CHAPTER TWO—PACIFIC ISLANDS REGION

Defining the Region

If you were to draw together all 58 million square miles of the Earth's land area and place it in the Pacific Basin, that land would still be an island in the middle of a great sea—the Pacific Ocean is vast. However, while some may view the sea as a barrier, for many others it is a highway. Historical trade routes and settlement patterns throughout the Pacific produced strong cultural links among the 30,000 Pacific Islands, and have resulted in distinctive Polynesian, Melanesian, and Micronesian spheres of influence. Later, colonial and post-colonial histories resulted in political alignments that crossed cultural boundaries. This exploration of climate change focuses on the Pacific Islands that are politically affiliated with the United States.

As inhabitants of small island states, the people of the Pacific share certain vulnerabilities to climate change and variability. Similarities include the processes of soil and coastal zone formation, susceptibility to ocean-born storm systems and tidal fluctuations, hydrology, biogeography (including population density, species density and distribution), and limited resource bases. Differences derive from variations in island geology such as history of formation (continental islands versus volcanic islands); relative size, isolation and age (from high island to atoll); extent and nature of reef formation; and the capacity of natural aquifers.

The economic strategies of each community reveal something of the relationship between island peoples and the physical elements of their islands. While human emotion and spirit can be affected by climate change and variability, it is the physical and material dimensions of the human experience that make us most vulnerable. Moreover, physical vulnerability is inextricably linked with social systems. These systems at local, island, regional and even international levels influence not only human exposure to climate change and variability, but also human adaptive capacities. The values and beliefs that underpin economic decisions— and the social structures that distribute opportunities and constraints— are all culturally informed. In sum, willingness to adapt, resilience to change, knowledge of climate systems, and trust in policy makers and partners all affect the vulnerability of island populations.

Describing the Region: Islands and Coastal Communities

Island Geography and Geology

American flag and U.S.-affiliated Pacific Islands (AF/USAPI) include the Hawaiian islands; the Samoan islands of Tutuila, Manua, Rose, and Swain; and islands in the Micronesian archipelagos of the Carolines, Marshalls, and Marianas. The Micronesian islands include the territory of Guam, the Commonwealth of the Northern Mariana Islands (CNMI), the Freely Associated States of the Republic of Palau (Palau), the Republic of the Marshall Islands (RMI), and the Federated States of Micronesia (FSM)— all north of the equator in the western Pacific. The Hawaiian islands lay further to the east, and American Samoa is the only AF/USAPI south of the equator.

Geomorphically, these islands are exceedingly varied and therefore difficult to generalize. The AF/USAPI include volcanic islands, continental islands, atolls, limestone islands, and islands of mixed geologic type. About half of the Caroline Islands and 80% of the Marshall Islands are atolls, some of which peak at only a few feet above present sea level. Volcanic islands, on the other hand, can reach heights of more than 13,000 feet, as does the snow-capped peak of Mauna Kea on the island of Hawai‘i.

Island landforms, however, are not solely the product of geological histories. In the Pacific, climatic and oceanographic controls are important causes of landform variation as well (Nunn 1999). Changes in rainfall and the water-table level are especially important in this regard and have been implicated in such fundamental processes as bedrock formation (Schmalz 1971), the development of the amphitheater-headed valleys commonly found in the Hawaiian Islands (Nunn 1994), and the development of phosphate rock (Stoddard and Scoffin 1983).

The combined affect of geologic, oceanographic, and climatological processes can have profound effects on the peoples who settle these islands. High volcanic islands, which tend to have larger surface areas, generally have more fresh water, better soils, and more diverse resource bases. Low-lying atolls, on the other hand, are especially prone to drought and erosion, and generally (at least on land) have limited natural resources. Finally, the interaction of climate and sea dramatically affects coastal zone formation and will continue to do so as sea levels rise.

Island Ecosystems

As might be imagined by the diversity of island forms, Pacific Island landscapes and biodiversity are many and varied as well. Warm temperatures and moisture have supported the growth of tropical forests on many islands, particularly the high islands. Forested areas are still common in upland areas of Hawai'i and American Samoa, Pohnpei, and Kosrae.

While even relatively small islands can host a diversity of forest types, atolls generally do not support dense forest vegetation in part because of the soil composition and hydrological constraints. These relatively small islands are coastal zones. Boundaries between land and sea fluctuate throughout the year. Mangrove forests fringe some islands, in zones where salt water and fresh water mix to form the breeding grounds for many valuable fish species. Rich lagoons interlace other islands, bountiful with fish and other marine life. Throughout the region, coral reefs are abundant and productive, attracting myriad fish species that in turn attract subsistence and commercial fishermen.

Though these Pacific ecosystems differ from each other in many important respects, they are all islands, and much of the condition and vulnerability of their biota derives from that fundamental characteristic. Oceanic islands have lower overall levels of biological diversity. Island species are much more likely to be endemic (found only on a single island or archipelago) and to occupy restricted habitats. Islands generally are more susceptible to disruption by biological invasions. The combination of land-use change, human-driven species introductions and certain unique characteristics of islands has made island species and ecosystems more vulnerable than their continental equivalents to human endangerment and destruction.

There are a number of conditions that affect most island ecosystems and their biological resources. The extinction of species and genetically distinct populations is an irreversible component of human-caused global change, and to date extinction has been disproportionately significant on islands. Any list of threatened or endangered species reveals that islands remain enormously vulnerable to future losses. The Hawaiian Islands, for example, make up only about 0.002% of the United States' land area, but are the sole home for nearly 30% of the nation's endangered species. Furthermore, biological invasions by human-transported alien species are a major driver of endangerment and extinction, and a significant element of change in their own right. The extent of biological invasion on islands generally is much greater than in continental systems, and, overall, constitutes the major ongoing threat to the unique biodiversity of islands.

Hawaiian Green Sea Turtles are among the endangered species in Pacific ecosystems that are affected by climate change and other natural factors.

Another feature that all of the islands in the Pacific Region share is a dependence on coral reefs, which in addition to hosting a wealth of marine life also provide a natural form of coastal protection against wave and wind damage. In addition to the many human-induced stresses, reefs are sensitive to temperature increases—as evidenced by significant coral bleaching associated with the 1997–1998 El Niño—as well as to the damaging effects of hurricanes and tropical cyclones. Finally, island ecosystems are affected by human population growth, economic strategies and governance systems.

Island People

The AF/USAPI are home to an estimated 1.7 million people, though the distribution of people throughout the islands is highly imbalanced (see Table 2.2). Consider that 1.2 million live in the state of Hawai'i, while the Republic of Palau is home to fewer than 19,000. This disparity is indicative of the range of diversity in human settlement in the region, as well as the range of challenges and opportunities facing communities in each island jurisdiction.

Similarly, population growth rates vary widely throughout the islands. The population of RMI, FSM, and Guam are all expected to double within the next 31 years, while the Republic of Palau will not double until 2068 (based on a natural rate of increase: Population Reference Bureau, 2000). These figures compare with an estimated doubling time of 51 years for global population. The high natural rate of increase in many AF/USAPI is accentuated by high migration rates. The distribution of populations within and between island groups can have dramatic implications for climate-society interactions. Consider, for instance, that in the Marshall Islands, 65% of the population is urban, while in the FSM only 27% is urban. The spatial distribution of human populations has clear implications for water

FOCUS: CLIMATE AND BIODIVERSITY

Climate variability—the ENSO cycle, decadal variations, and extreme events such as hurricanes and other major storms— has always influenced Pacific organisms and cultures. However, the consequences of climate variability for biodiversity have changed in recent years, for two primary reasons. First, many native species are now present only as small, often fragmented populations, frequently persisting only in marginal portions of their former range. These marginal environments may be particularly vulnerable to climate variability. For example, introduced mosquitoes and the avian malaria they transmit continue to plague Hawaiian honeycreepers, endemic species that have been crowded into high-elevation forests on the upper edge of their former range due to habitat destruction by humans and other introduced species, including birds and ungulates. ENSO-related drought conditions can be significant in these higher sites where the honeycreepers are now found.

A second reason why the effects of climate variability have changed is that introduced species are now widespread on most Pacific Islands, and disturbances such as hurricanes and other large storms generally further facilitate the establishment of those species. In the case of Hurricane Iniki on Kaua‘i, introduced species responded aggressively to fill the void left by the damage to native forests.

Climate change, therefore, has direct effects on Pacific Island species and ecosystems, and it is very likely that its effects are multiplied through interaction with land-use change, over-harvesting, species invasions and other aspects of human-caused changes in biodiversity. Components of climate change that affect biodiversity in Pacific Islands include:

- sea-level rise, which can jeopardize habitats and affect the availability of fresh-water resources, particularly on atolls and low islands;
- increasing temperatures, which can affect the viability of species (e.g., some corals are susceptible to small increases in temperature and may be unable to recover from bleaching if ocean temperatures exceed their optimal range);
- changes in rainfall, which can affect species and ecosystems directly through impacts on the availability of fresh-water resources; and,
- increasing carbon dioxide (CO_2) levels, which for some systems may have a greater effect than changes in temperature and precipitation.

Changes in CO_2 levels affect the growth, chemistry and efficiency of water use for native and introduced species, and these changes in turn affect the distribution of ecosystems and the palatability of plants as food for animals. For example, changes in growth rate may provide an advantage to some weedy, introduced species, while change in the distribution of ecosystems presents an opportunity for other introduced species. In marine ecosystems, there is evidence that skeleton-building by corals (calcification) can be reduced by elevated CO_2 levels, which, when combined with increasing temperatures, could represent a double stress for corals.

Finally, there is the possibility for “surprise” changes in the climate system that may occur abruptly rather than being manifested as gradual changes in trends or mean conditions.

Many of the strategies that Pacific Island communities could implement to reduce the vulnerability of species and ecosystems to climate variability and change involve reducing current human-related stresses on those species and ecosystems. Reducing these stresses is essential for building resilience to future climate changes. Some specific activities could include:

- Strengthening land-use policies and enforcing existing policies, which could make a substantial contribution to protecting terrestrial habitats and marine ecosystems from sedimentation and nutrient pollution;
- expanding education and public awareness programs, which can improve our understanding of the economic and cultural value of biological diversity, and enhance development of a sustained commitment to effective stewardship; and,
- developing more effective partnerships among scientists, government agencies, resource managers, businesses, and local communities, which could significantly enhance efforts to understand and respond to the consequences of climate variability and change on biodiversity and, more broadly, on Pacific Island communities.

management systems that are highly sensitive to climate change and variability. Furthermore, urban poor are, in general, notoriously vulnerable and least able to adapt to extreme events, so rural to urban migration, if not coupled with careful planning and infrastructure development, can increase overall sensitivity to climate change while reducing adaptive capacity. Conversely, migration in some instances is an adaptive strategy. The money sent to the islands from workers overseas (remittances) for instance, can help to alleviate domestic vulnerability by strengthening economic vitality.

Pacific Island Economies:

In small-island states, natural resources are generally limited. Geographic remoteness is typical, and the associated costs of transport and shipping have a profound influence on island economies. National, territorial or statewide economic profiles reflect a common bundle of strategies, though relative emphasis varies from island to island (see Table 2.1). Tourism, for instance, figures prominently in the gross domestic product of most island jurisdictions. It has been the largest source of income in the Republic of Palau (Osman, 2000), while in Hawai'i the travel and tourism industry produced an estimated $6.3 billion in 1998, second only to real estate in terms of its contribution to the state's GDP (World Travel and Tourism Council Hawai'i Tourism Report, 1999). Considerable tourism infrastructure has been developed in Hawai'i, Guam, and CNMI, though the prominence of tourism in CNMI's economy has dwindled since 1997 (Osman, 1999b). On the other hand, traffic to the Marshall Islands and American Samoa is more oriented to returning residents than to vacationing tourists.

