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Palaeovolcanic forcing of short-term dendroisotopic depletion: The effect of decreased solar intensity on Irish Oak

N. Ogle
Queen's University of Belfast

Christian Turney
University of Wollongong, turney@uow.edu.au

R.M. Kalin
Queen's University of Belfast

L. O'Donnell
Queen's University of Belfast

C.J. Butler
Armagh Observatory

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Abstract
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Keywords
Palaeovolcanic, forcing, short, term, dendroisotopic, depletion, effect, decreased, solar, intensity, Irish, Oak

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Palaeovolcanic forcing of short-term dendroisotopic depletion: 
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Neil Ogle,1,2 Chris S. M. Turney,1 Robert M. Kalin,3 Louise O’Donnell,3 
and C. John Butler4

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1. Introduction

[2] Considerable research has been carried out investigat-
ing the climatic and social repercussions of historical 
volcanic eruptions [e.g., Zielinski et al., 1995; Stothers, 
1996; Pyle, 1997; Brayshay and Grattan, 1999; Sadler and 
Grattan, 1999], partially because the ejecta can have a 
significant effect both proximally and more distant from 
the source. Numerous mechanisms have been proposed for 
how eruptions can drive global climate on the short, 
medium and long-term, though the production of fine ash 
and sulphate aerosols are considered to be the most critical 
products within a more distant context. Sulphate aerosols 
are typically 500 nm in diameter, and if sufficiently pow-
erful, an eruption may eject large quantities of these 
particles into the stratosphere (10–30 km). This loading, 
in combination with a residence time of several years 
[Rampino and Self, 1982; Devine et al., 1984], can transport 
aerosols around the planet in the Junge layer [Legrand and 
Delmas, 1987] reflecting incoming solar radiation and 
ameliorating global climate. Two important eruptions that 

had considerable social and climatic effects both globally 
and locally were Tambora (1815) and Laki (1783–84). The 
former gave rise to colder conditions in Northern Europe 
over a year after the eruption and the latter resulted in 
an abnormally hot summer and cold winter immediately 
following the eruption.

[3] The Tambora eruption (Sumbawa, Indonesia) is attrib-
uted to have killed around 90,000 people, largely through 
famine and disease following the eruption. The force of the 
eruption was so great (measuring 7 on the Volcanic Explo-
vitivity Index (VEI)), that its reverberation was heard up to 
2600 km away and the tephra plume extended 1300 km from 
source [Stothers, 1984]. In addition, Rampino and Self 
[1982] estimated that the total ejecta to be in the range of 
150–200 km$^3$. Climatic repercussions were such that mean 
temperatures decreased in the Northern Hemisphere mid-
latitudes by 0.8°C from 1815–1816, though the pattern was 
highly variable. For instance, temperatures in central Eng-
land in 1816 were 1.5–2.7°C cooler than those of 1815 
[Rampino and Self, 1982]. 1816 subsequently became 
known as the ‘year without a summer’ and led to the last 
great subsistence crisis in Europe [Harrington, 1992]. 
Stothers [1984] records that in London, 5 months after the 
eruption there were spectacularly coloured twilights and 
sunsets. Atmospheric haze was so acute that sunspots 
became visible to the naked eye and even 2.5 years subse-
quently some haze still remained.

[4] The Icelandic Laki eruption of 1783–84 was not the 
most explosive eruption (VEI = 4) especially when com-
pared with Tambora, however the cumulative effect of 
8 months of continuous atmospheric loading of sulphuric 
aerosols resulted in one of the most important climatically 
and socially repercussive events of the last millennium 
[Brayshay and Grattan, 1999; Demarée and Ogilvie, 2001]. In 
demographic terms volcanic aerosol-related death 
was widespread in Europe and North America [Jacoby et 
al., 1999; Grattan et al., 2003, 2004]. In England, between 
August 1783 and February 1784 an estimated 20,000 people 
died as a consequence of volcanic aerosol levels in the 
atmosphere [Witham and Oppenheimer, 2004].

