NSF - AGS 17-02789
Collaborative Research: Reconstructing South American monsoon sensitivity to internal and external forcing

Lead Principal Investigator (PI): *Laia Andreu-Hayles (Lamont-Doherty Earth Observatory of Columbia University, LDEO)*

Co-Principal Investigator (Co-PI): *Rosanne D'Arrigo (LDEO), Mathias Vuille (SUNY at Albany), Guaciara Dos Santos (University of California, Irvine)*

PROJECT SUMMARY

Overview:
The tropical Andes are a unique region of the world. It is a hotspot for biodiversity, and its geographic position makes it extremely vulnerable to climate change. It also contains nearly all the tropical glaciers on the globe, and recent, widespread glacial melting and snowline retreat are causing a rapid decline in hydrological reserves. This decline, together with upslope advances of population and agriculture, are causing great challenges for water availability, biodiversity and food security over this region. The climate of the tropical Andes results from complex interactions between the regional topography of the Andean Cordillera, trade winds and associated moisture influx from the tropical Atlantic Ocean and the Amazon; the Intertropical Convergence Zone (ITCZ) and its seasonal migration; and the tropical Pacific basin, dominated by the El Niño-Southern Oscillation (ENSO). Our understanding of this variability and the reliability of future climate model projections is challenged by the scarcity of long instrumental observations. In this context, tree rings will be used to provide valuable information about past environmental conditions in the region. They are excellent tools for improving knowledge of complex interactions between the climate system and biosphere, and for extending the short instrumental record. In this proposal, a plan is outlined to generate a network of tree-ring chronologies for a latitudinal transect across the tropical Andes, where such data are now exceedingly sparse. This network will provide valuable information about tropical Andean hydroclimate over the past few centuries, and in particular about ENSO, the Walker circulation, the migration of the ITCZ, and decadal and longer-term variability.

Intellectual merit:
The overarching goal of this proposed research is to significantly advance the science of tropical dendrochronology by developing a tree-ring network for the tropical Andes. While tree rings have been extensively used in temperate climates, the tropics remain relatively unexplored due to the difficulty of identifying consistent wood layers (tree rings) corresponding to seasonal or annual growing periods. The tropical Andes is an ideal region for overcoming these difficulties, as there are regions of pronounced seasonality and diverse forests. For this project, new tropical tree-ring chronologies will be generated by integrating classical dendrochronological techniques with geochemistry and mass spectrometry. Radiocarbon measurements (^{14}C) will ensure reliable dating and will also be used to improve the radiocarbon curve for the Southern Hemisphere. Stable isotope ratios ($\delta^{13}C$ and $\delta^{18}O$) will be measured for a subset of reliable chronologies to complement the traditional metrics (e.g. ring width) used in dendroclimatology. These isotopic data can be closely related to climate variables (of particular value when sample replication is limited) and can preserve lower-frequency climate variability better than detrended ring-width series in many cases. The resulting tree-ring series (ring-width and isotopes) will be used to reconstruct past climate variability and regional to larger-scale atmospheric dynamics. The

existing climate records, together with paleclimatic reconstructions (both those generated during this project and already published by our international collaborators) will then be compared with model output from the CMIP5/PMIP3 ensemble. The longest possible common period will be chosen to improve the understanding of climate over the tropical Andes. Analysis of model output and its uncertainties will also aid in the determination of suitable fieldwork sites for sampling trees.

Broader impacts:

This project has a very strong capacity building component. A Ph.D. student will be fully involved in the proposed work, learning basic dendrochronological methods and climate reconstruction development for the relevant tropical tree species. Research experience will be provided to undergraduate and graduate students through established Columbia University programs. Additionally, the PIs will interact with local scientists from institutions in several countries within the study region. This will include a workshop and field trips that will be conducted with scientists in Bolivia, Peru and Colombia, in collaboration with a well-established dendrochronology laboratory in Argentina. These intensive collaborations will greatly improve the opportunities to reconstruct the past hydroclimate variability of the tropical Andes. The resulting tree-ring network will also provide valuable data for a tree-ring based South American Drought Atlas now being developed.

PROJECT DESCRIPTION

1. Introduction and rationale

The tropical Andes are a unique region of the world, containing much of the globe's biodiversity (Myers *et al.*, 2000; Hoorn *et al.*, 2010), over 90% of all tropical glaciers (Kaser & Osmaton, 2007), and close to 10% of its freshwater reserves (FAO, 2010). The region is highly vulnerable to climate change, as evidenced by observed rapid widespread glacier retreat, which has led to the complete disappearance of several glaciers in recent years (Vuille *et al.*, 2008; Rabatel *et al.*, 2013). This retreat is depleting hydrological reserves (Baraer *et al.*, 2012), which, combined with upslope advances of population and agriculture, constitutes a pressing challenge for water availability and food security across this region.

Precipitation in the Bolivian/Peruvian Altiplano is highly seasonal and associated with the development of the South American Summer Monsoon (SASM; Fig 1a). The SASM is the dominant mode of variability over tropical and subtropical South America, responsible for more than 70% of the total annual precipitation in its core region (Fig. 1b; Vera *et al.*, 2006; Garreaud *et al.*, 2009; Marengo *et al.*, 2012). As such it is of vital importance for agriculture, hydropower production, mining and other socioeconomic activities. It also provides water for use during the dry season, intermittently stored as snow and ice on Andean glaciers. The SASM is defined by a clear seasonal cycle with an onset (Oct.-Nov., ON), mature (Dec.-Feb., DJF) and demise period (March-April, MA). It is distinctly different from the Atlantic Intertropical Convergence Zone (ITCZ), which remains well defined all year long. During the monsoon season strong upper-level easterly winds are established on the northern side of an upper-air anticyclone, the Bolivian High, leading to near-surface easterly upslope flow and favoring moisture influx from the Amazon basin toward the high Andes (Garreaud *et al.*, 2003).

Interannual and decadal-scale SASM variability over the Altiplano is strongly influenced by the El Niño - Southern Oscillation (ENSO) phenomenon (Fig. 1c), but also by the Pacific Decadal Oscillation (PDO) (Vuille & Werner, 2005; Garreaud *et al.*, 2009). The Andes of Peru and Bolivia receive below average precipitation during warm ENSO events (El Niño), resulting in negative glacier mass balance and widespread drought (Francou *et al.*, 2003; Garreaud *et al.*, 2003; Vuille *et al.*, 2008). By contrast, along the Peruvian coast El Niño is associated with increased rainfall, flooding and mudslides. Several studies have also highlighted the relevance of monsoon interactions with extratropical systems and in particular with cold air incursions along the Andes (Garreaud, 2000; Hurley *et al.*, 2015).

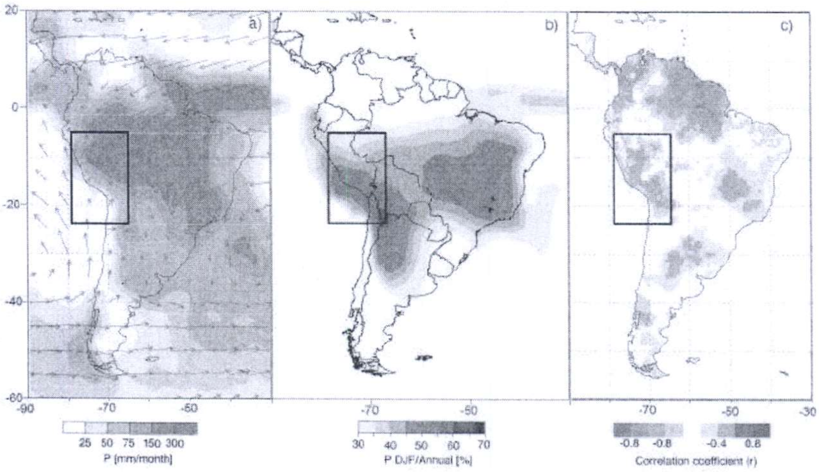


Figure 1. The climate of the Altiplano region in a large-scale setting. a) *Precipitation (in mm) and low-level wind field during mature phase of the SASM in January,* ***b)*** *Fraction of total annual precipitation (in %) falling during DJF, and* ***c)*** *correlation between multivariate ENSO index (MEI) and DJF precipitation. Figures a) and c) are modified from Garreaud et al. (2009); Figure b) is modified from Vuille et al. (2012). Black box highlights our proposed research domain.*

Recent droughts over the Amazon basin, as in 2005 and 2010, have exposed the inadequacy of the current monsoon prediction system and the vulnerability of the region to monsoon failure and extreme events (Marengo *et al.*, 2008; Zeng *et al.*, 2008; Lewis *et al.*, 2011). Such extreme events also affect the Andes of Peru and Bolivia, in particular in combination with ENSO. These episodes can have significant adverse impacts on socio-economic activities (Sulca *et al.*, 2016), with losses reaching several billions of US dollars in recent years.

The proposed study region (Fig. 1) features only very scarce coverage of observational climate data (e.g. Garreaud *et al.*, 2009), challenging our understanding of the tropical climate system and our ability to constrain future model projections (Urrutia & Vuille, 2009; Minvielle & Garreaud, 2011; Neukom *et al.*, 2015). Available historical observations frequently span less than 50 years and are often unreliable due to gaps and/or inconsistent measurements (Vuille *et al.*, 2015). Thus they are insufficient to assess the full amplitude of multi-decadal to centennial-scale climate variability that has affected the region during the last millennium (Bird *et al.*, 2011; Vuille *et al.*, 2012). They are equally inadequate for validating and constraining model simulations of the Last Millennium (LM) that have been performed as part of the Paleoclimate Modeling Intercomparison Project Phase 3 (PMIP3) / Coupled Model Intercomparison Project Phase 5 (CMIP5). This leaves natural archives as our only available tools to reconstruct past climate changes and to establish a long climate record against which model simulations can be evaluated.

The central Andes of Bolivia and south-central Peru are an ideal place to perform such an analysis, as the region is located at the nexus of monsoon and ENSO influence, allowing the reconstruction of the two most dominant and societally relevant climate modes affecting tropical South America. It is also a region that has seen a number of hydroclimatic reconstructions emerge over the past decade or more (see Fig. 3), from a variety of archives, including speleothems, lake sediments (e.g. Reuter *et al.*, 2009; Bird *et al.*, 2011; Kanner *et al.*, 2013; Apaestegui *et al.*, 2014) and ice cores (e.g. Thompson *et al.*, 2013). These records have helped to establish that significant low-frequency changes in the mean state occurred in the central Andes during the past millennium, most notably during the Little Ice Age (LIA, 1400-1850 C.E.) and that current monsoon strength appears to reside on the weaker end of the spectrum (Bird *et al.*, 2011; Vuille *et al.*, 2012; Wade, 2014). Most of these records, however, are based on stable oxygen isotopes and hence have been plagued by controversies surrounding their climatic interpretation. They are commonly assumed to reflect hydrologic conditions further upstream over the Amazon basin, rather than local climate in the Andes themselves (Vuille *et al.*, 2012). Furthermore, many of these records are not annually resolved and have considerable dating uncertainties, limiting their usefulness for analysis of climatic extremes, detection of volcanic signals or reconstruction of ENSO conditions in the Pacific.

Tree rings, on the other hand, are highly resolved (annual) and precisely dated, with often well-understood sensitivities to annual or seasonal variations in climate. This strong dependence on climate in many cases allows calibration/verification with instrumental records and development of stringent statistical models to reconstruct past climate variability. The tree-ring network proposed herein will cover almost the entire latitudinal gradient across Peru (7° to 18° S) to Bolivia (14° to 22° S), a region that is still highly undersampled, but where tree-ring studies are showing great promise (see next section). These new chronologies will provide valuable new information about the tropical Andean climate system and biosphere and its sensitivity toward internal (e.g. ENSO) and external (e.g. volcanic) forcing. Our main goals are therefore: **a)** to develop a network of tree-ring records across the tropical Andes of Peru and Bolivia, using classical dendrochronological techniques (via intensive fieldwork and processing of ring-width samples); **b)** to validate dating of our tree-ring records using radiocarbon (^{14}C) measurements, and consequently identify suitable species which later can be used to improve the existing ^{14}C curve of the Southern Hemisphere (SH; Hogg *et al.*, 2013); **c)** to constrain the sensitivity of the SASM to external forcing over this region by identifying volcanic signals in our tree-ring chronologies, while at the same time isolating the forced response to volcanic forcing using an ensemble of LM simulations run with and without volcanic forcing; and **d)** to place current ENSO and SASM conditions into a historical context by developing new ENSO and SASM reconstructions over this area of the world. In addition, our new tree-ring chronologies will provide an important contribution to ongoing efforts by the paleoclimate community (e.g. PAGES working groups) to reconstruct tropical hydroclimate using well-dated, high-resolution proxies, and to the generation of the South American Drought Atlas (SADA), work in progress by colleagues funded by the NSF P2C2 program. Our results will also aid in constraining future projections of hydroclimate in the region, as they will provide a necessary baseline against which model performance can be tested (e.g. Neukom *et al.*, 2015).

2. Background

2.1. Dendrochronology in the tropics

Coverage of tropical tree-ring chronologies is still very limited across the globe (Fig. 2). While tree rings have been extensively used in temperate climates, the tropics remain relatively unexplored due to the difficulty of identifying consistent, well-defined wood layers (tree rings) corresponding to annual growing periods. (Bräuning, 2011). Major progress in tropical dendrochronology in recent decades has shown, however, that some tropical trees produce annual bands due to cambial dormancy driven by unfavorable environmental conditions during a particular season of the year (Rozendaal & Zuidema, 2010). In contrast to extensive recent work in the tropics of Asia (e.g.; the Monsoon Asia Drought Atlas or MADA, Cook *et al.* 2010), in South America almost all climate-sensitive chronologies are at subtropical to higher latitudes (Boninsegna *et al.*, 2009; Bräuning, 2009; Stahle *et al.*, 2011; Villalba *et al.*, 2011), and these are very limited in length and coverage in the inner tropics closest to the equator. Our targeted region covers a latitudinal gradient from 7° S to 22° S along the west coast of South America and the Andean Cordillera (Fig. 3). Relative to some other tropical regions, the Central Andes in South America are ideal for conducting pioneering efforts in tropical dendrochronology, because: (1) the large biodiversity and dense forests provide a unique opportunity at a range of altitudes to identify appropriate species with visible tree rings; (2) its complex orography and regional atmospheric dynamics define sub-regions of distinct seasonality, that aid annual ring formation; and (3) the existence of continuous forests found along an elevational gradient of about 4000 m.a.s.l. will allow us to find trees growing at the edge of their species' altitudinal limits (e.g. elevational treeline) that are most likely to be sensitive to climate.

