

# Projecting Climate Change in Hawai'i



Image courtesy of Ben Isabel.

By **Kevin Hamilton**

**H**uman effects on the global climate system, principally through altering the atmospheric concentrations of carbon dioxide and other greenhouse gases, are expected to lead to significant warming and other associated changes in the climate worldwide. Human-induced climate changes are likely already observable in the global mean temperature and, over the next century, can be expected to significantly disrupt the varied habitats and environments in Hawai'i.

Isolated islands such as those of the Hawaiian archipelago are especially vulnerable. The unique landscape of plants and wildlife in Hawai'i is already under stress as native species compete with recently introduced invasive species. While the state of Hawai'i has only 0.2% of the land mass of the USA, fully 25% of the species on the US government's official endangered list are found only in Hawai'i. Climate change in Hawai'i will threaten habitats and perturb island ecosystems, not only on land, but also along the coastline and in the surrounding ocean. The latter will be further stressed by ocean acidification.

The systems that directly support the human population—including those producing the state's energy and food supply—are particularly vulnerable to disruption due to Hawai'i's isolated location, especially if patterns of extreme weather events change. As on all isolated islands, the continued supply of fresh water is an ever-present concern in

Hawai'i. Given the prohibitive cost of alternative fresh water sources (importation or desalination), each island in Hawai'i must rely on its own rainfall to supply the fresh water needs of a modern economy. On O'ahu nearly 1 million inhabitants and visitors must rely on watersheds that total only 1550 km<sup>2</sup> in area. Finally, many aspects of the unique indigenous culture in Hawai'i could be further stressed by significant changes in the local environment.

Climate change is a prominent concern among the general public in Hawai'i and also has received significant official attention. The state wishes to be a leader in conservation, clean energy and climate adaptation, and the legislature has passed a number of relevant laws in recent years (see box).

*Climate changes will likely impose major, but not fully understood, costs and other impacts on Hawai'i's people and the natural capital we depend upon to support our lives in the middle of the Pacific Ocean. Nowhere is it more obvious than in remote island chains like Hawai'i that our lives and the economy are intertwined with the health and function of the natural world around us.... Now is the time.... to plan for the inevitable effects of climate change.*

– Preamble to Act 73 of the Hawai'i Legislature (2010)

Until recently, the intense public and official interest in climate change in Hawai'i perhaps was not matched by the activity of the climate research community. The physical science working group contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) in 2007 included only a single paragraph discussing the special issues for small Pacific islands. Last year's Fifth IPCC Assessment Report is more generous, with ten paragraphs devoted to Pacific islands, mainly discussing projected shifts in regional rainfall patterns, but not touching on the small-scale variations that may occur within individual islands.

Over the last few years, however, the effort in the science community devoted to Hawai'i climate change has intensified. One driving force behind this increasing activity has been the local implementation of US Federal Government initiatives on regional climate research. The US Department of Interior (DOI) has recently created regional partnerships with academic institutions as part of a strategy to consider the effects of climate variation

and change in its mission to protect the nation's natural and cultural resources. Eight regional DOI Climate Science Centers were created across the nation. Hawai'i and the US affiliated Pacific islands are served by the Pacific Islands Climate Science Center (PICSC) established in 2011 as a partnership between the United States Geological Survey (USGS) and a consortium of academic institutions led by the University of Hawai'i (UH).

The US Department of Commerce through its National Oceanic and Atmospheric Administration (NOAA) has established a Regional Integrated Sciences & Assessments (RISA) program that supports regional research teams contributing to the capacity of communities to prepare for climate variability and change. In 2010, NOAA approved a joint proposal between UH and the East-West Center that has led to the creation of the RISA-funded Climate Adaptation Partnership for the Pacific (CAPP) focused on climate change and fresh water resources in Hawai'i and the insular Pacific.

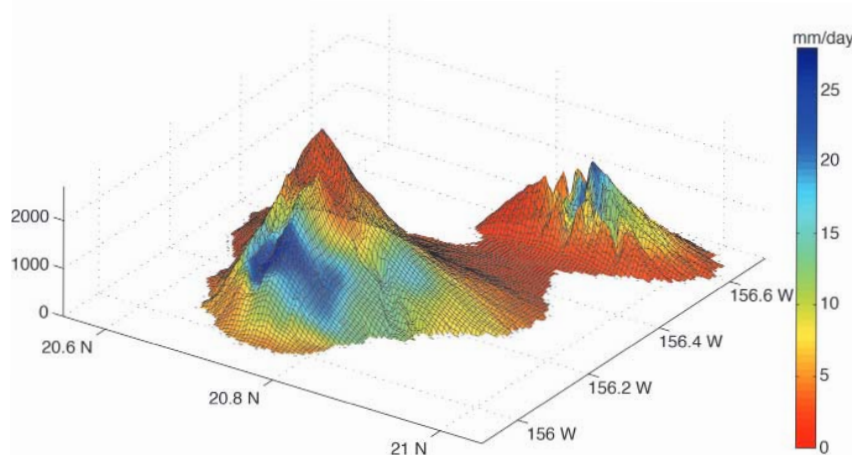
IPRC has been deeply involved in both PICSC and CAPP. I serve as the inaugural University Director of the

PICSC as well as IPRC Director here at UH, and I serve as one of five co-PIs in CAPP.

