Southwest Climate Science Center –FINAL TECHNICAL Report
(Section D.2- Special Terms and Conditions of Cooperative Agreement Award Notice)

1. **USGS GRANT/COOP AGREEMENT G13AC00339**

2. **PROJECT TITLE: Influence of interannual North Pacific Jet variability on Sierra Nevada Fire regimes**

3. **PRINCIPAL INVESTIGATOR EMAIL:** trouet@ltrr.arizona.edu

4. **CO-PRINCIPAL INVESTIGATOR EMAIL: jlbetanc@usgs.gov**

5. **PERSONNEL**
    a. Principal Investigator Dr. Valerie Trouet, University of Arizona
    b. Co-Investigators Dr. Julio Betancourt, USGS
    c. Undergraduate Students none
    d. Graduate Students – MS or MA Robert Shepard, University of Arizona
    e. Graduate Students – Ph.D. none
    f. Postdoctoral Researchers Dr. Flurin Babst and Dr. Soumaya Belmecheri, University of Arizona
    g. Other Mary Glueck, University of Arizona, research specialist

6. **PROJECT START DATE** :09/2013

7. **END DATE:** 09/2015 (no cost extension until 06/2016)

8. **PURPOSE AND OBJECTIVES:** *Describe the project goals and objectives, with particular emphasis on any changes made to the objectives as stated in the original proposal. If the objectives have been added to, eliminated, or modified, please explain why these changes have been made.*

Originally, we had two primary objectives for this project:

(1) To study **North Pacific Jet (NPJ) climatology** on interannual to decadal time scales by (a) extending the instrumental NPJ period back in time based on Twentieth Century Re-analysis data and (b) by developing a tree-ring based reconstruction of the winter NPJ position.

(2). To analyze the **influence of NPJ position on Sierra Nevada (SN) fire regimes**. For this purpose, we planned to use historical SN fire regime data to establish a pre-settlement NPJ-fire relationship and recent annual area burned data to determine whether this relationship persists into the 21st century.

We have reached **objective 1a** in a study of twentieth century NPJ climatology (Belmecheri et al. in prep; results section a), in which we develop a set of spatially and seasonally explicit jet stream indices across the Northern Hemisphere and relate them to climatological and ecosystem variables.

We had to deviate from our original approach to **objective 1b** slightly, because we found that a tree-ring based NPJ reconstruction based on existing tree-ring records from CA and the Northern Rockies was not feasible prior to ~1870 CE (see first progress report). We therefore have modified our approach for NPJ reconstruction and in collaboration with Eugene Wahl and Eduardo Zorita have applied a proxy surrogate reconstruction approach to reconstruct the position of the North Pacific Jet back to 1571 CE (Wahl et al. in prep.; results section d). This approach has also allowed us to analyze the influence of NPJ position on historical Sierra Nevada (SN) fire regimes (**objective 2**).

In addition to the above two objectives, we have leveraged the tree-ring and fire history data compiled in the framework of this project for two additional analyses. We combined the master chronology developed from the CA tree-ring data with an existing winter temperature reconstruction for CA (Wahl et al. 2014) to reconstruct (1500-1980 CE) Sierra Nevada (SN) April 1 Snow Water Equivalent (SWE) (Belmecheri et al. 2016; results section b). We prioritized this research avenue in spring and summer 2015 to provide a timely historical context for the 2015 April 1 SWE record low. Our prioritization paid off, because our work was published in *Nature Climate Change* in September 2015 and was picked up by a wide range of national and international media outlets (see section 14).

The SN fire history data set is unique in its completeness and allowed us to investigate many aspects of past SN fire regimes, including potential North Pacific Jet links (see results section d), but also socio-ecologically induced fire regime shifts and fire-climate modulations (results section c).

These objectives will allow us, as originally planned, to develop **data products (e.g.,** SN April 1 SWE reconstruction; results section b**) and management applications (e.g.,** projected climate-ecosystem reorganization in SN forests; results section d) **that can be translated to fire and fuels managers.**

9. **ORGANIZATION AND APPROACH:** *Explain how each research task is being conducted. Briefly list which research methods are being used to achieve results, including any new methods that were not described in the original proposal. Please also discuss any problems or delays encountered in conducting the research during the reporting period.*

As described above in section 8, we have organized the research tasks around the publication of four peer-reviewed publications. One of these publications (Belmecheri et al. 2016) has been published, the other three are in preparation and are planned to be submitted for publication in Spring 2016. SWCSC post-doctoral researcher Belmecheri is the lead author (and Trouet senior author) on two papers (results sections a and b) and the two other papers result from collaborations with Eugene Wahl and Eduardo Zorita (results sections d) and with Alan Taylor (results sections c).

The results – as well as methods – for each of the publications are described below in section 10. The main new methods that we applied that were not described in the original proposal include:

- **for the calculation of northern hemisphere jet (NHJ) indices**: a bottom-up approach informed by the seasonal and spatial coherence in NHJ variability that allows us to identify seasonally and longitudinally explicit indices of NHJ latitudinal variability. For more details, see results section a.
- **for the reconstruction of the North Pacific Jet (NPJ)**: we used Proxy Surrogate Reconstruction (PSR) model simulations in combination with annually-resolved paleoclimatic reconstructions to study the behavior of the NPJ over the past 500 years and to identify its influence on extreme dry/wet years and widespread/low-extent fire years in California**.** For more details, see results section d.

In addition to these science research tasks, we have organized a Technical Advisory Committee (TAC) meeting in Tucson AZ, on September 14-15, 2015. Participants of the meeting included all TAC members (see section 13b). During this TAC meeting (program attached at the end of this report), we have presented and discussed the results for the four research tasks. In addition to this, we have focused our discussion on the potential applications/implementation of our project outcomes. We discussed how our research will be relevant to (1) improving long-lead (weeks to months) forecasts of annual area burned, important for fire preparedness, anticipating fire suppression budgets, and scheduling prescribed fires; (2) estimating long-term probabilities for annual fire occurrence and conditions favorable/ unfavorable for controlled fires (for meeting long-term treatment targets) from periodicities identified in both the NPJ reconstruction and the fire-scar records; (3) evaluate the extent to which NPJ and regional annual fire occurrence has and will change due to anthropogenic warming.

10. **RESULTS:**

a. **TWENTIETH CENTURY NORTHERN HEMISPHERE JET (NHJ) STREAM VARIABILITY; BELMECHERI ET AL. (IN PREP.)**

Introduction

The increasing number of mid-latitude weather extremes in recent decades, the role of the NHJ in modulating these extremes, and potential future changes in NHJ amplitude and persistence have led to a recent surge in research interest in NHJ climatology (Woollings et al. 2014, Simpson et al. 2014). This interest is not limited to the meteorological and climate modeling community, but has diffused into research fields that study the impact of climate and future climate change on ecosystem and societal dynamics (e.g., Stark et al. 2016). However, the NHJ is a complex system of thousands of kilometers in length, hundreds of kilometers in width and also some kilometers in depth. To assess the socio-economic and ecosystem impacts of future changes in the NHJ features, a detailed NHJ climatology and NHJ evaluation metrics (or tools) that can be readily compared to societal and ecosystem variables are needed.

We here present a NHJ climatology that spans the entire Northern Hemisphere and includes all seasons. Our methodology is an alternative for the previous depictions and characterization of the NHJ mean latitudinal position and variability. We apply a novel bottom-up approach informed by the seasonal and spatial coherence in NHJ variability that allows us to identify seasonally and longitudinally explicit indices of NHJ latitudinal variability. We then examine how the various NHJ indices govern the geographical distribution of precipitation and temperature variability and their link to atmospheric circulation patterns.

In pursuing the diagnosis of 20th century NHJ climatology, our main goal is to develop seasonal and spatial NHJ latitudinal position indices that can be utilized as independent variables (from atmospheric circulation indices) to understand inter-annual precipitation and temperature variability in the northern hemisphere. Our intention with the development of NHJ indices is to (reduce) the vast complexity of NHJ dynamics into variables that are useful to researchers and managers in related fields to link ecosystem (e.g., forest disturbances, phenology, agricultural and forest productivity) and socio-economic (e.g. frequency of extreme weather events and related impacts) dynamics to upper-level atmospheric patterns. As an application example, we analyze the relationship between NHJ indices and spatial fields of the Normalized Difference Vegetation Index (NDVI) to illustrate the relationship between the NHJ latitudinal position, temperature anomalies, and terrestrial productivity.

Methods

To identify the latitudinal position of the NHJ, we used the Twentieth Century Reanalysis V2 (20CR) data set (1930-2012 CE) with a 2° spatial resolution and a one-month temporal resolution. From this data set, we extracted the grid of mean monthly 300 hPa scalar wind (m s^{-1}) for the entire NH. For each month, we defined the latitudinal position of the NHJ as the latitude at which the monthly averaged 300 hPa zonal wind speed was strongest (Barton and Ellis 2009) and extracted this NHJ latitude for each longitudinal grid box and for each month. This provides 12 monthly matrices of NHJ latitudinal position per longitude for 83 years (1930-2012 CE).