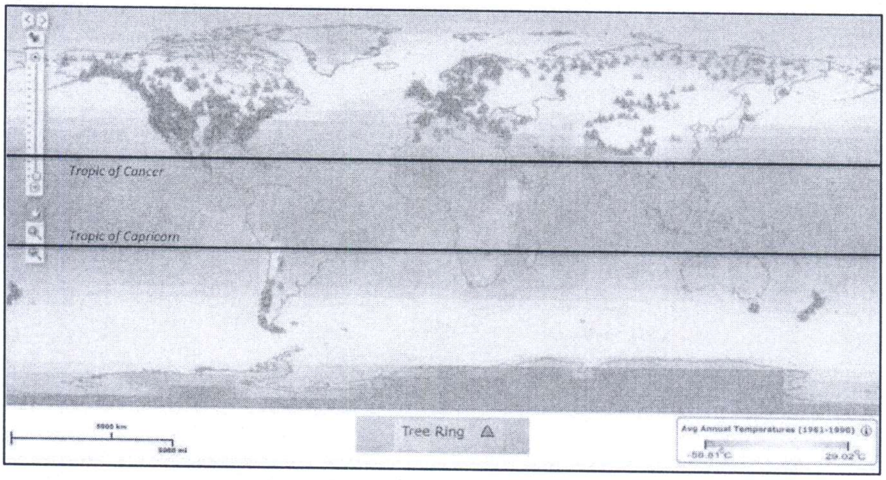


***Figure** 2. Green triangles indicate tree-ring chronologies available from the International Tree-Ring Data Bank (ITRDB). Note the dearth of tree-ring proxies within the tropics. Map created with the Interactive Map tool from the National Oceanic and Atmospheric Administration (NOAA) web page under the section 'Paleoclimatology' and subsections 'Datasets' and 'Tree Ring'.*

Tree species with dendroclimatic potential in the tropical Andes have been recently reviewed (Boninsegna *et al.*, 2009; Bräuning, 2009; Villalba *et al.*, 2011). Of particular interest is a network of *Polylepis tarapacana* chronologies from sites between 4000 and 5000 m.a.s.l. in the Altiplano, Central Andes (Fig. 3) that will be available for this project. These chronologies extend over the past 700 years, from 17° to 23° S (Solíz *et al.*, 2009). Fig. 4 shows that these records are very sensitive to annual precipitation linked to sea surface temperatures (SSTs) in the eastern tropical Pacific (Morales *et al.*, 2012). Due to this teleconnection, strong linkages have been established between ENSO and *P. tarapacana* tree-ring chronologies (e.g.; Christie *et al.*, 2009), as well as with other extratropical chronologies along the America (Villalba *et al.*, 2011), the SH (Li *et al.*, 2013) and the NH (Li *et al.*, 2011). These extratropical chronologies were also found to be sensitive to the Southern Annular Mode (Villalba *et al.*, 2012), which reflects location and strength of the southern westerlies. At high elevations further north (13°-16° S) near the border between Peru and Bolivia, other species such as *Polylepis pepei*, *P. subsericans* and *P. rugulosa* have been used to generate tree-ring chronologies sensitive to temperature during the rainy season (Jomelli *et al.*, 2012). At similar latitudes (15°-16° S) in Bolivia, but in dry forests located at lower elevations (200-420 m.a.s.l.), a *Centrolobium microchaete* tree-ring chronology showed significant relationships with temperature (negative) and precipitation (positive) in late-spring/early-summer (Lopez & Villalba, 2011). In the Bolivian rain forest (10º-11º S; 100 m.a.s.l), *Cedrela odorata*, *Amburana cearensis*, *Cedrelinga* and *Tachigali vasquezii* proved to be of value for dendrochronological analyses and were positively correlated with rainfall (Brienen & Zuidema, 2005; 2006). In subtropical montane ecosystems (20º-28º S), *Prosopis ferox, Juglans australis, Cedrela lilloi, Alnus acuminata* and *P. tarapacana* were also found to be sensitive to precipitation variability (Morales *et al.*, 2004; Morales & Villalba, 2012). Finally, in dry forest settings in southern Ecuador (4º22' S; 79º90' W), tree-ring chronologies of *Bursera graveolens* and *Maclura tinctoria* record past wet season (January–May) precipitation (Pucha-Cofrep *et al.*, 2015).

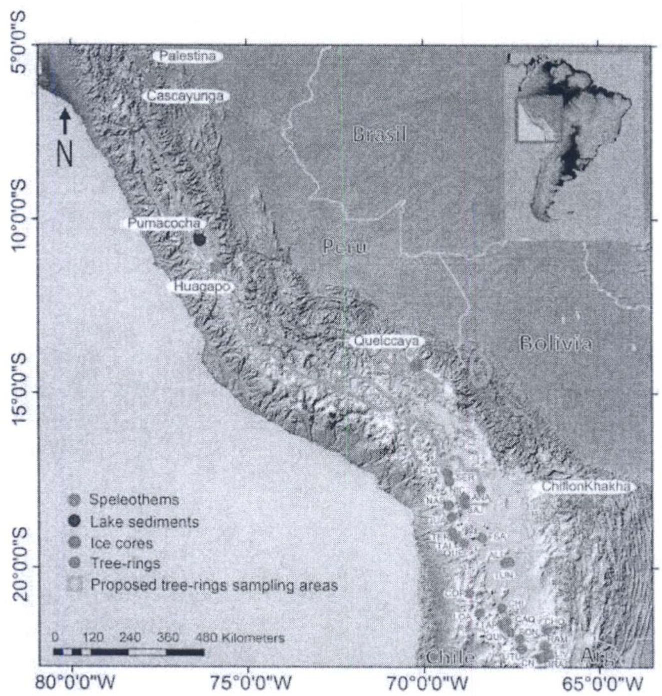
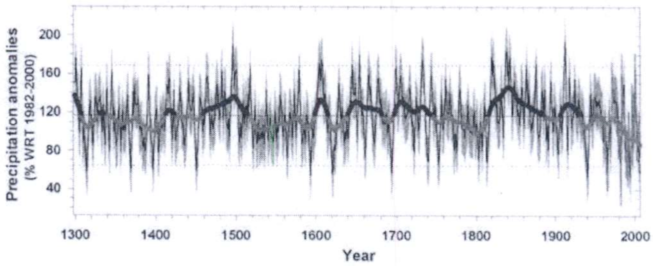


Figure 3. *Research domain for this project with all proxy sites (existing and proposed) as discussed in the text. The existing chronologies are composed of speleothems, lake sediments and ice cores in the northern domain, and tree ring-chronologies in the southern domain in Bolivia. Note the lack of tree-ring chronologies from 7-16º S where our tree-ring sampling will be conducted. The proposed tree-ring sampling areas are those indicated by pink contours.*



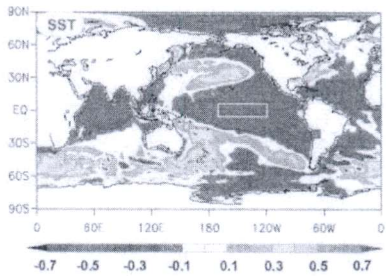


Figure 4 Left*: A tree-ring reconstruction of annual (Nov.–Oct.) precipitation in the Altiplano region, Central Andes, for the period 1300–2006 (in % of 1982–2000 mean precipitation). A 35-yr smoothing cubic spline indicates wet (blue) and dry (red) periods, respectively.* ***Right****: Spatial correlation between the annual (Nov.–Oct.) precipitation reconstruction and monthly averaged Nov.–Oct. SST for 1948–2006. Note strong correlation within white box representing the Niño 3.4 region in the tropical Pacific. Adapted from Morales et al. (2012).*

Carbon stable isotopes ($\delta^{13}C$) have also been measured in South American tropical tree species, including *Cedrela odorata* and *Swietenia macrophylla* from Brazil from 1850 to 1990 (Hietz *et al.*, 2005); *Mimosa acantholoba*, a Mexican dry forest species (Brienen *et al.*, 2010); and *Fitzroya cupressoides* in the Chilean extratropics over 1800–1991 (Leavitt & Lara, 1994; Urrutia-Jalabert *et al.*, 2015). These studies used $\delta^{13}C$ ratios to assess the physiological processes underlying tree growth patterns, but other work has focused on retrieving climatic information. For example, in southern Patagonia (49° S), the $\delta^{13}C$ ratios of *Nothofagus pumilio* are a good indicator of temperature along an altitudinal gradient (Srur *et al.*, 2008). Finally Kahmen *et al.* (2011) described the important role of Vapour Pressure Deficit (VPD) in $\delta^{18}O$, while other studies reported a large-scale coherent precipitation signal in several tree species from Bolivia (Baker *et al.*, 2015); precipitation in *Cedrela odorata* from the Bolivian Amazon (Brienen *et al.*, 2012); ENSO variability in *Bursera graveolens* and *Maclura tinctoria* from Ecuador (Volland *et al.*, 2016), and austral winter precipitation in *Tachigali myrmecophila* from Brazil and *Polylepis tarapacana* from Bolivia (Ballantyne *et al.*, 2011).

Taken as a whole, these existing tree-ring records do not represent a sufficiently dense network with adequate spatial and temporal resolution to address the questions proposed here. They do, however, provide strong evidence that the necessary groundwork for developing well-dated, tropical Andean tree-ring chronologies in the framework of the proposed research has been laid.

2.2. Confirming dating of tropical tree-ring chronologies using radiocarbon (^{14}C) measurements

Radiocarbon dating has been used to establish the **annual nature of growth rings**, which is particularly critical for (sub-) tropical species (Borman & Berlyn, 1981; Worbes, 1995; Lisi *et al.*, 2001). This method relies on the fact that the photosynthesized carbon in new plant growth reflects atmospheric $^{14}CO_2$ concentration. When above-ground nuclear weapons tests during the 1950s and 1960s doubled the concentration of ^{14}C/C in the atmosphere, followed by its rapid decline after the Test Ban Treaty, a bomb-pulse was created that now can be used as a time-specific signal (Borman & Berlyn, 1981; Worbes, 1995; Lisi *et al.*, 2001). Therefore, tree-ring/^{14}C cross-dating age estimates coinciding with the bomb-produced ^{14}C pulse can aid in evaluating tropical tree species as suitable candidates for tree-ring research. The ^{14}C *'bomb pulse dating'* (BPD) method can thus verify the calendar year of the carbon fixed in organic tissues after 1950 (as fraction modern carbon – FmC) by directly comparing its ^{14}C signal with pre-established ^{14}C atmospheric curves (e.g.; Levin & Hesshaimer, 2000; Levin *et al.*, 2008; Hua *et al.*, 2013).

The BPD method has helped to validate the calendar year in annual rings obtained through traditional dendrochronological techniques (e.g., Worbes & Junk, 1989; Biondi & Fessenden, 1999; Levin & Hesshaimer, 2000; Biondi *et al.*, 2007; Wils *et al.*, 2009; Andreu-Hayles *et al.*, 2015; Santos *et al.*, 2015), including species from sub-tropical and tropical areas (Borman & Berlyn, 1981; Worbes, 1995; Lisi *et al.*, 2001) and can therefore aid in evaluating additional tropical tree species as suitable candidates for tree-ring research. While it is well established that atmospheric ^{14}C signatures vary between the NH and SH (McCormac *et al.*, 1998), there is little definitive data on ^{14}C variation within the hemispheres themselves (i.e. the intra-hemispheric offsets). Intra-hemispheric offsets are important as they define the zonal division of the present ^{14}C atmospheric time scale (Hua *et al.*, 1999; 2013). However, the SH ^{14}C calibration curve is presently based solely on data from the eastern hemisphere, and is basically limited to a narrow mid-latitude band with most of the data from New Zealand, Tasmania, and South African sources. Therefore, for South America the intra-hemispheric boundary is still based on the modeled position of the ITCZ because no ^{14}C data was available when the SH ^{14}C time-scale calibration compilation was made (Hua *et al.*, 2013). The annual growth rings of two *Araucariaceae* species from subtropical South America (Hadad *et al.*, 2015; Santos *et al.*, 2015) and *Pseudolmedia rigida* from Bolivia (Fig. 5; Andreu-Hayles et al. 2015) have been successfully validated by the BPD methodology. However, many more tree-ring records from South America across the ITCZ winter boundary are needed.

An ongoing collaboration between Dr. G. Santos at the W. M. Keck Carbon Cycle Accelerator Mass Spectrometry Facility (KCCAMS) at the University of California, Irvine (UCI) and lead PI Andreu-Hayles at LDEO provides proof of concept for the BPD methodology described here. Two very distinct species have been tested by BPD: *P. rigida* collected in Bolivia (14°34' S; 68°46' W; Fig. 5) and *Prioria copaifera* located in the Colombian Pacific region (7° 15' N; 76° 58' W; Fig. 6). Eight annual tree rings for each species were manually extracted and packed within pre-labeled vials at the TRL. Wood samples were subjected to holocellulose extraction (Southon & Magana, 2010; Santos & Ormsby, 2013), and then combusted to CO_2 and reduced to graphite for ^{14}C-AMS measurements. Contrary to previous tropical tree-ring/^{14}C-dated ages in the literature, our work and the methodology proposed here include a precise assessment of the calendar year of the rings analyzed. We selected samples within a 70-year range, starting before the bomb-pulse era and beyond its slow decline. There is remarkable agreement of the *P. rigida* tree-ring ^{14}C data with the SH Zone 1-2 compilation data that shows the potential of this species for dendrochronological analysis (Fig. 5b). In contrast, discrepancies between the dating of the *P. copaifera* chronology and the ^{14}C SH curve were clearly identified with this approach, showing that this species produces more than one growth layer per year with a calendar-dating offset between ^{14}C and traditional cross-dating up to 40 years (Fig. 6a). One set of *P. copaifera* (termed Pg25 in Fig.6a) was ^{14}C processed and dated together with *P. rigida;* therefore issues associated with ^{14}C-AMS dating cannot be invoked. The *P. copaifera* samples, however, were visually cross-dated (Fig. 6b), measured and tested using statistical quality-dating controls prior to generation of a tree-ring chronology. This example illustrates that generating tree-ring chronologies in the tropics, where complex anatomies and growth patterns exist, requires age validation with additional methods, such as the BPD methodology.

