PACIFIC RISA PHASE III

SUPPORTING INTEGRATED DECISION-MAKING UNDER CLIMATIC VARIABILITY AND CHANGE IN HAWAIʻI AND THE US-AFFILIATED PACIFIC ISLANDS

A NOAA CAP/RISA Program | pacificrisa.org

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Cover photo: Mangroves line the edge of Jellyfish Lake in the Republic of Palau, supporting the marine ecosystem of this iconic tourism site that is threatened by climate change and non-native species. (Source: Laura Brewington)

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REGIONAL ROLE

The Pacific Regional Integrated Sciences and Assessments (Pacific RISA) program supports Pacific Island and coastal communities in adapting to the impacts of climate variability and change. We strive to enhance Pacific communities' abilities to understand, plan for, and respond to changing climate conditions. Our work is conducted through interdisciplinary research and partnerships with local, national, and regional stakeholders. As one of 12 NOAA CAP/RISA programs, the Pacific RISA emphasizes the engagement of communities, governments, and businesses in developing effective policies to build resilience in key sectors, such as water resources management, conservation, fisheries, agriculture, tourism, disaster management, and public health.

Vision. Resilient and sustainable Pacific communities using climate information to manage risks and support practical decision-making about climate variability and change. We strive to: (1) Meet critical climate information needs in Hawaiʻi and the US-Affiliated Pacific Islands (USAPI) region through interdisciplinary climate research, assessments, education, and training; (2) Provide integrated, locally-relevant climate information to decision-makers and communities; (3) Enhance regional and local capabilities to manage climate risks, build resilience in key sectors, and support sustainable development; and (4) Promote collaboration among Pacific regional, US national, and international institutions and programs providing climate information products and services.

Currently in its fourth phase of funding, the Pacific RISA program has evolved over two decades to meet the changing needs of Hawaiʻi and the USAPI. Phase I of the program (2003–2009) was funded through a series of modest awards supplemented by $150,000 of in-kind and financial support from the East-West Center (Honolulu, Hawaiʻi). This phase concentrated on expanding stakeholder relationships, assessing and adapting existing decision-support tools for extreme climate event impacts, and adding value to regional efforts to adapt climate projections and information to stakeholder needs. With full funding awarded for Phase II of the program (2010–2015), the Pacific RISA was able to capitalize on this established groundwork and pursue more in-depth climate research and decision support, which was reflected in the program results and the successful bid for a third full phase of funding.

"How can we effectively utilize climate science to manage the impacts of the changing climate across diverse sectors in the Pacific Islands region?"

FOCUS AREAS

Phase III Program Rationale. Hawaiʻi and the USAPI comprise a vast region with diverse cultures, ecosystems, and climate regimes. Pacific Islanders have taken significant actions to increase community and environmental resilience, collaboration, and adaptation to climate impacts. However, decision-makers throughout the region still need tailored information to plan effectively for climate variability and change. Whereas numerous federally-produced downscaled climate projections already existed for the contiguous United States, the first climate projections at island-appropriate scales were only recently released in Hawai'i, and many stakeholders have struggled with knowing what data exist, which data to use, and the associated uncertainties. Local and regional governments and communities need to begin preparing for long-term impacts now and want to choose adaptation options based on technical and socio-economic considerations.

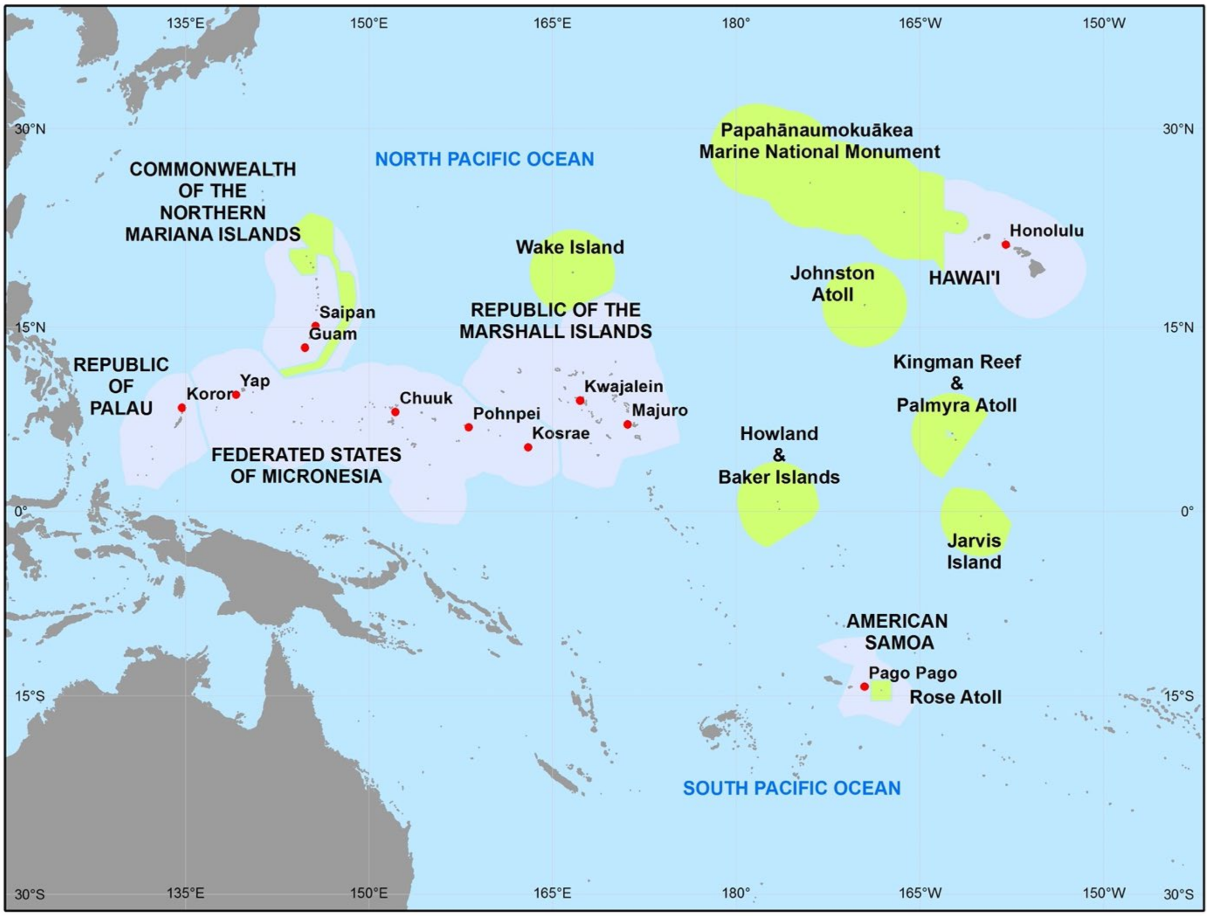

Figure 1: Geographic Scope. Pacific RISA serves the US Pacific Islands region, which includes the US State of Hawaiʻi, the US Territories of Guam and American Sāmoa, the Commonwealth of the Northern Mariana Islands (CNMI), the Republic of Palau, the Federated States of Micronesia (FSM), and the Republic of the Marshall Islands (RMI). Shaded areas indicate their exclusive economic zones. Green areas represent US Marine National Monuments in the Pacific. (Source: Keener et al. 2018)

Overarching Question and Objectives. Pacific RISA Phase III, "*Supporting Integrated Decision Making Under Climatic Variability and Change in Hawaiʻi and the US-Affiliated Pacific Islands*", addressed the overarching question: "*How can we effectively utilize climate science to manage the impacts of the changing climate across diverse sectors in the Pacific Islands region?*" All projects fell under four core objectives:

(I) Conduct place-based assessments of risk, vulnerabilities, and adaptation strategies;
(II) Support implementation of these strategies;
(III) Evaluate adaptation plans and policy throughout the region; and
(IV) Integrate technical climate information and policy outcomes.

Projects emphasized integrated research using social and physical science methods to generate, analyze, interpret, and translate climate information at multiple spatial and temporal scales for diverse stakeholders. The Pacific RISA strived to conduct stakeholder-inclusive, place-based science with sector-relevant thresholds and assign economic value to natural resources across sectors, island locations, and adaptation strategies. This work built on projections of climate change developed during Phase II by translating them for different user communities, increasing research scope on the impacts of climate variability, analyzing and communicating the differences between downscaled climate projections, and enhancing the breadth and diversity of our stakeholder network through regional assessments. The results of these analyses fed into projects that improved resilience, including evaluating the economics of natural resources and adaptation, assessing future impacts on freshwater quantity and quality, analyzing adaptive policies and the role of climate events on human migration, defining sector-specific decision thresholds, working with managers and policy-makers to ensure the research was relevant and usable, and improving program effectiveness in climate-related communication.

<table>
<tr><th colspan="3">Roadmap Linking Phase III Program Objectives and Projects</th></tr>
<tr><th>Program Objective</th><th>Project Title</th><th>Linkages</th></tr>
<tr><td rowspan="4">(I) Conduct place-based assessment of risk, vulnerabilities, and adaptation strategies</td><td>Dynamical seasonal prediction of precipitation for Hawaiian Islands</td><td rowspan="4">• Extended Phase II downscaling to additional Pacific Islands/territories
• Extended Phase II downscaling to climate variability at shorter temporal resolutions (ENSO, PDO)
• Extended Phase II hydrological work to additional Pacific Islands/territories
• Responded directly to stakeholder needs identified in Phase II
• Provided data and analyses for Objs. II, III, and IV</td></tr>
<tr><td>Evaluate similarities and differences between statistical and dynamical downscaling projections</td></tr>
<tr><td>Impact of future climate variability on freshwater resources</td></tr>
<tr><td>Assessing economic impacts of climate planning and adaptation</td></tr>
<tr><td rowspan="3">(II) Support implementation of adaptation strategies</td><td>Future climate scenario planning</td><td rowspan="3">• Built on Phase II scenario planning
• Used data from Obj. I and policy and regional findings from Obj. III
• Maintained and expanded on regional relationships established in Phase II
• Leveraged research and support from new partners/local and regional institutions
• Provided technical input for Objs. III and IV</td></tr>
<tr><td>Using ecosystem services valuation to assess trade-offs and opportunities</td></tr>
<tr><td>Indicators of climate variability, change, and sectoral impacts</td></tr>
<tr><td rowspan="3">(III) Evaluate adaptation plans and policies</td><td>Causes and impacts of climate-induced migration</td><td rowspan="3">• Built on Phase II climate and water policy analysis
• Improved planning and operations for Objs. I to IV
• Contributed to broader field of participatory science program evaluation</td></tr>
<tr><td>Legal and policy evaluation for adaptive capacity</td></tr>
<tr><td>Evaluate Pacific RISA performance</td></tr>
<tr><td rowspan="2">(IV) Integrate technical information and policy outcomes</td><td>Sustained climate assessment</td><td rowspan="2">• Responded directly to stakeholder needs identified in Phase II
• Integrated and communicated findings and data from Objs. I, II, and III
• Sustained regional climate assessment and supported ongoing NCA efforts</td></tr>
<tr><td>Translation and communication of climate uncertainty in the Pacific Islands</td></tr>
</table>

RESEARCH FINDINGS

Dynamical Seasonal Prediction of Preciptation for the Hawaiian Islands

Core Objective. (I) Conduct place-based assessments of risk, vulnerabilities, and adaptation strategies

The availability and spatial scale of regional climate model predictions for the Pacific Islands region are limited. Because of the small relative size and topographical diversity of Pacific Islands, significant downscaling of global model predictions is needed to make them applicable to island-scale decision-making. This represents critical groundwork for future climate scenario planning and modeling, which rely on spatially accurate information to make reliable predictions. During Phase II, the Pacific RISA supported the development of the Hawaiʻi Regional Climate Model (HRCM). The University of Hawaiʻi International Pacific Research Center (IPRC) created the HRCM as a dynamically downscaled regional model for the Hawaiian Islands at 15 km, 3 km, and 1 km horizontal grid scales that can be used to perform 20-year present-day (1990–2009) and projected late 21st century 20-year (2080-2099) climate simulations. However, seasonal projections of rainfall anomalies over the region were still desired by stakeholders for nearer-term decision-making.

Keeping in mind the increasing local demands for reliable future forecast information at island scales, this project pursued three main objectives during Phase III:

1. Seasonal prediction of precipitation over the Pacific Islands during the El Niño winter/spring of 2015–2016;
2. Evaluation of the NOAA prediction model capacity to forecast regional rainfall during El Niño (2015–2016) and La Niña (2016–2017);
3. Configuring the Hawaiʻi regional model to assess its ability to capture regional distribution of rainfall during an ongoing El Niño Southern Oscillation (ENSO) event (2015–2017).

Research Findings. The ENSO evolution of warm conditions (El Niño in 2015) followed by cold conditions (La Niña in 2016) provided a classic testbed for validating seasonal predictions of precipitation over the Pacific Islands made by the NOAA prediction model. The project team collected station-level rainfall observations for 2015-2016 and validated the model at different horizontal resolutions (12 and 3 km). Daily forecast data were downloaded from NOAA and archived locally to diagnose the solutions and update the forecast every 10 days. The model showed a high level of skill in forecasting winter/spring rainfall anomalies over the Pacific Islands, with a drought moving through the region brought by one of the strongest El Niño events since record keeping began 60 years ago. It started in the southwest Pacific, where it brought famine to Papua New Guinea and Vanuatu before reaching the south Pacific, tropical west Pacific, and Hawaiian Islands between December 2015 and May 2016. One key finding was the clear improvement in the prediction of seasonal-mean precipitation when the horizontal resolution was reduced from 15 to 3 km. Both the improved model physics and finer spatial resolutions are needed for realistic simulation of current climate and future projections.

Although the effect of El Niño in the Pacific Islands receives limited global attention, it has proved severe, particularly among vulnerable island populations. Prolonged drought can compromise not only freshwater supplies and food security, but can also have cascading impacts on public health, economies, food distribution, and even trigger civil unrest. Past experiences with regional drought, current actions being taken, and the most up-to-date predictions for El Niño's effects on the Pacific Islands, suggest strategies that governments and aid groups can take to prepare for this powerful climate event.