To develop NHJ latitudinal position indices from the above-described matrices, we proceeded as follows:
1- Per month, we correlated the time series of NHJ latitudinal position between neighboring longitudes, thus creating 12 monthly correlation matrices (180 X 180 longitudes) of NHJ longitudinal coherence. For each monthly correlation matrix, we computed average interseries correlation coefficients (rbar) for each longitude using correlation windows ranging from 1 (2º) to 10 (20º) neighboring longitudes, by increment of 2º. This resulted in 10 (longitudinal windows) rbar values for each longitude and for each month.
2- We then correlated the spatial series of 180 rbar values (1 value per longitude) between months for each of the 10 rbar correlation windows (e.g., the 10º rbar of December was correlated with the 10º rbar of January). These correlations resulted in 10 (12*12) matrices of between-months correlations, and allowed the identification of temporal coherence of NHJ latitudinal position.
3- The series of monthly NHJ position were most coherent (positively and significantly correlated for all rbar windows) for the months of January-February (JF), April-May (AM), July-August (JA), and October-November (ON) and we selected these four combinations of months to determine our seasonal (winter, spring, summer, and fall, respectively) NHJ indices.
4- We averaged monthly NHJ latitudinal position matrices for the four seasons identified in step 4 and re-computed longitudinal rbar-values using 10 correlation windows (cfr. step 2). The rbar values of different rbar window sizes show similar longitudinal sectors where the NHJ latitudinal position shows the strongest spatial coherence (defined as NHJ cores hereafter) with smoother features for the 20º window compared to the 2º window.
5- We applied a peak detection method to the rbar values of 10º longitudinal windows to determine the spatially coherent NHJ cores for each season.

Based on the longitudinal coherence of bimonthly NHJ time series, we detected 32 NHJ cores (8 for winter (JF), 8 for spring (AM), 7 for Summer (JA), 9 for fall (ON)). We averaged the latitudinal NHJ position over the longitudes in each of these NHJ cores to create 32 time series (1930-2012) of spatially and seasonally explicit latitudinal NHJ positions (NHJ index hereafter). We related NHJ index anomalies to regional climate in a correlation map analysis using the KNMI Climate Explorer (Trouet and Van Oldenborgh 2013). Positive NHJ index anomalies correspond to northerly positions and negative NHJ anomalies to southerly positions. We further compared the NHJ indices with atmospheric circulation indices (1930-2012), including El Niño southern oscillation (ENSO), Pacific North-America mode (PNA), North Atlantic oscillation (NAO), and Arctic oscillation (AO). We further conducted linear trend analyses for each NHJ index.

Results

Seasonal and spatial NHJ index distribution

The distribution of the NHJ positions -averaged over all longitudes - between seasons mimics the seasonal NH temperature gradient (Fig. 1), with the NHJ in a more equatorward position during winter (34±8 N) compared to spring (48±6 N), summer (49±6.5 N), and fall (42±7.5 N).

The amplitude of the latitudinal NHJ distribution is larger in the eastern hemisphere than in the western hemisphere (Fig. 1): in the northern African, Asian, and western Pacific regions, the bimonthly NHJ positions show single peak patterns and are primarily continuous between longitudes, particularly for the winter months (Fig. 1). A wider or multimodal distribution is observed over the North Atlantic and Eastern Pacific sectors for the winter months.

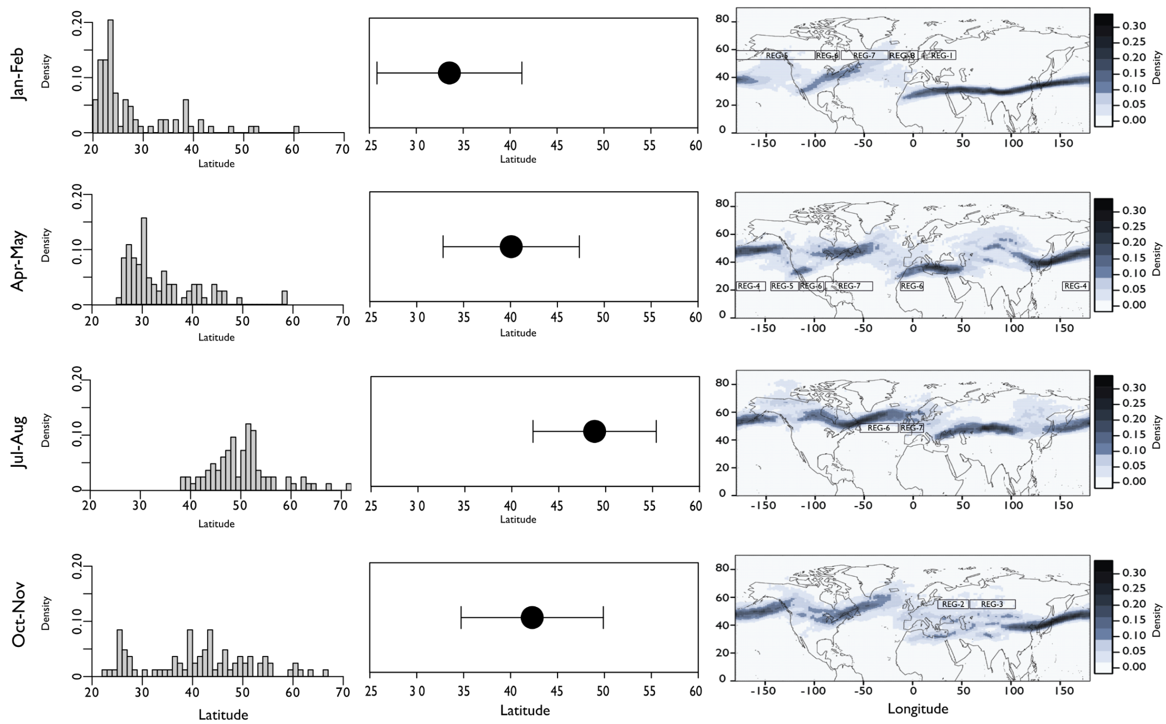

Figure 1. **Seasonal NHJ position**. **Left:** Probability density functions (PDFs) of the NHJ latitudinal position for each season (January-February, April-May, July-August, October-November). **Center:** Mean NHJ latitudinal position for each season derived by averaging the seasonal NHJ indices across the NH, with bars indicating ranges of ±1 standard deviation. **Right:** The geographic regions identified in this study**.** Black boxes indicate the longitudinal sectors for each seasons and are labelled with their abbreviations and numbered based on the total number of regions identified for each season. The grey shading represents the frequency of NHJ index occurrence at each longitude.

NHJ position and climate variability

The season with the most significant correlations between NHJ indices and precipitation is winter (JF). The regions showing significant correlations with precipitation during JF are mainly located over the N. Pacific/North America (regions JF 5, 6, and 7) (Fig. 2) and the N. Atlantic (region JF 8) sectors.

The NHJ position influences regional precipitation variability through its modulation of storm tracks: when the NHJ is in a northerly position, storm tracks bringing precipitation are deflected to the northern latitudes - resulting in positive correlations between NHJ index and precipitation anomalies in these regions - and vice versa. This is demonstrated for regions JF-REG5 during the winter season (Fig. 2 middle panel): a northerly (southerly) NHJ position is related to positive (negative) precipitation anomalies in NW America and negative (positive) precipitation anomalies in the SW. The NHJ position in the Northern Pacific/North America region thus creates a dipole precipitation pattern during the winter season. A strong positive pressure ridge off the American West Coast (Fig. 2 bottom panel) can explain this dipole pattern. A similarly consistent and significant dipole is observed in the temperature correlation map (Fig. 2 top panel) for the northern/central American sectors northerly NHJ anomalies are associated with warmer temperatures in the SE US and Central America and colder temperatures in the western and northern US.

In addition to this, our results support a connection between NHJ variability and ocean-atmosphere interactions over the northern Pacific Ocean: we found significant correlations between winter and spring NHJ indices for regions 5 and 6 and PNA and ENSO patterns. The relationship is negative, with northerly NHJ positions associated with negative ENSO and PNA indices. The North-South shift of the NHJ reflects a North-South shift of the Pacific storm tracks and projects strongly upon the PNA pattern. The positive precipitation anomalies in the American Southwest associated with positive ENSO phases and southerly NHJ position correspond to an amplified storm track and more persistent NHJ affecting rainfall in the southern coast of North America.