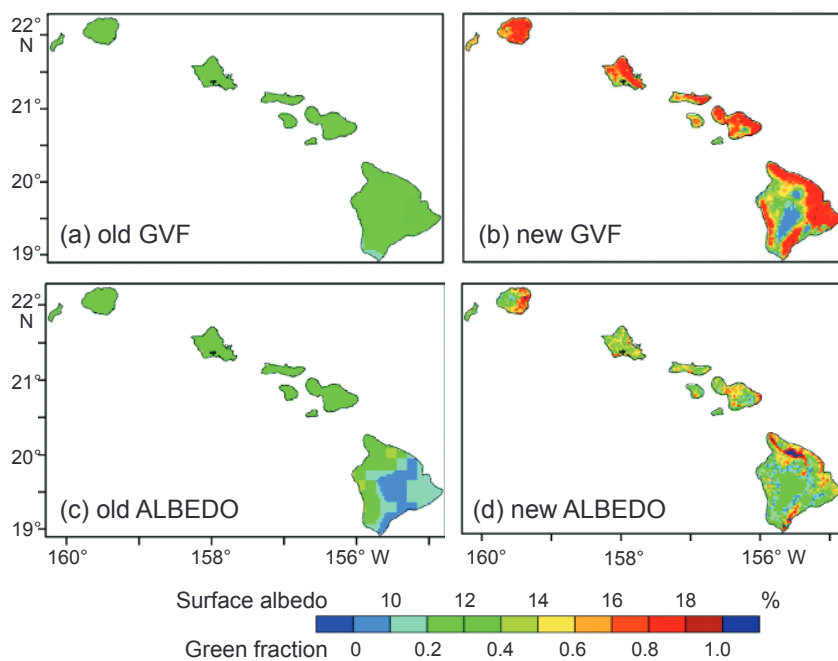
The new efforts on climate change research for Hawai'i and the broader insular Pacific are driven by the concerns of a variety of stakeholders and involve contributions from ecologists and social scientists as well as physical climate scientists. IPRC is the region's leader in climate modeling and diagnostics and has stepped up to spearhead the physical climate projections needed as part of this broader focus. Here I will review IPRC's continuing work on island-scale climate change projections and briefly describe some of the efforts of our partners who will use our projections as input to their own assessment of various impacts of long-term climate trends in Hawai'i.

### Island-scale Atmospheric Simulation

The currently available climate change projections from global coupled atmosphere/ocean models, as summarized for example in the recent IPCC assessment reports, have very limited direct application to Hawai'i or other Pacific islands. Such model projections have been performed with atmospheric models with effective horizontal grid-spacing typically ~100 km or more. State-of-the-art global models may represent all the Hawaiian Islands as just a handful of land grid-boxes or even ignore the presence of the Hawaiian landmasses entirely! Without a representation of the high and steep topographic relief characteristic of Hawai'i, such models cannot simulate even basic features of the winds, temperature and rainfall over the Hawaiian Islands.



**Figure 1.** Observed annual mean rainfall rate (mm/day) during 1990–2009 on Maui.



**Figure 2.** Comparison of green-vegetation fraction in the land cover of the Hawaiian Islands as represented in the standard WRF model (a) and in IPRC’s modified version (b). Same comparison for surface albedo in the original WRF (c) and in the modified WRF version (d).

An example of the topographic control of climate in Hawai‘i and the remarkably large horizontal gradients in climate elements is displayed in Figure 1. This very high-resolution representation of the topography of the island of Maui shows the observed 20-year mean rainfall for 1990–2009 in colored shading. East Maui is dominated by Haleakalā volcano (peak elevation 3055 m), and the rainfall is concentrated on the slopes facing the prevailing northwest surface trade winds. The summit is generally quite dry since it is well above the usual trade wind inversion. West Maui is dominated by the much eroded volcano known as Mauna Kahalawai (peak elevation 1,764 m), and in this area the highest mean rainfall rates are near the summits, which are often in the trade wind cloud layer. The rainfall rates plotted in Figure 1,

interpolated from a large number of individual rain gauges, are similar to results shown by Giambelluca et al. (2013) in their more sophisticated spatial analysis of 30 years of station data.

