Climate Change in the Federated States of Micronesia

Food and Water Security, Climate Risk Management, and Adaptive Strategies

REPORT OF FINDINGS 2010

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The initial idea and funding for this study originated with Karen Bennett of the USDA Forest Service who deftly and with great patience organized and promoted this work.

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Study Partners

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This study was initiated at the request of the federal and state governments of FSM and the USDA Forest Service. Using internet resources, scientific journals, reports, and personal accounts provided by partners, investigators reviewed previous work on coastal issues in the FSM. Investigators also reviewed (1) the state of knowledge describing coastal environmental response to sea-level rise; (2) the extent of scientific understanding of sea-level rise and variability; and (3) the status of global climate change. Reference materials are described in endnotes.

From April 14 -16, 2009 partners convened in Majuro, Republic of the Marshall Islands, at a conference entitled “Climate Change and the Micronesia Challenge: Ways Forward in Collaboration and Adaptation.” There, representatives of the governments of Palau, FSM, Guam, the Commonwealth of the Northern Mariana Islands and the Republic of the Marshall Islands summarized climate impacts, described government initiatives and engaged in activities to formulate goals and prioritize adaptation initiatives.

Between April 17 and May 6, 2009 investigators visited field sites with representative coastal problems, assessed and recorded relevant data, interviewed state and federal resource personnel, met with island communities, and familiarized themselves with local and national management policies and strategies.

Introduction

This is a report of findings following research and a three-week field assessment (April 2009) of the Federated States of Micronesia (FSM) in response to nation-wide marine inundation by extreme tides (December 2007, September 2008, December 2008).[3] The study was conducted at the request of the US Department of Agriculture Forest Service and the state and federal governments of FSM.

December 2008, high tides inundated coastal communities throughout Micronesia leading to a nationwide state of emergency. (Source: Kosrae Island Resource Management Agency staff)

First Steps to Climate Risk Management

Like other science-based planning challenges, managing climate risk involves complicated assessment based on the best available information originating, in part, with scientific research and place-based community knowledge. Effective progress on managing climate risk is facilitated by a strong partnership between scientists and planners in the context of community-based decision-making.

To simplify and summarize the many findings here, the following are proposed as "first steps" that can be pursued simultaneously in the next 12 to 36 months and thereafter. Additional findings can be considered and implemented within the framework of these first seven steps.

1. *Develop a national climate education program implemented through state, Non-Governmental Organization (NGO), and community groups.* Managing climate risk can be facilitated with community involvement – but first the community has to possess awareness and knowledge of climate risk. Training NGOs, community groups, and state staff can produce a corps of educators to achieve this goal and perpetuate the program.

2. *Explore the issues of sea-level inundation, drought, and food and water security.* Develop a high level of awareness and knowledge by key decision-makers and community groups. Each community can develop a shared vision of what is at risk and what qualities to protect that can inform a state plan, and ultimately a national plan. Steering committees of stakeholders can facilitate this process. State and national agencies, offices, and programs can be aligned with climate risk management.

3. *Install and maintain climate-monitoring stations throughout FSM*. It is important to improve knowledge of developing regional climate trends and develop model projections of future regional climate trends. Presently, climate models do not agree on regional projections. This problem can be improved by *funding research on regional-scale climate modeling* to provide the FSM with important information for managing risk.

4. *Make maps of inundation risk and vulnerability and develop an inundation timeline.* Marine inundation will continue and worsen with sea-level rise. Managing this problem can be facilitated with maps showing locations where inundation is likely. Remote sensing and aerial photographic imagery, and light detecting and ranging (LiDAR) topographic and bathymetric data are needed to build digital elevation models to conduct vulnerability studies.

5. *Create a national climate risk management plan with individual state plans* that emphasize community-based adaptation to provide a roadmap for managing climate risk.

6. *Build food and water resiliency.* Food and water are at risk now. Collect data on food and water resources and trends; with international assistance build technical knowledge of tropical agro-forestry practices; define per capita sustainability parameters for individual communities; stage emergency resources; and monitor sea level and rainfall to forecast events when food and water assistance will be needed.

7. *Develop international partners to assist with steps 1-6.*

Findings

During the course of the investigation, several findings were identified.

1. Climate and sea level in FSM are strongly modulated by the El Niño Southern Oscillation (ENSO). Under El Niño conditions the nation of FSM typically experiences drought. Under La Niña conditions the nation of FSM typically experiences higher than normal sea level. Drought and marine inundation by high sea level may damage soil, food resources, and drinking water.

2. Intense drought related to El Niño in the late 1990's required emergency food and water services for FSM communities. Protracted La Niña-like conditions during the first decade of the 21st century caused marine inundation that required emergency food and water services for FSM communities.

3. Global warming is likely to cause continued rise in global mean sea level and changes to the water cycle. Precipitation, and thus food and water resources in FSM, will be strongly linked to ENSO, though climate models do not agree on how ENSO will change with continued global warming.[4]

4. Most of the FSM population lives near or on the coast; the economy is tied to coastal resources and infrastructure. There is no specific coastal management policy in FSM; this contributes to problems in managing risks associated with climate change.

High tides in December 2008 damaged soil and food resources. (Source: Kosrae Island Resource Management Agency staff)

5. Coastal erosion is widespread. On atolls, coastal erosion threatens groundwater supplies and agro-forestry production. Mangrove and coastal strand forests have been lost, exposing the shoreline to environmental damage including erosion and coastal sedimentation. Dredging and use of coastal sand and gravel for construction has caused coastal erosion, beach loss, and led to shoreline hardening.

6. Oceanic changes such as increasing sea surface temperatures and acidification threaten marine ecosystems.

7. Alien species threaten coastal and watershed ecosystems, reducing their resilience.

8. Drinking water sources are not stable in FSM and food availability is dependent on imports (e.g., rice from Southeast Asia). Delivery to atolls by air and ship is typically unscheduled and unreliable. Funds for purchasing food and water supplies are scarce among atoll communities. Drought and marine inundation may damage island food and water supplies with little warning. As a result food and water security are the nation's top problems.

9. Climate risk management focused on community-based adaptation, and implemented through effective land use policies can improve food and water security, environmental conservation, and sustainability.

10. The true locus of authority in island communities is the community itself. Climate risk management that includes changes in land use policy can be facilitated with the participation of community stakeholders and landowners. "Community Based Adaptation" is the involvement of all stakeholders with government partners in defining adaptation steps. Non-government organizations can be valuable allies in managing climate risk in the FSM.[5]

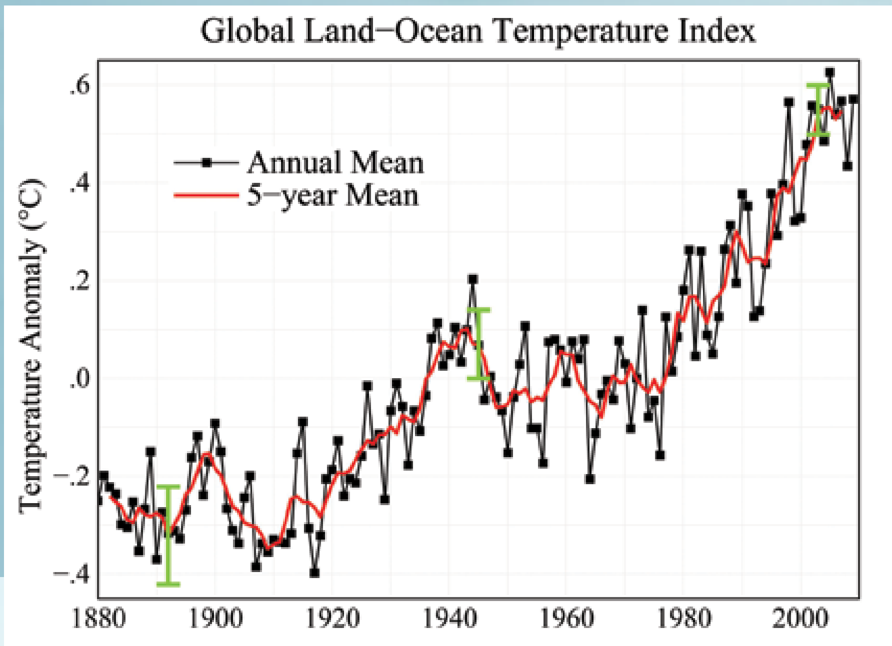
11. Significant challenges to the eventual success of climate adaptation efforts are posed by traditional and restrictive patterns of land use, decision-making and land tenure; lack of funding and planning; the remote nature of the population and geography; and a lack of abundant resources.

