Research Report - Final

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Project Title (continued)	on Critical Ecosystems in Hawai
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Final Report to PICCC

"Climate Change Impacts on Critical Ecosystems in Hawai'i and US Pacific Islands Territories"

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Submitted by: Dr. Oliver Elison Timm

Executive Summary

This final report summarizes the project's major accomplishments in research, training and product development. We have accomplished our primary goals of this project. With our research we contribute significant new information to the monitoring and assessment of ongoing climatic changes in Hawai'i. Over the last decades the general trends in the wet season rainfall was negative and given the modeled climate scenarios from CMIP3 and CMIP5, it is very likely these trends are going to continue in the 21st century. In this research project, we improved the spatial information content of our statistical downscaling method through the introduction of the *Rainfall Atlas of Hawai'i* station data sets and the use of improved large-scale climate predictor information. Furthermore, the statistical downscaling (SD) of the CMIP5 multi-model ensemble data updated the future rainfall projections to the latest estimated emissions scenarios (RCP4.5 and RCP8.5) and the newest climate model results for the 21st century. In summary of all the results, we find that the negative trend towards less wet-season (November-April) precipitation is very likely to continue in the 21st century. Most affected from this trend are the arid and semiarid regions of the Islands. This drying trend during the rain season could be an important climate stress factors for terrestrial ecosystems in arid and semiarid regions in Hawai'i.

In this report, we also highlight the our progress made in the development of a statistical downscaling model for Potential Evapotranspiration (PET). Major accomplishments include the systematic analysis of the contribution from net radiation, temperature, relative humidity, and winds to the variability of PET at the HaleNet stations between 1988-2012 from time scales of days to interannual variability. A prototype SD model has been developed and calibrated for the HaleNet stations on Haleakala, Maui.

The project offered continued support for training of two graduate (postgraduate) students in global climate and environmental change research. Research results were presented at international, national and regional conferences and in direct communication with land managers and stakeholders. Our team has prepared the statistical downscaling results as in different formats. This data product will be available for end-users (tentative release in Spring 2013). A manuscript is in preparation summarizing the downscaling results, which will be submitted to a peer-reviewed journal.

1. Accomplishments:

1.1 What are the major goals and objectives?

The major goal of this project was "to enable a continued monitoring and assessment of ongoing climatic changes and to provide quantitative, empirical-statistical estimates of future climatic changes and their impacts on biological resources in the Hawaiian Islands." Within this project we focused our attention to three main objectives:

(1) Estimate spatial patterns of projected rainfall changes for wet and dry season in Hawaiʻi
(2) Evaluate potential evapotranspiration (PET) for specific sites (HaleNet) to better understand its temporal and spatial variability and its relation to large-scale climate modes
(3) Assess the skills of statistical downscaling of future climate change scenarios to project changes in PET.

1.2 Major accomplishments under these goals

1.2.1 Estimation of spatial patterns in rainfall changes

We built our statistical downscaling model of future rainfall changes on the combination of composite analysis and multiple linear regression as described in Timm and Diaz (2009). During this project period we updated the composite analysis method to include a denser network of rainfall stations and more large-scale climate variables from the NCEP/NCAR reanalysis. Gap-filled monthly mean rainfall data from the *Rainfall Atlas of Hawaiʻi* project (Giambelluca *et al.*, 2012) were transformed into wet (November-April) and dry (May-October) season rainfall averages and the annual mean time series were screened for missing months/seasons. In total we used 948 of the 1104 stations for the statistical downscaling.

First, for each station the rainfall amounts are converted into percentages with respect to the station's 1978-2007 climatological mean value and sorted in ascending order. The composite analysis takes the years of the eight lowest and eight highest rainfall percentages. These low and high rainfall years, respectively, are then selected from the seasonal mean NCEP/NCAR reanalysis data to calculate low and high rainfall circulation anomalies with respect to the 1978-2007 climatology. The high (low) anomaly patterns serve as above (below) average rainfall indicators in the large-scale circulation using the variables listed in *Table 1*.

Table 1: Large-scale circulation variables used for the composite analysis

No	*Label*	*Variable*
1	zg500	Geopotential height at 500hPa
2	zg1000	Geopotential height at 1000hPa
3	Dt	Air temperature difference 1000hPa - 500hPa
4	su700	Zonal moisture transport in 700hPa
5	sv700	Meridional moisture transport in 700hPa

We measure each year the similarity between the composite pattern and the actual circulation anomalies (either reanalysis or modeled) using the mathematical vector-projection, which takes the spatial correlation and the amplitude of the anomaly pattern into account. The resulting time series are used in the next step as predictors for rainfall anomalies.

For each station, we applied multiple linear regressions (MLR) to obtain estimates for the rainfall anomalies from the large-scale predictor information. This was initially done for each station with its own optimal predictor time series (each station has 2x5=10 predictor time series for five variables with both low and high composite pattern). However, during the statistical downscaling development we identified that the predictor time series compared among the stations have a high level of redundant information (i.e. the predictor time series are highly correlated among each other). Therefore, it was possible to apply an objective statistical analysis of the covariance among the predictor time series using Principal Component Analysis (PCA).