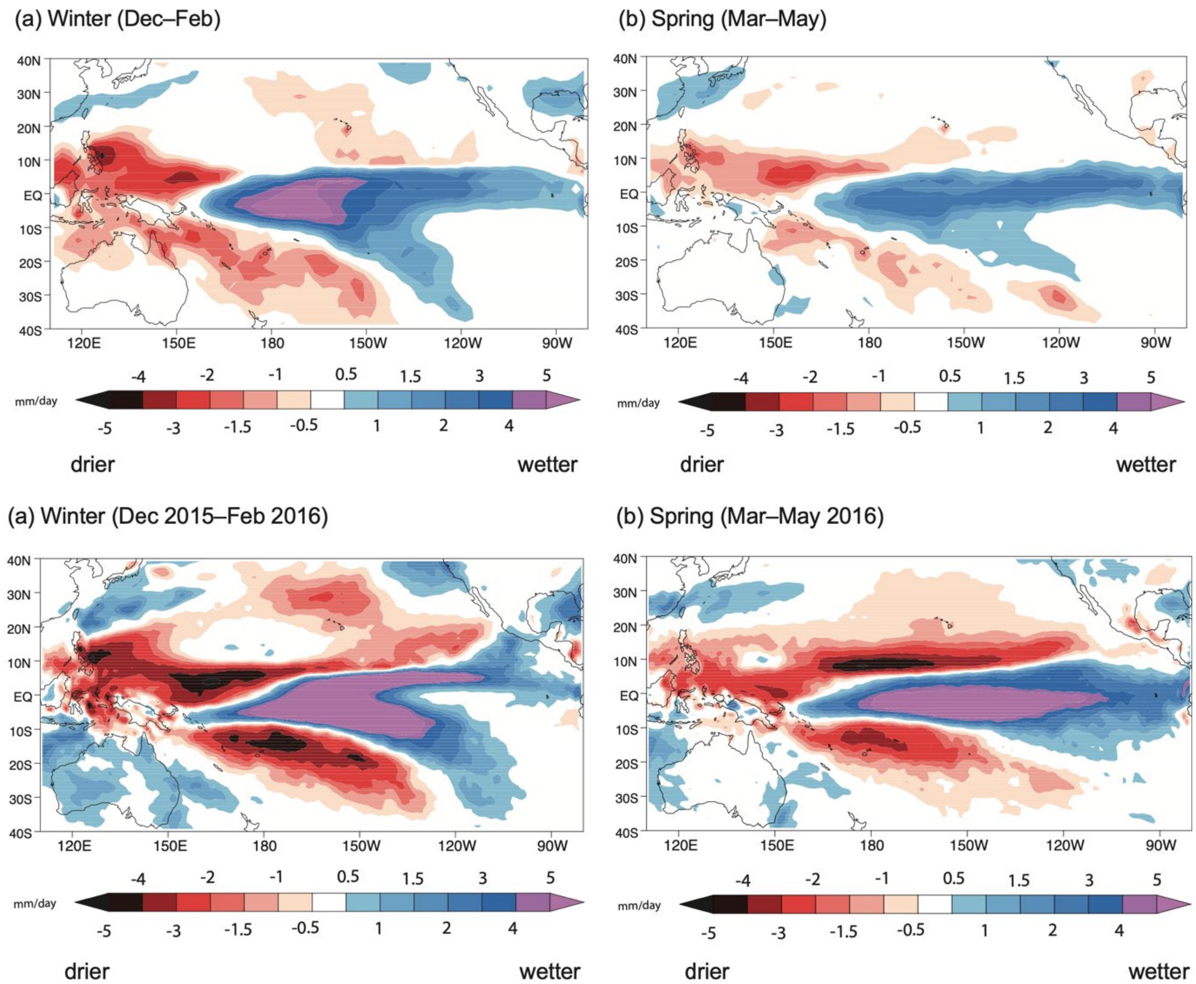

Figure 2. Data from seven past El Niño events show the average rainfall patterns in the Pacific during typical El Niño winter and spring (top); the predicted 2015–2016 El Niño event showed higher and more extensive rainfall than the average, followed by more extensive drought-like conditions (bottom). (Source: Annamalai et al. 2015)

Accomplishments. Model outputs were then used to force the High-Resolution Regional Atmospheric Model (HiRAM) for assessing regional distribution of precipitation over the Hawaiian Islands. HiRAM was used to generate "experimental" seasonal forecasts with a focus on the recent ENSO event (2015–2017). The goal was to downscale the NOAA operational forecasts based on the National Centers for Environmental Prediction (NCEP) Climate Forecast System model version 2 (CFSv2) and validate the HiRAM results with station-level observations. Results for the 2015–2016 El Niño winter and following spring were encouraging, and detailed physics-based diagnostics were performed to account for the improvement in the precipitation prediction at various horizontal resolutions in HiRAM. The work delivered fine-resolution surface temperature and precipitation products over the Hawaiian Islands. These products complemented and added value for the Pacific ENSO Applications Center’s (PEAC) seasonal forecast outlooks, adding a future climate component to their suite of precipitation forecasts. They were also integral to the development of models, data collection, and future scenario development conducted by the various projects within this award.

Links to Other Projects.

- ***Extended Phase II downscaling to additional Pacific Islands/territories***: Dynamically downscaled climate projections were produced for the Territories of American Sāmoa and Guam.

- ***Extended Phase II downscaling to climate variability at shorter temporal resolutions (ENSO, PDO)***: The Hawaiʻi regional model continued to be tested and fine-tuned for the regional spatial distribution of rainfall over the Hawaiian Islands with a focus on ENSO 2015–2017, during both the El Niño and La Niña phases. Ensemble simulations were performed and the results were compared with island-level rainfall observations.
- ***Provided data and analyses for Objs. II, III, and IV***: HiRAM solutions have been made available for use in other studies (e.g., assessing seasonal changes to groundwater, agriculture, landslides, etc.).
- ***Responded directly to stakeholder needs identified in Phase II***: Because of the small relative size and topographical diversity of Pacific Islands, significant downscaling of global model projections is needed to make them applicable to island-scale decision making. Whereas the continental United States has a variety of regionally appropriate downscaled projections to choose from, the Pacific Islands were not included in them, and stakeholders needed downscaled climate data that were appropriate for small island scales, steep topography, diverse microclimates, and regional climate processes.

Evaluate Similarities and Differences Between Statistical and Dynamical Downscaling Projections

Core Objective. (I) Conduct place-based assessments of risk, vulnerabilities, and adaptation strategies

During Phase II, future rainfall patterns were projected for the Hawaiian Islands using different downscaling techniques. Both statistical and dynamical downscaling methods utilize results from global climate models to make spatially-detailed projections of future changes. However, the approaches are very different and can produce conflicting results, which make communicating the results and understanding the confidence of the projections complex.

The purpose of the predictor selection and statistical downscaling work was to provide the most accurate projections possible of future rainfall for Hawaiʻi. These statistical downscaling results were compared to the dynamical results to attempt to reach consensus on future increases or decreases in rainfall across the state. This work also shed light on which geographical areas may be most difficult to capture in projections. The results provided insight for managers and planners to prepare for the risks of flood and drought, and associated changing patterns of rainfall and access to freshwater, while enhancing management of other valuable resources in Hawaiʻi.

This project also evaluated the robustness of the statistical model results and sought ways to improve their reliability. The goals of the first part of this study were to test: (1) the sensitivity to changes in large-scale climate information; (2) the use of new large-scale climate variables as predictors; and (3) the robustness against changes in the statistical downscaling method. In the second part, statistically and dynamically downscaled historical rainfall anomalies were compared to identify the weaknesses in each approach and provide guidelines for improving projections from both methods.

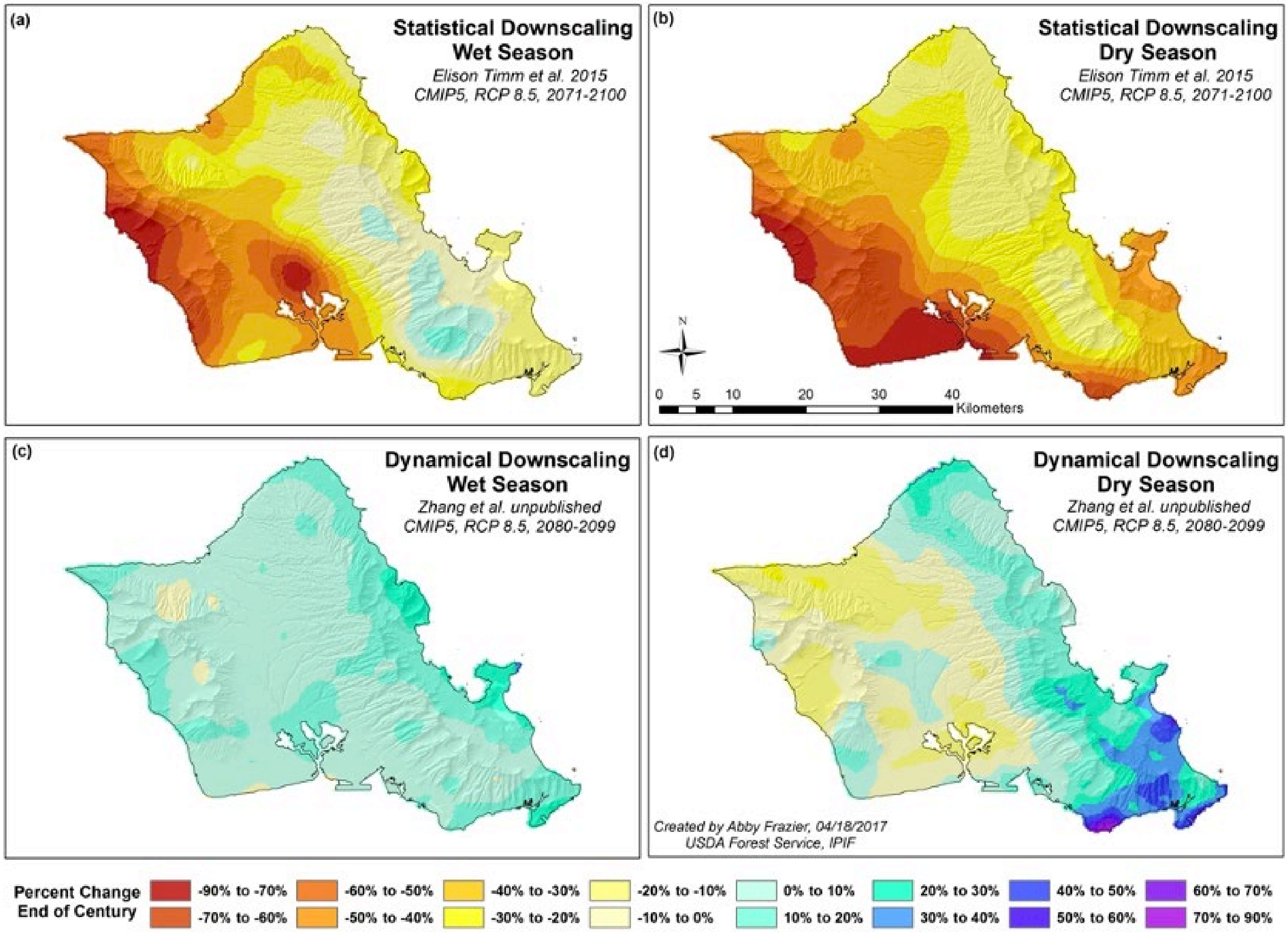

Figure 3. Percent change in seasonal rainfall at the end of the century on the Island of Oʻahu: comparing statistical (top) and dynamical (bottom) downscaling results (Sources: Zhang et al. unpublished; Elison Timm et al. 2015)

Research Findings. This project evaluated the predictor variables for possible use in a statistical downscaling model of precipitation, which laid the groundwork for future statistical downscaling for Hawaiʻi. While predictive skill of the set of competitive models for each season was very similar from model to model based on cross-validation results, models produced very different results when applied to future scenarios depending on varying predictors. Some models contained variables that better capture the global warming signal, such as those related to thermodynamics. For this reason, comparing the future rainfall projections between models of similar skill was of particular interest and may shed light on whether statistics alone are sufficient for model evaluation, or if background knowledge of the physical mechanisms of rainfall should be further incorporated into predictor selection.

Accomplishments. Data from this project has helped both researchers and stakeholders better understand and forecast the complex weather and climate of the Hawaiian Islands. The team assisted Haleakalā National Park on the Island of Maui with their climate change planning to complete a future climate scenario assessment for the park. They contributed to the Hawaiʻi Mesonet project, which set up climate monitoring infrastructure for Maui. These efforts have also contributed to the Hawaiʻi Climate Data Portal and the National Mesonet Program supported by NOAA.

In addition, this work informed the first Application of Climate Downscaling in Hawaiian Islands workshop, which stemmed from the ongoing need to evaluate how downscaled climate projections for

Hawaiʻi were being used by researchers, agencies, and decision-makers. Co-hosted by the Pacific RISA, the Pacific Islands Climate Adaptation Science Center (PICASC), and the Pacific Islands Climate Change Cooperative (PICCC), workshop attendees concluded that "Intermediate Modelers" (IM) were key to the transformation and communication of climate projections for resource management and decision-making. For these purposes, IM are defined as scientists who use future climate projections as inputs to local impact models, such as terrestrial ecosystem models (e.g., plant communities, native Hawaiian birds), hydrology models, or economic models.

As an outcome of the workshop, IM and climate modelers decided that non-expert "climate narratives" explaining projections for each Hawaiian island would be a useful product to help ensure that IM could accurately explain the assumptions that generated each set of projections to managers, and how they differ. This would allow managers to make an informed choice about how to use outputs from the different intermediate models and ensure consistency across IM about communication of the projections. As an exercise, workshop attendees worked together to create a draft "Climate Narrative" for the island of Maui. The product was said to be the most helpful workshop outcome and the Pacific RISA continued to help generate these narratives for IM on all Hawaiian Islands. By increasing the ability of the IM to translate information more easily and consistently from climate scientists to decision makers, groups were more confidently utilizing downscaling results in resource management decisions.

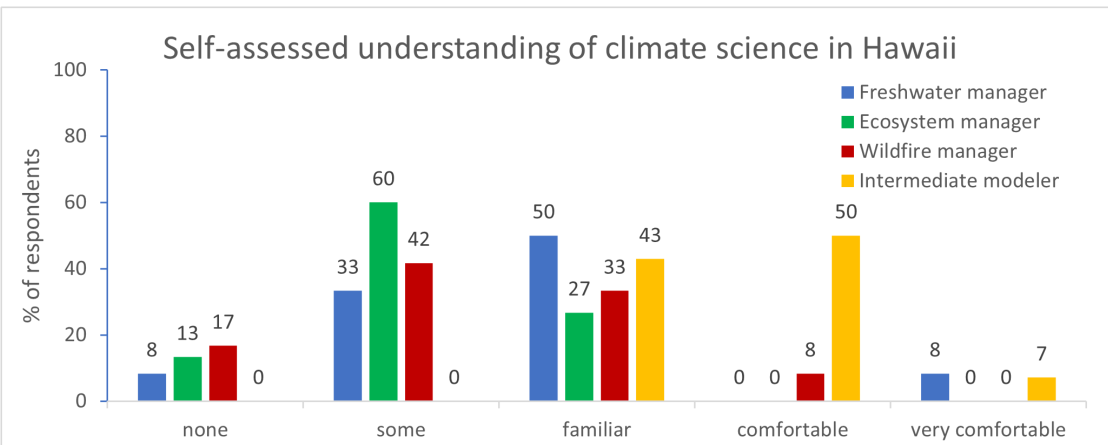

Figure 4. Compared to ecosystem and fire managers, freshwater managers reported the highest level of understanding of current climate science and findings in Hawaiʻi of the natural resource managers that were surveyed (50% were "familiar" with it and 8% reported being "very comfortable")**.**

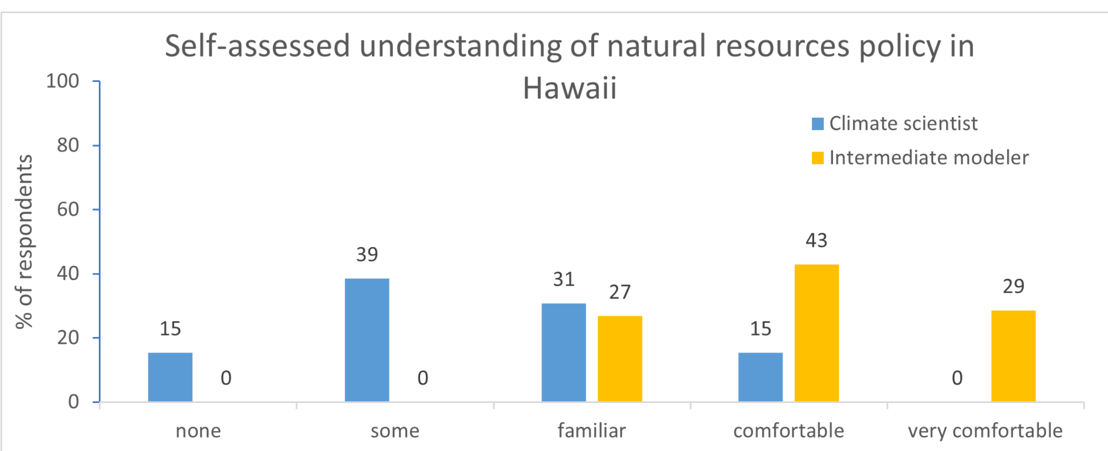

Figure 5. The IM group reported being much more comfortable with natural resource policies and management than the climate scientist group. IM play a crucial role in linking climate science to resource management.