[5] In total, 122 Mt of SO$_2$ was released from the eruption 
[Thordarson and Self, 2003], 95 Mt of which reached the 
upper troposphere/lower stratosphere where in contact with 
atmospheric moisture created approximately 200 Mt of 
H$_2$SO$_4$. Twenty-five megatons of H$_2$SO$_4$ remained 
aloft for over a year, the remaining 175 Mt contributing to 
the hot, blue, dry fog that hung over the European continent 
for over a year causing much anomalous atmospheric/
meteorological phenomena [Demarée and Ogilvie, 2001]. 
In combination with high surface summer temperatures, 
vigorous thunderstorms, lightning and hail the fog caused
profound damage to vegetation through leaf loss, scorching and drying [Grattan and Charman, 1994; Brayshaw and Grattan, 1999; Grattan and Pyatt, 1999; Thordarson and Self, 2001; van Swinden, 2001].

[6] A popular method for identifying past eruptions in sites distant from volcanic sources is the use of tree-ring widths (or a variation) to identify periods of stress under which the plant was growing [LaMarche and Hirschboeck, 1984; Bailie and Munro, 1988; Yamaguchi and Lawrence, 1993; Jones et al., 1995; Kalela-Brundin, 1996; Briffa et al., 1998]. The results have often been contradictory, however [Zielinski et al., 1995; Sadler and Grattan, 1999]. Although the method provides high-precision ages on inferred eruptions, not all events are detected using this approach, partially because the extreme effects rarely span more than a growing season, and sampling is often restricted to yearly increments. This study presents a complimentary approach using high-resolution stable carbon isotope ($\delta^{13}$C) analysis of Irish oak tree-rings before and after the Tambora and Laki eruptions.

[7] Interpretation of $\delta^{13}$C in climate terms is not straightforward. The stable carbon isotope composition of organic material from terrestrial C3 plants reflects the plant metabolism during the lifetime of a given tissue and is directly related to photosynthetic gas exchange [Farquhar et al., 1989]. The discrimination against $^{13}$C, relative to $^{12}$C, is related to the c/c$_a$ ratio of a leaf:

$$\delta^{13}C_p = \delta^{13}C_a - a - (b - a) * c_i/c_a \quad (1)$$

$\delta^{13}$C$_p$ the stable carbon isotope composition of organic material, %

$\delta^{13}$C$_a$ the isotopic composition of atmospheric CO$_2$, %

a the isotope fractionation of CO$_2$ through air during diffusion into the stomata ($\approx$4.4‰)

b the fractionation caused by carboxylation ($\approx$−27‰)

c$_i$ internal CO$_2$ concentrations of the leaf stomatal pore, ppm

c$_a$ external CO$_2$ concentrations, ppm

$\delta^{13}$C$_p$ is therefore intrinsically linked to c$_i$/c$_a$. Any environmental stress that influences the leaf stomatal conductance and/or net assimilation will affect the $\delta^{13}$C$_p$, through the impacts on c$_i$/c$_a$.

[8] Numerous environmental controls on $\delta^{13}$C$_p$ have been proposed, most importantly temperature via leaf-to-air vapour pressure deficit [Beerling, 1996; Turney et al., 1999], soil moisture/precipitation [Dupouey et al., 1993; Anderson et al., 1996] and irradiance [Schleser, 1995; Hanba et al., 1996].

2. Methods

[9] The oak tree ring series selected for this report came from Shane’s Castle located on the north coast of Lough Neagh in Northern Ireland. Temperature data related to Tambora came from observations made at Armagh Observatory 50 km to the south of the sample site and for the Laki eruption from central England, approximately 200 km to the south-east of the sample site [Parker et al., 1991]. In the laboratory, tree samples were dendrochronologically dated, submerged in water for several days and then each ring pared using a microtome. With a resolution of down to 20 μm, more than 30 samples could be shaved from a single ring. Dry wood shavings were then individually bleached to holocellulose in filter paper pouches using a deionised water, sodium chlorite, and hydrochloric acid solution. The process took several days. Five milligrams of dry holocellulose sample was then placed in Vycor® tubing with an excess of copper oxide to act as an oxygen source. The tubes were evacuated, sealed and then heated in a furnace to 950°C. Once cooled the CO$_2$ generated in the tubes was collected by passing the gas through a dry ice/ethanol trap and collecting in a suitable vessel under liquid nitrogen. The vessels used to collect the gas were then taken to the mass spectrometer (Micromass 602E) for $\delta^{13}$C analysis. Repeat analysis on the same wholewood sample yielded an analytical precision of better than 0.2‰ (at 1σ confidence limits).