We pooled the predictor time series of four island regions (Kaua'i, KA; O'ahu, OA; Maui, MA; Big Island, BI) and compressed the predictor information into four principal component (PC) time series, which explain essentially more than 85% of the total variability information in the predictor time series. The compression of the predictor information in the case of Big Island reduces the predictor time series from a total of 2400 (240 stations x 10 indices) to four predictor indices. It should be noted that the PCA compression basically determines the spatial degrees of freedom for the downscaled precipitation changes.

The calibration of the statistical downscaling was evaluated with an ANOVA F-test, which measures the ratio of explained to unexplained variance in the regression model. Furthermore, the majority of stations have statistically significant correlations (R_{cal}) between estimated and observed rainfall anomalies. We have also conducted a similar cross-validation as in Timm and Diaz (2009) where we used the earlier years (1958-1976) to obtain a more conservative test of the SD model. The cross-validation results show a considerable decrease at a number of stations (see previous report for FY 2011-2012). However, as we have shown in a related study

(Elison Timm et al., 2013) reanalysis data of moisture are less reliable prior to the satellite era. Therefore, we must assume that some of the lost downscaling skill during the earlier years is attributable to the loss in accuracy of the reanalysis data.

Table 2: Island sub-regions used in the statistical downscaling. The sub-region station groups are used to apply PCA on the pooled predictor time series.

No	*Label*	*Islands*
1	KA	Kauaʻi
2	OA	Oʻahu
3	MA	Maui, Lānaʻi, Molokaʻi
4	BI	Big Island

The statistical downscaling of the general circulation models from CMIP5 was done in a multi-model ensemble mode with equal weights given to the 32 available models. We used the 'historical' simulations from 1975-2005 and two future scenarios RCP4.5 and RCP8.5 (2006-2100). The process steps are similar to the downscaling of the reanalysis data. In order to avoid model biases, we use the modeled present-day (1975-2005) climatologies to standardize the resulting predictor time series and estimate the simulated future changes in the predictors relative to their present-day means and variances. In this project the main focus was on the wet-season average 2041-2071. The ensemble median results are shown in Figure 2 and Figure 3 for the RCP4.5 and RCP8.5 scenarios, respectively.

From the beginning of the project, one of our priorities was the product development. Whereas our statistical downscaling results are obtained at irregularly distributed point locations, geospatial interpolation methods were used to bring the downscaling results on an interpolated regular grid. We have applied an Ordinary Kriging for the four Island regions with ½ minute resolution. The resulting maps for the RCP4.5 and RCP8.5 scenarios are shown in Figure 4 and Figure 5, respectively. The interpolated maps show clearly that with the wet, windward-facing regions and are expected to maintain or to slightly increase their wet-season rainfall. Most parts of the Hawaiian Islands, however, are expected to experience a continued trend towards less wet-season precipitation. We note that the ensemble median results shown here are increasing the signal-to-noise ratio. The natural trend will be masked by a significant amount of variability on interannual, decadal and multidecadal time scales.

1.2.2 Temporal and spatial variability of PET in relation to large-scale climate

Potential Evapotranspiration (PET) time series were calculated using the hourly data of net radiation, temperature, relative humidity and winds from the HaleNet on Haleakalā, Maui. PET used in this project was based on the Penman-Monteith parameterization:

$$\lambda E = \frac{\Delta\left(R_{net} - G\right) + \frac{\rho C_p}{r_a}\left(e_s - e\right)}{\Delta + \gamma} \qquad \text{(Eq. 1)}$$

The main analysis of the spatiotemporal details of the PET was part of a parallel PICCC-sponsored project. Here the main focus was on (a) identification of the the key climate variables driving PET variations on time scales from hours to years. Data quality control, gap-filling and cross-validation of the PET data sets were ongoing tasks at the time of this project, and therefore we performed here in this project explorative studies with one station (HN151), where long gap-free intervals with hourly data were available for all variables. We have used station HN151 from HaleNet to perform a multi-resolution analysis (MRA) of the daily mean time series from 17-Jun-1988 to 6-March-2012 (n=8664, with still existing gaps were filled with long-term daily means from appropriate month). This study showed that PET is largely controlled by net radiation and temperature followed by specific humidity on the short time scales and the longest time scales resolved in this multi-year segment. Since net radiation and temperature are strongly correlated, and temperature and relative humidity are also correlated, we set the goal to apply the seasonal mean PET time series to perform composite analysis similar to the composite analysis with rainfall data in the previous section.

The calibration of the statistical downscaling with four stations of sufficient seasonal mean PET observations showed high correlations with the large-scale circulation. However the limited sample size will require more elaborated statistical cross validation methods. Our preliminary results suggest that net radiation changes associated with shifts in the cloud cover and/or precipitation will be crucial for the understanding of PET trends in future climate change scenarios. Given the precipitation changes shown on Maui near the HaleNet stations with the drying trends in the leeward sites and neutral or increasing rainfall along the windward slopes it is expected that large spatial gradients will also dominate PET trends in such regions. However, given the limited spatiotemporal information of PET, further quantification of PET changes must include additional information. It is concluded that in the absence of a dense observational network of the net radiation, and specific humidity (as well as wind and temperatures all at one site) it will be necessary to investigate how new PET parameterizations can be developed by integrating the information of spatial of precipitation, clouds cover, and solar radiation.

