Calibrating Natural Archives to Study the Climate of the Past

Creating reliable reconstruction of past climate is extremely important if we are to understand and predict current and future changes in climate. The powerful and complex computer generated models of climate, called General Circulation Models (GCMs), can produce a wide variety of possible future scenarios. To help determine which of these scenarios are the most plausible, it is useful to test the models against past climate, to see if they can accurately reconstruct past, known changes. However, the period of measured climate at c. 150 years is too short a window to test these models adequately. Reliable reconstruction of past climate are, therefore, vital to train and test models of future climate. It is also useful to be able to position modern and future climate in a long-term perspective, to understand whether we are still within, or have exceeded, the realms of natural climate variability. The long-term climate perspective, afforded by climate reconstructions, also allows us to understand how often, under natural conditions, we may expect to experience the extreme wet/dry and hot/cold conditions, such as the extremely hot and dry summers of 1976, 2003 and 2018. Such events can be extremely problematic for both human health and infrastructure, and understanding the return period for such events and whether this has changed over recent decades, would be very useful for planning purposes.

To create reconstructions of past climate using climate-sensitive proxies, such as tree rings, it is first necessary to establish the statistical relationship between the proxy and instrumental climate measurements. This is process is called calibration and must be carried out over the period for which both proxy and meteorological data exist, this is usually, but not always, the most recent past. Calibration is based upon the geological principle of Uniformitarianism, which can be summarised as "the present is the key to the past". In other words, if we can understand how climate is controlling tree ring growth at present, we can use this information to interpret a sequence of ancient tree rings in terms or past climate changes. Using this principle, and some simple statistics, we can numerically reconstruct how climate may have varied during a period for which we have tree rings data, but no climate data (normally any period pre c. 1850 CE). However, for this calibration and reconstruction to work we must make the important assumption that:

- The present-day climate-proxy relationship has not changed over time and can be applied in the past as affectively as in the present.

A major strength of the tree rings, as a climate archive, is that in most temperate, arctic and alpine regions, they produce one clearly defined growth ring every year. This perfect annual resolution means that they can be directly numerically compared to instrumental climate measurements. In this example we will explore the basic steps for establishing a relationship between tree rings and climate, where trees rings have perfectly resolved annual growth rings, using data from oak trees from the UK.

The aim of the calibration process is to establish a numerical relationship between a single climate variable and a measure of annual tree growth. When using direct measurements of tree growth, such as ring widths, trees are normally selected in regions where tree growth is limited by one single definable climate variable (e.g. temperature at high altitude and latitudes; moisture in dry regions).

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The most straightforward way to produce a calibration is to establish a simple linear model of the climate and proxy relationship, using regression. This means that one increment of tree growth is equal to one increment of temperature change (e.g. ±1°C = ±1mm of ring growth). A large body of research has established that, a nearly linear temperature-tree growth relationship provides an acceptable approximation of the growth – climate relationship across a wide geographic range. Other methods of calibration are available, which employ a variety of statistical models such as non-linear and multiple regression approaches, whilst others are based solely upon mechanistic modelling of tree ring processes. However, here we will consider the linear regression model technique.

The first step in calibration is to assemble suitable climate and tree ring data. It is important that both the climate and the tree ring data be correctly dated. For climate data is this rarely a problem, as we know exactly when and where the data were collected. For tree ring data this can be more challenging, but with care, each individual growth ring can normally be unambiguously assigned to a single growth year, by the process known as dendrochronology. Climate data are available on a range of timescales from hourly to annual averages. Tree ring data usually have one single value for each year, which represents conditions during the growing season. In the UK this will normally be the summer months. The climate data we will use are from the England and Wales Precipitation series, and our tree ring data are stable oxygen isotope ratios measured from the individual annual growth rings of oak trees from the Central England region.

We start by comparing the tree ring dataset with the climate data on a month-by-month basis (Figure 1). As one moves through the year, if the trees are climate sensitive then the statistical match (correlation) between climate and tree rings will increase and then decline through the growing season (Figure 1). This relationship should be stronger when the tree is growing and weak or non-significant in those months when the trees are growing by only a small amount or when the tree is dormant, during the winter. Figure 1 shows clearly that tree ring oxygen isotopes correlate best with the summer season rainfall, note that the correlations are negative, as the relationship between rainfall and tree ring oxygen isotopes is inverse. There are statistically significant correlations in May, June, July and August and no other months. If we have some understanding of tree growth, then we can look at this relationship and see if it makes sense – and in this case, it does. The tree rings analysed put on most of their growth in the summer months. The oxygen isotopes of the growth rings reflect the water drawn up through the roots as the tree grows. When the tree is dormant (and without leaves), in the winter and autumn, the strength of the correlation drops and is no longer significant.