For the last few years IPRC’s regional climate modeling experts, led by faculty member **Yuqing Wang**, have been working on ultra-fine resolution climate projections for Hawai‘i including the anticipated greenhouse gas climate forcing through the remainder of the 21<sup>st</sup> century. The modeling group has included two of IPRC’s more junior researchers **Chunxi Zhang** and **Axel Lauer** (now at the Institute for Advanced Sustainability Studies in Germany) as well as myself.

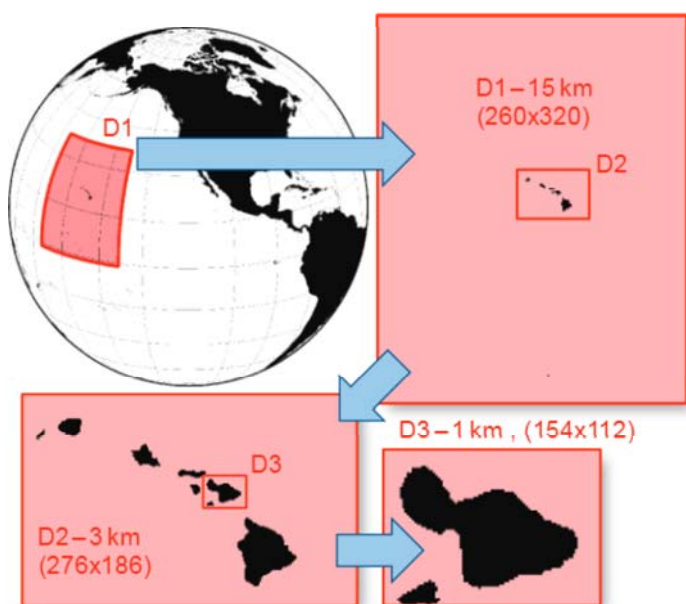
The main effort has been on developing a triply nested version of the community Weather Research and Forecasting (WRF) model and apply-

ing it to extended simulations of the climate around Hawai‘i. The WRF model was chosen as the basis for our work due to its community support and its well-developed capacity to handle nonhydrostatic equations and multiply nested grids. Nevertheless the standard “off-the-shelf” community WRF model required several modifications to the convection and cloud physics parameterizations as well as more accurate specification of surface properties. We call our WRF version the “Hawai‘i Regional Climate Model” (HRCM). Figure 2 shows examples of the changes in surface characteristics introduced into the WRF to derive HRCM. Details on the basis for these and other surface specification modifications in HRCM are presented in Zhang et al. (2012). Given the relatively small area of the islands, the land surface characteristics were not expected to have a large effect on climate simulations, but Zhang et al. (2012) show that the more realistic surface characteristics in HRCM do improve slightly the simulated diurnal temperature ranges and surface wind speeds.

The model initial and lateral boundary conditions for the atmosphere in the “present day” climate simulation were obtained from standard atmospheric reanalysis products.







**Figure 3.** The configuration of the nested grids for the study with the Hawai'i Regional Climate model focused on Maui.

The sea surface temperature (SST) specified in the HRCM runs was updated daily using NOAA global observational analysis. In addition, a diurnal SST variation was included based on the surface energy budget. Figure 3 displays the domain and grid structure for a triply nested version with the inner grid covering Maui and the immediately adjacent ocean. The outer, middle and inner domains have grid spacing of 15, 3 and 1 km, respectively.

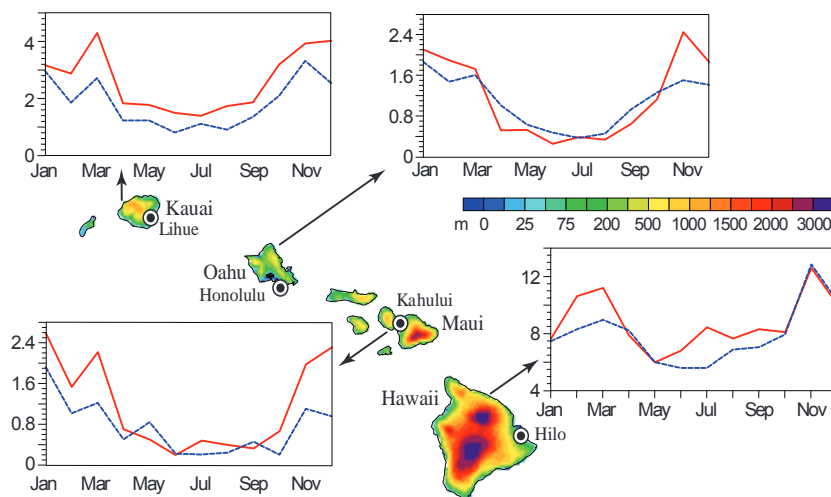
Zhang et al. (2012) discuss the formulation of HRCM and examine one year (November 2005 to October 2006) of retrospective simulation in a doubly nested version with finest horizontal resolution of 3 km. Since then our group has completed 20 years (1990–2009) of retrospective simulation (1990–2009) and a 20-year simulation driven with projected future conditions at the end of the current century (2081–2099). These new model integrations used a version of HRCM that included the 1-km grid over Maui.