1.3 Training opportunities and professional development

The project has been successful in the training of an early career scientist in her development of analytical skills in finding causal links between climatic changes on a larger scale and environmental impacts on a local scale. The training was accomplished through regular meetings with the students, team meetings and discussions with the project PIs. The post-graduate students participated actively in the preparation of peer-reviewed articles, contributed to public presentations at seminars at the University of Hawaiʻi and at international conferences.

1.4 Professional Development:

The project has provided opportunities for the PI to develop and foster his mentoring skills and experience in supervising graduate students and post-graduate researchers through discussions and guidance in the statistical data analysis.
The project also allowed for the development of new expertise in advanced statistical analysis methods. Post-Graduate Research Assistant M. Takahashi was trained in the theory and practical application of Self-Organizing Map (SOM) for the analysis of large multivariate data sets. Experience with SOM analysis is bringing great benefits to the early career scientist for future career opportunities.
Furthermore, the during this project GA students and PIs worked with a variety of statistical software packages, data formats, and programming languages that contributed to the development of practical and highly efficient research skills applicable to a wide range of environmental science disciplines.

1.5 Project Results Dissemination:

The PIs of the project had numerous presentations at conferences, workshops and webinar series that reached a broad audience. We have published two papers that were directly supported by this proposal and contributed to the overall success in the understanding of the large-scale climate to local rainfall connectivity.
A summary paper with the latest CMIP5 downscaling results is in preparation.

1.7 Problems Incurred during the Research Projects

There were a number of unexpected technical problems that caused a deviation of the proposed workflow and caused some delays in the research progress. In the end the problems were resolved and our proposed goals were reached.

(1) Delay in the spatial interpolation of the rainfall changes into island-wide maps

As the development of the statistical downscaling model was proceeding, we attempted to work in parallel on spatial interpolation of the station estimated rainfall changes into island-wide maps using objective interpolation methods. Initially we expected to work with a smaller rainfall station network (130 stations) instead of the full network from the *Rainfall Atlas of Hawai'i* (1104 stations).
It became clear that the larger station network would be available during the later phase of this project, and therefore it was decided to postpone the development of the spatial interpolation method to the end of the project. The lead-PI's decision underestimated the time needed to adopt, test, and validate the interpolation method for the future rainfall changes. Furthermore, only in the process of the objective interpolation, data problems were identified (such as two stations separated by less than 100m showed opposing rainfall anomalies). This required a careful step-by-step validation of the statistical downscaling method. We identified the problems (a parsing error during the initial file conversion). Furthermore, the learning experience from the step-by-step reinvestigation of the statistical downscaling helped to improve the workflow (introduction of the PCA method see Section 1.1.2). In the end, we resolved these problems and the final results are robust and to our best knowledge free of technical flaws.

The PET analysis, which was essentially a joint effort by this PICCC-sponsored project and a second PICCC-project was experiencing a slower progress than initially expected. The development of robust PET time series for the HaleNet stations required more intense data quality control and post-processing analysis. Even after intensive work on the production of homogenized hourly to monthly mean PET time series, gaps remained in the monthly and seasonal mean PET time series, which limits the application of the statistical downscaling methods we developed for the seasonal rainfall.
Overall, however, we were able to identify a robust relation between PET and large-scale climate variability that enables us to project CMIP5 model scenarios onto local PET changes. We accomplished therefore one of our main tasks towards the development of PET downscaling methods.

2. Products:

2.1 Publications, Conference papers, Presentations:

2.1.1 Peer-reviewed journals:

Significant impact of the project research has led to the publication and submission of the following articles:

- Elison Timm, O., M. Takahashi, T. W. Giambelluca, H. F. Diaz (2013), On the Relation between Large-Scale Circulation Pattern and Heavy Rain Events over the Hawaiian Islands: Recent Trends and Future Changes, J. Geophys. Res., doi: 10.1002/jgrd.50314.
- (in press) [Acknowledgement of federal support: yes]

- Elison Timm, O., H. F. Diaz, T. W. Giambelluca, and M. Takahashi (2011), Projection of changes in the frequency of heavy rain events over Hawaii based on leading Pacific climate modes, J. Geophys. Res., 116, D04109, doi:10.1029/2010JD014923. [Acknowledgement of federal support: yes]

- Diaz, H. F., and T. W. Giambelluca (2012), Changes in Atmospheric Circulation Patterns Associated with High and Low Rainfall Regimes in the Hawaiian Islands Region on Multiple Time Scales. Global and Planetary Change, Global and Planetary Change, 98-99, 97–108, doi:10.1016/j.gloplacha.2012.08.011.

