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INTCAL, SHCAL, OR A MIXED CURVE? CHOOSING A ^{14}C CALIBRATION CURVE FOR ARCHAEOLOGICAL AND PALEOENVIRONMENTAL RECORDS FROM TROPICAL SOUTH AMERICA

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ABSTRACT. Because the ^{14}C calibration curves IntCal and SHCal are based on data from temperate latitudes, it remains unclear which curve is more suitable for archaeological and paleoenvironmental records from tropical South America. A review of climate dynamics reveals a significant influx of Northern Hemisphere air masses and moisture over a substantial part of the continent during the South American Summer Monsoon (SASM). Areas affected by the SASM receive unknown amounts of input from both hemispheres, where an argument could be made for either curve. Until localized tree-ring data can resolve this, we suggest using a mixed calibration curve, which accounts for inputs from both hemispheres, as a third calibration option. We present a calibration example from a crucial period of environmental and cultural change in the southern Lake Titicaca. Given our current lack of data on past Δ^{14}C variation in South America, our calibrations and chronologies will likely change in the future. We hope this paper spurs new research into this topic and encourages researchers to make an informed and explicit choice of which curve to use, which is particularly relevant in research on past human–environmental relationships.

KEYWORDS: ^{14}C calibration curves, hemispheric variation in atmospheric ^{14}C, Intertropical Convergence Zone, mixed curve calibration, South American Summer Monsoon.

INTRODUCTION

Over the past decade, ^{14}C calibration curves have improved substantially. Current calibration curves such as IntCal13 (Reimer et al. 2013), developed from tree rings and other annualized archives from temperate latitudes of the Northern Hemisphere, have been applied worldwide, including South America. However, atmospheric ^{14}C concentrations vary in both time and space (Braziunas et al. 1995), including a marked difference between the Northern and Southern Hemispheres, due to less atmospheric ^{14}C in the Southern Hemisphere (Lerman et al. 1970). Efforts to quantify this variation (Vogel et al. 1993; Stuiver and Braziunas 1998; McCormac et al. 1998) led to the development of the Southern Hemisphere calibration curve (McCormac et al. 2002), most recently refined as SHCal13 (Hogg et al. 2013a). In South America, SHCal is currently used by many paleoenvironmental scientists (e.g. Gao et al. 2012; Engel et al. 2014; Martel-Cea et al. 2016; Nelson and Sachs 2016; Weide et al. 2017) and archaeologists (e.g. Capriles and Albarracín-Jordan 2013; Levine and Stanish 2013; Koons and Alex 2014; Barberena et al. 2016; Jones et al. 2017). However, some archaeologists have questioned its applicability in tropical South America because of potential mixtures of air from the Northern Hemisphere (Finucane et al. 2007; Rick et al. 2009; Ogburn 2012; Marsh 2012, 2015). This issue is particularly relevant for South America because this continent spans parts of both hemispheres and experiences atmospheric mixing near the equator. This paper addresses the issue of which curve is more appropriate in tropical South America based on global models of ^{14}C in the atmosphere and modern regional climate dynamics.

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The question of which curve to use in tropical South America has not been discussed in detail, in part because the difference in calibrated ages derived from the two curves is less than a century. This difference is negligible for many paleoenvironmental processes operating over long temporal scales but can be significant for shorter time-scale dynamics, such as those relevant to past human activities. As long as a set of dates is calibrated with the same curve, the order and estimated time span of climatic or archaeological events will be consistent. Difficulties may emerge, however, when attempting to compare paleoenvironmental and archaeological records from different studies to address the societal impacts of shorter-term climatic changes (e.g. Binford et al. 1997; Marsh 2015; Contreras 2017; Weide et al. 2017), because chronologies derived from different calibration curves cannot be directly compared. Furthermore, increasingly significant issues may arise when comparing local processes to global climatic, ecological, and cultural changes. While it is a laudable standard convention to publish uncalibrated dates to allow for later recalibration (Millard 2014), it is also true that certain multidisciplinary investigations into past human–environmental relationships may require a more exact calibration.

Here, we aim to highlight and clarify processes relevant to choosing a calibration curve based on global carbon models and modern regional climate patterns. For regions with potentially significant atmospheric mixing during the South American Summer Monsoon (SASM), we propose using a mixed calibration curve that accounts for potential mixtures of atmospheric ^{14}C in both hemispheres. One such area of particular interest to archaeology and paleoclimate study is the Lake Titicaca Basin of Bolivia and Peru, a region that we use as an example to evaluate this issue and approach. Given that our knowledge of past Δ^{14}C variation in the tropical regions of South America is essentially unknown at this time, our calibrations and chronologies will likely change in the future as we refine our understanding of past atmospheric Δ^{14}C in tropical South America. Nevertheless, we hope that this discussion spurs new research into this important topic and encourages researchers to make informed and explicit decisions about which calibration curve to use.

GLOBAL MODELS OF SPATIAL VARIATION IN ATMOSPHERIC Δ^{14}C

The Southern Hemisphere has lower Δ^{14}C values than the Northern Hemisphere, which results in older ^{14}C dates for tree rings of the same calendar year (Lerman et al. 1970; McCormac et al. 1998, 2002, 2004; Stuiver and Braziunas 1998). This difference has been attributed to the fact that the Southern Hemisphere has more of the world's ocean surface area: 61%, in contrast with 39% in the Northern Hemisphere (Braziunas et al. 1995; Stuiver and Braziunas 1998:331). Air–sea exchange of CO_2 injects relatively old carbon from the surface ocean into the atmosphere (see overviews in Dutta 2016; Turnbull et al. 2016), an effect that is strongest in the Southern Ocean surrounding Antarctica (Anderson et al. 2009; Franke et al. 2008; Rodgers et al. 2011). Here, strong winds induce upwelling of "old" deep water to the surface and into the atmosphere, to be subsequently mixed northward throughout the Southern Hemisphere (Krakauer et al. 2006; Rodgers et al. 2011). On a global scale, predominantly zonal winds in both hemispheres result in east–west zonal bands of different atmospheric ^{14}C concentrations. Winds are generally stronger near the poles and weaker in the tropics, resulting in a modeled north-to-south gradient of roughly 1‰ less ^{14}C (8 ^{14}C yr older) per 10° of latitude (Figure 1), as compared to levels in the Northern Hemisphere (Levin et al. 1987; Braziunas et al. 1995; Krakauer et al. 2006).

Global models are a useful first approximation to potential regional variation in Δ^{14}C but are based primarily on marine data. Past terrestrial variations of atmospheric Δ^{14}C values are best

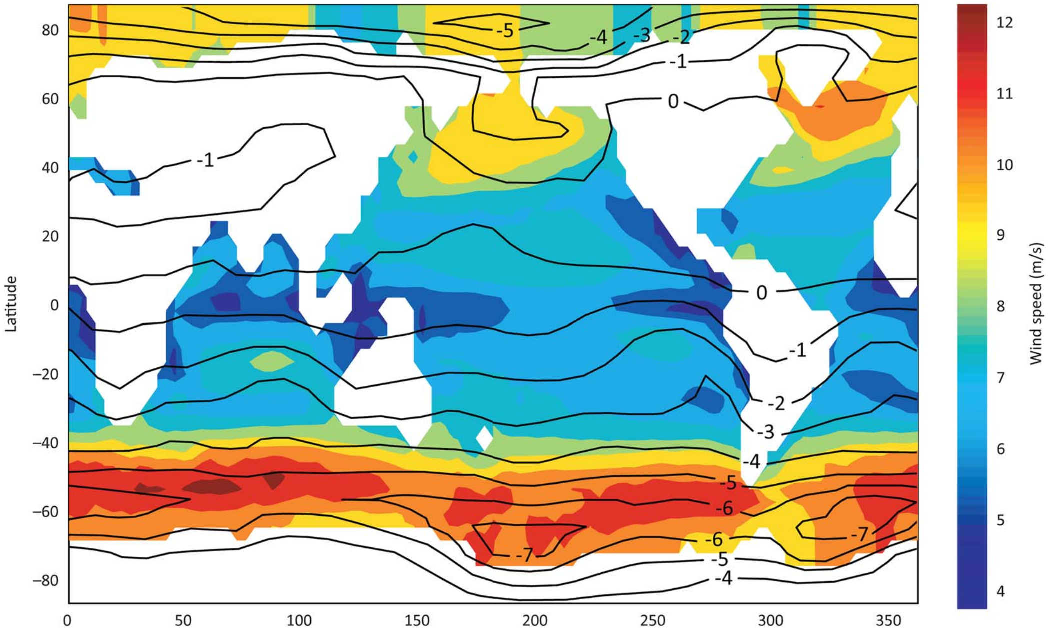

Figure 1 Global wind speeds (from Krakauer et al. 2006: Figure 1) and the latitudinal ^{14}C gradient (from Braziunas et al. 1995: Figure 9a). Contours show the difference (‰) from atmospheric carbon near Seattle. Note the strong correlation between winds and carbon depletion near Antarctica, which affects the entire hemisphere.