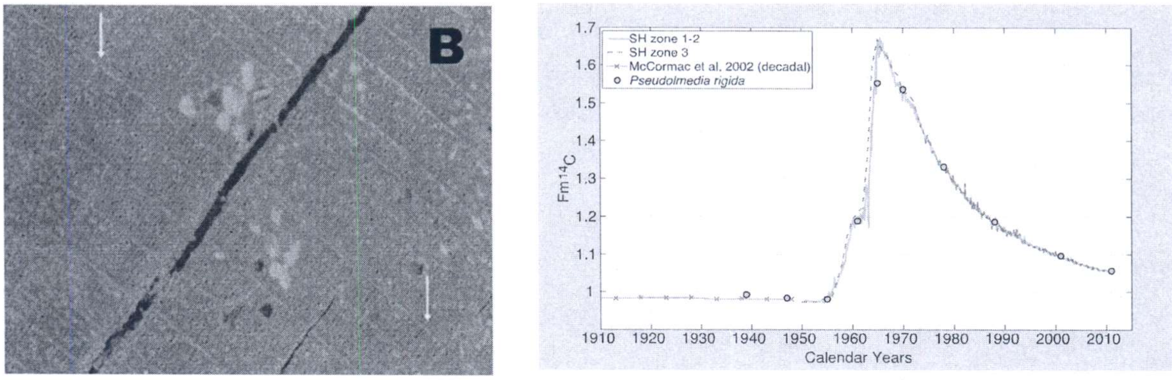


***Figure 5**. Pseudolmedia rigida in Madidi shows growth rings with annual periodicity (Andreu-Hayles et al., 2015). **Left**: tree rings of a **P. rigida** sample from Madidi. Arrows show a wedging ring (in 1993) that becomes locally absent in some parts of the stem disk. **Right**: Precise temporal agreement was found between the dendrochronological dates and the ^{14}C signatures in tree rings provided by the bomb-pulse ^{14}C atmospheric values for the Southern Hemisphere curve (SHCal zone 1–2).*

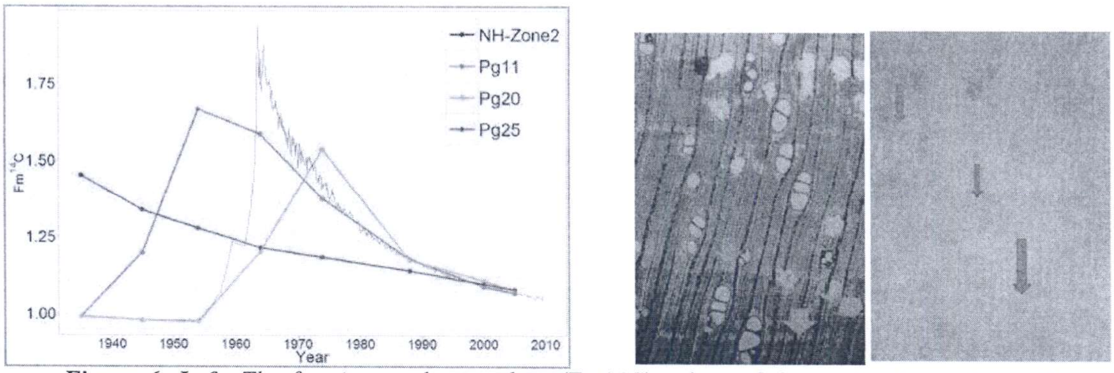


***Figure 6**. **Left**: The fraction modern carbon (Fm14C) values of the analyzed samples of P. copaifera, a tropical leguminous species growing in floodplains. Tree rings, defined by marginal lines of parenchyma selected from three different trees (Pg11, Pg20 and Pg25), are plotted against the atmospheric compilations for NH-Zone2 from 1950 to 2010 (Hua, Barbetti & Rakowski, 2013). **Right**: Anatomical details of tree rings from P. copaifera.*

2.3. Volcanic forcing of tropical South American hydroclimate

Volcanic eruptions provide the dominant external natural forcing over the LM (Atwood *et al.*, 2016). Recent results from LM ensemble simulations forced with volcanic aerosol reconstructions highlight the sensitivity of the tropical hydrological cycle to hemispheric asymmetries in this forcing. The preferential cooling of the hemisphere where the volcanic aerosol forcing is dominant leads to a shift of the tropical precipitation belt away from the cooled and toward the warmer hemisphere (Iles & Hegerl, 2014; Ridley *et al.*, 2015; Colose *et al.*, 2016b; Liu *et al.*, 2016). The tropical Andes and the Altiplano are strategically ideally located to investigate this aspect, as the hydrologic response is opposite between northern or southern hemisphere aerosol forcing (Fig. 7). While the theoretical framework and the energetics are quite well understood and reproduced across multiple models (Colose *et al.*, 2016a), the proxy-based model validation represents a real challenge. Identifying volcanic forcing in tropical proxies requires a high resolution and very accurate absolute dating of these records. In addition many of the most recent eruptions coincided with ENSO events in the Pacific, complicating identification of the volcanic fingerprint in climatic series (Adams *et al.*, 2003; Emile-Geay *et al.*, 2008; Pausata *et al.*, 2015; Stevenson *et al.*, 2016). While multi-decadal declines in precipitation have been identified in response to clusters of volcanic eruptions in speleothem records from Mesoamerica (Winter *et al.*, 2015), and reduced tropical SST following volcanic eruptions have been reconstructed from corals, tree rings and ice cores (D'Arrigo *et al.*, 2009), to our knowledge, to date no proxies yet exist in tropical South America that have documented the climatic response to volcanic forcing, although volcanic ash layers are routinely used for dating of Andean ice core records (De Angelis *et al.*, 2003; Vimeux *et al.*, 2009).

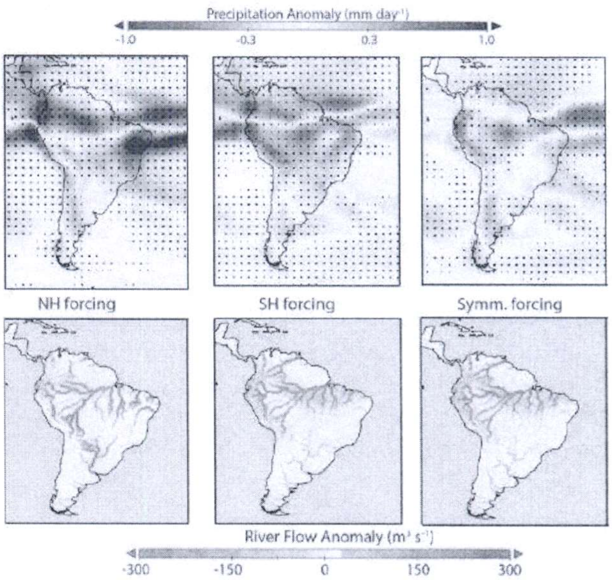


Figure 7: *Volcanic forcing of South American hydroclimate in CESM LM simulations.* ***Top row:*** *CESM Nov.-Mar. precipitation anomaly composite for events with dominant aerosol forcing in NH (left), SH (middle) and hemispherically symmetric aerosol forcing (right). Stippling indicates statistical significance at p<0.05.* ***Bottom row:*** *as above but for river discharge. Figure modified from Colose et al. (2016b).*

3. Scientific objectives

The following research questions will be addressed in this project:

• ***Research question 1. How has hydroclimate varied over the tropical Andes during the 2nd half of the LIA?*** As noted, a number of proxy records covering this period exist (see Fig. 3) and they tend to show wet and/or cold conditions over the Andes of Peru (e.g. Thompson *et al.*, 2006; Bird *et al.*, 2011). Tree-ring records from Bolivia (18-23° S) also indicate a wet period, but it is considerably shorter, spanning the 17th and first half of the 18th century (Morales *et al.*, 2012; 2015), while other lower-resolution proxies extend these wet and cold conditions to 1500 CE – 1800 CE. Moreover, within this long-term wet period, two severe decade-long droughts were recorded in the tree-ring reconstructions. Differences between these proxies may reflect distinct climate conditions between sites separated by several 100 km and the nature of the records themselves, capturing environmental changes at different frequency and time lags.

The tree-ring network proposed herein will allow us to reconstruct SASM variability over the entire region at interannual resolution. This result will enable 1) a thorough comparison of the climate sensitivity and response times of different proxies to the same monsoon forcing. It will also help in 2) establishing to what extent isotopic proxies record local versus large-scale upstream climatic effects. Furthermore the new tree-ring network will 3) place the current SASM amplitude and strength in a long-term context to determine the past envelope of variability relative to today, and to assess whether current monsoon strength indeed resides on the weak end of the spectrum as often portrayed) and 4) help determine how the frequency and persistence of climatic extremes (droughts/floods) have changed over time and in what ways the current recurrence rates of such extremes are different from the past. The latter issue is particularly relevant for socioeconomic activities, such as agriculture and herding, where anecdotal evidence suggests that environmental conditions in the region are rapidly changing (Gurgiser *et al.*, 2016; Sulca *et al.*, 2016).

• ***Research question 2. How has ENSO modulated SASM activity in the past?*** Our proposed study region spans a latitudinal transect from 7°S to 22°S. The entire Andean range across this transect receives monsoonal precipitation, and all locations are sensitive to ENSO, with reduced precipitation during El Niño events (Fig 1). Thus, our chronologies are strategically well placed to provide insights regarding

ENSO-SASM interactions and the past history of ENSO. However, these two modes are not independent of one another, as pointed out by Vuille & Werner (2005). Indeed ENSO significantly affects the timing and strength of the SASM over the tropical Andes. Earlier attempts at reconstructing the ENSO or monsoon history from proxies in the region were based on single records from one specific location, such as Laguna Pumacocha or the Quelccaya ice cap in Peru (Bird *et al.*, 2011; Thompson *et al.*, 2013), likely mixing these two signals. Furthermore these reconstructions are based on the isotopic composition of ice or lake calcite; and may thus record a hierarchy of influences on multiple spatial scales. The only ENSO reconstruction based on multiple sites used tree-ring chronologies from the Altiplano (Christie *et al.*, 2009; Morales *et al.*, 2012), but it does not include any information on ENSO-sensitive proxies from further north in Peru. Obtaining chronologies from multiple sites, where ENSO and SASM impact hydroclimate to varying degrees, is essential to distinguish between the climatic effects of these two modes. Our multi-site reconstruction effort will allow us to integrate ENSO-sensitive information over a much larger Andean transect and to effectively extract and separate coherent modes of variability (e.g. through EOF analysis) linked to either ENSO or the SASM.

• ***Research question 3. How do radiative perturbations associated with large volcanic eruptions affect environmental conditions over the tropical Andes?*** Diagnosing the sensitivity of the SASM to external forcing is of fundamental importance given the growing concerns over rapidly increasing greenhouse gas concentrations and the potential for increased drought over our study region (e.g. Urrutia & Vuille, 2009; Minvielle & Garreaud, 2011; Neukom *et al.*, 2015). Volcanic eruptions provide an ideal testbed to analyze monsoon sensitivity to external forcing as they provide for a well-constrained, time-limited and significant forcing signal that can be isolated in both models and tree rings with high confidence. In addition, as noted above, our Andean transect is strategically well chosen to analyze the response to different spatial forcing patterns (NH, SH and symmetric aerosol forcing). Tree-ring records are ideal for this type of analysis given their excellent chronological control and high temporal resolution. At the same time they can provide important constraints for model evaluation. For example Anchukaitis *et al.* (2010) noted that significant discrepancies exist between observed and simulated response to volcanic forcing over the Asian monsoon region. Similarly Stoffel *et al.* (2015) showed that model response to volcanic forcing includes an unrealistically strong surface temperature response, which is difficult to reconcile with the more muted response seen in tree-ring records (mainly those based on ring width rather than density parameters; Anchukaitis *et al.*, 2012b; D'Arrigo *et al.*, 2013), unless the model aerosol microphysics are changed.

4. Proposed research

The considerable species biodiversity of the tropical Andean forests increases our likelihood of identifying potential tree species for dendrochronology and developing a continuous tree-ring network. We will create a dataset of tree-ring records from several sub-regions within the tropical Andes (Fig. 3). Studies conducted by the PIs in Bolivia reveal high climatic sensitivity for *P. tarapacana* in the Altiplano (Fig. 4) and indicate that some species in more tropical environments show visible annual rings (Fig. 5). These chronologies are available for use in this project (see section 4.1 below). However, the spatial coverage of the current tree-ring network is still highly insufficient. For this reason, considerable time and resources will be allocated for fieldwork and for identifying appropriate species, suitable sites and stands of old-aged trees to fill these gaps and increase the number and length of the tropical Andean tree-ring records. Fieldwork and chronology development will be performed both at the TRL-LDEO and the laboratories of our collaborators in South America (see 'Unfunded collaborations' below). These collaborations are crucial if we are to overcome the myriad difficulties inherent in conducting fieldwork in foreign countries. The PIs will provide training to local partners, who will in turn provide assistance in species identification and fieldwork logistics (e.g.; guidance, hiring vehicles, field permits to work in national protected areas, etc.). Traditional dendrochronological techniques, including intensive fieldwork and standard dating, measurement and processing of wood samples, will be combined with geochemical methods and mass spectrometry to measure radioisotopes, such as ^{14}C, in order to verify the dating of the resulting chronologies. Calibration and verification analyses with instrumental and gridded data will be used to reconstruct hydroclimate variability and address our research questions (see above). Methodological details are described below.