Here I will present just a preliminary sampling of the results, focusing on the long-term means.

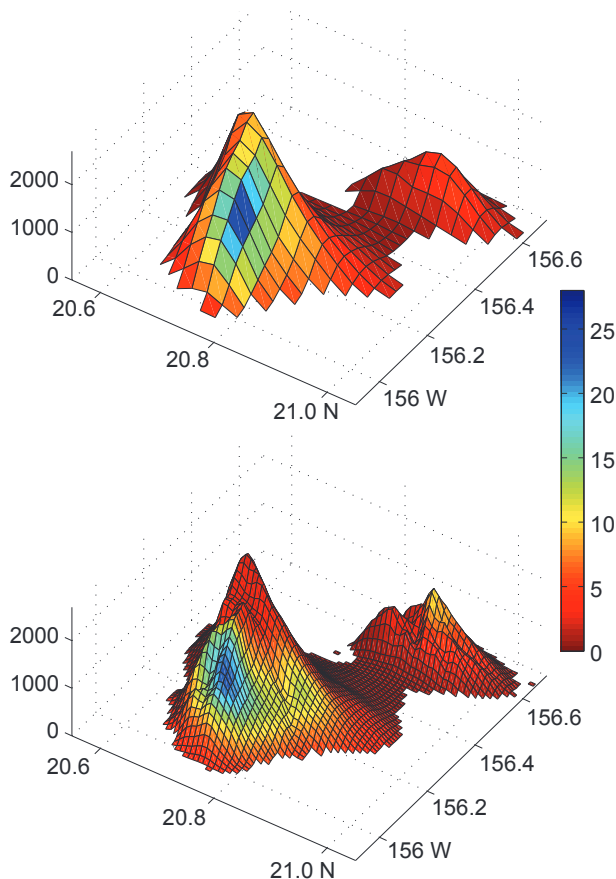
The present-day simulations have been compared with a large variety of observations. The most complete surface station observations are at the aviation weather (METAR) stations at Lihue (Kaua'i), Honolulu (O'ahu),

Kahului (Maui), and Hilo (Hawai'i Island) Airports. Figure 4 shows the 1990–2009 mean rainfall at these stations for each month of the year compared with the HRCM simulation results at the nearest grid point. The model captures the basic features of the annual cycle of rainfall, temperature and surface wind (not shown). The HRCM realistically simulates the range of variability of the observed trade wind inversion base heights, with a large majority of days having inversion heights between about 1.2 and 2.5 km, with the most frequently occurring heights around 1700–2000 m. The model simulation can be compared in detail with observed data from twice daily balloon soundings at both Lihue and Hilo, and at both stations, the model displays an overall low bias of about 200 m in the inversion height.

Simulating the geographical rainfall distribution over the individual islands is a particular challenge for a comprehensive model. The overall pattern of wet windward slopes and relatively dry leeward areas on each major



**Figure 4.** The long-term mean rainfall rate (mm/day) for each month of the year at the four major Hawai'i aviation weather sites. Red curves represent observations, blue the HRCM simulation. The topography of the islands is also shown.



**Figure 5.** Top: the topography and the 20-year mean rainfall rate (mm/day) over Maui in the 3-km grid doubly nested version of the HRCM. Bottom: in the 1-km triply nested version.

island is captured by the model (not shown) and the spatial correlation coefficient between observed and simulated mean rainfall rate computed on a 3-km grid over all land areas in the state exceeds 0.8. However when examined in detail, some significant problems in the mean rainfall simulation are apparent, particularly on Maui and O‘ahu, the islands with the steepest topographic slopes.