There are a number of consecutive months in which rainfall is significantly correlated with the oxygen isotopes (Figure 1), it therefore makes good sense to combine the precipitation values of these months into one value, to compare to the tree ring oxygen. The results in Figure 1 show that combining the rainfall values for these four months (May to August) appears to be useful, as the result is a higher correlation (-0.72) than for any individual month. If we take the correlation coefficient (-0.72) and square it (-0.72x-0.72 = 0.52) we get what is called the R^2 value. This number is useful as it tells us how much of the annual variability in the oxygen isotope series is explained by the annual variability of summer precipitation, in this case 52%. This is high for a natural climate proxy, but it needs to be borne in mind that 48% of the variability remains unexplained, and so our proxy reconstruction of precipitation will not be perfect.

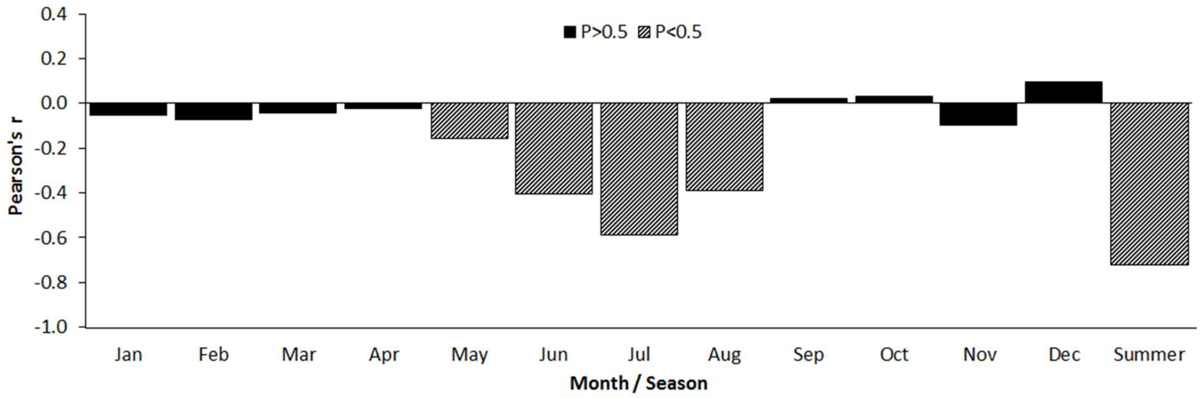


Figure 1. A bar chart showing the correlation (Pearson's r) between stable oxygen isotopes from UK oak trees and the England and Wales precipitation series. Each month of precipitation data for one year are compared to the oxygen isotope value for the year of ring growth, over the period 1850 to 2012 CE. Statistically significant results (p<0.05 or the 95% significance level) are shown in grey and non-significant in black. The combined (sum) precipitation data for all the significant months are then combined, into one "Summer" precipitation value (the sum of May to August precipitation) and this is again compared to the tree ring oxygen.

Once we are satisfied with the relationship between our proxy data and the modern climate data, we can we can produce a statistical model of this relationship, which can be summarised by a regression equation and visualised as in Figure 2. For this model to be used to reconstruct climate the proxy data should be on the horizontal (x-axis) and the climate data on the vertical (y-axis), as is shown in Figure 2. Figure 2A shows the data from Figure 1 as a scatterplot, showing the rainfall and isotope value for each year as a single point, it also displays the R^2 value. The relationship between rainfall and isotopes can be described as linear. High years of rainfall have low isotope values and vice versa. While the relationship is not perfect, it is, as we have seen, strong and statistically significant. The solid black line in Figure 2A runs as closely as possible to all of the points, within some statistical constraints. This is the line of best fit or the regression model. Figure 2B shows only this model line.

We could now use these data to reconstruct climate. However, it is first prudent to make some further checks. Correlation is a test of association between two series and unless the correlation is perfect, as mentioned earlier, there will some unexplained variance, in this case 48%. We know that we are not going to reconstruct all of the ups and downs in annual climate perfectly, but it is extremely important that we can capture the long term, low frequency changes in climate. If we cannot do this, then any discussion of modern climate change in reference to past long term changes will be meaningless. There are two main tests of this that are normally used in tree-ring climate research; the reduction of error (RE) and the coefficient of efficiency (CE). Both RE and CE work by splitting the calibration data set into two halves (or as nearly as possible) and seeing if one half of the data set is capable of reconstructing the other effectively. This is especially difficult when the data has a trend or a step in it, and the CE statistic is especially effective at looking for this. Both statistics have a theoretical range from minus infinity to +1. Any results below zero are considered failures. Any results above zero pass the test, but clearly the nearer to 1 the result is, the better the data perform. We will not go into further detail of these tests but more information is available, see the following reference for a link to online resources (National Research Council, 2006)