4.1. Existing tree-ring width chronologies available for this project

Our collaborators from IANIGLA-CONICET (Mendoza, Argentina) and Universidad Austral (Valdivia, Chile) have agreed to provide 25 well-dated ring-width *Polylepis tarapacana* chronologies for this project (Fig. 3). The chronologies are from sites located between 17° to 23° S and 64° to 70° W. *P. tarapacana*, a highly moisture-sensitive woody species, has been used to generate a network of multi-century tree-ring width chronologies along the South American Altiplano from 17 to 23° S (Morales *et al.*, 2012). As the yearly growth of *Polylepis* trees varies depending on hydrological balance (Morales *et al.*, 2004; Solíz *et al.*, 2009; Carilla *et al.*, 2013), annual rings of these trees have been used to reconstruct past precipitation and lake area fluctuations (Morales *et al.* 2012, 2015). Seven of these chronologies are more than 500 years in length. The shortest chronology starts in 1890 C.E., while the oldest dates back to 1226 C.E., covering most of the last millennium. Further north, a few other preliminary chronologies are available from Peru (e.g.; *Cedrela odorata, Prosopis spp.*) and Bolivia (e.g.; *Polylepis pepei*) as a result of an ongoing collaboration among L. Andreu-Hayles, R. Isela (*Herbario Nacional de Bolivia*), P. Jørgensen (Missouri Botanical Garden), M. Morales (IANIGLA, Argentina) and J.R. Rojas (*Universidad Continental*, Peru). Overall, the spatial coverage of the current tree-ring network is quite dense in the southern tropics, but still clearly insufficient for regional to large-scale climate studies in the inner tropics.

4.2. Development of new tree-ring chronologies

Fieldwork will be performed in Peru and Bolivia in collaboration with our local partners (see 'Unfunded collaborations' below). We will make an intensive field effort to increase the spatial coverage of the existing tree-ring network. This will be accomplished by exploring new sites across the Andes of Peru, but also along the eastern slope of the Bolivian Andes (e.g. permanent plots from Madidi National Park). We will focus mainly on the collection of wood from species for which tree-ring chronology development has already been demonstrated (e.g.: *P. tarapacana, P. pepei, P. subsericans, P. rugulosa, Cedrela odorata*; see references in section 2.1) or for which evidence of visible tree-ring boundaries have been shown, such as *Pseudolmedia rigida, Gynoxys compressissima*, *Weinmannia fagaroides* and others listed in a recent review (IAI Report, 2014). Additional species not previously identified will also be explored when appropriate. We will sample at least ten new sites located along the Peruvian Andes, which is presently the least represented region in our network. Finally, we will also update and extend back in time the current *P. tarapacana* network from the Bolivian Altiplano, particularly for northwest Bolivia, where existing chronologies are not well replicated and currently record only short time periods. During the proposed field work botanists with expertise in tropical flora (see letters of collaboration) will aid in species identification following established protocols (e.g. voucher collection). Specifically, this project will generate tree-ring chronologies from living and dead trees to develop paleoclimate reconstructions. Six <u>fieldwork campaigns</u> of 21 days each will be conducted during the first two years of the project, including (**Fig. 3**), **Region 1**: Madidi National Park in Bolivia (species listed in IAI report, 2014); **Region 2**: Tacna, southern Peru (mainly *P. rugulosa* and *P. tarapacana*), Puno (*P. Pepei*), Cusco (*P. subsericans*); **Region 3**: Bagua Grande, Piura, northern Peru (mainly *C. odorata*); **Region 4**: Altiplano, northern Bolivia (*P. tarapacana*); **Region 5**: Huaraz, northern Peru (*Polylepis sericea*, *Alnus acuminata*); and **Region 6:** Huancayo (*P. pepei*) and Junin, central Peru (*P. subsericans* and *P. pepei*, respectively).

<u>Sampling strategy</u>: Site selection will focus on undisturbed natural old-growth forests. Isolated trees or trees growing in open forests will be sought to maximize the climate signature recorded in the trees. In order to develop robust chronologies, between 20 and 40 or more samples will be collected per site. Due to the eccentric patterns of radial growth and the presence of twisted trunks in *Polylepis*, most of the samples from living trees will be obtained as wedges or cross-sections from multi-stemmed individuals and relict wood using chainsaws, complemented with multiple cores collected using increment borers (6-8 per tree). We will also search for cross sections from stumps or dead trees in the field. While these materials are generally well preserved due to the dry climate of the Altiplano, there is some urgency in the sampling of dead wood on the eastern Andean slopes, where the high rate of decomposition in these humid environments can deteriorate wood very quickly. Samples from logs will also be obtained from local sawmills or villages (e.g.; buildings). **Laboratory methods**: Standard dendrochronological techniques (Stokes & Smiley, 1968; Fritts, 1976; Cook & Kairiukstis, 1990) will be used to cross-date the samples and to build a master tree-ring chronology for each site. Cores will be mounted and sanded until cells are clearly visible under a binocular microscope (Stokes & Smiley, 1968). All samples will be visually cross-dated to avoid dating errors due to missing (locally absent) or false (double) rings (Yamaguchi, 1991). Tree-ring widths will be measured to the nearest 0.001 mm for all cores, and cross-dating will be statistically verified using the program Cofecha (Holmes, 1983). We will classify tropical wood structure into four types (Worbes, 1995): (1) density variations; (2) marginal parenchyma bands; (3) repeated pattern of alternating fiber and parenchyma bands; and (4) variations in vessel distribution/size.

4.3. Radiocarbon (^{14}C) measurements

We will test for the annual nature of tree rings in about ~**18 species/sites**. In each case, the absolute calendar year will be confirmed by ^{14}C accelerator mass spectrometry (^{14}C-AMS) measurements from the cellulose of 8 rings selected from the pre- and post-bomb peak (e.g.; Fig. 5b). Multiple ^{14}C measurements, whose formation years were estimated from the last 70 years will allow us to precisely determine the periodicity of the tree growth variations. Identification of any long-lived tree species with confirmed annual resolution will help to extend back the dataset needed to improve the ^{14}C atmospheric curve for the SH, especially at lower latitudes (see 'Broader impacts' below). **Laboratory methods**: In order to perform ^{14}C-AMS measurements at KCCAMS, we will combust and reduce to graphite holocellulose extracts following standard protocols (Santos *et al.*, 2004; Southon & Magana, 2010; Santos & Ormsby, 2013). High-precision ^{14}C-AMS measurements with a precision better than 0.3% will be obtained using a modified compact AMS system (Beverly *et al.*, 2010), followed by a suite of control woody materials (e.g. secondary standards and blanks) for proper calibration and background corrections (as described in Andreu-Hayles *et al.*, 2015; Hadad *et al.*, 2015; Santos *et al.*, 2015).

4.4. Statistical analyses of ring width

Standardization methods designed to extract climate information from tree-ring records and to remove biological age trends and non-climatic disturbances (Cook & Kairiukstis, 1990) will be used to detrend individual ring-width series to generate traditional chronologies. Age-related trends will be removed using conservative curve fits (e.g. smoothing splines, Cook & Peters, 1981), negative exponential/linear regression, or Regional Curve Standardization (RCS) to preserve lower frequency variance. The most suitable standardization methodology, including novel approaches such as the 'Signal Free' method (Melvin & Briffa, 2008), will be chosen on a case-by-case basis.

4.5. Local climatic calibration of tree-ring records

To extract climate information from the tree-ring chronologies, statistical techniques will be applied to relate them with observed station-based and gridded climatological data. The results will be used for developing reconstructions of local climate and relationships with ENSO- and SASM-indices. Instrumental temperature and precipitation data will be compiled for comparison with tree-ring series and spatiotemporal reconstructions within the study region. Co-PI Vuille maintains a dense climatological database for the Andes with >800 station records from Peru and Bolivia (Vuille *et al.*, 2000; 2003; 2008; 2015). Additionally, our international collaborators will provide local station records for their respective countries. We will also use high-quality reanalysis data of monthly temperature, precipitation and drought indices derived from various products: ERA-Interim, NCEP/NCAR and 20th Century reanalysis (Kalnay *et al.*, 1996; Compo *et al.*, 2011; Dee *et al.*, 2011). All datasets are publicly available, and also stored and continually updated on LDEO and UAlbany servers.

Correlation and linear regression analyses, including Monte Carlo techniques to account for autocorrelation, will help identify climate variables important to growth. To examine spatial and temporal relationships between tree-ring chronologies and climate, spatial correlation maps will be generated. The Kalman filter, a dynamical regression technique, will be applied to assess time-dependent changes in growth response to climate (Kalman, 1960; Visser & Molenaar, 1990). Spectral analyses, including time-space filtering using wavelets (Torrence & Compo, 1998), will be used to identify time-varying and frequency-dependent relationships between tree rings and climate. We will test robustness of resolved frequencies using Monte Carlo techniques on synthetic datasets and null hypotheses. A key step will be to assess the extent to which the tree-ring data have coherent and climate-linked spectra across time and space through wavelet, Multi Taper Method (MTM) and Singular Spectrum Analysis (SSA) techniques. Potential for spurious regressions, and ability to evaluate statistics for significance, will be tested against red noise null hypotheses taking into account uncertainty in both tree-ring and climate data. We fully recognize that non-climatic factors can affect relationships between tree rings and climate, such as insect attacks, pathogens, and CO_2/nutrient fertilization, but by working with chronologies over a large area we will be able to retrieve the climatic signal in our data. Additionally, identification of common variance shared by tree-ring chronologies using Principal Component Analyses (PCA) will provide information concerning the strength of the shared climatic signal, allow detection of temporary couplings and decoupling in the covariance between time-series, and show periods or more/less external forcing.

4.6. Paleoclimatic reconstruction of ENSO and SASM indices

We will use principal component regression analysis (Cook & Kairiukstis, 1990) and where possible point-by-point regression (Cook *et al.*, 1999; Cook *et al.*, 2004) to calibrate the broad-scale information in the tree-ring network against instrumental climate data. We will use these regression models to reconstruct gridded surface air temperature, SST, SLP, and hydroclimate data for the tropical Pacific domain. This type of climate field reconstruction (Cook *et al.*, 2010) is novel relative to standard reconstructions based only on individual point indices. This will allow us to reconstruct SST-based ENSO indices such as Nino3.4 or SLP-based indices such as the Southern Oscillation Index (SOI). Several studies using ice cores (Bradley *et al.*, 2003; Thompson *et al.*, 2013) or tree rings (Christie *et al.*, 2009; Morales *et al.*, 2012; Li *et al.*, 2013) have highlighted the potential to reconstruct tropical Pacific SST fields from central Andean proxies. We will also compare our tree-ring chronologies to rainfall variability over the core monsoon domain to test the feasibility of a tree-ring based monsoon (SASM) reconstruction. As shown by Hurley *et al.* (2015), precipitation variability in the central Andes of southern Peru is associated with large-scale perturbations in convective activity and rainfall over the western and central Amazon basin, highlighting the potential of Andean proxies to reconstruct monsoon variations over the Amazon basin. Several suitable monsoon indices based on total rainfall amount, outgoing longwave radiation, and vertical wind shear or low-level wind field have been proposed and may be suitable targets for reconstruction (Jones & Carvalho, 2002; Vuille & Werner, 2005; Vuille *et al.*, 2012). This two-pronged approach will also allow us to address the second research question (see section 3) regarding the historical ENSO-SASM relationship and its (non-) stationarity during periods of distinctive radiative forcing, such as the 2nd half of the LIA. To further explore temporal variability, statistics will be computed for different temporal scales (e.g.; interannual, decadal) after time-scale decomposition (Cook *et al.*, 2010). Several sub-periods will also be considered to explore changes in variability and teleconnections. Robustness and skill of our reconstructions will be evaluated using split-sample cross-validation methods, in which part of the instrumental data is withheld during calibration for later use in independent model evaluation. A nested modeling procedure that accounts for distinct time spans in the network will optimize the length of the final reconstructions.

4.7. Diagnosing the impact of volcanic forcing on central Andes hydroclimate

The impacts of volcanic eruptions on the South American monsoon and tropical hydroclimate were analyzed as part of the PhD work of Co-PI Vuille's PhD student Chris Colose in another NSF-funded project (see section 9 – results from prior NS support). These model results provide a blueprint for the type of hydroclimatic signal we expect to see in tree-ring records from the tropical Andes following large volcanic eruptions (see Fig. 7). Clearly, our chosen domain is strategically well placed to identify the asymmetric response to volcanic aerosol forcing from either hemisphere. We will use superposed epoch analysis to identify the tree-ring response to volcanic forcing, relying on the revised volcanic forcing chronology by Sigl *et al.* (2015). Comparing observed and simulated response to volcanic forcing will allow us to test whether they agree in sign, amplitude, timing, and persistence following an eruption. We will test whether the tree-ring response is scalable as in models, where larger eruptions lead to a proportionally larger precipitation and/or temperature response over South America (Colose *et al.*, 2016a). Stoffel *et al.* (2015) pointed out that the temperature response following volcanic eruptions in most models is inconsistent with the more muted response seen in high-latitude tree ring records. To what extent this also applies to tropical tree rings, which are more moisture sensitive, is not clear. Aside from superposed epoch analyses we will also focus on the response to individual eruptions that are best resolved in our tree ring chronologies. These events can serve as a test bed to diagnose the physical climate response in the models over the tropical Andes, and how climate change associated with eruptions physically affected tree-ring growth. It also allows us to assess to what extent the response to volcanic forcing differs depending on the mean state of the background climate at the time of the eruption (e.g. Pausata *et al.*, 2015). Aside from CMIP5/PMIP3 simulations run with and without volcanic forcing (e.g. Otto-Bliesner *et al.*, 2016) we will also rely on new LM runs slated to come online as part of PMIP4/CMIP6 (Kageyama *et al.*, 2016), and a new set of idealized volcanic forcing experiments that form part of the VolMIP/CMIP6 project (Zanchettin *et al.*, 2016). These runs will be particularly useful for hypothesis testing of a) how Andean trees might respond to a close succession of strong volcanic eruptions, b) in what way they respond to volcanic forcing during ENSO events, c) their sensitivity to asymmetric aerosol forcing and d) whether the trees document a longer-term response to volcanic forcing as induced though interactions with the tropical oceans (Zanchettin *et al.*, 2016). As an outcome from this research we will establish the first quantitative estimate of the hydroclimatic response to volcanic forcing in the region, thereby gaining important new insight into the sensitivity of the Andean climate system to abrupt changes in radiative forcing. Our results will also be useful for model diagnosis and contribute to further model improvements. Past assessments of LM runs over the SASM domain within the PMIP3/CMIP5 framework have pointed to model deficiencies and lack of realism in simulating slow-varying changes in mean precipitation over America during key periods such as the LIA (Rojas *et al.*, 2016), despite realistically simulating changes in atmospheric circulation. To what extent the models fair better at simulating abrupt, time-limited climate change events in this region is currently unknown.