For Maui we can see the improvement when the model grid spacing is reduced to 1 km. Figure 5 compares the 1990–2009 mean rainfall over Maui simulated on the 3-km grid in the doubly nested HRCM (top) with the results from the 1-km grid in the triply nested HRCM (bottom). The topography used in each version is represented and the grid lines show the horizontal resolution of the model. With the summit of Haleakalā noticeably smoothed out, the topography at 3-km resolution is much blander than the actual topography (compare Figure 1). This leads to a simula-

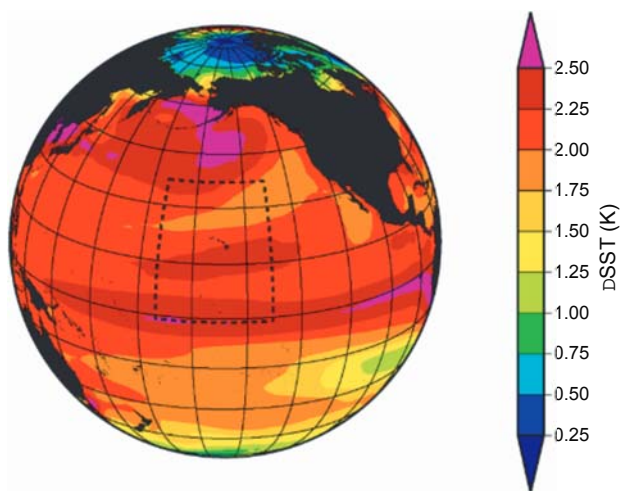
tion with too much rainfall in the highlands of East Maui. With the more realistic topography at 1-km resolution, the rainfall simulation improves dramatically, with the dry uplands on Haleakalā now well represented. Other biases improve as well, notably the peak rainfall on the highlands of West Maui increases along with the topographic height of the summit there.

The good news is that we are able to get a reasonable simulation of the detailed patterns of rainfall gradients, but, at least for Maui, this apparently requires at least a 1-km horizontal resolution. O‘ahu has two very narrow mountain chains and we expect even finer resolution may be needed there. We have begun a HRCM integration with an inner grid over O‘ahu with 800-m horizontal resolution. Although Hawai‘i Island features the state’s two tallest mountains, the typical topographic slopes there are significantly smaller than on Maui or O‘ahu and the rainfall simulation at 3-km resolution appears to be reasonably good.

The HRCM is able to simulate successfully even some fairly subtle aspects of the hydrological cycle. For example, we have compared the HRCM simulation of the diurnal rainfall cycle in Hawai‘i with observations at 173 rain gauge stations that have hourly data (not shown). On each island the HRCM simulation reproduces the dominant pattern in the observations reasonably well. Notably in both observations and model, the mean rainfall rate tends to peak in the early morning on the windward sides and in the afternoon on the leeward sides.

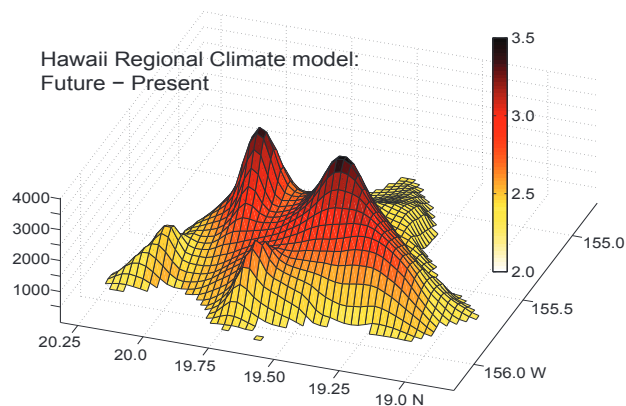
## Island-scale Climate Change Projections

We have completed a 20-year climate change projection experiment appropriate for late 21<sup>st</sup> century conditions using the triply nested version of HRCM with the inner grid over Maui. The SSTs and lateral boundary conditions for this experiment have been based on multimodel means of the CMIP3 global coupled models using the SRESA1B scenario for the 21<sup>st</sup> century. Lauer et al. (2013) discuss the details of the “pseudo-global warming” method we employed and show results of some calculations that support using a multimodel mean of global coupled model results to force a regional model such as HRCM. The annual mean of the ocean surface warming imposed in the late 21<sup>st</sup> HRCM projections is shown in Figure 6 (see next page).



**Figure 6.** The ocean surface warming in the late 21<sup>st</sup> century simulation with HRCM.

The model projected annual mean surface air temperature increase (average of 2180–2099 minus 1990–2009) is shown in Figure 7 for Hawai‘i Island. The view is from the southwest and the two summits are Mauna Loa in the foreground and Mauna Kea in the rear. Near the coast the air temperature increase reflects the imposed surface warming (based on the global model results) of the adjacent ocean. In the interior of the island, a clear pattern of intensified mean warming with topographic height is evident. This is seen in the warming projection for the other islands as well (not shown). It is interesting that the historical surface air tem-



**Figure 7.** The change in annual mean surface air temperature in the late 21<sup>st</sup> century HRCM simulation relative to the 1990–2009 simulation (C). Plotted for the Hawai‘i Island topography as represented at 3-km resolution in the HRCM.