determined with tree-ring ^{14}C dates. Models and tree-ring data broadly agree on an interhemispheric Δ^{14}C difference of 3–5‰, based on comparisons between tree rings from mid-latitudes in the Northern (53–54°N) and Southern (39°S) Hemispheres (McCormac et al. 1998:1323; Krakauer et al. 2006:407). This is consistent with modern air differences of 3–4‰ between Northern and Southern Hemisphere data recorded in the western Pacific Ocean (Kitagawa et al. 2004). Other than this clear interhemispheric difference, proposed regional variations in atmospheric ^{14}C have not been confirmed. Some tree-ring datasets have unexplained offsets that are not included in current calibration curves and do not always follow the expectations of global models (see Stuiver and Braziunas 1993, 1998; Reimer et al. 2004). Future research is required to determine whether differences are statistically significant and, if so, what may cause them, for example, regional ^{14}C variation, diachronic ^{14}C variation, or inter-laboratory differences (McCormac et al. 2002; Hogg et al. 2011, 2013a, 2013b).

Braziunas et al.'s (1995: Figure 9a) global model of Δ^{14}C concentrations suggests spatial differences in ^{14}C concentrations in South America. It estimates that concentrations at ~0–30° S in South America are 1–2‰ lower than in the Northern Hemisphere, roughly half of the difference documented in higher latitude tree-rings from the Southern Hemisphere (Figure 1). Following this, a recent model of Holocene ^{14}C used an arithmetic mean of IntCal and SHCal for tropical regions between 20°N and 20°S (Roth and Joos 2013:1884). This sensible approach was used because the two curves are derived from mid-latitude tree rings, so low-latitude tree rings should have intermediate dates somewhere between those of the two curves. Low-latitude dates could potentially be modeled to have greater error ranges, because carbon concentrations in the tropics and neo-tropics are not well defined (McCormac et al. 2004:1088).

The picture is complicated by diachronic shifts in inter-hemispheric carbon differences, which have varied over time by 1–10‰ (McCormac et al. 2004:1088). For the period 200 BC–AD 1850, SHCal13 calibrated ages range from 2 ^{14}C yr younger to 83 ^{14}C yr older than IntCal ages, with a periodicity of ~130 yr (McCormac et al. 2002:641; Hogg et al. 2009, 2011, 2013a:1889). Dendrochronological evidence suggests that the inter-hemispheric ^{14}C difference was reduced to nearly zero at the end of the Little Ice Age (Turney et al. 2016). Temporal variation in the inter-hemispheric difference seems to be correlated with modes of variation in atmospheric circulation, such as the El Niño–Southern Oscillation (ENSO) (Turney and Palmer 2007:175).

The inter-hemispheric difference also varies seasonally, specifically near the equator during monsoon seasons, when air masses can move north or south across the tropical equator (Rozanski et al. 1995; Hua et al. 2004a; Kitagawa et al. 2004; Hua and Barbetti 2007). This is not accounted for by current carbon models or calibration curves but is a factor at low latitudes. It is best quantified with ^{14}C measurements of tree-rings during the post-bomb era, because the large quantities of carbon released in nuclear testing amplify regional differences (Hua et al. 2013). Based on cross-dated *Pinus kesiya* tree rings in Thailand, Hua and Barbetti (2007:8) estimated a 52 ± 13% contribution of Southern Hemisphere air masses during the Southwest Asian monsoon in pre-bomb years (this estimate could be used in OxCal's mixed curve calibration; see below). In Japan, a large set of prehistoric tree-ring dates showed significant differences from IntCal, which the authors attributed to monsoon input of air from the Southern Hemisphere (Suzuki et al. 2010:1606). For South America, bomb-era ^{14}C dates from Amazonian trees suggest a close match to SHCal (Jenkins 2009; Andreu-Hayles et al. 2015; Santos et al. 2015), but there are not yet sufficient data to assess or quantify potential CO_2 contributions from the Northern Hemisphere. Future research may user older tree rings from different altitudes and latitudes to refine spatial and temporal Δ^{14}C variation in South America due to factors such as altitude, latitude, period, and region (see Jenkins et al. 2013; Morales et al. 2013).

DEFINING HEMISPHERIC MIXING AND AIR MASS SOURCES IN TROPICAL SOUTH AMERICA

Despite its name, which implies a global reach, IntCal is based on samples from temperate latitudes (47–54°N) of the Northern Hemisphere. Similarly, SHCal is derived from tree-ring measurements from mostly temperate latitudes in New Zealand (40°S), Chile (55°S), South Africa (21–33°S), and Tasmania (42°S) (see citations in Hogg et al. 2013a:1890). Given the latitudinal gradient of ^{14}C, these curves are most appropriate at the same latitudes of the trees used for calibration, but may not be appropriate for the under-sampled tropics. Assuming well-mixed atmospheres within each hemisphere, McCormac et al. (2004:1088) and Hogg et al. (2013a:1900) have suggested that the thermal equator or Intertropical Convergence Zone (ITCZ) should be used to delimit the spatial boundary between the two curves. Their data show a well-mixed Southern Hemisphere atmosphere, at least at the latitudes of their sampled sites. However, using the ITCZ as an operational boundary is problematic, because it is a marine phenomenon that is not clearly defined over the continents. Moreover, it moves seasonally and over longer paleoclimatic time scales (Haug et al. 2001; Schneider et al. 2014). The lack of clarity regarding the zonal boundaries of atmospheric mixing between the two hemispheres warrants a more careful consideration of South American climate. Specifically, we address spatio-temporal patterns and amounts of inter-hemispheric atmospheric transport. The ITCZ is a zone of atmospheric convergence over the oceans (Figure 2), which migrates in response to variation in latitudinal temperature gradients (Chiang and Blitz 2005). The ITCZ has a direct influence on the climatology of coastal regions of northeastern South America, including the northern Nordeste of Brazil (Hastenrath and Heller 1977) and the north coast of Venezuela

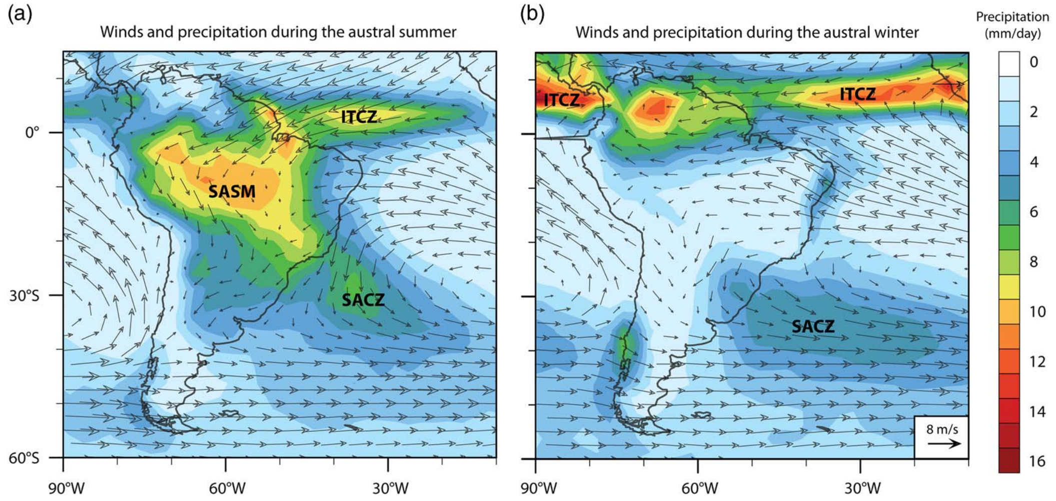

Figure 2 Major climate systems and long-term (1979–2010) means of precipitation and winds at 925 hPa in South America, showing average values during (a) the austral summer (December–February) and (b) the austral winter (July–August), based on data from the Climate Prediction Center merged analysis of precipitation (Xie and Arkin 1997).