5. Broader impacts

This project has a very strong capacity building component. We will provide **cross-disciplinary educational and international research experiences** across multiple scales of academia. Foreign and US research-oriented graduate and undergraduate students will participate in all aspects of this research, including fieldwork, laboratory proceedings, data analyses, presentation of results in conferences and meetings and contributions in peer-reviewed scientific publications. This project will involve postdoctoral researchers, graduates and undergraduates from both the USA and international (South American) institutions. A **postdoctoral scientist** (LDEO) and **Ph.D. students** (SUNY-Albany, LDEO) will be involved in the proposed work. Students will learn basics of dendrochronological analysis and will generate climate reconstructions using complex tropical tree species, which will be crucial for future advances in tropical dendrochronology. The PIs will provide guidance, training, laboratory experience, and one-on-one mentoring of focused independent research projects related to the larger framework of this proposal. Coordination with **international institutions** will foster the capabilities of local tree-ring laboratories within the tropical Andes. Training for graduates and undergraduates in these institutions will be an important commitment for the PIs. Field trips will be conducted with existing and developing groups in Bolivia and Peru, along with a scientist from IANIGLA as instructor. A **workshop** will be held during the second year in Huancayo (Peru) and students/researchers from Peru and Bolivia will be invited to participate. This workshop will provide training in tree-ring research to 15 students (field, laboratory work) and climate data analysis. Annual field campaigns in each project year in each country will provide training *in situ* and will facilitate interactions between foreign partners and the PIs. Those activities will not only enhance the broader impacts, but foster a long-lasting network of regional dendrochronology laboratories to advance the reconstruction of hydroclimate in the tropical Andes.

Earth2Class is a partnership between scientists at the Observatory and classroom educators. For over 16 years, the program has extended the impact of LDEO's research by holding over 160 workshops involving 80 Lamont scientists. The structure consists of Saturday/summer workshops paired with a website of extensive curriculum materials to disseminate cutting-edge science to educators in New York and New Jersey. Each workshop highlights discoveries made by Lamont scientists, enabling participants to learn first-hand about important investigations and gain a better understanding of the nature of scientific research. The goals of these workshops align well with the Next Generation Science Standards (NGSS; States, 2013) which calls for the analysis of geoscience data and models to make evidence-based forecasts of global and regional climate change. NGSS also expects educators to construct explanations for how the availability of natural resources and changes in climate are influenced by human activity. We will prepare two tailored **bilingual E2C workshops** (one in New York City and one in Albany) based on this project that will focus on the importance of paleoclimate research and why it is necessary to have a long-term perspective of climate variability to understand climate change, which dovetails nicely with NGSS expectations for educators. We will enrich this course with relevant examples from our research in the Central Andes. The workshops for New York and New Jersey educators will be run in year 2 (SUNY, Albany) and 3 (LDEO, Palisades) of the project by the PIs and Dr. Michael J. Passow (see Letter of collaboration), the founder of E2C. The workshops will be conducted in both Spanish and English. The content available online will be translated into Spanish with the aid of our collaborators. We anticipate that such connections will result in meaningful discussions about comparative geoscience educational opportunities in our countries, as well as the production of classroom teaching materials available in both English and Spanish for both South American and US educators. These resources, along with archived materials from the workshop presentations, will be posted on the E2C website that steadily receives about 150,000 hits per month. Thus, the materials will be accessible and created for educators at the middle and high school levels, which will result in wide dissemination for educators nationally and internationally.

All project participants and collaborators interested in the multiple applications of ^{14}C methodology will be invited to attend an annual short course in '**Radiocarbon in Ecology and Earth System Science**' at UCI with PI Dr. Santos as instructor. This one-week course exposes undergraduates, national and international researchers of all levels to the uses of ^{14}C in the current and past global carbon cycle in atmospheric, oceanic and terrestrial ecosystems.

The development of new tree-ring chronologies in the Central Andes will represent a significant advancement in **tropical dendrochronology** and in our understanding of regional to global climate dynamics. Filling current gaps in the tropical Andes will greatly facilitate construction of the **South American Drought Atlas** (collaborative work between Dr. Cook from the TRL and Drs. Villalba and Morales from IANIGLA). The NADA (Cook *et al.*, 2004) and MADA (Cook *et al.*, 2010), North American and Monsoon Asian Drought Atlas, respectively, have been extensively used to study past climate dynamics (Coats *et al.*, 2013). These atlases provide a long-term context of climate variability not available from instrumental data. Project deliverables will include **spatio-temporal reconstructions** of Andean precipitation and SSTs variability (e.g.; point-by-point regression), as well as interannual reconstructions of modes of climate variability described by indices of ENSO and SASM. Composite analyses will document the past influence of these climate modes along our north-south transect. Having direct information on how ENSO has influenced this region in the past is crucial for mitigating ENSO impacts such as droughts (Altiplano) and floods (coastal areas) and will provide stakeholders with direct and applicable information about the effects of ENSO in the region, unlike previous reconstructions based on extratropical teleconnections (Li *et al.*, 2011; 2013).

Providing a long-term context for monsoon variability in this region and advancing our understanding of how sensitively it responds to changes in radiative forcing are crucial aspects for mitigating the negative impacts of climate change in the region. The looming threat of increased aridity in the region (e.g. Minvielle & Garreaud, 2011; Neukom *et al.,* 2015) and the portrayed weakening of the SASM over the last century (Bird *et al.,* 2011; Vuille *et al.,* 2012) render our results applicable and societally relevant for all future **adaptation efforts**.

The analysis of 18 tree-ring chronologies by means of ^{14}C-AMS will allow us to select suitable long-living tropical tree species for improving **the past ^{14}C atmospheric record of the SH**. A ^{14}C curve specific to tropical/subtropical South America from dendrochronologically dated wood is still lacking.

Present pre-bomb calibration of the ^{14}C time-scale for the SH combines ^{14}C and dendrochronological analyses from decadal wood samples of 0-1000 cal yr BP. Beyond this short tree-ring dataset, the SH curve was initially expanded back to 11ka cal yr BP based on the NH dataset and random model effects. Recently it has been extended to 50ka cal yr BP, with the addition of new tree-ring/^{14}C values (SHCal13 curve; Hogg *et al.*, 2013), and assuming an inter-hemispheric offset similar to the one measured for the past 0-2000 cal BP (McCormac *et al.*, 2004).

6. Work plan and timetable

The PIs will be organized in research teams according to their disciplines of expertise: dendrochronology lead by the TRL PIs (**Dr. Andreu-Hayles** and **Dr. D'Arrigo**), climate lead by SUNY, Albany (**Dr. Vuille**) and ^{14}C lead by KCCAMS-UCI (**Dr. Santos**). The work plan below details specific tasks and the responsible research team and collaborators for each deliverable. All the PIs will be involved in project meetings, training activities, writing of publications and results presentation.

AIMS		Partner	Year 1	Year 2	Year 3
1. NEW DATA SETS: To generate reliable annually dated tree-ring chronologies					
1.1	Field campaigns (tree-ring collection)	LDEO-Collab.			
1.2	Dendrochronological lab tasks	LDEO-Collab.			
1.3	Radiocarbon measurements	UCI			
2. DATA ANALYSES					
2.1	Time series analyses (tree-ring data)	LDEO-Collab.			
2.2	Calibration and climatic reconstructions	LDEO-ALB			
2.3	ENSO-SASM diagnosis in models & observations	ALB			
2.4	Diagnosing the impact of volcanic forcing	ALB			
2.5	Publication preparation	All			
3. MEETINGS, OUTREACH AND EDUCATIONAL ACTIVITIES					
3.1	International workshop, Huancayo, Peru	All			
3.2	Earth2Class, LDEO, USA	LDEO-ALB			
3.3	Student workshop UCI, USA	UCI			
3.4	PIs annual meeting	All			
3.5	Conferences	TBD			

7. Unfunded collaborations

This project will involve formal collaborations with scientists from dendrochronological and botanical institutions in the study region; in **Peru** with those from the *Universidad Continental* in Huancayo and *Universidad de Piura*; and in **Bolivia** with investigators from the Missouri Botanical Garden (USA) in collaboration with *Herbario Nacional de Bolivia* in La Paz. Additionally, we will collaborate with researchers from the well-established dendrochronology laboratories in Mendoza, **Argentina** (IANIGLA, CONICET) and *Universidad Austral* in **Chile** (see Letters of collaboration).

8. Relevance to NSF P2C2 Program

This project is highly relevant to a key area of research interest of the P2C2 program: '*What were the regional responses of coupled climate systems such as ENSO, the monsoons, NAM, and the MOC during past climate changes?*' A key deliverable of this project will be the first tree-ring network that spans a sizeable area of the tropical Andes sensitive to ENSO influence, yet at the same time located squarely in the core region of the South American monsoon. Our new paleoclimate reconstructions from a poorly represented area of the tropics will improve current knowledge about past ENSO and monsoon history. The results can also inform our understanding of larger-scale climate variability beyond the immediate study region. Additionally, reconstructions will serve as a testbed for model simulations of the Last Millennium, allowing us to assess their performance, quantify model error and bias and thereby constrain model uncertainty going forward. Finally advances in tropical dendrochronology resulting from this project will act as guidelines for further development of chronologies and reconstructions throughout the global tropics.

9. Results from Prior NSF Support

- NSF-PLR 15-04134: ***Response of High-latitude Forests to a Warmer and CO2-enriched Atmosphere: Tree Rings in a Process-based Model*** **(PI Andreu-Hayles**; \$579,971; 06/15/15 – 5/31/2018). Intellectual Merit: So far this project has generated new isotopic records at 2 tree line white spruce (*Picea glauca*) forests in the northern boreal forests of North America. This project uses of a process-based mechanistic model, MAIDENiso, to distinguish between the confounding effects of increases in temperatures and atmospheric CO_2 and to predict boreal forest response under different scenarios, and the NASA GISS ModelE2 general circulation model to provide inputs to MAIDENiso. No publications were produced under this award yet. Broader Impacts: 1 technician, 1 undergraduate and 1 PhD student are being trained in isotopic proceedings. This research addresses dynamic processes in rapid climate change.

- NSF ATM 0902051: ***NSF Seasonality of the Arctic: Shifting Seasonality of Northern Forest Response to Arctic Environmental Change*** (Lead PI: **R. D'Arrigo**; Co-PIs: K. Anchukaitis, S. Goetz, P. Beck; Unfunded collaborator: **L. Andreu-Hayles**; $381,154; 06/15/2009 – 5/31/2012, extended 06/1/2012 – 5/31/2013). *Intellectual Merit:* The sensitivity of northern forests to Arctic warming and related seasonality effects is highly complex, involving shifts in the timing and dynamics of multiple factors that can significantly impact tree growth. Ring-width and density data were used to identify and describe the nature of seasonal response to climatic and environmental changes for white spruce (*Picea glauca*) to investigate the response of boreal forests to changes in climate and seasonality. *Broader Impacts:* This project generated a detailed assessment of how boreal forests respond to warming-induced seasonality changes in Alaska, and how these changes may influence Arctic and global systems in the future. A PolarTREC teacher participated in fieldwork with the LDEO PIs, and blogged about her results with students and educational groups. Results/data were archived/submitted to ITRDB, and via publications and presentations. Post-doc Andreu-Hayles contributed to this research (Andreu-Hayles *et al.*, 2011; Beck *et al.*, 2011; Berner *et al.*, 2011; Anchukaitis *et al.*, 2012a; Beck *et al.*, 2013), and in relation to the Andreu-Hayles et al. (2011) paper a perspective piece (Williams et al., 2011) and media reports (e.g.; New York Times among others) were published.

- DEB–1144888: ***Is carbon biosequestration by plants feasible? Revealing the source of carbon embedded in phytoliths by using isotope analyses ($\delta^{13}C$ and ^{14}C measurements) and nanoparticles.*** **(PI Dos Santos** $431,439; 1/01/12-1/01/15, extended 1/01/15 – 1/01/17). Intellectual Merit: Although biosilica formation in higher plants (phytoliths) has been studied for decades, the source of the carbon embedded in those structures has never been directly attained. We reported for the first time that plants incorporate soil organic carbon (SOC) via roots and relocate it into phytoliths, inappropriate as carbon proxy of plants, and its impacts in isotopic and dating studies (Corbineau *et al.*, 2013; Alexandre *et al.*, 2015; Gallagher *et al.*, 2015; Reyerson *et al.*, 2016; Santos *et al.*, 2016). Broader Impacts: This funding supported an international Ph.D. candidate, two Specialist Researchers, a Postdoctoral Fellow and an undergrad Honor's Thesis. Findings have also been disseminated to colleagues and students through Dr. Santos webpage, domestic and international scientific meetings and at the UCI research programs listed above.

- AGS-1303828: ***High-resolution reconstruction of the South American monsoon history from isotopic proxies and forward modeling.*** **(PI M. Vuille;** $571,281; 09/01/2013 – 08/31/2017). *Intellectual Merit:* This project focuses on monsoon reconstruction from ice cores and speleothems, and diagnosing monsoon sensitivity to radiative forcing in CMIP5/PMIP3 models. Within this project we developed an isotopic forward model for tropical ice core $\delta^{18}O$, which can be linked with output from isotope-enabled paleoclimate models simulating past $\delta^{18}O$ variations in tropical ice cores. *Broader Impacts:* One Postdoc (John Hurley) and one PhD student (Chris Colose) were supported through this award, which also included a 6-month student exchange with the Univ. of Sao Paulo in Brazil. Results from this research have been disseminated through presentations at over a dozen meetings and guest lectures in the US, Iceland, France, Switzerland, Argentina, Chile and Brazil. Research methods, analyses and interpretation of paleoclimatic results from this project are showcased in both the undergraduate and graduate classroom (the PI teaches a shared resource course in Paleoclimatology, ENV450/ATM 550). To date the following publications have resulted from this award (Apaestegui *et al.*, 2014; Hurley *et al.*, 2015, 2016; Strikis *et al.*, 2015; Bustamante *et al.*, 2016; Colose *et al.*, 2016a, 2016b; Flantua *et al.*, 2016; Moquet *et al.*, 2016; Novello *et al.*, 2016; Rojas *et al.*, 2016).