Table 2.1: Economic Comparison of American Flag and U.S.-Affiliated Pacific Islands

Region/ country or territory	GDP (US$ in millions)	Per capita GDP (US$ in thousands)	Major income sources	Major Sources of External Investment	Major Future sources of Income
FSM	230.0	1,977	¥ U.S. payments ¥ Government services ¥ Fisheries ¥ Tourism	U.S., Japan	¥ Compact status being renegotiated ¥ Fisheries development
Guam	3,065.8	18,766	¥ Tourism ¥ Military ¥ Trade ¥ Services	U.S., Japan, Korea	¥ Tourism ¥ Services
RMI	102.1	2,009	¥ U.S. payments ¥ Kwajalein Missile Range ¥ Government services ¥ Copra ¥ Fisheries	U.S., Japan	¥ U.S. military compact being renegotiated ¥ Fisheries
CNMI	664.6	8,367	¥ Tourism ¥ Garment manufacturing ¥ Trade ¥ Services	Japan, Korea, Hong Kong, U.S.	¥ Tourism ¥ Services
Palau	129.3	6,989	¥ U.S. Compact Payments ¥ Tourism	Japan, U.S.	¥ Compact money ¥ Tourism
American Samoa	253.0	4,295	¥ Tuna Canneries ¥ Government Services ¥ Remittances from Samoans overseas.	U.S.	¥ Canneries ¥ Remittances ¥ U.S. entitlements
HawaiÕ i	35,146.4	29,164	¥ Tourism ¥ Services ¥ Trade ¥ Government	U.S., Japan, Australia	¥ Tourism ¥ Defense services ¥ Trade ¥ Government

Source: Osman, W. Pacific Island Fact Sheet. Bank of HawaiÔ i Economic Reports, 2001

Waikiki, Hawai'i is a premiere global destination for tourism, which comprises a varying but substantial proportion of all economic activity in the Pacific Islands.

Another component of economies throughout the AF/USAPI, particularly in the freely associated states (Palau, FSM and the Republic of Marshall Islands), is the significant role of government spending. Compact payments for exclusive access to island waterways and military rents have buttressed the public sector and, in several jurisdictions, have been the primary source of revenue for recipient governments. By contrast, the private sector plays a key role in other jurisdictions, notably Hawai'i, Guam, and CNMI. In Guam, private sector employment replaced government as the largest employer for the first time in 1998 (Osman, 1999a). In CNMI, lax labor and immigration laws and access to U.S. markets have hastened the development of garment

THE EFFECTS OF MIGRATION

Migration (both within and across international borders) is one of the most important processes affecting both the structure of Pacific Island populations and the growth and distribution of Pacific Island workforces. Migration patterns are shaped, at least in part, by differential resource bases, historical geopolitical relations, and vulnerability to climate-related extreme events such as hurricanes, typhoons, cyclones, and drought.

Prior to FSM's independence, internal migration trends revealed a movement of people from outlying islands to administrative centers (Sudo 1997), in part because urban centers held the promise of education, medical care, and income (Appleyard 1988). This movement, though, also includes climate refugees who flee drought-stricken or typhoon-ravaged islands and atolls; it is a movement away from places that are perceived as personally dangerous, or conditions that are difficult (Pirie 1994).

Net Migration Rate in American Flag and U.S.-affiliated Pacific Islands (2000 estimates)

Country or territory	Net migration rate
FSM	11.65 migrant(s)/1,000 population
Guam	5.35 migrant(s)/1,000 population
RMI	0 migrant(s)/1,000 population
CNMI	19.06 migrant(s)/1,000 population
Palau	5.01 migrant(s)/1,000 population
American Samoa	3.74 migrant(s)/1,000 population

Source: CIA World Factbook

While substantial migration from Guam and American Samoa began after WWII, a wave of Micronesian migrations followed independence of the trust territories. Hawai'i, Guam and CNMI in particular have attracted many migrants from other islands' jurisdictions; so many, in fact, that Guam and CNMI have asked the federal government for repayment of expenses linked to Micronesian migrants granted access to U.S. territories by virtue of the compact of free association (Osman 2000).

Many islanders moved to urban centers abroad as well. In 1990, 62.4% of American Samoans lived abroad. Roughly 30% of Palauan nationals have emigrated to live in foreign countries; at the same time, Palau has accepted the same number of Philippine and Chinese laborers (Sudo 1997). Like Palau, other AF/USAPI have attracted migrants from throughout Asia and the Pacific. CNMI, for instance, has experienced a net in-migration flow (Rappaport 1999) largely due to the emergence of the garment and manufacturing industry.

The bottom line is that migration, both internal and international, is a key factor in determining the distribution and density of communities, and can have a profound effect on climate/society interactions in the AF/USAPI.

manufacturing, which grew from 13% of CNMI's gross business receipts (in 1990) to 29.3% (in 1998) (Osman, 1999b). In Hawai'i, financial services and digital technology are beginning to play a substantial role in the state's changing economy.

Where island resource bases are limited, marine resources are often extensive. Exclusive Economic Zones (EEZ), which extend up to 200 miles out from each jurisdiction, offer a source of income to many islands through sale of fishing rights to U.S., Japanese, Taiwanese, Korean, and other fishing fleets. American Samoa is the only AF/USAPI to have invested substantially in the value-added tuna canning industry, but tuna transshipment has been an important small industry in Guam and has provided some employment in Palau. Estimates of expenditure on fuel, provisions, and services by tuna fleets on Guam have been as high $118 million per year.

In general, commercial agriculture in the AF/USAPI serves domestic markets, though export-oriented plantation agriculture was once the foundation of Hawai'i's economy. Commercial agriculture also played a major role in Micronesia during the Japanese occupation. In the RMI, copra production has been and continues to be an important source of income. Subsistence and semi-subsistence agriculture, on the other hand, are major components of many local economic strategies.

Social systems

Migration and settlement have infused the region with considerable social and cultural diversity. Monsoon winds propelled early migrants (about 4,000–5,000 years ago) from the Philippines and Indonesia all around the Pacific Basin. The first settlers arrived in Palau and Yap, then continued north to Guam and through the Northern Marianas. The Caroline and Marshall archipelagoes were probably settled by peoples from the Solomon Islands or Vanuatu (Kirch, 2000). Today, there are seventeen languages spoken in the FSM alone, including two Polynesian dialects, fourteen Micronesian languages, and English. Polynesian migration patterns are characterized by fantastic voyages. Using only the stars and stories, early settlers journeyed thousands of miles across open ocean to reach the most geographically remote islands in the world— Hawai'i. While it is difficult to generalize about traditional society in a region as vast as this, some commonalities are evident. The importance of clans and lineages in local social organization, the prominent role of chiefs, and the close cultural, economic and spiritual relationship with land

SUBSISTENCE PRACTICES

Island economies employ a range of strategies to secure and sustain the welfare of their communities. At the household level, island livelihoods include a combination of subsistence farming and fishing, salaried or wage labor, and entrepreneurial ventures— though relative emphasis on each of these economic strategies varies widely among the jurisdictions. Hawai'i, Guam and CNMI, for instance, have well-developed cash economies, strong links with international markets, and service sectors that play key roles in their economies. To illustrate, revenues from services accounted for 18.1% of CNMI's gross business revenues in 1998 (Osman 1999b). In other jurisdictions such as FSM and American Samoa, nonmarket production is the cornerstone of local economies. Nonmarket production includes subsistence activities and production for nonmonetary trade, both of which figure prominently in island economies but are not fully represented in official figures.

Traditional agriculture, though still practiced, has changed considerably. Changing patterns of land tenure, new consumer preferences, and changing conditions in wider society have altered land-use practices in many of the AF/USAPI. While few livelihoods rely exclusively on subsistence activities, nonmarket fishing, cultivation, and animal husbandry continue to play a significant role in local and, hence, island-wide economies. As these activities are most closely associated with the physical environment, they are the most sensitive to climate change and variability.

Subsistence fishing is still an important food source for most island communities. The FAO estimates that worldwide average annual consumption of fish is 13 kg per capita; however, average consumption in Palau exceeds 100 kg per capita (Lal and Fortune, 2000). In all the Pacific Islands (except Tonga) subsistence catches far outweigh the commercial harvest, including for tuna (Lal and Fortune, 2000).

Despite changing preferences and availability of imported foods, subsistence agriculture continues to play a major role in the AF/USAPI. Consider that of the 1,126 farms in American Samoa in 1990, 88% produced solely for subsistence (Osman, 1997). Indigenous cultivation systems incorporate a range of land uses including home gardens, shifting cultivation and agroforestry (tree crops such as coconuts, breadfruit, and bananas). In Yap, as much as 27% of the vegetation may be classified as agroforest (Falanruw, 1994). Cultivation of wetland taro still plays a significant role in the lives and livelihoods of many islanders, particularly in the FSM, where it is the staple crop. Wetland taro is very sensitive to changes in precipitation and saltwater intrusion.

and sea, for instance, are all characteristic of pre-contact social systems.

Contact with Europeans began with Magellan's fleet. His was the first recorded circumnavigation of the globe and included a landing in Guam in 1521. Not long after, the Spaniards arrived and claimed the islands for the Crown. Soon after, soldiers appeared in Guam, Saipan, and Palau. Catholic missionaries followed. During this period, many of Guam's indigenous Chamorro communities were relocated. German, English, and Russian whaling expeditions began frequenting the area in the early 19th century, and new patterns of migration emerged at the turn of the 20th century. Germans purchased many islands from the Spanish, and American soldiers in the wake of the Spanish American War later claimed the islands that had not been sold. Japanese forces began to arrive in 1914 and asserted jurisdiction over the German land claims. Japanese influence and migration to the region continued through World War II (Hezel 1995).

After World War II, the United States by U.N. Mandate established a "Strategic Trust" relationship with what is now the RMI, the FSM, the Republic of Palau, and the CNMI. American military personnel and administrators established themselves throughout the region and brought with them American social and cultural institutions.

Contemporary social systems throughout the AF/USAPI vary widely; they are a mix of traditional Micronesian or Polynesian rules and institutions as well as those adopted from colonial or industrialized countries. In some sense Hawai'i and Guam stand at one end of the spectrum of economic development and westernization. At the other end are the FSM and American Samoa. In Hawai'i and Guam, cash economies are highly developed and highly dependent on tourism, and very few people rely on

Subsistence fishing supports much of the rural population in many Pacific islands, yet is particularly susceptible to climate-induced changes in coastal ecosystems (photo by Joseph Konno).

Table 2.2: Comparison of Regional Populations

Region/ country or territory	Last census	Population at last census	Mid-year population estimate 2000	Mid-year population estimate 2010	Land area (km^2)	Population density (people/ km^2) circa 2000	Projected annual population growth rate (%) circa 2000	Projected population doubling time (in years)
FSM	1994	105,506	118,100	141,900	701	168	1.9	36
Guam	1990	133,152	148,200	171,700	541	274	1.0	66
RMI	1999	50,840	51,800	63,200	181	286	2.0	35
CNMI	1995	58,846	76,700	90,700	471	163	5.5	13
Palau	1995	17,225	19,100	23,000	488	39	2.2	32
American Samoa	1990	46,773	64,100	80,300	200	321	2.9	24
HawaiÔ i	2000	1,211,537	1,211,537	1,440,000	16,636.5	72.8	0.7	NA

Source: Secretariat for the Pacific Community, Oceania DemographicsÑ except for HawaiÔ i data, which derives from the U.S. Census 2000, the State of HawaiÔ i Databook 1999, and the Population Reference Bureau.

subsistence gardening or fishing. In American Samoa and the FSM, traditional political structures are still in place and people outside the urban centers rely heavily on fishing and gardening for their food. In Guam and Hawai‘i, western legal systems dominate, whereas in American Samoa and the FSM, traditional norms continue to govern behavior in rural areas.

Chiefly systems persist throughout the islands, and have retained an especially influential role in planning and decision-making in the RMI, parts of the FSM, and American Samoa. Environmental management in the islands, to be effective, relies on collaboration between these various decision-making authorities, each of which brings something unique to the process. Local and national decision-making and planning organizations are augmented by grassroots, regional, and international organizations. These organizations and institutional arrangements, if constructively engaged, can enhance the adaptive capacity and reduce the sensitivity of island coastal communities to climate change and variability. Such cooperation could be through the sharing of knowledge, experience and information about climate conditions and the effects of climate on environmental and social systems.

Today’s Climate

In spite of fundamental physical similarities, the range of variation within the Pacific Islands is extraordinarily broad. The islands differ geomorphologically, from atolls with small, low islets and extensive lagoons, to raised limestone islands, to volcanic high islands with substantial topographic and internal climatic diversity (microclimates). They differ climatically as well, from wet western equatorial islands to seasonal tradewind environments—and they differ in their exposure and sensitivity to cyclones and to ENSO-related climatic variability. The following brief summaries highlight the prevailing climatic conditions in the jurisdictions addressed in this Report. Most of the material in this section is excerpted from reports on the individual jurisdictions contributed to the Pacific Meteorological Needs Analysis Project (PMNAP) conducted by the South Pacific Regional Environment Programme (SPREP, 2000).