Links to Other Projects.

- ***Responded directly to stakeholder needs identified in Phase II***: Both statistical and dynamical downscaling methods have inherent uncertainties and stakeholders in policy and management positions needed to know how and why the projections differ. Characterizing the strengths and weaknesses of each method, as well as the similarities and differences in the results, helped the Pacific RISA create stakeholder-tailored maps, tables, and other desired products specific to different management sectors that inform how downscaled climate projections can best be used in terms of time frame (e.g., seasonal, inter-annual, or long-term prediction) and sectoral and spatial application (e.g., agriculture, health, watershed or island-wide basis).
- ***Extended Phase II downscaling to climate variability at shorter temporal resolutions (ENSO, PDO)***: Statistically downscaled seasonal forecasts were developed for Hawaiʻi to capture local and regional climate variability, which found more reliable results for the wet season (Nov–April) compared to the dry season (May–Oct).

Future Climate Scenario Planning

Core Objective. (II) Support implementation of adaptation strategies

For the last century, the Island of Maui in Hawaiʻi has been the center of environmental, agricultural, and legal conflict with respect to both surface and groundwater allocation. Planning for sustainable future freshwater supply requires adaptive policies and decision-making that emphasize private and public partnerships and knowledge transfer between scientists and non-scientists. During Phase II, the Pacific RISA created downscaled dynamical and statistical future climate projections for Maui and integrated them with a participatory scenario building process to quantify future changes in island-scale climate and groundwater recharge under different land uses. Using scenario-based tools that are policy-responsive and not reliant on known probability distributions, stakeholders can plan for a range of likely situations.

The Pacific RISA used a participatory scenario process that first identified key stakeholders making short and long-range decisions about freshwater resource management. A set of four future land cover maps that reflected different urban development, forest conservation management, and agricultural trajectories was then co-developed with them. End-of-century mean annual groundwater recharge was estimated using a US Geological Survey (USGS) Pacific Islands Water Science Center water-budget model, under the four future land cover scenarios: Future 1 (conservation-focused), Future 2 (status-quo), Future 3 (development-focused), and Future 4 (balanced conservation and development). Two Pacific RISA-generated downscaled climate projections for the late 21st century were also included in the modeling framework: a Coupled Model Intercomparison Project Phase 5 (CMIP5) representative concentration pathway (RCP) 8.5 projection that represented a “dry climate” future with reduced island-wide rainfall and a CMIP Phase 3 (CMIP3) A1B projection that represented a “wet climate” future with higher island-wide rainfall. Results were compared to recharge estimated using a 2017 baseline land cover map and current climate to understand how land management and climate change could influence groundwater recharge.

Research Findings. Comparison of water-budget outputs under the future land cover and climate scenario combinations predicted the following for Maui:

- The “wet” and “dry” climate projections indicated contrasting effects on estimated recharge across most of the island;

- Compared to 2017 land cover and current climate, recharge under the dry climate projection increased by 12%, 1%, 0%, and 11% for land cover Futures 1 to 4, respectively. Corresponding increases under the wet climate future were 11%, 1%, 1%, and 9%;
- Although island-wide recharge increased across all future land cover scenarios for both the wet and dry climate projections, certain land cover changes strongly impacted groundwater recharge in localized areas:
    - For example, the incorporation of wetland taro cultivation in Futures 1 and 4 produced dramatic increases in recharge due to its intensive, non-consumptive irrigation;
    - Conversion from fallow land to diversified agriculture increased irrigation, and therefore recharge;
    - Within the cloud zone elevation (610–2100 m), conversion from grassland to native or alien forest led to increased fog interception, which increased recharge;
- New future urban expansion is currently slated for coastal areas that are already water-stressed and had low recharge projections.

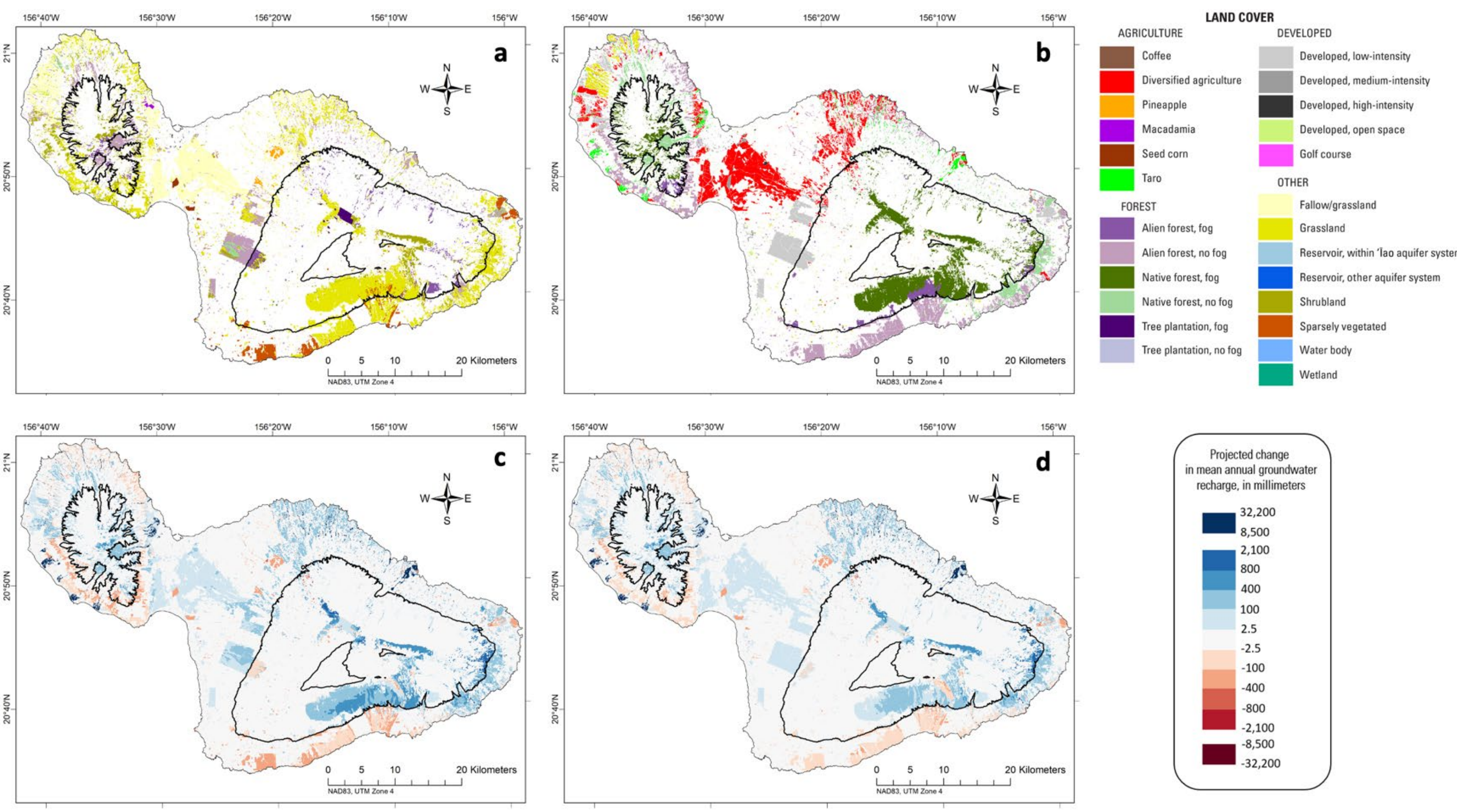

Figure 6. (a) 2017 baseline land cover for Maui. Only areas that were subject to change under the Future 1 land cover scenario are shown; (b) Land cover change from 2017 conditions to Future 1. Change in mean annual recharge for Future 1 and (c) Wet future climate; (d) Dry future climate. The solid contour lines represent the base (610 m) or top (2500 m) of the cloud zone. Recharge increased where grassland converted to any type of forest above the cloud zone, where new diversified agriculture appeared, and where taro cultivation was introduced. Recharge decreased where grassland changed to alien forest below the cloud zone, seen along the leeward areas of west and east Maui. (Source: Brewington et al. 2019)

Accomplishments. The results of this project demonstrated that improved understanding of the impacts of watershed management on groundwater yields and management costs—particularly in the context of climate and land cover change—is critical to informing water use planning and facilitating integrated land and water management. The project also showed that a spatially-explicit scenario planning process and modeling framework can communicate the consequences and tradeoffs of land cover change under a changing climate, and the outputs from this study served as relevant tools for landscape-level management and interventions. As one example, the watershed partnerships that manage higher elevation lands where climate projections strongly diverge are concerned with native forest protection and restoration efforts, especially fencing for feral ungulates, requiring significant financial and human capital. Emphasizing that the future climate in those regions could be much wetter or drier compared to today may assist upper watershed conservation planning under conditions of uncertainty. Furthermore, drying trends shown in both climate projections could affect future agricultural and groundwater development in areas targeted for urban expansion or diversified agriculture.

The utility and broad usage of the outcomes of this project also significantly increased Pacific RISA's visibility in Hawaiʻi. The scenario methodology was used in a University of Hawaiʻi-led National Science Foundation program investigating water resources on Oʻahu under climate change that employed a similar explicit land cover-based approach. Given the broad success and applicability of this project, the Hawaiʻi Commission on Water Resources Management (CWRM) funded a similar scenario-based approach to predict future groundwater resources on all the main Hawaiian Islands in partnership with the USGS. On Maui, the project helped decision makers plan for an uncertain future and led to multiple value-add projects—including incorporating novel economic valuation of future adaptation alternatives into the scenario processes as part of Pacific RISA Phase III. The work was also expanded to American Sāmoa, focused on predicting future freshwater sustainability under climate and land use scenarios.

Links to Other Projects.

- ***Built on Phase II scenario planning***: During Phase III, the Pacific RISA continued to work with stakeholders in Maui to incorporate future adaptation alternatives into the scenario process. Scenario planning efforts were expanded to Oʻahu and the USAPI, beginning in American Sāmoa.
- ***Used data from Obj. I***: Dynamical and statistical downscaled projections of future climate change and variability were integrated into the water-budget modeling framework.

In addition to these project linkages, the Honolulu Board of Water Supply (BWS), aware of Pacific RISA's work developing future climate scenarios for Maui, chose to pursue a similar infrastructure-centered process for Oʻahu. This Water Resources Foundation-funded project, "*Developing Future Climate Scenarios with the Honolulu Board of Water Supply*", provided much-needed information about how changing climate patterns could affect both quality and quantity of the water supply. Even with conservation measures and infrastructures repairs, for example, freshwater demand on Oʻahu is still projected to increase by 5 to 15% by 2040, with the most increases in areas of existing high population density. The BWS partnered with the Pacific RISA, the University of Hawaiʻi, and Brown & Caldwell consultants to assess projected climate change impacts on their infrastructure and identify vulnerabilities over the next 20 to 70 years using a scenario planning approach to consider a range of plausible future climate and socioeconomic conditions. A vulnerability assessment was produced that considered extreme heat, coastal erosion, waves, groundwater, storm flooding, annual and seasonal drought patterns, and changes in groundwater recharge impacts. This work helped the BWS prioritize adaptive actions to minimize the range of climate impacts, including urgent capital improvements and updates to engineering standards.

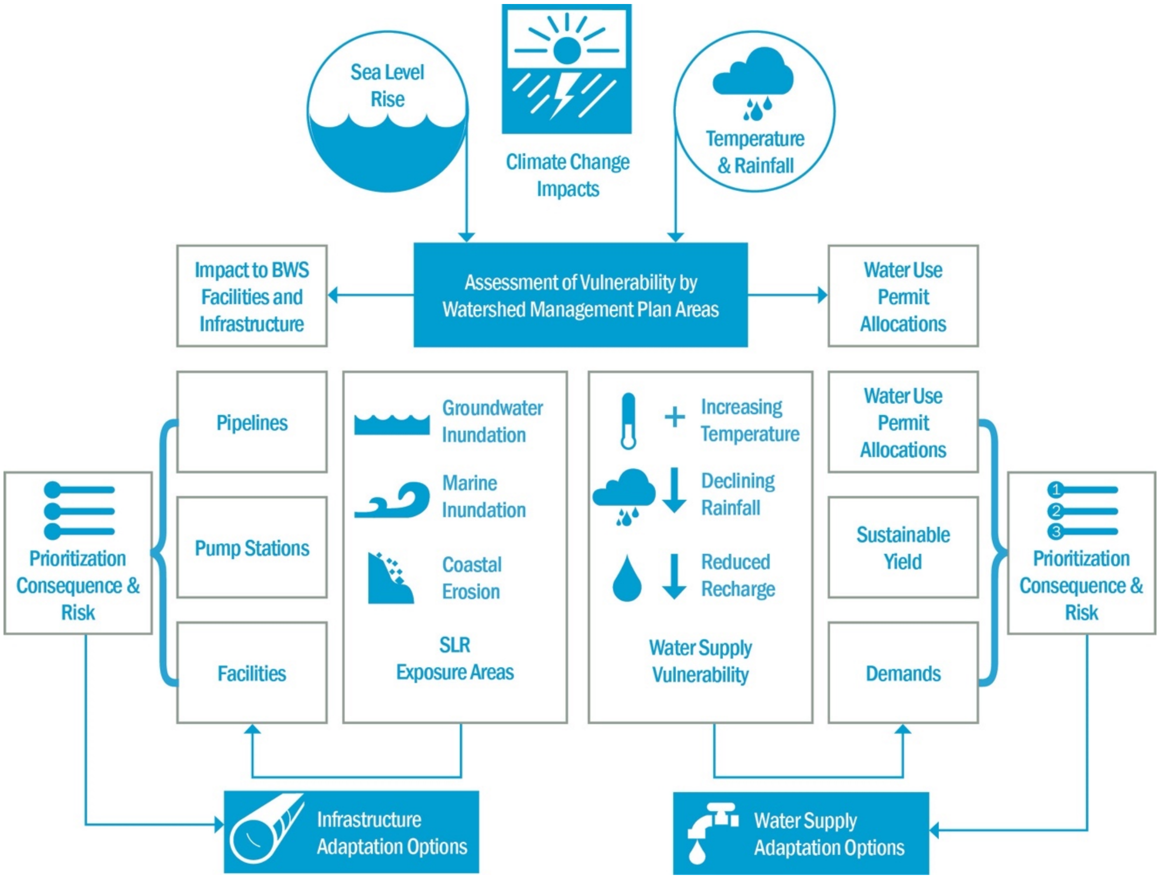

Figure 7. Overview of the BWS vulnerability assessment framework to inform infrastructure improvements and engineering standards on Oʻahu. (Source: Honolulu Board of Water Supply 2019)

Impact of Future Climate Variability on Freshwater Resources

Core Objective. (I) Conduct place-based assessments of risk, vulnerabilities, and adaptation strategies

Freshwater Resource Modeling and Assessments in American Sāmoa

The freshwater lens on Tutuila Island, American Sāmoa, is a precious and dynamic resource that serves the Territory's capital of Pago Pago and surrounding populated areas. Despite ample precipitation, American Sāmoa's groundwater resources are vulnerable to the effects of climate change and variability, such as prolonged drought and saltwater intrusion due to sea level rise and wave overwash. A better understanding of the relationship between ENSO and freshwater quality and quantity has been identified as a critical research need for planning. This project promoted integrated, adaptive management of surface water and groundwater in American Sāmoa. The multi-year efforts included: (1) Investigating the impacts of climate change and variability on water balance components; (2) Estimating groundwater recharge parameters under different climate and land management scenarios; (3) Measuring water level response to precipitation events; (4) Analyzing the impacts of climate on water levels and quality, and extreme peak and low flows; and (5) Evaluating potential high-elevation groundwater resources as alternatives to development in the basal-groundwater lens. Inspired by the success of the Maui future climate scenario planning work, the team developed Tutuila-specific land use/cover change scenarios with American Sāmoa stakeholders, which served as input data for freshwater and flood modeling, and inundation mapping.