(Poveda et al. 2006). ITCZ variability also may affect the climate inland of these regions by controlling the strength and trajectory of the advection of air and moisture onto the continent (Curtis and Hastenrath 1999).

The ITCZ does not extend across the continent (Cook 2009; Baker and Fritz 2015), despite being commonly misrepresented this way in many paleoenvironmental and archaeological publications. Rather, low-level convergence over the southern tropical continent during the austral summer is a separate feature of the South American summer monsoon (SASM). The SASM is a near continental-scale circulation system that advects air and moisture from the tropical Atlantic Ocean across the Amazon Basin, southeastward along the eastern flank of the Andes in a low-level jet and exits the continent in the region of the South Atlantic Convergence Zone (SACZ) (e.g. Zhou and Lau 1998; Garreaud et al. 2009; Jones and Carvalho 2013; Novello 2017). The intensity of the SASM is strongest in the austral summer (December–February). Over much of tropical and subtropical South America south of the equator, the majority of annual precipitation occurs during this monsoon season (Garreaud 2009). Inter-annual variation in the SASM is associated with sea-surface temperature gradients in the tropical Atlantic and increased flow associated with an anomalously cold North Atlantic (Nobre and Shukla 1996; Chang et al. 1997). On paleoclimatic time scales, temporal changes in SASM intensity are forced by variation in insolation, greenhouse gas concentrations, glacial boundary conditions, and remote ocean–atmosphere interactions (Vuille et al. 2012; Baker and Fritz 2015).

Low-level atmospheric transport into the Amazon Basin is predominantly derived from the equatorial and tropical southern Atlantic during the austral winter (Curtis and Hastenrath 1999) (Figure 2a). During the austral summer, backtrajectory LaGrangian analyses of low-level flow across the continent (Figure 3) indicate that air masses from the northern tropical Atlantic are the dominant moisture source for the northern Amazon, the eastern Andes, and the adjacent Altiplano (Vimeux et al. 2005; Insel et al. 2013; Sturm et al. 2007). This flow extends to regions

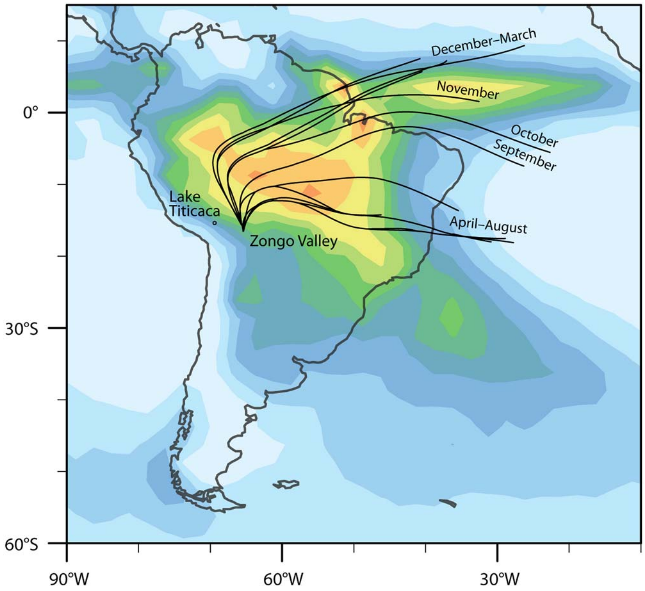

Figure 3 Backtrajectories of moisture sources for the Zongo Glacier in Bolivia near Lake Titicaca based on δD (from Vimeux et al. 2005:Figure 5). Each line represents the dominant moisture trajectory per month. The base map shows summer precipitation as in Figure 2a. See Vimeux et al. (2005:Figure 6) for monthly images of precipitation and backtrajectories.

as far south as 35°S, although most moisture and strong winds dissipate around 20–25°S (Cook 2009; Garreaud 2009). As this flow moves across the continent, air masses originating in the tropical Atlantic are modified by land-surface processes, as documented in the distillation of water isotopes such as δD (Vimeux et al. 2005) and $\delta^{18}O$ (Insel et al. 2013). During winter months (April–August), air masses originating in the South Atlantic (*friajes*) reach as far north as ~10°N, but they transport less moisture than summer flows.

Because CO_2, unlike water vapor, is well mixed through the vertical column and has a different source function than water vapor, its seasonal variation of source and trajectory are different from (and less well-known) than those of the predominantly low-level water vapor. In the absence of good regional information on spatial patterns of ^{14}C variation, we use SASM circulation as an admittedly imperfect foundation for assessing sources of ^{14}C to continental regions of tropical South America.

The circulation of the SASM takes places during the rainy austral summer (Figure 2b). Even for equatorial locales of the Amazon basin, there is a pronounced increase in precipitation during the SASM season, which is the growing season for deciduous and annual plants. However, it has recently been shown (Wu et al. 2016) that ecosystem primary productivity is quite variable across the basin: forests located in wetter, less seasonal, equatorial regions tend to “green up” during the dry season, while in drier, more seasonal, sub-equatorial regions ecosystem-scale primary productivity varies with seasonal precipitation variation. On the dry and highly seasonal Altiplano, carbon uptake by plants is strongly correlated with seasonal precipitation amount. On the eastern slopes of the Andes, backtrajectories suggest that there is a clear influence of Northern Hemisphere moisture for five months of the year, November–March (Figure 3). Hence, carbon uptake during these months very likely includes carbon that originates from the

Northern Hemisphere, both today and during analogous intervals of the past. The influence of SASM suggests that the carbon concentrations of these regions are likely somewhere between the concentrations represented by IntCal and SHCal. This agrees with global models' expectations for ^{14}C concentrations at these latitudes of South America (Figure 1). The boundaries of the SASM include the eastern Andes to the the west and go as far south as 35°S. Because winds and SASM precipitation dissipate around 20–25°S, we use this as the approximate southern edge of the SASM-influenced area, though the boundaries remain poorly defined. It is not currently possible to define this area better, which could be a focus of future research.

Various paleoclimatic data have been used to infer changes in the mean position of the ITCZ in oceanic regions adjacent to tropical South America (Haug et al. 2001; Sachs et al. 2009; Nace et al. 2014), as well as variation in the intensity of the SASM at decadal to orbital time scales (Baker and Fritz 2015). Yet these inferences of past changes in atmospheric circulation are spatially imprecise, so it also is unclear where paleoclimate variation affected air mass transport and spatial variation in ^{14}C over the continent. These limitations constrain our ability to infer the spatio-temporal variations of past circulations and place more exact limits of the appropriate use of IntCal or SHCal in the past.

In terms of defining areas for each calibration curve, we can draw on the following salient points from the modern climate of South America.