12. The above problems converge to place FSM, especially communities on atoll islets and in other coastal settings, at the forefront of risk from climate change. A national strategy to manage climate risk, beginning with public education, and based on community decision-making, would facilitate improving food and water security in FSM.

Map showing location of the Federated States of Micronesia (FSM) in the Pacific Ocean immediately north of the equator at longitude 158° 15° E and latitude 6° 55° N. From west to east: Yap, Chuuk, Pohnpei, and Kosrae.

The Federated States of Micronesia

The FSM is an oceanic nation of over 600 islands in the western tropical Pacific. Land varies from low-lying, forested atoll islets, typically 1 to 5 meters above mean sea level, to densely vegetated and eroded extinct shield volcanoes of several hundred meters elevation. On the main islands of each state (Kosrae, Pohnpei, Chuuk, and Yap) are modern developing communities; on the atoll islets are low-technology, traditional communities dependent on fishing, agro-forestry, groundwater, and rainfall. The population throughout FSM lives in the coastal zone and both community types are vulnerable to climate-related changes in precipitation, sea level, storms, and coastal erosion. Because drought and sea-level rise are amplified by regional El Niño Southern Oscillation (ENSO) processes, formerly sustainable atoll communities now rely on imported food and water during times of stress.

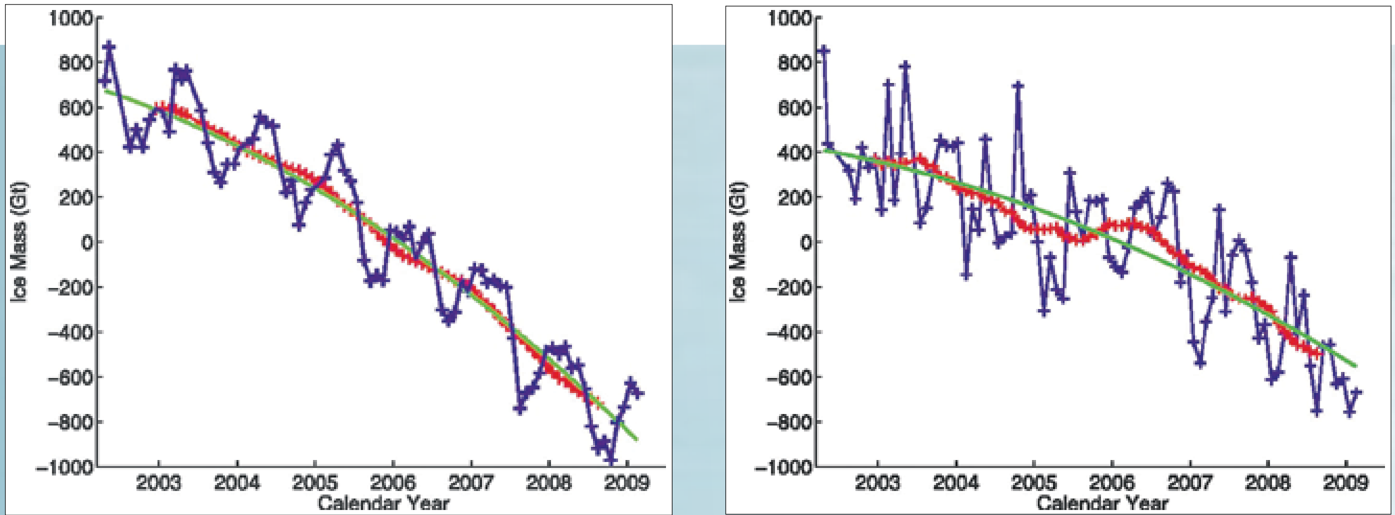


Except for a leveling-off between the 1940s and 1970s, Earth's average surface temperature has increased since 1880. The last decade has brought global average surface temperature to the highest levels ever measured. This graph shows global annual mean surface temperature relative to 1951-1980. As shown by the red line, long-term trends are more apparent when temperatures are averaged over a five year period. (Source: NASA)

Climate Change

From one year to the next global warming may not be evident. But measured by decade, the instrumental record beginning in 1880 shows that the temperature of Earth's surface (including the shallow ocean) has increased over the past century, markedly so since the 1970s.[6] According to the National Aeronautics and Space Administration (NASA) global surface temperatures have increased about 0.8°C since the late-19th century, and the linear trend for the past 50 years of 0.2°C per decade is nearly twice that for the past 100 years.[7] The year 2009 was only a fraction of a degree cooler than 2005, the warmest year on record, and tied with a cluster of other years — 1998, 2002, 2003, 2006, and 2007— is the second warmest year since record keeping began. Scientific analysis of modern and past climates has shown that Earth is warmer now than at any time in the past 1300 years.[8]

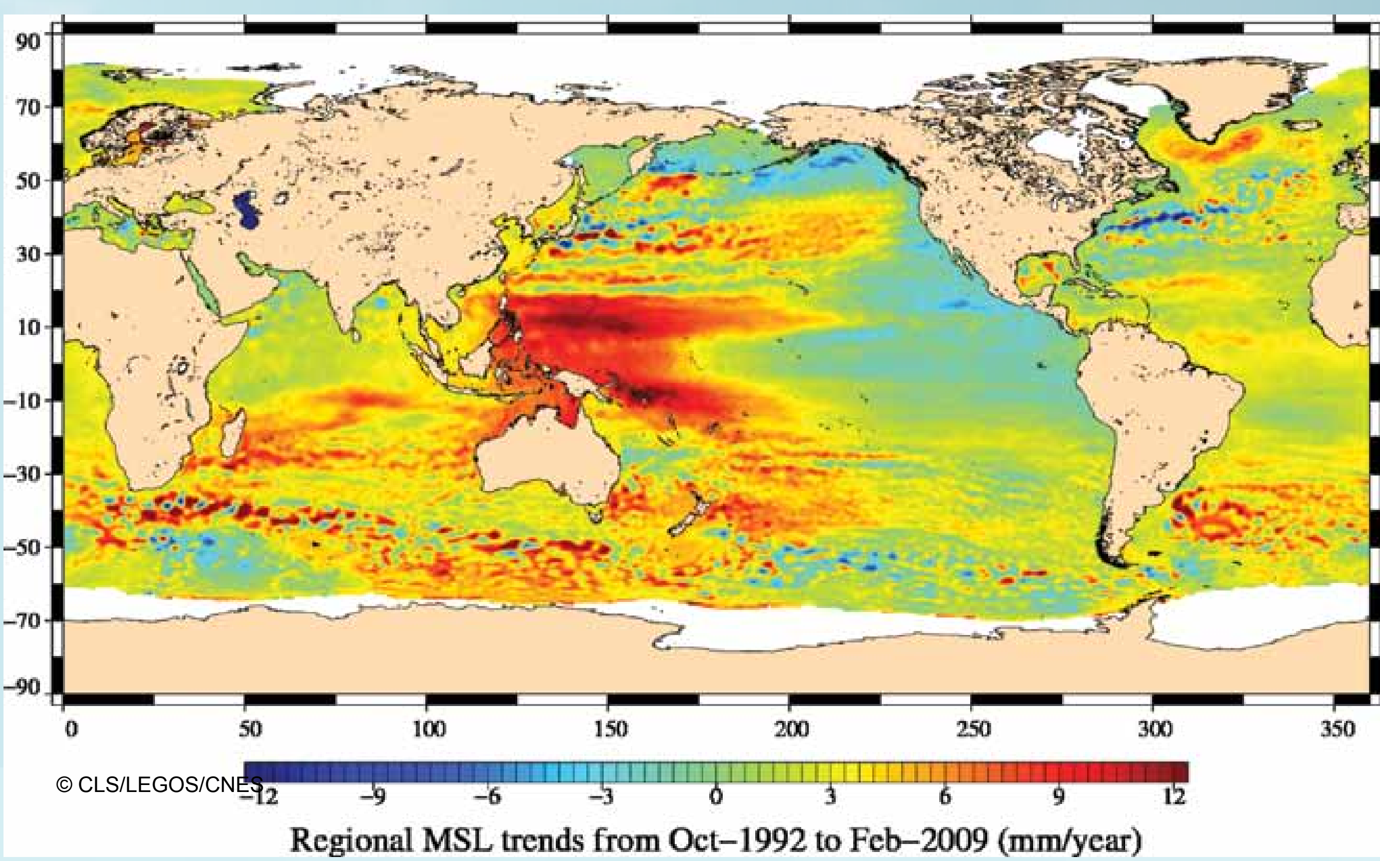
Global warming is having measurable impacts on human communities and natural ecosystems[9] (for instance, because of climate change, ecosystems must migrate an average of 0.4 kilometers per year to stay within their natural climate zone[10]). Antarctica has warmed at a rate commensurate with global patterns, about 0.12°C per decade since 1957, for a total average temperature rise of 0.56°C.[11] In Greenland, 2007 marked an overall rise in the summertime melting trend over the highest parts of the ice sheet.[12] Melting in areas above 2000 meters rose 150 percent above the long-term average, with melting occurring on 25-30 more days in 2007 than the average in the previous 19 years. As measured by satellite, melting from Greenland and Antarctic ice sheets has accelerated during the period April 2002 to February 2009.[13]