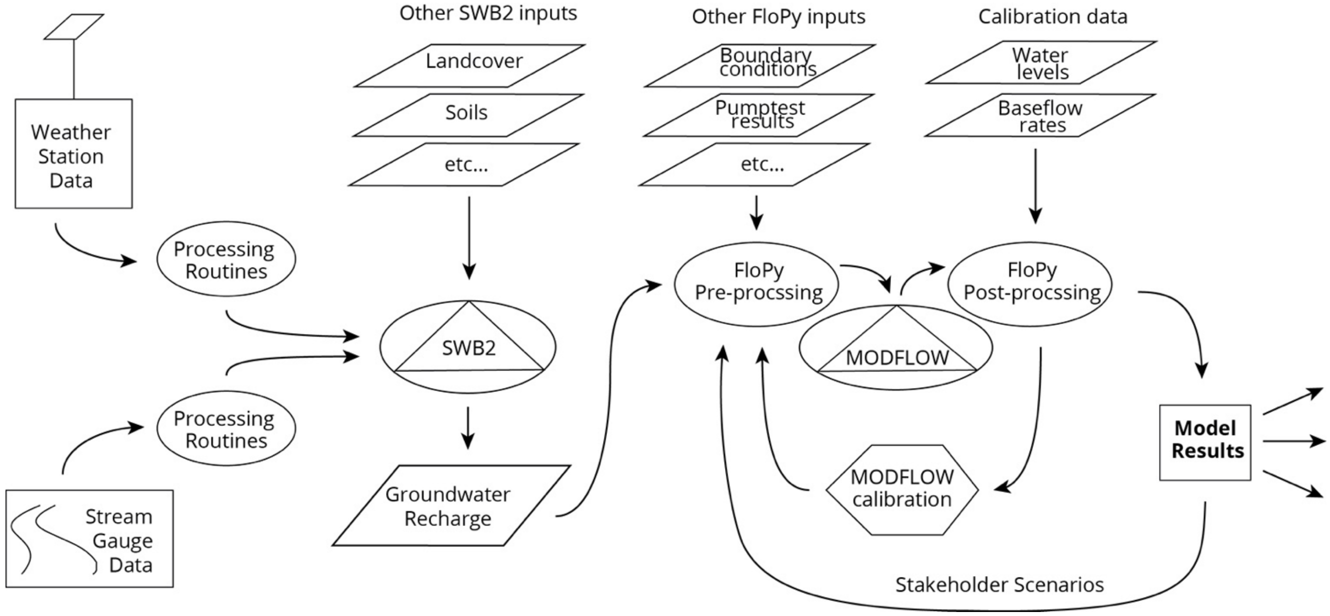

Figure 8. The data and modeling framework for the integrated groundwater, climate, and land cover project in American Sāmoa. (Source: Chris Shuler)

Translating Science into Policy Decision Tools in American Sāmoa

Pacific RISA's groundwater modeling work with the American Sāmoa Power Authority (ASPA) directly supported ASPA's mission of managing and providing a sustainable supply of water to the Territory. During Phase III a new water-budget model projected groundwater recharge availability for the end of the 21st century considering climate change effects using a dynamically downscaled global climate model. Groundwater recharge estimates for 2080–2099 under RCP4.5 and RCP8.5 future climate scenarios were generated and delivered to local stakeholders.

The team used cloud-based methods to collaborate with stakeholders in American Sāmoa and applied open-source tools to develop a collaborative hydrologic modeling framework that integrated data collection and modeling components, including the monitoring network, a water budget model, and a groundwater modeling framework. The open-source framework allows for seamless integration of multiple computational components into a dynamic cloud-based workflow that is immediately accessible to stakeholders, resource managers, or anyone with an internet connection.

Hydrologic Monitoring Network. On Tutuila Island, weather monitoring and stream gauging operations were initiated by the USGS in the 1950s. By 2008, however, all USGS monitoring activity across the Territory had ceased. Although this legacy data remains as a valuable tool, climate change and variability have continued reduce its applicability as time passed. Because this information is a critical component of sustainable water management, the University of Hawaiʻi Water Resources Research Center and ASPA entered into a cooperative agreement for the purpose of developing a new weather station, stream gauging, and aquifer monitoring network. The instruments used in this network were intended to be simple, robust, and easily maintained to ensure longevity and continuity of data.

Figure 9. University of Hawaiʻi graduate student Taylor Viti assists with streamflow measurement for development of the Tutuila monitoring network. (Source: Chris Shuler)

Accomplishments. This groundwater and watershed modeling work, as well as the established monitoring networks, have yielded crucial information about water quality and quantity under climate change and variability in American Sāmoa. Groundwater models provided water resource managers with alternate potential sources of freshwater to improve adaptive capacity under future climate conditions as well as the quantitative basis to engage with regulating authorities as they plan for a robust freshwater supply. The Soil and Water Assessment Tool (SWAT) models developed for American Sāmoa were upscaled and used to estimate coverage and quantity of the Heʻeia and Nuʻuanu area watersheds on the Island of Oʻahu, Hawaiʻi. Two online, interactive outreach products now exist to support stakeholder utility of these research program outputs:

1. A website to promote understanding of the integrated groundwater modeling framework;
2. A Github repository: This repository is open-source and makes all data, code, and results publicly available.

Furthermore, the first high-resolution water budget model for an entire high-basaltic island within the South Pacific Convergence Zone was developed by the Pacific RISA. This, in addition to application of the model to project future conditions under both climate change and land cover change scenarios, make this project one of the most rigorous assessments of present and future water resources availability in the South Pacific region to date.

In Fagaʻalu Valley, a crucial watershed of Tutuila Island, nutrient delivery via groundwater was identified as an important process. The watershed modeling results agreed with the geochemical tracer results, and lent an additional degree of confidence to these estimates. While the stream is the primary source of sediment to the bay, the effects of groundwater on coastal water geochemistry cannot be ignored, and coastal health management should consider groundwater as an additional source of potential contamination.

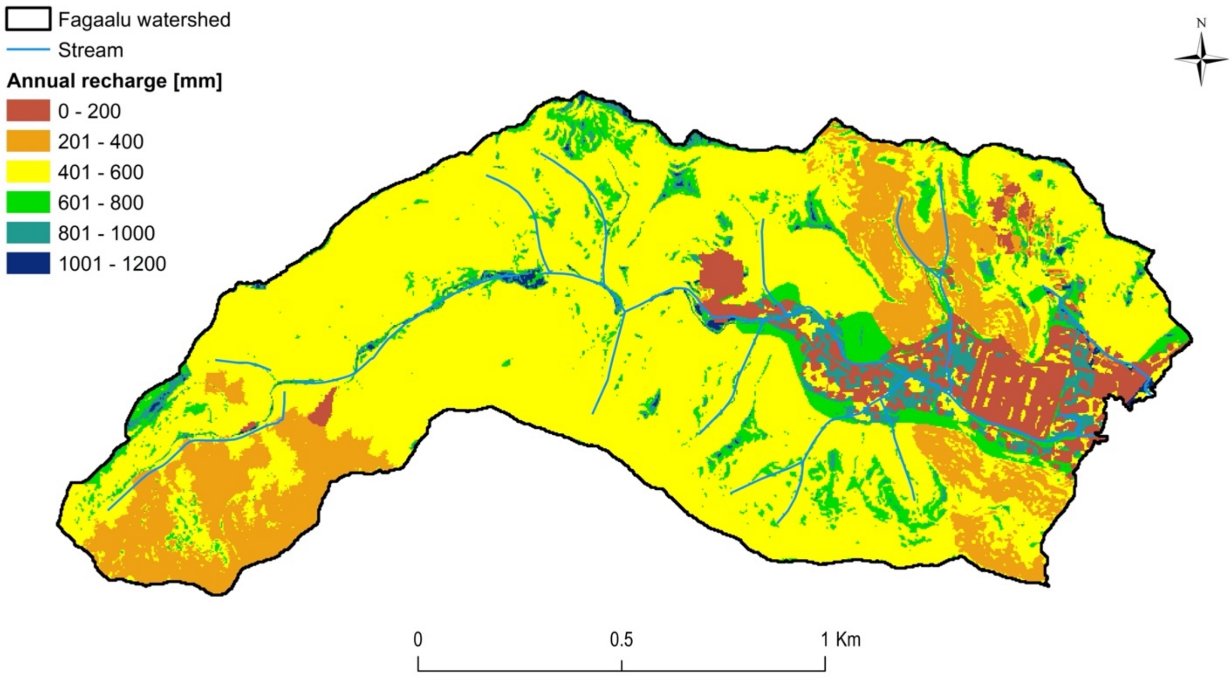

Figure 10. Projected annual groundwater recharge for the Faga'alu Valley on Tutuila Island from the Soil and Water Assessment Tool (SWAT) model. (Source: Chris Shuler)

Hawai'i Watershed Modeling

Following the suitability and applicability testing of the SWAT modeling framework for Tutuila Island and Faga'alu Valley watershed in American Sāmoa, the model was used to estimate the groundwater coverage and amount of water that can be potentially harvested from important watersheds on O'ahu. The team used the statistical downscaled rainfall anomalies reports developed under Pacific RISA Phase II for the Hawaiian Islands for RCP4.5 and 8.5. SWAT model performance comparison for daily streamflow simulation was done for both the He'eia and Nu'uanu area watersheds.

Research Findings. Regarding climate change impacts on water resources, extreme peak and low flows analysis indicated that an increase in peak flows of up to 22% was expected for a higher return period under the RCP8.5 scenario. High-flow events could potentially cause flooding and damage to infrastructure. In contrast, the future extreme low flows were expected to further decrease by 56% compared to baseline levels due to less rainfall availability and high evapotranspiration (ET) during the dry season. Consequently, by the end of the 21st century, more frequent drought periods are expected, which would negatively affect agricultural crop productivity, freshwater availability, and ecological functioning of river riparian ecosystems. Startlingly, although the temperature was projected to increase, monthly actual ET was expected to decrease by up to 8% in the future. This was most likely due to less rainfall availability (moisture limitation), indicating that rainfall change was the main factor for the general decrease in ET as compared to temperature change. Overall, the water budget components such as surface runoff, baseflow, streamflow, ET, soil moisture, and recharge were projected to decrease by the end of the century. Compared to the other water budget components, the monthly baseflow values were expected to consistently decrease in the future. Additionally, the amount of water potentially harvested by the Nu'uanu reservoir was expected to decrease by up to 36%, indicating less freshwater availability in the future with serious implications for sustainability.

Figure 11. The Nuʻuanu reservoir and watershed area on the Island of Oʻahu. (Source: Honolulu Board of Water Supply)

Accomplishments. The replication/upscaling of the methodology utilized for Faga'alu Valley in American Sāmoa was successful in Hawaiʻi. Whereas the Heʻeia watershed experiences a scarcity of hydrological and climate data, the Nuʻuanu area has relatively good quality data. Model performance evaluation results ranged from "satisfactory" under scarcity of data (Heʻeia) to "very good" for relatively good quality data (Nuʻuanu). These findings highlighted the importance of using multiple gauging stations within a watershed to capture the high climate variability and improve model performance, which was particularly important for the Heʻeia watershed.

Modeling Future Freshwater Resources for DoD Installations and Communities in Guam

Building on the Hawaiʻi and American Sāmoa future climate and freshwater modeling, in this project funded by the US Department of Defense (DoD) Strategic Environmental Research and Defense Program (SERDP), the Pacific RISA collaborated with the USGS Pacific Water Science Center, the University of Hawaiʻi, and the University of Guam to investigate the impact of projected climate changes on surface and groundwater resources in Guam. Potential effects on DoD installations and the ability for the civilian Guam Waterworks Authority's (GWA) to supply the island's population with freshwater were identified. With plans to relocate 4,000 US Marines from Japan to Guam by 2024, the government of Guam and the DoD need to know how population growth and climate change will impact water resources. This project investigated future impacts of RCP8.5 on regional climate, sea level rise, typhoon tracks, groundwater recharge, salinity of wells, and streamflow. The Pacific RISA led the stakeholder outreach and response component of the project. In a series of engagements, the team examined the effect of alternate information presentation formats (e.g., tabular, graphical, spatial/map-based, range) on decision makers' understanding and use of climate and hydrology information.

Research Findings. Using simulations of a regional climate model downscaled to a finer spatial resolution, Guam's water resources were projected to diminish relative to current climate conditions. Future average temperature increases and average rainfall decreases could lead to reduced streamflow in southern Guam and reduced groundwater recharge. In the predicted future climate, average temperatures in southern Guam increased by about 3°C and overall rainfall decreased by about 7%, leading to an 18% decrease in streamflow. Higher sea level and reduced future recharge were predicted to reduce water availability from the Northern Guam Lens Aquifer (NGLA). The composite chloride concentration from production wells was predicted to increase to 304 mg/L (well above the drinking water standard of 250 mg/L) under future climate conditions and at current withdrawal rates, compared with 126 mg/L under historic climate conditions. Most of this increase was due to reduced recharge, because higher sea level only played a small role in increasing salinity. A redistributed withdrawal scenario in which the composite concentration was 291 mg/L offered only slight improvement. Should future droughts reduce recharge proportionally to the decreases observed during historic droughts, the composite concentration would be about 900 mg/L and more than 70% of Guam's production wells would produce water unsuitable for drinking.