American Samoa

American Samoa has a tropical maritime climate with abundant rain and warm, humid days and nights. Annual rainfall, usually in the form of showers, averages about 125 inches a year at the airport, but varies greatly over small distances because of topography. For example, Pago Pago, less than 4 miles north of the airport, at the head of a hill-encircled harbor open to the prevailing wind, receives nearly 200 inches a year. The crest of the range receives substantially more than 250 inches. The driest months are June through September (winter in the southern hemisphere, where American Samoa is located) and the wettest are December through March (summer in the southern hemisphere). Heavy showers and long rainy periods can occur in any month. Flooding rains are not unknown and some of these are associated with tropical cyclones that usually only affect American Samoa during El Niño periods. The prevailing winds throughout the year are easterly trades, interrupted more often in summer than winter, and sometimes associated with tropical cyclones, convergence bands, and upper level disturbances.

Commonwealth of the Northern Mariana Islands

Climatologically, the Mariana Islands are considered the sunniest islands in Micronesia. Rainfall is concentrated in July, August and September. Northeast tradewinds dominate from November to March with easterly winds predominant from May to October. Typhoon season runs from July to January, and the islands of the CNMI are usually subject to at least one typhoon each year.

Saipan is the largest island in the CNMI and the second largest of the Mariana Islands (Guam is the largest). Saipan is the most populated island and is the seat of government as well as the site of most economic activity in the CNMI. The west coast of Saipan is protected by a fringing barrier reef, while the relative absence of reefs on the east make that side of the island subject to strong waves fed by the tradewinds, particularly during Saipan's winter (November to April).

Average year-round temperature is 84° F with an average humidity of 79%. The ocean temperature averages 82° F. Occasional passing rain showers and gentle prevailing northeast tradewinds provide an environment that has been described as, "as perfect as it gets."

Federated States of Micronesia

The following paragraphs provide brief summaries for each of the individual states that comprise the FSM.

Kosrae— Kosrae is the only FSM state without outer islands, and is the most easterly state in the country. It has the smallest land area (only 42 square miles, or 112 square kilometers) and consists of two islands joined by a causeway. Kosrae's climate is tropical oceanic, and heavy rainfall has created numerous perennial streams. The average annual temperature is 81° F and average annual rainfall is 175.9 inches (4466 mm). Located only 5° north of the equator, Kosrae experiences periods of heavy rainfall associated with the Intertropical Convergence Zone (ITCZ). Most tropical storms pass north of the state, but the effects of typhoons can be felt in the area.

The 1997–98 El Niño drought had a devastating effect on taro, an important subsistence crop in many Pacific islands, including the Federated States of Micronesia (photo by Joseph Konno).

Pohnpei— Kolonia, capital of the island state of Pohnpei, receives roughly 16 feet (192 inches) of annual rainfall, with twice that amount falling on the interior mountains. Annual rainfall at the weather observatory is 193.6 inches, and average annual temperature is 80° F. The island's highest point, at 2540 feet (798 meters), is the summit of Mount Nahnalaud, thought to be one of the wettest spots in the world, with an average annual rainfall exceeding 400 inches. Pohnpei is a large state, with most of its islands and atolls in the north-central, southwest, and western parts of the state. The northern part of Pohnpei is where tropical disturbances often form, though most develop into full-blown typhoons north and west of the state. The southernmost atoll in the state is Kapingamarangi, located 2° north of the equator, and subject to droughts, particularly during La Niña events.

Chuuk— From about November to June, the climate of Chuuk is influenced chiefly by northeasterly tradewinds with average monthly speeds of 8 to 12 mph. By about April, however, the trades begin to weaken, and by July give way to the lighter and more variable winds of the doldrums. Between July and November, the island is frequently under the influence of the ITCZ. This is also the season when moist southerly winds and tropical disturbances, many associated with the ITCZ, are most frequent, and when humidities often are oppressively high. Rainfall at Chuuk averages about 140 inches a year, and temperature is remarkably uniform; high temperatures are generally in the middle 80s, and low temperatures in the middle 70s.

Although the major typhoon tracks of the western Pacific lie to the north and west of Chuuk, several of the storms have passed close enough to the island to cause widespread damage, including Supertyphoon Nina in November 1987; Nina was the most intense and devastating storm to have struck the vicinity, and a few days later, it decimated the Philippines as well.

FOCUS: THE 1997–1998 EL NIÑO— CLIMATE SCIENCE SERVING SOCIETY

The 1997–1998 El Niño event offers a vivid example of what climate means to people in the U.S.-Affiliated Pacific Islands (defined in Chapter One) and how information about potential consequences can be used to support decision-making and benefit society. This summary of the Pacific Islands' experience during the 1997–1998 El Niño comes from the work of the PEAC, which is a partnership among NOAA, the University of Hawai'i, the University of Guam, and the Pacific Basin Development Council.

By May 1997, most ocean-atmosphere observations and predictive models indicated that a significant El Niño was developing. El Niño events have significant consequences for U.S.-affiliated Pacific Islands, including droughts, changes in tropical storm/hurricane patterns, and changes in ocean conditions that affect economically significant resources like fisheries. For purposes of brevity, this example will focus primarily on El Niño-related changes in rainfall that led to severe drought conditions in many of the Pacific Islands.

In June 1997, PEAC alerted governments in the U.S.-affiliated Pacific Islands that a strong El Niño was developing and that changes in rainfall and tropical storm patterns in late 1997 through June 1998 might be like those experienced in 1982 and 1983. In September 1997, PEAC issued its first quantitative rainfall forecast, saying that severe droughts were likely beginning in December. PEAC also told governments that the risk of typhoons and hurricanes would be higher than normal in the RMI, eastern islands in the FSM, and in American Samoa. With the exception of Hawai'i, all Pacific Island governments served by PEAC developed drought response plans, aggressive public information and public education programs, and drought or El Niño task forces. The public information campaigns informed the public of what they might expect from El Niño, and what measures they could take to mitigate damaging consequences; these included water conservation, boiling water to prevent outbreaks of certain diseases associated with drought conditions, and reducing the risk of wildfires that often increase during drought conditions. In Pohnpei State for example, a video was produced and aired on the public radio station four times a day; public service announcements were aired on local television and radio stations; information hotlines were set up; brochures were prepared and distributed, and presentations on El Niño and drought were made in local schools. Water management agencies in Majuro, Pohnpei, Chuuk, Kosrae, Yap, Palau, Guam and Saipan developed and implemented water conservation plans. In Palau, the Department of Public Works surveyed the water distribution system in Koror and completed repairs on about 80% of the system before the drought set in. Throughout the FSM, people repaired water catchment systems and local vendors were able to supply new household catchment systems to meet the demand that developed in response to the public information campaign. The FSM government made deliveries of water to outer islands in Chuuk and Yap. In November 1997, the FSM Congress appropriated $5 million to address the potential impacts of anticipated drought conditions, and the U.S. Ambassador to the Republic of the Marshall Islands requested assistance from the U.S. Commander-in-Chief-Pacific (CINCPAC) to secure equipment and replacement parts to refurbish pumps for wells and increase storage capacity.

Even with these precautionary measures, the 1997–1998 El Niño produced such extensive drought conditions that water rationing became necessary in many areas. Water hours were imposed on most islands, with conditions on Majuro being the most severe. During April and May 1998, the water utility on Majuro was only supplying seven hours of water every fourteen days until pumps for wells on Laura islet were repaired. In Palau and Pohnpei, municipal water was available for only a couple of hours each day at the height of the drought. In the outer islands of Pohnpei, water was supplied by ship, and tanker trucks delivered water to schools in rural areas on the main island. Water supplied to the Koror-Airai area in Palau was reduced from 111 million gallons per month to 9.3 million gallons per month during the height of the drought.

see "El Niño" on facing page...

Yap— The ITCZ lies near Yap during the northern summer, particularly as it moves northward in July and southward again in October. At such times, showers and light, variable winds predominate, interspersed with heavier showers or thunderstorms, occasionally accompanied by strong and shifting winds. The average annual temperature is 81° F, and average annual rainfall is 121.5 inches. More than a quarter of all Yap's residents live on the outer islands, the rest on Yap.

Tropical cyclones or typhoons affect Yap much less often than they do Pacific Islands further to the north and west (the CNMI to the northeast, and the Philippines to the west and northwest, for example). June to December are the months of greatest storm frequency, but fully developed typhoons are uncommon near Yap.

Guam

The Pacific Ocean ends at Guam; its western shores signal the beginning of the Philippine Sea. This 209-square-mile island, southernmost of the Marianas, is the largest in Micronesia. Guam's climate is almost uniformly warm and humid throughout the year. Afternoon temperatures are typically in the middle to high 80s, with nighttime temperatures in the low 70s or high 60s. Relative humidity commonly ranges from 65 to 75% in the afternoon, and 85% or higher at night. Rainfall and wind conditions vary markedly, and it is these elements and variations that really define the seasons.

"El Niño" continued...

Agriculture suffered from the droughts everywhere except Guam. In the CNMI, citrus and garden crops were most affected, and the local hospital had to buy imported fruits and vegetables rather than rely on local suppliers. A limited damage assessment was done on Pohnpei, and serious losses of both food and cash crops were sustained. Losses of staple crops of taro and breadfruit in FSM exceeded 50%, and over half the banana trees evaluated had died or were seriously stressed. Sakau (kava) was probably the most serious economic loss because it had recently become a major cash crop. On Yap, taro losses were estimated at 50–65%, and betel nut prices increased more than 500% despite the fact that only 15–20% of the trees were lost. In Palau, food shipments increased from twice a month to once a week.

While the above example has focused largely on water, other climate-related consequences were felt throughout the islands; these included changes in the migratory patterns of economically significant fish stocks like yellowfin tuna, which resulted in losses for some island jurisdictions but opportunities for others; stresses on some coral reefs associated with increased temperatures; extreme tides from El Niño-related variations in sea level, as well as increased sedimentation from erosion in areas affected by wildfires; losses of important fresh-water shrimp, eels and fish as rivers and streams dried up; and reduced local air quality conditions in areas such as Yap, Pohnpei, Palau and Guam, which were affected by increased wildfires locally and haze from wildfires in Indonesia.

Still, the consequences could have been worse. Advance warning made possible by emerging forecasting capabilities and a focused program of education and outreach clearly helped mitigate the negative impacts of these climate effects, a good example of how real people in real places can benefit from climate assessment and adaptation. Pacific Island communities, governments and businesses are learning how to factor new information about climate variability into their decisions and are now looking for information about how patterns of natural variability (like ENSO) might be affected by climate change in the long term. Scientists and decision-makers throughout the Pacific are learning how, by working together, they can begin to address the challenges and opportunities of climate variability and change (Hamnett, Anderson, Guard, and Schroeder, 2000).

There are two primary seasons and two secondary seasons on Guam. The primary seasons are the dry season, which extends from January through April, and the rainy season from mid-July to mid-November. The secondary seasons are May to mid-July and mid-November through December; these are transitional seasons that may be either rainy or dry, depending upon the climatic nature of the year. On average, about 15% of annual rainfall occurs during the dry season, and 55% during the rainy season.

Throughout the year, the dominant winds on Guam are the tradewinds, which blow from the east or northeast. The trade are strongest and most dominant during the dry season, when wind speeds of 15 to 25 mph are common. During the rainy season there is a breakdown of the trades, and on some days the weather may be dominated by westerly moving storm systems that bring heavy showers, or steady and sometimes torrential rain. Of all the countries and territories discussed in this report, Guam and the CNMI are most subject to typhoons, which are most frequent from June through November. Historically, Guam has been affected by as many as four typhoons in a single season. They occur most frequently during the latter half of the year, but they either strike or pass sufficiently close to produce high winds and heavy rains in every month.

Hawai'i

Hawai'i's climate is one of the most spatially diverse on Earth. Because of this spatial variation of climate, Hawai'i resembles a continent in miniature. It has ecosystems ranging from deserts to tropical rain forests and even subalpine mixed forests, all in very close proximity. Hawai'i is located in the tropics and surrounded by the Pacific Ocean, with the nearest continental land mass more than 2,000 miles away. The ocean supplies moisture to the air and acts as a giant thermostat, assuring small seasonal temperature variations. Hawai'i's warmest months are August and September, and its coolest months are February and March. For most of the state, there are only two seasons: the warm or "kau" season from April to September, and the cool or "ho'oilo" season from October to March. A semipermanent high pressure zone, usually northeast of the

A billboard on Pohnpei encourages water conservation in preparation for the 1997–98 El Niño. (photo courtesy of U.S. National Weather Service, Pacific Region Headquarters)

The Intertropical Convergence Zone takes up residence around August and September of each year near Ulithi Atoll, in Yap, FSM.

islands, provides the northeasterly tradewinds for which the state is famous. This high tends to be more persistent and stronger in the warm months, producing steady tradewinds and less rain. In the cool months, the tradewinds may be interrupted for days or weeks by the invasion of fronts, wind shear lines, or low pressure systems from the north, and by "Kona Storms"[3] near the islands. The cool season has more frequent southerly and westerly winds and more clouds and rainfall, sometimes producing flash flooding. Hawai'i's mountains, valleys and ridges significantly influence every aspect of its weather and climate (Sanderson, 1993).

