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Author(s)	Galvin, Stephen, D.
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The Impact of Volcanic Eruptions on the Climate and Ecology of Ireland since A.D. 1800

Stephen Galvin

**Department of Geography
School of Geography and Archaeology
College of Arts, Social Sciences and Celtic Studies
National University of Ireland, Galway**

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ABSTRACT

Global warming and the influence of anthropogenic changes to the environment are dominant themes in climate research today. However, the trends brought about by these processes have the potential to be abruptly altered by the impact of large-scale volcanic eruptions, particularly those at lower latitudes. The injection of volcanic matter into the atmosphere has the ability to influence temperature, precipitation and wind regimes. An additional outcome is the reduction of atmospheric transparency, which in turn has consequences for the biological environment and ecosystems through the limiting of photosynthesis. Although global and hemispheric impacts are known, the broad nature of this scale fails to indicate how local climate and ecosystems can be expected to react following volcanic eruptions. A number of studies have looked at individual aspects on more micro-scales – Dawson *et al.* (1997) examined peaks in gale frequency in Edinburgh following three low-latitude volcanic eruptions; Jones *et al.* (2003) used temperature records from three stations to assess the long-term response to eruptions; Kyncl *et al.* (1990) examined Central European climatic and tree-ring response to a single eruption. Local assessments of volcano-climate interactions tend to focus on either one single climatic element, or one single eruption event.

The focus of this study is to determine to what extent five large-scale low-latitude volcanic eruptions and six lesser Iceland-based events have had on the climate and ecology of Ireland over the past ~200 years. The analysis used is two-fold, concentrating firstly on archival climate data, followed by the examination of dendroecological trends and a new dendroclimatic reconstruction. Armagh Observatory, Co. Armagh, provides detailed temperature, precipitation and wind direction data from 1796 onwards, while *Taxus baccata* (yew) tree-ring indices from Killarney National Park in Co. Kerry are used to reconstruct temperature and precipitation for that area since 1803. The newly constructed indices were also examined in conjunction with 13 other tree-ring series from throughout Ireland.

The temperature record from Armagh proved particularly responsive in the spring and autumn of the year following larger eruptions, displaying notable downturns. Precipitation tended to decrease in the summer following an eruption, while the wind regimes recorded increases in northeasterly, easterly and southwesterly directions in the months immediately after eruptions. This study is the first to systematically explore the impact of volcanic eruptions on tree-growth in Ireland. Dendrological data from Irish *Quercus* records showed that the changes in climatic patterns coupled with the reduced photosynthesis that follows eruptions have implications for growth in Ireland. In addition, temperature and precipitation reconstructions using *T. baccata* have proved that not only is the species a viable source of information in Ireland but that it can also be used to support the idea of post-volcanic eruption downturns in growing conditions. By combining each of these aspects (recorded and reconstructed climate, as well as dendroecological data), a more complete assessment of volcano-climate/ecology interactions was established.

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In memory of Paddy Doré.

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CHAPTER 1: INTRODUCTION

1.1 RATIONALE

There are numerous causes of climatic change. Anthropogenic and natural changes in climate are, more often than not, gradual processes. Much climate change research is focused on how the actions of humans, primarily through energy use, but also urbanisation and land use change, are having a prominent effect on global climate (Karl and Trenberth, 2003; Dale, 1997). A change of climate in Ireland is likely to have significant impacts on the distribution of species and on the composition of habitats (Berry *et al.*, 2002), while also influencing grass yields (Holden and Brereton, 2002). With Ireland's agri-food sector accounting for around 8% of GDP and 25% of net foreign earnings (Teagasc, 2010), the stability of the climate is important so that agricultural production remains prosperous.