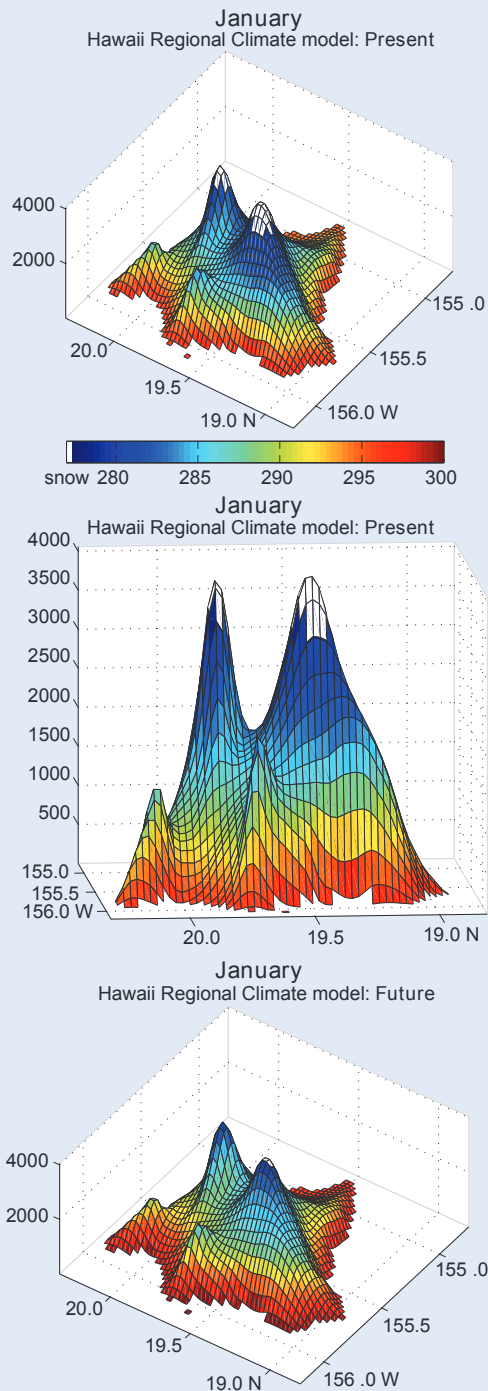
perature rise observed at Hawai‘i stations over the last few decades has also been found to be intensified at higher altitudes (Giambelluca et al., 2008). The mean warming over 90 years at the summits of Mauna Loa and Mauna Kea is predicted to be close to 3.5°C, equivalent to an upward displacement of the temperature climatology by about 500 m along the mountain. We find that one consequence of the very substantial warming will be the almost complete disappearance of snow from the summits of the mountains on Hawai‘i Island (see box).

We have also begun to analyze the projected changes in long-term mean rainfall (not shown). The overall pattern is for more rainfall on the windward sides of the islands and less rainfall on the leeward sides. The change in annual mean rainfall in the model projections can be roughly characterized as “wet areas get wetter” and “dry areas get drier.” Similar results are apparent in the 1-km simulation over Maui, with enhanced rainfall over the northeast-facing slopes of East Maui and over the highlands of West Maui, but less rainfall in the rain shadow of East Maui (not shown).

The regions where the rainfall is projected to increase are dominated by topographically forced rain during trade wind conditions. The increased rainfall in these regions may, to first order, be a response to increased atmospheric boundary layer moisture in the warmer climate. The normally dry areas in Hawai‘i generally depend on convective events for their rainfall, and in our model convection is suppressed (on average) in the warmer climate. The fraction of days with a clearly defined trade wind inversion is projected to rise from about 80% in present day to roughly 90% at the end of the century. The projected rise in the fraction of days with trade wind inversions represents a large decrease in the fraction of days during which significant convective rain events have the possibility of forming. Our model results suggest that the increased average stability of the atmosphere under global warming conditions leads to less convective rain, and hence more drying of the already arid rain shadow areas of the islands. Note that increased potential evapotranspiration caused by the higher air temperatures is also projected for almost all areas in Hawai‘i (not shown), exacerbating the drying trend predicted for the rain-shadow regions.



# The End of Hawai'i's White Mountains?



The 20-year January mean surface air temperature and snowfall climatology from the HRCM simulations. The white areas are those that receive at least two inches of snowfall over the month on average. Top: present day looking northeastward; middle: looking eastward; bottom: late 21<sup>st</sup> century.

Lucky visitors to Hawai'i Island in winter time may enjoy the lovely sight of the snow covered peaks of Hawai'i's two tallest mountains: Mauna Loa (4169 m) in the south and Mauna Kea (4207 m) in the north. Mauna Kea, which means "white mountain" in Hawaiian, is believed to be the home of **Poli'ahu**, the Hawaiian deity of snow. Though the summits of these mountains are mostly clear and the clouds keep below an inversion layer around 1500–2500-m height, the typical weather pattern usually breaks down several times each winter, and convective storms blanket the summits in snow. There is little systematic monitoring of snowfall, unfortunately, but large snowstorms can cover the mountains down to about 3500 m.