Rainfall distribution closely resembles topographic contours; amounts are greatest over ridges and windward areas (northeast slopes of ridges and mountains) and least in leeward lowlands. The islands receive more than 400 inches of rain on Mt. Wai'ale'ale on Kaua'i, more than 200 inches on higher windward elevations of all islands, and less than 15 inches in many leeward areas. The leeward and other dry areas have mostly dry warm months, and receive most of their rainfall from cool-season storms. The wetter regions show smaller seasonal differences because of the persistent tradewind showers. El Niño conditions usually disrupt this pattern, producing drought conditions, along with more frequent tropical storms and hurricanes. Tropical storms and hurricanes, although not frequent, have significantly affected the state in the late 1800s, 1959, 1982, and 1992 (Sanderson, 1993).

Republic of the Marshall Islands

The climate in the RMI is tropical, with tradewinds prevailing throughout the year. Tropical storms and typhoons are rare, although more likely during the summer months and El Niño years. Tropical storms are more likely to produce damaging effects over the northern islands, but can affect the entire country. Minor storms of the easterly-wave type are quite common from March to April and October to November. The trades are frequently interrupted during the summer months by the movement of the ITCZ across the area. Rainfall is heavy, with the wettest months being October and November. Precipitation generally falls in showers, but continuous rain is not uncommon. One of the outstanding features of the climate is the consistent temperature regime; the range between the coolest and warmest months averages less than one degree. The average annual rainfall on Majuro (the most densely populated island, where the capital is located) is about 131 inches.

Republic of Palau

Precipitation is heavy in Palau, though variable from month to month and year to year. In Koror, where the weather station is located, annual rainfall of 150 inches or more is not uncommon. Normal monthly precipitation exceeds 10 inches, and in some years each month has received at least 15 inches. Precipitation is heavy during December and January, decreasing sharply when the ITCZ moves well south of the islands. February, March, and April are the driest months of the year. Winds are generally light to moderate, and the northeast trades prevail from December through March. During April, the frequency of tradewinds decreases, and there is an increase in the frequency of east winds. In May, the winds are predominantly from southeast to northeast.

The ITCZ usually moves northward across Koror during June, bringing with it heavy rainfall and thunderstorms that may yield an inch of rain in 15 to 30 minutes. The ITCZ remains in the vicinity of Koror, though most commonly northward, from July through January, with heavy rainfall persisting. Temperatures and humidity are high.

Model-based Scenarios of Future Climate Conditions

This section provides a brief technical discussion of the results of recent efforts to anticipate future climate conditions using complex computer models that simulate the behavior of key components of the earth's climate system. These projections of future climate change for the Pacific Region are based on two approaches. The first approach uses a single, global, coupled ocean-atmosphere model to project

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[3] *A "Kona storm" is a low-pressure system that develops in the upper troposphere, gradually extends to lower altitudes, and may eventually appear as a low at the earth's surface. Kona storms form near the Hawaiian Islands every year, but locations and effects vary. If a Kona storm develops to the west of Hawai'i, moist showery southerly winds may persist for more than a week and rainfall totals are often large. Kona storms forming to the east of the Hawaiian Islands tend to bring rain that falls largely over ocean areas (Sanderson, 1993).*

seasonal changes for the Pacific Region. This single-model approach has been supplemented with a review of the results of a multimodel ensemble used in the third assessment report of the Intergovernmental Panel on Climate Change (See Cubasch et al, 2001 for details on the models and emissions scenarios).

The single-model climate change projections shown here are based on the results from two models: the Hadley model run at the Hadley Center for Climate Prediction; and the first-generation, coupled, general-circulation model of the Canadian Center for Climate Modeling and Analysis.

These two models were run for 100+ years, ending in 2100, using the core greenhouse-gas emissions scenario for the National Assessment, which is a 1% rate of annual increase in CO_2, and commensurate changes in sulfate aerosols (the GHG+A scenario). The 1% rate of increase is based on rates of observed increases modified by estimates of how the current sources of emissions are likely to change in the future; as such, it is deemed plausible as a "business as usual" case with little policy intervention anticipated in the future.

In these models, increased CO_2 causes warming by limiting outgoing long-wave radiation in the absence of a simultaneous reduction in incoming solar radiation. Increased sulfate aerosols produce a net cooling over regions where sulfur emissions are greatest, generally corresponding to industrial regions in the midlatitudes of the northern hemisphere. The "direct effect" of these aerosols (reflection of some of the incoming solar radiation before it can reach the earth's surface) is accounted for in the models, but the radiative forcing of increased aerosols is weaker than that of the CO_2, so by the end of the 21st century a general (but not spatially uniform) warming of the globe is projected to occur. Additional information on these model emission scenarios is provided at the web site (http://www.cgd.ucar.edu/naco/emissions.html).

As the results from the Hadley and Canadian models were generally consistent, all figures in this report's discussion of specific results will be from the Hadley model; comparisons with Canadian results will be made if necessary. In general, the details of important Pacific Island climate processes such as ENSO were better resolved in the Hadley model, thus the rationale for using the Hadley results in these figures.

The multimodel ensemble summary in this report represents an average of nine "state-of-the-science" global, coupled climate models from groups in the U.S., Canada, Germany, Australia, the U.K. and Japan. The multimodel ensemble was run with two of the scenarios (A2 and B2) described in the IPCC Special Report on Emissions Scenarios (SRES). The multimodel ensemble results shown here present annual means. The comparison of detailed seasonal results from the Hadley model with the annual mean multimodel results provides a comprehensive picture of the types of climate changes projected to occur in the Pacific during the 21st century. In addition, the ensemble method provides scientists with a tool for quantifying levels of uncertainty among the models' projections of changes in key climate variables, such as surface temperature and precipitation. The use of multimodel ensembles for this purpose is briefly described in a sidebar that precedes this chapter's summary.

Climate Change Projections from a Single Model

The following sections describe the results of the single model-run for temperature, rainfall, ENSO, tropical cyclones and sea level for the Pacific Islands addressed in this Report. Two time periods were used in the analysis of future changes in temperature and rainfall:

- average conditions from 2025–2034 minus the model's 1961–1990 base-period average (called "short-lead" in the figure captions); and,
- average conditions from 2090–2099 minus the model's 1961–1990 base-period average (called "long-lead" in the figure captions).

Long-lead results for the 2090–2099 period are more uncertain and speculative than those for the 2025–2034 period, although they may sometimes serve to amplify and further define the same patterns shown in the short-lead results. The two seasons analyzed are December-January-February (DJF) and June-July-August (JJA). These are thought to represent the two seasonal extremes. However, changes in certain phenomena, such as tropical cyclones that peak during the transition seasons, may not be optimally represented.

Temperature

The primary effects of climate change in the tropical Pacific Basin are projected to be a gradual warming of the sea-surface temperature (SST) and the air temperature. About 1° C (1.8° F) of warming is projected per 20 to 45 years. As shown for the Hadley model in Figures 2.1 (2025–2034) and 2.2 (2090–2099), warming in this model is projected to be greater in the following areas: a region along and slightly south of the equator extending from the international dateline on the west to the South American coast on the east, and in the region that extends east-northeastward from the equatorial Central Pacific to the

United States-Mexico border and the southwest coast of the United States. The area of warming generally resembles a horseshoe-shaped pattern that is concentrated north and slightly south of the equator east of the dateline.

The warming in the equatorial East Pacific is projected to be greater during the peak El Niño season of DJF. Hawai‘i is on the northern edge of the fastest warming area in the northern leg of the horseshoe, with projected increases in SST of 1.3° C (2.3° F) by the 2025–2034 period (Figure 2.1) and 3.0° C (5.4° F) by the 2090–2099 period (Figure 2.2). The outer edges of the east-southeastward leg of the horseshoe affects American Samoa, the northern Cook Islands and French Polynesia, with projected increases in SST of 0.5° C (0.9° F) by 2025–2034 and 1.3 to 2.0° C (2.3 to 3.6° F) by 2090–2099.

The projected warming pattern for the Canadian model is in general agreement with the Hadley model, with somewhat warmer temperatures along the northern and southern legs of the horseshoe pattern, reaching 1.6° C (2.9° F) in the short-lead results, and 4 to 5° C (7.2 to 9½ F) in the long-lead results.

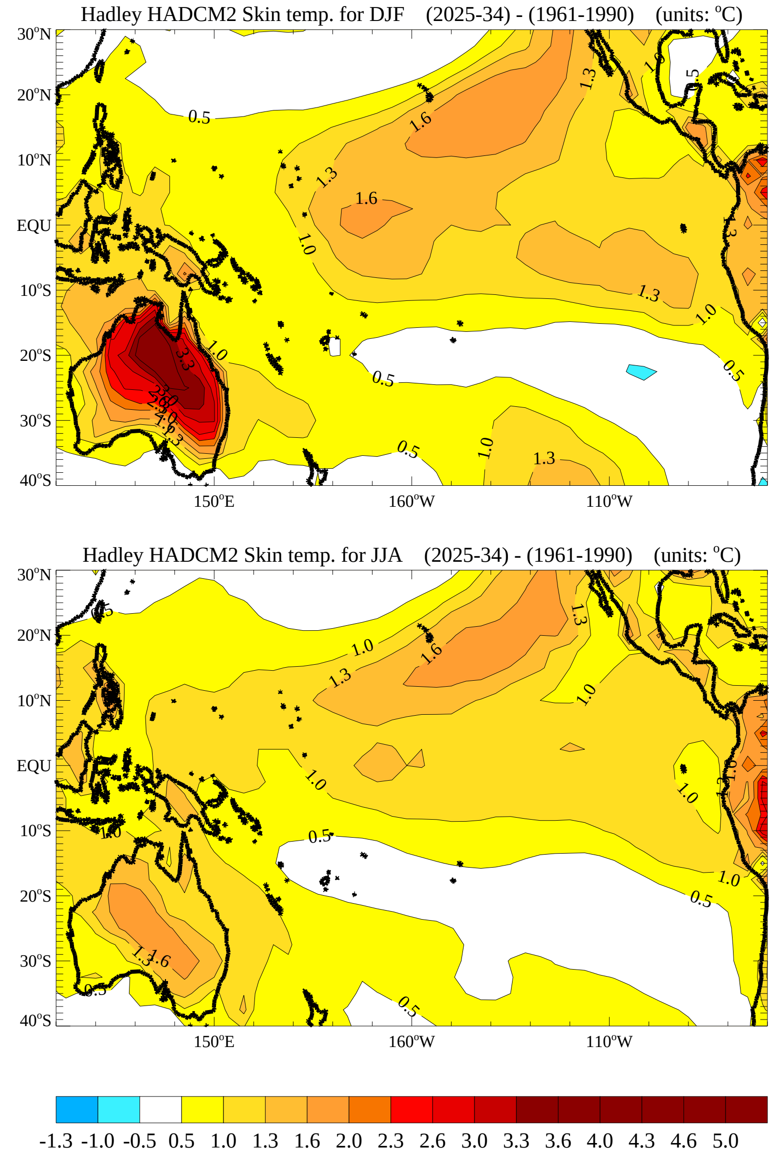

Figure 2.1: Projected changes in skin temperature (SST over ocean, and surface-air temperature over land) difference for the short-lead results (the model's 2025–34 average minus the model's 1961–90 base period average) for the seasons DJF and JJA, in °C.

Rainfall

Accompanying the warming in the Hadley model, certain parts of the region are projected to experience increases in rainfall due to the fact that warmer water produces more moisture and the atmosphere above a warmer ocean surface can absorb and hold more moisture. The most likely locations for increased rainfall are near the equator in the vicinity of the dateline, where the SST is already nearly warm enough to support convection (cumulus cloud growth and precipitation).[4] Any additional increase in ocean temperatures in these areas, then, would result in marked increases in convection, and therefore rainfall. It is important to note that, during an El Niño, the SST in these equatorial regions near the dateline exceeds the temperature threshold for convection. Increased rainfall is therefore projected along the two warming "arms" of the horseshoe-shaped temperature pattern described above.