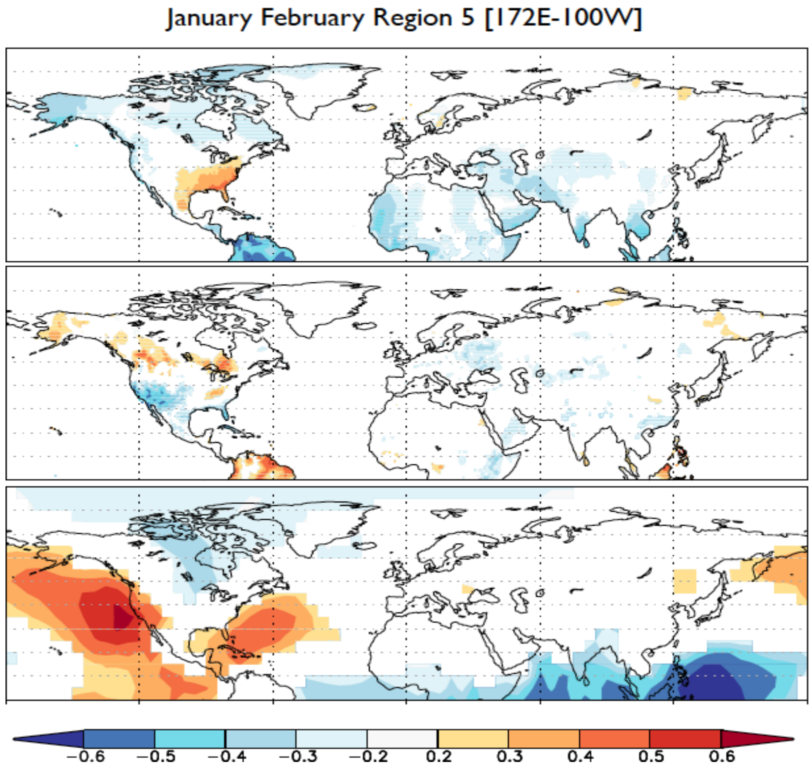

Figure 2. Pearson correlation maps (1930-2012CE) of Jan-Feb NHJ index 5 (172E-100W) with gridded 0.5º CRU TS3.23 Jan-Feb temperature (Top), precipitation (middle), and sea level pressure (bottom) anomaly data (Kaplan et al 2000). The NHJ position exhibits a significant relationship with precipitation for the eastern part of the N. American sector where northerly positions are related to positive anomalies in the NE US.

Application: NHJ position and terrestrial productivity

Our NHJ indices can be used to study the impact of NHJ variability in various ecosystem (e.g., phenology, wildfires, ecosystem productivity), extreme weather (e.g., hurricanes, heat waves, floods), and societal processes in a spatially explicit way. As an example, we compared the spring NHJ indices to a satellite-derived NDVI time series (1981-2006 CE), a proxy for terrestrial productivity that integrates numerous photosynthetic factors related to ecosystem structure and function. The NHJ region that showed spatially the most significant correlations with NDVI was Spring (April-May) region 4 (152W-150E; Fig 3 right panel), which displayed a negative and spatially broad correlation with NDVI over northern Eurasia. The region 4 NHJ index was also negatively correlated with NDVI over Scandinavia and western N. America. The correlations were positive with NDVI in Northern-Eastern America (mainly centered on the great lakes region in the US and Canada). Northerly spring NHJ positions in the Pacific thus result in reduced terrestrial productivity in northern Eurasia and increased productivity in NE America. Furthermore, the NHJ index-NDVI correlation map mimics the NHJ-temperature correlation map (Fig. 3 left panel). The negative correlations with NDVI correspond to negative correlation of NHJ position with temperature anomalies and vice versa.

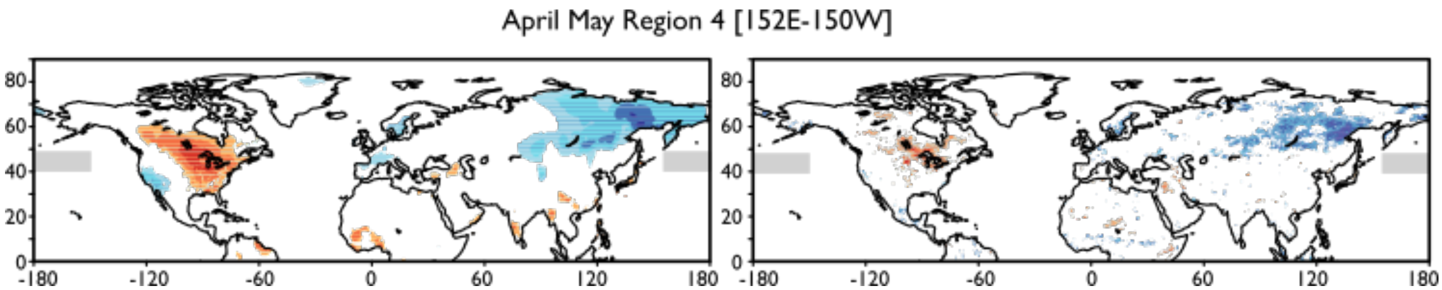

Figure 3. Pearson correlation maps of Apr-May NHJ index region 4 (North Pacific) with gridded 0.5º CRU TS3.23 Apr-May Temperature (left) and Normalized Difference Vegetation Index-NDVI data (Kaplan et al 2000; right) for 1981-2006. The NHJ index over a large portion of the eastern pacific sector shows a typical W- E dipole with colder temperature and warmer temperature respectively associated with northerly NHJ position. The grey box indicates the NHJ index longitudinal sector.

B. MULTI-CENTURY EVALUATION OF SIERRA NEVADA SNOWPACK; BELMECHERI ET AL. (2016)

As described in the first progress report for this grant (03/12/2015), we found that a tree-ring based NPJ reconstruction based on existing tree-ring records from California (CA) and the Northern Rockies (NR) was not be feasible prior to ~1870 CE. In an effort to leverage the work we had done to compile 1,935 blue oak (*Quercus douglasii*) tree-ring series from 33 sites (Meko et al. 2011) in a cross-dating exercise to develop one CA master chronology, we combined this CA master chronology with an existing winter temperature reconstruction for CA (Wahl et al. 2014) to reconstruct (1500-1980 CE) April 1 Snow Water Equivalent (SWE) over the whole Sierra Nevada range. Our reconstruction explains 63% of the variance in Sierra Nevada April 1 SWE and reveals that the 2015 SWE low is unprecedented in the context of the past 500 years (Fig. 4). The estimated return interval for the 2015 SWE value — as calculated based on a generalized extreme value (GEV) distribution — is 3,100 years and confirms its exceptional character. We also find that the 2015 SWE value is strongly exceptional — exceeding the 95% confidence interval for a 1,000-year return period — at low-elevation Sierra Nevada sites where winter temperature has strong control over SWE, but less so at high-elevation sites, where it exceeds the 95% confidence interval for only a 95-year return period.

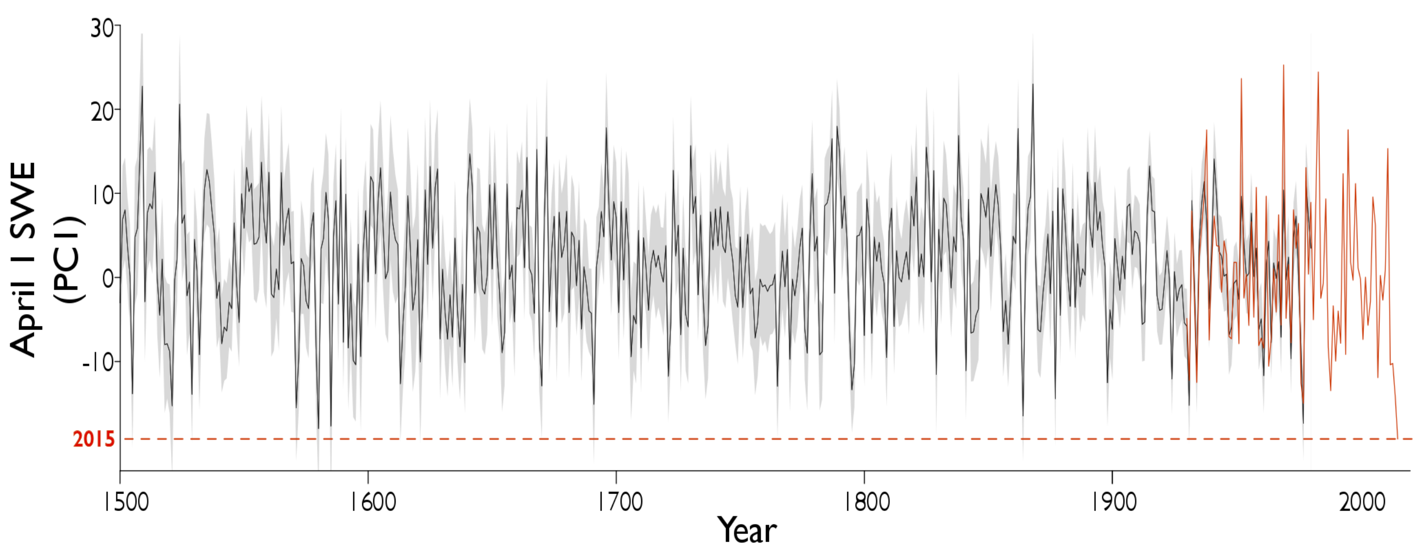

Figure 4. Sierra Nevada April 1 SWE reconstruction (1500-1980 CE). Instrumental (1930–2015; red curve) and reconstructed (1500–1980; black curve) first Principal Component (PC1) of Sierra Nevada 1 April SWE values. The

SWE reconstruction was calibrated against the PC1 of 1 April SWE measurements from 108 Sierra Nevada stations and explains 63% of its variance over the period of overlap (1930–1980). The grey shading around the reconstruction indicates the combined error estimation. The 2015 SWE value is indicated by the red dashed line.

