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

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[1] The climatic effects of historical volcanic eruptions are well documented in the literature. What are less certain however, are the effects of eruptions on more distant environments, particularly vegetation. Here we present sub-annual $\delta^{13}C$ records from two high-resolution Irish oak (*Quercus* spp.) chronologies that span the Laki (Grímsvötn) 1783–84 and Tambora 1815 eruptions. In both instances, a significant depletion in $\delta^{13}C$ is recorded within the trees following the eruption ($\sim$1.8‰). Historical meteorological datasets from observatories near to the trees sampled demonstrate that the shifts in carbon isotopic content cannot be accounted for by changes in local climate. We postulate atmospheric loading of ejecta from the eruptions resulted in significantly reduced irradiance, increasing discrimination within the trees. **Citation:** Ogle, N., C. S. M. Turney, R. M. Kalin, L. O'Donnell, and C. J. Butler (2005), Palaeovolcanic forcing of short-term dendroisotopic depletion: The effect of decreased solar intensity on Irish oak, *Geophys. Res. Lett.*, *32*, L04708, doi:10.1029/2004GL021623.

1. Introduction

[2] Considerable research has been carried out investigating 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 powerful, 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 attributed 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 Explosivity 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 England 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 subsequently some haze still remained.

[4] The Icelandic Laki eruption of 1783–84 was not the most explosive eruption (VEI = 4) especially when compared 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_2SO_4. Twenty-five megatons of H_2SO_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, violent thunderstorms, lightning and hail the fog caused

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profound damage to vegetation through leaf loss, scorching and drying [*Grattan and Charman*, 1994; *Brayshay 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; *Baillie 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_i/c_a ratio of a leaf:

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

$\delta^{13}C_p$	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 Stadial [*Turney et al.*, 1997], a shift in magnitude similar to that seen in the Shane's Castle tree-

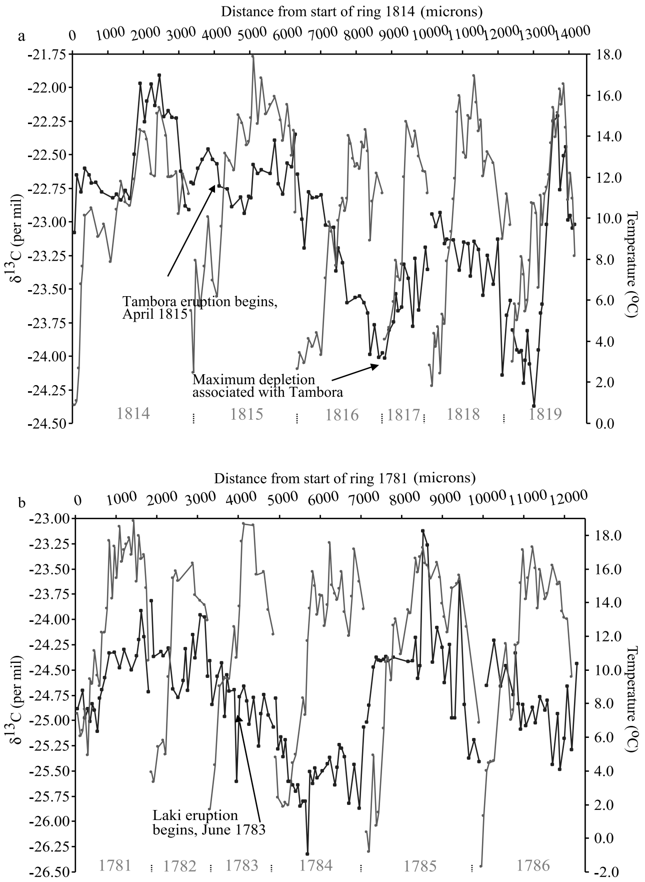

Figure 1. δ^{13}C values (blue lines) and weekly growing season (March–September) temperature record (red lines) spanning (a) 1814–1819 and (b) 1781–1786. The approximate timing of the Tambora and Laki eruptions in the record is noted. See color version of this figure in the HTML.

rings. The associated temperature decline into the Younger Dryas was of the order of 6°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 δ^{13}C values following either eruption.

[15] In the absence of other stress-inducing conditions we suggest possible causes for δ^{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 the depletions could be the volume of sulphur compounds in the atmosphere having an adverse effect on photosynthesis. Related to this however we believe is the most likely cause: a decrease in irradiance caused by increased light scattering and light absorbing as a result of aerosols in the atmosphere generated by both eruptions. The Dust Veil Index of *Lamb* [1970], the Volcanic Explosivity Index of *Newhall and Self* [1982] and the recent estimates of *Hartmann and Mouginis-Mark* [1999] and *Thordarson and Self* [2003] point to the high aerosol content generated by both eruptions. While surface temperatures may have been marginally cooler regionally (the 1783 summer temperatures notwithstanding), plants are extremely sensitive to decreases in sunlight below optimal conditions. Contemporary studies indicate that changes in the δ^{13}C of terrestrial plant tissue can result from changes in light levels. Decreasing irradiance leads to low photosynthetic activity, increasing the intercellular CO_2 concentration and resulting in a relative depletion in ^{13}C [*Ehleringer et al.*, 1986; *Farquhar et al.*, 1989; *Schleser*, 1995]. It seems likely, therefore, that the significant shifts in isotopic values we record here are as a result of changes in irradiance and not meteorological conditions *per se*.

[16] European oak ring width chronologies narrow in the years following Tambora, suggesting the trees were responding to a downturn in climatic conditions and a reduction in growth, but ring widths immediately following the Laki eruption do not show an appreciable narrowing. Narrow rings can be found in 1785–1786–1787 but whether or not this is volcanic-related is questionable [*Zielinski et al.*, 1995]. Pine chronologies however from Eurasia and North America do show a distinct paling and a reduction in density in the years following Laki [*Zielinski et al.*, 1995; *Kalela-Brundin*, 1996]. Therefore it would appear that this isotopic method of detecting past volcanic eruptions may compliment and support the traditional techniques of ring widths or ring densities.

4. Conclusions

[17] 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, δ^{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 δ^{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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