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[4] Convection refers to the process of cloud formation and precipitation associated with areas where warm, tropical air rises through the atmosphere and, as it expands and cools, leads to the formation of clouds—a process through which latent heat is added to the atmosphere as water condenses to form clouds. As a result, weather tends to be disturbed in these areas. In the tropics, warm air rises to the top of the troposphere and moves off toward the poles. These areas of "rising" air movement are complemented by areas in which colder air tends to move downward through the atmosphere ("sinking" air), and then toward the equator. Alternating areas of rising and sinking air are found around the globe between the poles and the equator, and help characterize the world's weather zones. As a general rule, weather in areas of sinking air tends to be dry and relatively calm.

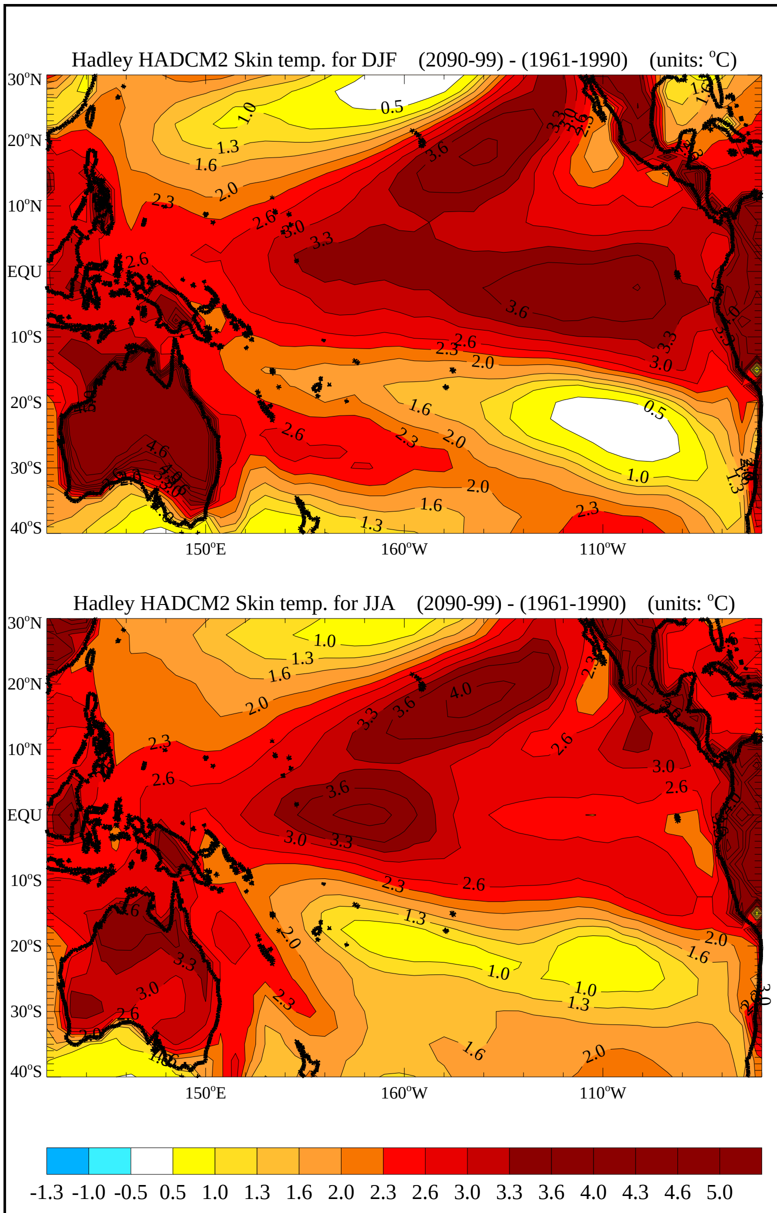

Figure 2.2: Projected changes in skin temperature for the long-lead results (the model's 2090–99 average minus the model's 1961–90 base period average) for the seasons DJF and JJA, in °C.

Scientists expect seasonal variations in this anticipated rainfall pattern. For example, they do not project any significant change in winter, when ocean temperatures are cooler in areas to the east of the horseshoe's vertex (the place where the curve in the horseshoe is the sharpest—in this case, where it crosses the equator). During the boreal summer months of June, July and August, increased rainfall is projected to occur along a line from the equatorial vertex (near Kirabati) all the way to the southernmost Hawaiian island. Model projections for 2025–2034 (Figure 2.3), indicate that areas of increased rainfall in the horseshoe in the southern hemisphere extend to 10° south, on a line stretching from Kirabati at the equator to American Samoa.

The results for the period 2090–2099 (Figure 2.4) show this area extending further south to between 15 and 20° south, with the largest increases in precipitation along a line extending from RMI in the north to Tahiti in the south. The regions near 10° north and to the west of the dateline (e.g. FSM) would also receive substantially greater precipitation in the long-lead results than in the short-lead results.

During the austral summer months of December, January and February, the increased rainfall is tantamount to an intensification of the South Pacific Convergence Zone, an area of the ocean that provides one of the principal sources of heat, and therefore energy, to the atmosphere. Model projections for 2025–2034 (Figure 2.3), indicate enhanced rainfall along a broad band extending from 10° north and 160° east (including the easternmost islands of Micronesia and the RMI) through the equatorial dateline and southeast to near 10° south and 130° west, near the Marquesas Islands. This region of enhanced precipitation is further enlarged in the projections for 2090–2099 (Figure 2.4), with increased rainfall extending further east along the equator, and large increases near the Marquesas Islands. This area also extends further westward to encompass the westernmost islands of Micronesia.

Decreased precipitation could be experienced in all seasons in areas near the equator east of about 140° west longitude (e.g., Fanning and Christmas Islands). Since rising air must fall somewhere else (see Footnote 4), areas of rising air (usually accompanied by cloud formation and rainfall) alternate with neighboring areas of sinking air that tend to be relatively dry. For this reason, dryness could also increase poleward of the most rapidly warming equatorial regions, such as north of the Hawaiian Islands, affecting many of the AF/USAPI west of Hawai‘i, and tropical South Pacific Islands farthest off the equator but west of French Polynesia. This would imply that, except for the boreal summer season in the long-lead results, where there is greater precipitation, the western portion of the FSM would become drier, for example in Yap and Chuuk. The eastern part of the FSM (possibly Pohnpei, but more likely Kosrae) not only could be exempt from this drying trend, but could become wetter, being closer to the rain-producing warmed SST near the dateline. South of the equator, island areas such as New Caledonia, Vanuatu, Fiji, southern Tonga, and Niue could become drier.

All these possible rainfall-change scenarios are more uncertain than the temperature-increase scenario and should therefore be considered cautiously. The exact location of the borderlines between neighboring regions of enhanced rainfall and suppressed rainfall is particularly uncertain. This uncertainty will be discussed in more detail later, in the context of results from the multimodel ensemble experiments. Some of the locations near the boundary between the regions made alternately wetter and drier by El Niño appear also to be on the boundary for the rainfall effects of climate change; examples of such locations are Apia in Samoa, and Niualakita in southern Tuvalu.

The patterns for projected precipitation changes in the Canadian model are generally similar to those in the Hadley model. The differences include somewhat stronger reductions in precipitation over the Western Pacific for the short-lead results in the Canadian model, as well as a generally noisier pattern of precipitation changes (small-scale variations between positive and negative precipitation changes) in the Canadian model for much of the region west of the dateline and south of 20° north; this encompasses much of the area around the FSM, the RMI and south to Fiji.

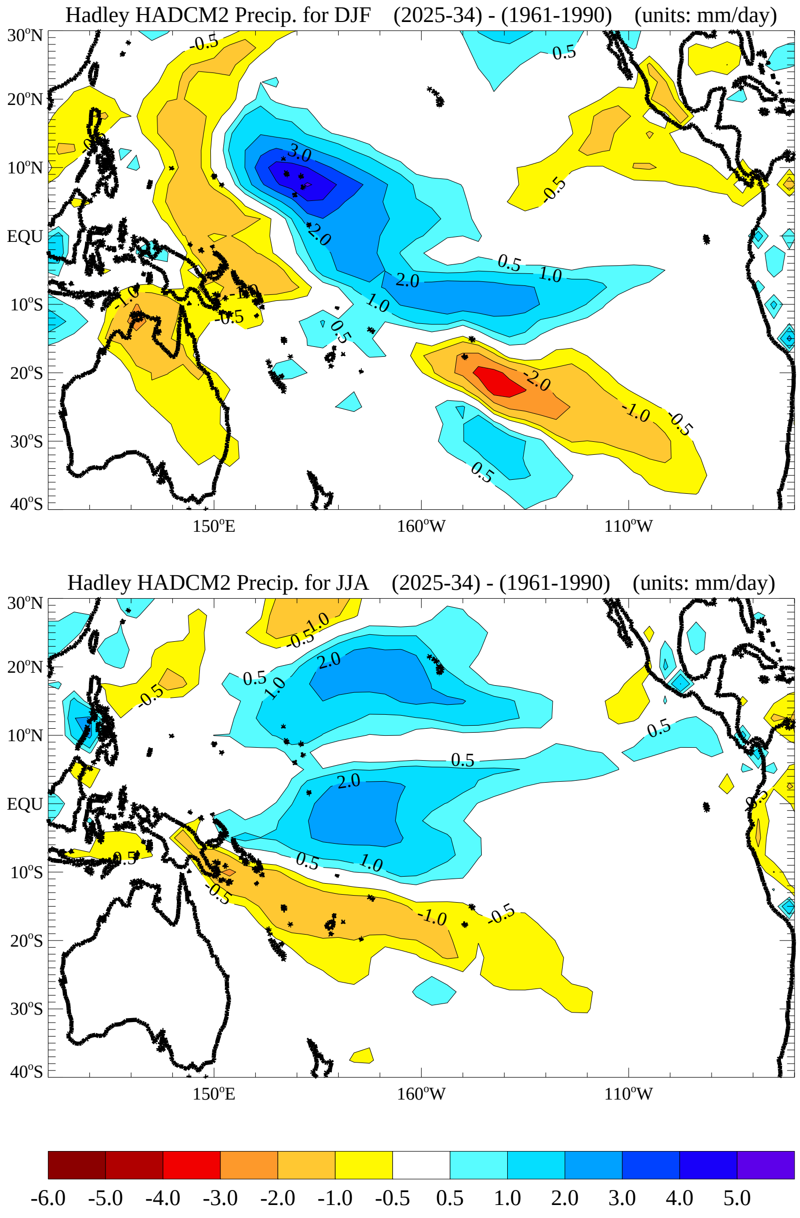

Figure 2.3. Projected changes in total precipitation change for 2025–2034 (for DJF and JJA), in units of mm/day.

Natural Variability/ENSO

In the Hadley model, the pattern of increased SSTs along the equatorial Central and Eastern Pacific suggests a greater tendency for El Niño-like conditions, with SSTs steadily warming in the Central and Eastern equatorial Pacific Ocean. The increase of precipitation in this same region is indicative of the warming pattern seen in the model results in DJF for both the short- and long-lead results. In this analysis, anomalies of SSTs in the Niño-3 region (defined as 5° N to 5° S and 150° W to 90° W) are used to measure the strength of El Niños and La Niñas. The time-series of the Niño-3 SST anomaly index from the Hadley model (Figure 2.5) shows a general warming trend through 2099, with the average SST increase in this region of almost 3° C (5.4° F).