C. ANTHROPOGENIC MODULATION OF HISTORICAL (1600-PRESENT) SIERRA NEVADA FIRE REGIMES; TAYLOR ET AL. (IN PREP.)

We developed a tree-ring based Sierra Nevada (SN) fire history reconstruction that covered the period 1490-1900 CE and merged it with twentieth century annual area burned data (see first progress report; Fig. 5). A spatial correlation map analysis shows that this SN fire time series is strongly correlated with reconstructed summer PDSI (Palmer Drought Severity Index) values over central CA (see first progress report). The SN fire history data set is unique in its completeness and allows us to investigate many aspects of past SN fire regimes, including potential North Pacific Jet links (see results section d). A regime shift analysis of the time series (Fig. 6) reveals three significant shifts that can potentially be related to CA socio-ecological changes in 1776 (CA mission establishment), 1866 (Gold Rush), and 1904 (widespread SN fire suppression). The regime shift analysis of only the fire suppression period with a shorter window shows a shift in 1962 to a period with half the area burned followed by a shift in 1987 to a period with the highest area burned since 1905.

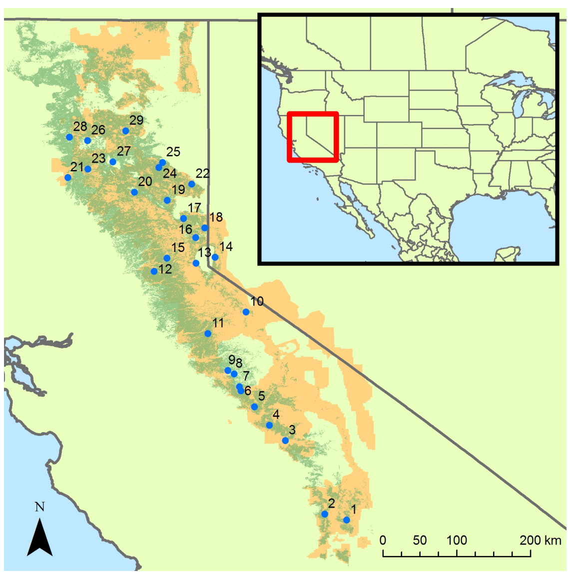

Figure 5. Location of fire scar collection sites in dry forests (green shading) in the Sierra Nevada, USA.

Annual area burned in the Native American period (1600-1768) nearly doubled with the shift to the Spanish-Mexican Period (1769-1848) ($P<0.05$) when the Native American population declined rapidly (Fig. 7). Average annual area burned during the Gold Rush-Settlement period (1849-1904) was similar to the Native American period ($P>0.05$) as the population of California increased to nearly 1.5×10^6 people by 1905. Area burned in the fire suppression period (1905-2014) was four to eight-fold lower ($P<0.05$) than in any other socio-ecological period and the human population climbed to nearly 39×10^6. Also modulation of fire-climate relationships was associated with socio-ecological conditions: there was a remarkable strengthening of the summer moisture-area burned relationship at interannual time scales that began in *ca*. 1770 and persisted for nearly a century. Strengthening of this relationship coincided with change from Native American to Spanish-Mexican socio-ecological conditions and to the 1776 fire regime shift to a period when annual area burned doubled (Fig. 7). The summer moisture-area burned relationship weakened between 1865 and 1910 and after

1950, and the weakening coincided with the end of the Gold Rush and then implementation of a fire suppression policy.

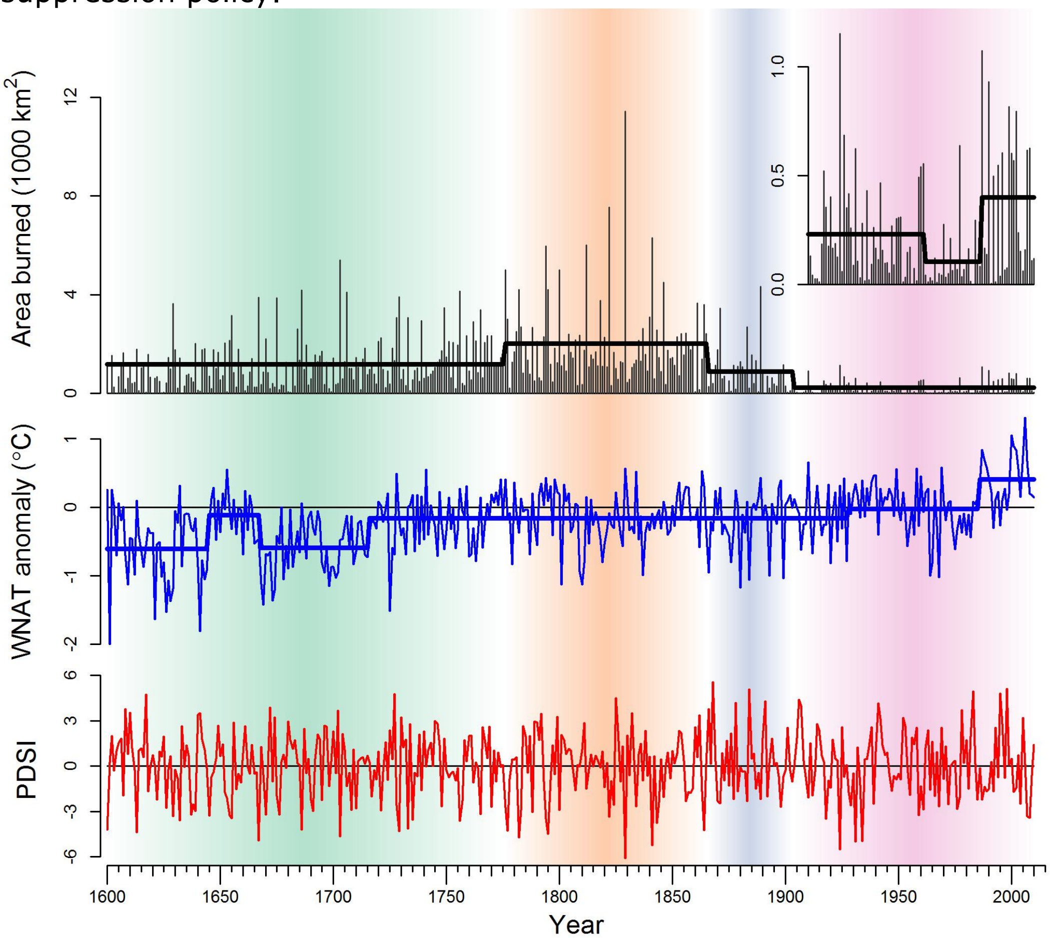

Figure 6. Regime shift analysis of area burned in SN dry forests, summer PDSI (Cook and Krusic 2004), and summer temperature (Briffa et al. 2001). A switch to a new regime (fire or climate) is shown by the horizontal line. The change point (P<0.05) was identified using a 30-year window following Rodionov (2004), except for the 1910-2014 inset period. A 15-year window and change point of P<0.1 was used for this period.

In conclusion, the hypothesis that socio-ecological systems have been pivotal in controlling SN dry forest area burned and modulating fire-climate relationships was supported by our analysis. Interannual climate variability influenced area burned over the entire record of fire. But, humans constrained the climate-area burned relationship through various socio-ecological processes that affected fire-fuel-climate interactions. Area burned across dry forests in the SN doubled with the demise of Native American fire management and became very strongly driven by interannual variation in moisture as fuels became more continuous. Shifts to lower area burned and weaker fire-moisture relationships accompanied periods when livestock were introduced or active suppression was implemented. A strong area burned and climate-area burned response to Native American depopulation in the SN supports a perspective of widespread Native American influence on vegetation and other resources in the Sierra Nevada and in California through fire use (Keeley 2000; Anderson 2005; Lightfoot and Parish 2009).