Ice loss 2002-2009, Greenland (left) and Antarctica (right). (Source: Velicogna, 2009)

Global warming has resulted in measurable changes to the water cycle in many locations. Tropical winds have slowed.[14] Some regions of the world are experiencing increased drought and others are seeing an increase in rainfall; some regions have seen a decline in rainstorm intensity and others have seen an increase. As with predicting future ENSO conditions, climate models do not agree on future rainfall patterns in FSM. However, models agree that as a global average, tropical settings are likely to see increased rainfall and rainstorm intensity.[15]

This image, created with sea surface height data from the Topex/Poseidon and Jason-1 satellites, shows precisely where and at what rate sea level has changed, 1992-2009. The complex surface reflects the influence of warm and cool bodies of water, currents, and winds. (Source: NASA[16])



The rate of global mean sea-level rise has approximately doubled since 1990.[17] However, sea level not only did not rise everywhere, but actually declined in some large areas. The pattern of sea-level change is complex due to the fact that winds and ocean currents affect sea level, and those are also changing.[18] Because of global warming, sea-level rise is expected to continue—and accelerate—for several centuries. However, the specific pattern of future sea-level rise from one location to another is not known. Research indicates that global mean sea level may exceed 1 meter above the 1990 level by the end of the 21st century.[19]

Sea-level rise today has accelerated above rates in the late 20th century when most land use planning and development took place. Thus, current land use policies and development may not take into consideration issues related to present sea-level rise. These circumstances increase the vulnerability of coastal communities to climate impacts. Continued sea-level rise may increase marine inundation of coastal roads, port facilities, and other development. Salt water intrusion may intensify in coastal wetlands and groundwater systems. Taro patches near sea level, estuaries, low-lying forestry stands, and other ecosystems in coastal settings may experience increased wave energy and rising salinity over time.

Extreme spring tides, known in Micronesia as "king tides," are the forefront of this change. King tides cause marine inundation that damages groundwater resources, taro beds, soil, and agro-forestry resources in coastal settings, especially on low atoll islets. On high islands, communities located at the intersection of intensifying storm runoff and rising ocean waters may endure increased flooding and drainage problems.

Taro crops on Nukuoro Island, Pohnpei, Federated States of Micronesia, were destroyed by seawater that swept over the shoreline and "bubbled up" through the water table in December 2008. Taro, a food staple, was damaged or destroyed in approximately 60 percent of atoll communities. Drought and high sea levels have negatively impacted the stability of food and water supplies. (Source: Pohnpei Environmental Protection Agency staff)

The tropical west Pacific is the site of pronounced ENSO conditions. El Niño conditions are characterized by a general decrease in the intensity of the trade winds; in the FSM this may cause a decrease in net precipitation, which in the past led to persistent drought, especially during strong events such as those that occurred in 1997-1998. La Niña conditions are characterized by intensification of the trade winds driving a rise in sea level and precipitation. Rising sea level generates coastal erosion, marine inundation, and salt contamination of soil, food, and water sources.

The relationship of these characteristics to the Pacific Decadal Oscillation (PDO) and other climatic processes (including global warming) is postulated but poorly understood. However, satellite altimetry shows that sea level in the tropical western Pacific has been rising an average of 5-10 millimeters per year since 1993, well above the global mean of about 3 millimeters per year over the same period. Whether this is tied directly to global warming, or to a combination of warming and protracted La Niña conditions, the PDO, or some other process is not known.

Events

The islands of FSM were severely impacted by drought during El Niño conditions of 1997-1998. Insufficient rainfall caused water and food shortages including staples such as taro, coconut, breadfruit, banana, yam, sweet potato, citrus, sugar cane, and others. Communities among the atolls survived because bottled water, food supplies, and reverse osmosis pumps were imported.

In 2007 and again in 2008, FSM communities were flooded by a combination of large swell and spring high tides that eroded beaches, undercut and damaged roads, intruded aquifers and wetlands, and inundated communities.[20] Once again food and drinking water were in short supply. Seawater flowed into coastal wetlands and surged up through the water table, killing taro, breadfruit, and other foods. Fresh water ponds and wetlands turned brackish and have not recovered. Crop sites in use for generations were physically and chemically damaged or destroyed on approximately 60 percent of inhabited atoll islets.[21] A nationwide state of emergency was announced on December 30, 2008 and food security was declared the top priority in the nation.

Chronic Problems and Management Issues

In addition to these events chronic problems are present in FSM. There is persistent coastal erosion that threatens roadways, agro-forestry production, habitable dwellings, and shallow coastal aquifers. There is loss of coastal strand forests and mangrove wetlands due to uncontrolled cutting, slow salinization of wetlands and lakes, salt diffusion into soils adjacent to brackish water bodies, and salinization of well water. Interviews with atoll residents on several islands have revealed that freshwater wetlands and lakes that have been historically important for food production have turned brackish over the past two decades. The spread of alien plant and insect species throughout FSM watersheds is decreasing ecosystem diversity and resilience and is threatening food sources.

Some scientists have proposed that atoll islets, because they are composed of reef-derived sand and gravel, might continue to accrete during sea-level rise as sediment is added by storm and overwash processes.[22] However, before the fate of the island land mass is determined by overwash, it will have become uninhabitable due to saltwater intrusion into aquifers, wetlands, and soils that will contaminate food and water resources.

Incompatible management of coastal development and natural resources exacerbate these problems. For instance, forest thinning and canopy loss tends to dry the soil and reduce the capture of precipitation. Mining beaches, reefs, and lagoons for construction materials can lead to erosion and habitat loss.[23] Continued building along the shoreline with no set-back exposes the community to coastal hazards. Use of submersible pumps in

In Chuuk, formerly productive taro beds have become open salt ponds over the past two decades. *(Source: C. Fletcher)* wells can encourage over-pumping and salinization. Waste disposal without regard to groundwater resources threatens contamination. An overall lack of data on sustainability parameters underlies many of these issues. An absence of master planning tends to promote *ad hoc* decision-making (further influenced by the need for rapid decision-making in the wake of recent crises). Arable land is scarce and a strongly traditional land use system involving complex land tenure relationships and a high number of invested stakeholders make it difficult to enact changes in policy.

Invasive species such as Meramia pultata, a particularly aggressive species, have taken over entire hillsides and invaded wetlands. (Source: C. Fletcher)

There are also data gaps that hamper comprehensive planning. Water management suffers from a lack of adequate hydraulic modeling and calculations of sustainable yield. Atoll aquifer systems are poorly understood and there is little knowledge of what sustainable groundwater withdrawal rates are appropriate from one island to the next, as well as among the main islands. Rates of coastal erosion are not measured and thus development on eroding shores does not take this hazard into account. As a result shoreline hardening is widespread and beach loss is common. This interferes with FSM plans for the development of tourism. Land elevation is a major data gap that could be resolved with airborne LiDAR surveys available from several sources.[24] Mapping topography and bathymetry in the coastal zone, matched with geospatial information on community parameters (infrastructure, roads, development, etc.) would allow for a risk and vulnerability analysis (RVA). RVA is an important step in developing a plan to manage climate risk and to design adaptation strategies. There are other data gaps as well: soil and agro-forestry geospatial layers, wave and sea-level monitoring instrumentation are lacking, geospatial information on climate and ocean processes (for instance, lagoon circulation is poorly understood), and others. Perhaps the most crucial data gap is the lack of site specific climate data to constrain down-scaled global circulation projections. Although this is a problem globally, the need for regional and local-scale climate modeling in the FSM is critical. Projecting future rain, storm, wind, evapotranspiration, surface temperature, ENSO patterns, and other fundamental parameters needs to be the target of focused modeling research so that climate risk management activities can be planned.