2.1.2 Books and non-periodical, one-time publications:

Nothing to report

2.1.3 Other publications:

R. J. Longman, T. W. Giambelluca, and O. Elison Timm, The spatial dynamics of potential evapotranspiration in Hawai'i: How driving variables are influenced by the trade wind inversion, poster presentation B23E-0505, AGU Fall Meeting, San Francisco, California, USA, Dec. 2012.
[Acknowledgement of federal support: yes]

O. Elison Timm. From global warming to regional changes in Hawaii's water cycle, 2012. Pacific Islands Climate Change Cooperative Webinar Series, Aug. 16th, 2012.
[Acknowledgement of federal support: yes]

M. Takahashi, M., O. Elison Timm, T.W. Giambelluca, H.F. Diaz, A.G. Frazier, High and Low Rainfall Events in Hawai'i in Relation to Large-Scale Climate Anomalies in the Pacific:

Diagnostics and Future Projections, poster presentation GC51D-1024, AGU Fall Meeting, San Francisco, California, USA, Dec. 2011.
[Acknowledgement of federal support: yes]

O. Elison Timm, T. W. Giambelluca, M. Takahashi, and Diaz H. F. Future climate change in Hawaii, oral presentation, APEC Climate Symposium, Honolulu, Hawaii, Oct 17–20th, 2011.

O. Elison Timm, T. W. Giambelluca, H. F. Diaz, and M. Takahashi. Expected rainfall changes over Hawaii in the 21st century, poster presentation, Hawai'i Conservation Conference, Honolulu, Hawaii, U.S.A, 2011.
[Acknowledgement of federal support: yes]

2.2 Internet & Web-Sites:

We are in the process of preparing interactive dynamic maps to project geospatial data products from the statistical downscaling. Currently, the Asia-Pacific Data-Research Center (APDRC) uses *Google Earth* technology to display the station-based future rainfall changes. We will further update the project pages to allow the public to download the downscaled precipitation scenario data in tabulated form including a more complete set of statistical quantaties (mean,meadian, standard deviation etc. from the multi-model ensemble). Interpolated map data will be made available in tabulated spreadsheets (*CSV* format) and *netcdf* format. This material will be hosted on the APDRC (http://apdrc.soest.hawaii.edu/projects/SD/). Furthermore, we will provide the data sets to PICCC.

2.3 Technologies & Techniques:

Nothing to report

2.4 Inventions, patent applications, licenses:

Nothing to report

2.5 Other products:

Nothing to report

3 Participants and other collaborating organizations

3.1 Individuals that have worked on the project

Name: Oliver Elison Timm
Project Role: PI
Nearest person month worked: 3mo/yr
Contribution to project: Research, Product development, product dissemination, and supervision of GA research assistant.
Funding support: PICCC #12200-A-J024, USFWS F10AC00077)
Collaboration with foreign collaborator: Nothing to report
Travel to foreign country: Nothing to report
Duration of stay: Nothing to report

Name: Thomas W. Giambelluca
Project Role: Co-PI
Nearest person month worked: 1 mo/yr
Contribution to project: Research and supervision
Funding support: PICCC #12200-A-J024, USFWS F10AC00077
Collaboration with foreign collaborator: Nothing to report
Travel to foreign country: Nothing to report
Duration of stay: Nothing to report

Name: Henry F. Diaz
Project Role: Co-PI
Nearest person month worked: 1.5mo/yr
Contribution to project: Research, Product development and dissemination
Funding support: PICCC #12200-A-J024,USFWS F10AC00077
Collaboration with foreign collaborator: Nothing to report
Travel to foreign country: Nothing to report
Duration of stay: Nothing to report

Name: Mami LeMaster

Project Role: Research Assistant
Nearest person month worked: 9mo
Contribution to project: Large-scale climate analysis and classification of local climate variability
Funding support: PICCC #12200-A-J024, USFWS F10AC00077
Collaboration with foreign collaborator: Nothing to report
Travel to foreign country: Nothing to report
Duration of stay: Nothing to report

Name: Abby Frazier

Project Role: Research Assistant
Nearest person month worked: 0.5mo
Contribution to project: Geospatial mapping of station data to continuous maps
Funding support: PICCC #12200-A-J024, USFWS F10AC00077
Collaboration with foreign collaborator: Nothing to report
Travel to foreign country: Nothing to report
Duration of stay: Nothing to report

3.2 Other Organizations involved as partners

Organization Name: Asia-Pacific Data Research Center
Location: Univ. Hawaiʻi at Mānoa, Honolulu, HI, U.S.A.
In-kind support & facilities: computing facilities, data server support
Collaborative research: APDRC IT experts collaborate on the web-page development and dynamic mapping web application
Personnel exchanges: nothing to report

Organization Name: Japan Agency for Marine-Earth Science and Technology
In-kind support & facilities: JAMSTEC sponsors the International Pacific Research Center and provided financial base support for the PI
Location: Yokosuka and Yokohama, Kanagawa, Japan
Collaborative research: nothing to report
Personnel exchanges: nothing to report

3.3 Other collaborators or contacts involved

3.3.1 Collaborators within recipient's organization:

Name: Ryan Longman
Title: Graduate Student
Affiliation: Dept. Geog., Univ. Hawaiʻi at Mānoa
Contribution to project: Large-scale climate analysis and classification of local PET variability

3.3.2 Collaborators outside recipient's organization

We note that this project involved a total of four institutions—The University of Hawai'i at Manoa, The University of Colorado at Boulder, the federal National Oceanic and Atmospheric Administration, the Japan Agency for Marine-Earth Science and Technology; the latter two via in-kind support for co-PI Diaz and PI Elison Timm, respectively.