1. The ITCZ mixes air masses over the oceans and its influence on inland areas is indirect. Hence its position does not provide a clear spatial limit of where SHCal is valid in tropical South America.
2. Atmospheric circulation over tropical and subtropical South America is strongly influenced by the SASM, a circulation system that brings Northern Hemisphere air—and likely carbon—into large parts of the Amazon and eastern Andes during the austral summer, which is the primary plant growing season in many areas.
3. SASM circulation provides a good initial approximation of where air masses and ^{14}C from the two hemispheres may be mixing, although it is unclear how carbon concentrations change as low-level air flows inland.
4. Various aspects of atmospheric circulation (ITCZ position, SASM strength, westerlies) have changed on decadal to orbital scales throughout the Holocene. These changes are imprecisely known, hence the position, spatial footprint, and temporal variation of circulation are necessarily imprecisely defined.

Based on these large-scale modern patterns, we propose the following regions for three different calibration curves (Figure 4). These areas are defined at a continental scale, based primarily on modern wind patterns but also precipitation location and intensity (Figure 2), as well as global ^{14}C gradients (Figure 1).

1. Northern South America is little influenced by Southern Hemisphere air in any season. Most likely, carbon concentrations are close to those used to define IntCal.
2. In the areas where SASM circulates in the Amazon and eastern Andes, plants likely have a significant uptake of Northern Hemisphere air. The degree of mixing with Southern Hemisphere air remains unknown, but probably dissipates towards the eastern and southern boundaries. Hence a mixed calibration curve that allows for variation between both IntCal and SHCal may be appropriate.

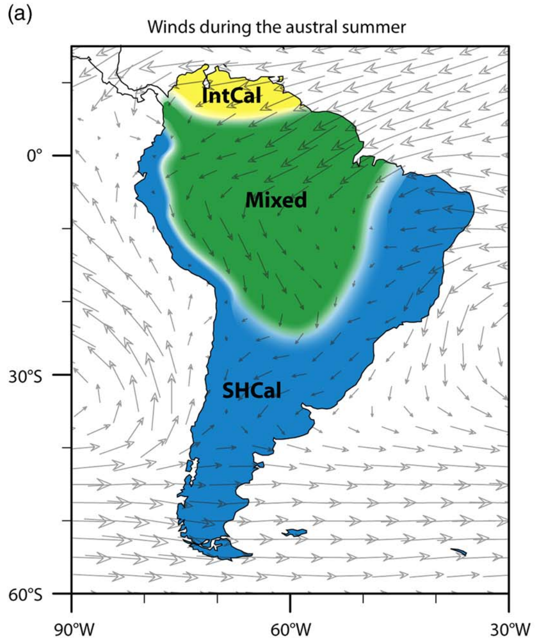

Figure 4 Suggested calibration curves for different parts of South America and winds during the austral (a) summer and (b) winter. The boundaries between the areas are not clear, but are generally estimated as the extension of the area affected by the SASM, which receives strong inputs from part of the Atlantic Ocean in the Northern Hemisphere (Figures 2–3). The southern and western boundaries of the area for the mixed curve are based primarily on SASM wind and precipitation during the austral summer (Figure 2a); the northern boundary is based primarily on patterns during the austral winter (Figure 2b).

3. South and east of the SASM-influenced Amazon and Andes, there is little to no mixing of Northern Hemisphere air. Along the Pacific coast of tropical South America, south of the equator, southeasterly trade winds tend to dominate circulation year-round, so even at low latitudes, there is likely little input of Northern Hemisphere air. Hence carbon concentrations in this region should track SHCal.

The limits between these three regions remain unclear and cannot be reliably defined on small spatial scales, not to mention diachronic shifts. For researchers working in areas of the SAMS-influenced zone, we recommend using a mixed calibration curve, which is appropriate for areas with known or potential SASM influence because it allows for any degree of mixing, including none, of the ^{14}C of the two hemispheres. This approach may also be useful for researchers working at tropical latitudes on other continents.

APPLYING A MIXED CALIBRATION CURVE

Mixed curves (Buck 2004:16) can be calculated using the OxCal program (Bronk Ramsey 2001:356). A recent update to OxCal makes it possible to specify a mixture for each curve with the `Mix_Curve` command. Using this command, the term `U(0,100)` "allows the model complete freedom to have any mixture" (Bronk Ramsey and Lee 2013:722), as in the example we present below. Marsh et al. (2017:5, Appendix A) applied this same mixed curve to Inca dates at an archaeological site in Ecuador. Carbon dates were compared to the historic date of the arrival of the Spanish in AD 1532, so differences of a few decades between the calibration curves were crucial (Ogburn 2012). Despite the usually wider error range of the mixed curve, it provided a more accurate estimate of the dated samples and therefore, more robust comparisons to historic dates. Given the short-lived nature of the Inca Empire and the speed of the Spanish conquest, small adjustments in calibrated ages may lead to profound changes in our historical sequences of events and narratives of cause and effect.

The practical effect of hybrid calibration usually increases error ranges of calibrated ages, although this varies with the vagaries of both curves. Wider error ranges correctly reflect the lack of information currently available on the concentrations of atmospheric carbon in regions impacted by the SASM, including Ecuador. SHCal is older than IntCal for the same calendar year, so for calibrations of the same ^{14}C date, SHCal returns a more recent calibrated age than IntCal. Median dates fall roughly half way in between dates calibrated with IntCal or SHCal, following expectations of both global carbon models and climate patterns. This strongly supports using the mixed curve in SASM-affected parts of South America (Figure 4).

While mixed curves can potentially produce error ranges that are slightly larger, Bayesian models can be used to reduce the ranges, yielding more accurate and precise results. In the Inca example mentioned above, Bayesian constraints resulted in age estimates with very small 1σ error ranges of 10–15 yr, despite the wider error ranges of a mixed calibration curve (Marsh et al. 2017:5). Bayesian models can incorporate chronological information from other sources and model the effect of temporal constraints based on stratigraphy, material associations, tephra layers, and historical information (Bronk Ramsey 2009). We demonstrate the application of a mixed calibration curve as well as the difference in dates among the three calibration curves in the following example from the Lake Titicaca Basin.

THE FILLING OF LAKE TITICACA AND THE EMERGENCE OF AGROPASTORALISM

The relationship between environmental change and the emergence of agropastoralism in the Lake Titicaca Basin is an excellent example of an issue that requires high-resolution comparisons of climate and cultural chronologies. Based on available paleoclimatic and archaeological records, the transition to agriculture involving domesticated camelids and plants such as quinoa coincided with increased precipitation and in-filling of the lake basin in the late Holocene. Both of these changes were profound and involved qualitative shifts that require high-precision dating in order to delineate cause and effect, as well as to differentiate between punctual change and gradual evolution.

Numerous paleoenvironmental studies have demonstrated a radical change from very dry conditions in the mid-Holocene to warmer and wetter conditions in the late Holocene. Multiple proxies with centennial to millennial resolution establish that this shift took place between 4500 and 3000 yr BP (e.g. Abbott et al. 1997; Mourguiart et al. 1998; Seltzer et al. 1998; Cross et al. 2000; Tapia et al. 2003; Baker et al. 2001, 2005; Fritz et al. 2006; Weide et al. 2017). Archaeological studies have documented sites dating between 3600 and 3000 cal BP with evidence of domesticated plants and animals, ceramic production, and more permanent settlements with non-domestic architecture, such as sunken courts: all significant changes associated with the adoption of an agropastoral lifeway (Browman 1981; Bandy 2006; Bruno and Whitehead 2003; Capriles et al. 2014; Hastorf 2008; Marsh 2015, 2016). Using a Bayesian model cross-referencing dates from Abbott et al.'s (1997) four lake cores and IntCal calibrated radiocarbon (^{14}C) dates from 14 archaeological sites, Marsh (2015) found that the earliest agropastoral occupation in the region was highly correlated with the rise in lake level at ~3540 cal BP (calibrated with IntCal), a refined estimate of a temporal trend identified in earlier studies (e.g.