Climate change events, chronic problems, data gaps, lack of master planning, and entrenched land uses decrease the sustainability of FSM communities in the face of changing climate conditions. As a result, the following exist:

1. Vulnerability to natural hazards and difficulty recovering from natural hazards.
2. Loss of culture as traditional practice is replaced by imported resources.
3. Vulnerability to global warming.
4. Strain on national and state resources.
5. Problem solving by crisis management.

Effective climate risk management will be expensive, requiring external sources of funding and partnerships with other nations. These partners are going to be most amenable to providing resources to the FSM when they see that internal programs and policies are being upgraded and improved. Such improvements will raise the overall probability of successfully meeting the climate challenge and increase the likelihood that external investment success will be compounded and consistent with domestic climate risk management.

Coastal erosion in FSM is a chronic problem at many sandy beaches. Sea-level rise causes annual rates of erosion to accelerate. (Source: Kosrae Island Resource Management Agency staff).

Climate Risk Management

Internally derived study findings indicate that successful management of climate risk in FSM would be promoted by strategies that encourage adapting to climate change as well as continued attendance at international venues where FSM representatives may share their story.

Successfully achieving climate adaptation within the FSM may be facilitated by two steps: (1) forming international partnerships to aid adaptation efforts; and (2) continuing the development of internal policies focused on building resilient and sustainable communities. In the coastal zone this may be facilitated with the following:

1. Public education on climate risks in FSM including education of government workers and other decision-makers, of community members, and of landowners in particular.

2. The true locus of authority lies with island communities. Community-based adaptation offers an opportunity to effectively institute adaptation measures with immediate benefit.

3. Working within traditional land use policies to implement climate risk management as this will engender more domestic partnerships.

4. Defining best management practices and aligning government programs and policies with these practices.

5. Strategic redevelopment of coastal communities vulnerable to flooding now and in coming decades.

6. Conserving and promoting island and oceanic ecosystem services.

7. Preserving and promoting traditional culture to facilitate adaptation strategies and community accord.

8. Improving food and water security with a focus on domestic production as a core strategy in the national economy.

9. Master planning of communities focused on sustainability with enhanced government services such as health, sanitation, water and power, emergency services, and others.

Management Realities

Traditional land use and tenure, unstable slopes among the high islands, complexities in groundwater availability, alternative plans for using watershed lands by owners and various groups, low motivation and appreciation of climate risk, data gaps, and lack of adequate financing all signal that managing climate risk will be challenging. Approached carelessly, the situation could lead to displaced communities lacking real economic underpinning and low social standing. Moving and upgrading basic infrastructure will be expensive. There is little public land, and landownership is a complex and traditional foundation of political power in the FSM. Hence, the most positive outcome will result when authorities assess the feasibility of various climate risk management strategies in a realistic light.

Following marine inundation in late 2008, a nationwide state of emergency was announced and food security was declared the top priority in the nation (Source: Kosrae Island Resource Management Agency staff).

Land — On the small, low islands of the FSM, land is scarce. Because sustainability has always depended on appropriate land management, decision-making in the region has traditionally rested with landowners. Hence, in the FSM, land equals power and land possession and occupancy (i.e., tenure) influence political relationships and decision-making.[25] Complex, diverse, and often competing tenure systems governing ownership and access rights to land have developed throughout the islands. Traditionally, inheritance of land rights depended on membership in a lineage or clan (generally patrilineal in Yap and a few atolls in Pohnpei, and generally matrilineal elsewhere).[26] These rights were often subject to chief-centered authority and control, but in most cases, the oldest male member of the lineage managed the estate. However, after a century of colonial rule, systems of land tenure followed a path away from descendant group ownership toward a western model of individualized tenure.

Greater individual self-interest accompanying westernization is weakening traditional systems of land tenure based on lineage. However, in Micronesia, authority regarding land use policies lies also with the local community. Hence, to implement any adaptation strategies will require that landowners, local communities, and decision-making bodies are all in agreement with regard to the need for climate risk management and the design of adaptation steps. Non-government organizations will be indispensible partners in these efforts because they lack conflict of interest in most cases. A binding element in this situation can be *climate risk education*. A program of education involving this complex web of decision-makers may allow the group to approach the problem with a similar level of knowledge and with a more common point-of-view than otherwise.

The reality of land tenure and decision-making authority in FSM means that government agencies seeking to implement new land use policies must work closely with landowners, land users, NGOs, and local communities with whom most real decision-making authority lies. Hence, an early step will consist of instilling a common understanding of climate change impacts specific to FSM. Change is hardest for stakeholders who are invested in the current system (and in current land use policies and practices). As with any similar effort to educate invested stakeholders, there is likely to be an initial tendency toward intransigence and a lack of recognizing the need for change. For this reason, envisioning changes to existing policies within the familiar framework of the existing system may engender greater trust, willingness, and acceptance of changes compared to an approach that does not incorporate familiar elements.

Chronic coastal erosion threatens the tourism infrastructure throughout Micronesia. (Source: C. Fletcher)

In addition to major redevelopment, successful climate risk management may consist of adopting new polices of *effective coastal zone management*. The FSM government does not have a system of coastal management; for instance, there is no policy guiding shoreline development. A new house or road may be placed at the water's edge or on infill recently dredged from the reef. Local decision-making on coastal development is based on tradition, convenience, and landowner permission. What may appear to be random placement of houses and other buildings is related to land tenure issues: (1) one builds where one has traditional land rights or are granted these by traditional leaders; (2) there is some squatting, particularly by outer islanders who lack land on a main island where they are employed; (3) government buildings are on rented land as there is almost no public land. Zoning and land use classification have been nearly impossible to achieve given the reluctance of landowners to relinquish any land use options.

Compounding the above, there is an overall scarcity of arable and habitable land. The main islands of Kosrae, Pohnpei, and Chuuk are characterized by a narrow coastal plain backed by steep and unstable slopes. Yap also has unstable slopes related to the lithology of the bedrock (serpentinite, greenstone, and other metamorphics). Studies by hydrologists describe complex and difficult-to-access groundwater reserves that may not reflect the abundance of rainfall.[27] On high islands the typical focus of development and community activity is on or near the coastal fringe. Ocean access is important to nearly every Micronesian. For example, lacking a truck to tow a boat, residents need to live at the water's edge both for mooring opportunities and to protect their boats. Being on the water's edge also allows for dumping garbage, sewage, and pig waste directly into the lagoon.

Erosion on atoll islets has undermined and damaged infrastructure built during WWII. (Source: C. Fletcher)

Relocating homes as a step in climate adaptation requires addressing these already problematic sanitation issues. In an era of rising sea level and growing population, exposing new development to high risk with continued development at the water's edge is clearly not in the best interest of the community. Thus, basic social services are interconnected with climate risk management strategies within the limited island geography: waste disposal, transportation, food and water availability, emergency services, local economy, dwelling design, public health, and even family planning (number of members in a dwelling, level of family wealth, multiple generations, etc.) are all impacted by sea-level rise, storm surge, coastal erosion, and drought.

