional analyses of climate change are limited by the inability of GCMs to model regional climates satisfactorily, including complexities arising from the interaction of global, regional, and local processes. For example, uncertainties in changing monsoonal activity and ENSO due to natural variations and anthropogenic emissions are important information gaps needed for accurate climate projections. A particularly critical modeling gap for Southeast Asia is the fact that GCMs cannot consistently project the magnitude and location of future precipitation on a country-specific scale. Another important data gap is the lack of reliable medium-term climate projections that can be used for planning adaptive strategies for the next 20-30 years. Similarly, scientific projections of water supply and agricultural productivity are limited by inadequate knowledge of various climate and physical factors. 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 issues exist for the biological and ecological systems that will be affected by future climate change.
- In social science research, scientists and analysts have only partial understandings of the important factors affecting vulnerability, resilience, and adaptive capacity. As with the physical science data gaps, research agendas on vulnerability, adaptation, and decision-making abound (e.g., http://books.nap.edu/catalog.php?record_id=12545).
- Important research factors are still unaccounted for given the current available data. The early approach to carbon cycle modeling is a good example of this type of information gap. The first carbon cycle models did not include carbon exchanges involving the terrestrial domain because modelers assumed that the exchange was about equal. As a result, the only factor modeled was deforestation; the omission of terrestrial carbon exchange rendered the models inadequate. Ecosystems research models are another example—they are only beginning to account for changes in pests populations, such as the pine bark beetle.
- Social models have been developed to simulate consumption, with the assumption of wellfunctioning markets and rational actor behavior, and mitigation/adaptation policies, but without attention to the social feasibility of enacting or implementing such policies. Since anthropogenic climate change is the result of human decisions, the lack of knowledge about human motivation, intent, and behavior is a serious shortcoming in these social models.

Overall, research about climate change impacts on Southeast Asia has been undertaken in a piecemeal fashion: 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.

Specific research and data gaps regarding climate change and adaptive capacity in Southeast Asia include the following:

- Wang et al^{cxxxix} found that a suite of 11 GCMs used to simulate observed interannual rainfall variations had the poorest skill over the Southeast Asian portion of the domain. The authors concluded that current GCM shortcomings in representing natural ENSO variability make it difficult to project changes in ENSO-related rainfall in Southeast Asia.
- Murdiyarso^{cx1} summarized many of the difficulties of using GCMs and crop models to accurately simulate the impacts of climate change on agriculture in Southeast Asia. He noted that GCMs cannot reliably predict changes in drought and storm frequencies, which makes it impossible to model future crop yield changes.
- Luo and Lin^{cxli} noted that continued refinement of dynamic crop simulation models that can utilize GCM scenarios is needed. The simulation models must be able to synthesize the range of possible crop impacts, including CO₂ fertilization, temperature, disease, and changes in soil and water. Four specific high-priority research needs were identified, including assessment of the crop- and region-specific benefit of CO₂ fertilization, development of more integrated agricultural models which account for biophysical and socioeconomic factors, inclusion of socioeconomic factors in the models, and evaluation of the relative importance of climate variability versus changes in mean climate parameters.
- Sivakumar et al^{cxlii} noted that it is necessary to understand potential crop responses to the range of possible climate scenarios. Evaluation of future changes in crop yield associated with variations in the frequency and intensity of extreme climate events, such as floods, storms, and droughts, is particularly important. Assessment of sustainability practices, agricultural productivity, changes in erosion, degradation of soil quality, and ecosystem health also need careful consideration.
- Rosensweig et al^{cxliii} noted that improved observation networks are urgently needed in Southeast Asia in order to document the sensitivity of physical and biological systems to warming in the region.
- Burke et al^{cxliv} noted a need for better information about the location of coral reefs and the threats to their survival.
- Kobayashi^{cxlv} noted that there is a need for detailed studies of the magnitude and extent of climate change impacts on urban settlements, particularly in developing countries.
- Sia Su^{cxlvi} noted that future climate change research must incorporate important weather factors, such as relative humidity, pressure, and wind speed/direction, which can influence the effects of climate on disease outbreaks and associated morbidity and mortality rates.
- Penny^{cxlvii} identified the need for comprehensive modeling that reflects increased snowmelt and monsoon rainfall to assess the implications for food security, wetlands management, and biodiversity in Southeast Asia.
- Preston et al^{cxlviii} identified the need to include the potential for irreversible loss of large ice sheets in the Arctic and Antarctic in projections of global sea level rise. Contributions from large ice sheets could rapidly increase global sea level, with devastating impacts on the coastal and island nations of Southeast Asia.

- Thanh et al^{cxlix} identified research gaps with regard to land-ocean interactions and coastal impacts in Vietnam and upland countries. Research needs include synchronization of research and applied scale data and greater public availability of data. More detailed, integrated and comprehensive investigations are required to obtain information on coastal nutrients, pollutants, material fluxes and coastal interaction processes that have been impacted by both human activities and climate change.
- Hanh and Furukawa^{cl} identified information gaps on sea level rise and coastal zone vulnerability in Vietnam.
- Mapalo^{cli} identified research gaps for evaluating climate change and sea level rise at Olango Island in the central Philippines. Research needs include information on storm surge, quantification of coral and sand extraction, natural disaster impact data, groundwater salinity and transmissibility data, endangered species information, assessment of the impacts of mangroves on sea grass beds, and a detailed topographic map of the region.