REFERENCES

Adams, J.B., Mann, M.E. & Ammann, C.M. (2003) Proxy evidence for an El Nino-like response to volcanic forcing. *Nature*, **426**, 274-278.

Alexandre, A., Basile-Doelsch, I., Delhaye, T., Borshneck, D., Mazur, J.C., Reyerson, P. & Santos, G.M. (2015) New highlights of phytolith structure and occluded carbon location: 3-D X-ray microscopy and NanoSIMS results. *Biogeosciences*, **12**, 863-873.

Anchukaitis, K.J., Buckley, B.M., Cook, E.R., Cook, B.I., D'Arrigo, R.D. & Ammann, C.M. (2010) Influence of volcanic eruptions on the climate of the Asian monsoon region. *Geophysical Research Letters*, **37**

Anchukaitis, K.J., D'Arrigo, R.D., Andreu-Hayles, L., Frank, D., Verstege, A., Curtis, A., Buckley, B.M., Jacoby, G.C. & Cook, E.R. (2012a) Tree-Ring-Reconstructed Summer Temperatures from Northwestern North America during the Last Nine Centuries. *Journal of Climate*, **26**, 3001-3012.

Anchukaitis, K.J., Breitenmoser, P., Briffa, K.R., Buchwal, A., Buntgen, U., Cook, E.R., D'Arrigo, R.D., Esper, J., Evans, M.N., Frank, D., Grudd, H., Gunnarson, B.E., Hughes, M.K., Kirdyanov, A.V., Korner, C., Krusic, P.J., Luckman, B., Melvin, T.M., Salzer, M.W., Shashkin, A.V., Timmreck, C., Vaganov, E.A. & Wilson, R.J.S. (2012b) Tree rings and volcanic cooling. *Nature Geoscience*, **5**, 836-837.

Andreu-Hayles, L., D'Arrigo, R., Anchukaitis, K.J., Beck, P., S. A., Frank, D. & Goetz, S. (2011) Varying boreal forest response to Arctic environmental change at the Firth River, Alaska. *Environmental Research Letters*, **6**, 045503.

Andreu-Hayles, L., Santos, G.M., Herrera-Ramirez, D.A., Martin-Fernandez, J., Ruiz-Carrascal, D., Boza-Espinoza, T.E., Fuentes, A.F. & Jorgensen, P.M. (2015) Matching dendrochronological dates with the southern hemisphere C-14 bomb curve to confirm annual tree rings in *Pseudolmedia Rigida* from Bolivia. *Radiocarbon*, **57**, 1-13.

Apaestegui, J., Cruz, F.W., Sifeddine, A., Vuille, M., Espinoza, J.C., Guyot, J.L., Khodri, M., Strikis, N., Santos, R.V., Cheng, H., Edwards, L., Carvalho, E. & Santini, W. (2014) Hydroclimate variability of the northwestern Amazon Basin near the Andean foothills of Peru related to the South American Monsoon System during the last 1600 years. *Climate of the Past*, **10**, 1967-1981.

Atwood, A.R., Wu, E., Frierson, D.M.W., Battisti, D.S. & Sachs, J.P. (2016) Quantifying Climate Forcings and Feedbacks over the Last Millennium in the CMIP5-PMIP3 Models. *Journal of Climate*, **29**, 1161-1178.

Baker, J.C.A., Hunt, S.F.P., Clerici, S.J., Newton, R.J., Bottrell, S.H., Leng, M.J., Heaton, T.H.E., Helle, G., Argollo, J., Gloor, M. & Brienen, R.J.W. (2015) Oxygen isotopes in tree rings show good coherence between species and sites in Bolivia. *Global and Planetary Change*, **133**, 298-308.

Ballantyne, A.P., Baker, P.A., Chambers, J.Q., Villalba, R. & Argollo, J. (2011) Regional Differences in South American Monsoon Precipitation Inferred from the Growth and Isotopic Composition of Tropical Trees. *Earth Interactions*, **15**

Baraer, M., Mark, B.G., McKenzie, J.M., Condom, T., Bury, J., Huh, K.I., Portocarrero, C., Gomez, J. & Rathay, S. (2012) Glacier recession and water resources in Peru's Cordillera Blanca. *Journal of Glaciology*, **58**, 134-150.

Beck, P.S.A., Andreu-Hayles, L., D'Arrigo, R., Anchukaitis, K.J., Tucker, C.J., Pinzón, J.E. & Goetz, S.J. (2013) A large-scale coherent signal of canopy status in maximum latewood density of tree rings at arctic treeline in North America. *Global and Planetary Change*, **100**, 109-118.

Beck, P.S.A., Juday, G.P., Alix, C., Barber, V.A., Winslow, S.E., Sousa, E.E., Heiser, P., Herriges, J.D. & Goetz, S.J. (2011) Changes in forest productivity across Alaska consistent with biome shift. *Ecology Letters*, **14**, 373-379.

Berner, L.T., Beck, P.S.A., Bunn, A.G., Lloyd, A.H. & Goetz, S.J. (2011) High-latitude tree growth and satellite vegetation indices: Correlations and trends in Russia and Canada (1982-2008). *J. Geophys. Res.*, **116**, G01015.

Beverly, R.K., Beaumont, W., Tauz, D., Ormsby, K.M., von Reden, K.F., Santos, G.M. & Southon, J.R. (2010) THE KECK CARBON CYCLE AMS LABORATORY, UNIVERSITY OF CALIFORNIA, IRVINE: STATUS REPORT. *Radiocarbon*, **52**, 301-309.

Biondi, F. & Fessenden, J.E. (1999) Radiocarbon analysis of Pinus lagunae tree rings: Implications for tropical dendrochronology. *Radiocarbon*, **41**, 241-249.

Biondi, F., Strachan, S.D., Mensing, S. & Piovesan, G. (2007) Radiocarbon analysis confirms the annual nature of sagebrush growth rings. *Radiocarbon*, **49**, 1231-1240.

Bird, B.W., Abbott, M.B., Vuille, M., Rodbell, D.T., Stansell, N.D. & Rosenmeier, M.F. (2011) A 2,300-year-long annually resolved record of the South American summer monsoon from the Peruvian Andes. *Proceedings of the National Academy of Sciences of the United States of America*, **108**, 8583-8588.

Boninsegna, J.A., Argollo, J., Aravena, J.C., Barichivich, J., Christie, D., Ferrero, M.E., Lara, A., Le Quesne, C., Luckman, B.H., Masiokas, M., Morales, M., Oliveira, J.M., Roig, F., Srur, A. & Villalba, R. (2009) Dendroclimatological reconstructions in South America: A review. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **281**, 210-228.

Borman, F.H. & Berlyn, G. (1981) *Age and Growth Rate of Tropical Trees: New Directions for Research.*

Bradley, R.S., Vuille, M., Hardy, D. & Thompson, L.G. (2003) Low latitude ice cores record Pacific sea surface temperatures. *Geophysical Research Letters*, **30**

Bräuning, A. (2009) Climate variability of the tropical Andes since the late Pleistocene. *Adv. Geosci.*, **22**, 13-25.

Bräuning, A. (2011) Editorial note for the special issue on 'Tropical Dendroecology'. *Trees*, **25**, 1-2.

Brienen, R. & Zuidema, P. (2005) Relating tree growth to rainfall in Bolivian rain forests: a test for six species using tree ring analysis. *Oecologia*, **146**, 1-12.

Brienen, R.J.W. & Zuidema, P.A. (2006) Lifetime growth patterns and ages of Bolivian rain forest trees obtained by tree ring analysis. *Journal of Ecology*, **94**, 481-493.

Brienen, R.J.W., Zuidema, P.A. & Martinez-Ramos, M. (2010) Attaining the canopy in dry and moist tropical forests: strong differences in tree growth trajectories reflect variation in growing conditions. *Oecologia*, **163**, 485-496.

Brienen, R.J.W., Helle, G., Pons, T.L., Guyot, J.-L. & Gloor, M. (2012) Oxygen isotopes in tree rings are a good proxy for Amazon precipitation and El Niño-Southern Oscillation variability. *Proceedings of the National Academy of Sciences*, **109**, 16957-16962.

Bustamante, M.G., Cruz, F.W., Vuille, M., Apaestegui, J., Strikis, N., Panizo, G., Novello, F.V., Deininger, M., Sifeddine, A., Cheng, H., Moquet, J.S., Guyot, J.L., Santos, R.V., Segura, H. & Edwards, R.L. (2016) Holocene changes in monsoon precipitation in the Andes of NE Peru based on delta O-18 speleothem records. *Quaternary Science Reviews*, **146**, 274-287.

Carilla, J., Grau, H.R., Paolini, L. & Morales, M. (2013) Lake Fluctuations, Plant Productivity, and Long-Term Variability in High-Elevation Tropical Andean Ecosystems. *Arctic Antarctic and Alpine Research*, **45**, 179-189.

Christie, D.A., Lara, A., Barichivich, J., Villalba, R., Morales, M.S. & Cuq, E. (2009) El Niño-Southern Oscillation signal in the world's highest-elevation tree-ring chronologies from the Altiplano, Central Andes. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **281**, 309-319.

Coats, S., Smerdon, J.E., Seager, R., Cook, B.I. & González-Rouco, J.F. (2013) Megadroughts in Southwestern North America in ECHO-G Millennial Simulations and Their Comparison to Proxy Drought Reconstructions*. *Journal of Climate*, **26**, 7635-7649.

Colose, C.M., LeGrande, A.N. & Vuille, M. (2016a) The influence of volcanic eruptions on the climate of tropical South America during the last millennium in an isotope-enabled general circulation model. *Climate of the Past*, **12**, 961-979.

Colose, C.M., LeGrande, A.N. & Vuille, M. (2016b) Hemispherically asymmetric volcanic forcing of tropical hydroclimate during the last millennium. *Earth System Dynamics*, **7**, 681-696.

Compo, G.P., Whitaker, J.S., Sardeshmukh, P.D., Matsui, N., Allan, R.J., Yin, X., Gleason, B.E., Vose, R.S., Rutledge, G., Bessemoulin, P., Bronnimann, S., Brunet, M., Crouthamel, R.I., Grant, A.N., Groisman, P.Y., Jones, P.D., Kruk, M.C., Kruger, A.C., Marshall, G.J., Maugeri, M., Mok, H.Y., Nordli, O., Ross, T.F., Trigo, R.M., Wang, X.L., Woodruff, S.D. & Worley, S.J. (2011) The Twentieth Century Reanalysis Project. *Quarterly Journal of the Royal Meteorological Society*, **137**, 1-28.

Cook, E.R. & Peters, K. (1981) The smoothing spline: a new approach to standardizing forest interior tree-ring width series for dendroclimatic studies. *Tree-Ring Bulletin*, **41**, 45-53.

Cook, E.R. & Kairiukstis, L. (1990) *Methods of Dendrochronology in Applications in the Environmental Sciences* Kluwer, Dordrecht, 394 pp.

Cook, E.R., Meko, D.M., Stahle, D.W. & Cleaveland, M.K. (1999) Drought Reconstructions for the Continental United States*. *Journal of Climate*, **12**, 1145-1162.

Cook, E.R., Woodhouse, C.A., Eakin, C.M., Meko, D.M. & Stahle, D.W. (2004) Long-Term Aridity Changes in the Western United States. *Science*, **306**, 1015-1018.

Cook, E.R., Anchukaitis, K.J., Buckley, B.M., D'Arrigo, R.D., Jacoby, G.C. & Wright, W.E. (2010) Asian Monsoon Failure and Megadrought During the Last Millennium. *Science*, **328**, 486-489.

Corbineau, R., Reyerson, P.E., Alexandre, A. & Santos, G.M. (2013) Towards producing pure phytolith concentrates from plants that are suitable for carbon isotopic analysis. *Review of Palaeobotany and Palynology*, **197**, 179-185.

D'Arrigo, R., Wilson, R. & Anchukaitis, K.J. (2013) Volcanic cooling signal in tree ring temperature records for the past millennium. *Journal of Geophysical Research-Atmospheres*, **118**, 9000-9010.

D'Arrigo, R., Jacoby, G., Buckley, B., Sakulich, J., Frank, D., Wilson, R., Curtis, A. & Anchukaitis, K. (2009) Tree growth and inferred temperature variability at the North American Arctic treeline. *Global and Planetary Change*, **65**, 71-82.

De Angelis, M., Simoes, J., Bonnaveira, H., Taupin, J.D. & Delmas, R.J. (2003) Volcanic eruptions recorded in the Illimani ice core (Bolivia): 1918-1998 and Tambora periods. *Atmospheric Chemistry and Physics*, **3**, 1725-1741.

Dee, D.P., Uppala, S.M., Simmons, A.J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M.A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A.C.M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A.J., Haimberger, L., Healy, S.B., Hersbach, H., Holm, E.V., Isaksen, L., Kallberg, P., Kohler, M., Matricardi, M., McNally, A.P., Monge-Sanz, B.M., Morcrette, J.J., Park, B.K., Peubey, C., de Rosnay, P., Tavolato, C., Thepaut, J.N. & Vitart, F. (2011) The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, **137**, 553-597.

Emile-Geay, J., Seager, R., Cane, M.A., Cook, E.R. & Haug, G.H. (2008) Volcanoes and ENSO over the past millennium. *Journal of Climate*, **21**, 3134-3148.

FAO (2010) Climate Change Adaptation in the Tropical Andes. *Food and Agriculture Organization, United Nations*, TCP/RLA/3112 factsheet.

Flantua, S.G.A., Hooghiemstra, H., Vuille, M., Behling, H., Carson, J.F., Gosling, W.D., Hoyos, I., Ledru, M.P., Montoya, E., Mayle, F., Maldonado, A., Rull, V., Tonello, M.S., Whitney, B.S. & Gonzalez-Arango, C. (2016) Climate variability and human impact in South America during the last 2000 years: synthesis and perspectives from pollen records. *Climate of the Past*, **12**, 483-523.