Atolls — Low-lying atoll islets pose special management challenges. Dozens of atoll islets in the FSM are occupied by human communities of a few hundred people each. These islets are composed of sedimentary accumulations of calcium carbonate ($CaCO_3$) sands and cobbles derived from the skeletal fragments of reef-dwelling organisms including coral and various carbonate-secreting algae. Some sediments are loose, and others are lithified by natural cements. Loose sedimentary deposits may be transported in various directions (seaward, lagoonward, or along the shore) and redeposited on the island surface by storm overwash and winds. Some researchers hypothesize that the tendency for high water events to carry sediment from the reef margin into island interiors may allow these islands to accrete upward with rising sea level.[28] The islet landform might thus persist under a regime of accelerated sea-level rise associated with global warming. Other researchers speculate that atoll islets are pinned on the reef by rock ramparts and when rising waters breach these cemented deposits on oceanic shores, the islet will become unstable and rapidly erode out of existence.[29]

Drought and sea-level rise threaten food and water security, coastal communities, and an ancient way of life. Oblique aerial photograph from Satawan Atoll, Chuuk State, FSM, showing low-lying atoll islets perched on the reef rim. (Source: C. Fletcher)

The debate among geologists regarding the fate of atoll islets neglects one point that is important to clarify for the media who tell the FSM story; marine inundation, the same process that carries sediment to the island interior, is extremely damaging to atoll freshwater supplies, the soil, the forests that supply food, and the wetlands in which island residents grow taro as a consumable staple. Long before the question of atoll landforms surviving sea-level rise is settled, human communities will have been forced to abandon these environments unless a climate adaptation strategy is developed that provides them with potable water and sufficient food. Ideally, adaptation steps can be implemented to secure the tenure of additional generations of families before, and if, abandonment becomes necessary. However, key questions persist: What are the recovery rates of groundwater, soil, wetlands and other necessary resources after they have been intruded by marine overwash events? Are there adaptation measures that will accelerate recovery rates? Can overwash events be anticipated and incorporated into planning so that community recovery (resilience) is enhanced? Are there key settings on atolls where adaptation steps can protect critical resources? What are the hydraulic properties of atoll aquifers and how severely are they damaged by individual inundation events? Are adaptation strategies available that may promote continued habitation of atolls even if they are inundated on an annual basis? Providing answers to these and other questions, and filling other key data gaps, constitute an important aspect of managing the climate risk in the FSM.

In Chuuk, this formerly freshwater lake was used for irrigation and in support of wetlands for taro production. The water is now brackish and taro beds along the shores are no longer productive. (Source: C. Fletcher)

Water — Atoll aquifers consist of a layer of freshwater floating on saltwater. Recharge from rainfall typically forms a thin lens of freshwater that is buoyantly supported by denser, underlying saltwater, and mixing forms a zone of transitional salinity. The thickness of this mixing zone is determined by the rate of recharge, tidal dynamics, and hydraulic properties of the aquifer. The freshwater zone of atoll islets is formed largely within unconsolidated sand and gravel, with some coral and a few cemented layers of sandstone and conglomerate.[30] The freshwater portion of the aquifer typically follows the long axis and elongated shape of the islets. The maximum elevation of the water table is near or slightly above mean sea level. The thickest part of the freshwater lens, which may reach several tens of meters, may be located near the center of the islets in areas where there is a greater abundance of fine-grained and less-permeable sediment; or on the lagoon side if that location is characterized by finer-grained sediment. Fine sediment has reduced permeability and thus retains water. The center of islets is also typically the lowest point; hence wetlands and open pools of water fed by the aquifer are not uncommon. Factors that control the thickness of the freshwater lens include variation in rainfall and recharge, shape of the landmass, and lithologic variability which controls permeability.[31] The freshwater-saltwater transition zone is commonly twice as thick as the freshwater lens it underlies, indicating high dispersion from tidal mixing.

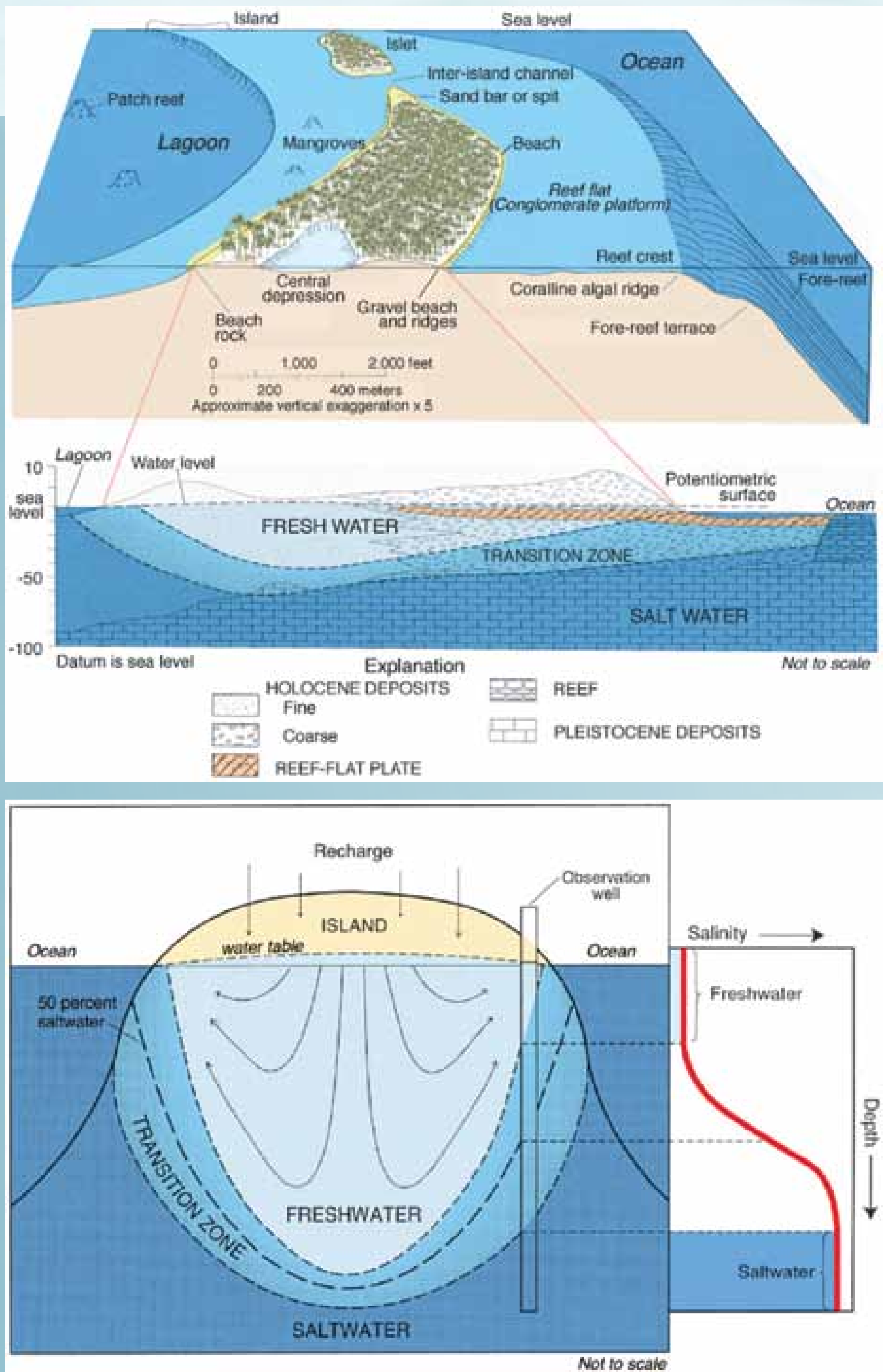
Wells with submersible pumps often create a cone of depression that draws underlying brackish water. Many communities on atoll islets now rely on catchment systems as their primary water source. (Source: C. Fletcher)

The hydrogeologic framework of an atoll islet is conceptualized as four units.[32] The islet itself constitutes the first unit; catching rainfall, a fraction of which is lost to evaporation and transpiration (by plants), islet sediments form a freshwater lens fed by infiltration. There is no appreciable surface runoff due to the high permeability of the soil and sediments.

The second unit is the reef-flat plate. The reef-flat plate consists of well-cemented reef cobbles, sands, and other carbonate sediments. It runs from the seaward reef flat, under the islet, and thins toward the lagoon shore. The plate forms a stable foundation upon which the islet sediments accumulate. The plate is usually no more than 3-5 meters thick and acts as a confining bed to the underlying unconsolidated sediments. Islanders tell of saltwater “bubbling up” during extreme tides and there are tales of caverns that run from the islet interior to the sea. These may describe fissures, cavernous porosity, in the reef plate.

Beneath the plate is a layer of unconsolidated Holocene sediments consisting of fragments of coral, *Halimeda* (a reef-dwelling calcareous alga), and foraminifera. These sediments hold a freshwater lens that may be thickest on the lagoon side of islets if the unit has highest permeability (coarse sediment) on the ocean side and lower permeability (fine sediment) on the lagoon side, thus retaining water.