Browman 1981; Binford et al. 1997; Rigsby et al. 2003). While this general correlation is evident, it is still not clear which change occurred first. If the lake level rose after the establishment of agropastoralism in the basin, then one narrative might suggest that people responded to mid-Holocene aridity by adopting new food resources. Then, when the lake level rose, this food source was more widely grown. However, if the lake level rose first, it would support an alternative narrative that people began farming the region only after there was more rainfall. More dates from this period as well as paired paleoenvironmental and archaeological samples are needed to resolve this. Here we compare the results provided by each calibration curve discussed here, particularly the mixed curve.

In the following example, we recalibrate one paleoclimate date and one archeological date processed at the same laboratory (Figure 5). The paleoclimate date is from a reed sample in a lake core in the southern basin of Lake Titicaca, CAMS-4978 (Abbott et al. 1997), located near an erosional surface that marks the end of mid-Holocene aridity. The archaeological date (CAMS-25871) is from the Formative site of Chiripa on the southern shore of Lake Titicaca. The sample comprises five *Chenopodium* seeds (from the Early Formative Santiago plaza) and is associated with domestic quinoa from one of the site's earliest occupations

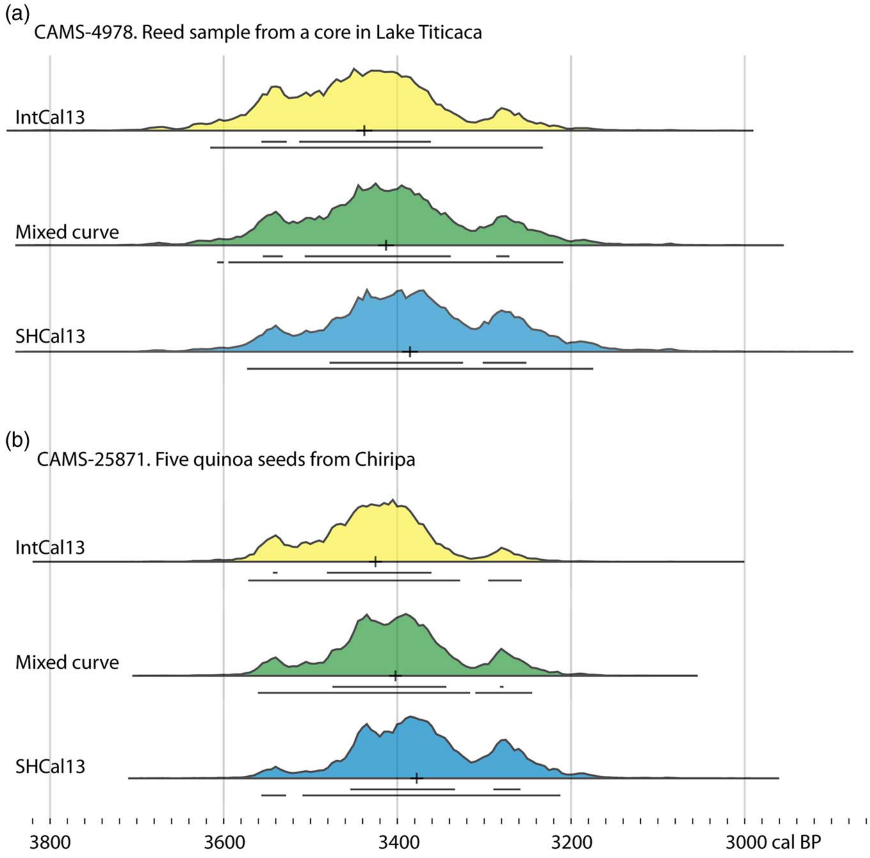

Figure 5 Comparison of IntCal13, mixed, and SHCal13 calibrations for (a) a paleoclimate date from a core in Lake Titicaca (CAMS-4978), which is associated with the rise of lake level, and (b) an archaeological date on *Chenopodium* seeds (CAMS-28571) associated with an early agropastoral occupation of the Chiripa site on the southern shore of Lake Titicaca. The horizontal lines below each curve indicate the 68% and 95% probability ranges.

(Whitehead 1999; Bruno and Whitehead 2003). We used the following code in OxCal to calibrate these two dates with a mixed curve.

```
Plot()
{
 Curve("IntCal13","IntCal13.14c");
 Curve("SHCal13","SHCal13.14c");
 Mix_Curve("Mixed","IntCal13","SHCal13",U(0,100));
 R_Date("CAMS-4978",3210,80);
 R_Date("CAMS-25871",3200,60);
};
```

Figure 5 shows the subtle differences in the shape of the probability distributions and the error ranges. At this place and span on the calibration curves, the mixed calibration has a 2–3 yr smaller error than the SHCal13 calibration. The absolute difference between the curves is quite small, so the differences between the error ranges of different curves depends on the subtle variations in the shape of both IntCal and SHCal. Both the IntCal and mixed curves show a *slightly* earlier mean for the end of the dry period, compared to the presence of domesticated quinoa at Chiripa. The SHCal curve means are nearly identical, and, as anticipated, slightly later. This part of the Andes is near the edge of the SASM-influenced zone in South America (Figure 4). The low-level jet that moves east over the Amazon continues to the edge of the Andes and does impact the Lake Titicaca Basin, though the degree of impact remains unclear. Thus, we would suggest that the IntCal curve is not appropriate; choosing SHCal would assume no input from the Northern Hemisphere, which remains unclear. Hence a mixed curve seems most appropriate because it makes no assumptions about the hemisphere that ^{14}C comes from, a correct reflection of the lack of data on the impact of the SASM in the Lake Titicaca Basin. It allows for the full possible range of ^{14}C input, from 100% Northern Hemisphere to 100% Southern Hemisphere air.

The difference between curves may seem minor in absolute terms, but for such rapid, profound changes, the sequence of events is a key element in our historical narratives and understanding of human–environment interactions. Clearly, a simplistic comparison of two calibrated dates cannot resolve this complex human–climate interaction, but we present this example to highlight the importance of refined chronologies, which must be explicit on two fronts. First paleoenvironmental and archaeological datasets must be calibrated with the same curve, and secondly, the curve choice should be based on the location of the samples. In areas with potential mixing, such as in the Lake Titicaca Basin, researchers should be explicit about the assumptions of curve choice and perhaps present multiple calibrations. Ideally, further interdisciplinary dialogue among researchers toward a consensus on the most appropriate calibration curve would facilitate future comparisons between paleoenvironmental and archaeological datasets.

FUTURE RESEARCH

Future research on tropical tree rings will undoubtedly refine our knowledge of temporal and spatial variation of atmospheric Δ^{14}C in South America, as well as the specific areas where each calibration curve is appropriate. Specifically, these datasets could be directed at identifying potential mixtures of Northern Hemisphere air, based on wiggle-matching and Bayesian comparison to identify the most suitable curve. However, these datasets are not yet available in South America. Using extant bomb-era data, it might be more feasible to assess inter-hemispheric air mixtures during monsoon phenomena, as has been done for Thailand and Japan (Hua et al. 2004b; Suzuki et al. 2010), which could be applied in OxCal.

Additional tree-ring data could also be used to better identify the spatial boundaries of SASM influence, in addition to changes in ^{14}C. Speleothem data, lake varves, or other similarly high-resolution and continuous records could complement detailed tree-ring chronologies. SASM influence implies seasonal variability in ^{14}C, so future research may consider the variation in different plants' seasonal uptake of atmospheric $^{14}CO_2$. For example, most tropical plants grow continuously throughout the year, but in some lowland areas, grasses grow during the dry season, because they are flooded during the rainy season. This issue may be relevant for tree rings used to refine ^{14}C curves, as well as the selection of archaeological or paleoenvironmental samples for dating.