Measures such as the development of forms of renewable energy and the reduction of carbon emissions from industry and transport are being adopted in an effort to reduce the potential impact of long-term anthropogenic climate change (IPCC, 2007). However, natural and more abrupt changes in climate over the time span of years to decades, such as those brought about by volcanic eruptions or changes in ocean circulation patterns, have the potential to impact society to such an extent that they would pose clear risks to humans' ability to adapt (Clark and Weaver, 2008). Current understanding and modelling capability is not sufficient to specify details of future abrupt climate change (Overpeck and Cole, 2006). It is for this reason that examining climatic changes from throughout history would give a better indication as to what is likely to happen should such abrupt transformations occur again. It is estimated that the eruption of Toba, a super-volcano on the island of Sumatra in Indonesia, 73,500 (±2,000) years ago brought about a global volcanic winter for six to 10 years, with worldwide temperatures between 3°C and 5°C cooler, and up to 15°C cooler in the high latitudes (Rampino and Self, 1992; Rampino, 2002). A repeat of such an eruption would be catastrophic, but smaller volcanic events also have the potential to lower global temperatures by between 0.2°C and 0.5°C for one to three years after the eruption (Self *et al.*, 1981). Such seemingly slight alterations in temperatures can nonetheless have a prominent influence on regional weather, agriculture and society.

Písek and Brázdil (2006) emphasise the need for local or regional scale studies of the effects of large-scale volcanic eruptions. The focus of this thesis is to determine to what extent large-scale low-latitude volcanic eruptions and lesser, but geographically closer, Iceland-based events have had on the climate and ecology of Ireland over the past ~200 years. The analysis used is two-fold, concentrating firstly on archive-based climate data, followed by the examination of dendroecological trends and dendroclimatic reconstructions. Armagh Observatory, Co. Armagh, provides detailed temperature, precipitation and wind direction data from 1796 onwards. *Taxus baccata* (yew) tree-ring indices from Killarney National Park in Co. Kerry will be examined in conjunction with 13 Irish *Quercus* (oak) tree-ring series from the International Tree Ring Data Bank to investigate any volcano-induced downturns in growth. Meanwhile the *T. baccata* series will also be used to reconstruct temperature and precipitation for the Killarney area since 1803, thus facilitating an assessment of any changes in trends in the years following volcanic eruptions. This research aims to increase the understanding of the impact volcanic eruptions have in Ireland. The findings will allow climate modelers, paleoclimatologists and biogeographers to understand to what extent volcanic events could influence climatic variables in Ireland. By presenting post-volcanic eruption climatic downturns and their ecological effects, the study will show that abrupt climate change events over-and-above the backdrop of a warming world can have a notable impact on a local scale and will illustrate the need for regional analysis of the impact of volcanic eruptions.

1.2 THE CLIMATE OF IRELAND

Ireland has a temperate maritime climate, principally due to the dominating influence of the Atlantic Ocean and the Gulf Stream. As a result, the climate is considered to be mild, moist and changeable, with abundant rainfall and a lack of temperature extremes in comparison to many other countries at similar latitude

(Rohan, 1986). The Köppen Climate Classification categorises Ireland as Cfb (temperate, without a dry season, but with a warm summer) (Peel *et al.*, 2007). The average annual temperature is ~9°C, with the midlands and eastern parts of the island experiencing more extremes than other areas as a result of the reduced influence of the Atlantic Ocean. The prevailing southwesterly winds help control the rainfall amounts, with values ranging from ~800 mm in the east midlands to ~2,800 mm in more elevated areas of the west, southwest and northwest of the island (Met Éireann, 2010). The accumulation of this precipitation tends to be highest in the winter and lowest in the early summer. The number of days per year within which more than 1 mm of rain falls varies from 150 to over 200, depending on location (Met Éireann, 2010).

With the month-to-month climate of Ireland dominated by the Atlantic Ocean, notable variations occur as a result of the periodicity of the North Atlantic Oscillation (NAO). The redistribution of atmospheric mass between the Arctic and the subtropical Atlantic moves from one phase to the other over a period of about eight years (Rogers, 1984) – although Hurrell and Deser (2009) point out that there is no preferred time-scale of variability for the NAO – producing large changes in surface temperature, winds, storminess and precipitation over the Atlantic (Hurrell and Deser, 2009). A study by Jennings *et al.* (2000) showed that, in Ireland, mean winter air temperature, wind speed, rainfall, relative humidity and cloud amount were all positively related to NAO index values. When NAO values are positive there is an increase in westerly winds and, as a consequence, summers are cooler and dryer with winters being milder and wetter, while the opposite is true of periods of negative NAO values (Butler *et al.*, 1998).