3.3.3 Collaborators with others outside the United States

Nothing to report

4 Impact of the project

4.1 Development of the principal discipline(s) of the project

Nothing to report

4.2 Other disciplines

The previous downscaling results and the newly derived preliminary results from this research have already been incorporated as regional climate change information into biological disciplines, where the effects of anthropogenic climate changes important drivers for changes in ecosystem distribution, vector diseases such as avian bird flu among others.

4.3 Development of human resources

Nothing to report

4.4 Physical, institutional, and information resources that form infrastructure:

Nothing to report

4.5 Technology transfer

Nothing to report

4.6 Society beyond science and technology

Nothing to report

4.7 Dollar amount spent in foreign country(ies)

Nothing to report

5 Changes/Problems

See section 1.7.

5.1 Changes in the approach and reasons for change

The major changes made in the project research execution compared with the initially proposed research method are:

1. Transition from a small rainfall station network (130 stations) to the *Rainfall Atlas of Hawai'i* network (1104 station)
2. Application of multi-model ensemble CMIP5 data sets instead of pre-selected subset of models (32 models instead of 6 models).
3.

Both changes were introduced to the benefit of the final results. The denser station network improved the spatial details of the downscaling, and the use of a larger ensemble model improved the robustness of the statistical downscaling and enhanced the confidence in the downscaling results.

5.2 Actual or anticipated problems or delays and actions or plans to resolve them

Nothing to report

5.3 Changes that had significant impact on expenditures:

Nothing to report

5.4 Significant changes in use or care of human subjects, vertebrate animals, and/or biohazards

Nothing to report

6 Special Reporting Requirements:

Nothing to report

Appendix

A. Figures

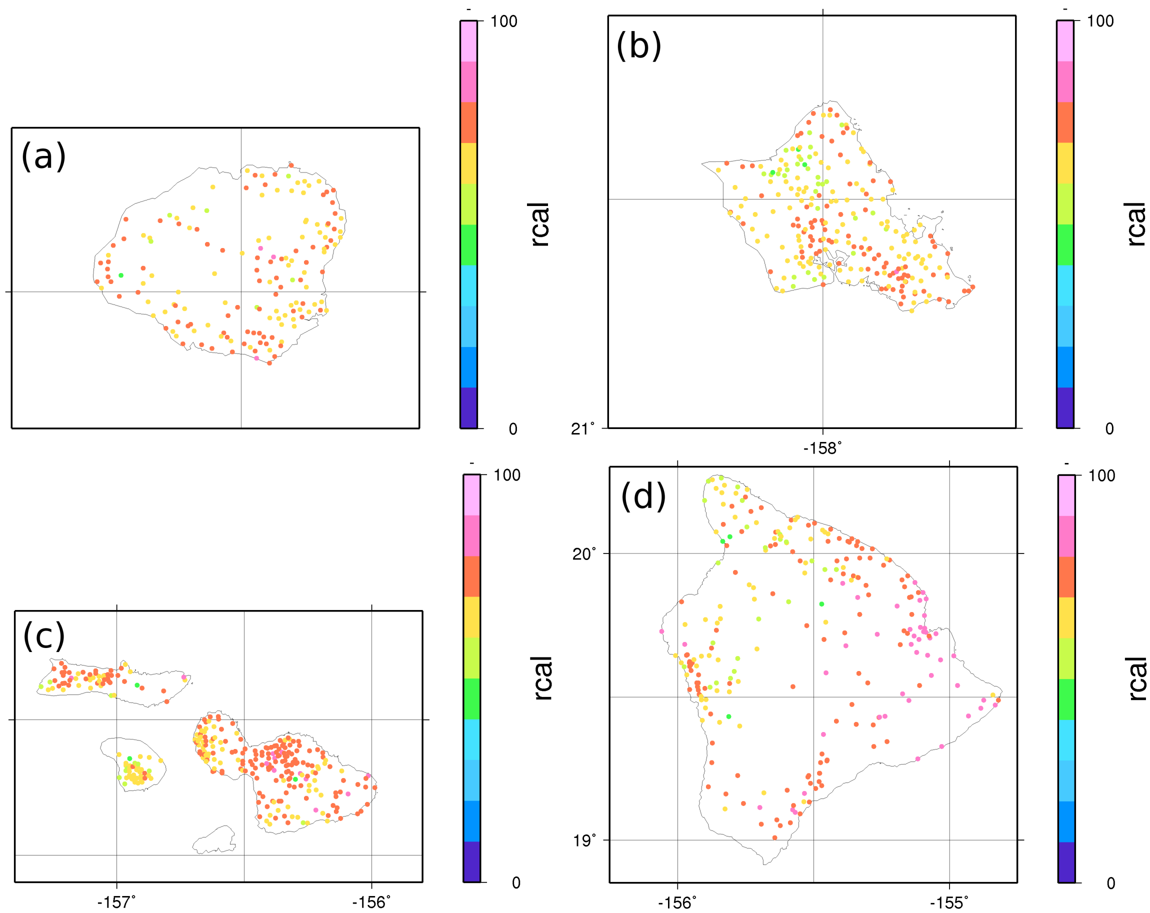

Figure 1: Statistical Downscaling (SD) calibration results of the wet season. Shown are the correlation coefficients between the station rainfall anomalies and the SD estimates during the fitting period 1978-2007. Correlations greater than approx. 0.58 are statistically significant at the 10% level. Note that the autocorrelation was not taken into account in this test. (a) Kaua'i; (b) O'ahu; (c) Moloka'i, Lāna'i, Maui; (d) Hawai'i (Big Island).