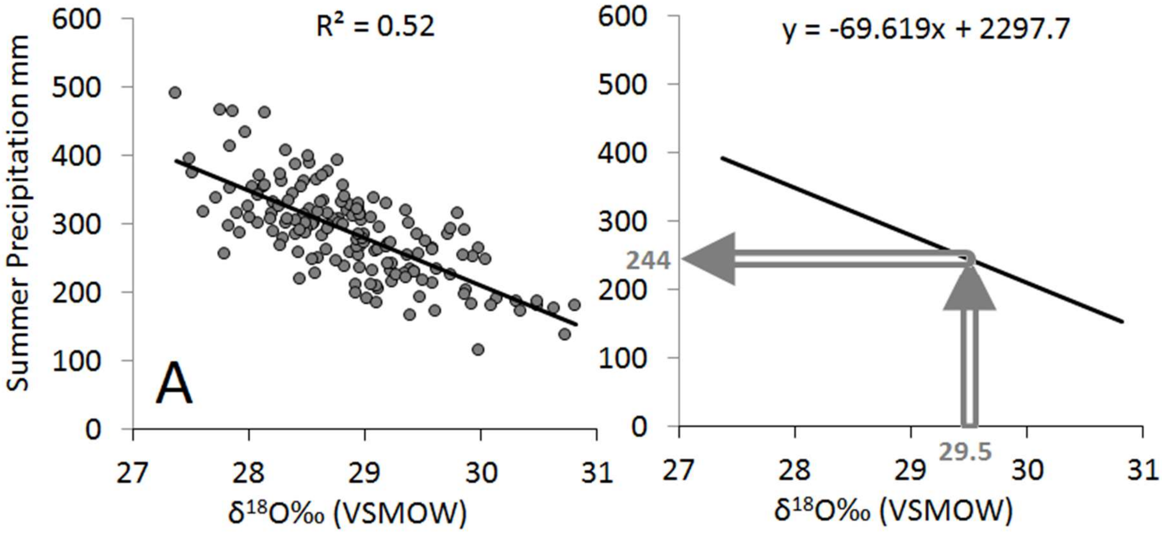


Figure 2. Panel A shows a scatterplot of the relationship between oak oxygen isotopes (‰) and "Summer" (sum of May to August) precipitation (mm), showing the squared correlation coefficient (R^2) inset and regression line of best fit (black solid line). Panel B shows only the line of best fit and how this model can be used to reconstruct the precipitation of a year (grey arrows), for which we have only isotope data. Inset is the regression equation, which describes this line statistically.

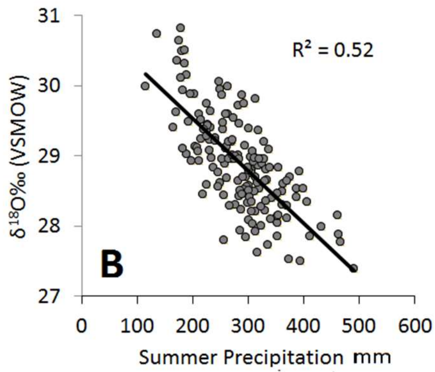
Once we have thoroughly tested the proxy data against climate, over the period for which we have both climate data and proxy data (the calibration period), we can use these data to reconstruct past climate with some measure of confidence. We can now use an oxygen isotope values, for years which we have no rainfall data, to predict or reconstruct the rainfall of those summers. The open arrows in Figure 2B show how this is done. Here we have an oxygen isotope value of 29.5, for a year prior to rainfall measurements. We can draw a vertical line from 29.5 on the horizontal (x-axis) until it meets the model line and then read the corresponding rainfall value on the vertical (y-axis), in this case almost exactly 244mm, this is the rainfall that our model would predict for that summer. However, instead of this rather laborious process, we can use the regression equation shown at the top of Figure 2B to do this work for us, as follows.

- $y = bx + a$
- y (rainfall) = $b*x$ (isotope) + a
- 243.99mm = -69.619 x 29.5 + 2297.7

An example of a climate reconstruction following these procedures can be seen in Figure 3. Annual stable oxygen isotopes from a sample of at least 10 trees per year have been calibrated and verified against summer (May to August) England and Wales precipitation. In this example, we have calibrated only over the period 1850 to 2012 CE, and reconstructed climate back to 1766 CE. This will enable us to see how well our reconstruction performs prior to the calibration. Figure 3A shows measured precipitation (in grey) plotted against out reconstructed precipitation (in black), visually the match is a good one, but it is important to verify this with some statistics. Figure 3B shows the correlation between oxygen isotopes and summer rainfall, and displays the squared correlation (R^2) which established the explained variance between proxy and climate data. Note that in Figure 3B the climate data is now on the horizontal axis and the proxy data on the vertical axis, by statistical convention this is the correct way to display the data, however to reconstruct climate this must be reversed as in Figure 2. Figure 3C shows the verification statistics where one half of the data are used to test the other, discussed earlier. The R^2 is high in all cases, while both RE and CE are both well above zero (maximum possible for both is 1) and so pass both these tests.