The fourth unit is the highly permeable Pleistocene limestone beneath the island that was deposited during the last interglacial period, lying approximately 8-28 meters below the surface of the modern reef platform. The high permeability of this basement unit is due to erosion and subaerial dissolution under lower sea level. This unit typically contains seawater and a thin transition zone where the freshwater lens in the overlying Holocene unit extends to this depth. Cavernous porosity may also characterize portions of this unit.



Schematic drawing showing the features of a typical windward reef rim of an atoll. The fore-reef terrace is most likely a relict Pleistocene feature with a veneer of Holocene accretion. The exposed ocean side beaches are commonly steep and gravel rich, whereas the lagoon side beaches are more protected and tend to be gently-sloping and sand rich. The freshwater lens is usually best developed where the islands are underlain by thick deposits of unconsolidated sediment. Shown are saltwater, transition zone, freshwater, and a graph showing the relation of salinity to depth. (Source: Modified from Ayers and Vacher, 1986; Anthony, 1996)

National Strategy

A national strategy will facilitate managing climate risk in FSM. FSM communities are now experiencing marine inundation and drought. The population of FSM is projected to be 105,830 by 2015, a population equivalent to a modestly sized U.S. city (e.g., Cambridge, Massachusetts; Clearwater, Florida; West Covina, California).[33] It is entirely possible to significantly redevelop a community of this size over the course of several decades, even with the geographic challenges of the FSM. However, to effectively make this change, the desire and will must exist within the many local FSM communities. Hence, *climate change education is a critical first step*. Community groups and NGOs will be important partners in this effort.

Lack of planning and action at this time may result in a growing population of displaced climate migrants with no coherent strategy to accommodate their needs. This may lead to economic and social stress within the FSM.

Climate Risk Management Strategies

The National Oceanic and Atmospheric Administration (NOAA) and the US Geological Survey (USGS) convened a "Sea-level Rise and Inundation Community Workshop" in Washington D.C. in late 2009.[34] The workshop proceedings declare that the vulnerability of coastal communities to coastal inundation is increasing. The risk is projected to increase due to continued coastal development, changes in the frequency and intensity of inundation events, and, critically, acceleration in the rate of sea-level rise along our vulnerable shorelines. The desired outcome of the workshop was to develop a shared framework for a broad partnership to reduce coastal vulnerability and increase coastal resilience at local and regional levels: "The most important thing is for coastal communities to get started in preparing for a future with a higher stand of sea level and more frequent flooding." The planning framework emerging from the workshop (below) provides a strategy for moving forward.

- Define the Problem
  - o Explore the issues of sea level inundation with the community.
  - o Develop a shared vision of what is at risk and what qualities to protect.
  - o Form a steering committee of stakeholders.
- Gather Data, Information, and Tools
  - o Make maps of the problem on time scales of concern (5, 10, 25, 50 years).
  - o Identify and value the assets at risk.
  - o Develop models and monitoring of flooding hazards.
- Identify and Explore Alternative Strategies
  - o Identify strategies for dealing with inundation scenarios.
  - o Develop guidance/policies.
  - o Stage strategies on appropriate time scale.
- Build and Sustain Capacity and Support
  - o Align existing programs.
  - o Build the institutional capacity and the political will to execute strategies.
  - o Institutionalize the program and keep current.

Consistent with the planning framework described above, and based on numerous discussions with FSM government officials, concerned scientists, technical experts, and island inhabitants, as well as direct observations, this study identified the following climate risk management strategies:

Overarching Strategy #1. Establish climate risk management as a national priority.

a. *View climate risk management as an opportunity*. The FSM can emerge as a stronger and more resilient nation for the 21st century if climate management is creatively and strongly engaged. This opportunity can be utilized to:

   i. Strengthen food and water security with steps that emphasize island sustainability.

   ii. Strengthen and promote traditional Micronesian culture as a source of community pride.

   iii. Enhance conservation programs with an emphasis on ecosystem services.

   iv. Strengthen and promote health services, family planning, quality of life, and sense of place, and enrich other aspects of daily Micronesian life.

   v. Improve the national physical infrastructure, the work place, the living place, education, transportation, government services, environmental conservation, and other components of island living.

Coastal forests such as mangroves tend to stabilize eroding shorelines and provide ecosystem services that can facilitate successful adaptation to climate change.
(Source: C. Fletcher)

b. *Develop a multi-faceted climate change education program* for local communities, NGOs, landowners, land-tenured decision-makers, permitting authorities, government staff, and the public.

   i. Recognize that climate change is factual and has genuine impacts in terms of daily Micronesian life.

   ii. Emphasize that climate risk management and adaptation are "must achieve" national priorities.

   iii. Integrate climate risk management with daily FSM life.

   iv. Host international "climate summits" and local/regional workshops and other types of meetings throughout the nation.

   v. Form partnerships with NGOs and community groups.

c. Develop a *national climate risk management plan* emphasizing adaptation that originates with the involvement of local communities. Utilize community-based adaptation. Clearly articulate state-specific and atoll/island-specific elements of the plan.

   i. Prescribe climate risk "best management practices" for all lands.

   ii. Develop a planning structure based on community and NGO input.

   iii. Involve land-owners as decision-makers in adapting to risk.

   iv. Define the climate risk context of government agency activities.

   v. Develop land use policies that manage national climate risk.

Overarching Strategy #2. *Adapt to sea-level rise* and associated impacts.

a. Map vulnerable areas and develop a timeline of inundation with sea-level modeling.

b. Develop adaptation guidelines for assessing critical existing infrastructure and development and determining when and what action is needed to reduce vulnerability.

   i. For areas of critical infrastructure where protection or retrofit is appropriate, describe effective approaches to protect or rebuild infrastructure and development so that climate risk is reduced.

   ii. For areas where alternative strategies can be used, describe innovative approaches to shift infrastructure and development away from vulnerable areas.

   iii. Build long-term coastal retreat and redevelopment planning into land use policies that emphasize climate risk management. Retreat would combine both vertical (in place) and horizontal (relocation) components. Ensure new development is appropriately sited and designed.

   iv. On main islands, describe conceptual steps to gradually redevelop communities away from high risk regions. What new or existing approaches can be employed to direct future development away from areas subject to coastal hazards? Can new buildings and infrastructure be built or sited in ways that avoid and are resistant to climate hazards?

   v. On outer islands, describe new standards for community master planning that "buy time" in the course of 21st century climate change.

Poured cement foundations allow taro to grow with some protection from seawater intrusion. These "cement taro" patches have been successfully used throughout Yap state. *(Source: C. Fletcher)*

c. Plan for food and water threats due to sea-level rise.

    i. Implement a sea-level prediction system. Include predictions of concurrent water level events such as waves, meso-scale eddies, weather-related surges, tides, and others.

    ii. Map areas subject to marine inundation.

    iii. Improve knowledge of groundwater resources and their relationship to high water events.

    iv. Expect and plan for climate events. Plan enhanced emergency response to marine inundation events including pre-staging resources and rapid delivery.

    v. Increase food and water security where threatened by sea-level rise with specialized planning for sustainable agro-forestry production.

d. Plan for accelerated coastal erosion and its impacts by developing place-based (site-specific) erosion management plans.

    i. Manage and conserve sand as a natural resource. View beaches as "sand management projects" and define best practices that promote beach conservation.

