1. ADMINISTRATIVE:

Name and contact information of the Recipient:

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Office of Research Services
2530 Dole Street, Sakamaki Hall, D-200
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Title:
Reconstructing past Hawaiian precipitation using stable carbon isotope analysis of Māmane trees

Agreement number:
12170-B-G103

Date of Report:
December 25, 2013

Period of time covered by the report:
July 01, 2011 through September 30, 2013

Actual total cost:
$42,888

2. PUBLIC SUMMARY:

We analyzed the chemical composition of wood produced by Māmane, a tropical tree growing in Hawai'i, in order to reconstruct changes in climate over the Hawaiian Islands. Specifically, we measured changes in the relative abundance of carbon and oxygen isotopes taken up by the trees during photosynthesis at high elevation sites on Mauna Kea. We found that these isotopes reflect the climatic conditions (precipitation and temperature) under which the trees lived, allowing us to reconstruct relative changes in climate extending back ~130 years. Our results indicate decadal-scale changes in precipitation that correlate well with large-scale atmospheric and ocean circulation patterns that dominate much of the Pacific. In addition, we interpret a general decrease in precipitation since the 1920s that is consistent with rain-gauge measurements. Our long-term climate record also correlates well with measurements showing a decrease in snow cover on Mauna Kea. These results demonstrate how detailed measurements of the wood chemistry of Māmane trees can be used to extend our record of natural climate variability in Hawai'i to a wider geographic extent and across longer time periods than the instrumental record allows. This new climate record produced from Māmane wood has implications for better understanding background, natural climate variability in the Hawaiian Islands and may further help conservation efforts in the fragile upland tropical ecosystem.

3. PROJECT REPORT

A. TECHNICAL SUMMARY:

Goals:

This project was designed to reconstruct Hawai'i precipitation by measuring the carbon isotopic composition ($\delta^{13}C$) in annual growth rings of 100+ year-old Māmane trees from the upper slopes of Mauna Kea on the Island of Hawai'i. We set out to produce a proof-of-concept $\delta^{13}C$ dataset from Māmane wood samples to document the potential for a sub-annually resolved paleo-climate archive. This dataset would be used to develop a new multi-century precipitation reconstruction from Māmane wood in order to help conservation efforts in the fragile upland tropical ecosystem.

We produced 2445 $\delta^{13}C$ datapoints from a total of five different Māmane trees (one tree was measured in triplicate) growing on the upper slopes of Mauna Kea on the Island of Hawai'i. We determined that the rings produced by Māmane were annual based on excellent association between the growth bands and the cyclic intra-ring $\delta^{13}C$ record. Based on this result, the length of the record was determined to represent ~130 years (1880-2009) of growth. We observed decadal patterns in $\delta^{13}C$ change that matched decadal climate variability in observed rainfall on Hawai'i. We also interpreted a long-term trend of increasing precipitation from the 19th century to the 1920s followed by decreasing precipitation through the present. The decrease in precipitation interpreted from the $\delta^{13}C$ record is consistent with observations of decreased snowfall on Mauna Kea for this same ~70-year interval. This proof-of-concept record shows that more ancient Māmane wood could be analyzed to extend our precipitation record to better understand natural, background climate variability in the Hawaiian Islands.

In order to evaluate the potential for intra-annual oxygen isotope measurements to provide additional climate information, we extracted cellulose from sub-samples of Māmane wood across individual rings. These oxygen isotope values determined from cellulose ($\delta^{18}O_{cellulose}$) were combined with a global dataset to produce a unifying relationship for the environmental controls on seasonal changes in $\delta^{18}O_{cellulose}$ measured across tree rings. We found that the intra-annual change in $\delta^{18}O_{cellulose}$ measured across tree rings reflect seasonal changes in temperature and precipitation amount. Using the Māmane record we were able to demonstrate how combined $\delta^{13}C$ and $\delta^{18}O_{cellulose}$ records can be used to accurately reconstruct summer and winter precipitation amounts, as well as maximum and minimum growing season temperatures.

Major Research Accomplishments:

1) Developed the longest and highest-resolution tree-ring $\delta^{13}C$ record in the Hawaiian Islands.
2) Produced the first high-resolution, intra-annual $\delta^{18}O_{cellulose}$ measurements for the genus *Sephora*.
3) Identified seasonal changes in $\delta^{13}C$ and $\delta^{18}O_{cellulose}$ that relate to seasonal changes in climate.
4) Showed that average seasonal changes in $\delta^{13}C$ and $\delta^{18}O_{cellulose}$ measured in Māmane reflect average seasonal changes in temperature and precipitation amount.
5) Confirmed that concentric growth bands in Māmane are formed annually.
6) Produced a novel proxy for reconstructing seasonal climate using intra-ring isotope measurements. Demonstrated its accuracy for five diverse climate sites worldwide, including Hawai'i.
7) Produced first application of a novel correction for the effects of changes in atmospheric carbon dioxide levels to a long-term tree-ring record.

8) Found preliminary correlation between terrestrial, oceanic, and atmospheric processes over the Hawaiian Islands.
9) Identified decadal trends in $\delta^{13}C$ that match observed rainfall on the island of Hawai'i.
10) Identified a long-term trend of drying climate conditions on Hawai'i over the last 70 years.

How our research results contributed to the advancement of scientific knowledge and/or climate change adaptation regionally and/or nationally:
The methods and results produced here are widely applicable. These techniques can be applied to a wide range of tree species, including both angiosperms and gymnosperms, and any climate environment in which trees live today. The oxygen isotope method developed from this project represents a wholly new understanding of the relationship between climate, the oxygen isotope content of precipitation, and tree-ring cellulose. The work completed here resulted in a novel demonstration of how high-resolution intra-ring carbon and oxygen isotope measurements can be used together to quantify seasonal climate from modern or fossil wood. This has important implications for quantifying climate change in remote regions of the world, sites for which the instrumental record is lacking, or extending the climate record beyond the instrumental period. Understanding the full range of climate conditions in which a forest has experienced is critical to planning conservation efforts in a changing climate.