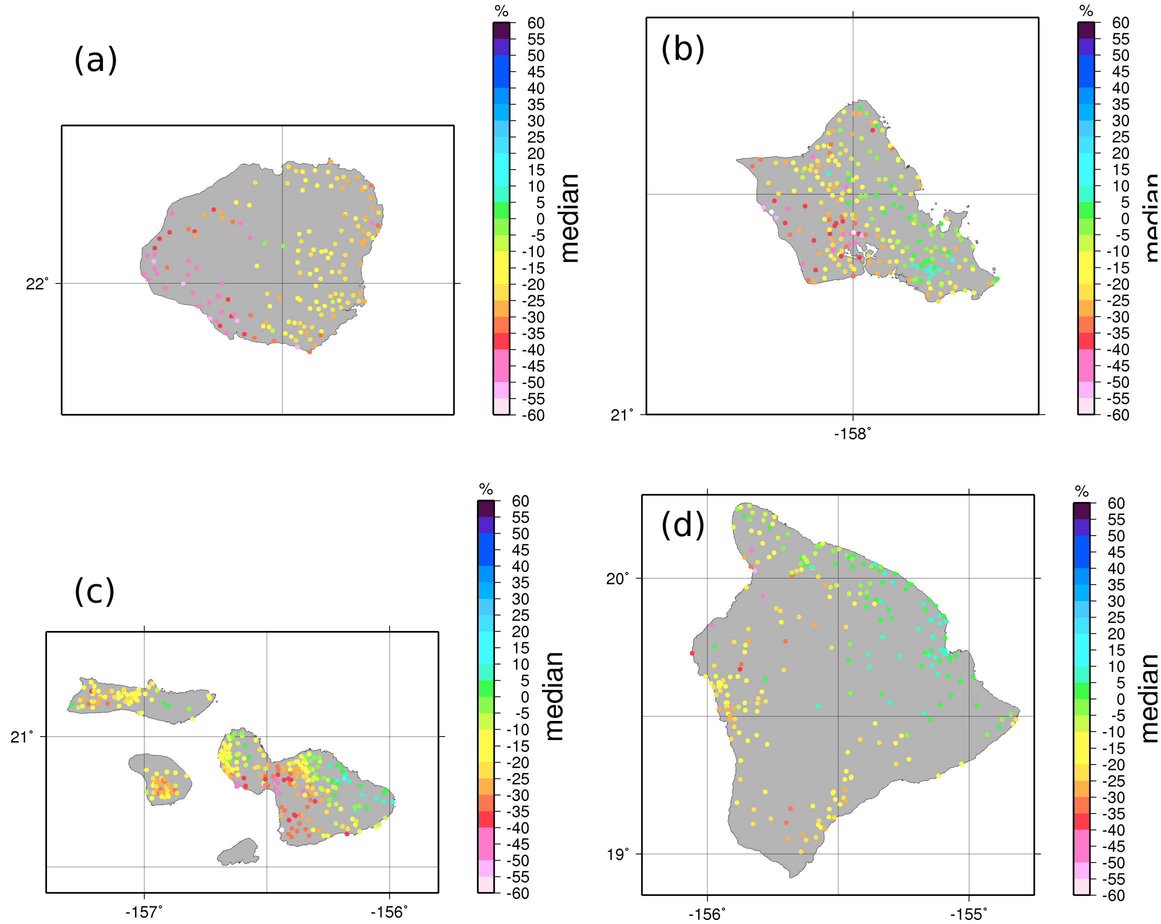

Figure 2: SD results of the 32-model CMIP5 ensemble for the moderate warming scenario RCP4.5. Shown are the stations multi-model ensemble medians for the mid of the 21st century averaged over the modeled years 2041-2071.