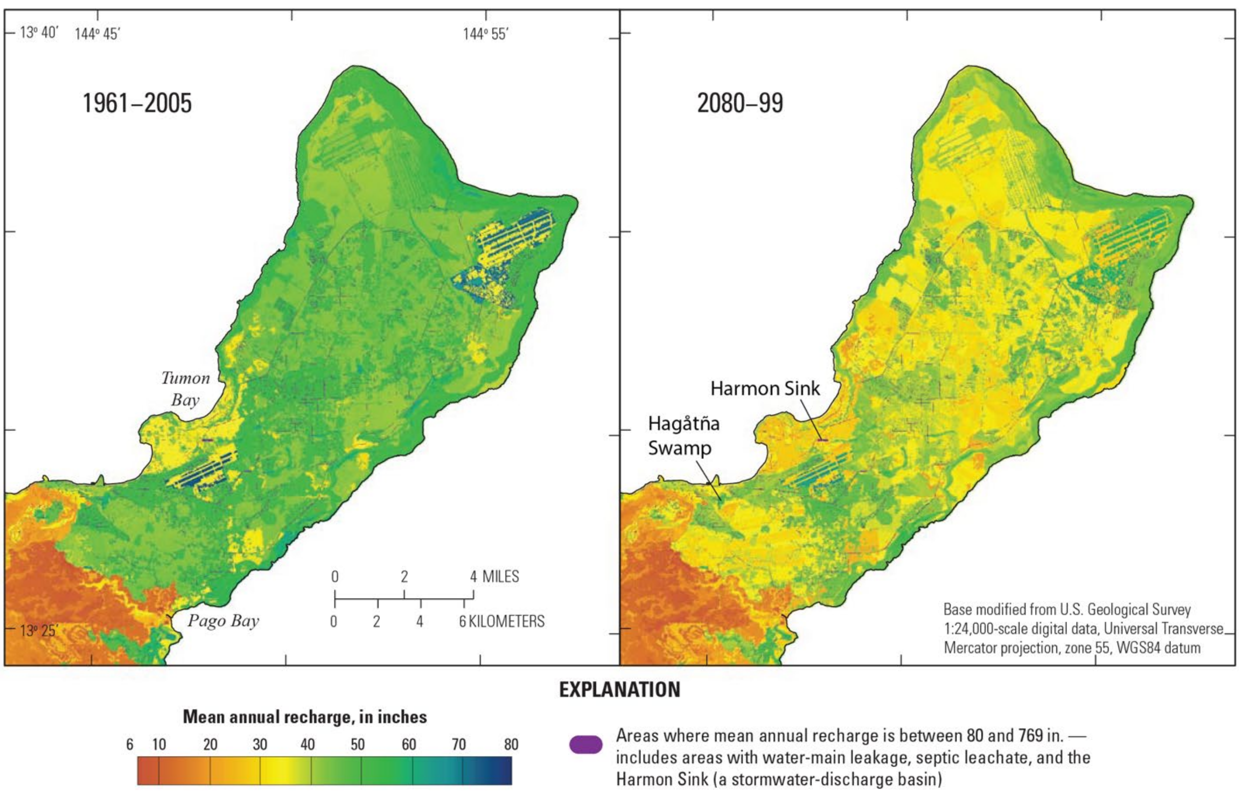

Figure 12. The distribution of mean annual groundwater recharge estimated for the NGLA for historic (1961–2005) climate conditions (modified from Johnson 2012) and future (2080–2099) climate conditions under RCP8.5. (Source: Gingerich et al. 2019)

Accomplishments. Through the stakeholder engagement process, several key themes emerged:

1. Decision makers in Guam value engagement with scientists;
2. Decision makers identified diverse climate-sensitive decisions that could be supported with information about future climate conditions;
3. Existing resources varied in familiarity and perceived usefulness to decision makers;
4. Climate information seemed harder to understand than water information;
5. Preferred information formats depended on the intended use and potential audiences;

6. Suggestions were made about how to improve climate and water information for freshwater managers; and
7. Information users need training, collaboration, and technical information.

Upon request from stakeholders, several science products clearly and concisely summarized the project's background and simplified main findings, and were written in a manager-oriented style. These included: (1) An information sheet summarizing Guam's historic hydrological and climatological trends with respect to temperature, precipitation, ENSO impacts, sea level, and typhoons; (2) A briefing sheet for managers outlining the watersheds and water systems of Guam, and how climate information is relevant to their future planning, and; (3) An executive summary of key findings from the study summarizing future climate impacts, related uncertainties, and management options and scenarios. These products were distributed in hard copy to all stakeholders and university partners, and are available electronically on the Pacific RISA website.

Final science products included: (1) Projections of climate impacts for 2080-2099 under RCP8.5 using a downscaled dynamical regional climate model; (2) Projections of future typhoon magnitude and occurrence; and (3) Estimates of future sea level, streamflow, reservoir sedimentation, groundwater recharge, and groundwater salinity under future climate projections.

Links to Other Projects.

- ***Responded directly to stakeholder needs identified in Phase II***: These efforts built from the water and policy analysis for American Sāmoa, which used stakeholder input to identify climate adaptation planning opportunities in the Territory. The were also strongly informed by a series of workshops on drought and resource management led by NOAA and partners across the region.
- ***Provided data and analyses for Objs. II, III, and IV***: Information about water quality and quantity under climate change and variability impacts in American Sāmoa served as inputs for the Pacific Islands Regional Climate Assessment (PIRCA) report for the Territory, as well as the Fourth National Climate Assessment chapter on Hawaiʻi and the USAPI.
- ***Identified gaps that informed new Pacific RISA work***: The implementation of the American Sāmoa water-budget model was only recently completed and that of the groundwater model is ongoing, but conversations with stakeholders suggest potential future impacts from this work. This includes helping water managers quantify the recharge and value of Malaeimi Valley, an area that currently feeds some of the most productive well fields on Tutuila Island and has been proposed as a designated special management area. However, ASPA is currently dealing with a land dispute occurring in the valley in which a single landowner has blocked all access to the valley and is presently involved in a court case about previously negotiated use of water resources in the area. Applying the water-budget model and quantifying the amount of recharge in the valley will assist policy makers and resource managers in working through this issue.

Ecosystem Services Valuation and the Economic Impacts of Adaptation

Core Objective. (II) Support implementation of adaptation strategies

Assessing Economic Impacts of Climate Planning and Adaptation

This project generated a set of rules concerning climate variables, management options, and policy alternatives that informed the ecosystem services and adaptation strategies for Maui. Semi-structured interviews were conducted with Maui stakeholders in water resources management to address the following core questions:

1. What adaptation measures are decision makers currently investigating that are related to freshwater resources, and what state or county level policies relate to those decisions?
2. What economic and ecosystem services valuation information is relevant to freshwater policies?
3. In what form would stakeholders best be able to utilize climate impact and adaptation valuation information?
4. What planning timelines are relevant for integrating climate adaptation into valuation analyses?
5. What kinds of economic factors impact your ability to plan for the future?

Accomplishments. The interview results were used to design a web survey of more than 350 Maui Island residents. The survey collected data on their interactions with the natural environment to evaluate the economic benefits of outdoor recreation on Maui. The team recorded all outdoor locations (beaches, city parks, open spaces, etc.) visited by each respondent in the month prior to the survey and the number of times each location was visited. They also collected data on socio-demographic characteristics, including the location of the residence. A subsequent workshop was held on Maui to ground-truth the survey and interview results through discussion and engage natural resource managers and tourism stakeholders in identifying potential gaps in adaptation strategies of interest, policies, or groups that may have been marginalized in the assessment process. The workshop contributed to a final, prioritized set of rules concerning climate variables, management options, and policy alternatives that was used to inform Phase III ecosystem services modeling.

Using Ecosystem Services Valuation to Assess Trade-offs and Opportunities

Although island-scale projections of climate variability and change have been released and integrated into planning documents, managers still lacked detailed information on the value and tradeoffs associated with future climate impacts and the implementation of different adaptation strategies. Limited efforts have been made to assign value to an island's natural resources. Policy-makers and managers needed measures of valuation to decide between alternative adaptation options and weigh the potential costs of inaction. This project built on the participatory scenario process developed in Phase II to generate a set of rules concerning climate variables, management options, and policy alternatives, which were then used to inform ecosystem services valuation and adaptation strategies for Maui. This project utilized watershed-scale modeling to inform a decision support tool that quantified, mapped, and valued ecosystem services from land to sea. Existing models for Maui, such as InVEST42 and ARIES43, were employed to guide management by predicting how key ecosystem services will change under alternative management policies and climate change scenarios.

Research Findings. Through surveys and interviews, the research team identified the key ecosystem services that are likely to be impacted by climate change and agricultural/environmental policies on Maui. They also developed a travel cost model to value the economic benefits that outdoor recreation provides to residents. They engaged with community members, thought leaders, and decision-makers to develop scenario elements, identify priority ecosystem services, derive likely management and policy alternatives, and incorporate local knowledge. A list of these services and their main drivers is provided in the table below. Then, a conceptual framework was developed linking four spatially-explicit models, informed by the set of rules created above, that was designed to assess the trade-offs and opportunities arising with climate change and explore alternative policy scenarios.

Priority ecosystem services in Maui and their main drivers. (Source: Kirsten Oleson)

Ecosystem service	Main direct drivers
Crop and livestock	*Land use and development, policy, water availability, climate, soil and land quality, input and output prices*
Wild animals hunting	*Land use and development, crop and livestock decisions climate, policy*
CO_2 emissions and sequestration	*Land use and development, crop and livestock decisions, policy*
Land biodiversity	*Land use and development, climate, crop and livestock decisions, policy*
Drinking water and groundwater recharge	*Land use and development, climate, crop and livestock decisions, water availability, policy*
Cultural and use values from in-stream flow	*Land use and development, climate, crop and livestock decisions, stream flows, policy*
Land recreation, aesthetics, and non-use values	*Land use and development, climate, policy, stream flows*
Near shore fishing	*Land use and development, climate change, policy, Marine Protected Areas (MPAs), buffer zones*
Marine recreation, aesthetics, and non-use values	*Land use and development, climate change, policy, MPAs, buffer zones*
Jobs availability from tourism, agriculture, and development	*Land use and development, climate change, stream flow, policy, MPAs*

Note: Drivers encompass only factors that are likely to change with climate change and the different adaptation options considered in the project.

An interdisciplinary system of models was created by analyzing case studies regarding increasingly complex issues, leading to a gradual development of the modeling framework. The first issue addressed was the impact of climate change and extreme weather events. The team estimated the loss in value generated by “brown water” events in Maui and possible adaptation strategies. During brown water events, typically caused by heavy rain, people are advised to stay out of flood and coastal waters due to excess soil runoff and possible overflowing cesspools, sewers, pesticides, and pathogens. These types of events are common on Maui and are expected to increase if heavy rainfall becomes more common with climate change. The team also provided a cost-benefit analysis of different strategies designed to mitigate their occurrence.

Accomplishments. The economic impacts of brown water events that affect Maui’s beaches were estimated and presented to decision makers. The team also developed a hydrological model linking daily rainfall to sediment and nutrient outputs for the island. This hydrological model was a specification of the SWAT model: a river basin, hydrological response unit-scale approach to quantify the impact of land management practices in watersheds. It provided water quantity and nutrient and sediment loads at every outlet point on the island. This model also projected how sediment loads will change with the climate and land use change expected in the future. The team worked with Hawaiʻi State Division of Aquatic Resources (DAR) and The Nature Conservancy (TNC) to include the modelling work developed in this project as part of the “Hawaiʻi 30x30” implementation guidelines. This major policy initiative aims at achieving effective management of 30% of Hawaiian coastline by 2030.

Figure 13. Brown water event (post-rain) affecting nearshore areas and coastal waters in Maui. (Source: Bill Rathfon)

Links to Other Projects.

- ***Responded directly to stakeholder needs identified in Phase II***: This project supported improved decision making by producing better information about the nature of change in ecosystem service supply and value due to climate variability and change, as well as the trade-offs posed by alternative courses of action.
- ***Used data from Obj. I***: The HRCM model projections, as well as seasonal projections of climate variability (ENSO), were used to examine the long-term climate change impacts on ecosystem service flows and values.
- ***Built on Phase II scenario planning***: The future land cover scenarios that were developed for Maui were used to frame watershed-scale modeling of ecosystem services. The economic valuation work attached more explicit values to the different adaptation options of interest in the future climate scenarios.
- ***Maintained and expanded on regional relationships established in Phase II***: The participatory scenario process for Maui generated a list of key stakeholders who make short and long-range decisions about freshwater resource management. This project also leveraged the network of regional freshwater decision makers identified through the PIRCA process.

Indicators of Climate Variability, Climate Change, and Sectoral Impacts

Core Objective. (II) Support implementation of adaptation strategies

With dozens of regional sources of historical weather and climate data, as well as forecasts and projections, it remains a challenge to translate these data into actionable information relevant to different decision sectors such as freshwater management, agroforestry, or human health. This project took the first step in translating these data by synthesizing and agreeing upon a set of foundational measures, or indicators, of change. This information about the trends and patterns in physical, biological, chemical, and ecological observations under a changing climate have facilitated communication and informed decisions among public and private sector stakeholders across the international Pacific Islands region. Key climate variables included physical measures such as temperature, rainfall, and sea level, as well as biological, chemical, and ecological observations that were indicative of current, past, and possible future states of the climate system. Included also in this broad category were climate indices commonly recognized to provide information about the state of the climate (e.g., the Oceanic Niño Index (ONI) and Pacific Decadal Oscillation (PDO)). Sources for information about climate variables are typically measurements obtained from in situ stations, satellites, or models. These observing systems and models provide information that can be used to characterize mean and extreme states on: (1) global, regional, subregional or local scales; and (2) monthly or seasonal to annual or interannual bases in terms of the magnitude, frequency, and duration of a particular variable. Sector or resource-specific impacts indicators include measures that can be used to characterize the direct and indirect impacts on assets of interest within both built and natural environments. More broadly, they include any measure that can be used to characterize an attribute relevant to assessing the state/condition of a given sector or concern.

Accomplishments. To generate and select a set of climate indicators, a series of formal and informal discussions and workshops were conducted with stakeholders in the public and private sectors and members of the scientific community who had technical expertise and practical experience related to climate change and variability. These were iterative, employing a dialog process to solicit input, generate results, collect feedback, and generate new results. Selected indicators were represented in the "*State of the Environment Scorecard*". These had a defined relationship to climate variability and change and were scientifically defensible, linked to the indicators conceptual framework, locally and regionally relevant, and scalable.

This set of climate indicators was used to coordinate across international weather and climate data organizations in the region (e.g., Australia's Bureau of Meteorology (BOM), New Zealand's National Institute of Water and Atmospheric Research (NIWA), World Meteorological Organization (WMO) Region V, the Secretariat of the Pacific Regional Environment Programme (SPREP)). Specifically, they helped frame the discussion of international cooperation and coordination around data, climate adaptation, and translation into sectoral thresholds and impacts. A future goal is to establish a more extensive set of indicators, ultimately covering the full spectrum acknowledged in the conceptual model.

Links to Other Projects.

- ***Maintained and expanded on regional relationships established in Phase II***: During Phase III, The Pacific RISA increased working partnerships across the Pacific Islands and WMO Region V via establishing a working group that came to a consensus on a set of regionally applicable climate indicator variables. This group published the 2017 State of the Environment report, which became a foundational document for researchers, island Meteorological Offices, and the Fourth National Climate Assessment (2018) and PIRCA reports (2020–2021).
- ***Leveraged research and support from new partners/local and regional institutions***: By coordinating weather and climate data across NOAA, NIWA, BOM, SPREP, and other regional entities, this project created a framework for international coordination and collaboration that served to reduce redundancies, leverage project outputs, and share best-practices in sectoral climate adaptation via case studies and "climate stories" (narrative examples of lived experiences and applications of climate information).
- ***Identified gaps that informed new Pacific RISA work***: With a baseline set of climate indicator variables, Pacific RISA researchers and partners are extending this research to include climate

impacts indicators and key thresholds of change across sectors of interests. This project directly informed the collaboration and publication of the 2021 Pacific Climate Change Monitor, spurred the first Pacific Climate Change Conference (PCCC) in 2022, and helped inform jurisdictional PIRCA reports and a collaboration on climate indicators via the United Nations Sustainable Development Goal (SDG) Dashboards in the Freely Associated States between the Pacific RISA and the Hawaiʻi Green Growth Local2030 Island Network.