The primary influences upon climatic phenomena can be categorised as being periodic (orbital variability, solar variability/sunspots, North Atlantic Oscillation) or episodic (meteorite impacts, volcanic eruptions). The periodic influences work on timescales as lengthy as 100,000 years (eccentricity – Muller and McDonald, 1997) to 11 years, where pulses in climatic phenomena are attributable to sunspot cycles (Barry and Chorley, 2003), while the periodicity of NAO can be quite irregular at between two and eight years (Rogers, 1984; Schneider and Schonwiese, 1989). Of the episodic events, volcanic eruptions are more influential. Large-scale volcanic eruptions, through their emission of dust and aerosols, can cause temperatures to fall for one to two years (Rampino and Self, 1982; Robock, 2000; de Silva, 2005). The increased atmospheric albedo as a result of the presence of volcanic aerosols acts to reflect the sun’s radiation back into space and produce cooling at the surface of the earth by between 0.2°C and 0.5°C (Self *et al.*, 1981). Post-volcanic eruption climatic downturns in Ireland will be the focus of this dissertation. Influences can manifest themselves in temperature (Self *et al.*, 1981), precipitation (Church *et al.*, 2005), wind direction (Dawson *et al.*, 1997; Kelly *et al.*, 1996; Groisman, 1992) and tree-ring widths (Gervais and MacDonald, 2001), therefore each element will be examined in detail.

CHAPTER 2: THEORETICAL BACKGROUND

2.1 THE STUDY OF VOLCANO-CLIMATE INTERACTIONS

Volcanic eruptions are important natural causes of climate change on many timescales. Plutarch’s writings from circa A.D. 100 are believed to be the earliest known documentation of the climatological impacts of volcanic eruptions. One passage describes events in 44 B.C.: a dim sun that was “pale and without radiance,” resulted in a cold summer “owing to the feebleness of the warmth” (de Silva, 2005: 1). This spell of poor weather was responsible for the destruction of crops and the onset of famine from Rome to Egypt. While a direct link is not obvious, it is accepted that Plutarch was relaying the effects of an eruption of Mount Etna that year. Benjamin Franklin (1784) is widely accredited to be the first person to associate irregular weather with volcanic eruptions (Robock, 2000; Grattan and Pyatt, 1999; Stothers, 1996), having suggested that the eruption of an Icelandic volcano, now known to be Laki, was likely to be the cause of the violent storms and dry blue fog experienced in many parts of Europe in 1783.

The understanding of how volcanic eruptions interact with and influence weather and climate has since advanced considerably. Humphreys (1920) suspected that catastrophic volcanic eruptions had an influence on climate, but it was not until Mitchell (1961), who averaged the effects of several eruptions in order to separate the volcanic effect from other fluctuations such as solar variability and carbon dioxide concentrations, that more substantial evidence was beginning to be produced. Since then research by, amongst many others, Robock (2000; 1991), Self *et al*. (1997), Robock and Mao (1992), Mass and Portman (1989), Stothers (1984) and Rampino and Self (1984) has shown that the activity of volcanoes throughout the world and throughout geological time has had a marked influence on weather and climate. Meanwhile Lamb’s (1970) development of the Dust Veil Index has, perhaps more than any other, been extremely influential in the modern study of interactions between volcanic eruptions and climate. This index will be examined in detail in the next section.

2.2 VOLCANIC INDICES

A perfect volcanic index would convey the net radiation deficit brought about by explosive volcanic eruptions (Robock and Free, 1995; Robock, 2000). However, no such index exists. Those that are in use each suffer from at least one problem, be it incomplete geographical or temporal coverage, an intrinsic assumption that surface air temperatures drop after an event, or that elements of the eruptions other than stratospheric aerosol loading are included in their formulation (Robock, 2000). Methods of measuring post-volcanic eruption fluctuations in ground level and atmospheric radiation have shown significant changes occurred following the El Chichón 1982 (Robock, 1983) and Mount Pinatubo 1991 (Stenchikov *et al.*, 1998) events. The quantification of the impact of earlier eruptions has to rely on surface radiation measurements combined with indirect measures such as geological evidence and reports of red sunsets in diaries and paintings. These methods can easily result in the problem of omitting volcanoes as often eruptions only appear in indices if there is a direct report of their occurrence (Robock, 2000). The remainder of this section will examine in detail the two volcanic indices that were employed in this thesis.