Specifically for the Altiplano, additional dates from *Polylepis tarapacana* tree-ring sequences (Morales et al. 2012, 2013) would be especially welcome for assessing carbon concentrations to evaluate temporal, latitudinal, and altitudinal variation in atmospheric ^{14}C. Trends on the high-altitude Altiplano may be vey different than those in nearby tropical forests. The Altiplano is a distinctive area in terms of altitude, growth season, atmospheric influence, and long-term human impact on the environment, making it an attractive case study for refining carbon concentrations in both the air and its complex of large lacustrine basins. These lakes have significant influence on local carbon cycles and additional data are necessary to refine them (Abbott et al. 1997:172; Marsh 2015:16–17).

The spatial limits of SASM influence could be refined with more detailed climate modeling. Isotope backtracking is the most reliable approach for defining sources of water vapor on different parts of the continent, which could better define the area influenced by the SASM (Insel et al. 2013; Sturm et al. 2007). Such studies could be undertaken in regions where paleoclimatic and archaeological researchers work together closely, such as the Lake Titicaca Basin. In terms of global modeling, it would be timely to update Braziunas et al.'s (1995) widely cited global carbon model. It is based on differences from carbon in Seattle only (Figure 1); an updated map could compare carbon concentrations at the multiple sampled locations used to build IntCal. There are large sets of modern marine ^{14}C data that have been mostly used to address the industrial carbon footprint (Krakauer et al. 2006), which could also be harnessed to refine the pre-industrial latitudinal gradient of atmospheric ^{14}C and its variability on continental scales.

CONCLUSION

We argue for greater consideration of tropical South American atmospheric processes in choosing a calibration curve for ^{14}C dates. In clarifying the contemporary flow of air masses through the South American atmosphere, we suggest that different parts of the continent are best calibrated with IntCal, SHCal, or a mixed curve (Figure 4). IntCal is appropriate at the northern end of the continent, which is dominated throughout the year by air from the Northern Hemisphere. SHCal is appropriate south and east of the area affected by the SASM, as well as the Pacific coast of the continent. These regions do not receive winds or moisture from the Northern Hemisphere. For the large tropical and subtropical parts of the continent, where there is an unknown degree of mixing of air masses from the Northern and Southern Hemispheres, we suggest a mixed curve. This includes a very large area affected by SASM during the growing season, when carbon uptake includes Northern Hemisphere air. Researchers should continue to be explicit about which curve is being used, acknowledge potential biases of the chosen curve, recalibrated previous dates, and apply the same curve to all dates.

As regional curves and offsets continue to improve, it is timely to strive toward a consensus among researchers, principally to facilitate comparisons between published datasets, which presently is difficult. Particularly for archaeologists, this may require the recalibration of long-lived cultural chronologies developed with IntCal. Refining these details, however, will improve our understanding of important past societal changes, as well as past human–environmental interactions through improved comparisons with paleoclimatic records and global trends. The issues discussed here might also be relevant in future refinements of ^{14}C calibration curves and for calibrating ^{14}C dates from tropical regions in other continents. In fact, an argument could be made for using a mixed curve for tropical latitudes around the world—anywhere where the relative contributions of mid-latitude air from the two hemispheres is unknown.

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REFERENCES

Abbott MB, Binford MW, Brenner M, Kelts KR. 1997. A 3500 ^{14}C yr high-resolution record of water-level changes in Lake Titicaca, Bolivia/Peru. *Quaternary Research* 47(2):169–80.

Anderson RF, Ali S, Bradtmiller LI, Nielsen SHH, Fleisher MQ, Anderson BE, Burckle LH. 2009. Wind-driven upwelling in the southern ocean and the deglacial rise in atmospheric CO_2. *Science* 323(5920):1443–8.

Andreu-Hayles L, Santos G, Herrera-Ramírez D, Martin-Fernández J, Ruiz-Carrascal D, Boza-Espinoza T, Fuentes A, Jørgensen P. 2015. Matching dendrochronological dates with the southern hemisphere ^{14}C bomb curve to confirm annual tree rings in *Pseudolmedia Rigida* from Bolivia. *Radiocarbon* 57(1):1–13.

Baker PA, Fritz SC. 2015. Nature and causes of quaternary climate variation of tropical South America. *Quaternary Science Reviews* 124:31–47.

Binford MW, Kolata AL, Brenner M, Janusek JW, Seddon MT, Abbott M, Curtis JH. 1997. Climate variation and the rise and fall of an Andean civilization. *Quaternary Research* 47:235–48.

Braziunas TF, Fung IY, Stuiver M. 1995. The pre-industrial atmospheric $^{14}CO_2$ latitudinal gradient as related to exchanges among atmospheric, oceanic, and terrestrial reservoirs. *Global Biogeochemical Cycles* 9(4):565–84.

Bronk Ramsey C. 2001. Development of the radiocarbon calibration program. *Radiocarbon* 43(2A):355–63.

Bronk Ramsey CB. 2009. Bayesian analysis of radiocarbon dates. *Radiocarbon* 51(1):337–60.

Bronk Ramsey C, Lee S. 2013. Recent and planned developments of the program OxCal. *Radiocarbon* 55(2–3):720–30.

Browman DL. 1981. New light on Andean Tiwanaku. *American Scientist* 69:408–19.

Bruno MC, Whitehead W. 2003. *Chenopodium* cultivation and Formative period agriculture at Chiripa, Bolivia. *Latin American Antiquity* 14(3):339–56.

Buck CE. 2004. Bayesian chronological data interpretation: Where now? In: Buck CE, Millard A, editors. *Tools for Constructing Chronologies.* London: Springer. p 1–24.

Capriles JM, Albarracín-Jordan J. 2013. The earliest human occupations in Bolivia: a review of the archaeological evidence. *Quaternary International* 301:46–59.

Capriles JM, Moore KM, Domic AI, Hastorf CA. 2014. Fishing and environmental change during the emergence of social complexity in the Lake Titicaca Basin. *Journal of Anthropological Archaeology* 34:66–77.

Chiang JCH, Bitz CM. 2005. Influence of high latitude ice cover on the marine Intertropical

Convergence Zone. *Climate Dynamics* 25(5): 477–96.

Cook KH. 2009. South American climate variability and change: remote and regional forcing processes. In: Vimeux F, Sylvestre F, Khodri, editors. *Past climate variability in South America and surrounding regions*. New York: Springer. p 193–212.

Contreras DA. 2017. Correlation is not enough–building better arguments in the archaeology of human-environment interactions. In: Contreras DA, editor. *The archaeology of Human–Environment Interactions: Strategies for Investigating Anthropogenic Landscapes, Dynamic Environments, and Climate Change in the Human Past*. New York: Routledge. p 3–22.

Cross S, Baker PA, Seltzer GO, Fritz SC, Dunbar RB. 2000. A new estimate of the Holocene lowstand level of Lake Titicaca, central Andes, and implications for tropical paleohydrology. *The Holocene* 10(1):21–32.

Curtis S, Hastenrath S. 1999. Trends of upper-air circulation and water vapour over equatorial South America and adjacent oceans. *International Journal of Climatology* 19:863–76.

Dutta K. 2016. Sun, ocean, nuclear bombs, and fossil fuels: radiocarbon variations and implications for high-resolution dating. *Annual Review of Earth and Planetary Sciences* 44(1):239–75.

Engel Z, Skrzypek G, Chuman T, Šefrna L, Mihaljevič M. 2014. Climate in the western cordillera of the central Andes over the last 4300 years. *Quaternary Science Reviews* 99:60–77.

Finucane BC, Valdez JE, Pérez Calderon I, Vivanco Pomacanchari C, Valdez LM, O'Connell T. 2007. The end of empire: new radiocarbon dates from the Ayacucho Valley, Peru, and their implications for the collapse of the Wari state. *Radiocarbon* 49(2):579–92.

Franke J, Paul A, Schulz M. 2008. Modeling variations of marine reservoir ages during the last 45 000 years. *Climate of the Past Discussions* 4(1):81–110.

Garreaud RD. 2009. The Andes climate and weather. *Advances in Geosciences* 22:3–11.