Overarching Strategy #3. Climate risk management is a community-based decision-making process in the context of scientific information. *Describe data gaps* preventing full and detailed assessment of climate risk and potential steps to fill these.

a. Describe research programs and specific elements for sectors where data gaps can be filled by research.

b. Describe research needs and steps that can be taken immediately for high island and low island communities.

c. Describe priority data.[35]

    i. Produce maps of sea-level inundation on specific time scales. These will need high-resolution elevation data in the form of digital elevation models and aerial photographs. These maps will form the basis of future planning for adaptation and other forms of climate risk management.

    ii. Collect data to characterize food and water resources and characteristics germane to sustainability.

    iii. Collect data to understand landforms and where and how water will flow; these include geomorphology, LiDAR, topography/bathymetry, vertical datums, etc.

    iv. Monitor data and environmental drivers, including tides, water levels, waves, precipitation, temperature, evapotranspiration, storms, weather characteristics, historical and predictive shoreline erosion data, local sediment budget, etc.

    v. Develop a model of future sea-level rise that includes details about sea level extreme states and variability (e.g., using the nearest tide gauge record). Depict extreme events and variability on specific future timeframes (e.g., 5, 10, 25, and 50 years). Develop an exceedence model to describe growing frequency and magnitude of inundation events.

vi. Expand network of climate-monitoring stations. Collect climate data across FSM to provide ground truth to down-scaled climate models.

vii. Support expanded research in down-scaled climate modeling for the western Pacific and FSM region with special emphasis on water-related and storm-related climate processes. Develop model projections of ENSO and impacts in FSM. Support expanded research to model sea-level rise, events, and exceedence thresholds. Support expanded research to provide risk and vulnerability analysis of sea-level rise including inundation flood maps showing marine flooding on the basis of digital elevation models and aerial photographs.

viii. Develop consistent sea-level rise scenarios and projections across agencies to support local planning with uniform assumptions. This includes not only the amount of sea-level rise projected within a given area, but also the general timeframe within which these changes are anticipated.

ix. Collect data to characterize vulnerabilities and impacts of sea-level rise; these include population data, land use, buildings and critical infrastructure, natural resources, economic information, etc.

x. Collect data on community characteristics including demographics, societal vulnerabilities, economic activity, public attitudes, and understanding of risks, etc.

xi. Develop legal frameworks and administrative structure; these include zoning, permitting regimes, legislative restrictions, etc.

Overarching Strategy #4. *Adapt to drought* and improve community sustainability under restricted water conditions.

a. Implement a water resources research program that improves understanding of groundwater, surface water, and their sustainable use.

b. Improve high island water accessibility and retrofit and replace infrastructure in the context of climate risk management.

c. Predict drought events and plan for increased frequency and duration of drought including improvements to emergency services.

d. Plan for more intense rains and the impacts that accompany them: flash flooding, mass wasting, inundation, drainage problems, cut-off communities, and others.

e. Improve low island water planning, usage, and conservation.

f. Identify data gaps in water resources and steps to fill these.

g. Support hydrologic modeling of island aquifer systems.

h. Support down-scaled climate modeling that emphasizes water resources.

i. Expand network of water monitoring instrumentation.

j. Develop a *water management plan for each island* including each inhabited atoll islet and neighboring resource islets.

Overarching Strategy #5. *Plan for changing ocean conditions* (e.g., ocean acidification, warming, storminess, etc.).

Overarching Strategy #6. Ensure that critical watershed, coastal, and ocean habitats and ecosystem services are protected and maintained.

Overarching Strategy #7. Build global awareness of the plight of threatened island communities and associated threats to food and water security.

Overarching Strategy #8. *Build partnerships within the international community* to provide resources and underpin policy changes leading to adaptation steps.

Overarching Strategy #9. Enhance partnerships by vigorously executing internal policy and planning studies designed to identify benchmarks and timetables leading to land use changes and adaptation activities.

Overarching Strategy #10. Monitor research pertaining to sea-level rise, water-cycle changes, and storminess. Exercise flexibility in national planning and prioritization in light of local climate trends and predictions.

State Findings

Specific findings for each state are available upon request.

Kosrae State

The island of Kosrae is the easternmost island in the Federated States of Micronesia. Kosrae is a 112 km^2 volcanic island surrounded by mangroves and coastal strand forests that have been historically used for lumber and fuel by residents. There is a shallow fringing reef spotted with boulders of limestone quarried from the fore-reef by high-energy wave events (storms, tsunamis, and other overwash processes). There are no outer islands. The island has steep, heavily vegetated watersheds with unstable slopes. Intense rainfall denudes exposed soil in areas of deforestation. Invasive vegetation is prolific and has taken a foothold in every watershed. The population of approximately 8,247 is largely dependent upon fishing and farming for their livelihood.[36]

Kosrae has unique needs with regard to climate risk management and adaptation. The majority of the coastline is experiencing chronic erosion, in places related to engineering projects that have caused down-drift sediment deficiencies over the past four decades.[37] Additional causes of erosion include offshore mining of the reef flat for construction materials, beach mining for sand and gravel resources, and interruptions to alongshore sediment transport by engineering projects; in some areas erosion is occurring for reasons that are not entirely known but are probably, in part, related to sea-level rise. The widespread “telescoping” of erosion along the coast by armoring, and beach loss in front of seawalls and revetments, has produced a chronic deficiency in sand that formerly constituted beautiful beaches ringing the island. These beaches lent protection to coastal communities, ambience to tourism and a quality of life to residents that is at risk.

The maximum overwash elevation of the recent tide surges is likely to be reached in future events with greater frequency. Generally, designing structures such that overwash may run beneath the structure increases community resilience. Buildings with their lowest horizontal structural component set above the maximum elevation of the December 2008 overwash plus 1 meter will be less prone to damage and more resilient to recovery. The maximum overwash elevation, plus 1 meter, represents a base flood elevation (BFE) for new construction and for renovation of existing buildings.

Pohnpei State

Pohnpei is a “high” volcanic island, having a rugged, mountainous interior with some peaks as high as 760 meters. It measures about 130 kilometers in circumference and is roughly circular in shape. Pohnpei Island is the largest, highest, most populated, and most developed island in FSM. A coral reef surrounds the island, forming a protected lagoon. There are no beaches on Pohnpei – the coast is surrounded by mangrove swamps growing on muddy substrate eroded from interior wetlands in the rainy environment. Several smaller islets, many of them inhabited, lie nearby within the lagoon-reef complex. The population of Pohnpei is approximately 34,840. Pohnpei is more ethnically diverse than any other island in the FSM. This is largely due to it being home to the capitol of the national government, which employs hundreds of people from the other FSM States having distinct ethnic and cultural origins. The indigenous makeup also includes people from the outer islands within the State, which comprise multiple regional ethnicities. Outer islands in Pohnpei include Pingelap, Mokil, Ant, Pakin, Ngatik, Nukuoro, and Kapingamarangi. These are atoll islets that suffered extreme hardship during the marine inundation events of 2007 and 2008.

Pohnpei’s climate is tropical and humid. Kolonia town receives about 4.95 meters of rain annually. Typhoons rarely hit Pohnpei; more often they are spawned in Micronesia and move on to Guam and the Commonwealth of the Northern Marianas Islands. Every several years or so (on average), a mildly damaging tropical storm or depression will affect Pohnpei. Strong El Niño events can cause prolonged drought of many weeks or even months, as was seen in 1997-1998. Torrential rainstorms can also strike Pohnpei. These rainstorms have caused serious landslides and mud slides in the past and represent a natural hazard that may worsen as changes to the water cycle occur with continued global warming.

The tidal surges of 2007 and 2008 caused significant damage to coastal infrastructure in low-lying areas. Without a specific plan to manage coastal problems, Pohnpei shoreline areas will lack a degree of resiliency, resources will be exposed to depletion, and improvements through investment may be outpaced by the scale of climate change unless a specific plan is developed.

Chuuk State

The main population center of Chuuk State is the Chuuk Lagoon, an archipelago with mountainous islands surrounded by a string of islets on a barrier reef. The two major geographical divisions of the Chuuk Lagoon are Faichuuk, the western islands, and Namoneas, the eastern islands. On July 2, 2002, heavy rains from Tropical Storm Chataan caused more than 30 landslides that killed 47 people and injured dozens of others in the state’s deadliest weather disaster. The landslides occurred throughout the day, some within just minutes of one another. Most of the roads and transportation systems are poor or in disrepair. Potholes in the coastal road of the business district of Chuuk are often filled with either saltwater at high tide or runoff that cannot drain due to the low elevation. Drinking water is unpotable.

Chuuk State, population 53,106, also includes several additional sparsely populated outer island groups, including the Mortlock Islands to the southeast, the Hall Islands (Pafeng) to the north, Namonuito Atoll to the northwest, and the Pattiw Region to west. The Pattiw Region is of particular interest in that it contains some of the most traditional islands in the Pacific which are culturally related to the outer islands of Yap. The Pattiw Region includes the islands of Pollap, Tamatam, Poluwat, and Houk.