B. PURPOSE AND OBJECTIVES:

The following objectives described in our proposal were met: 1) we found that $\delta^{13}C$ variations reflected rainfall data measured from nearby gauges; 2) we compared $\delta^{13}C$ variations to the width of annual rings, but found low correlation; 3) we showed that sub-annual $\delta^{13}C$ variations track observed seasonality, consistent with our earlier work; 4) we found a strong association between $\delta^{13}C$ variations and the dominant modes of Pacific climate variability; and 5) we found long-term $\delta^{13}C$ trends suggesting dryer conditions in the latter part of the sampling period (~1930 to 2009) than the previous ~50 years (1880-1930). We are currently investigating the correlation between past $\delta^{13}C$ inter-annual variability and longer-term El Niño proxies.

In addition to these original project objectives, we added an analysis of the oxygen isotope composition of cellulose extracted from a sub-sample of Māmane tree-rings. This addition resulted in a wholly new proxy for reconstructing seasonal climate that we expect to submit for publication shortly. This was made possible by the budget re-allocation authorized in year two of our project, which allowed for the training of a young scientist in sample preparation for stable isotope analysis. Because the extraction of cellulose is required for measuring oxygen isotopes in plant tissues accurately, the additional personnel support was critical to being able to carry out these significantly more labor-intensive measurements.

C. ORGANIZATION AND APPROACH:

We sampled five different Māmane trees from the upper slopes of Mauna Kea (Fig. 1). The number of trees selected exceeded the number used in all previous studies (a search through the literature found that 14 previous high-resolution $\delta^{13}C$ records used only 1-4 trees). One sample was a core taken in January of 2010 from a living tree (MKM04A) and therefore the date of the outermost wood is known. All other samples were taken from slabs cut from trees in which growth had stopped and therefore their ages were unknown. These samples were radiocarbon dated to determine their approximate ages (see section D. Project Results). One tree (M15) was analyzed across three radial sections to demonstrate reproducibility at both high- and low-resolution (see section D. Project Results). For all measurements, we sub-sampled each ring by hand using a razor blade in order to precisely follow the curved ring anatomy. Samples were weighed into tin capsules and $\delta^{13}C$ values determined using a Costech ECS 4010 Elemental Analyzer in conjunction with a Thermo Fisher Delta V stable isotope mass spectrometer in Hope Jahren's laboratory at the University of Hawai'i at Mānoa. A sub-set was extracted for cellulose using methods modified from Brendel et al. (2000), Gaudinski et al. (2005), and Evans and Schrag (2004). The resulting pure α-cellulose samples were weighed into silver capsules and analyzed for $\delta^{18}O_{cellulose}$ using a Delta V IRMS coupled to a TC/EA configured with a zero-blank autosampler. All $\delta^{18}O_{cellulose}$ values were normalized to the VSMOW-SLAP scale using two internal laboratory α-cellulose reference materials previously calibrated using IAEA-601 and IAEA-602 benzoic acid primary reference materials, which follows standard international practices.

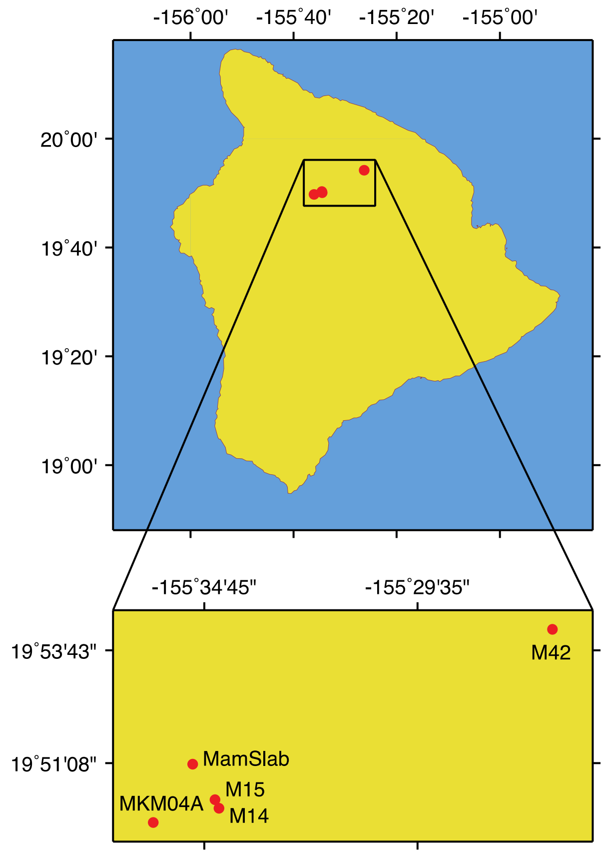

Figure 1. Locations of the five different Māmane trees sampled for this study.

D. PROJECT RESULTS:

We produced both high- and low-resolution $\delta^{13}C$ datasets as well as a high-resolution $\delta^{18}O$ dataset made on cellulose extracted from whole wood. A summary of the results from these analyses is below.

Table 1. Summary of carbon isotope data generated in this project.

Sample ID	Measurements/ring	No. rings	Total no. $\delta^{13}C$ measurements
High-resolution			
M15-1	18.4	24.0	441
M15-2	16.4	48.0	789
MKM04A	25.1	23.0	579*
Overall	*19.0*	*95.0*	*1809*
Low-resolution			
M14	1.0	59.0	59
M15	2.0	109.5	220
M42	1.0	64.0	64
MamSlab	1.0	90.0	90
Overall	*1.0 to 2.0*	*322.5*	*433*

*Measured in triplicate.

$\delta^{13}C$ measurements:

We produced three high-resolution $\delta^{13}C$ records across Māmane trees (average of 19 $\delta^{13}C$ measurements per ring) (Fig. 2; Table 1). The average thickness of each subsample ranged between ~50-75 µm. One record was from MKM04A and two replicate cores were measured from M15. The two high-resolution records on M15 overlapped across 7 years of growth and aligned visually (blue and red curves in Fig. 3). A low-resolution record from this same tree (purple curve in Fig. 3) aligned well with the two high-resolution records and showed similar visual trends across the periods of overlap (3 and 43 years, respectively).

We produced an additional four, low-resolution (1-2 measurements per ring) $\delta^{13}C$ records across the following Māmane trees: M14, M15, M42, and MamSlab (Fig. 4; Table 1). These showed long-term trends similar to the high-resolution records although for some records the absolute $\delta^{13}C$ values were offset to significantly higher (or lower) values (Fig. 5).

