The importance of "year zero" in interdisciplinary studies of climate and history

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The mathematical aberration of the Gregorian chronology's missing "year zero" retains enduring potential to sow confusion in studies of paleoclimatology and environmental ancient history. The possibility of dating error is especially high when pre-Common Era proxy evidence from tree rings, ice cores, radiocarbon dates, and documentary sources is integrated. This calls for renewed vigilance, with systematic reference to astronomical time (including year zero) or, at the very least, clarification of the dating scheme(s) employed in individual studies.

paleoclimate | year zero | climate reconstructions | dating precision | geoscience

The harmonization of astronomical and civil calendars in the depths of human history likely emerged from the significance of the seasonal cycle for hunting and gathering, agriculture, and navigation. But difficulties arose from the noninteger number of days it takes Earth to complete an orbit of the Sun. In revising their 360-d calendar by adding 5 d, the ancient Egyptians were able to slow, but not halt, the divergence of civil and seasonal calendars (1). Introduction of the leap year (the Julian calendar) under Julius Caesar slowed and reversed the direction of the disparity. The formulation of the BC/AD calendar is attributed to the sixth century monk Dionysius Exigius, and, over the next centuries, it became Christendom's standard ecclesiastical chronometer. It had no "year zero": 1 BC (before Christ), was followed by AD (anno Domini) 1. It was revised in 1582, under Pope Gregory XIII, with rules for leap year suppression, leading to introduction of the familiar Gregorian calendar. Although, by then, Western civilization had caught on to the mathematical concept of "zero" thanks to medieval Arabian scholarship, the calendar retained Dionysius' scheme.

Pitfalls of Dating Error

While implications of combining time series with and without year zero are obvious, historians and scientists have still not collectively agreed on a calendrical convention, nor, more generally, is there standardization of epochs within and between communities and disciplines. Ice core specialists and astronomers use 2000 CE, while, in dendrochronology, some laboratories develop multimillennial-long tree-ring chronologies with year zero but others do not. Further confusion emerges from phasing of the extratropical growing seasons between hemispheres (2): there is an approximately 6-mo lag between boreal and austral vegetation periods. Since the seasonal formation of secondary cell walls in Southern Hemisphere vegetation starts in the boreal autumn of a given year and ends in the boreal spring of the following year, austral tree rings span two calendar years. Represented by the IntCal Working Group (3), the radiocarbon community generally references dates to AD 1950 (= 0 y BP, before present) and excludes year zero (4), but depends on the astronomical or historical dating of dendrochronological or other source materials (with or without year zero).

Additional uncertainty in high-resolution radiocarbon dates may arise from interhemispheric and intrahemispheric differences in the length and timing of growing seasons (5). While tree growth at the high northern latitudes can be restricted to a few weeks between the end of June and early August, seasonal

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dormancy does not occur in the tropics. Wet and dry deposition in the polar regions is also controlled by seasonality of atmospheric dynamics and meteorology.

Uncertainty of a few months to years has little or no consequence for many lower-resolution studies of Holocene climate and environmental variability. However, a single year offset is enough to destroy any statistical relationship between annual time series and can reduce the variance in their means substantially. Absolute chronometric correspondence between datasets also becomes critical whenever causal associations between climate forcing, climate variation, and societal change are investigated. Yet many studies have highlighted assorted imprecisions and misunderstandings concerning ice core, radiocarbon, and historical chronologies and their ramifications (e.g., refs. 6–8). Interdisciplinary projects and international networks applying combinations of geographically diverse tree-ring and ice core records, radiocarbon measurements, and documentary and archaeological sources for climate reconstructions and historical studies before the Common Era (e.g., refs. 9–13) raise the stakes of misassociations. At the very least, mixing different data and timescales, in tandem with a lack of clarity or consistency in the use of astronomical and historical calendars, can lead to confusion. Further, these issues are likely to be increasingly encountered as multiparameter/multiproxy studies at annual resolution before the Common Era are proliferating (e.g., refs. 14–16). As an illustration of the problem, Fig. 1 shows how combined assessments of tree-ring series and chronologies from both hemispheres (that may or may not include year zero), along with quasi-independent evidence from volcanic eruptions and cosmogenic signatures (17), can result in multiyear dating error.

Potential and Opportunities

Tree rings provide the only natural archive claiming annual precision before the Common Era. Continuous chronologies that extend more than 2,000 y back in time, either based on very old species, such as *Agathis australis*, *Fitzroya cupressoides*, *Juniperus occidentalis*, *Lagarostrobos franklinii*, and *Pinus longaeva*, or a combination of living, historical, subfossil, and/or archaeological wood, are now available from different parts of South and North America, several regions of Europe and Scandinavia, northern and