However, the background setting for the ENSO phenomenon may be altered somewhat, with effects that are difficult to project. That is, the character of ENSO itself may change with the overall warming of the ocean and atmosphere. This creates some uncertainty about the details of the future climate conditions in the Pacific. Presently,

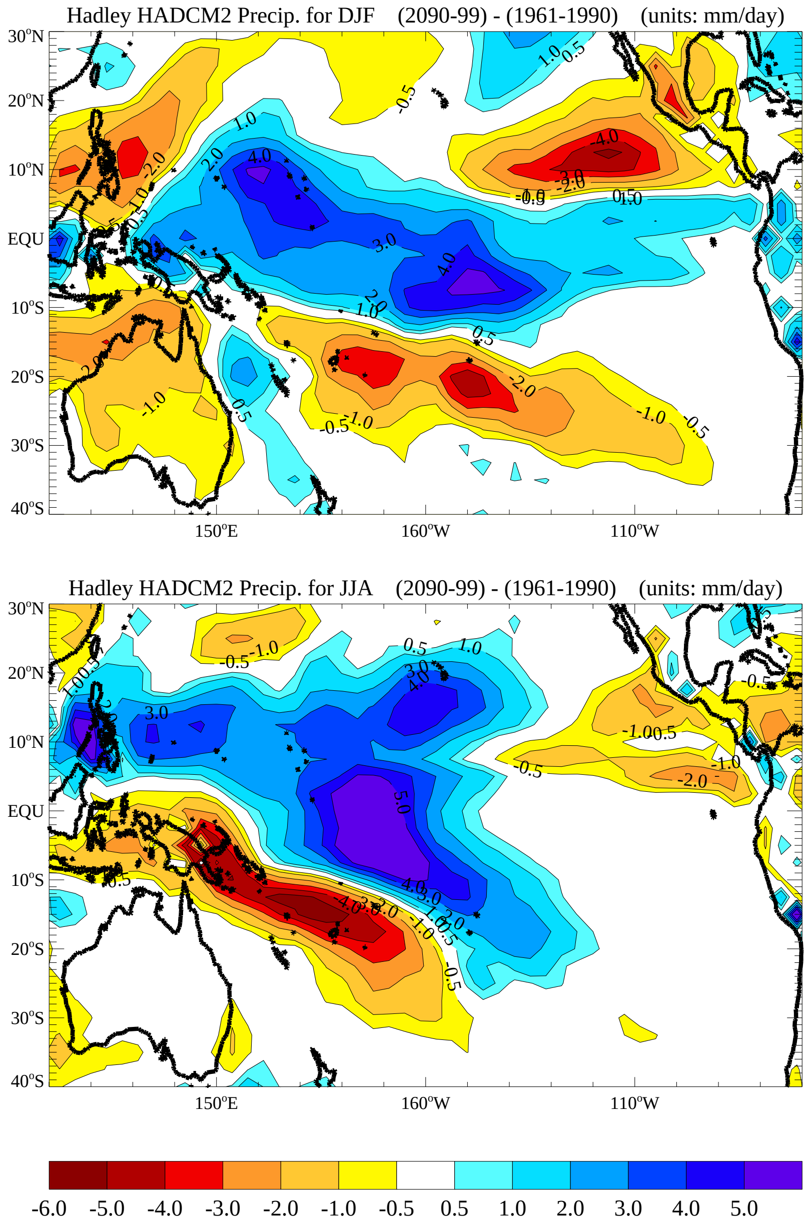

Figure 2.4. Projected changes in total precipitation change for 2090–2099 (for DJF and JJA), in units of mm/day.

some models project an increase in El Niño amplitude, and some show little change or a slight decrease (Cubasch et al., 2001). This is actively being examined by the research community, but limitations in the models' ability to simulate ENSO restricts the certainty of projections of El Niño behavior.

Tropical Cyclones

Pacific tropical cyclones generally develop over ocean water that exceeds roughly 28° C (82.4° F). During the past 30 years, such warm water has generally been limited to the Western tropical Pacific, which has been the source of most cyclone activity. This region extends farther east than usual during El Niño, posing an increased cyclone threat to islands farther east. The cyclones normally develop somewhat north or south of the equator and to the west of the dateline, and initially move toward the west with the tradewinds. They then curve poleward and finally eastward, threatening islands well off the equator, such as Guam, the RMI, or the Hawaiian Islands.

With global climate change, the region of very warm ocean water is projected to expand farther toward the east into areas that now expect warm water only during El Niño. The projected result is a gradual increase in the frequency of tropical cyclones for islands in the Central and East-Central Pacific, both north and south of the equator. Storm frequencies for the far Western Pacific may not decrease as they would presently during El Niño events, because the SST there will also be increasing, albeit at a slower rate. In fact, the frequency could increase slightly. In that case, the overall result would be an eastward extension of the tropical region that would

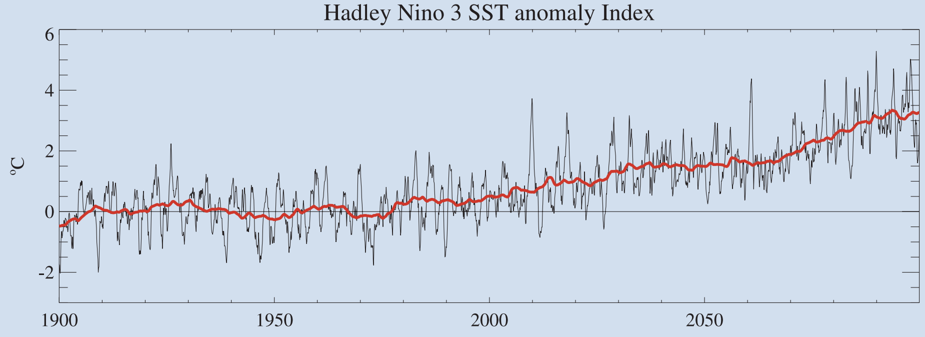

Figure 2.5. Monthly Niño-3 SST anomaly time-series (thin black line) for the period 1900–2099. The El Niño 3 region is defined as 5° N to 5° S and 150° W to 90° W, with the base years for the climatology defined as 1950–1979. The thick red line is the 10-year running average. Units are in °C.

normally experience cyclones, especially during the local summer and fall, when they are most likely. However, none of the global coupled climate models currently in use, including the Hadley, have sufficient spatial resolution to accurately simulate individual tropical cyclones. Experiments with embedded hurricane models in the global models suggest a slight intensification of tropical cyclones with more intense precipitation and somewhat higher peak wind-speeds in a warmer future climate (Cubasch et al., 2001).

Large-scale midlatitude storms are a function of the frequency and intensity of cyclonic activity, which must be computed from frequent (usually daily) measurements. Storms cause large changes in sea-level pressure (SLP) on a short time scale and, as a result, intraseasonal variation in SLP is an indicator of storminess— low pressure systems and their fronts in the extratropics, and tropical cyclone activity in the tropics. The Hadley data are calculated as standard deviations of SLP, filtered with a Murakami filter that isolates the synoptic variability between 2.5 and 8 days.

Figure 2.6 shows projected changes in the ratio of SLP variance for two periods (2006–2036 and 2070–2100) compared to a baseline period of 1990–2020 in the Hadley model. Figure 2.6 illustrates that in the near future more storminess is projected for a region extending north and east of the Hawaiian Islands to the area north of the FSM and east of the CNMI. For the far future (2070–2100), the storminess in this region is enhanced further and enlarged to encompass the entire Hawaiian Islands as well as most of the FSM and the RMI. The equatorial region between 100° west and the dateline (north of the French Polynesian Islands but including the Marquesas Islands) is also expected to experience more storminess in the far future. In the southern hemisphere between 10° and 30° south, storminess is projected to decrease for regions between 170° east and 90° west, which would include Fiji and the French Polynesian Islands. The area surrounding American Samoa is near the zero-line separating the regions of increased or decreased storminess in the far future.

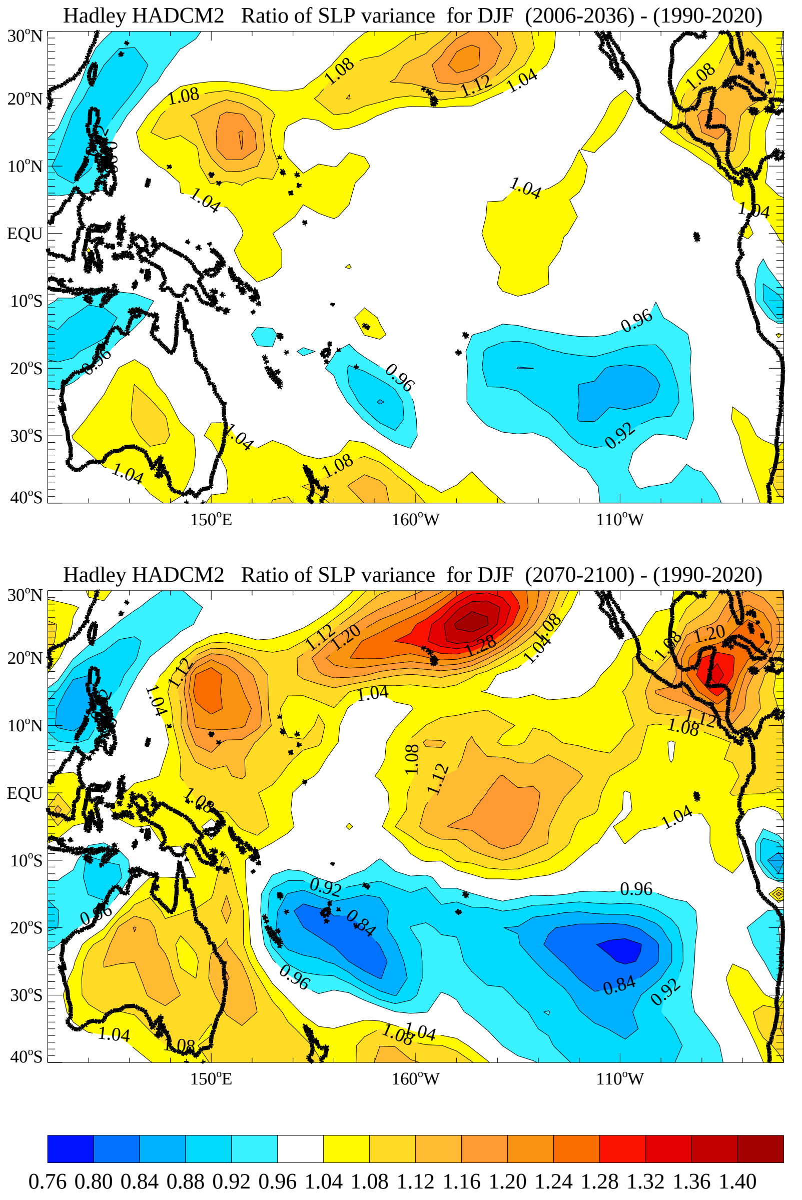

Figure 2.6. The ratio of SLP variance for DJF for the period 2006–2036 compared to 1990–2020, and the period 2070–2100 compared to 1990–2020. Higher ratios (>1) indicate more storminess in the future periods.

Sea Level

While increased sea-level rise can disrupt coastal areas over much of the Earth, atolls are particularly vulnerable to the phenomenon. Entire Pacific nations and archipelagos have maximum elevations of no more than two meters above sea level; even a relatively small sea-level rise could affect a large fraction of island area.

Sea-level rise can result in the loss of low-lying coastal areas— including agricultural land, human settlements and valuable ecosystems— through erosion and inundation. Sea-level rise also can accelerate reduction in the volume of

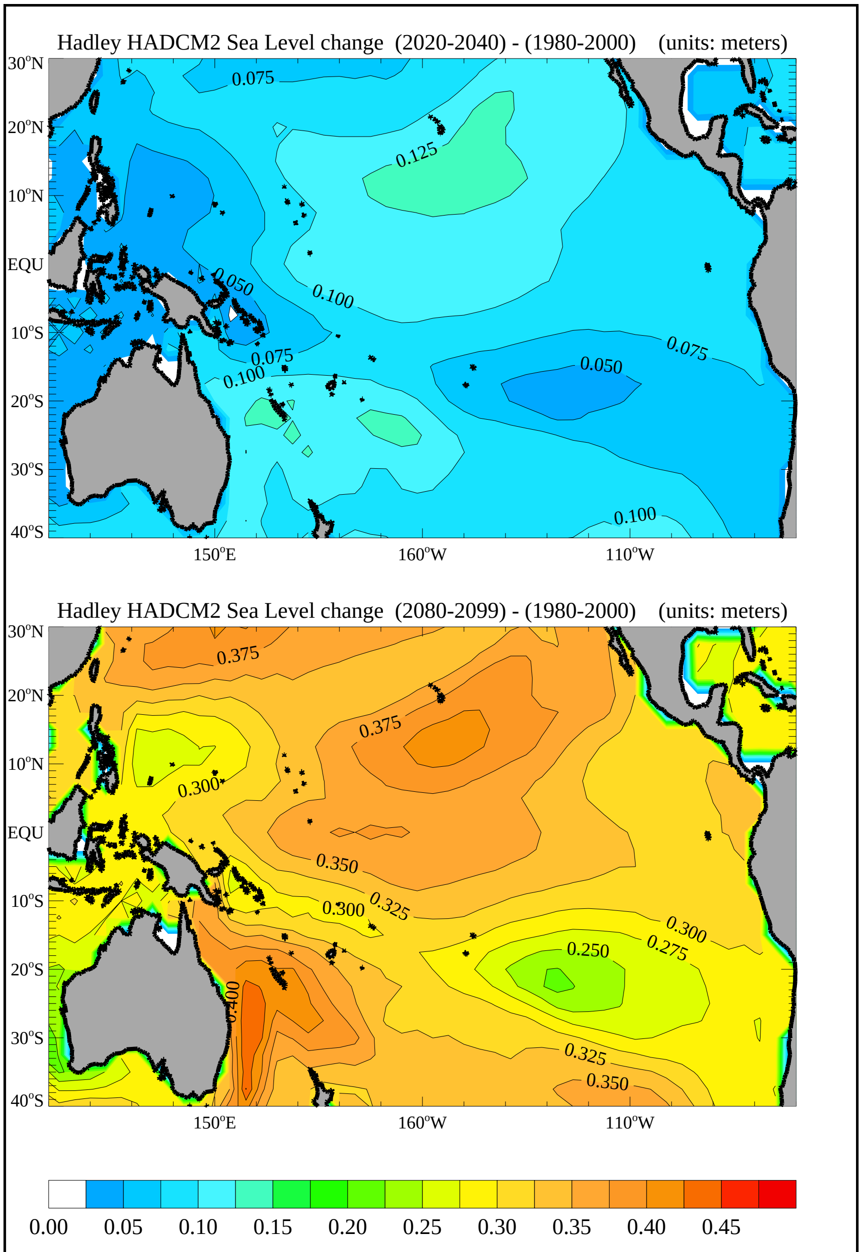

Figure 2.7. Sea-level rise for the period 2020–2040 minus 1980–2000, and the period 2080–2099 minus 1980–2000; units in meters.

the fresh-water lenses of low-lying atolls, further stressing fresh-water resources that may already be affected by reduced rainfall. Higher sea level conditions could also exacerbate the damaging effects of tropical cyclones and storm surge.