2.2.1 Dust Veil Index (DVI)

Lamb (1970) formulated the Dust Veil Index (DVI) in an effort to quantify the impact explosive volcanic eruptions have “on surface weather, on lower and upper atmospheric temperatures, and on the large-scale wind direction” (Lamb, 1970: 470). It is a numerical index that measures the impact of a particular eruption’s release of dust and aerosols in the years after the event. Five different methods are employed to determine the DVI for any particular eruption. Final DVI values are averages, sometimes corrected subjectively, of the estimates produced by as many of the five methods as data availability permits. One method used is to make subjective estimates based on previous compilations of secondary historical sources. Three methods incorporate formulae devised to systematise the estimation of the DVI after the initial subjective estimates have been made. These three formulae estimate the DVI based on (1) the depletion of radiation following the eruption, (2) temperature variations following the eruption, and (3) the amount of solid material dispersed as dust after an eruption.

The fifth and final method relates to a value being allocated to an eruption depending on its latitude (Lamb, 1970).

Robock (1979) used the DVI to create a simulation of the energy balance during the Little Ice Age, something that showed that volcanic aerosols were a dominant factor in the cooling pattern that occurred at that time. The index is widely recognised as being the best indicator of the post-volcanic eruption distribution of dust (Robock and Mao, 1995; Robock, 1981; Lough and Fritts, 1987). However, it is difficult to assign a DVI value to eruptions that occurred during time periods where not all the defining criteria are available, while smaller eruptions and those that occur close together – both geographically and temporally – also prove difficult to assess. In addition, the DVI has been criticised for the fact that it employs climatic data in its formation, which results in circular reasoning as the index is often used to gauge post-eruption temperature changes (Bradley, 1988). However, a modified model created by Robock (1981), which excluded temperature information, produced results that did not differ significantly from those formed using the original DVI criteria. For the purposes of this study, Lamb's (1970) DVI is correlated with temperature, precipitation and various tree-ring indices in an effort to gauge how closely related its fluctuations are with local-scale variables that should, in theory, display an influence.

2.2.2 Volcanic Explosivity Index (VEI)

Devised by Newhall and Self (1982), the Volcanic Explosivity Index (VEI) is used to provide a relative measure of the explosiveness of volcanic eruptions. Volume of products, eruption cloud height and qualitative observations (using terms ranging from gentle to mega-colossal) are used to determine the explosivity value. The scale ranges from 0 for non-explosive eruptions (less than 10^4 m^3 of tephra ejected with an eruption column height of less than 100 m) to 8 for mega-colossal (explosive eruptions that eject 10^{12} m^3 of tephra and have a cloud height of over 25 km). Each interval on the scale represents a ten-fold increase in observed eruption criteria. Newhall and Self (1982) admit that their index alone is of limited use in the examination of volcano-climate interactions as there is no assessment of the amount of aerosols emitted or the size of the particles produced, two primary facilitators of the onset of post-volcanic eruption weather phenomena. This thesis uses the VEI to portray a general sense of the relative size of eruptions and does not assume that larger values have an intrinsic association with downturns in climate.

2.3 VOLCANIC MATTER IN THE ATMOSPHERE AND ITS CLIMATIC IMPACT

The gases produced by volcanic eruptions impact upon the earth's climate through a set of complex interactions. These gases are dominated by water vapour and carbon dioxide (~80% and 10% respectively), with the remaining 10% made-up of anything from five to eight other gases and aerosols depending on parent material, the most common of which tends to be sulphur dioxide (SO_2). It is the volcanic aerosols, rather than the ash, that are the principal medium for climatic interference. Volcanic eruptions act as a catalyst in the loss of ozone through chemical reactions and changes in atmospheric dynamics (de Silva, 2005). Chlorine (Cl) and bromine (Br), volcanic aerosols that can aid in the destruction of ozone depletion, are rained out before they reach the stratosphere. Introduced elements thus do not directly cause ozone depletion. Instead, the volcanic aerosols that reach this layer change stratospheric chemistry in a manner that activates pre-existing, anthropogenic chlorine and bromine. Such heterogeneous reactions are seen to be a crucial part of the aerosol-ozone connection (Solomon *et al*., 1996). "The reactions involve atmospheric gases as well as liquid and solid aerosols. They are inversely temperature dependent and thus lead to enhanced stratospheric ozone depletion at mid-latitudes and polar regions" (de Silva, 2005: 5).