	WHERE DO WE STAND?	A LOOK AHEAD	READ MORE IN SECTION
GREENHOUSE GASES			
Carbon Dioxide	Increasing	Increasing	1
WEATHER AND CLIMATE			
Surface Temperature			2
Regional Average	Increasing	Increasing	
Frequency of Hot Days	Increasing	Increasing	
Frequency of Cold Nights	Decreasing	Decreasing	
Rainfall			3
Annual Average			
Central Pacific	Decreasing	Change*	
Western Pacific	No Change	Increasing	
South Pacific	Increasing	Increasing	
Extreme Wet Days			
Central Pacific	Decreasing	Increasing	
Western Pacific	IncreasingT	Increasing	
South Pacific	Increasing	Increasing	
Extreme Dry Days			
Central Pacific	Increasing	Change*	
Western Pacific	No Change	Change*	
South Pacific	No Change	Change*	
Surface Winds & Tropical Cyclones			4
Tradewinds	No Change	Change*	
Monsoon Winds	No Change	Change*	
Winds >Than 34 Knots			
Central Pacific	Decreasing	Change*	
Western Pacific	Increasing	Decreasing	
South Pacific	Increasing	Increasing	
Tropical Cyclone Frequency			
Central Pacific	No Change	Increasing	
Western Pacific	No Change	Decreasing	
South Pacific	No Change	Decreasing	
Tropical Cyclone Intensity			
Central Pacific	No Change	Increasing	
Western Pacific	No Change	Increasing	
South Pacific	No Change	Increasing	

	WHERE DO WE STAND?	A LOOK AHEAD	READ MORE IN SECTION
COASTS AND OCEANS			
Sea Level			5
Global	Increasing*	Increasing	
Central Pacific	Increasing	Increasing	
Western Pacific	Increasing	Increasing	
South Pacific	Increasing	Increasing	
Flood Frequency			
Central Pacific	Increasing	Increasing	
Western Pacific	Increasing	Increasing	
South Pacific	Increasing	Increasing	
Sea Surface Temperature (SST)			6
Regional SST	Increasing	Increasing	
Degree Heating Weeks	Increasing	Increasing	
Ocean Acidification			7
Global Aragonite Saturation State	Decreasing	Decreasing	
Regional pH	Decreasing*	Decreasing	
Ocean Chlorophyll Concentration			8
Chlorophyll Concentration	Decreasing*	Decreasing	

(red)	Increasing trend, likely to increase
(yellow)	No clear trend, neutral changes
(blue)	Decreasing trend, likely to decrease
*	Asterisk denotes indicator is highly variable from year-to-year
T	Highly variable from location to location

The "State of the Environment Scorecard" provides a quick snapshot of where things stand and what we might look forward to as far as changes in environmental conditions in Hawaii and the USAPI. The eight indicators of change covered in this report fall into three categories: Greenhouse Gases; Weather and Climate; and Oceans and Coasts. Some indicators are further subdivided by various sub-indicators that describe a particular measure affiliated with their overall indicator and/or by geographic location (i.e., Central, Western, or South Pacific). Patterns of change observed and projected for each indicator or sub-indicator are shown in the table as increasing, decreasing or no change and are highlighted in red, blue and yellow respectively. Also shown in the table is the section number in the report where more information can be found on each indicator.

Figure 14. State of the Environment Scorecard. (Source: Marra et al. 2017)

Causes and Impacts of Climate-Induced Migration

Core Objective. (III) Evaluate adaptation plans and policy throughout the region

Though much research and debate has focused on the relationship between climate and migration, it is widely recognized that a lack of rigor characterizes research on the nexus of the two. Climatic changes often act in concert with other socioeconomic factors to drive relocation. Policy-makers require empirical data and analysis of the existing policy framework around migration. Decision-makers at local and state levels need information to anticipate possible future impacts of climate on migration and for communities and sectors at all scales to plan accordingly.

The Pacific RISA Climate and Migration Project aimed to clarify the extent to which people in the Republic of the Marshall Islands (RMI) were migrating to the United States because of climate change, and the role that ecosystem services played in their migration decisions. The research used household survey instruments to better understand the effects of migration on migrants themselves, among communities on three atolls in the RMI and in US destination states (Hawaiʻi, Oregon, and Washington). Finally, the research analyzed shared perceptions on climate change and migration. This allowed for a more robust assessment of the current state of well-being for Marshallese migrants, contributed to informed discussions regarding whether migration is a successful adaptation strategy, and provided context for assessing which legal, economic, and social services migrants may need in coming years.

Research Findings. The household survey analysis highlighted that the primary drivers of migration away from the RMI were better education, better health care, job opportunities, and familial connections. There was a divergence between those respondents who had already migrated to the US and those who were still living in the RMI, however. Migrants based in the US ranked environmental problems as a major driver for migration, whereas RMI-based respondents placed more emphasis on the lack of jobs, drought, lack of freshwater security, and sea level rise as their major migration drivers. Almost all US respondents pointed out the increase in king tides, droughts, and heat waves in the country. They also noted that sea level rise and especially access to drinkable water or freshwater resources were factors that would prevent them from returning home to RMI.

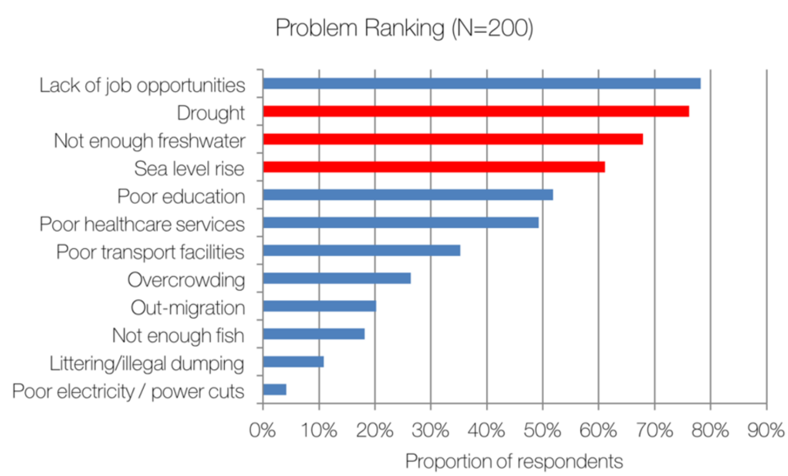

Figure 15. Researchers used the "Q methodology" in the RMI, a semi qualitative approach to discern patterns of decision-making regarding migration (L). Results of a problem ranking exercise (R) with a sample of 200 households in RMI included three climate-related stressors (red bars) that proved to be very important to respondents, ranking 2nd (drought), 3rd (not enough freshwater), and 4th (sea level rise). (Source: Marshall Islands Climate and Migration Project)

Accomplishments. Numerous publications, reports, and policy briefs were produced from this project, which describe the drivers of migration and the level at which climate impacts affect migration decision-making. A policy brief on Marshallese perspectives on migration in the context of climate change highlighted key findings on migration patterns, drivers, and impacts, and described the tension between being prepared to move and fortifying to stay in place. All resources can be found via the Marshall Islands Climate and Migration Project website. This research has been cited in publications of the United Nations Framework Convention on Climate Change (UNFCCC), shared by the UN humanitarian information service ReliefWeb, and reported by Marshall Islands-based journalists.

Links to Other Projects.

- ***Identified gaps that informed new Pacific RISA work***: This work informed a NOAA International Research and Applications Project (IRAP) project focused on climate change, health, and migration led by the Pacific RISA that commenced in 2018 in collaboration with the RMI Ministry of Health and Human Services, NOAA, and the University of Hawaiʻi Sea Level Center to improve climate information delivery to the RMI health sector, and inform health service providers in Hawaiʻi about migration, health, and environmental change in the Pacific Islands region. That research in turn contributed to a successful proposal submission by the UN Environment Programme to the Green Climate Fund, through which the Pacific RISA is generating climate early warning systems for specific sectors, including health, in the RMI and Palau.

Legal and Policy Evaluation for Adaptive Capacity

Core Objective. (III) Evaluate adaptation plans and policy throughout the region

This project applied a framework developed during Phase II to analyze law and policy in American Sāmoa, providing guidance to natural resource managers and policy makers on how best to incorporate flexible adaptation strategies into existing water planning and policies.

A key component of enhancing adaptive capacity for diverse sectors and islands is to employ a reliable yet flexible process for: (1) Evaluating the existing law and policies regarding their capability to facilitate climate adaptation; and (2) Identifying opportunities to employ effective models for building adaptive capacity. Pacific RISA developed a framework for place-based evaluation of adaptive capacity suited to this task, with applicability across diverse Pacific Islands. Legal and policy evaluation work in Phase III identified adaptive characteristics of American Sāmoa's particular law and policy regime. From this review, the Pacific RISA recommended specific adaptive strategies for freshwater management enabled by the existing law and policy regime. The project considered climate change issues affecting American Sāmoa, including a projected increase in frequency and intensity of extreme rainfall events, rising sea level, and rising air temperatures.

Research findings. The analysis confirmed the need for effective climate change adaptation strategies, particularly with respect to protecting water quality. The existing law, policy, and management framework for freshwater resources is somewhat fractured, consisting of overlaid US federal environmental laws and regulations, territorial laws and policies, utility management of groundwater, and village-based management of surface water. This framework presents both challenges and opportunities with regard to adaptation. The report identified improved monitoring of groundwater sources and water quality as foundational adaptive measures for future water and infrastructure planning. Additionally, it highlighted ENSO as a crucial predictor of impacts for decision makers, including ASPA, the American Sāmoa Environmental Protection Agency (ASEPA), and the American Sāmoa Department of Commerce.

Accomplishments. A water and policy analysis was completed for American Sāmoa, which used stakeholder input to identify climate adaptation planning opportunities in the territory. ASEPA and ASPA are currently incorporating recommendations that resulted from this research in their water monitoring and management protocols. In addition, this approach facilitated the identification of potential law and policy changes, yielding a growing list of adaptation strategies applicable to island settings.

Links to Other Projects.

- ***Utilized methods tested in Phase II climate and water policy analysis***: Pacific RISA piloted new methods for legal and policy analysis when it evaluated Hawaiʻi's water policy framework for its adaptive features in Phase II. Those methods then became the basis of a similar analysis for American Sāmoa, when the team tested the transferrability and effectiveness of creating a policymaking toolkit specific to water management in this vastly different island context.
- ***Informed Pacific RISA's freshwater resource modeling and assessments in American Sāmoa:*** Pacific RISA's groundwater and watershed modeling and installation of new monitoring networks were consistent with the law and policy evaluation's findings regarding the need for a more complete understanding of the water resources to guide future investments and adaptive measures.

SUSTAINED CLIMATE ASSESSMENT

The Pacific Islands Regional Climate Assessment

Core Objective. (IV) Integrate technical climate information and policy outcomes

The Pacific RISA, in collaboration with NOAA and the PICCC, had a major role in writing the technical input for the Third US National Climate Assessment (NCA3, 2012). A collaboration formed to develop that report, which represented the initial milestone in a sustained process of information exchange among a network of scientists, governments, businesses, and communities in the Pacific Island region—under what became known as the Pacific Islands Regional Climate Assessment (PIRCA). During Phase III, with support from the PICASC, NOAA, and the East-West Center, the Pacific RISA hired a dedicated Sustained Assessment Specialist (SAS) to coordinate all PIRCA-related activities, including updated jurisdiction-specific assessments to meet the need for more detailed, sector-specific information across the region.

The PIRCA launched a much-needed update to the 2012 report and built upon the Fourth US National Climate Assessment (NCA4), examining trends and future projections for foundational climate change indicators. The co-development process, involving more than 125 authors and technical contributors, addressed gaps by outlining climate change risks in key sectors and identifying research and information needs to support responses that enhance resilience. A case study of the decade-long assessment effort identified characteristics of the PIRCA that are foundational to its effectiveness: framing climate information in human and decision-centric ways; use of inclusive and non-extractive methods; willingness to shift approaches to meet stakeholder objectives; leveraging the resources of the Pacific RISA and other boundary organizations; taking the time to build relationships; and creating a dedicated position to sustain collaborations and relationships within the region and at larger assessment scales. The experience and the feedback received through an external evaluation suggest that these lessons are transferable to other regions and scales.

Accomplishments. The SAS and Pacific RISA held a series of workshops in 2019 that enabled local technical experts and managers across a variety of sectors to inform the development of the PIRCA reports for Palau, Guam, American Sāmoa, and the CNMI. To host the workshops, the core team partnered closely with local institutions, including Palau's Office of Climate Change, Guam's Climate Change Resiliency Commission, the CNMI Bureau of Environmental and Coastal Quality, and American Sāmoa Community College. Participants shared input on how climate variability and change is affecting local sectors such as tourism, ecosystems, fisheries, health, agriculture, disaster management, infrastructure planning, cultural resources, and the economy. In the months following the workshops, authors and contributors iterated on the reports' development.

Figure 16. Technical contributors at the NCA-PIRCA Workshop for Palau in July 2019 at the Palau National Marine Sanctuary headquarters (L). Lt. Governor Josh Tenorio welcomed the Pacific RISA to Guam and announced the new Climate Change Resiliency Commission, who partnered with Pacific RISA to host the Guam PIRCA Workshop in October 2019 (R). (Sources: Zena Grecni (L) and PICASC (R))

Four co-developed PIRCA reports were released in 2020 and 2021. These reports have been used in funding proposals for adaptation projects, to inform National Adaptation Plans, and in governments' communications with the public and decision-makers at local, national, and international scales. Independent evaluation found that the PIRCA reports were widely perceived as high-quality, useful documents that stakeholders view as credible and legitimate, and that by leading the PIRCA, the Pacific RISA has had a traceable impact on planning and policy-making at state and federal levels.

Links to Other Projects.

- ***Responded directly to stakeholder needs identified in Phase II***: A 2013 evaluation of the first PIRCA and Pacific RISA's role leading regional contributions to NCA3 revealed the need for jurisdiction-specific and sector-specific information; external evaluation and information stakeholder input demonstrated the over-emphasis on Hawaii in previous regional assessments and the NCA.
- ***Strong link to the US National Climate Assessment***: The PIRCA workshops and assessment reports used NCA4 as a springboard, expanding upon the findings to create robust, jurisdiction-specific climate summaries. In turn, the PIRCA process involved new contributors in a regional network and will enable future NCAs to incorporate fine-grained, local information regarding climate risks, impacts, and adaptation solutions.
- ***Synthesizes research from other Pacific RISA projects***: The PIRCA drew on expertise from across the Pacific RISA team and synthesized findings that multiple RISA-affiliated researchers have produced.

National Climate Assessment

Core Objective. (IV) Integrate technical climate information and policy outcomes

NCA4 Volume II was released in November 2018. The Hawaiʻi and Pacific Islands regional chapter took over two years to complete, during which Pacific RISA, federal partners, and the US Global Climate Research Program (USGCRP) brought together the expertise of 11 authors and nearly 80 technical contributors from the region—representing more than 60 agencies, departments, and organizations. "*Chapter 27: Hawaiʻi and U.S.-Affiliated Pacific Islands*" offered an authoritative and inclusive examination of the risks and impacts of climate change and variability in the region. Since its publication, the chapter has been widely reported on and referenced in the region—arguably becoming the most trusted resource on the impacts of climate change in Hawaiʻi.

Figure 17. Former Honolulu Mayor Kirk Caldwell called a Press Conference at Honolulu Harbor in November 2018 with Climate Change Commission members Dr. Chip Fletcher (left) and Dr. Victoria Keener (right), and Chief Resilience Officer Josh Stanbro (second from left) after the release of NCA4 to discuss how findings from the report showed that the City needed to advance its policies surrounding climate change adaptation and sea level rise planning. (Source: City & County of Honolulu)

Accomplishments. Guided by Pacific RISA's Phase III Lead PI and with support from the SAS, a diverse team authored the regional chapter for NCA4. The chapter highlighted significant climate-related challenges for Pacific Islands, including strained freshwater supplies, damaged and compromised coastal infrastructure, coral reef decline and associated economic loss, and greater stresses on native biodiversity and species. Recognizing that NCA4 could not fulfill the needs for locally-relevant information in the USAPI, the Pacific RISA launched a process to develop climate science and impact summaries through the PIRCA (see above) that expand upon the findings of NCA4 and offer locally-relevant climate assessments.

Links to Other Projects.