Sea-level rise and climate change can accelerate beach erosion and also affect other forms of natural protection such as mangroves and coral reefs. Some recent studies suggest that the "net effect of sea-level rise on mangroves is unclear," noting that if the rise is gradual, the effect could be beneficial for mangroves in some sites (World Bank, 2000). On the other hand, the potential loss of coral reefs from SSTs rising above the coral's preferred temperatures could jeopardize the natural protection afforded by the reefs, and thus exacerbate the shoreline effects of wave action as well as periodic and long-term variations in sea level; this could also be influenced by other factors associated with climate change. For example, a possible reduction in the rate of coral reef growth as a result of an increase in carbon dioxide (CO_2) in seawater could mean that these natural protective barriers will be unable to keep up with sea-level rise, thus exposing shoreline areas to storm surge and wave energy that would otherwise have been dissipated by the reef. Loss of freshwater resources associated with saltwater intrusion as a result of sea-level rise could also be exacerbated by other factors affecting the availability of freshwater such as changes in rainfall or patterns of natural variability such as El Niño.

As these examples illustrate, it is important to recognize that any accelerated sea-level rise associated with climate change will be accompanied by other changes whose combined effects should be understood and addressed.

For the Hadley model, the sea-level change for the two periods analyzed is shown in Figure 2.7: 2020–2040 minus 1980–2000, and 2080–2099 minus 1980–2000. The model-based scenarios used in the National Assessment project a sea-level rise of between 10 and 12 cm (3.9 to 4.7 inches) for much of the tropical Pacific for the short-lead results, and a rise of between 30 and 38 cm (11.8 to 15.0 inches) for the long-lead results.

The worldwide, eustatic sea-level change shown in Figure 2.7 represents thermal expansion and glacial melt, but not ice-sheet melt because of the uncertainty of the net effect of climate change on Antarctic and Greenland ice sheets. Sea-level rise varies with location because of local heating and thermal expansion. Isostatic rebound and subsidence must be factored in when using these values to compute relative sea-level rise at a particular location.

It should be noted that projections of sea-level rise depend crucially on the choice of future emissions scenarios. Using the full range of 36 scenarios summarized in the IPCC Special Report on Emission Scenarios (SRES), the IPCC Third Assessment Report projects a rise in sea level ranging from 9 to 88 cm (3.5 to 34.7 inches) at the end of the 21st century (Church et al., 2001). The single-model results presented here use only one emissions scenario, and should therefore be evaluated in this broader context.

To provide some historical perspective for these projected changes, Table 2.3 (see page 34) provides a summary of mean sea-level trends at selected stations in the Pacific Islands covered by this Report. In addition, it must be noted that some Pacific Islands experience significant short-term variations in sea level associated with ENSO events. For example, sea level at Kwajalein is reported to have dropped 20 cm (7.9 inches) during the 1982–1983 El Niño. The University of Hawai‘i's Pacific Sea Level Data Center notes that for one tidal station in the western Pacific (at Malakal, Palau), sea level dropped 15 cm (5.9 inches) below the long-term average during the 1997–1998 El Niño, and rose almost 30 cm (11.8 inches) above normal during the La Niña that followed.

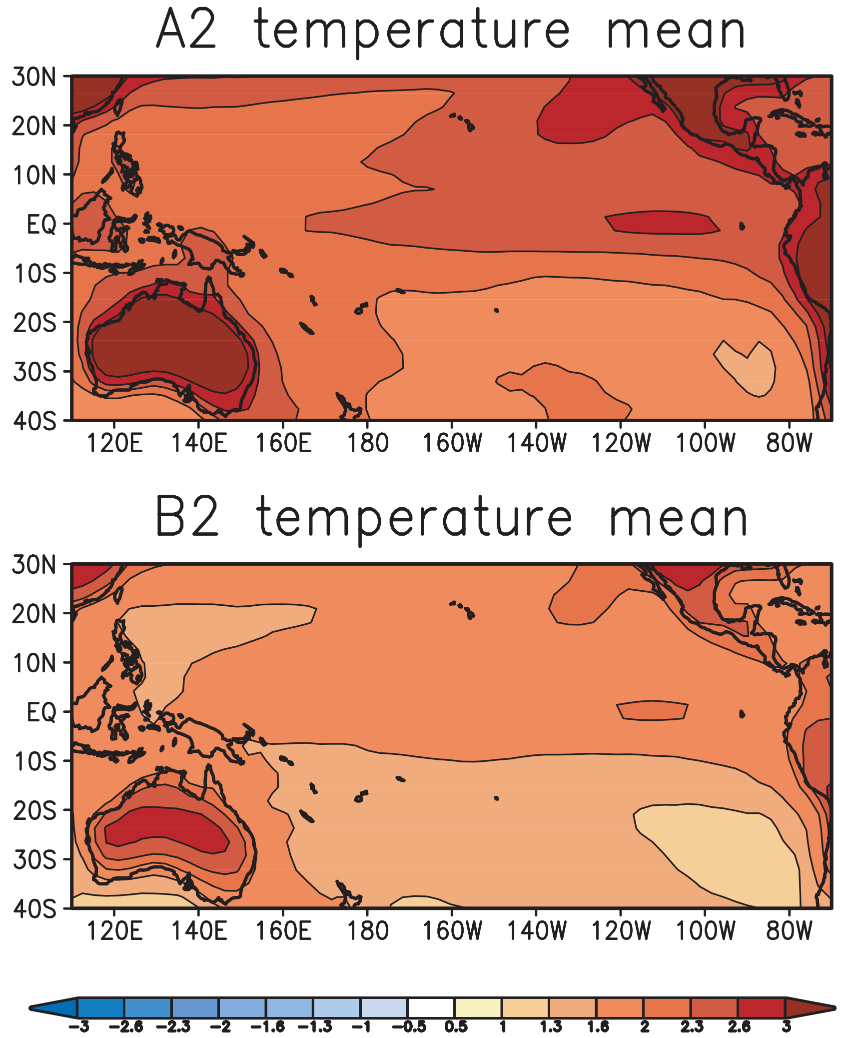

Figure 2.8: Mean surface air temperature change from the nine-member multimodel ensemble for the SRES A2 scenario, 2071–2100 minus 1961–1990 (above), and mean surface air temperature change for SRES B2 scenario (below); units in ½C.

Climate Change Projections from a Multimodel Ensemble

Annual mean surface temperature change for the nine-member multimodel ensemble is shown in Figure 2.8 for the end of the 21st century (years 2071–2100 minus 1961–1990) for two of the emissions scenarios (A2 and B2) used in the IPCC SRES. The main difference between the scenarios used in the multimodel ensemble and the scenario used for the Hadley model above is that the more recent SRES estimates for future sulfur emissions have been reduced, thereby producing less negative radiative forcing from that source, and allowing more warming from the increase in greenhouse gases. The patterns of warming caused by sulfate aerosols do not substantially affect the Pacific Region since they are restricted mainly to industrial areas. The other differences between the A2 and B2 scenarios are that A2 generally has greater increases of greenhouse gases, and thus more positive radiative forcing than B2. Therefore, the climate changes in A2 are generally greater than in B2, and the net radiative forcing is less than in the scenario used in the Hadley model, which is closer to the A2 scenario.

The multimodel ensemble results both show a general warming of the tropical Pacific in agreement with the Hadley model, with greater warming east of the dateline relative to the Western Equatorial Pacific (see Figure 2.8). This so-called "El Niño-like response," noted above, is stronger in scenarios in the multimodel ensemble than in

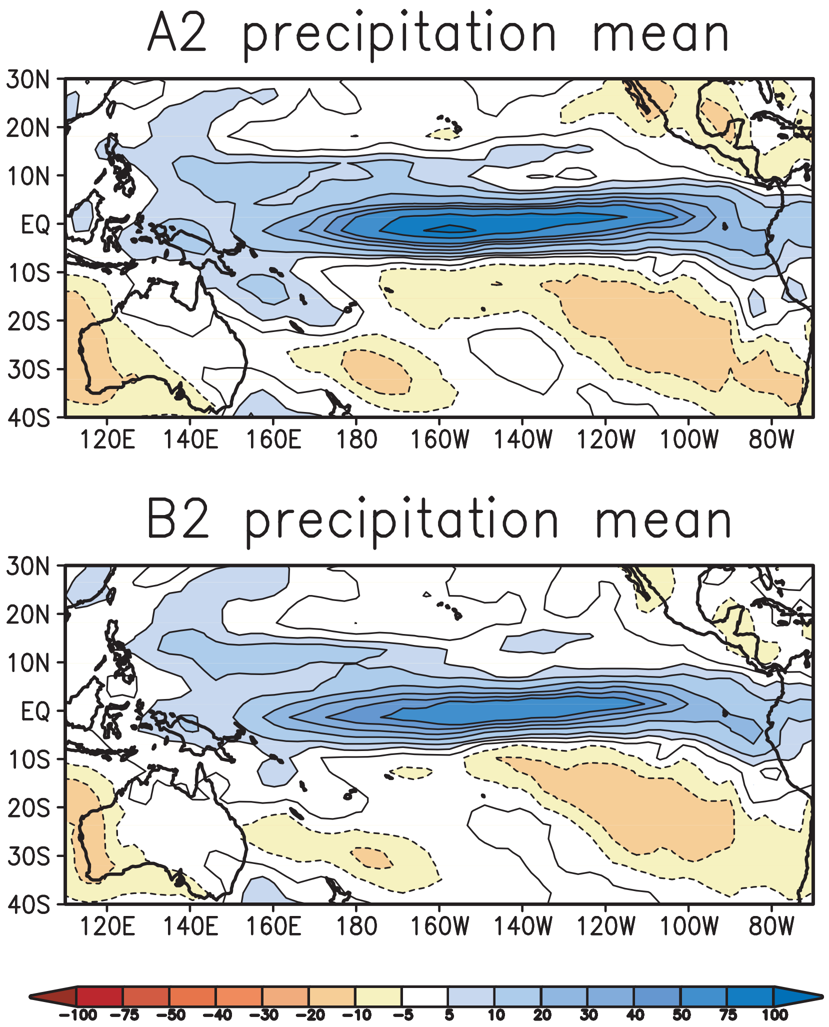

Figure 2.9: Mean percentage change in precipitation from the nine-member multimodel ensemble for the SRES A2 scenario, 2071–2100 minus 1961–1990 (above); and mean percentage change in precipitation for SRES B2 scenario (below).

the Hadley model, with surface temperature increases greater than 2° C (3.6° F) in B2 and 2.6° C (4.7° F) in A2 in the equatorial Pacific.