ⁱ 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. Jr. Miller, and Z. Chen (Cambridge: Cambridge University Press, 2007), http://www.ipcc.ch/ipccreports/ar4-wg1.htm.

ⁱⁱ R. Boer and A. Faqih, "Current and Future Rainfall Variability in Indonesia," AIACC (Assessments of Impacts and Adaptations to Climate Change in Multiple Regions and Sectors) Semi-Annual Report (July to December) 2003, http://sedac.ciesin.columbia.edu/aiacc/ (accessed April 8, 2009).

ⁱⁱⁱ J.A. Church, N.J. White, R. Coleman, K. Lambeck, and J.X. Mitrovica, "Estimates of regional distribution of sea level rise over the 1950-2000 period," *J. Clim.*, 17 (2004): 2609–2625; J.A. Church, N.J. White, and J.R. Hunter, "Sea level rise at tropical Pacific and Indian Ocean islands," *Global Planet. Change*, 53, no. 3 (2006): 155–168.

^{iv} B. Bhaskaran and J.F.B. Mitchell, "Simulated changes in Southeast Asian monsoon precipitation resulting from anthropogenic emissions," *Int. J. Climatol.* 18 (1998): 1455-1462.

^v Heiko Paeth, Anja Scholten, Petra Friederichs, and Andreas Hense, "Uncertainties in climate change prediction: El Niño-Southern Oscillation and monsoons," *Global and Planetary Change* 60 (2008): 265-288.

^{vi} 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. Jr. Miller, and Z. Chen (Cambridge: Cambridge University Press, 2007), http://www.ipcc.ch/ipccreports/ar4-wg1.htm.

^{vii} Asian Development Bank, *The Economics of Climate Change in Southeast Asia: A Regional Review*, April 2009, http://www.adb.org/Documents/Books/Economics-Climate-Change-SEA/default.asp.

^{viii} Central Intelligence Agency (CIA), *The 2008 World Factbook*, https://www.cia.gov/library/publications/the-world-factbook/index.html (accessed April 24, 2009).

^{ix} Central Intelligence Agency (CIA), *The 2008 World Factbook*, https://www.cia.gov/library/publications/the-world-factbook/index.html (accessed April 24, 2009); Thailand Meteorological Department, *The Climate of Thailand*, http://www.tmd.go.th/en/archive/climateconditions.php (accessed April 15, 2009).

^x Central Intelligence Agency (CIA), *The 2008 World Factbook*, https://www.cia.gov/library/publications/the-world-factbook/index.html (accessed April 24, 2009).

^{xi} Central Intelligence Agency (CIA), *The 2008 World Factbook*, https://www.cia.gov/library/publications/the-world-factbook/index.html (accessed April 24, 2009).

^{xii} Central Intelligence Agency (CIA), *The 2008 World Factbook*, https://www.cia.gov/library/publications/theworld-factbook/index.html (accessed April 24, 2009); Philippine Atmospheric, Geophysical, and Astronomical Services Administration, *Climatology and Agrometeorology*, http://kidlat.pagasa.dost.gov.ph/cab/main.htm (Accessed April 15, 2009).

^{xiii} Central Intelligence Agency (CIA), *The 2008 World Factbook*, https://www.cia.gov/library/publications/the-world-factbook/index.html (accessed April 24, 2009).

^{xiv} Central Intelligence Agency (CIA), *The 2008 World Factbook*, https://www.cia.gov/library/publications/the-world-factbook/index.html (accessed April 24, 2009).

^{xv} Central Intelligence Agency (CIA), *The 2008 World Factbook*, https://www.cia.gov/library/publications/the-world-factbook/index.html (accessed April 24, 2009).

^{xvi} A.M. Jose, L.M. Sosa, and N.A. Cruz, "Vulnerability assessment of Angat water reservoir to climate change," *Water, Air, and Soil Pollution* 92 (1996): 191-201.

^{xvii} 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. Jr. Miller, and Z. Chen (Cambridge: Cambridge University Press, 2007), http://www.ipcc.ch/ipccreports/ar4-wg1.htm.

^{xviii} Intergovernmental Panel on Climate Change (IPCC), *Special Report on Emissions Scenarios (SRES)*, eds. Nebojsa Nakicenovic and Rob Swart (Cambridge: Cambridge University Press, 2000),

http://www.ipcc.ch/ipccreports/sres/emission/index.htm.

^{xix} Intergovernmental Panel on Climate Change (IPCC), *The IPCC Data Distribution Centre, HadCM2 GCM Model Information*, http://www.ipcc-data.org/is92/hadcm2_info.html (accessed April 1, 2009).

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