2.3.1 Local diurnal changes

Larger particles, such as fragments of ash, fall out of the stratosphere relatively quickly following volcanic eruptions. This results in their influence on local climate being short-lived, while a more widespread effect is nonexistent. Symons (1888), after the 1883 Krakatau eruption, and Robock and Mass (1982) after the 1980 Mount St. Helens eruption, showed that this temporary atmospheric loading reduced the amplitude of the diurnal cycle of surface air temperature in the region of the ash cloud. It is estimated that the area directly affected by volcanic ash from Mount St. Helens cooled by as much as 8°C during the day and warmed by the same amount at night (Robock and Mass, 1982). However these effects disappear as soon as the particles settle on the ground (Robock, 2000). This is the result of the sheer unloading of the particles, or high levels of precipitation in the troposphere.

2.3.2 Stratospheric warming

Only larger Plinian-style pyroclastic eruptions such as Toba 73,500 (±2,000) years ago, Tambora in 1815, Cosigüina in 1835, Krakatau in 1883, El Chichón in 1982 and Mount Pinatubo in 1991 penetrate the tropopause and the stratosphere, distributing particles in this dryer layer of the atmosphere. This reduces the likelihood of the emissions being rained out (de Silva, 2005). The aerosols produced have an atmospheric residence time of one to two years, depending on the latitude and altitude of the initial injection (Robock, 2000; de Silva, 2005). "Stratospheric sulphate aerosols generated by volcanic eruptions have had a far-reaching impact on the radiation budget, atmospheric and surface temperatures, regional weather patterns, global climate changes, and atmospheric chemistry, including environmentally important atmospheric effects such as global ozone depletion" (Self *et al*., 1993: 2). The particles absorb the warm up-welling thermal radiation from the surface, only to re-emit this radiation at a lower temperature, thus warming the layer of the atmosphere within which they reside (Pollack *et al.*, 1993) by ~1.0°C for up to two years (Robock, 2000).

Because the increased concentration of volcanic aerosols remains in the stratosphere, they also act to reduce temperatures in the layers below, that is, the troposphere and the earth's surface. This is made possible by the fact that the aerosols reduce the amount of sunlight reaching these levels, essentially increasing the albedo effect in the atmosphere (Pollack *et al.*, 1976). Simulations of temperature changes within the troposphere associated with the Agung eruption in Bali in 1963 (Hansen *et al.*, 1980) and El Chichón in 1982 (Pollack *et al.*, 1991) show that the solar perturbation is more significant than the thermal disruption, hence the cooling aspect becoming dominant in the months and years following an eruption.

2.3.3 Surface temperatures: summer cooling and winter warming

Eruptions that occur close to the equator and penetrate the stratosphere have a greater impact on global climate due to the ease at which the particles are circulated in the atmosphere. Models created by Robock *et al.* (1995) have shown that tropical eruptions cause greater stratospheric heating in the tropics than in the higher latitudes. This produces an enhanced pole-to-equator temperature gradient, particularly in winter. “In the Northern Hemisphere winter, this enhanced gradient produces a stronger polar vortex, and this stronger jet stream produces a characteristic stationary wave pattern of tropospheric circulation resulting in winter warming in the Northern Hemisphere continents” (Robock, 2003: 4). The effects of this gradient are reversed in the summer months, creating a relative cooling effect that dominates at lower latitudes and Northern Hemisphere continents (Robock, 2003). This is a consequence of the fact that there is more sunlight to intercept in these regions during the summer months.

Post-volcanic eruption cooling during the summer months is a direct result of aerosol radiative forcing in the atmosphere. However, the warming that occurs in winter is a consequence of induced changes in tropospheric circulation brought about by stratosphere-troposphere dynamical interaction and is therefore often difficult to investigate and simulate (Kirchner *et al.*, 1999). Nonetheless, winter warming following volcanic eruptions, particularly in January in the Northern Hemisphere, has been identified in both recorded sea surface temperatures (Robock, 1991) and in general circulation models (GCMs) (Kirchner *et al.*, 1999), with the latter producing increases of 1.0°-2.0°C.