The implications of these surface-temperature changes are reflected in the changes in annual mean precipitation in Figure 2.9. The mean “El Niño-like” surface-temperature changes produce a similar El Niño-like change in precipitation, with an eastward shift of anomalous precipitation; they also produce increases approaching 100% in the equatorial Pacific near 160° W (just north of American Samoa) in A2, and greater than 50% east of the dateline in B2 (see Figure 2.9). Since the surface-temperature changes in the multimodel ensemble are more concentrated east of the dateline near the equator, areas in which precipitation increased more than 10% are confined mainly east of about 160° E and between about 5° N and 5° S, in a region just north of the Marquesas Islands. The Hadley precipitation changes extend more broadly in latitude, and occur farther west. For both A2 and B2, areas of decreased precipitation in the multimodel ensemble are projected to occur around French Polynesia and westward to near Fiji, and also near Hawaiʻi, though those decreases are about 10% or less.

The Use of Multimodel Ensembles to Quantify Uncertainty

Scientists can use multimodel ensembles like the ones described here to help quantify levels of uncertainty in model-based projections of climate change. The greater the agreement– or consistency– among models in an ensemble, the more confident a scientist will be about a projection. To provide an idea of model consistency, or conversely, of the level of uncertainty associated with climate change projections, the range of model responses for surface-temperature increase across the tropical Pacific is around 2 to 3° C (3.6 to 5.4° F) in A2, and 1.5 to 2° C (2.7 to 3.6° F) in B2 (see Figure 2.10). The range is less and thus the consistency among the nine models is generally greater in the equatorial tropics between 20° N and 20° S. As in the Hadley model, there is a relative maximum of warming projected to occur in a band extending through the Hawaiian Islands, with a relative minimum in the Southeast Pacific south of about 15° S.

Another measure of model uncertainty in the trajectory of the indicated change that scientists use is the multimodel signal divided by the multimodel standard deviation at every grid point. Where these values are greater than 1.0, the multimodel climate changes are more consistent relative to the noise. For annual mean temperature differences in the multimodel ensemble, all areas in the Tropical Pacific have signal-to-noise values greater than 1.0 (not shown), indicating significant model consistency for the temperature changes shown in Figure 2.8.

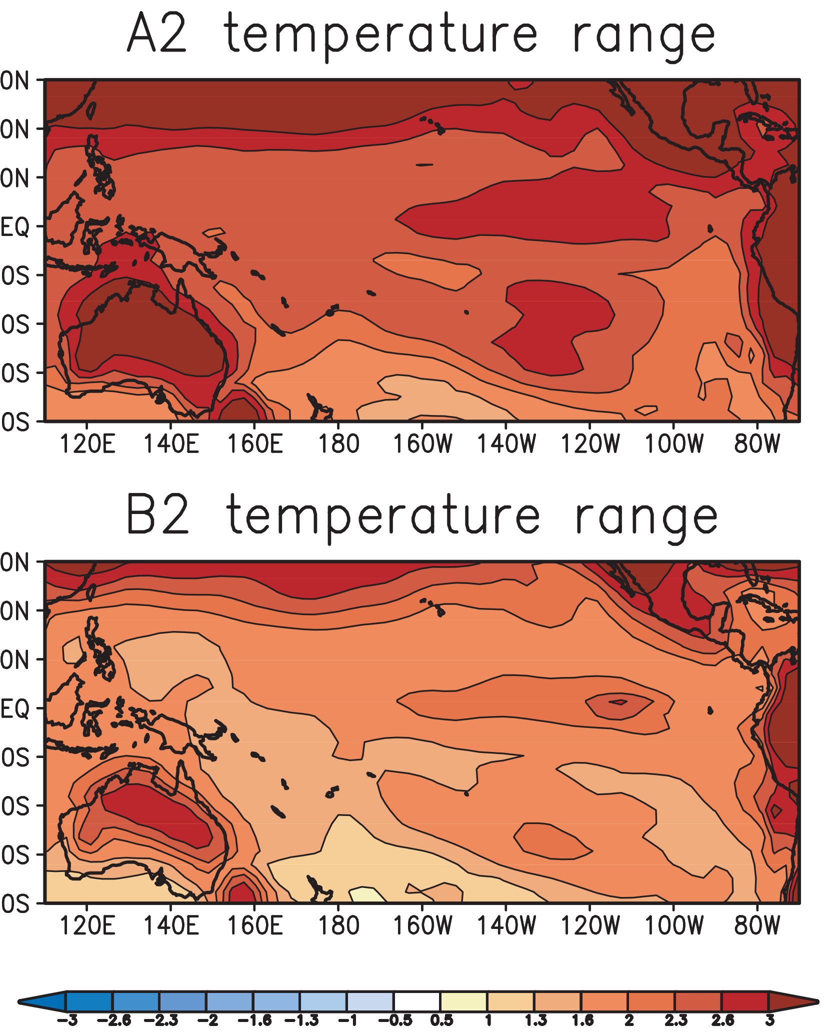

Figure 2.10: Range of surface air temperature change (highest ensemble member value minus lowest ensemble member value at each grid point around mean temperature changes) for the SRES A2 scenario (above); and range of surface air temperature change for the SRES B2 scenario (below).

As noted for the Hadley model, precipitation projections are much more uncertain than temperature projections. The range of precipitation changes for A2 and B2 exceed 200% in the Equatorial Pacific for both scenarios, with smaller values to the north and south (see Figure 2.11). Additionally, the signal-to-noise calculation for the multimodel ensemble has values greater than 1.0 only in a few regions of the Western Equatorial Pacific (not shown). Thus there is much more scatter among the model results, and therefore greater uncertainty, about precipitation compared to temperature.

Summary

The model-based climate-change scenarios reviewed in this chapter highlight the following important issues that were central to discussions of vulnerability in the Pacific Assessment:

- a general warming trend in surface air temperatures across the region, with implications for human settlements and marine and terrestrial ecosystems;
- a net regional enhancement in the hydrological cycle with a trend toward higher precipitation in some areas, but with important subregional differences that include drier conditions in some areas and uncertainties about the potential effects of changes in hurricanes and tropical storms that often provide a large percentage of rainfall in certain areas;

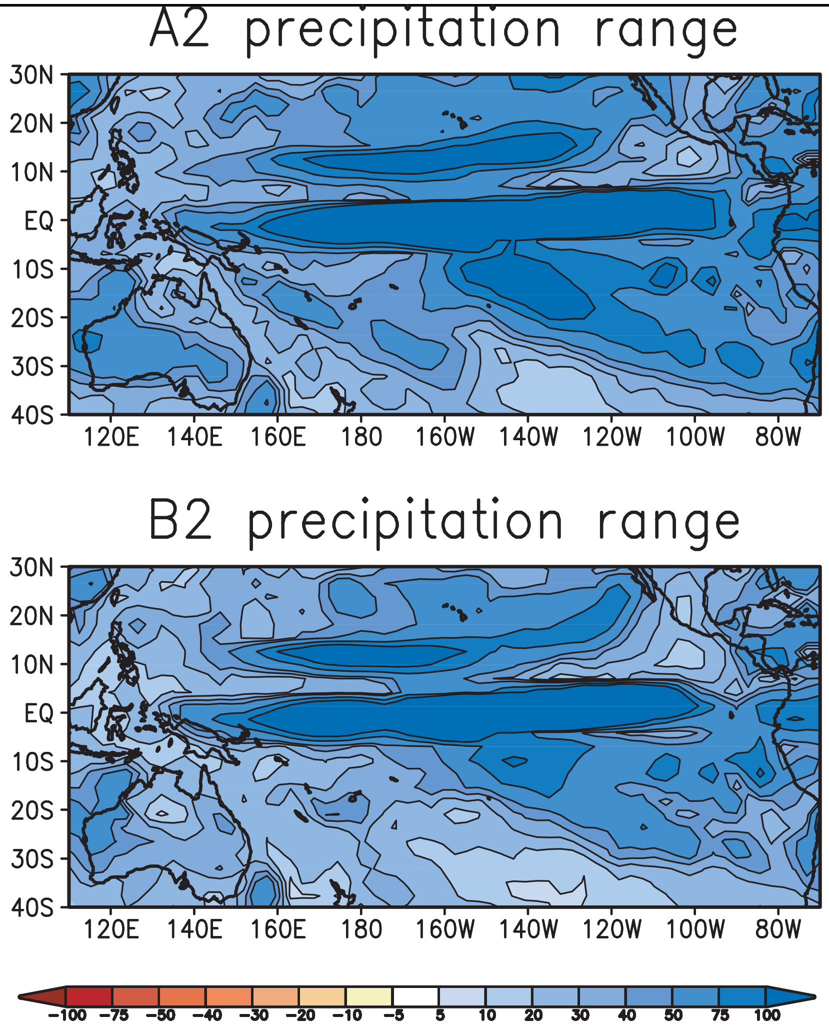

Figure 2.11: Range of percentage change in precipitation (highest ensemble member value minus lowest ensemble member value at each grid point around mean precipitation changes) for the SRES A2 scenario (above); and range of percentage change in precipitation for SRES B2 (below).

- potential changes in natural climatic variability, including the possible emergence of a persistent El-Niño-like condition that could affect rainfall, tropical storms and ocean conditions, and, in turn, economically important fisheries and coral reefs;
- potential changes in hurricanes and tropical cyclones associated primarily with variations in SST and with possible changes in ENSO, as well as long-term changes in the normal SST;
- increased ocean temperatures, with implications for temperature-sensitive resources like coral reefs and fisheries; and,
- changes in sea level, including both periodic changes associated with ENSO events and a long-term rise in sea level.

Table 2.3: Mean Sea Level Trends at Selected Pacific Island Stations.

Location	Rate of Change	Record Duration	Total Change
HawaiÔ i			
Honolulu	1.5 +/- 0.2 cm/decade (0.6 +/- 0.1in/decade)	1905Ð 2000	14.2+/- 1.9 cm (5.6 +/- 0.8 inches)
Hilo	3.2 +/- 0.5 cm/decade (1.3 +/- 0.2 in/decade)	1927Ð 2000	23.9 +/- 3.7 cm (9.4 +/-1.5 inches)
Nawiliwili	1.4 +/- 0.4 cm/decade (0.5 +/- 0.2 in/decade)	1954Ð 2000	6.4 +/- 1.9 cm (2.5 +/- 0.7 inches)
Kahului	2.1 +/- 0.5 cm/decade (0.8 +/- 0.2 in/decade)	1950Ð 2000	10.8 +/- 2.6 cm (4.2 +/- 1.0 inches)
MokuÔ oloe	0.8 +/- 0.5 cm/decade (0.3 +/- 0.2 in/decade)	1957Ð 2000	3.5 +/- 2.2 cm (1.4 +/- 0.9 inches)
Guam	0.4 +/- 0.6 cm/decade (0.1 +/- 0.2 in/decade)	1948Ð 2000	2.0 +/- 3.2 cm (0.8 +/- 1.3 inches)
American Samoa			
Pago Pago	1.6 +/- 0.5 cm/decade (0.6 +/- 0.2 in/decade)	1948Ð 2000	8.5 +/- 2.7 cm (3.4 +/- 1.0 inches)
RMI			
Majuro	2.8 +/- 1.0 cm/decade (1.1 +/- 0.4 in/decade)	1968Ð 2000	9.2 +/- 3.3 cm (3.6 +/- 1.3 inches)
Kwajalein	1.1 +/- 0.4 cm/decade (0.4 +/- 0.2 in/decade)	1946Ð 2000	5.9 +/- 2.2 cm (2.3 +/- 0.9 inches)
Wake	2.0 +/- 0.5 cm/decade (0.8 +/- 0.2 in/decade)	1950Ð 2000	10.3 +/- 2.6 cm (4.1 +/- 1.0 inches)
FSM			
Pohnpei	2.8 +/- 1.9 cm/decade (1.1 +/- 0.7 in/decade)	1974Ð 2000	7.5 +/- 5.1 cm (3.0 +/- 2.0 inches)
Kapingamarangi	-1.6 +/- 2.3 cm/decade (-0.6 +/- 0.9 in/decade)	1978Ð 2000	-3.7 +/- 5.3 cm (-1.5 +/- 2.1 inches)
Yap	-1.1 +/- 1.8 cm/decade (-0.4 +/- 0.7 in/decade)	1969Ð 2000	-3.5 +/- 5.8 cm (-1.4 +/- 2.3 inches)
Palau			
Malakal	0.2 +/- 1.8 cm/decade (0.1 +/- 0.7 in/decade)	1969Ð 2000	0.6 +/- 5.8 cm (0.3 +/- 2.3 inches)

Original data for this table provided by Mark Merrifield, University of HawaiÔ i (Merrifield, 2000).