3. Results and Discussion

[10] The dataset spanning the Tambora eruption (1814–1819) is given in Figure 1a. The $\delta^{13}$C values vary over a 3‰ range (−21.5‰ to −24.5‰) [Ogle, 1995]. A rapid depletion in $\delta^{13}$C values is recorded throughout the entire 1816 growing season (March–September) with a total depletion of approximately 1.6‰.

[11] 1817, the narrowest ring of the series indicates reduced growing conditions at this time, two years after the eruption of Tambora. In contrast, the isotopic values are partially recovering with a gradual enrichment in $^{13}$C prior to further depletion in 1818 before a sharp enrichment in 1819.

[12] Figure 1b displays a similar scenario for the Laki eruption of 1783–84. In this data set ranging from 1781–1786 the total spread in $\delta^{13}$C values is approximately 3.5‰. Throughout 1783 and into 1784 $\delta^{13}$C values deplete by as much as approximately 2‰ before values become more enriched during the summer months of 1784 and reach their pre-eruption values at the start of 1785. With abnormally high surface air temperatures in 1783 one would expect $\delta^{13}$C to enrich therefore we discard temperature as a forcing mechanism for the observed depletion.

[13] So it appears that both the isotopic records of Laki and Tambora record shifts to lighter values for approximately 6 and 10 months respectively. What is most intriguing with the isotope data in both of these cases is the apparent time lag of depletion following both eruptions. In the case of Tambora, the wood appears to be recording a shift in photosynthetic conditions sometime around 8 months following the eruption coincident with models that calculate the time it takes for aerosols from low latitude eruptions to reach higher latitudes. The depletive effect of the Laki eruption is almost instantaneous suggesting a relationship with tropospheric aerosol transport from this relatively close volcano. Continued depletion in later years could be related to stratospheric aerosol load.

[14] Studies on northwest European terrestrial species and organ-specific plant macrofossils suggest a shift of ~1.5‰ associated with the transition from the Late glacial Interstadial (a period of comparable warmth to the present) to the Younger Dryas Stadal [Turney et al., 1997], a shift in magnitude similar to that seen in the Shane’s Castle tree-
rings. The associated temperature decline into the Younger Dryas was of the order of \(6 \degree C\) during the warmest months [Lowe et al., 1999], several degrees greater in variation than that observed in our records. It seems again unlikely therefore, that changes in temperature can account for the significant shifts in \(\delta^{13}C\) values following either eruption.

In the absence of other stress-inducing conditions we suggest possible causes for \(\delta^{13}C\) depletion. As a result of the Tambora eruption the Icelandic low pressure area was forced southwards bringing cooler conditions to Western Europe with increased summer rainfall. Perhaps this may explain the Tambora depletion but not Laki with its associated high summer temperatures in 1783. A second possible cause for these depletions is a response to ejecta loading the stratosphere or when the prevailing environmental conditions allow the troposphere, and occlude the sun thereby hindering optimal photosynthetic operation and allowing the maintenance of high intercellular \(CO_2\) concentrations. We consider \(\delta^{13}C\) to be a sensitive, precise indicator of past volcanic eruptions that compliments more traditional techniques, such as ring widths or ring densities and should be used alongside other methods. We acknowledge the limitations of the sampling strategy of this study but the results warrant further investigation.

The 

4. Conclusions

While it is accepted that temperatures on a regional scale take a downturn in response to massive volcanic eruptions this study has shown that despite growing season temperatures remaining constant in the North of Ireland at the time of the Laki and Tambora eruptions, \(\delta^{13}C\) in an Irish oak exhibited rapid depletion. We believe the most likely cause for these depletions is a response to ejecta loading the stratosphere or when the prevailing environmental conditions allow the troposphere, and occlude the sun thereby hindering optimal photosynthetic operation and allowing the maintenance of high intercellular \(CO_2\) concentrations. We consider \(\delta^{13}C\) to be a sensitive, precise indicator of past volcanic eruptions that compliments more traditional techniques, such as ring widths or ring densities and should be used alongside other methods. We acknowledge the limitations of the sampling strategy of this study but the results warrant further investigation.

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