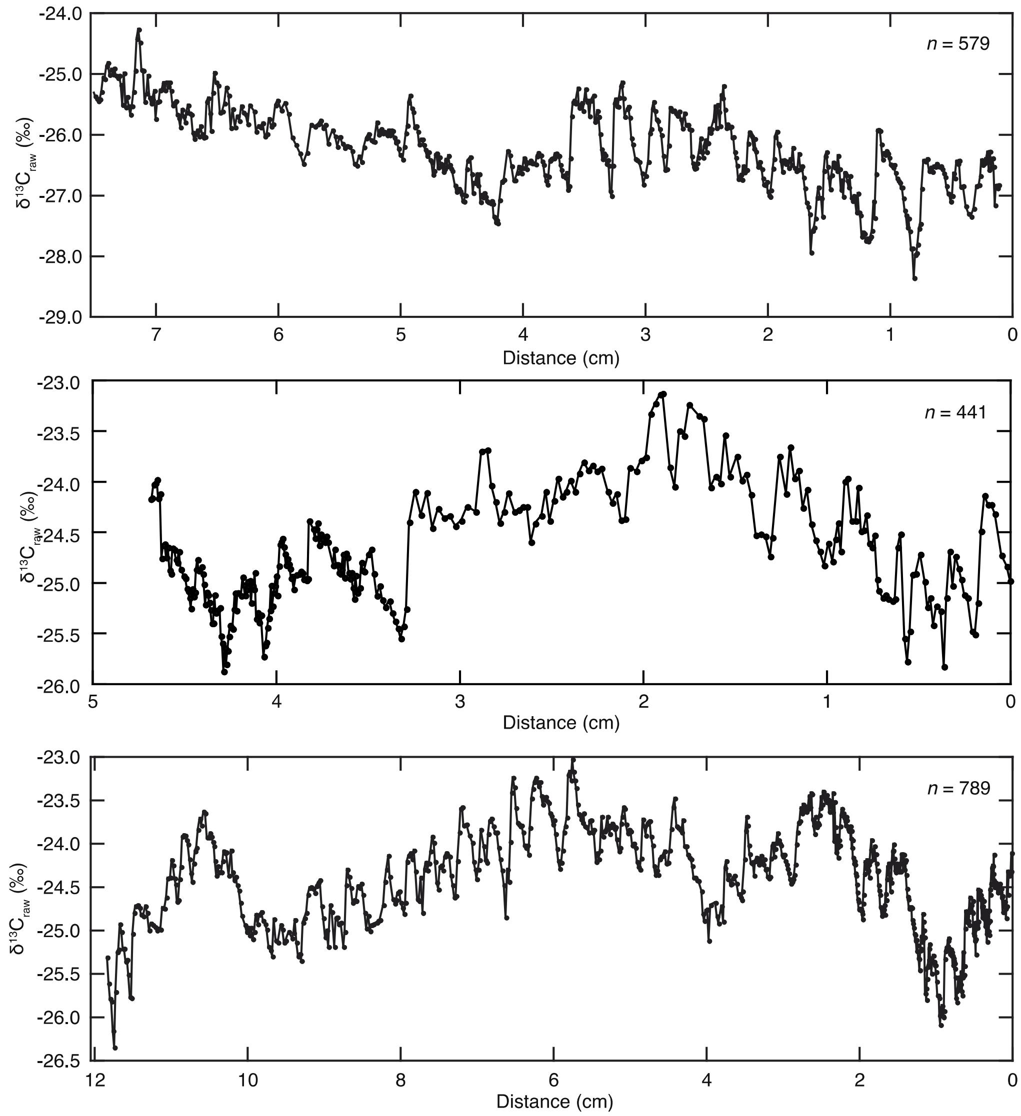

Figure 2. High-resolution $\delta^{13}C$ data from three Māmane samples. The direction of growth is left to right in each panel. From top to bottom, the samples are MKM04A, M15-1, and M15-2. The x-axis for each panel is plotted independently of the others, relative to the initial subsample made at a position defined as distance = 0 cm; therefore these records do not align as shown.

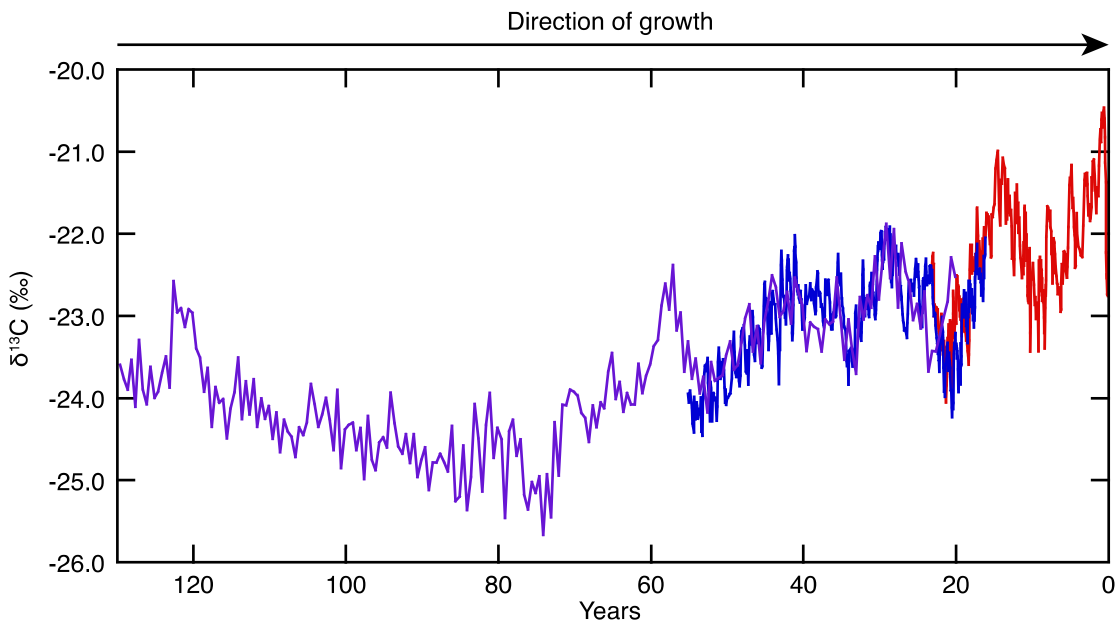

Figure 3. High- and low-resolution $\delta^{13}C$ alignment of three radial sections of sample M15. The blue and red curves were sampled at 16 to 18 $\delta^{13}C$ measurements per ring, and the purple curve was sampled at 2 measurements per ring. All rings were adjusted to an equal spacing to align the records. All $\delta^{13}C$ data are shown here corrected for changes in the carbon-isotope composition of atmospheric CO_2 and for changes in CO_2 concentration after Schubert and Jahren (2012, *Geochimica et Cosmochimica Acta*). For this correction, year "0" was set equal to the year 2001.