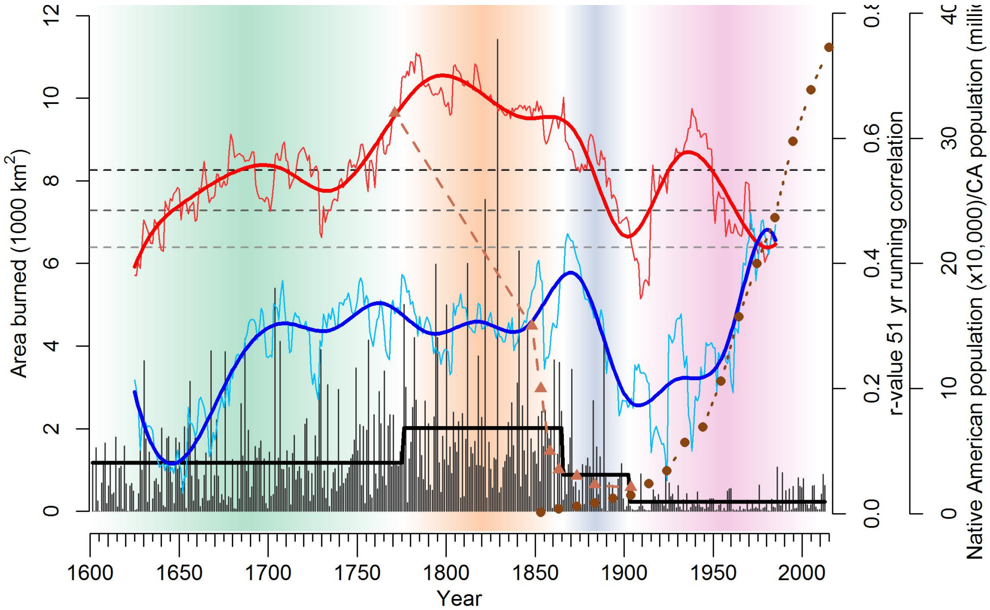

Figure 7. Variation in strength of fire-climate relationships in SN dry forests and CA population size. The values are 51-year running Pearson product moment correlation coefficients between area burned, summer PDSI, and summer temperature plotted on the 26th year of the window. PDSI values and their corresponding correlation coefficients were inverted for presentation.

D. Past and Future Relationships of Fire, Moisture, and Jet Stream Conditions in California; Wahl et al. (in prep.)

As an outcome of the preliminary work on this project, PI Trouet has established a collaboration with Eugene Wahl (NOAA) and Eduardo Zorita (HZG, Germany) to develop a Proxy Surrogate Reconstruction (PSR)-based NPJ reconstruction. PSR is a proxy-model analog method in which data from coupled ocean-atmosphere general circulation model (CGCM) simulations are reordered to maximize temporal agreement between multiple proxy records and commensurate data drawn from the model output. The reordered model data set can be used to more fully characterize climate patterns implied by sparse and diverse proxy data.

We used annually-resolved paleoclimatic reconstructions and PSR model simulations to study the behavior of the North Pacific Jet (NPJ) over the past 500 years and to identify its influence on extreme dry/wet years and widespread/low-extent fire years in California**.** For this purpose, we proxy-based reconstructions of summer soil moisture (Cook et al. 2008), water-year mean precipitation (Diaz and Wahl, 2015), and February-March near-surface air temperature (Wahl et al., 2014) over western and southwestern North America in a PSR method to reconstruct three-dimensional fields of winter (December-February) atmospheric circulation over the period 1571-1977 CE.

We extracted 200 hPa zonal (u) and meridional (v) wind components from the three-dimensional fields for analysis of winter NPJ conditions. We analyzed the latitudinal position and the strength of the reconstructed NPJ during extremely wet/dry years in CA based on a tree-ring reconstruction of October-June precipitation for central and southern California (Griffin and Anchukaitis, 2014), which is nearly independent of the NPJ reconstruction. In a similar way, we stratified NPJ winter conditions according to highest and lowest fire years, as reconstructed based on a completely independent SN-wide fire history record (see results section c). The patterns of the relationship of the u- and v-components of the NPJ with CA precipitation and fire (Figure 8a-d) highlight the spatial similarities between the moisture and fire responses to the NPJ components.

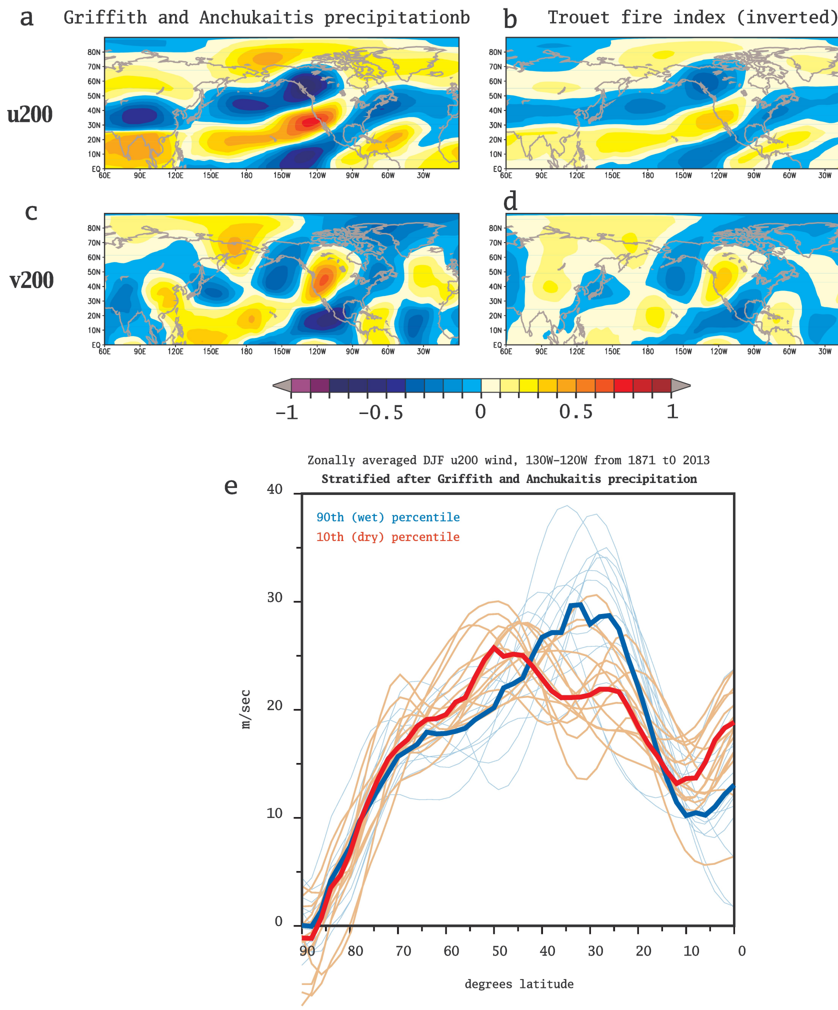

Figure 8. Link between reconstructed winter atmospheric circulation and past SN fire activity and winter precipitation. (a-d) Correlation patterns (1571-1900 CE) between: reconstructed water year precipitation (a) and SN fire activity (b) and reconstructed zonal component of the winter mean 200 hPa u; reconstructed water year precipitation (c) and SN fire activity (d) and reconstructed meridional component of the winter mean 200 hPa wind; rectangles show longitudinal window (120W-130W) used for analysis of maximum 200 hPa u wind. (e) Latitudinal profiles of the 200 hPa u averaged between 130W and 120W for the 10% driest and 10% wettest winters in the western US in the period 1871-2013 according to the 20CR Reanalysis.

As suggested by evaluation of reanalysis data for the 20th century (Fig. 8e), pre-20th century extremes for both dry and high-fire conditions (defined as ≤ 10% of their distributions) are strongly associated with a weakening, reduction of southward extent, and more latitudinal spread of maximum velocity for the NPJ zonal component in the temperate northeastern Pacific and far western United States (Fig. 9a-b, red curves). Similarly, extreme wet and low-fire conditions (defined as ≥ 90% of their distributions) are strongly associated with a strengthening, greater southward extension, and more latitudinal focus of maximum velocity for the NPJ zonal component in this region, allowing enhanced northern Pacific storm track activity and tropical moist air flow into California (Fig. 9a-b, blue curves).

The clarity of our results allows evaluation of potential changes in the likelihood of extreme fire-year conditions through the rest of the 21st century as anthropogenic forcing of climate progresses, based on winter NPJ conditions extracted from climate model scenarios. Such evaluation into the future is all the more critical in light of the unprecedented build-up of fuels in regional wildland areas that has occurred due to fire suppression activity since the early 1900s, leading to a 'fire deficit' (Marlon et al. 2012) and recent "super fires" under extreme dry conditions (Dennison et al. 2014). Results from the MPI 21st century scenarios indicate a tendency towards the relatively "wet/low-fire" NPJ state in California (as defined by the pre-20th century conditions we identify) by the end of the 21st century (Fig. 10a-c). This tendency is most clearly associated with the RCP8.5 high greenhouse gas emissions scenario (Fig. 10c). In that case, the "wet/low-fire" NPJ state would occur in conjunction with strongly increasing temperatures and the likelihood of more precipitation occurring as rain rather than snow (Ashfaq et al. 2013), which itself has implications for wildfire potential that are not directly identifiable from pre-20th century "wet/low-fire" NPJ conditions.