The tidal surges of 2007 and 2008 caused significant damage to coastal infrastructure, food resources, and housing. It is apparent that investment in Chuuk already scheduled to refurbish the main road and buried infrastructure is committed and planned for immediate ground breaking. Unfortunately, the pace of climate change has already made some design elements of these large infrastructure projects out of date. Adding to the elevation of the main road in Chuuk would likely permit avoidance of significant drainage problems related to sea-level rise for a period of years to decades depending on the amount of adjustment. The addition of 0.5 meters to the roadbed, and incorporation of enhanced drainage features, will likely pay dividends in flooding avoidance for a few decades.

Yap State

Yap's indigenous cultures and traditions are still strong compared to neighboring regions. The main district of Yap consists of four islands with geology that is non-volcanic in origin. The four are very close together and joined within a common coral reef and entirely formed from uplift of the Philippine Plate. The land is mostly rolling hills densely covered with vegetation. Mangrove swamps line much of the shore although beaches are common in some areas. An outer barrier reef and lagoon surrounds the islands and their fringing reef.

Colonia is the capital of Yap State. It administers both Yap proper and 14 atolls reaching to the east and south for some 800 kilometers, namely Eauripik, Elato, Fais, Faraulep, Gaferut, Ifalik, Lamotrek, Ngulu, Olimarao, Piagailoe (West Fayu), Pikelot, Sorol, Ulithi, and Woleai atolls, as well as the island of Satawa. The 2009 state-wide population was 11,780. The state has a total land area of 102 km^2.

The tidal surges of 2007 and 2008 caused significant damage to coastal infrastructure, food resources, and housing. Yap is well developed and has a generally high quality of life. Nonetheless, water on the main islands is nonpotable and this is a major issue that has not been resolved despite several decades of effort. The central business district of Yap is built around a harbor, the shoreline of which is armored by well-designed and engineered walls and revetments. However, the top elevation of most of this coastal protection is only 30-60 centimeters above high tide. By mid-century or earlier, these protections will need upward extension to protect the critical roads, fuel depots, buildings, and freight handling facilities lining the harbor. Over the next decade, climate risk management can focus on building a community-based adaptation program to improve climate risk management.

Endnotes

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[3]For example see the web video of flooding in Pohnpei: http://www.youtube.com/watch?v=wfur8cUKAfk

[4]"…changes in ENSO interannual variability differ from model to model." From p. 780, Section 10.3.5.4- El Niño, Chapter 10, Global Climate Projections. IPCC, 2007: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

[5]According to the London-based International Institute for Environment and Development (http://www.iied.org/) community based adaptation (CBA) is emerging as a key response to climate risk management. Tailored to local cultures and conditions, CBA supports and builds on autonomous adaptations to climate variability. CBA is participatory – a process involving both local stakeholders, and development and disaster risk reduction practitioners. As such, it builds on existing cultural norms while addressing local development issues that contribute to climate vulnerability. CBA is gaining ground in many regions.

[6]AR4, 2007.

[7]See "2009: Second Warmest Year on Record; End of Warmest Decade" http://www.nasa.gov/topics/earth/features/temp-analysis-2009.html; last accessed January 29, 2010.

[8]R. D'Arrigo, R. Wilson, G. Jacoby, 2006 "On the long-term context for late twentieth century warming" *Journal of Geophysical Research – Atmospheres* 111.D3: D03103.

[9]*Global Climate Change Impacts in the United States*, T.R. Karl, J.M. Melillo, T.C. Peterson (eds.) The U.S. Global Change Research Program, Cambridge University Press, 2009.

[10]S.R. Loarie, P.B. Duffy, H. Hamilton, G.P. Asner, C.B. Field, D.D. Ackerly, 2009 "The Velocity of Climate Change" *Nature* 462: 1052-1055.

[11]E. Steig, D. Schneider, S. Rutherford, M. Mann, J. Comiso, D. Shindell, 2009 "Warming of the Antarctic Ice-sheet Surface Since the 1957 International Geophysical Year" *Nature* 457: 459-463; See also http://earthobservatory.nasa.gov/IOTD/view.php?id=36736; last accessed January 16, 2010.

[12]See: http://earthobservatory.nasa.gov/IOTD/view.php?id=8264; last accessed January 16, 2010.

[13]I. Velicogna, 2009 "Increasing Rates of Ice Mass Loss from the Greenland and Antarctic Ice Sheets Revealed by GRACE" *Geophysical Research Letters* 36: L19503.

[14]G. A. Vecchi, B.J. Soden, A.T. Wittenberg, I.M. Held, A. Leetmaa, M.J. Harrison, 2006 "Weakening of Tropical Pacific Atmospheric Circulation due to Anthropogenic Forcing" *Nature,* 441:73–76.

[15]AR4, 2007.

[16]NASA, Jet Propulsion Laboratory, 2008 "Rising waters: new map pinpoints areas of sea-level increase" http://globalclimatechange.jpl.nasa.gov/news/index.cfm?FuseAction=ShowNews&NewsID=16

[17]M.A. Merrifield, S.T. Merrifield, G.T. Mitchum, 2009 “An anomalous recent acceleration of global sea-level rise” *Journal of Climate*, 22:5772-5781.

[18]Global sea-level rise is measured by satellite detection of the ocean surface. NASA, “Rising Water: new map pinpoints areas of sea level increase”: http://climate.nasa.gov/news/index.cfm?FuseAction=ShowNews&NewsID=16; last accessed January 16, 2010.

[19]M. Vermeer, S. Rahmstorf, 2009 “Global sea level linked to global temperature” *Proceedings of the National Academy of Sciences*, 106.51: 21527–21532. See also C.H. Fletcher, 2009 “Sea Level by the End of the 21st Century: A Review” *Shore and Beach,* 77.4: 1-9.

[20]The event evolved from a coincidence of unusually high tides (moon near perigee – closest distance to Earth) and a low pressure system north of Wake which generated northerly swell in the 4-5 meters (~13-16 feet) range from Majuro to Chuuk. Marine inundation caused damage to crops, property, and resources in coastal areas throughout Micronesia. Damage assessments were conducted among islands of Kosrae, Pohnpei, Chuuk, and Yap states focusing on impacts to agricultural crops and groundwater resources.

[21]Shigetani, M., and members of the Preliminary Damage Assessment Team, 2009 Preliminary Damage Assessment, Federated States of Micronesia: High Tide Event, December 7-12, 2008; USAID, FEMA.

[22]See for instance: Kench, P.S., McLean, R.F., Nichol, S.L., 2005 “New model of reef-island evolution: Maldives, Indian Ocean” *Geology*, 33.2: 145-148.

[23]Ramsay, D., 2000 *The Kosrae Shoreline Management Plan, Summary of Recommendations*, Kosrae Island Resource Management Agency (KIRMA), 25p. See http://www.kosraecoast.com/ for additional resources. He, C., 2001 *Coastal erosion assessment, Malem Village, Kosrae State, Federated States of Micronesia*, SOPAC Technical Report 341, 25p.; Cote, J.M., Jackson, R., 1997 *Kosrae Coastal Protection Strategy, Report to the Kosrae Island Resource Management Agency*, 44p with appendices; Xue, C., 1996 *Coastal sedimentation, erosion and management of Kosrae, Federated States of Micronesia*, SOPAC Technical Report 228, 90p.

[24]One leading source is the Joint Airborne Lidar Bathymetry Technical Center of Expertise (JALBTCX). The centers mission is to perform operations, research, and development in airborne lidar bathymetry and complementary technologies to support the coastal mapping and charting requirements of the US Army Corps of Engineers (USACE), the US Naval Meteorology and Oceanography Command, and the National Oceanic and Atmospheric Administration (NOAA). See: http://shoals.sam.usace.army.mil/

[25]Bryan P. Oles, 2007, *Culture of the Federated States of Micronesia*, http://www.everyculture.com/Ma-Ni/Federated-States-of-Micronesia.html

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[32]Ayers, 1986.

[33]See the population projections at: http://www.spc.int/prism/country/fm/stats/Projections/proj-index.htm

[34]Sea-level rise and Inundation Community Workshop, December 2009, Convened by the National Oceanographic and Atmospheric Administration Coastal Services Center, U.S. Geological Survey Coastal and Marine Geology Program.

[35]NOAA, USGS Sea-level rise and Inundation Community Workshop, December 2009.

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