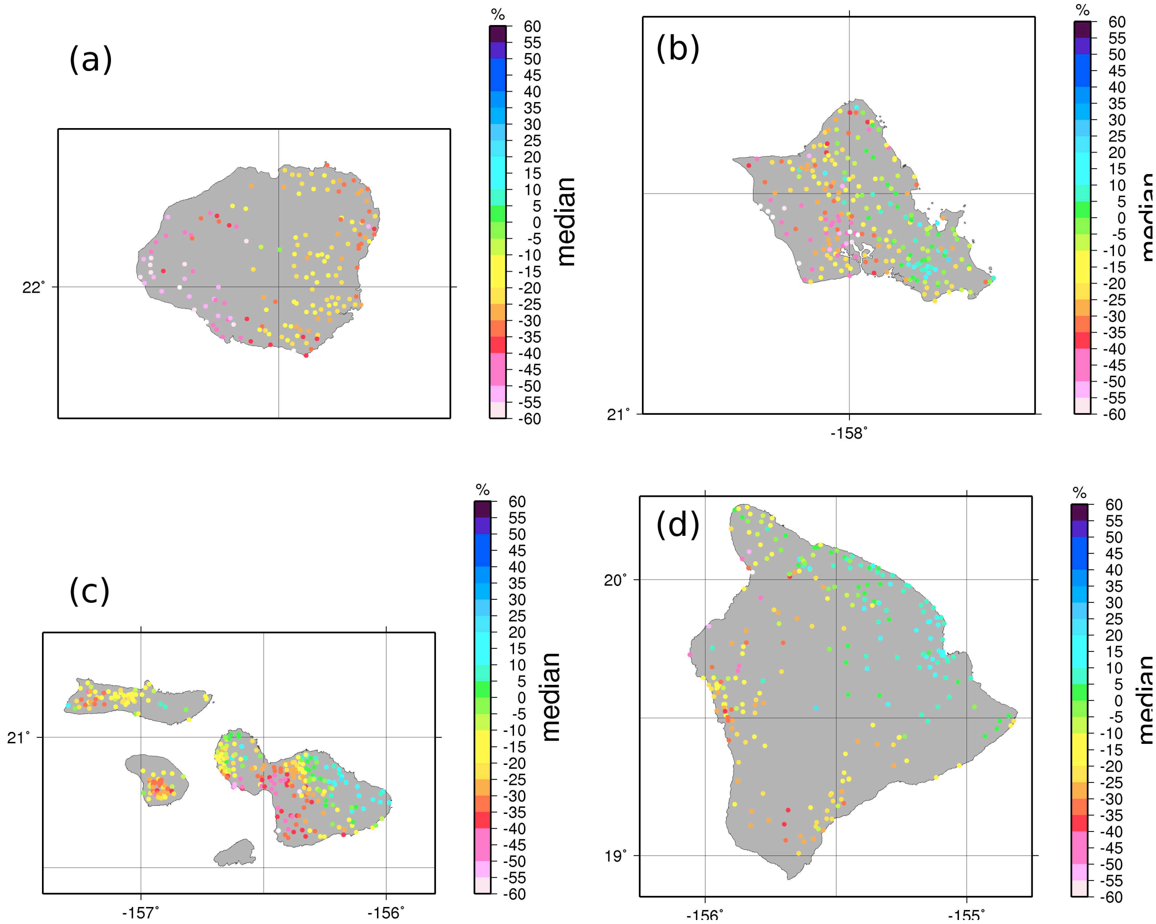

Figure 3: Same as in Figure 3 but for the more severe warming scenario RCP8.5.

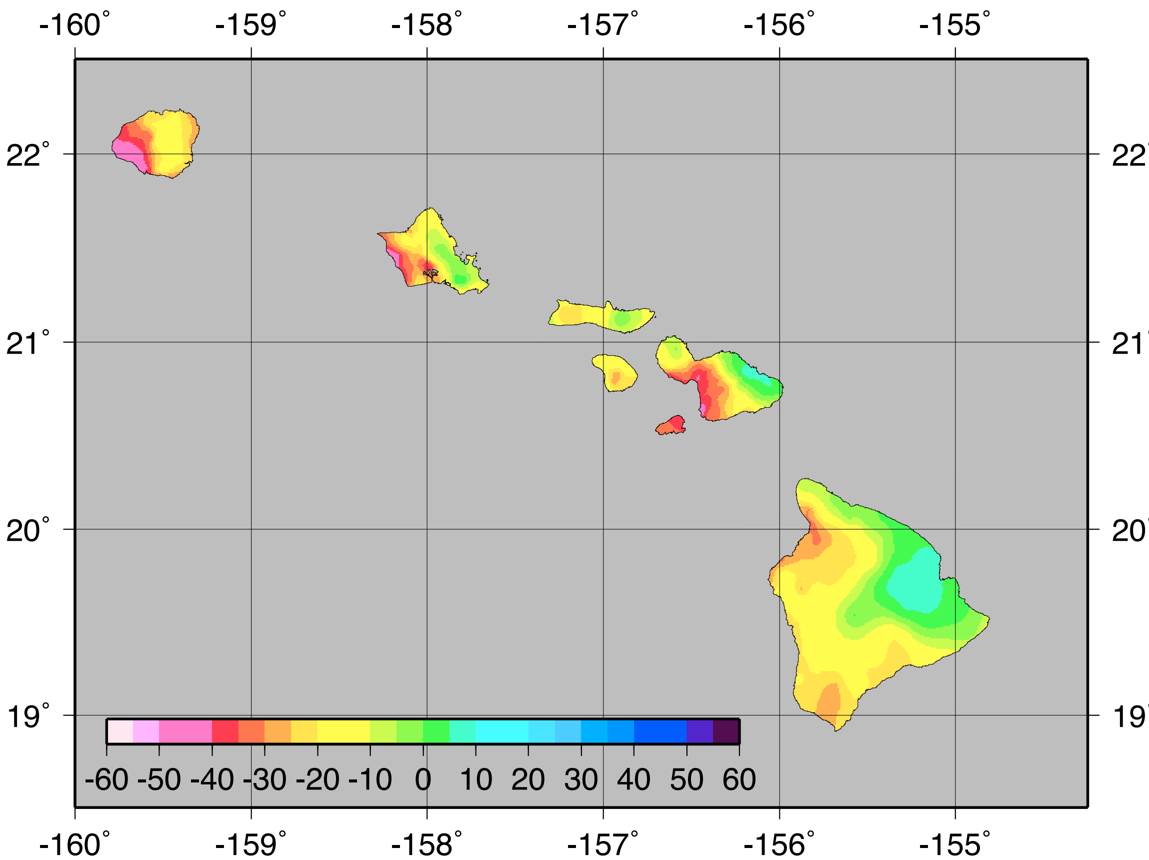

Figure 4: Interpolated maps using ordinary Kriging for the CMIP5 RCP4.5 ensemble median (average for the years 2041-2071). Units are given in percent.