Francou, B., Vuille, M., Wagnon, P., Mendoza, J. & Sicart, J.E. (2003) Tropical climate change recorded by a glacier in the central Andes during the last decades of the twentieth century: Chacaltaya, Bolivia, 16 degrees S. *Journal of Geophysical Research-Atmospheres*, **108**

Fritts, H. (1976) *Tree rings and climate*. Academic Press, New York , 433 pp.

Gallagher, K.L., Alfonso-Garcia, A., Sanchez, J., Potma, E.O. & Santos, G.M. (2015) Plant growth conditions alter phytolith carbon. *Frontiers in Plant Science*, **6**

Garreaud, R., Vuille, M. & Clement, A.C. (2003) The climate of the Altiplano: observed current conditions and mechanisms of past changes. *Palaeogeography Palaeoclimatology Palaeoecology*, **194**, 5-22.

Garreaud, R.D. (2000) Cold air incursions over subtropical South America: Mean structure and dynamics. *Monthly Weather Review*, **128**, 2544-2559.

Garreaud, R.D., Vuille, M., Compagnucci, R. & Marengo, J. (2009) Present-day South American climate. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **281**, 180-195.

Gurgiser, W., Juen, I., Singer, K., Neuburger, M., Schauwecker, S., Hofer, M. & Kaser, G. (2016) Comparing peasants' perceptions of precipitation change with precipitation records in the tropical Callejon de Huaylas, Peru. *Earth System Dynamics*, **7**, 499-515.

Hadad, M., Santos, G.M., Roig Juñent, F.A. & Grainger, C.S.G. (2015) Annual nature of the growth rings of Araucaria araucana confirmed by radiocarbon analysis. *Quaternary Geochronology*,

Hietz, P., Wanek, W. & Dunisch, O. (2005) Long-term trends in cellulose delta C-13 and water-use efficiency of tropical Cedrela and Swietenia from Brazil. *Tree Physiology*, **25**, 745-752.

Hogg, A., Hua, Q., Blackwell, P., Buck, C., Guilderson, T., Heaton, T., Niu, M., Palmer, J., Reimer, P., Reimer, R., Turney, C. & Zimmerman, S. (2013) ShCal13 Southern Hemisphere calibration, 0-50,000 cal yr BP. *Radiocarbon* **55**, 1889-1903.

Holmes, R.L. (1983) Computer-assisted quality control in tree-ring dating and measurement. *Tree-Ring Bulletin*, **43**, 68-78.

Hoorn, C., Wesselingh, F.P., ter Steege, H., Bermudez, M.A., Mora, A., Sevink, J., Sanmartín, I., Sanchez-Meseguer, A., Anderson, C.L., Figueiredo, J.P., Jaramillo, C., Riff, D., Negri, F.R., Hooghiemstra, H., Lundberg, J., Stadler, T., Särkinen, T. & Antonelli, A. (2010) Amazonia Through Time: Andean Uplift, Climate Change, Landscape Evolution, and Biodiversity. *Science*, **330**, 927-931.

Hua, Q., Barbetti, M. & Rakowski, A.Z. (2013) Atmospheric Radiocarbon for the Period 1950–2010. *Radiocarbon*, **55**, 2059–2072.

Hua, Q., Barbetti, M., Worbes, M., Head, J. & Levchenko, V.A. (1999) Review of radiocarbon data from atmospheric and tree ring samples for the period 1945-1997 AD. *Iawa Journal*, **20**, 261-283.

Hurley, J.V., Vuille, M. & Hardy, D.R. (2016) Forward modeling of O-18 in Andean ice cores. *Geophysical Research Letters*, **43**, 8178-8188.

Hurley, J.V., Vuille, M., Hardy, D.R., Burns, S.J. & Thompson, L.G. (2015) Cold air incursions, O-18 variability, and monsoon dynamics associated with snow days at Quelccaya Ice Cap, Peru. *Journal of Geophysical Research-Atmospheres*, **120**, 7467-7487.

IAI Report (2014) Dendrochronological analyses of wood samples collected in the Madidi National Park, Bolivia. Activity part of Inter-American Institute for Global Change Research (IAI) Project funded by the John D and Catherine T. MacArthur Foundation: "Impactos del cambio climatico en la biodiversidad de los Andes Tropicales: Riesgo asociado al clima, vulnerabilidad y herramientas para toma de decision y conservacion".

Iles, C.E. & Hegerl, G.C. (2014) The global precipitation response to volcanic eruptions in the CMIP5 models. *Environmental Research Letters*, **9**

Jomelli, V., Pavlova, I., Guin, O., Soliz-Gamboa, C., Contreras, A., Toivonen, J.M. & Zetterberg, P. (2012) Analysis of the Dendroclimatic Potential of Polylepis pepei, P. subsericans and P. rugulosa In the Tropical Andes (Peru-Bolivia). *Tree-Ring Research*, **68**, 91-103.

Jones, C. & Carvalho, L.M.V. (2002) Active and break phases in the south American Monsoon system. *Journal of Climate*, **15**, 905-914.

Kageyama, M., Braconnot, P., Harrison, S.P., Haywood, A.M., Jungclaus, J., Otto-Bliesner, B.L., Peterschmitt, J.Y., Abe-Ouchi, A., Albani, S., Bartlein, P.J., Brierley, C., Crucifix, M., Dolan, A., Fernandez-Donado, L., Fischer, H., Hopcroft, P.O., Ivanovic, R.F., Lambert, F., Lunt, D.J., Mahowald, N.M., Peltier, W.R., Phipps, S.J., Roche, D.M., Schmidt, G.A., Tarasov, L., Valdes, P.J., Zhang, Q. & Zhou, T. (2016) PMIP4-CMIP6: the contribution of the Paleoclimate Modelling Intercomparison Project to CMIP6. *Geosci. Model Dev. Discuss.*, **2016**, 1-46.

Kahmen, A., Sachse, D., Arndt, S.K., Tu, K.P., Farrington, H., Vitousek, P.M. & Dawson, T.E. (2011) Cellulose delta O-18 is an index of leaf-to-air vapor pressure difference (VPD) in tropical plants. *Proceedings of the National Academy of Sciences of the United States of America*, **108**, 1981-1986.

Kalman, R.E. (1960) A new approach to linear filtering and prediction problems. *Transactions of the ASME – Journal of Basic Engineering*, 35-45.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Leetmaa, A., Reynolds, R., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K.C., Ropelewski, C., Wang, J., Jenne, R. & Joseph, D. (1996) The NCEP/NCAR 40-Year Reanalysis Project. *Bulletin of the American Meteorological Society*, **77**, 437-471.

Kanner, L.C., Burns, S.J., Cheng, H., Edwards, R.L. & Vuille, M. (2013) High-resolution variability of the South American summer monsoon over the last seven millennia: insights from a speleothem record from the central Peruvian Andes. *Quaternary Science Reviews*, **75**, 1-10.

Kaser, G. & Osmaton, H. (2007) *Tropical Glaciers*. New York: Cambridge. p. 19. ISBN 978-0-521-63333-8. .

Leavitt, S.W. & Lara, A. (1994) South-American tree-rings show declining delta-C-13 trend. *Tellus Series B-Chemical and Physical Meteorology*, **46**, 152-157.

Levin, I. & Hesshaimer, V. (2000) Radiocarbon - A unique tracer of global carbon cycle dynamics. *Radiocarbon*, **42**, 69-80.

Levin, I., Hammer, S., Kromer, B. & Meinhardt, F. (2008) Radiocarbon observations in atmospheric CO2: Determining fossil fuel CO2 over Europe using Jungfraujoch observations as background. *Science of The Total Environment*, **391**, 211-216.

Lewis, S.L., Brando, P.M., Phillips, O.L., van der Heijden, G.M.F. & Nepstad, D. (2011) The 2010 Amazon Drought. *Science*, **331**, 554-554.

Li, J., Xie, S.-P., Cook, E.R., Huang, G., D'Arrigo, R., Liu, F., Ma, J. & Zheng, X.-T. (2011) Interdecadal modulation of El Nino amplitude during the past millennium. *Nature Clim. Change*, **1**, 114-118.

Li, J., Xie, S.-P., Cook, E.R., Morales, M.S., Christie, D.A., Johnson, N.C., Chen, F., D/'Arrigo, R., Fowler, A.M., Gou, X. & Fang, K. (2013) El Nino modulations over the past seven centuries. *Nature Clim. Change*, **3**, 822-826.

Lisi, C., Pessenda, L., Tomazello-Filho, M. & Rozanski, K. (2001) 14C Bomb effect in tree rings of tropical and subtropical species of Brazil. *Tree-Ring Research* **57**, 191–196.

Liu, F., Chai, J., Wang, B., Liu, J., Zhang, X. & Wang, Z.Y. (2016) Global monsoon precipitation responses to large volcanic eruptions. *Scientific Reports*, **6**

Lopez, L. & Villalba, R. (2011) Climate Influences on the Radial Growth of Centrolobium microchaete, a Valuable Timber Species from the Tropical Dry Forests in Bolivia. *Biotropica*, **43**, 41-49.

Marengo, J.A., Nobre, C.A., Tomasella, J., Oyama, M.D., De Oliveira, G.S., De Oliveira, R., Camargo, H., Alves, L.M. & Brown, I.F. (2008) The drought of Amazonia in 2005. *Journal of Climate*, **21**, 495-516.

Marengo, J.A., Liebmann, B., Grimm, A.M., Misra, V., Dias, P.L.S., Cavalcanti, I.F.A., Carvalho, L.M.V., Berbery, E.H., Ambrizzi, T., Vera, C.S., Saulo, A.C., Nogues-Paegle, J., Zipser, E., Seth, A. & Alves, L.M. (2012) Recent developments on the South American monsoon system. *International Journal of Climatology*, **32**, 1-21.

McCormac, F.G., Hogg, A.G., Blackwell, P.G., Buck, C.E., Higham, T.F.G. & Reimer, P.J. (2004) SHCal04 Southern Hemisphere calibration, 0-11.0 cal kyr BP. *Radiocarbon*, **46**, 1087-1092.

McCormac, F.G., Hogg, A.G., Higham, T.F.G., Lynch-Stieglitz, J., Broecker, W.S., Baillie, M.G.L., Palmer, J., Xiong, L., Pilcher, J.R., Brown, D. & Hoper, S.T. (1998) Temporal variation in the interhemispheric C-14 offset. *Geophysical Research Letters*, **25**, 1321-1324.

Melvin, T.M. & Briffa, K.R. (2008) A "signal-free" approach to dendroclimatic standardisation. *Dendrochronologia*, **26**, 71-86.

Minvielle, M. & Garreaud, R.D. (2011) Projecting Rainfall Changes over the South American Altiplano. *Journal of Climate*, **24**, 4577-4583.

Moquet, J.S., Cruz, F.W., Novello, V.F., Strikis, N.M., Deininger, M., Karmann, I., Santos, R.V., Millo, C., Apaestegui, J., Guyot, J.L., Siffedine, A., Vuille, M., Cheng, H., Edwards, R.L. & Santini, W.

(2016) Calibration of speleothem delta O-18 records against hydroclimate instrumental records in Central Brazil. *Global and Planetary Change*, **139**, 151-164.

Morales, M.S. & Villalba, R. (2012) Influence of precipitation pulses on long-term Prosopis ferox dynamics in the Argentinean intermontane subtropics. *Oecologia*, **168**, 381-392.

Morales, M.S., Villalba, R., Grau, H.R. & Paolini, L. (2004) Rainfall-controlled tree growth in high-elevation subtropical treelines. *Ecology*, **85**, 3080-3089.

Morales, M.S., Carilla, J., Grau, H.R. & Villalba, R. (2015) Multi-century lake area changes in the Southern Altiplano: a tree-ring-based reconstruction. *Clim. Past*, **11**, 1139-1152.

Morales, M.S., Christie, D.A., Villalba, R., Argollo, J., Pacajes, J., Silva, J.S., Alvarez, C.A., Llancabure, J.C. & Gamboa, C.C.S. (2012) Precipitation changes in the South American Altiplano since 1300 AD reconstructed by tree-rings. *Climate of the Past*, **8**, 653-666.

Myers, N., Mittermeier, R.A., Mittermeier, C.G., da Fonseca, G.A.B. & Kent, J. (2000) Biodiversity hotspots for conservation priorities. *Nature*, **403**, 853-858.

Neukom, R., Rohrer, M., Calanca, P., Salzmann, N., Huggel, C., Acuña, D., Christie, A.D. & Morales, S.M. (2015) Facing unprecedented drying of the Central Andes? Precipitation variability over the period AD 1000–2100. *Environmental Research Letters*, **10**, 084017.

Novello, V.F., Vuille, M., Cruz, F.W., Strkis, N.M., de Paula, M.S., Edwards, R.L., Cheng, H., Karmann, I., Jaqueto, P.F., Trindade, R.I.F., Hartmann, G.A. & Moquet, J.S. (2016) Centennial-scale solar forcing of the South American Monsoon System recorded in stalagmites. *Scientific Reports*, **6**

Otto-Bliesner, B.L., Brady, E.C., Fasullo, J., Jahn, A., Landrum, L., Stevenson, S., Rosenbloom, N., Mai, A. & Strand, G. (2016) CLIMATE VARIABILITY AND CHANGE SINCE 850 CE An Ensemble Approach with the Community Earth System Model. *Bulletin of the American Meteorological Society*, **97**, 735-754.

Pausata, F.S.R., Grini, A., Caballero, R., Hannachi, A. & Seland, O. (2015) High-latitude volcanic eruptions in the Norwegian Earth System Model: the effect of different initial conditions and of the ensemble size. *Tellus Series B-Chemical and Physical Meteorology*, **67**

Pucha-Cofrep, D., Peters, T. & Bräuning, A. (2015) Wet season precipitation during the past century reconstructed from tree-rings of a tropical dry forest in Southern Ecuador. *Global and Planetary Change*, **133**, 65-78.