Garreaud RD, Vuille M, Compagnucci R, Marengo J. 2009. Present-day South American climate. *Palaeogeography, Palaeoclimatology, Palaeoecology* 281:180–95.

Gayo EM, Lattorre C, Maldonado A, DePol-Holz R. 2012. Hydroclimate variability in the low-elevation Atacama Desert over the last 2500 yr. *Climate of the Past* 8:287–306.

Hastenrath S, Heller L. 1977. Dynamics of climatic hazards in northeast brazil. *Quarterly Journal of the Royal Meteorological Society* 103(435):77–92.

Haug GH, Hughen KA, Sigman DM, Peterson LC, Röhl U. 2001. Southward migration of the Intertropical Convergence Zone through the Holocene. *Science* 293(5533):1304–8.

Hogg AG, Bronk Ramsey CB, Turney C, Palmer J. 2009. Bayesian evaluation of the Southern Hemisphere radiocarbon offset during the Holocene. *Radiocarbon* 51(4):1165–76.

Hogg A, Palmer J, Boswijk G, Reimer P, Brown D. 2011. Investigating the interhemispheric ^{14}C offset in the 1st millennium AD and assessment of laboratory bias and calibration errors. *Radiocarbon* 51(4):1177–86.

Hogg AG, Hua Q, Blackwell PG, Niu M, Buck CE, Guilderson TP, Heaton TJ, Palmer JG, Reimer PJ, Reimer RW. 2013a. SHCal13 Southern Hemisphere calibration, 0–50,000 cal yr BP. *Radiocarbon* 55(2):1889–903.

Hogg A, Turney C, Palmer J, Cook E, Buckley B. 2013b. Is there any evidence for regional atmospheric ^{14}C offsets in the Southern Hemisphere? *Radiocarbon* 55(4):2029–34.

Hua Q, Barbetti M, Zoppi U. 2004a. Radiocarbon in annual tree rings from Thailand during the pre-bomb period, AD 1938–1954. *Radiocarbon* 46(2):925–32.

Hua Q, Barbetti M, Zoppi U, Fink D, Watanasak M, Jacobsen GE. 2004b. Radiocarbon in tropical tree rings during the Little Ice Age. *Nuclear Instruments and Methods in Physics Research B* 223:489–94.

Hua Q, Barbetti M. 2007. Influence of atmospheric circulation on regional $^{14}CO_2$ differences. *Journal of Geophysical Research* 112:D1902.

Hua Q, Barbetti M, Rakowski AZ. 2013. Atmospheric radiocarbon for the period 1950–2010. *Radiocarbon* 55(4):2059–72.

Insel N, Poulsen CJ, Sturm C, Ehlers TA. 2013. Climate controls on Andean precipitation $\delta^{18}O$ interannual variability. *Journal of Geophysical Research: Atmospheres* 118(17):9721–42.

Jenkins HS. 2009. Amazon Climate Reconstruction Using Growth Rates and Stable Isotopes of Tree Ring Cellulose from the Madre de Dios Basin, Peru [PhD dissertation]. Durham, NC: Department of Earth & Ocean Sciences, Duke University.

Jenkins HS, Baker PA, Negrón-Juárez RI. 2013. Eventos extremos de seca na Amazonia revelados pelos registros de aneis de arvores. In: Borma L, Nobre C, editors. *Secas na Amazonia*. Sao Paulo: Editora Oficina de Testos. p 29–46.

Jones C, Carvalho LMV. 2013. Climate change in the South American monsoon system: present climate and CMIP5 projections. *Journal of Climate* 26(17):6660–78.

Jones KB, Hodgins GWL, Sandweiss DH. 2017. Radiocarbon chronometry of site QJ-280, Quebrada Jaguay, a Terminal Pleistocene to early Holocene fishing site in southern Peru. *The Journal of Island and Coastal Archaeology*. In press.

Kitagawa H, Mukai H, Nojiri Y, Shibata Y, Kobayashi T, Nojiri T. 2004. Seasonal and secular variations of atmospheric $^{14}CO_2$ over the western Pacific since 1994. *Radiocarbon* 46(2):901–10.

Koons ML, Alex BA. 2014. Revised Moche chronology based on Bayesian models of reliable radiocarbon dates. *Radiocarbon* 56(3):1039–55.

Krakauer NY, Randerson JT, Primeau FW, Gruber N, Menemenlis D. 2006. Carbon isotope evidence for the latitudinal distribution and wind speed dependence of the air–sea gas transfer velocity. *Tellus B: Chemical and Physical Meteorology* 58(5):390–417.

Lerman JC, Mook WG, Vogel JC. 1970. C^{14} in tree rings from different localities. In: Olsson IU, editor. *Radiocarbon Variations and Absolute Chronology, Proceedings, XII Nobel Symposium.* Hoboken, NJ: John Wiley. p 275–301.

Levin I, Kromer B, Wagenbach DT, Münnich KO. 1987. Carbon isotope measurements of atmospheric CO_2 at a coastal station in Antarctica. *Tellus B: Chemical and Physical Meteorology* 39(1–2):89–95.

Levine A, Stanish C. 2013. The importance of multiple ^{14}C dates from significant archaeological contexts. *Journal of Archaeological Method and Theory* 21:824–36.

McCormac FG, Hogg AG, Higham TFG, Lynch-Stieglitz J, Broecker WS, Baillie MGL, Palmer J, Xiong L, Pilcher JR, Brown D. 1998. Temporal variation in the interhemispheric ^{14}C offset. *Geophysical Research Letters* 25(9): 1321–4.

McCormac FG, Reimer PJ, Hogg AG, Higham TFG, Baillie MGL, Palmer J, Stuiver M. 2002. Calibration of the radiocarbon time scale for the southern hemisphere: AD 1850–950. *Radiocarbon* 44(3):641–51.

McCormac FG, Hogg AG, Blackwell PG, Buck CE, Higham TFG, Reimer PJ. 2004. SHCal04 southern hemisphere calibration, 0–11.0 cal kyr BP. *Radiocarbon* 46(3):1087–92.

Marsh EJ. 2012. A Bayesian re-assessment of the earliest radiocarbon dates from Tiwanaku, Bolivia. *Radiocarbon* 54(2):203–18.

Marsh EJ. 2015. The emergence of agropastoralism: Accelerated ecocultural change on the Andean altiplano, ~3540–3120 cal BP. *Environmental Archaeology* 20(1):13–29.

Marsh EJ. 2016. The disappearing desert and the emergence of agropastoralism: An adaptive cycle of rapid change in the mid-Holocene Lake Titicaca Basin (Peru–Bolivia). *Quaternary International* 422:123–34.

Marsh EJ, Kidd R, Ogburn D, Durán V. 2017. Dating the expansion of the Inca empire:Bayesian models from Ecuador and Argentina. *Radiocarbon* 59(1): 117–40.

Martel-Cea A, Maldonado A, Grosjean M, Alvial I, de Jong R, Fritz SC, von Gunten L. 2016. Late Holocene environmental changes as recorded in the sediments of high Andean Laguna Chepical, central Chile (32°S; 3050 m a.s.l.). *Palaeogeography, Palaeoclimatology, Palaeoecology* 461:44–54.

Millard A. 2014. Conventions for reporting radiocarbon determinations. *Radiocarbon* 56(2):555–9.

Morales MS, Christie DA, Villalba R, Argollo J, Pacajes J, Silva JS, Alvarez CA, Llancabure JC, Gamboa Soliz CC. 2012. Precipitation changes in the South American altiplano since 1300 AD reconstructed by tree-rings. *Climate of the Past* 8(2):653–66.

Morales MS, Nielsen AE, Villalba R. 2013. First dendroarchaeological dates of prehistoric contexts in South America:Chullpas in the central Andes. *Journal of Archaeological Science* 40(5):2393–401.

Mourguiart P, Corrège T, Wirrmann D, Argollo J, Montenegro ME, Pourchet M, Carbonel P. 1998. Holocene palaeohydrology of Lake Titicaca estimated from an ostracod-based transfer function. *Palaeogeography, Palaeoclimatology, Palaeoecology* 143(1):51–72.