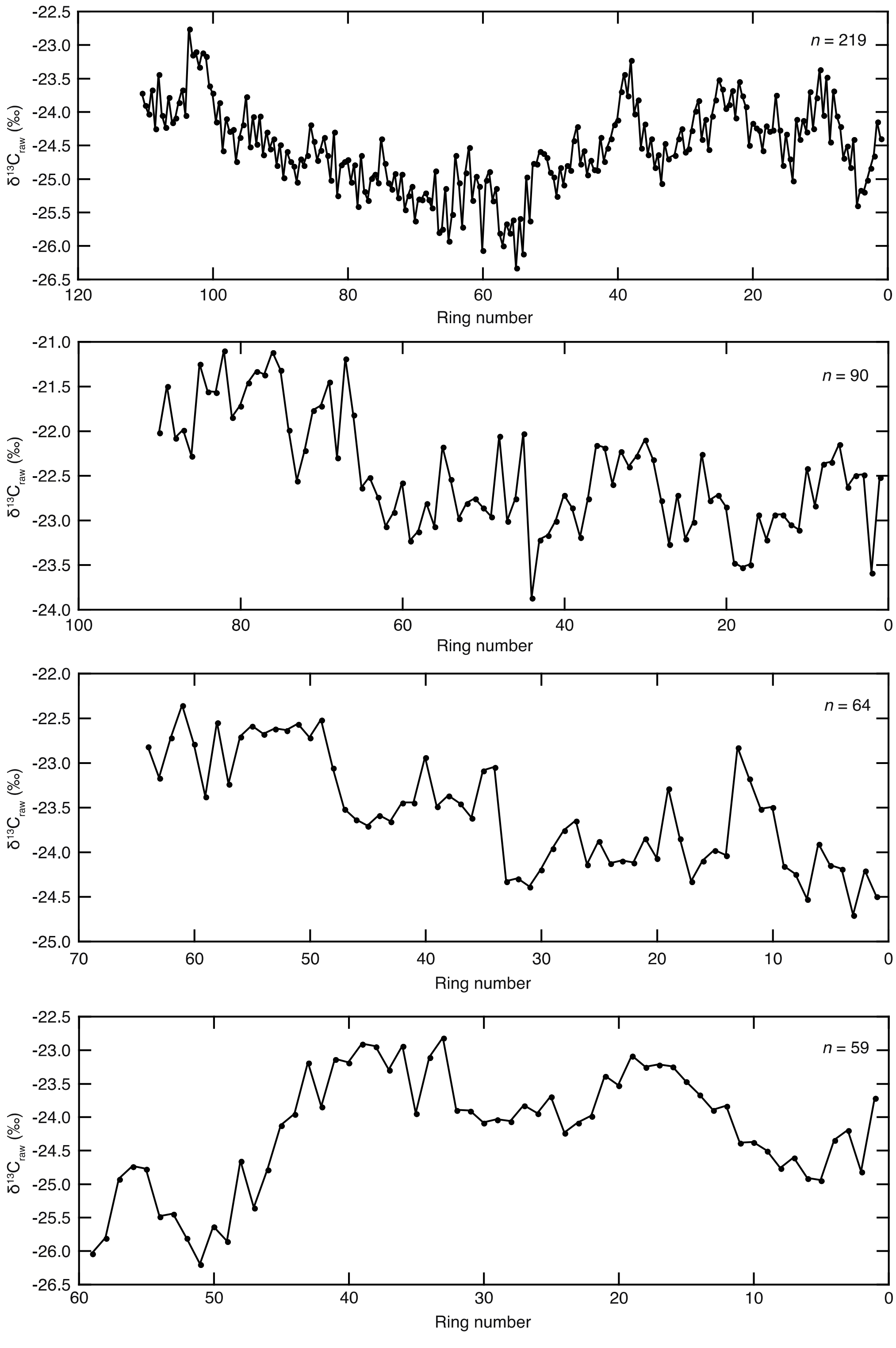

Figure 4. Low-resolution $\delta^{13}C$ data (1-2 $\delta^{13}C$ measurements/ring) from four Māmane samples. The direction of growth is left to right in each panel (outermost ring number = 0; ring numbers do not correspond across samples). From top to bottom, the samples are: M15, MamSlab, M42, and M14. Large-scale (i.e., >1‰) trends of changing $\delta^{13}C$ value are observed in each sample.