Identifying specific volcano-induced temperature change is difficult at times as the signal can be obscured by, for example, North Atlantic Oscillation (NAO). The NAO is a large-scale alternation of atmospheric mass between the Icelandic Low and Azores High (Cook *et al.*, 1998). Between the months of November and

April, the NAO is responsible for the majority of weather variability over western and northern Europe, influencing wind speed and direction, temperature, and moisture distribution, and the number and track of storms (Osborn, 2000) as this is the period of strongest pressure gradients and inter-annual variability (Rogers, 1984). The NAO index, which expresses the temporal behaviour of the oscillation, is defined as the normalised sea-level pressure difference between Stykkishólmur or Akureyri, Iceland, and Ponta Delgadas, Azores (Rogers, 1984). For this reason, it is important to understand the interaction that occurs between NAO and local-scale climate in Ireland. Hurrell (1995) showed that during the winter half of the year, the index provides a simple means of explaining much of the variability seen in surface temperature and precipitation patterns over Europe – a positive value will produce mild, wet winters while a negative value will see the opposite prevail. Consequently, the appropriate phase of NAO has the potential to accentuate or mask the impact of volcanic eruptions.

Evidence exists for the ability of multiple volcanic eruptions to impact upon temperatures on the scale of decades (Zielinski, 2000). A model created by Robock (1979) put forward the idea that a series of volcanic eruptions played a large role in the onset of The Little Ice Age (~1430-1850), whereby summer temperatures were lowered often enough that the long-term averages were cooler than they would have been without eruptions. Conversely, Overpeck *et al.* (1997) postulate that the lack of any climatically-effective volcanic events in the period between the 1920s and the 1950s contributed to the overall warm conditions during these decades, as volcanically-induced cool summers that would lower the mean annual temperature were not a feature in the Northern Hemisphere. McElwain and Sweeney (2007) point out that 1945 is still the warmest year in Irish records, thus showing that the hemispheric trend of increased temperatures during this time was also applicable on the smaller Irish scale.

2.3.4 Reduced precipitation

A further outcome from a reduction in surface temperatures following volcanic eruptions is a fall in precipitation levels. Robock and Liu (1994) created a model that simulated post-eruption temperatures and precipitation values, showing that the latter will be reduced by 0.03 mm day^{-1}. No obvious reduction is apparent in the Southern Hemisphere, but a large reduction occurs in the Northern Hemisphere. This, Robock and Liu (1994) point out, is because the majority of the intertropical convergence zone (ITCZ), where most of the change in precipitation occurs, is north of the equator. It can be explained by reduced strength of the ITCZ following cooling in the tropics. The model created also showed that cloudiness decreased following volcanic eruptions, producing the same pattern as precipitation.

Church *et al.* (2005) showed that large volcanic eruptions result in rapid reductions in ocean heat content as well as global mean sea level, with the latter falling by as much as 5 mm following the eruption of Mount Pinatubo in 1991. In the three years after the eruption, Church *et al.* (2005) estimate that evaporation decreased by as much as 0.1 mm day^{-1}. Meanwhile, Gillett *et al.* (2004) used regression analysis to examine whether anthropogenic, solar or volcanic forcings had an influence on global terrestrial precipitation levels. Of these three, only the volcanic signal was detectable in the records. Combining the three elements to form one dataset and running a multiple regression resulted in the volcanic signal again being identified, but not the anthropogenic or solar forcings, a result that supports that of Broccoli *et al.* (2003). In addition, Gillett *et al.* (2004) point out that the modelled precipitation's response to volcanic forcing is significantly underestimated compared to that observed, suggesting that their results could be scaled-up and would still fit well. Conversely, Baker *et al.* (1995) put forward the idea that volcanic eruptions can increase regional precipitation levels as a result of aerosols in the atmosphere creating condensation nuclei. This theory is supported by Caseldine *et al.* (1998) whose analysis of peat accumulation in Corlea, Co. Longford showed that the Hekla-4 eruption in Iceland in 2310 ± 20 B.C. was followed by wet conditions and a major flooding episode (although they do point out that relying on a limited amount of information from a single site can lead to misleading data).