Nace TE, Baker PA, Dwyer GS, Silva CG, Rigsby CA, Burns SJ, Giosan L, Otto-Bliesner B, Liu Z, Zhu J. 2014. The role of north Brazil current transport in the paleoclimate of the Brazilian nordeste margin and paleoceanography of the western tropical Atlantic during the late Quaternary. *Palaeogeography, Palaeoclimatology, Palaeoecology* 415:3–13.

Nelson DB, Sachs JP. 2016. Galapagos hydroclimate of the Common Erafrom paired microalgal and mangrove biomarker 2H/1H values. *PNAS* 113:3476–81.

Ogburn DE. 2012. Reconceiving the chronology of Inca imperial expansion. *Radiocarbon* 54(2): 219–37.

Poveda G, Waylen PR, Pulwarty RS. 2006. Annual and inter-annual variability of the present climate in northern South America and southern Mesoamerica. *Palaeogeography, Palaeoclimatology, Palaeoecology* 234(1):3–27.

Reimer PJ, Baillie MG, Bard E, Bayliss A, Beck JW, Bertrand CJ, Blackwell PG, Buck CE, Burr GS, Cutler KB, Damon PE, Edwards RL, Fairbanks RG, Friedrich M, Guilderson TP, Hogg AG, Hughen KA, Kromer B, McCormac G, Manning S, Bronk Ramsey CB, Reimer RW, Remmele S, Southon JR, Stuiver M, Talamo S, Taylor FW, van der Plicht J, Weyhenmeyer CE. 2004. IntCal04 terrestrial radiocarbon age calibration, 0–26 cal kyr BP. *Radiocarbon* 46(3):1029–58.

Reimer PJ, Bard E, Bayliss A, Beck JW, Blackwell PG, Ramsey CB, Grootes PM, Guilderson TP, Haflidason H, Hajdas I, Hatté C, Heaton TJ, Hoffma DL, Hogg AG, Hughen KA, Kaiser KF, Kromer B, Manning S, Niu M, Reimer RW, Richards DA, Scott EM, Southon JR, Staff RA, Turney CSM, van der Plicht J. 2013. IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. *Radiocarbon* 55(4):1869–87.

Rick JW, Mesia C, Contreras D, Rodriguez Kembel S, Rick R, Sayre M, Wolf J. 2009. La cronología de Chavín de Huántar y sus implicancias para el Periodo Formativo. *Boletín de Arqueología PUCP* 13:87–132.

Rigsby CA, Baker PA, Aldenderfer MS. 2003. Fluvial history of the Rio Ilave Valley, Peru, and its relationship to climate and human history. *Palaeogeography, Palaeoclimatology, Palaeoecology* 194(1):165–85.

Rodgers B, Mikaloff-Fletcher E, Bianchi D, Beaulieu C, Galbraith D, Gnanadesikan A, Hogg G, Iudicone D, Lintner R, Naegler T, Reimer J, Sarmiento L, Slater D. 2011. Interhemispheric gradient of atmospheric radiocarbon reveals natural variability of southern ocean winds. *Climate of the Past* 7(4):1123–38.

Roth R, Joos F. 2013. A reconstruction of radiocarbon production and total solar irradiance from the Holocene ^{14}C and CO$_2$ records: implications of data and model uncertainties. *Climate of the Past* 9(4):1879–909.

Rozanski K, Levin I, Stock J, Falcon REG, Rubio F. 1995. Atmospheric ^{14}CO$_2$ variations in the equatorial region. *Radiocarbon* 37(2):509–15.

Sachs JP, Sachse D, Smittenberg RH, Zhang Z, Battisti DS, Golubic S. 2009. Southward movement of the Pacific Intertropical Convergence Zone AD 1400–1850. *Nature Geoscience* 2(7):519–25.

Santos GM, Linares R, Lisi CS, Tomazello Filho M. 2015. Annual growth rings in a sample of Paraná pine (*Araucaria Angustifolia*): toward improving the ^{14}C calibration curve for the Southern Hemisphere. *Quaternary Geochronology* 25:96–103.

Schneider T, Bischoff T, Haug GH. 2014. Migrations and dynamics of the Intertropical Convergence Zone. *Science* 513:45–53.

Seltzer GO, Baker PA, Cross SL, Dunbar RB, Fritz SC. 1998. High-resolution seismic reflection profiles from Lake Titicaca, Peru-Bolivia: evidence for Holocene aridity in the tropical Andes. *Geology* 26(2):167–70.

Stuiver M, Braziunas TF. 1993. Sun, ocean, climate and atmospheric ^{14}CO$_2$: an evaluation of causal and spectral relationships. *The Holocene* 3(4):289–305.

Stuiver M, Braziunas TF. 1998. Anthropogenic and solar components of hemispheric ^{14}C. *Geophysical Research Letters* 25(3):329–32.

Sturm C, Hoffmann G, Langmann B. 2007. Simulation of the stable water isotopes in precipitation over South America: comparing regional to global circulation models. *Journal of Climate* 20(15):3730–50.

Suzuki K, Sakurai H, Takahashi Y, Sato T, Gunji S, Tokanai F, Matsuzaki H, Tsuchiya YS. 2010. Precise comparison of ^{14}C ages from Choukai Jindai cedar with IntCal04 raw data. *Radiocarbon* 52(4):1599–609.

Tapia PM, Fritz SC, Baker PA, Seltzer GO, Dunbar RB. 2003. A late Quaternary diatom record of tropical climatic history from Lake Titicaca(Peru and Bolivia). *Palaeogeography, Palaeoclimatology, Palaeoecology* 194:139–64.

Turnbull JC, Graven H, Krakauer NY. 2016. Radiocarbon in the atmosphere. In: Schuur EAG, Druffel ERM, Trumbore SE, editors. *Radiocarbon and Climate Change*. New York: Springer. p 83–137.

Turney CS, Palmer J, Hogg A, Fogwill CJ, Jones R, Ramsey CB, Fenwick P, Grierson P, Wilmshurst J, O'Donnell A, Thomas Z, Lipson M. 2016. Multi-decadal variations in Southern Hemisphere atmospheric ^{14}C: evidence against a southern ocean sink at the end of the Little Ice Age CO$_2$ anomaly. *Global Biogeochem. Cycles* 30:211–8.

Turney CS, Palmer JG. 2007. Does the El Niño–Southern Oscillation control the interhemispheric radiocarbon offset? *Quaternary Research* 67(1): 174–80.

Vogel JC, Fuls A, Visser E, Becker B. 1993. Pretoria calibration curve for short-lived samples, 1930–3350 BC. *Radiocarbon* 35(1):73–85.

Vuille M, Burns SJ, Taylor BL, Cruz FW, Bird BW, Abbott MB, Kanner LC, Cheng H, Novello VF. 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(4): 1309–21.

Vimeux F, Gallaire R, Bony S, Hoffmann G, Chiang JC. 2005. What are the climate controls on δD in precipitation in the Zongo Valley (Bolivia)? Implications for the Illimani ice core interpretation. *Earth and Planetary Science Letters* 240(2): 205–20.

Weide DM, Fritz SC, Hastorf CA, Bruno MC, Baker PA, Guedron S, Salenbien W. 2017. A ~6000 yr diatom record of mid- to late Holocene fluctuations in the level of Lago Wiñaymarca, Lake Titicaca (Peru/Bolivia). *Quaternary Research*. In press.

Whitehead WT. 1999. Radiocarbon dating. In: Hastorf, editor. *Early settlement at Chiripa, Bolivia:Research of the Taraco Archaeological Project*. Contributions of the Archaeological Research Facility. Vol. 57. Berkeley, CA: University of California. p 17–22.

Xie P, Arkin PA. 1997. Global precipitation: a 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model outputs. *Bulletin of the American Meteorological Society* 78:2539–58.