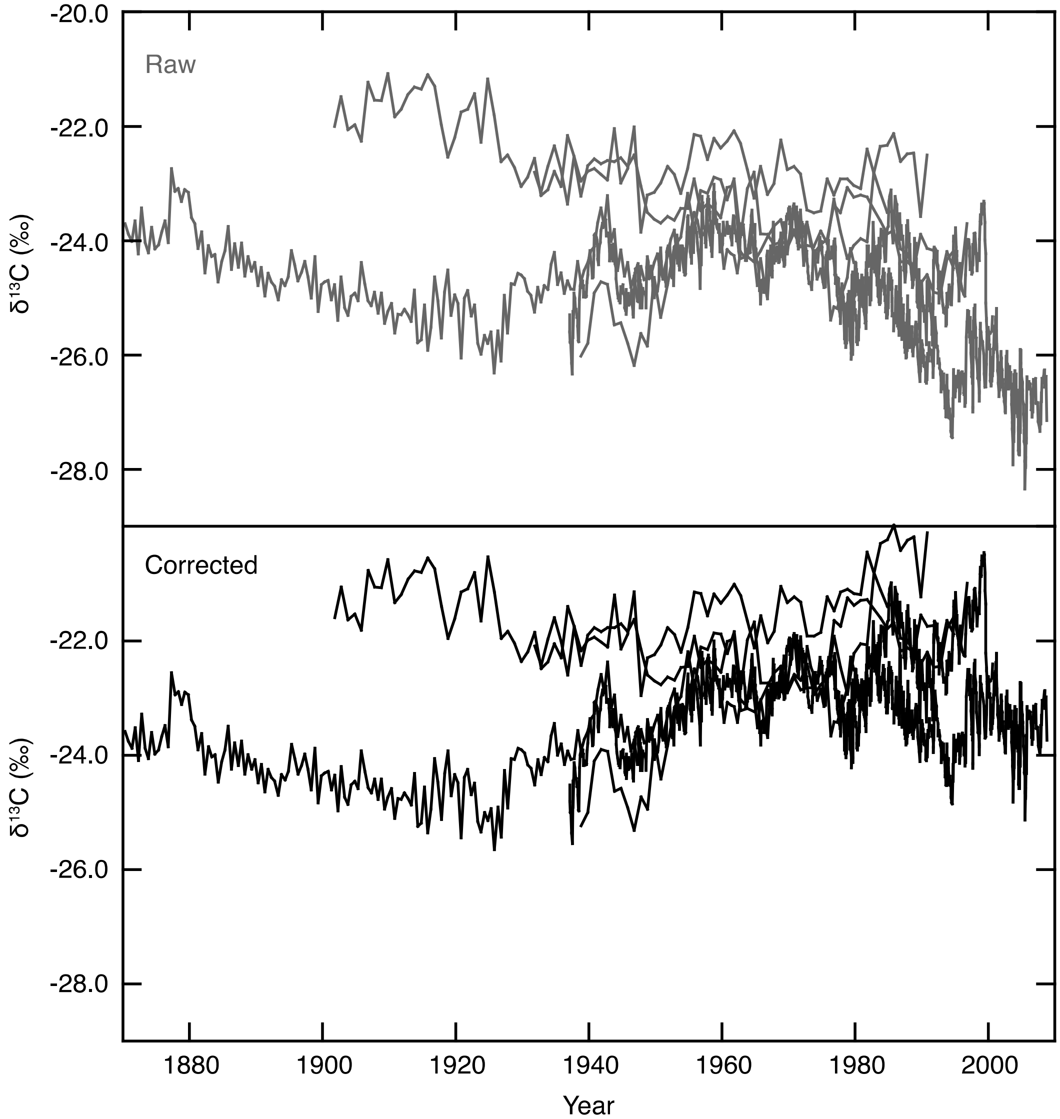

Figure 5. Raw (top) and corrected (bottom) $\delta^{13}C$ data for all samples measured in this study. The "corrected" data were corrected for changes in the $\delta^{13}C$ value of atmospheric CO_2 and changes in atmospheric CO_2 concentration since the year 1850 *after* Schubert and Jahren (2012, *GCA*). Atmospheric data were obtained from Mauna Loa and ice core records. Note that the long-term decreasing trend in $\delta^{13}C$ observed in the raw dataset disappears when the $\delta^{13}C$ values are corrected for changes in atmospheric chemistry. The downward trend in $\delta^{13}C$ values observed in the raw dataset results from the burning of fossil fuels and is not a climate signal.

$\delta^{18}O$ measurements:

We produced a high-resolution $\delta^{18}O$ record on cellulose (n = 56) extracted from across four tree rings of sample M15. Data are shown in Fig. 6. We identified a seasonal increase and decrease in the $\delta^{18}O_{cellulose}$ value. Using a global dataset of similar $\delta^{18}O_{cellulose}$ records, we determined that the seasonal change in $\delta^{18}O_{cellulose}$ results from seasonal changes in the $\delta^{18}O$ value of meteoric water, which in turn is affected by seasonal changes in temperature and precipitation amount. Therefore, by using combined high-resolution $\delta^{13}C$ and $\delta^{18}O_{cellulose}$ records, seasonal changes in precipitation and temperature could be calculated. For the Māmane records we calculated average summer and winter precipitation equal to 172 and 230 mm, respectively, and maximum and minimum average monthly temperatures equal to 18.5 and 8.6 ^{o}C, respectively. The actual values reported from a nearby weather gauge are 146 and 256 mm (summer and winter), and 15.5 and 11.6 ^{o}C (summer and winter).

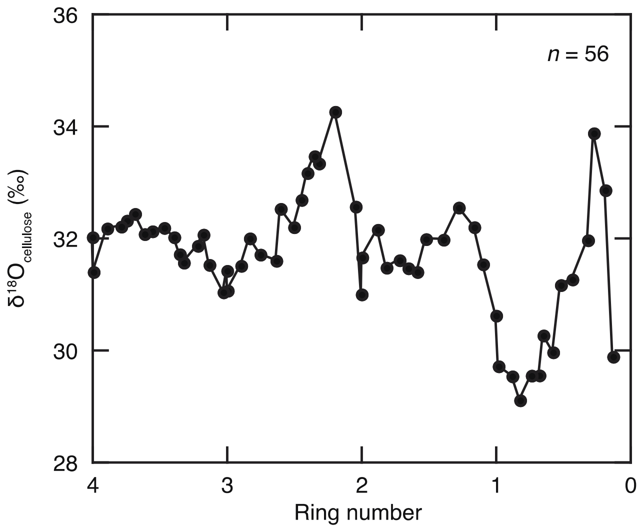

Figure 6 High-resolution $\delta^{18}O$ data from a single Māmane sample. The direction of growth is left to right.

Radiocarbon dating:

We extracted cellulose from four rings from each of four samples (M14, M15, M42, and MamSlab) for radiocarbon analysis at the Woods Hole Oceanographic Institution National Ocean Sciences AMS Facility. Because the trees proved to be significantly older than we had hypothesized, the dating error was large. The outermost (i.e., youngest) ring for each of the samples was calculated as follows (range includes the dating error): MamSlab = 1970-2001, M14 = 1954-2002, M15 = 1959-2001, and M42 = 1966-1991. Although the dates were imprecise, the recognition that these all represented trees that had stopped growing more than a decade ago greatly facilitated the alignment of the records with our well-dated MKM04A sample, which is the only sample to have been cored from a living tree. Because these trees were older than initially thought, the compiled $\delta^{13}C$ record extends a greater length in time than expected, and likely reaches back to the late 1800s. One possible alignment, based on the ^{14}C dates, between mean annual precipitation and $\delta^{13}C$ values is shown in Fig. 7. For this alignment high values of $\delta^{13}C$ correspond to lower levels of mean annual precipitation (as expected), but this correspondence disappears pre-1940.