- ***Responded directly to stakeholder needs identified in Phase II***: Both participatory processes to develop the regional chapter and its content addressed needs identified in external evaluation and stakeholder consultations completed in Phase II. These included the need for better USAPI representation, a focus on human-centric and decision-centric topics, and assessment of issues of concern for Indigenous people.
- ***Integrated and communicated findings and data from Objs. I, II, and III***: Several Pacific RISA-affiliated researchers were NCA4 authors, enabling the report to accurately convey findings of integrated research that increased confidence in consensus statements about future rainfall and filled knowledge gaps since NCA3.

PROGRAM ACCOMPLISHMENTS

Accomplishments

- Planning models and tools were developed to aid decision makers
- Over 25 new partnerships established
- Pacific RISA continued to be a trusted source for climate information in the region

Outreach & Awareness

- More than 100 publications
- Regional, national, county, and community-hosted events on climate change adaptation

Capacity Building Opportunities

- Over 30 capacity building workshops on climate resilience for various stakeholders
- 16 students and interns supported the research and outreach

Collective Outputs

Downscaling for the Hawaiian Islands, Guam, and American Sāmoa. Fine-resolution surface temperature and precipitation products over the Hawaiian Islands (dynamical and statistical), Guam (dynamical), and American Sāmoa (dynamical) were developed for modeling and future scenario planning. For the US territories, these are the only downscaled climate projections currently available to plan for future impacts, adaptations, and policies. Downscaled climate projections have been subsequently used in hydrological models to plan for future freshwater needs and have informed management and policy across all three jurisdictions.

Future Land Cover Scenarios for Maui Island. The future land cover scenarios and associated maps for Maui Island are used in a growing number of policy-relevant and research applications, increasing Pacific RISA's visibility and program trust in Hawaiʻi. The University of Hawaiʻi worked with Pacific RISA to develop a similar modeling approach in a high-use aquifer on the Island of Oʻahu and the team collaborated with the Honolulu BWS to conduct a scenario-based vulnerability assessment of the island's water infrastructure under anticipated climate change. The Hawaiʻi Commission on Water Resources Management also funded a similar scenario-based approach to predict future groundwater resources on all the main Hawaiian Islands in partnership with the USGS.

American Sāmoa Tools and Monitoring Infrastructure. Groundwater models have provided American Sāmoa water resource managers with alternate potential sources of freshwater to improve adaptive capacity under future climate conditions as well as a quantitative basis to engage with regulating authorities as they plan for a robust freshwater supply under a changing climate. The Pacific RISA team developed the first high-resolution water budget model for an entire high-basaltic island within the South Pacific Convergence Zone. This, in addition to application of the model to project future conditions under both climate change and land cover scenarios, made this project one of the more rigorous assessments of present and future water resource availability in the region to date.

Fourth US National Climate Assessment. The Pacific RISA, federal partners, and the USGCRP brought together the expertise of 11 authors and nearly 80 technical contributors from the region to produce "*Chapter 27: Hawaiʻi and U.S.-Affiliated Pacific Islands*" within NCA4 Volume II. The chapter provided an authoritative and inclusive examination of the risks and impacts of climate change and variability in the region. Since its publication, the chapter on Hawaiʻi and the USAPI has been widely reported on and referenced in the region.

Climate Change and Health. The Pacific RISA was invited to sit on the Hawaiʻi Climate Change and Health Working Group (HCCHWG), convened as a result of the Climate Change and Health Policy Action bill (HCR 108, SD1) passed in 2015 by the Hawaiʻi State Legislature. Along with the multi-agency working group, they co-authored a white paper outlining research priorities and gaps on climate and health that was submitted to the Hawaiʻi Department of Health. It included key findings and recommendations that were integrated into the Hawaiʻi Health Survey so that key variables could be tracked by the Department of Health. A major recommendation was that comprehensive and coordinated climate adaptation strategies were needed by Hawaiʻi's public health system and related services, engaging researchers, planners, and policymakers to support adaptation to changing environmental challenges and conditions.

El Niño and Pacific Island Fact Sheets. The strong El Niño event that occurred during 2015–2017 had significant impacts in Hawaiʻi and the Pacific Islands region, including extended drought conditions, enhanced risk of damaging tropical cyclones, increased risk of coral bleaching, and possible spread of vector borne disease and illness. Impacts varied by island, however, and in fall of 2015 the NOAA Hawaiʻi and Pacific Islands ENSO Tiger Team created seven fact sheets outlining physical impacts on various sectors and projected trends in relevant climate variables for Hawaiʻi, American Sāmoa, Guam, the CNMI, Palau, the FSM, and the RMI. Pacific RISA PIs worked closely with the Pacific ENSO Applications Climate Center (PEAC) and the University of Hawaiʻi to help raise awareness of the impacts of El Niño by answering common questions including: What is El Niño? What might the impacts be in your region?

What about impacts such as sea level rise, tropical cyclones, and rainfall? Fact sheets can be found on the Pacific RISA website.

Stakeholder Impacts

Regional

Pacific Islands Regional Climate Assessment. The PIRCA website and reports address the need for locally-specific information about how climate is changing, the risks and impacts in key sectors, and key research and information needed to support adaptation. Those leading climate resilience initiatives have used the PIRCA in a variety of policy, capacity-building, and management contexts. The Guam PIRCA report responded to the need for science-based guidance to inform new legislation in Guam. Inspired by an adaptation option presented in the PIRCA, one novel statute created the Tumon Bay Insurance Task Force, comprised of Guam Government representatives, to examine the prospect and evaluate the feasibility of parametric insurance for the beaches and coral reefs of Tumon Bay (*Guam Public Law 35-107*, 2020). Another new law established a task force to explore the possibility of establishing conservation regions to select Guam Government properties that overlay the Northern Guam Lens Aquifer to protect the island's main freshwater aquifer, considering future drought projections (*Public Law 35-141 2021*). The PIRCA informed updates to the CNMI's main resource management plan and was cited in funding proposals to support National Adaptation Plan development in Palau. In American Sāmoa, an Executive Order was released that established a territorial Climate Resilience Office to coordinate climate adaptation projects across departments and better access to federal funding. Local stakeholders and PIRCA technical contributors agreed that the PIRCA was a key document in informing the order (E.O. 010-2021).

Pacific Invasives Partnership. During Phase III the Pacific RISA was invited to join the Pacific Invasives Partnership (PIP) working group. The PIP is the umbrella regional coordinating body for agencies working on invasive species issues in more than one country of the Pacific, and promotes planning and assistance from international agencies to meet the invasive species management needs of Pacific countries and territories. With the involvement of the Pacific RISA, the PIP prepared policy recommendations around invasive species and climate change in the region. Ecosystem resilience and adaptation to climate change were highlighted as a key thematic framework for island and territorial officials to pursue, with examples from Hawaiʻi and Pacific Islands. A Pacific RISA literature summary of climate change and invasive species impacts, interactions, and future risks in Pacific Islands was also used to craft language within New Zealand's Pacific Reset strategy for Pacific Island engagement and to prepare a successful Green Climate Fund proposal submitted by SPREP for invasive species eradication work in Niue and Tonga. The literature summary further served as a springboard for the Hawaiʻi Climate Change and Invasive Species Working Group that formed in 2020 and is now the Pacific Regional Invasive Species and Climate Change (RISCC) management network.

The Micronesian Conference of Leaders. Pacific RISA was invited to join the East-West Center Pacific Islands Development Program (PIDP) in convening the Micronesian Conference of Leaders in 2019, during which Pacific Island leaders were brief on Pacific RISA's use-inspired research on climate change. This collaboration with PIDP is of note because PIDP is the sole US and northern hemisphere member of the Council of Regional Organizations of the Pacific (CROP) established by Pacific Island Forum Leaders in 1988 to improve cooperation, coordination, and collaboration among Pacific inter-governmental organizations.

National

Fourth National Climate Assessment. US Senators used NCA4 Chapter 27 to communicate with their constituents about risks to key things of value (e.g., economy, tourism, water) from climate change and variability. Senator Hirono (HI) met with Pacific RISA team members about the findings and needs identified in the chapter.

Climate Resilience Toolkit. The Climate Resilience Toolkit is a national website established under the Obama White House and headed by NOAA. The purpose of the Toolkit is to help stakeholders in different regions and sectors in the United States find climate information that is helpful for their adaptation and planning. Hawaiʻi and the Pacific Islands became one of the first regions featured on the site. Included in the content are five case studies adapted for the site by the Pacific RISA and NOAA collaborators, including "*Collaborating for Success: Sustaining Water Supply on a Pacific Island*", which examined the partnership between ASPA and the University of Hawaiʻi in American Sāmoa. It describes how this partnership helped ASPA implement an integrated approach to quantifying ground and surface water resources on the Island of Tutuila.

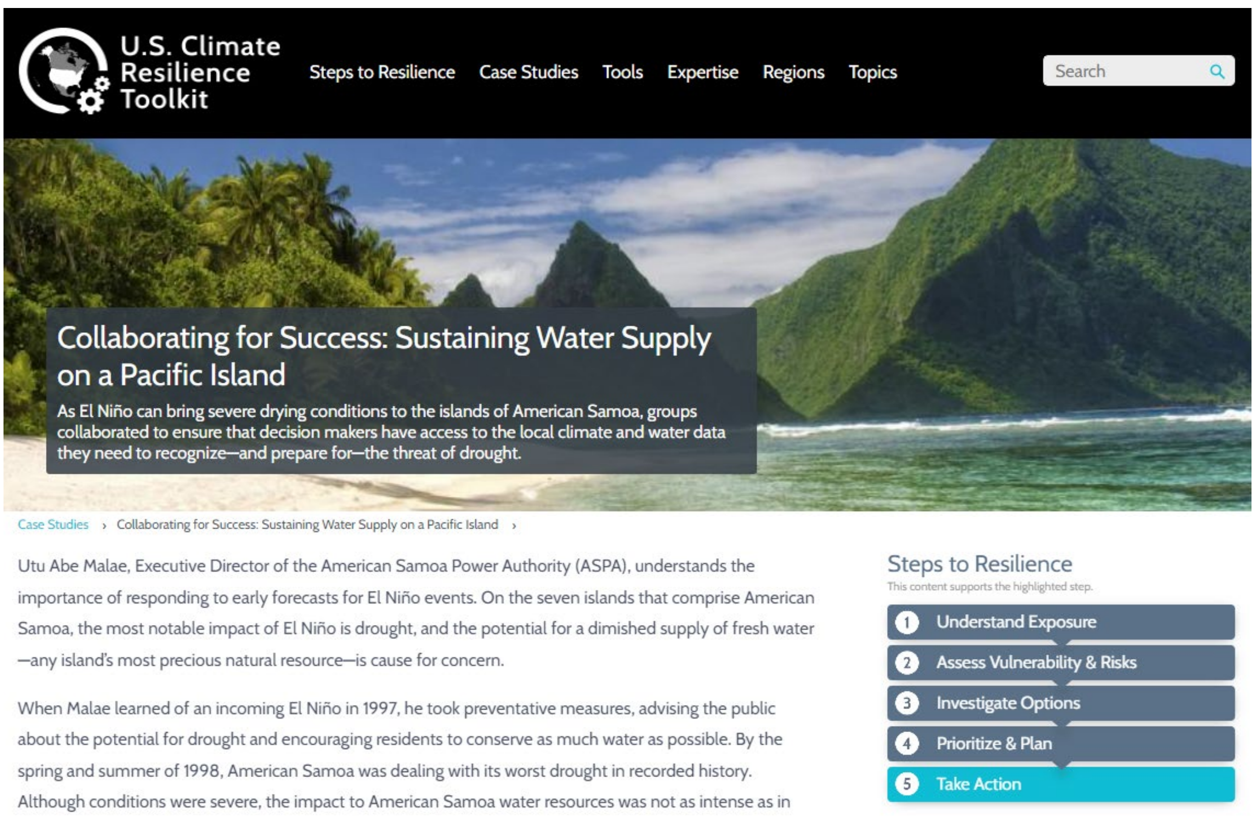

Figure 18. A screenshot from the Climate Resilience Toolkit Case Study by Pacific RISA for American Sāmoa. (Source: Climate Resilience Toolkit)

State/Territorial

Fourth National Climate Assessment. The former Mayor of Honolulu (Kirk Caldwell) used NCA findings for Hawaiʻi to justify policies, including updating energy and building codes, the potential for a Carbon Tax, and investments in infrastructure. The Honolulu Office of Climate Change, Sustainability, and Resilience used report figures to talk with members of the public about climate change impacts on the Island of Oʻahu.

Freshwater Resource Modeling in American Sāmoa. In 2008, the USGS removed its final stream gauging site in American Sāmoa, effectively terminating a decades-long hydrologic monitoring program. From 2008 to 2015, there was a hydrologic data gap, but in 2015 the Pacific RISA collaborated with ASPA to install four inexpensive weather stations. By leveraging spare money from existing grants for equipment, salary funding from Pacific RISA, and travel costs, the new ASPA-University of Hawaiʻi hydrologic monitoring network was created. Additional equipment funds from the ASEPA were leveraged to expand the network to eight stream gauges, seven weather stations, and several groundwater monitoring well instruments. ASPA has since dedicated a full-time hydrologic technician position to upkeep and maintenance of the network, and is hosting weather station data on the company website. By working collaboratively with ASPA, the Pacific RISA was able to produce publicly available hydrologic data at a fraction of the previous cost. This hydrologic data is not only being used by Pacific RISA researchers and ASPA, but has also been directly applied by other stakeholders such as the American Sāmoa Renewable Energy Committee who used weather station data to assess photovoltaic resource availability at sites across Tutuila, or by the ASEPA who used streamflow data to calculate nutrient loads for assessing how population and land use is affecting coral reefs.

Figure 19. Marine Sanctuaries staff being trained to take streamflow measurements in American Sāmoa. (Source: Chris Shuler)

Hawaiʻi State Climate Change Conferences. In 2019, the Pacific RISA organized and co-hosted the first Hawaiʻi State Climate Conference with the Hawaiʻi Department of Land and Natural Resources (DLNR) in partnership with the Ulupono Initiative. The meeting featured opening remarks by former Hawaiʻi Governor David Ige, and Susanne Case, the former Chair of DLNR. Panel discussions highlighted state climate initiatives and planned and possible adaptation and mitigation actions in three areas: (1) Hawaiʻi's emissions from the transportation sector; (2) How to accelerate adaptation to sea level rise; and (3) Innovations in financing and implementation of adaptation. The cross-cutting theme of the conference was equity in climate adaptation planning. The meeting was attended by over 350 people representing communities, academia, government, advocacy, industry, and students. Held just before the opening of the Hawaiʻi state legislative session, the conference gave legislators an opportunity to engage more meaningfully with ideas for climate adaptation measures. The success of the first conference has led to subsequent, annual Hawaiʻi State Climate Conference events, with the next event scheduled for January 2023.

Figure 20. Chair of the Hawaiʻi DLNR, Susanne Case, speaks to a packed audience at the first annual Hawaiʻi Climate Change Conference in 2019. (Source: East-West Center)

County

Maui County Land Cover Scenario Planning. The future land cover scenario maps for Maui have been distributed widely throughout county and state levels of governance and are being used in an increasing number of policy-relevant and research applications, including ecosystem services valuation for Maui, the West Maui Ridge to Reef initiative, and a project on Maui sustainability that was led by the PICCC. Furthermore, the outputs of the water-budget model and associated geospatial data layers clearly demonstrated the tradeoffs between urban development, watershed conservation, agricultural practices, and water resources under a changing climate.