2.3.5 Changes in wind patterns/intensity

Hunt (1977) created a model to simulate conditions after the 1883 eruption of Krakatau. It showed that a reduction in low-latitude jet stream wind intensity can be expected as a result of the increased concentration of volcanic matter. A less intense, but more variable, reduction was simulated in higher latitudes. Hunt’s (1977) model goes on to highlight an increase in weak westerly flows of air, with more extensive easterlies also apparent, between 50 and 100 days after an eruption. However, Hunt (1977) also points out that no substantial modification to macro-scale wind patterns should be expected following large volcanic eruptions. Meanwhile, Dawson *et al.* (1997) show a close link between increased gale-day frequency in Edinburgh, Scotland, and the eruptions of Tambora in 1815, Krakatau in 1883 and El Chichón in 1982.

Kelly *et al.* (1996) highlight the fact that mean sea level pressure in the North Atlantic was anomalously altered in the months following the eruption of Mount Pinatubo in 1991, indicating a strengthening of westerly winds in the area, a result also highlighted by Graf *et al.* (1993). However, Kelly *et al.* (1996) draw attention to the fact that this pattern of pressure departure is very similar to that experienced during the positive phase of North Atlantic Oscillation. Meanwhile, Dawson *et al.* (1997) found that, in the months following the eruptions of Tambora in 1815 and Krakatau in 1883, wind directions in Edinburgh experienced a notable increase in northeasterly and easterly components, before giving way to a southwesterly and westerly airstream, something that supports Hunt’s (1977) model that presented the idea that variability, and not necessarily intensity, is a feature of post-eruption wind regimes in higher latitudes.

A summary of the impact of volcanic eruptions on weather and climate can be seen in Table 2.1.

Table 2.1: The effects of large explosive volcanic eruptions on weather and climate (after Robock, 2000; Zielinski, 2000; Dawson *et al.*, 1997; Hunt, 1977). SW = shortwave, LW = longwave, NH = Northern Hemisphere.

Result	**Cause**	**Commencement**	**Duration**
Reduction of diurnal cycle in region of volcano	Blockage of SW radiation & emission of LW radiation	Immediate	1- 4 days
Increased wind direction variability	Volcanic matter altering sea level pressure	50 days	3-5 months
Reduced tropical precipitation	Blockage of SW radiation, reduced evaporation	1-3 months	1-2 years
Summer cooling in NH tropics/subtropics	Blockage of SW radiation	1-3 months	1-2 years
Stratospheric warming	Stratospheric absorption of SW and LW radiation	1-3 months	1-2 years
Winter warming of NH continents	Stratospheric absorption of SW and LW radiation	6 months	1 or 2 winters
Global cooling	Blockage of SW radiation	Immediate	1-2 years
Global cooling from multiple eruptions	Blockage of SW radiation	Immediate	10-100 years

2.4 THE CLIMATIC IMPACT OF HIGH-LATITUDE (ICELANDIC) ERUPTIONS

Volcanic activity in Iceland is unique as the island features almost all types of volcano and eruption styles (Thorarinsson and Sæmundsson, 1979). However, because of the high-latitude location of Iceland, the impacts of eruptions are less far-reaching in comparison to low-latitude events. Aerosols produced in low-latitude eruptions have, in comparison, a widespread distribution as circulation patterns facilitate a more global spread. The normal stratospheric meridional circulation lifts the aerosols in the tropics, transports them poleward in the mid-latitudes, and brings them back into the troposphere over a period of one to two years (Trepte and Hitchman, 1992).

Eruptions in Iceland are often not violent enough to directly inject matter into the stratosphere. As a result, the material produced is too heavy to be suspended in the atmosphere in such a manner that would facilitate a more extensive distribution (Robock, 2000), or, in the case of lighter aerosols, the material becomes incorporated into water droplets or clouds in the troposphere and falls back to ground level in the form of rain (de Silva, 2005). If the source of the aerosols is long-lived and sufficiently large, that is, if an eruption continues for a number of months, they can perturb the earth’s radiation budget and potentially impact upon climate, at least while the eruption continues (Stevenson *et al.*, 2003).