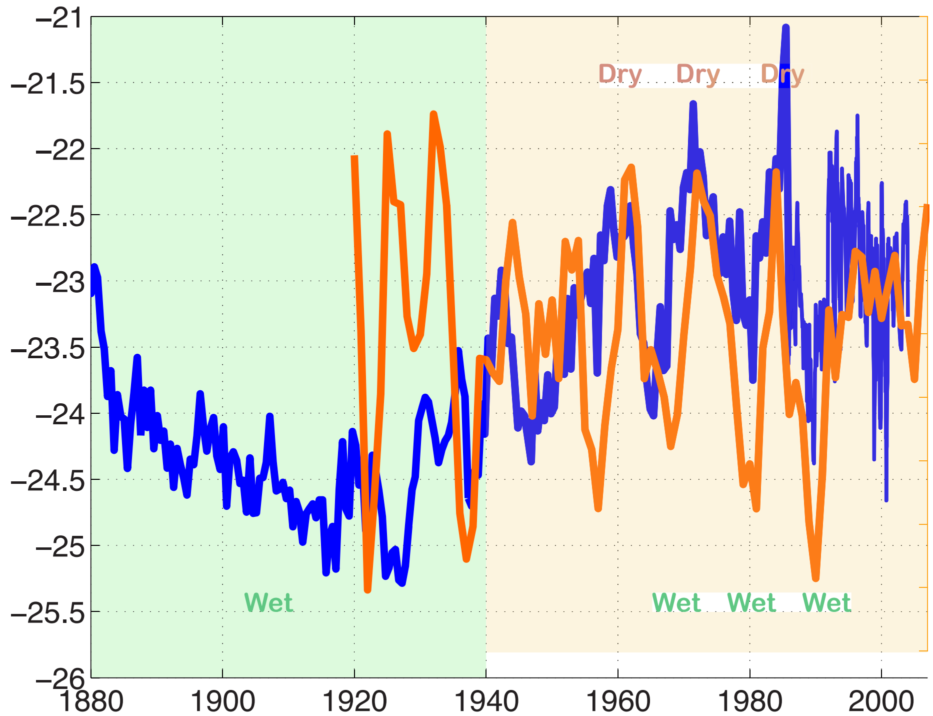

Figure 7. Preliminary plot showing averaged δ^{13}C data determined from all samples and mean annual precipitation. Note the decadal-scale correlation between precipitation and δ^{13}C for the period since 1940. We hypothesize that the poorer correlation pre-1940 is due to the limited number of samples measured for this period and the compounding effect of irregular growth rings.

E. ANALYSIS AND FINDINGS:

Identification of annual growth rings in Māmane wood

Annual growth rings are suggested but not confirmed from anatomical observations of Māmane wood. Here we used high-resolution (intra-ring) measurements of δ^{13}C and δ$^{18}O_{cellulose}$ across Māmane wood to confirm the annual nature of these rings (Fig. 6 and 8). We observed intra-ring variations that on average exceed 1‰ for both δ^{13}C and δ$^{18}O_{cellulose}$ (Fig. 6 and 8). The minima in δ^{13}C and δ$^{18}O_{cellulose}$ corresponded to ring boundaries. The corresponding minima in both δ^{13}C and δ$^{18}O_{cellulose}$ values are consistent with interpretation for minima temperatures and maximum precipitation occurring contemporaneously. This is consistent with measurements from nearby weather stations indicating greater precipitation falling during winter relative to summer months. This interpretation is consistent with isotope theory and empirical relationships indicating positive correlations between δ$^{18}O_{cellulose}$ and temperature and increased discrimination against ^{13}C during periods of high water availability. Based on the ring anatomy and intra-ring isotope values, annual rings can thus be identified in the Māmane samples. However, double or missing peaks in δ^{13}C or δ$^{18}O_{cellulose}$ within a growth band, or missing growth bands in different radial sections around the tree trunk increases dating error as the chronology is extended back in time. We recommend extending the high-resolution δ$^{18}O_{cellulose}$ data to match the length of the high-resolution $\delta^{13}C$ record produced here. The lack of high-resolution isotope data beyond the year 1940 hampers efforts to correlate these isotope values with climate parameters.

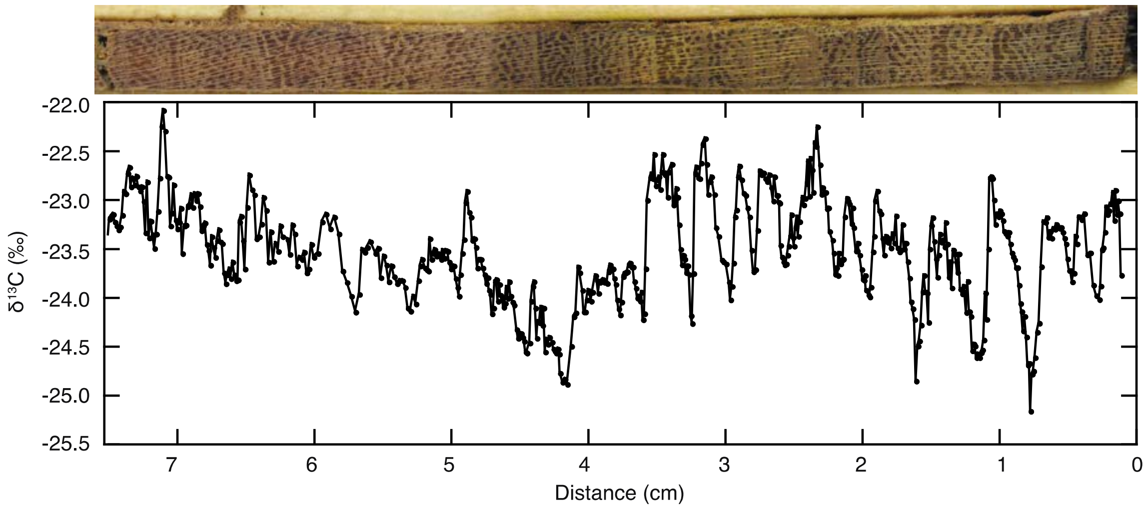

Figure 8. A repeating cyclic pattern of increasing and decreasing $\delta^{13}C$ values was identified within each anatomically distinct growth band. High-resolution $\delta^{13}C$ data shown here for MKM04A are aligned with an image of the core. Similar changes in $\delta^{13}C$ value have been observed in 10 genera of evergreen trees growing around the world, including from other tropical locations, and are interpreted as resulting from seasonal changes in precipitation and post-photosynthetic remobilization of carbon (Schubert and Jahren 2011, *GCA*). Direction of growth is from left to right.