Ecosystem Services Valuation. Decision-makers in Hawaiʻi have been very interested in the concept of economic valuation of traditionally non-monetary resources, and liked the approach that Pacific RISA used on Maui of using brown water days as a means of determining costs of climate impacts. The Pacific RISA estimated that the "welfare loss" of a relatively common two-week brown Maui represented an estimated loss of $678,000 for residents. They also examined the "welfare benefits" of reef restoration activities in economic terms, with potential gains estimated at upwards to $40 million/year. Stakeholders who attended informational sessions on these results found the information to be important for justifying efforts to manage watersheds, control erosion from new development, and other initiatives to reduce coastal pollution.

The City & County of Honolulu Commission on Climate Change. In 2016, the City and County of Honolulu Commission on Climate Change (HCCC) was established under the Revised Charter of the City and County of Honolulu. This same amendment also mandated the creation of the Office of Climate Change, Sustainability and Resiliency (OCCSR). The HCCC created a commission of five members appointed by the mayor to gather the latest science and information on climate change impacts to Hawaiʻi and provide advice and recommendations to the mayor, City Council, and executive departments as they look to draft policy and engage in planning for future climate scenarios. Lead PI

Keener was nominated and confirmed to the HCCC in January 2018 and served as Chair from 2020 to 2021. Documents written by the Commission include guidance on sea level rise planning, shoreline setbacks, a One Water framework, financial risk, social equity in adaptation, the social cost of carbon, and reducing greenhouse gas emissions from buildings. Guidance has directly informed city policies.

Figure 21. Members of the HCCC at the swearing-in ceremony at Honolulu City Hall, with Mayor Caldwell (center) and Chief Resilience Officer Josh Stanbro (far left) of the OCCSR (L). Clustering results of a "visioning" exercise coordinated by the Pacific RISA prior to the confirmation of HCCC members (R). (Sources: City & County of Honolulu (L), and Victoria Keener (R))

Program Evaluation

During Phase II, the Pacific RISA was the first RISA program to make evaluation a discrete objective, underscoring the importance of developing theory, methods, and metrics that could help the program understand and demonstrate how its research and outreach activities were or were not effective. An action-logic model (ALM) was developed reflecting the conceptualization of change. Pacific RISA's evaluation work in Phase III had two primary goals: (1) Assess the value of the Pacific RISA program as a regional leader supporting real-world decision makers with climate information and services that are unique yet coordinated with other regional programs; and (2) Support and adaptively improve ongoing climate information and services.

As a baseline product, Pacific RISA external evaluator Dr. Suzanne Moser analyzed and reported on advancements in the action-logic model and evaluation efforts for Phase II that reviewed 17 projects and 41 internal tracking sheets. Her report found that the Pacific RISA acted as a climate boundary organization of remarkable stability and productivity and was a well-managed program that effectively navigated staff turnover as well as funding delays and declines—accomplishing much with remarkably little. Although research clearly dominated Pacific RISA's work, almost all projects involved the wide range of stakeholders they were designed to serve. This deep engagement with stakeholders ensured that the Pacific RISA was seen as the trusted go-to information source in the region. Despite the heavy emphasis on science, typical scientific outputs—peer-reviewed publications—were not the dominant output. Instead, products for, and encounters with, stakeholders were by far the most prominent outputs of the organization. As such, Dr. Moser found that the Pacific RISA emerged as a model transdisciplinary program. The core team retained the most effective components of the evaluation process for Phase III and has continued to iterate and refine program functions.

This analysis led the team to attempt to better define the internal metric tracking process and refine a Pacific RISA Theory of Change (TOC) via a two-day workshop with PIs and collaborators. All PIs participated in an exercise to walk through research and outreach activities and identify their function, relevant outputs, and desired outcomes, while identifying what is needed to achieve such outputs (both internal and external factors), and finally think of how to measure and track indicators of success. The workshop enabled the Pacific RISA to cross-walk each section of the annual NOAA tracking sheet to determine which metrics are relevant and meaningful, and which ones may not be needed. Ultimately, the relationships that the Pacific RISA has in the region and the different strengths, services, and products they provide for different stakeholders, construct a narrative about the program's broader impact and outcomes, and how various partner organizations play substantial supporting roles in achieving those goals.

From workshop results and interviews with stakeholders and collaborators, Dr. Moser created a framework of the core functions of the Pacific RISA as it informed the TOC and the ways in which the program acts as a research collective and boundary organization. This included four main functions of being responsive, supportive, generative, or critical for stakeholders, made up of the co-production of technical research projects and products, policy analysis, trusted local and regional assessments, and convening at different spatial scales with diverse partners.

Stakeholder-identified functions of Pacific RISA as a climate boundary organization. (Source: Moser 2017)

	Stakeholder Need Known	**Stakeholder Need Unknown**
Policy/Management Solution Known and Adequate	Responsive: Helps stakeholders identify their goals and resource needs and then works to meet those needs	Supportive: Supports the advancement of policy and management solutions and the creation of political will
Policy/Management Solution Unknown or Inadequate	Generative: Opens the decision space to novel ideas and approaches in ways that generate new or different conversations	Critical: Advances policy and management debates by being a constructively critical, credible, outside voice on existing or missing approaches

A longitudinal evaluation of the PIRCA process was a project that encompassed all of these functions, and responded to a previous PIRCA evaluation (2012–2013) that showed Pacific RISA stakeholders wanted assessments to reflect more inclusively the needs and input of decision-makers from across the region. Between late 2021 and early 2022, evaluation was conducted to assess how the ongoing PIRCA process is evolving and responding to expressed stakeholder needs. The evaluation process involved data collection from two principal sources: a survey and interviews with assessment participants and beneficiaries. The majority of respondents were based in Hawaiʻi, but all jurisdictions for which the NCA4 regional chapter and PIRCA reports had been prepared were represented, as well as a few continental US respondents.

The interviews revealed types of impacts that exemplified how the core functions of the Pacific RISA program are perceived in a particular project. The PIRCA, for example, was perceived as:

- **A go-to information source**: Several interviewees pointed to the importance of information synthesis and compilation of disparate sources of data: "*The PIRCA helps people know what data exist—and that's super helpful*." "*It's simply nice to have a nice summary concentrated* *in one place*." As another put it, "*prior to the PIRCA, I was the Helpline… well, more like a Help Desk*." And, as an observer more distant to the process noted, "*Everyone seems to know about the PIRCA—not sure how this happened*."

- **Increased relevancy and local specificity**: "*The PIRCA [jurisdiction]-specific reports basically accomplish filling the gaps of NCA4, especially the sector-specific recommendations on adaptation*."
- **Greater ease of cross-jurisdictional collaboration**: "*The fact that multiple jurisdictions have similar reports makes it easier for them to work together, which helps address the capacity limits they all struggle with (e.g., CNMI and Guam)*."
- **Impetus for focused work group**: The PIRCA reports pointed to the need to look at invasive species, which motivated the formation of the Pacific Regional Invasive Species and Climate Change (RISCC) management network.
- **Support for funding applications**: Repeatedly, interviewees noted how the reports helped them apply for much needed funding. "*There are lots of impacts here already being observed. But you can't get a grant just because you see something. It helps to have a report that documents it. … We have pockets of information, but nothing as comprehensive as this*." Or, as another stated, "*The big thing is to channel money into these places. You need to have a solid evidence base. These days, you need to link to the climate issue, not just a vanilla development issue. The PIRCA is crucial for that*."
- **Support for and linkage to the global sustainability agenda**: Several interviewees also made connections to broader global policy agendas, which also link the Pacific Islands to potential funding sources, especially related to the SDGs. "*The PIRCA can feed into Goal 13*" (which is focused on climate action, i.e., "*Take urgent action to combat climate change and its impacts*"). "*It helps build island-level capacity to do this sort of thing*." Reiterated by another interviewee, who said, "*On SDG Goal 13—PIRCA is a keystone reference document for that*."

Phase III internal and external programmatic and project-level evaluation has continued to refine the functions, impact, and breadth of the Pacific RISA program and its evolution into a mature boundary organization that is a trusted source of climate research and policy analysis in the Pacific Islands region.

Summary

The interdisciplinary and decision-relevant scope of research projects in Phase III of the Pacific RISA program demonstrate the reach of climate-relevant management outcomes, policies, decision-tools, and collaborations at local and regional scales in the Pacific Islands. While Phase II outcomes were primarily on short- and middle-term timescales, the continued evolution of the program throughout Phase III showed long-term impacts in local and regional policy outcomes, shifts in thinking about climate adaptation, and significant growth in collaborative networks.

APPENDIX 1. Publications

2022

Coffman, M. & Schjervheim, M. (2022). Climate change adaptation across the Pacific: A landscape assessment for curriculum development. University of Hawai'i at Mānoa Institute for Sustainability and Resilience, Honolulu, HI.

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Krzesni, D. & Brewington, L. (2022). Climate Change, Health, and Migration in the Marshall Islands: Profiles of Resilience and Vulnerability. East-West Center, Honolulu, HI, 70 pp. Available from: https://www.eastwestcenter.org/publications/climate-change-health-and-migration-profiles-resilience-and-vulnerability-in-the

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Moser, S.C. (2022). Impacts of the second PIRCA & NCA4's Pacific Islands Chapter: Evaluation of the Pacific RISA's efforts in guiding a sustained regional assessment process. Susanne Moser Research & Consulting, Hadley, MA.

Oji, R., Hesam, M. & Keener, V.W. (2022). Using social network analysis to assess climate change professionals’ communications in Iran. *Weather, Climate, and Society* 14(1), 349-363. https://doi.org/10.1175/WCAS-D-21-0002.1

Okuhata, B.K. (2022). Assessment of Groundwater Age and Transport in West Hawai‘i Aquifers. PhD Dissertation. University of Hawai’i at Mānoa, Honolulu, HI, 126 pp. Available from: https://scholarspace.manoa.hawaii.edu/items/160bb6c3-1542-4609-b5ea-9ab0fbc5e2d0

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APPENDIX 2. Partnerships

Links with Other NOAA Programs

Organization/Agency/Division	Description
NOAA Regional Climate Services Director	The Pacific RISA worked closely with NOAA RCSD John Marra to develop the Pacific Islands Climate Change Forum (PICCF) and the related writing and launch of the Pacific Climate Change Monitor (PCCM) Report. The PCCM and PICCF have been developed in collaboration with the Secretariat of the Pacific Regional Environment Programme (SPREP) and the World Meteorological Organization (WMO), with technical support provided by the Australian Bureau of Meteorology (BOM), National Institute of Water and Atmospheric Research (NIWA), APEC Climate Centre (APCC), Meteo- France, US National Oceanic and Atmospheric Administration (NOAA), Pacific Community (SPC) and the University of Hawaiʻi in partnership with the Pacific Islands Climate Services (PICS) Panel, representing the Pacific Islands Meteorological offices.
NOAA Pacific Islands Regional Team (PIRT)	Over the Phase III years, the PIRT has been variably active depending on the presence of a NOAA Coordinator. The PIRT is an effort to coordinate NOAA offices and projects across the region, including NWS, NESDIS, NMFS, NOS, and core partners such as Hawaiʻi Sea Grant and Pacific RISA.
NOAA Education and Outreach Specialist, Inouye Regional Center	The Pacific RISA collaborated with Education and Outreach Specialist, Leon Geschwind, to translate project outcomes and PIRCA findings for K-12 teacher trainings on climate science in Hawaiʻi, American Sāmoa, CNMI, and Guam.
NOAA Hawaiʻi Sea Grant	The Pacific RISA coordinates with the Hawaiʻi Sea Grant program on events and projects, served on Advisory Committees for Sea Grant staff, and collaborated closely with extension agents in American Sāmoa, Hawaiʻi, and RMI. This collaboration has included co-authorship and in-county workshop coordination.
National Marine Sanctuary of American Sāmoa	Lead PI Keener collaborates with the Sanctuary on climate impacts planning and locally relevant projections via her appointment to the American Sāmoa Climate Change Working Group.

Non-NOAA Partnerships

Organization/Agency/Division	Description
US Global Change Research Program	The Pacific RISA led authorship of the NCA4 Hawaiʻi and Pacific Islands regional chapter, which brought together federal partners, regional experts, and the USGCRP. Since its publication, the chapter has been widely reported on and referenced in the region.
American Sāmoa Power Authority	The Pacific RISA continue a long-standing partnership with ASPA. In partnership, they have developed a new level of institutional collaboration, hiring the first joint hydrologic technician physically based at ASPA and funded 50% by the University of Hawaiʻi Water Resources Research Center and 50% by ASPA.
Honolulu Climate Change Commission	Lead PI Keener served as an appointed Commissioner to the Honolulu Climate Change Commission, informing the Mayor and City Council and Departments about local climate impacts and policy relevant to both adaptation and mitigation planning.
US Department of Defense/INDOPACOM	The Pacific RISA worked in collaboration with the USGS-Pacific Water Science Center, the University of Hawaiʻi, and the University of Guam to investigate the impact of projected changes in Guam's climate on surface and groundwater

	resources, and the potential effects on DoD installations and the civilian Guam Waterworks Authority (GWA) ability to supply the island's population with freshwater. Lead PI Keener is appointed to the DoD INDOPACOM Climate Impacts Working Group which advises leadership on regional climate- related environmental security impacts.
County of Maui	With the USGS, the Pacific RISA developed future land cover maps that have been used in many applications, including a water-budget modeling framework showing predicted future groundwater resources under multiple climate change scenarios on Maui.
City and County of Honolulu Board of Water Supply	The Honolulu Board of Water Supply (BWS) partnered with the Pacific RISA, the University of Hawai'i, and Brown & Caldwell consultants to assess projected climate change impacts on their infrastructure and identify vulnerabilities over the next 20 to 70 years using a scenario planning approach to consider a range of plausible future climate and socioeconomic conditions.
Pacific Invasives Partnership	The Pacific RISA joined the Pacific Invasives Partnership (PIP) working group, the regional coordinating body for agencies working on invasive species issues in more than one country of the Pacific. Other PIP members include the Pacific Community (SPC), SPREP, CSIRO, Island Conservation, The Nature Conservancy, and the University of the South Pacific.
Pacific Islands Climate Adaptation Science Center	The Pacific RISA has worked closely with the PICASC on regional climate downscaling and modeler workshops, the Hawai'i and Pacific Islands chapter of the Fourth and Fifth (in-progress) US-National Climate Assessments, and the PIRCA reports.
USGS Pacific Islands Water Science Center	Pacific RISA partnered with the USGS Pacific Islands Water Science Center on groundwater recharge modeling under future climate projections in the County of Maui and Territory of Guam.
American Sāmoa Climate Change Working Group	Lead PI Keener is appointed to the American Sāmoa Climate Change Working Group, an interdepartmental group of managers at the Territorial and Federal scale that synthesize and plan for climate impacts in different local sectors.

Pacific Islands Regional Climate Assessment

Through the PIRCA coordination and sustained assessment process, the Pacific RISA has partnered with many federal agencies, state and local governments, non-governmental/non-profit organizations, universities and research institutes, as well as community-based organizations:

- CNMI PIRCA: Authors from the CNMI Office of Planning and Development, the NOAA Office for Coastal Management, and the East-West Center—along with 50 technical contributors from local governments, NGOs, researchers, and community groups.
- American Sāmoa PIRCA: Authors from American Sāmoa Community College, University of Hawai'i, and the East-West Center—along with 25 technical contributors from local governments, NGOs, researchers, and community groups.
- Palau PIRCA: Authors from the Republic of Palau's Office of Climate Change, the Coral Reef Research Foundation, the Palau International Coral Reef Center, and the East-West Center—along with 30 technical contributors from government and nongovernmental organizations, research, and community groups.
- Guam PIRCA: Authors from the East-West Center, University of Guam, and 38 technical contributors from government and nongovernmental organizations, research, and community groups.