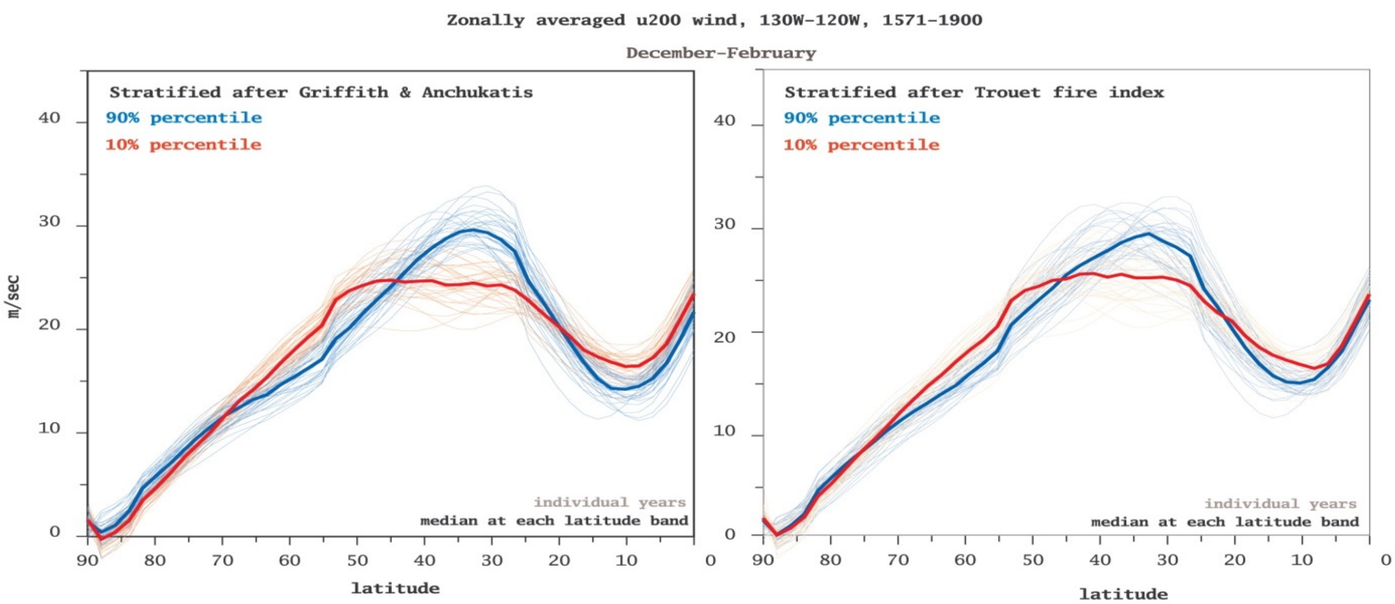

Figure 9 Latitudinal wind profiles of the reconstructed winter mean 200 hPa u winds for individual extreme winters in the period 1571-1900, averaged between 130W and 120W. 200 hPa zonal wind for the 10% driest and 10% wettest winters according to reconstructed CA precipitation (a) and for the 10% years with strongest and 10% years with weakest SN fire activity (b). The thick lines in each panel indicate the median value of each group of winters.

The potential occurrence of a typically wet/low-fire NPJ state (as defined by conditions prior to modern fire suppression) in conjunction with strongly increasing temperatures in the later 21st century indicates the corresponding possibility of a major physical shift in climate-fire relationships in California. Even with mildly enhanced wet-season precipitation and overall unchanged annual mean soil moisture for the state as a whole (Fig. 10b), reduced snowpack moisture persisting into the late spring and summer in the montane regions (Ashfaq et al., 2013) would generally be associated with drier soil conditions during the fire season in forested ecosystems, which would occur in conjunction with higher temperatures. The results reported here provide critical multi-century perspective on just how fundamental a projected climate-ecosystem reorganization would be in SN forests, and thus helps better determine the regional environmental and economic risk associated with the RCP 8.5 "Business as Usual" emissions scenario in one of the world's most important economic areas.

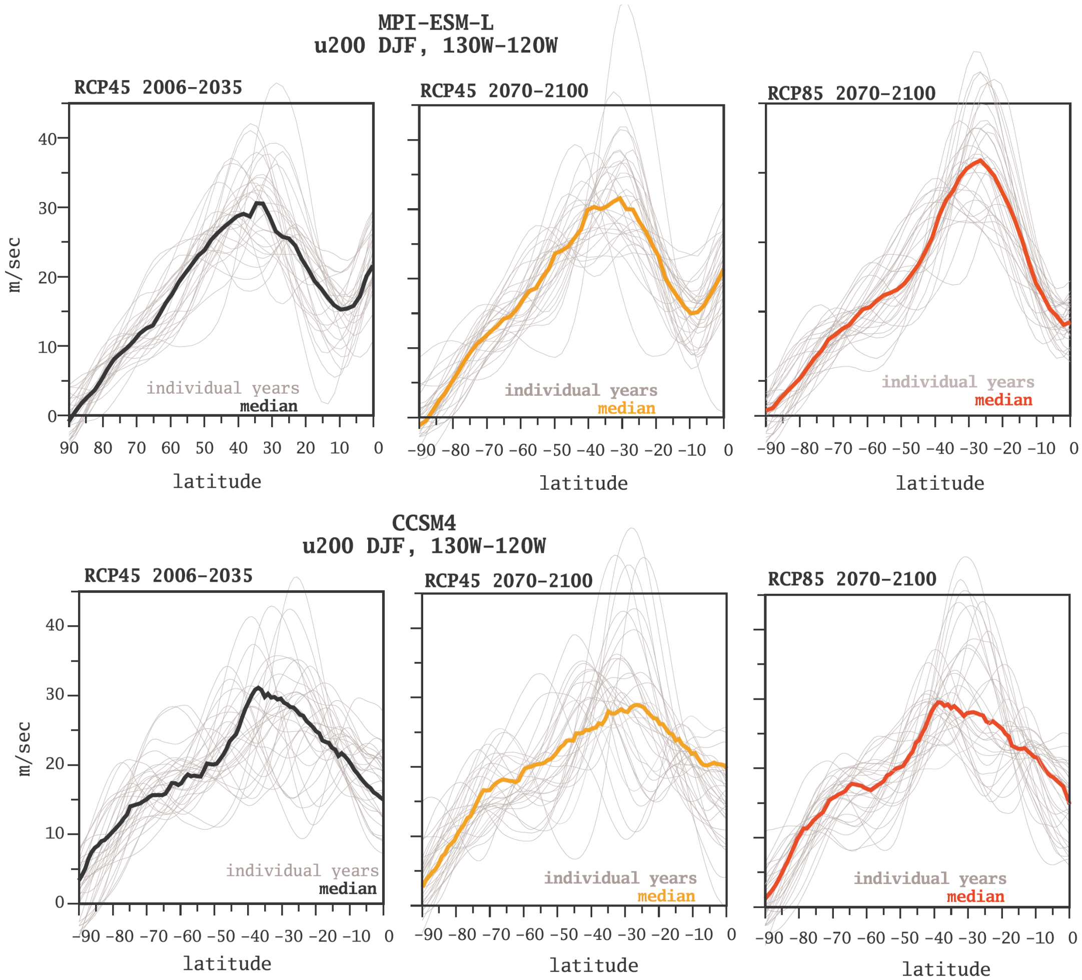

Figure 10. Projected changes in the position and intensity of the North Pacific Jet. Latitudinal profiles of winter mean 200 hPa u wind averaged between 130W and 120W simulated by the MPI-ESM and CCSM4 models over three periods in the 21st century, driven by future atmospheric concentrations of anthropogenic greenhouse gases according to 2 RCPs: (a) simulated by MPI-ESM-P under RCP 4.5 over 2006-2035; (b) under RCP 4.5 over 2070-2100; (c) under RCP 8.5 over 2070-2100; (d-f) as (a-c) but simulated by CCSM4; (The thick lines in each panel indicate the median value of each group of winters.

11. **NEXT STEPS:** *State and describe the next steps in the research, including an updated project timeline and anticipated completion date.*

The primary first steps in the project will be to finalize the three manuscripts that are in preparation for publication. All three manuscripts are planned to be submitted for publication in Spring 2016 and thus by the extended project end date (June 2016). Two of these publications (Wahl et al. and Taylor et al.) are aimed for publication in high-impact journals and if successful, both publications have potential to attract strong media attention (Cfr. Belmecheri et al. 2016). Adequately answering media questions and thus providing ample outreach for our work, will thus also be a next step.