Determination of seasonal climate

We compiled a comprehensive dataset that included high-resolution $\delta^{18}O_{cellulose}$ data (defined as $\geq$3 measurements per ring) from a total of 781 distinct rings from 31 sites spanning 112 degrees of latitude. This dataset includes the data on Māmane tree rings produced here. The resultant dataset was taxonomically diverse and included 12 angiosperm genera (*Carapa*, *Cordia*, *Goupia*, *Hyeronima*, *Ocotea*, *Populus*, *Quercus*, *Rhizophora*, *Samanea*, *Sophora*, *Tachigali*, and *Tectona*) and 7 conifer genera (*Larix*, *Metasequoia*, *Picea*, *Pinus*, *Podocarpus*, *Sequoia*, and *Tsuga*). For each, we measured the seasonal change in $\delta^{18}O_{cellulose}$ ($\Delta\delta^{18}O_{cellulose}$) as the average difference between the extreme $\delta^{18}O_{cellulose}$ values obtained nearest the point of highest ($\delta^{18}O_{cellulose(Tmax)}$) and lowest ($\delta^{18}O_{cellulose(Tmin)}$) growing season temperatures. We compared this seasonal change in $\delta^{18}O_{cellulose}$ to the seasonal change in the $\delta^{18}O$ value of meteoric water ($\delta^{18}O_{MW}$) at each of the sites. From this we found that the seasonal change in $\delta^{18}O_{cellulose}$ is dampened by 1/3 relative to the seasonal change in $\delta^{18}O_{MW}$. Thus we were able to relate seasonal changes in $\delta^{18}O_{cellulose}$ to seasonal changes in $\delta^{18}O_{MW}$ at each site. Because both fundamental physical chemistry and empirical datasets suggest that both the temperature and precipitation amount exert an influence over the isotopic composition of the resultant rainfall we quantitatively tested the relationship between the seasonal change in $\delta^{18}O_{MW}$ and these two climate parameters. For this we compiled the average monthly precipitation (mm), temperature (^{o}C), and $\delta^{18}O_{MW}$ value ($\delta^{18}O_{MW(month)}$) for each of 365 globally distributed sites using the International Atomic Energy Agency (IAEA) Global Network of Isotopes in Precipitation (GNIP) month-by-month database. We then determined an empirical relationship between temperature and $\delta^{18}O_{MW}$ value that allowed us to relate seasonal changes in temperature to seasonal changes in $\delta^{18}O_{cellulose}$ (by knowing that seasonal changes in $\delta^{18}O_{cellulose}$ are dampened relative to seasonal changes in $\delta^{18}O_{MW}$, which are driven by seasonal changes in temperature). We found, however, that this relationship was quite poor for tropical sites in which seasonal changes in temperature are small, yet seasonal changes in precipitation amount can be large. By including a term to account for seasonal changes in precipitation amount, we determined a global relationship relating seasonal changes in $\delta^{18}O_{cellulose}$ to seasonal changes in temperature and precipitation amount:

$$\Delta\delta^{18}O_{cellulose(model)} = [(17.57T_{max}) / (39.89 + 0.44T_{max}) - (17.57T_{min}) / (39.89 + 0.44T_{min}) + A(P_{winter} - P_{summer})]*M$$

where $T_{min} \geq 0$ °C, $A = 0.0082$, and $M = 0.66$ based on empirical relationships. Comparison of $\Delta\delta^{18}O_{cellulose}$ to $\Delta\delta^{18}O_{cellulose(model)}$ shows that measured intra-annual changes in $\delta^{18}O_{cellulose}$ determined across tree rings can be modeled by seasonal changes in temperature and precipitation amount ($R^2 = 0.82$). The value for $M = 0.66$ determined here is consistent with previous estimates (0.52-0.77); varying the value for M within this range had only a small affect on the correlation coefficient we determined ($R^2 = 0.82$) for the 1:1 line, $\Delta\delta^{18}O_{cellulose} = \Delta\delta^{18}O_{cellulose(model)}$ ($R^2 = 0.75$ for slope = 0.52; $R^2 = 0.79$ for slope = 0.77). The value of A = 0.0082, which was optimized for the modern precipitation dataset, is nearly identical to the value that yields the highest correlation with the tree-ring dataset (A = 0.0091 increases the R^2 value from 0.81 to 0.82). This equation thus provides a way of interpreting intra-annual changes in $\delta^{18}O_{cellulose}$ that is applicable to diverse tree species with different leaf morphologies and growth strategies growing under a wide range of climate conditions.

Because the above equation has four unknowns (T_{max}, T_{min}, P_{winter}, and P_{summer}), additional information or equations are required to solve for these variables. Two of these values, P_{winter} and P_{summer}, can be determined for Māmane from high-resolution, intra-ring $\delta^{13}C$ measurements using equations presented in Schubert and Jahren (2011), and demonstrated within Schubert et al. (2012) for other evergreen species. We can then use the high-resolution $\delta^{18}O_{cellulose}$ data shown in Fig. 6, to quantify both maximum and minimum average monthly temperatures of the annual cycle (T_{max} and T_{min}).

We illustrate the potential for this technique to accurately predict seasonal climate in Hawaii by applying it to the Māmane data generated here. We first determine P_{summer} and P_{winter} from the intra-ring $\delta^{13}C$ data (after Schubert and Jahren, 2011; Schubert et al., 2012) to be equal to 172 and 230 mm, respectively. We then can use these $\delta^{13}C$-based estimates of P_{winter} and P_{summer} to calculate T_{max} and T_{min} using the $\delta^{18}O_{cellulose}$ data (Fig. 6). Here, we calculate maximum and minimum average monthly temperatures equal to 18.5 and 8.6 °C, respectively. We note that the actual values reported from a nearby weather gauge are 146 and 256 mm (summer and winter), and 15.5 and 11.6 °C (summer and winter). These results suggest that seasonal climate (T_{max}, T_{min}, P_{winter}, and P_{summer}) could be accurately quantified in the Hawaiian Islands using intra-ring isotope profiles on Māmane trees.