The figures at left show results of the Hawai'i Regional Climate Model simulations for "present day" (1990–2009) and the late 21<sup>st</sup> century. The white coloring denotes areas where the 20-year mean snowfall for January is greater than 5 cm (5 mm liquid water equivalent). The model results suggest that by the end of the present century the significant snow cover of the mountains on Hawai'i Island may disappear.



Satellite image of Hawai'i Island on February 28, 2002, showing snowcaps on Mauna Kea and Mauna Loa.



Photo of snow-capped Mauna Kea taken off the east coast of Hawai'i Island. Credit Ben Isabel, Hawai'i Island resident.

## What Will Be the Practical Impacts?

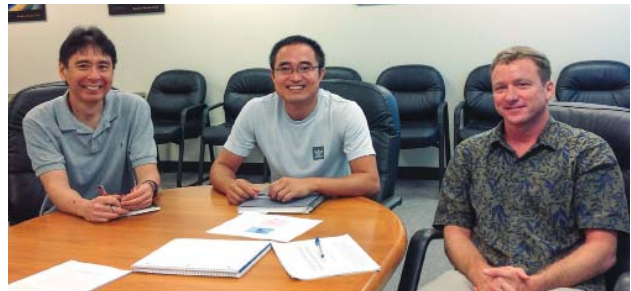
The climate changes expected by century's end in Hawai'i will not have a great direct impact on human comfort or human health, as we expect Hawai'i to still enjoy an exceptionally moderate and pleasant climate (at least in the areas with substantial population). However, climate change will significantly impact the islands through its effects on both the natural and manmade environment. Our IPRC group is now at the center of a busy network of researchers (some based in Hawai'i and some elsewhere) who are using their expertise to study the impacts of our projected climate changes. We have interacted so far with at least 8 research groups who have begun to use our data or have concrete plans to do so. The issues being investigated are those of obvious interest to Hawai'i residents, including fresh water availability, geographical distributions of naturally occurring plant species, carbon storage in the biosphere, agricultural practices, and the viability of native bird species. I will very briefly introduce three of these studies below. In all cases the analyses by our partners are still ongoing and we anticipate they will present their results in future publications.

### Fresh Water on Maui

The focus on Maui for our first triply nested simulations was motivated by our participation in a major effort to inform stakeholders on Maui about the implications of climate change for fresh water sustainability. This project is coordinated by the CAPP: researchers at the East-West Center (EWC) are leading the outreach to stakeholders and assessing their concerns. Colleagues at UH's Water Resources Research Center (WRRC) and the USGS Pacific Islands Water Science Center (PIWSC) are modeling the groundwater response to prospective climate changes. Of the main islands, Maui likely presents the most complicated and contested water-use situation, with huge demands from agricultural users, a legacy of extensive water tunnel and aquaduct infrastructure, and a fragmented pattern of ownership and governance (only a small fraction of Maui's water resources are under public control although a larger fraction actually originates as rainfall on public lands).

The CAPP project focuses on the 'Iao Waihe'e watershed in central and west Maui, where CAPP researchers have started to hold meetings with stakeholders to discuss the project's purpose and methods. Over 50 representatives of

various Maui water management groups have already made suggestions on how to assess groundwater availability under a changing climate and how to change water management practices accordingly. The basic information the modelers at IPRC have generated on projected climate changes is being used in the IPRC/WWRC/PIWSC/EWC partnership to provide guidance to the large group of stakeholders whose decisions will affect the sustainability of fresh water on Maui.



PIWSC scientists Delwyn Oki (left) and Alan Mair (right) discuss the use of IPRC's climate projections with IPRC's Chunxi Zhang (center).

### Avian Malaria and Hawaiian Forest Birds

The Hawaiian honeycreeper family (*Drepanididae*) includes 19 extant and at least 10 extinct species. These small colorful birds are all endemic to Hawai'i although they are similar to various finch species in other places. Quoting the classic study of Benning et al. (2002): "[the honeycreepers] represent a dramatic example of anthropogenic extinction. Crop and pasture land has replaced their forest habitat, and human introductions of predators and diseases, particularly of mosquitoes and avian malaria, has eliminated them from the remaining low- and mid-elevation forests. ... anthropogenic climate change is likely to combine with past land-use changes and biological invasions to drive several of the remaining species to extinction..."