C

Calibration peiod	AD 2012-1931	AD 1930-1850	AD 2012-1850
Verification period	AD 1930-1850	AD 2012-1931	
Verification RE	0.56	0.47	
Verification CE	0.55	0.45	
Calibration R^2	0.57	0.46	0.52



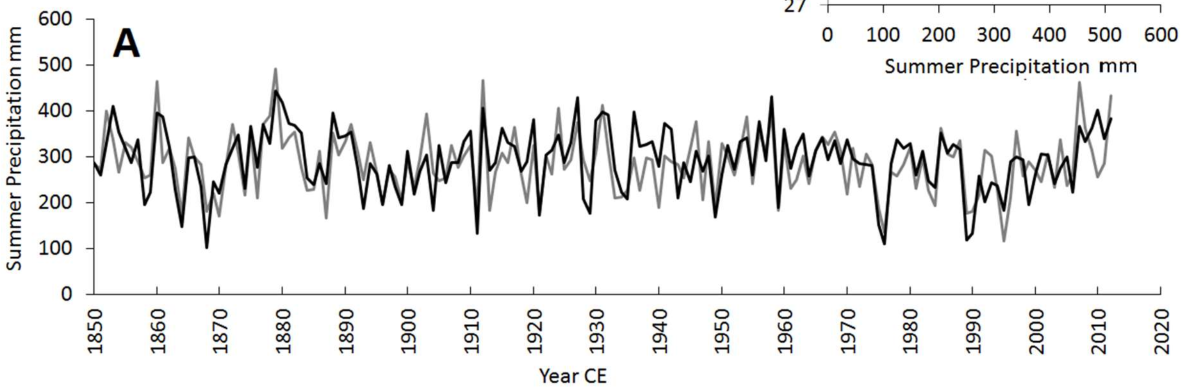


Figure 3. Panel A shows meteorological data from the summer England and Wales precipitation (EWP) series (May to August) in grey plotted against precipitation values reconstructed from oxygen isotopes in oak tree rings, in black. Panel B shows a scatterplot of summer EWP against oak oxygen isotopes for the period 1850 to 2012 CE, displaying the R^2 value. Panel C shows the calibration statistics for the relationship between oxygen isotopes and summer precipitation for the period 1850 to 2012 CE, values for all three statistics have a theoretical maximum of one.

References and Resources:

Leijonhufvud, L., Wilson, R., Moberg, A., Söderberg, J., Retsö, D., & Söderlind, U. (2010), Five centuries of Stockholm winter/spring temperatures reconstructed from documentary evidence and instrumental observations, Climatic Change, 101, 109-141. https://doi.org/10.1007/s10584-009-9650-y

Loader, N. J., Young, G. H. F., Grudd, H., & McCarroll, D. (2013), Stable carbon isotopes from Torneträsk, northern Sweden provide a millennial length reconstruction of summer sunshine and its relationship to Arctic circulation, Quaternary Sci. Rev., 62, 97-113. https://doi.org/10.1016/j.quascirev.2012.11.014

McCarroll, D., Loader, N. J., Jalkanen, R., Gagen, M., Grudd, H., Gunnarson, B. E., et al. (2013), A 1200-year multi-proxy record of tree growth and summer temperature at the northern pine forest limit of Europe, Holocene, 23(4), 471-484. http://journals.sagepub.com/doi/10.1177/0959683612467483

National Research Council (2006), Surface Temperature Reconstructions for the Last 2,000 Years, The National Academies, Washington, D.C. Available as a free download: https://www.nap.edu/catalog/11676/surface-temperature-reconstructions-for-the-last-2000-years

Young, G. H. F., Loader, N. J., McCarroll, D., Bale, R. J., Demmler, J. C., Miles, D., et al. (2015), Oxygen stable isotope ratios from British oak tree-rings provide a strong and consistent record of past changes in summer rainfall. Clim Dyn (2015) 45: 3609. https://doi.org/10.1007/s00382-015-2559-4

The UK Oak project: https://www.oak-research.co.uk/

England and Wales Precipitation Record: https://www.metoffice.gov.uk/hadobs/hadukp/

Central England Temperature Record: https://www.metoffice.gov.uk/hadobs/hadcet/

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