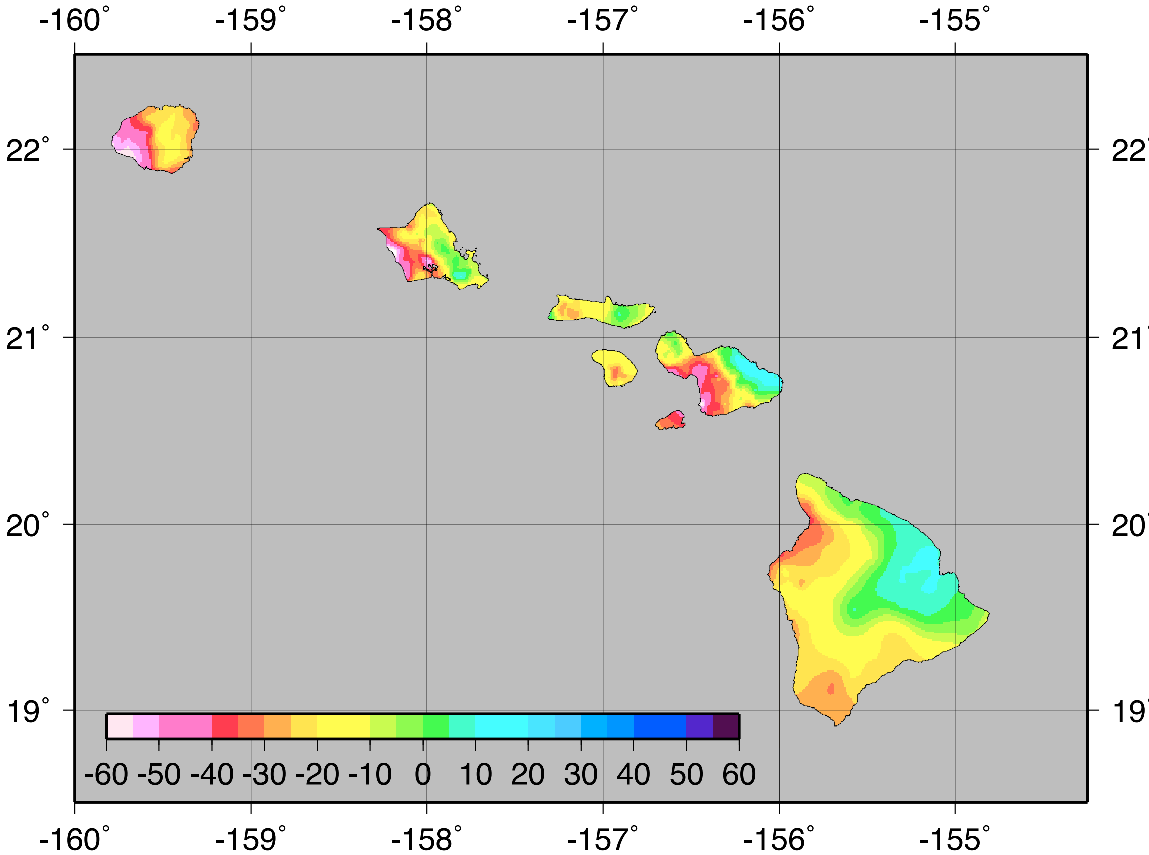

Figure 5: Same as in Figure 4 but for the CMIP5 RCP8.5 scenarios averaged over the years 2041-2071.

C. References

[1] Giambelluca, T.W., Q. Chen, A.G. Frazier, J.P. Price, Y.-L. Chen, P.-S. Chu, J.K. Eischeid, and D.M. Delparte, 2012: Online Rainfall Atlas of Hawaiʻi. Bull. Amer. Meteor. Soc., doi: 10.1175/BAMS-D-11-00228.1

[2] Elison Timm, O., H. F. Diaz, T. W. Giambelluca, and M. Takahashi (2011), Projection of changes in the frequency of heavy rain events over Hawaiʻi based on leading Pacific climate modes, , J. Geophys. Res.: Atmos., 116(D4), 1–12, doi:10.1029/2010JD014923

[3] Elison Timm, O., M.Takahashi, T. W. Giambelluca and H. F. Diaz, 2013: On the relation between large-scale circulation pattern and heavy rain events over the Hawaiʻian Islands: Recent trends and future changes, J. Geophys. Res.: Atmos., 118, 1–13, doi:10.1002/jgrd.50314.