The immediate objectives for this project will thus be reached within the projects timeframe, but in addition to these, the project has generated many new ideas and collaborations. I have received a NSF CAREER grant (2014-2019) that is related to this project and aims at tree-ring based jet stream reconstruction throughout the Northern Hemisphere. This NSF funding will allow us to continue research on some of the follow-up ideas that were generated during the course of this project, including (but not exclusive to):

- using tree-ring data to reconstruct the various NHJ index data developed in Belmecheri et al. (in prep.); we have already started this work; *follow up on results section a*
- linking NHJ index data to US (and potentially global) phenology, terrestrial productivity, and fire data; *follow up on results section a*
- extreme event analysis based on the NHJ index data; *follow up on results section a*
- investigate geographical differences (N vs. S Sierra Nevada) and influence of ENSO in April 1 SWE reconstructions; *follow up on results section b*
- combining tree-ring based April 1 SWE reconstructions with snow model results to improve our mechanical understanding of the relative influence of temperature vs. precipitation in snow formation; *follow up on results section b*

We will apply for additional funding (e.g., NSF Geography and Spatial Sciences program) to execute the abovementioned scientific ideas.

12. **OUTPUTS**

a. *Please list any* ***peer-reviewed publications*** *that have resulted from this project (full citations). Please include articles in preparation, in review, accepted, or published.*

- Belmecheri S, Babst F, Wahl ER, Stahle DW, Trouet V (2016) Multi-century evaluation of Sierra Nevada snowpack. *Nature Climate Change* doi:10.1038/nclimate2809*: Most read Nature Climate Change publication (09/28/2015)*
- Belmecheri S, Babst F, Betancourt J, Trouet V (in prep.) Twentieth Century Northern Hemisphere jet stream variability. *To be submitted to Ecosystem Interactions in Spring 2016.*
- Wahl ER, Zorita E, Trouet V, Betancourt J, Taylor AH (in prep.) Past and Future Relationships of Fire, Moisture, and Jet Stream Conditions in California. *To be submitted to Nature Climate Change in Spring 2016.*
- Taylor AH, Trouet V, Skinner AC (in prep.) Socioecological transitions trigger fire regime shifts and modulate fire-climate interactions in the Sierra Nevada, USA (1600-2014 CE). *To be submitted to PNAS in Spring 2016.*

b. ***Non-peer-reviewed publications*** *(full citations).*

- Trouet V, Belmecheri S (2015) The 2015 Sierra Nevada snowpack is at a 500-year record low. *The Conversation* 09/14/2015: https://theconversation.com/the-2015-sierra-nevada-snowpack-is-at-a-500-year-record-low-47380
- Trouet V (2015) How We Discovered the Sierra Nevada Snowpack Is at a 500-Year Low. *ZocaloLocalSquare* 09/22/2015: http://www.zocalopublicsquare.org/2015/09/22/how-we-discovered-the-sierra-nevada-snowpack-is-at-a-500-year-low/ideas/nexus/

c. *Please list any* ***conference talks*** *you have given based on this project (conference title, date, and location).*

- Belmecheri S, Babst F, Wahl E, Stahle D, Trouet V; **Third Ameridendro Conference** (Mendoza, Argentina, March 28-April 1, 2016) *Multi-century Evaluation of Sierra Nevada Snowpack*, oral presentation (invited)
- Trouet V, Wise E.: **AGU 2015 Conference** (San Francisco, CA, December 15 2015) Session convener: *"Hydroclimate and Atmospheric Circulation Patterns on Multidecadal to Millennial Timescales"*
- Belmecheri S, Babst F, Betancourt J, Trouet V; **AGU 2015 Conference** (San Francisco, CA, December 15 2015) *Twentieth Century Northern Hemisphere jet stream variability*, poster presentation
- Wahl E, Zorita E, Trouet V, Diaz H; **AGU 2015 Conference** (San Francisco, CA, December 15 2015) *500-year Reconstructions of Circulation in the Northeastern Pacific*

and Western North America: Relation to Precipitation and Fire Conditions in California and Precipitation in Hawai'I, oral presentation (Invited)

- Trouet V, Belmecheri S, Babst F, Wahl E, Stahle D; **AGU 2015 Conference** (San Francisco, CA, December 15 2015) *Multi-century Evaluation of Sierra Nevada Snowpack*, oral presentation
- Trouet V, Babst F, and Betancourt J: **MTNCLIM 2014 Conference, Cirmount** (Midway, UT, September 15-18 2014) *Reconstructing North Pacific Jet Variability and its influence on Sierra Nevada Fire regimes* (INVITED)
- Trouet V, Babst F, and Betancourt J **AAG meeting** (Tampa, FL, April 6-12 2014) *Taking Dendrochronology to the next level: reconstructing jet stream variability* (INVITED) NOTE: because of a death in my immediate family, I was not able to present this talk.
- Trouet V, Babst F, and Betancourt J: **9th International Conference On Dendrochronology** (Melbourne, AUS, January 13-17 2014) *North Pacific Jet Variability over the last 600 years*
- Trouet V, Babst F, and Betancourt J: **AGU Meeting (**San Francisco, CA, December 8 2013**)** *A tree-ring based reconstruction of North Pacific Jet Variability and its influence on Sierra Nevada Fire regimes*, oral presentation

d. *Please list any **data outputs, maps, decision-support or other informational tools** developed as part of this project and provide: 1) a very brief description of the product 2) Internet links if applicable.*

- Our Sierra Nevada snowpack reconstruction is publicly available through the NOAA Paleoclimate website: https://www.ncdc.noaa.gov/cdo/f?p=519:1:0::::P1_STUDY_ID:19319
- The 32 NHJ index data set (Belmecheri S et al. (in prep.)) will be made publicly available through the KNMI Climate Explorer website after publication of the manuscript: https://climexp.knmi.nl/

13. **OUTREACH AND ENGAGEMENT:** *Describe all project-related outreach opportunities to date.*

a. *Please list any **presentations, seminars, webinars, or workshops** made to stakeholders, the public at large, or any other group outside the research community.*

- Trouet V: *A tree-ring based reconstruction of Northern Hemispere Jet variability and its impacts*: Seminar in the UA Department of Geosciences, February 8, 2016
- Trouet V: *A tree-ring based reconstruction of Northern Hemispere Jet variability and its impacts*: Seminar in the UA Department of Soil, Water, and Environmental Sciences, March 21, 2016
- Trouet V and Betancourt J: *A tree-ring based reconstruction of North Pacific Jet variability and its influence on Sierra Nevada fire regimes:* Presentation for SE Arizona Chapter of the American Meteorological Society (SEACAMS), October 15 2013
- Betancourt J, Babst F, and Trouet V: *Winter North Pacific Jet position: Western U.S. Climate, Water, and Wildfire Variability in the Axis of the North-South Dipole*: SW Climate Science Center webinar, March 27 2014
- Trouet V: Climatenexus.org telepresser panelist:
  - January 2014: California Drought; resulting in (amongst others)
    - Summit County Voice (01/30/2014): http://summitcountyvoice.com/2014/01/30/california-drought-linked-with-global-warming/
    - Tucson News Now (01/30/2014):
      - http://www.tucsonnewsnow.com/story/24595460/drought-worsens-in-arizona-rest-of-southwest
      - Random Lengths News (03/07/2014): http://issuu.com/randomlengthsnews/docs/rln_03--06-14_edition

- The Arizona Republic (02/08/2014):
http://www.azcentral.com/weather/articles/20140201arizona-water-fears-dry-winter.html
- Climateacces.com (02/18/2014):
- www.climateaccess.org/blog/californiadrought-climate-change-and-brake-failure

b. ***Communications with decision-makers****, including their name and agency and the date(s) and frequency of your communications. Information on whether the decision-makers were involved in the design of the project plan or if the research has been tailored to address a specifically stated management need is also helpful.*

A common problem in translational science is the premature release of information and technology to end users. To regularly vet the research, data products, and management applications as they evolve, we have established a five-member TAC: Tim Brown, Desert Research Institute (http://www.dri.edu/tim-brown); Greg McCabe, Branch of Regional Research, Water Mission, USGS, Denver (http://profile.usgs.gov/gmccabe); Courtenay Strong, Department of Atmospheric Sciences, University of Utah; (http://www.inscc.utah.edu/~strong/); Carl Skinner, Pacific SW Research Station, USDA-Forest Service (http://www.fs.fed.us/psw/programs/ff/staff/cskinner/); Tony Westerling, UC-Merced (http://ulmo.ucmerced.edu/). All five scientists have agreed to serve on the TAC.

We have an organized a Technical Advisory Committee (TAC) meeting in Tucson AZ, on September 14-15, 2015. Participants of the meeting included all TAC members apart from Tony Westerling. During this TAC meeting (program attached at the end of this report), we have presented and discussed the results of the four foreseen publications (see results section). In addition to this, we have focused our discussion on the potential applications/implementation of our project outcomes. We discussed how our research will be relevant to (1) improving long-lead (weeks to months) forecasts of annual area burned, important for fire preparedness, anticipating fire suppression budgets, and scheduling prescribed fires; (2) estimating long-term probabilities for annual fire occurrence and conditions favorable/ unfavorable for controlled fires (for meeting long-term treatment targets) from periodicities identified in both the NPJ reconstruction and the fire-scar records; (3) evaluate the extent to which NPJ and regional annual fire occurrence has and will change due to anthropogenic warming.