F. CONCLUSIONS AND RECOMMENDATIONS:

One of the significant challenges in this work was to verify the alignments of the $\delta^{13}C$ records made on different trees. Because of the limited number of samples and non-uniform tree rings characteristic of Māmane, standard dendrochronological methods could not be used. We attempted to use ^{14}C dates to better constrain the sample ages, but the trees were determined to be older than we expected. Therefore, all the rings that were dated yielded ages older than the targeted bomb spike, which resulted in less precise ages. Future work would date tree rings towards the outer part of each sample. These additional dates would give better constraint to the alignment of our $\delta^{13}C$ records.

Determination of annual growth bands in Māmane wood allows for this species to be used for paleoclimate reconstructions. Intra-ring $\delta^{13}C$ measurements can be used to quantify seasonal precipitation, whereas ring-to-ring $\delta^{13}C$ measurements can be used to infer long-term qualitative trends in water-availability at a site. Although the low-resolution $\delta^{13}C$ records potentially allow for longer climate records to be produced more quickly than high-resolution records, variability in the absolute $\delta^{13}C$ values among closely growing samples complicates the making of a quantitative reconstruction of mean annual precipitation. Whole-ring $\delta^{13}C$ measurements on Māmane, in isolation, are therefore unlikely to provide a quantitative reconstruction of changes in mean annual climate. These records do however, allow for relative trends in water availability to be detected as closely spaced trees do show similar trends that are consistent with independent climate records.

Our work on high-resolution $\delta^{18}O$ measurements made on cellulose extracted from Māmane tree rings shows that intra-annual changes in $\delta^{18}O_{cellulose}$ reflect changes in seasonal temperatures and precipitation amount. Using a combined, multi-isotope approach, high-resolution $\delta^{13}C$ and $\delta^{18}O$ measurements can be used to reconstruct the ranges in temperatures and precipitation amount that a forest experienced during its lifetime. Although the $\delta^{18}O$ record produced here for Māmane is short, the good agreement between our calculated seasonal climate paramaeters and measured values suggests potential for using this combined approach to extend the record to match the length of the $\delta^{13}C$ records produced here.

Because of the short length of the $\delta^{18}O_{cellulose}$ record produced here, we cannot evaluate the effects of changes in the height of the trade wind inversion or large-scale shifts in vapor transport patterns on long-term trends in $\delta^{18}O_{cellulose}$. Complete evaluation of the effects of inconsistent growth rates, different tree-rooting depths, and the impact of snowmelt on the $\delta^{18}O$ value of tree-ring cellulose at the beginning of the growing season may play a role at some sites, but were not evaluated here. The analysis produced here does show, however, that variation in $\delta^{18}O_{cellulose}$ is dominated by variability in seasonal temperature and precipitation. Like the $\delta^{13}C$ record, differences in the absolute $\delta^{18}O_{cellulose}$ value are likely to exist among even closely spaced trees, making quantitative reconstructions of mean annual conditions from whole-ring measurements difficult. As shown with a global dataset of high-resolution $\delta^{13}C$ records (Schubert and Jahren, 2011), the relative changes in $\delta^{18}O_{cellulose}$ should remain consistent regardless of differences in absolute values. It is important to note that although species differences, elevation, and the distances from the coast are known to affect absolute $\delta^{18}O$ values, these parameters are not an issue when interpreting intra-ring records because none of these parameters change seasonally.

Workers have commonly correlated intra-annual $\delta^{18}O_{cellulose}$ measurements with seasonal temperature, precipitation, and/or humidity (which is related to temperature and precipitation) data for sites with known climate records in order to calibrate a local climate proxy. Because it is not possible to make these calibration relationships on cellulose extracted from samples for which no instrumental records exist, it is important to have a general, widely applicable relationship that can be used on samples from remote sites or with limited modern climate data. The wide applicability of our intra-annual isotope proxies to both angiosperms and gymnosperms growing under a wide range of climate conditions worldwide makes it particularly relevant to reconstructing changes in seasonal climate across the Pacific Islands. Based on these results, additional work to produce a long-term, high-resolution $\delta^{18}O_{cellulose}$ record of Māmane trees and extension of the Māmane $\delta^{13}C$ record *via* collection and analysis of sub-fossil wood could produce a first opportunity to reconstruct seasonal climate using the new dual $\delta^{13}C$ and $\delta^{18}O_{cellulose}$ approach developed here.

G. OUTREACH:

Public talks:

University of Louisiana at Lafayette, "Reconstruction of past climate from tree rings," March 6, 2013.

Southern Methodist University, "Photosynthetic responses of plants to changing climate," March 23, 2012.

University of Louisiana at Lafayette, "High-resolution tree-ring records as a proxy for seasonal climate," February 27, 2012.

University of Hawaii at Mānoa, "Climate reconstructions from a new analysis of tree rings," February 10, 2012.

H. SCIENCE OUTPUTS:

Peer-review articles:

Draft circulating to co-authors (to be submitted to *Geochimica et Cosmochimica Acta*):

Schubert, BA, Jahren, AH, Sternberg, LSL, Steffenrem, A, and Kvaalen, H. "Determination of seasonal temperature from high-resolution profiles of oxygen isotopes in tree-ring cellulose."

In preparation:

Schubert, BA, Timmermann, A, Jahren, AH, and Hart, P. "Hawaiian precipitation reconstructed from carbon isotope measurements in tree rings."

Presentations:

Schubert, BA, Jahren, AH, Timmermann, A. "High-resolution carbon isotope analysis of Māmane trees," Holocene Paleoclimate in the Hawaiian Islands and Its Large-Scale Context, Hawai'i, November 7-8, 2011 (oral).

Timmermann, A, Schubert, BA, Jahren, AH, Hart, P. "Stable Carbon Isotope Variations of Māmane Trees – a Paleo Raingauge for Hawai`i? PICSC/PICCC Science Review Symposium, July 15, 2013 (oral).

Schubert, BA and Jahren, AH. "High-resolution oxygen isotope profiles in tree-rings and how to interpret them," American Geophysical Union Fall Meeting, December 12, 2013 (oral).

Meeting Session Convener:

Goldschmidt 2014 Theme 19e: "Seasonally-Resolved Archives of Environmental and Climate Change: Opportunities and Challenges," Goldschmidt, Sacramento, CA, June 8-13, 2014.