Rabatel, A., Francou, B., Soruco, A., Gomez, J., Caceres, B., Ceballos, J.L., Basantes, R., Vuille, M., Sicart, J.E., Huggel, C., Scheel, M., Lejeune, Y., Arnaud, Y., Collet, M., Condom, T., Consoli, G., Favier, V., Jomelli, V., Galarraga, R., Ginot, P., Maisincho, L., Mendoza, J., Menegoz, M., Ramirez, E., Ribstein, P., Suarez, W., Villacis, M. & Wagnon, P. (2013) Current state of glaciers in the tropical Andes: a multi-century perspective on glacier evolution and climate change. *Cryosphere*, **7**, 81-102.

Reuter, J., Stott, L., Khider, D., Sinha, A., Cheng, H. & Edwards, R.L. (2009) A new perspective on the hydroclimate variability in northern South America during the Little Ice Age. *Geophysical Research Letters*, **36**

Reyerson, P.E., Alexandre, A., Harutyunyan, A., Corbineau, R., De la Torre, H.A.M., Badeck, F., Cattivelli, L. & Santos, G.M. (2016) Unambiguous evidence of old soil carbon in grass biosilica particles. *Biogeosciences*, **13**, 1269-1286.

Ridley, H.E., Asmerom, Y., Baldini, J.U.L., Breitenbach, S.F.M., Aquino, V.V., Prufer, K.M., Culleton, B.J., Polyak, V., Lechleitner, F.A., Kennett, D.J., Zhang, M., Marwan, N., Macpherson, C.G., Baldini, L.M., Xiao, T., Peterkin, J.L., Awe, J. & Haug, G.H. (2015) Aerosol forcing of the position of the intertropical convergence zone since AD 1550. *Nature Geoscience*, **8**, 195-200.

Rojas, M., Arias, P.A., Flores-Aqueveque, V., Seth, A. & Vuille, M. (2016) The South American monsoon variability over the last millennium in climate models. *Climate of the Past*, **12**, 1681-1691.

Rozendaal, D. & Zuidema, P. (2010) Dendroecology in the tropics: a review. *Trees - Structure and Function*, 1-14.

Santos, G.M. & Ormsby, K. (2013) Behavioral Variability in ABA Chemical Pretreatment Close to the 14C Age Limit. *Radiocarbon* **55**, 534-544.

Santos, G.M., Alexandre, A. & Prior, C.A. (2016) From radiocarbon analysis to interpretation: A comment on "Phytolith Radiocarbon Dating in Archaeological and Paleoecological Research: A Case Study of Phytoliths from Modern Neotropical Plants and a Review of the Previous Dating Evidence", Journal of Archaeological Science (2015), doi: 10.1016/j.jas.2015.06.002." by Dolores R. Piperno. *Journal of Archaeological Science*, **71**, 51-58.

Santos, G.M., Linares, R., Lisi, C.S. & Tomazello Filho, M. (2015) Annual growth rings in a sample of Paraná pine (Araucaria angustifolia): Toward improving the 14C calibration curve for the Southern Hemisphere. *Quaternary Geochronology*, **25**, 96-103.

Santos, G.M., Southon, J.R., Druffel-Rodriguez, K.C., Griffin, S. & Mazon, M. (2004) Magnesium perchlorate as an alternative water trap in AMS graphite sample preparation: A report on sample preparation at KCCAMS at the University of California, Irvine. *Radiocarbon* **46**, 165-173.

Sigl, M., Winstrup, M., McConnell, J.R., Welten, K.C., Plunkett, G., Ludlow, F., Buentgen, U., Caffee, M., Chellman, N., Dahl-Jensen, D., Fischer, H., Kipfstuhl, S., Kostick, C., Maselli, O.J., Mekhaldi, F., Mulvaney, R., Muscheler, R., Pasteris, D.R., Pilcher, J.R., Salzer, M., Schuepbach, S., Steffensen, J.P., Vinther, B.M. & Woodruff, T.E. (2015) Timing and climate forcing of volcanic eruptions for the past 2,500 years. *Nature*, **523**, 543-+.

Solíz, C., Villalba, R., Argollo, J., Morales, M.S., Christie, D.A., Moya, J. & Pacajes, J. (2009) Spatio-temporal variations in *Polylepis tarapacana* radial growth across the Bolivian Altiplano during the 20th century. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **281**, 296-308.

Southon, J.R. & Magana, A.L. (2010) A Comparison of Cellulose Extraction and ABA Pretreatment Methods for AMS 14C Dating of Ancient Wood. *Radiocarbon* **52**, 1371-1379.

Srur, A.M., Villalba, R., Villagra, P.E. & Hertel, D. (2008) Influences of climatic and CO(2) concentration changes on radial growth of Nothofagus pumilio in Patagonia. *Revista Chilena De Historia Natural*, **81**, 239-256.

Stahle, D.W., Diaz, J.V., Burnette, D.J., Paredes, J.C., Heim, R.R., Fye, F.K., Acuna Soto, R., Therrell, M.D., Cleaveland, M.K. & Stahle, D.K. (2011) Major Mesoamerican droughts of the past millennium. *Geophysical Research Letters*, **38**, L05703.

States, L. (2013) *Next generation Science Standards: By States, For States*. National Academy Press, Washington DC. ISBN: 978-0-309-27227-8

Stevenson, S., Otto-Bliesner, B., Fasullo, J. & Brady, E. (2016) "El Nino Like" Hydroclimate Responses to Last Millennium Volcanic Eruptions. *Journal of Climate*, **29**, 2907-2921.

Stoffel, M., Khodri, M., Corona, C., Guillet, S., Poulain, V., Bekki, S., Guiot, J., Luckman, B.H., Oppenheimer, C., Lebas, N., Beniston, M. & Masson-Delmotte, V. (2015) Estimates of volcanic-induced cooling in the Northern Hemisphere over the past 1,500 years. *Nature Geoscience*, **8**, 784-+.

Stokes, M. & Smiley, T. (1968) *An introduction to tree-ring dating*, University of Chicago Press, Chicago, 73 pp.

Strikis, N.M., Chiessi, C.M., Cruz, F.W., Vuille, M., Cheng, H., Barreto, E.A.D., Mollenhauer, G., Kasten, S., Karmann, I., Edwards, R.L., Bernal, J.P. & Sales, H.D. (2015) Timing and structure of Mega-SACZ events during Heinrich Stadial 1. *Geophysical Research Letters*, **42**, 5477-5484.

Sulca, J., Vuille, M., Silva, Y. & Takahashi, K. (2016) Teleconnections between the Peruvian Central Andes and Northeast Brazil during Extreme Rainfall Events in Austral Summer. *Journal of Hydrometeorology*, **17**, 499-515.

Thompson, L.G., Mosley-Thompson, E., Davis, M.E., Zagorodnov, V.S., Howat, I.M., Mikhalenko, V.N. & Lin, P.-N. (2013) Annually Resolved Ice Core Records of Tropical Climate Variability Over the Past ~1800 Years. *Science*,

Thompson, L.G., Mosley-Thompson, E., Brecher, H., Davis, M., León, B., Les, D., Lin, P.-N., Mashiotta, T. & Mountain, K. (2006) Abrupt tropical climate change: Past and present. *Proceedings of the National Academy of Sciences*, **103**, 10536-10543.

Torrence, C. & Compo, G.P. (1998) A Practical Guide to Wavelet Analysis. *Bulletin of the American Meteorological Society*, **79**, 61-78.

Urrutia, R. & Vuille, M. (2009) Climate change projections for the tropical Andes using a regional climate model: Temperature and precipitation simulations for the end of the 21st century. *J. Geophys. Res.*, **114**, D02108.

Urrutia-Jalabert, R., Malhi, Y., Barichivich, J., Lara, A., Delgado-Huertas, A., Rodriguez, C.G. & Cuq, E. (2015) Increased water use efficiency but contrasting tree growth patterns in Fitzroya cupressoides forests of southern Chile during recent decades. *Journal of Geophysical Research-Biogeosciences*, **120**, 2505-2524.

Vera, C., Higgins, W., Amador, J., Ambrizzi, T., Garreaud, R., Gochis, D., Gutzler, D., Lettenmaier, D., Marengo, J., Mechoso, C.R., Nogues-Paegle, J., Silva Dias, P.L. & Zhang, C. (2006) Toward a unified view of the American Monsoon Systems. *Journal of Climate*, **19**, 4977-5000.

Villalba, R., Lara, A., Masiokas, M.H., Urrutia, R., Luckman, B.H., Marshall, G.J., Mundo, I.A., Christie, D.A., Cook, E.R., Neukom, R., Allen, K., Fenwick, P., Boninsegna, J.A., Srur, A.M., Morales, M.S., Araneo, D., Palmer, J.G., Cuq, E., Aravena, J.C., Holz, A. & LeQuesne, C. (2012) Unusual Southern Hemisphere tree growth patterns induced by changes in the Southern Annular Mode. *Nature Geoscience*, **5**, 793-798.

Villalba, R., Luckman, B., Boninsegna, J., D'Arrigo, R., Lara, A., Villanueva-Diaz, J., Masiokas, M., Argollo, J., Soliz, C., LeQuesne, C., Stahle, D., Roig, F., Aravena, J., Hughes, M., Wiles, G., Jacoby, G., Hartsough, P., Wilson, R.S., Watson, E., Cook, E., Cerano-Paredes, J., Therrell, M., Cleaveland, M., Morales, M., Graham, N., Moya, J., Pacajes, J., Massacchesi, G., Biondi, F., Urrutia, R. & Pastur, G. (2011) Dendroclimatology from Regional to Continental Scales: Understanding Regional Processes to Reconstruct Large-Scale Climatic Variations Across the Western Americas. *Dendroclimatology* (ed. by M.K. Hughes, T.W. Swetnam and H.F. Diaz), pp. 175-227. Springer Netherlands.

Vimeux, F., Ginot, P., Schwikowski, M., Vuille, M., Hoffmann, G., Thompson, L.G. & Schotterer, U. (2009) Climate variability during the last 1000 years inferred from Andean ice cores: A review of methodology and recent results. *Palaeogeography Palaeoclimatology Palaeoecology*, **281**, 229-241.

Visser, H. & Molenaar, J. (1990) Detecting time-dependent climatic responses in tree rings using the Kalman filter. *Methods of Dendrochronology* (ed. by E.R.C.a.L.K. (Eds.)), pp. 270-276. Kluwer, Dordrecht.

Volland, F., Pucha, D. & Braeuning, A. (2016) Hydro-climatic variability in Southern Ecuador reflected by tree-ring oxygen isotopes. *Erdkunde*, **70**, 69-82.

Vuille, M. & Werner, M. (2005) Stable isotopes in precipitation recording South American summer monsoon and ENSO variability: observations and model results. *Climate Dynamics*, **25**, 401-413.

Vuille, M., Bradley, R.S. & Keimig, F. (2000) Interannual climate variability in the Central Andes and its relation to tropical Pacific and Atlantic forcing. *Journal of Geophysical Research-Atmospheres*, **105**, 12447-12460.

Vuille, M., Bradley, R.S., Werner, M. & Keimig, F. (2003) 20th century climate change in the tropical Andes: Observations and model results. *Climatic Change*, **59**, 75-99.

Vuille, M., Franquist, E., Garreaud, R., Lavado Casimiro, W.S. & Caceres, B. (2015) Impact of the global warming hiatus on Andean temperature. *Journal of Geophysical Research-Atmospheres*, **120**, 3745-3757.

Vuille, M., Francou, B., Wagnon, P., Juen, I., Kaser, G., Mark, B.G. & Bradley, R.S. (2008) Climate change and tropical Andean glaciers: Past, present and future. *Earth-Science Reviews*, **89**, 79-96.

Vuille, M., Burns, S.J., Taylor, B.L., Cruz, F.W., Bird, B.W., Abbott, M.B., Kanner, L.C., Cheng, H. & Novello, V.F. (2012) A review of the South American monsoon history as recorded in stable isotopic proxies over the past two millennia. *Climate of the Past*, **8**, 1309-1321.

Wade, L. (2014) CLIMATE SCIENCE Chasing South America's monsoon. *Science*, **346**, 1042-1043.

Williams, A.P., Chonggang, X. & Nate, G.M. (2011) Who is the new sheriff in town regulating boreal forest growth? *Environmental Research Letters*, **6**, 041004.

Wils, T.H., Robertson, I., Eshetu, Z., Sass-Klaassen, U.G. & Koprowski, M. (2009) Periodicity of growth rings in Juniperus procera from Ethiopia inferred from crossdating and radiocarbon dating. *Dendrochronologia*, **27** 45-58.

Winter, A., Zanchettin, D., Miller, T., Kushnir, Y., Black, D., Lohmann, G., Burnett, A., Haug, G.H., Estrella-Martinez, J., Breitenbach, S.F.M., Beaufort, L., Rubino, A. & Cheng, H. (2015) Persistent drying in the tropics linked to natural forcing. *Nature Communications*, **6**

Worbes, M. (1995) How to measure growth dynamics in tropical trees - A review. *Iawa Journal*, **16**, 337-351.

Worbes, M. & Junk, W.J. (1989) Dating Tropical Trees by Means of ^14C From Bomb Tests. *Ecology*, **70**, 503-507.

Yamaguchi, D.K. (1991) A simple method for cross-dating increment cores from living trees. *Canadian Journal of Forest Research*, **21**, 414-416.

Zanchettin, D., Khodri, M., Timmreck, C., Toohey, M., Schmidt, A., Gerber, E.P., Hegerl, G., Robock, A., Pausata, F.S.R., Ball, W.T., Bauer, S.E., Bekki, S., Dhomse, S.S., LeGrande, A.N., Mann, G.W., Marshall, L., Mills, M., Marchand, M., Niemeier, U., Poulain, V., Rozanov, E., Rubino, A., Stenke, A., Tsigaridis, K. & Tummon, F. (2016) The Model Intercomparison Project on the climatic response to Volcanic forcing (VolMIP): experimental design and forcing input data for CMIP6. *Geoscientific Model Development*, **9**, 2701-2719.

Zeng, N., Yoon, J.-H., Marengo, J.A., Subramaniam, A., Nobre, C.A., Mariotti, A. & Neelin, J.D. (2008) Causes and impacts of the 2005 Amazon drought. *Environmental Research Letters*, **3**