An obvious use of our research results is as input to the monthly and seasonal outlooks that Predictive Services at the National Interagency Coordination Center (NICC) produces operationally. Tim Brown (DRI) presented the Climate, Ecosystem and Fire Applications (CEFA) program at the TAC meeting, which has long been developing these outlooks that incorporate past, present, and future climate and fuels information to anticipate significant fire potential (e.g., http://www.cefa.dri.edu/Current_Research/current_cefa_projects.php). The outlooks are designed to inform decision makers for proactive wildland fire management.

The principal users of insights and data products are fire and fuels managers within federal and state land management agencies and the tribes, such as the *CEFA,* the *California Fire Science Consortium* (CFSC; funded by the USDA-DOI Joint Fire Science Program), the *California Fuels Committee (CFC)*, and the *California LCC*. The *CFC* is an effective, stakeholder and neighborhood-focused community of practice focused on managing fuels in CA. The results from our project will provide a needed bridge between the fire planning and management communities and the LCC's in CA and adjacent regions. We will provide important perspectives on winter NPJ influences on snowpack, timing of snowmelt, streamflow from snowmelt, early spring greenup and flowering, bird migration/insect emergence, and fire risk. *CEFA, CFSC, CFC*, and *CLCC* provide multiple venues for quick dissemination of results from our project, including data portals (e.g., California Climate Commons), webinars (CFC), blogs, and field visits.

c. *Are you aware of any* ***resource management decisions*** *that have come out of this project? If so, please provide a brief description.*

Not yet.

14. **OTHER** project impacts, outcomes, or communications not discussed above.

Our Sierra Nevada snowpack publication in Nature Climate Change (Belmecheri et al. 2016) has received very broad national and international media attention, including multiple radio (NPR, KUNR, KPCC,, KXJZ, KCTV, …) and TV (Weather Channel) interviews. Below is a selective list:

- Arizona Public Media https://www.azpm.org/p/crawler-stories/2015/9/14/71951-ua-research-sierra-nevada-snowpack-lowest-in-500-years/
- New York Times: http://www.nytimes.com/2015/09/15/science/california-snow-report.html?_r=0
- LA Times: http://www.latimes.com/science/sciencenow/la-sci-sn-snowpack-20150911-story.html
- CNBC: http://www.cnbc.com/2015/09/14/sierra-nevada-snowpack-lowest-in-500-years.html
- Washington Post: http://www.washingtonpost.com/news/energy-environment/wp/2015/09/14/scientists-say-its-been-500-years-since-california-was-this-dry/
- Reuters: http://www.reuters.com/article/2015/09/14/us-environment-california-idUSKCN0RE1QQ20150914
- New Scientist: https://www.newscientist.com/article/dn28162-sierra-nevadas-500-year-snowpack-low-deepens-california-drought/
- National Geographic: http://news.nationalgeographic.com/2015/09/15914-Sierra-California-snowpack-mountains-drought-centuries/
- CBS: http://www.cbsnews.com/news/sierra-nevada-snowpack-lowest-in-500-years/
- The Guardian: http://www.theguardian.com/us-news/2015/sep/14/california-drought-sierra-nevada-snowpack-500-year-record-low
- Popular Mechanics: http://www.popularmechanics.com/science/environment/a17323/californias-sierra-nevada-mountains-snowpack/
- Tucson News now: http://www.tucsonnewsnow.com/story/30043293/u-of-a-finds-that-sierra-nevada-snow-pack-lowest-in-centuries
- San Francisco Chronicle: http://www.sfgate.com/science/article/This-year-s-snowpack-the-bleakest-in-500-years-6503680.php
- Arizona Daily Star: http://tucson.com/news/blogs/scientific-bent/year-bottom-for-snowpack-in-sierras/article_421c9ec4-28bc-5515-9327-c96c08f468a1.html
- Discovery: http://news.discovery.com/earth/global-warming/sierra-nevada-snowpack-worst-in-five-centuries-150914.htm
- Time Magazine: http://time.com/4033800/sierra-nevada-mountains-snow/
- The Sacramento Bee: http://www.sacbee.com/news/state/california/water-and-drought/article35262120.html
- Yale Climate Connections: http://www.yaleclimateconnections.org/2015/12/sierra-nevada-snowpack-at-500-year-low/
- Orange County Register: http://www.ocregister.com/articles/snowpack-701151-water-california.html

In addition to the wide press coverage, our colleague Russ Monson paid elaborate attention to the Belmecheri et al. Sierra Nevada snowpack results in his public lecture in the UA *Earth*

Transformed series on February 8. This lecture was held for an audience of ~2,000 people.

15. **BUDGET:** *Briefly describe the budget, with particular emphasis on changes to the budget that was submitted in the original proposal. Please discuss reasons for substantial budget modifications or why funds have not been spent as expected.*

We had originally budgeted funding for 1 graduate student for 2 years, for summer salary for PI Trouet and Co-I Betancourt, for a TAC meeting, for a fact sheet, and for a desktop computer.

The only major change to the originally proposed budget, has been that a post-doctoral researcher (Soumaya Belmecheri) was hired on this project for the period January-September 2015 rather than a graduate student. The preliminary work (instrumental and tree-ring data compilation and analysis) has been conducted by research specialist Mary Glueck and MS student Robert Shepard in AY 2014-2015 and summer 2014, but it became clear that the more advanced quantitative skills of a post-doctoral researcher were required for further analysis. We therefore hired Soumaya Belmecheri in year 2 of the project.

Submitted by:
(Project PI name) **Valerie Trouet** **02 / 15 / 2016**

(Project Co-Principal name(s)) **Julio Betancourt** **02 / 15 / 2016**

Reviewed by:
Jonathan T. Overpeck, Award PI
University of Arizona ________________ **/ / /15**

Stephen T. Jackson,
SWCSC Director, USGS ________________ **/ / /15**

Forwarded to:

USGS Grants Administrator ________________ **/ / /15**

Technical Advisory Committee Meeting

14-15 September 2015, Laboratory of Tree Ring Research-University of Arizona
Tucson –AZ

Influence of interannual North Pacific Jet variability on Sierra Nevada Fire regimes

PIs: Valerie Trouet, Julio Betancourt

Program:

Day 1-September 14

Morning:

9 AM Presentation of the project and adjustments from original objectives (Valerie Trouet)
9:45 –Discussion
10:15 AM Jet Stream climatology of N. hemisphere and focus on North Pacific Jet (Soumaya Belmecheri)
11:00- Discussion
11:30: Multi century evaluation of the Sierra Nevada snowpack (Soumaya Belmecheri)
12:00- Discussion

12:30-2PM Lunch break

Afternoon:

2 PM- Fire/human interactions in the Sierra Nevada (Valerie Trouet)
2:30 Discussion
3:15 PM The Climate, Ecosystem and Fire Applications (CEFA) program at DRI (Tim Brown)
4: 00 – 5:00 pm Discussion
Dinner at 7 PM

Day 2-September 15

Morning:

9AM- Translational Science outcome of the project (Julio Betancourt)
11:00 AM: North Pacific Jet reconstruction - work in Collaboration with E. Wahl (Valerie Trouet)
11:30 AM-Discussion
12-2 PM Lunch break

Afternoon

2- 5 PM *Discussion of Application/implementation of the project products*

A common problem in translational science is the premature release of information and technology to end users. To regularly vet the research, data products, and management applications as they evolve, we have established a five-member TAC: Tim Brown, Desert Research Institute (http://www.dri.edu/tim-brown); Greg McCabe, Branch of Regional Research, Water Mission, USGS, Denver (http://profile.usgs.gov/gmccabe); Courtenay Strong, Department of Atmospheric Sciences, University of Utah; (http://www.inscc.utah.edu/~strong/); Carl Skinner, Pacific SW Research Station, USDAForest Service (http://www.fs.fed.us/psw/programs/ff/staff/cskinner/); Tony Westerling, UC-Merced (http://ulmo.ucmerced.edu/).

We anticipate that our research will be relevant as input to seasonal outlooks which incorporate past, present, and future climate and fuels information to anticipate significant fire potential. The outlooks are designed to inform decision makers for proactive wildland fire management.

The TAC-members present at the meeting together with the project PIs will discuss the application of data products and managements practices. Data products and management applications will be translated to fire and fuels managers in the region through the *Program for Climate, Ecosystem and Fire Applications* at DRI, the *California Fire Science Consortium*, the *California Fuels Committee*, and the *California LCC.*

Dinner at 7 PM

List of participants:

Soumaya Belmecheri (post-doc; UA)
Valerie Trouet (PI, UA)
Julio Betancourt (co-I, USGS)
Amy Hudson (PhD student, UA)
Timothy Brown (DRI)
Gregory Mccabe (USGS; Skype)
Alison Meadow (UA)
Carl Skinner (USFS)
Courtenay Strong (University of Utah)
Tamara Wall (DRI)