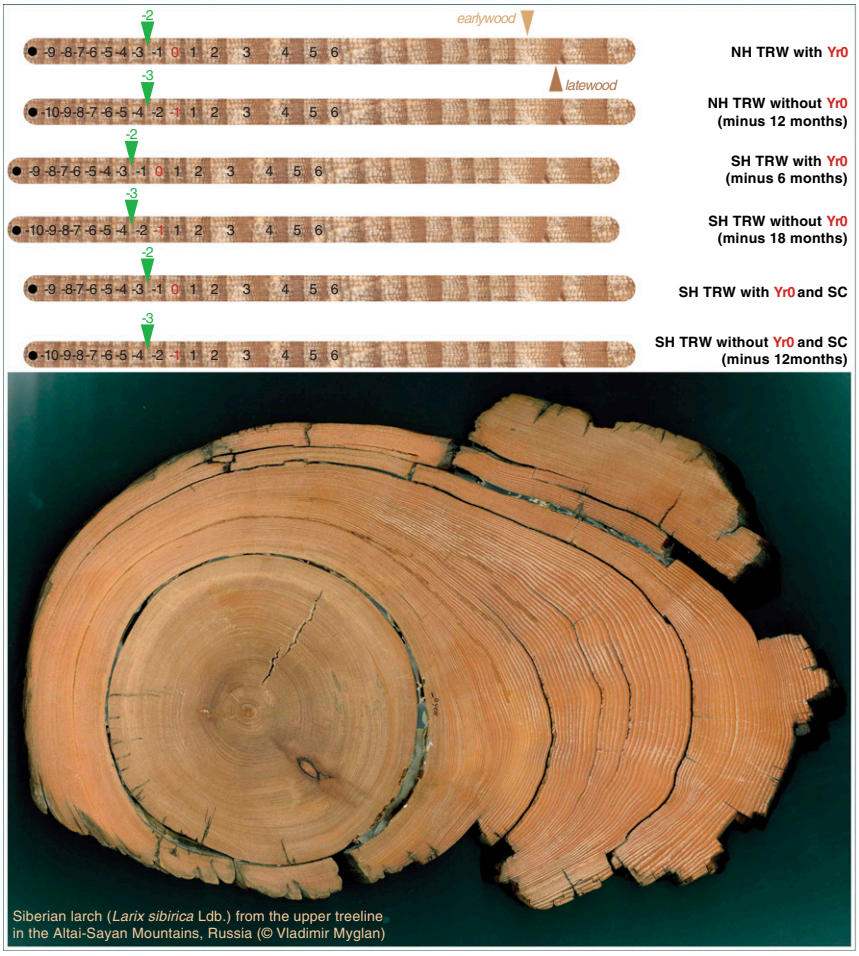

Fig. 1. Potential for confusion. The combination of individual tree-ring width series and their combined chronologies with or without "year zero," and with and without application of the "Schulman Shift"—the correction for a half-year offset in the timing of extratropical tree growth on both hemispheres—can result in up to 18 mo of dating uncertainty. Additional error may arise from the consideration of quasi-independent evidence of cosmogenic radiocarbon spikes and possible linkages with the climatic fingerprints of volcanic eruptions that can vary substantially in space and time. Another level of dating uncertainty emerges from associations between natural proxy archives and historical events for which documentary and archaeological sources often rely on different calendars and narrative dating schemes. Last but not least, a simple lack of consistency in and transparency concerning the nature of different datasets used and timescales applied has considerable potential to sow confusion. Image credit: Vladimir Myglan (photographer).

southern Siberia, the Tibetan Plateau, and Tasmania and New Zealand. Their application to the dating of ancient materials and reconstruction of different climate parameters at annual precision depends on two conventions: the systematic use (or exclusion) of year zero and the assignment of each tree ring to the date of the year in which its growth began. Furthermore, the temporal precision and analytical detail for multimillennial-long ice core records from Antarctica and Greenland have increased substantially (e.g., refs. 10 and 18), allowing major volcanic eruptions to be dated within a year and sometimes yielding evidence of the source volcano. Once more, a consistent use or exclusion of year zero, in all direct and indirect data, would reduce, if not eliminate, uncertainties.

Recent investigations of the societal impacts of volcanic forcing of climate exemplify the importance and complexity of integrating different datasets before the Common Era. Among them is a study of the impacts of the eruption of Okmok, Alaska, on the contemporary Mediterranean world (12). In this work, the eruption was dated independently to early 43 BCE (Gregorian calendar) based on ice core measurements with geochemical classification of volcanic glass shards identifying Okmok as the source. Synchrony of sulfur deposition in Greenland ice cores and tree-ring–derived summer temperatures substantiate the ice core dating. Having identified a volcanic event and its climatic signal (which persists for several years), historical linkages are evaluated in the study. This work would have been significantly compromised had the year zero issue not been rigorously addressed.

Another example of the importance of dating precision is a study of long-range volcanic influence on the ancient Mediterranean world that employs quasi-dated historical records and ice core evidence for volcanic events (11). Based on superposed epoch analysis, a technique highly sensitive to even small dating issues, this study suggests the vulnerability of Ptolemaic Egypt (305–30 BCE) to the impacts of volcanically forced changes in monsoonal precipitation on agricultural production of the Nile delta. Again, dating inconsistency between the various natural and human archives would have challenged any association between volcanic eruptions, monsoon dynamics, flood suppressions, and societal revolts.

Recommendations for Best Practice

We argue that tree-ring chronologies should always use the year zero when extending before the Common Era. Moreover, tree-ring series from temperate regions of the Southern Hemisphere should lag rather than precede those from the Northern Hemisphere by approximately 6 mo. Likewise, the use of "BP" should be avoided without clear specification of the reference epoch and timescale used. Finally, any cross-disciplinary and multidisciplinary study that aims for annual precision before the Common Era, and combines evidence from natural proxy archives and historical and archaeological sources, should ideally be based on astronomical calendars (including year zero), or, at the very least, clarify the dating scheme(s) employed.

Data Availability. There are no data underlying this work.

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