The effect of avian malaria on native bird populations is particularly serious and is closely coupled to climate change. **Joy Liao**, postdoctoral researcher at the University of Wisconsin, and **Michael Samuel**, a scientist at the USGS National Wildlife Health Center in Wisconsin, are using IPRC's climate forecasts to assess for the first time quantitatively the long-term impact of climate change on bird malaria distribution and on Hawai'i's forest birds. In regions where mosquitoes can thrive and efficiently transmit malaria among birds, almost none of the native forest birds can survive. So the populations of forest birds, including the Hawaiian honeycreepers are largely restricted to higher elevations where the climate is not hospitable



for mosquitoes. As the climate warms, however, the region where the birds can avoid malaria will move up in elevation. When this zone is above the remaining forest regions, then the birds will face extinction. Climate change could add another chapter to Hawai'i's sad history of extinctions of endemic birds and other native species.

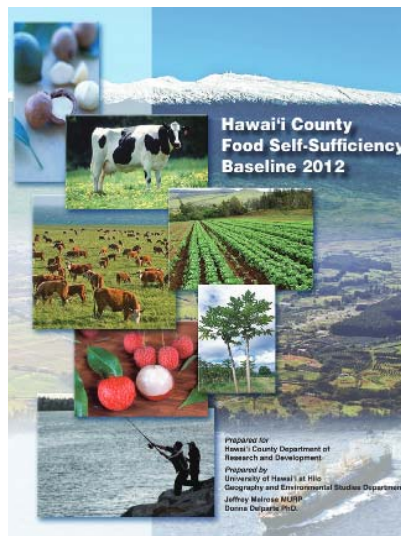


The Common 'Amakihi (*Hemignathus virens*) one of the beautiful honeycreeper species found only in Hawai'i.

## Agriculture in Hawai'i

In the middle of the 20<sup>th</sup> century more than half the food consumed by Hawai'i's population was produced in the state. That fraction has now fallen below 12%, but agriculture is still an important component of the state's economy and efforts to improve food security by increasing local production is a priority for Hawai'i state and local governments. Agriculture can also support the state's economy, particularly through growing the more successful Hawaiian export crops, notably coffee (*Coffea arabica*) and macadamia nuts (*Macadamia integrifolia*). We can foresee that climate change will complicate agricultural planning in Hawai'i. Quantitative projections of how climate change will affect agriculture and agricultural practices in Hawai'i are now being pursued by **Jacob Gross**, a graduate student in the Department of Natural Resources and

Environmental Management (NREM) in UH's College of Tropical Agriculture and Human Resources. Working with NREM faculty member **Tomoaki Miura**, Gross is first creating a tool that rates the suitability of land in Hawai'i for specific crop types under present-day conditions, and then will apply IPRC's temperature and rainfall forecasts to project future suitability for these crops.



A 2012 report prepared for the county government of Hawai'i Island.

## Conclusion

Regional climate modeling has been one important focus of IPRC's activities from its early days. IPRC's investment in building expertise in this area has allowed us to take the lead over the last few years in projects requiring very fine-resolution modeling of projected climate changes for Hawai'i. We find that with fairly "middle of the road" assumptions concerning future emissions scenarios, significant surface warming and rainfall changes can be expected over Hawai'i, and that these changes will have significant geographical structure within each island. Even as we here at IPRC work to refine our modeling results, our many partners are already

researching how our projected climate changes will affect natural and man-made systems in the islands. As in other places throughout the world, we can expect climate changes over the century to yield some benefits, but likely these will be outweighed by deleterious and disruptive impacts. We hope our efforts, together with those of our partners, will result in the best possible information for adaptation planning.

## References

- Benning, T.L., D.A. LaPointe, C.T. Atkinson, and P.M. Vitousek, 2002: Interactions of climate change with biological invasions and land use in the Hawaiian Islands: Modeling the fate of endemic birds using a geographic information system. *Proc. Natl. Acad. Sci.*, **99**, 14246–14249.
- Giambelluca, T.W., H.F. Diaz, and M.S.A. Luke. 2008: Secular temperature changes in Hawai'i. *Geophys. Res. Lett.*, **35**: L12702.
- Giambelluca, T.W., Q. Chen, A.G. Frazier, J.P. Price, Y.-L. Chen, P.-S. Chu, J.K. Eischeid, and D.M. Delparte, 2013: Online Rainfall Atlas of Hawai'i. *Bull. Amer. Meteor. Soc.*, **94**, 313–316.
- Lauer, A., C.X. Zhang, O. Elison Timm, Y. Wang, and K. Hamilton, 2013. Downscaling of climate change in the Hawaii region using CMIP5 results: On the choice of the forcing fields. *J. Climate*, **26**, 10,006–10,030.
- Zhang, C., Y. Wang, A. Lauer, and K. Hamilton, 2012: Configuration and evaluation of the WRF Model for the study of Hawaiian regional climate. *Mon. Wea. Rev.*, **140**, 3259–3277.