Zielinski (2000) points out that Icelandic volcanic material may reach the stratosphere by way of the very buoyant clouds generated above large fire fountains (e.g., Stothers *et al.*, 1986; Thordarson and Self, 1993), and because of the lower tropopause at higher latitudes. Consequently, Icelandic volcanic aerosols can, at least potentially, influence climate. Yet the analysis of the impact of Icelandic volcanic eruptions tends to focus on the distribution of ash clouds (Davies *et al.*, 2010; Thordarson and Larsen, 2007; Lacasse, 2001; Grönvold *et al.*, 1995; Thorarinsson, 1949). These clouds can also have an influence on weather and climate, but in a quite confined area that is usually restricted to parts of Ireland, Scandinavia, Britain, and Central/Northern continental Europe, as was evidenced by the eruption of Eyjafjallajökull in April-May 2010 (Davies *et al*, 2010). However, the prevailing tropospheric wind patterns at the time of an eruption are the dominant influence on this distribution, as opposed to the stratospheric circulation cells that aid the spread of volcanic aerosols from larger eruptions at low latitudes.

Icelandic eruptions of climate-forcing magnitude are rare. One prominent example in recent history, the eruption of the Laki fissure in 1783-4, has been the focus of many studies (see, for example, Witham and Oppenheimer, 2005; Thordarson and Self, 2003; Highwood and Stevenson, 2003; Thordarson *et al.*, 1996; Fiacco *et al.*, 1994; Angell and Korshover, 1985; Sigurdsson, 1982). This VEI 4 eruption created an aerosol veil that remained in the Northern Hemisphere for over five months (Thordarson and Self, 2003), while also creating a strong-smelling dry blue fog over much of continental Europe (Grattan and Brayshay, 1995). Most research examining the climatic influence and fatality estimates of Icelandic volcanism focuses on this 1783-4 Laki event because the impact was widespread. Eruptions of a lesser magnitude could potentially have had an impact on climate on a smaller scale, but are yet to warrant extensive examination. Písek and Brázdil (2006) point out that there needs to be more attention paid to the climatic effects of eruptions on a local level. Here, volcanic signals do not necessarily manifest as strongly as they do on a hemispheric or global scale due to the influence of local effects and circulation patterns. As a result, it is necessary to investigate these micro-scale interactions fully.

2.5 VOLCANO-CLIMATE INTERACTION RESEARCH IN IRELAND

Studies within which both Ireland and volcanic eruptions are focal points are somewhat rare. Those that have been published tend to be dominated by various biological themes. Firstly, tephrochronological analysis (Holmes *et al.*, 1999; Dwyer and Mitchell, 1997; Pilcher *et al.*, 1996; Pilcher *et al.*, 1995; Pilcher and Hall, 1992), where deposits of microscopic tephra in peat bogs are studied, is used to date, or corroborate existing dates of, volcanic eruptions. Secondly, concentrations of carbon in trees have been examined in an effort to show that growth anomalies in the wake of the eruptions of Laki in Iceland in 1783 and

Tambora in Indonesia in 1815 may not necessarily be linked to downturns in climate. While surface temperatures may have been marginally cooler after these eruptions, plants are extremely sensitive to decreases in sunlight below optimal conditions, thus the increased scattering of light as a result of large concentrations of volcanic aerosols in the atmosphere manifesting itself in changes in stable carbon isotopes (Ogle *et al.,* 2005). The veil of ejecta hindered optimal photosynthetic operations, which brought about an increase in CO_2 in the cells of the trees and in turn affected growth.

A further approach was one taken by Oppenheimer (2003) where first-hand accounts of hardships suffered in Ireland (failed harvests, bleak weather and fever epidemics) in the wake of the eruption of Tambora in Indonesia in 1815 were collated. Meanwhile, a study by Wilson (1999) examined sunspot observation days in Dessau, Germany and compared the data with annual mean temperatures from the Armagh Observatory record as well as frequency and location of large-scale volcanic eruptions during the period 1818-1858. Although concentrating on yearly mean temperatures, Wilson (1999) found stronger correlations between large cataclysmic volcanic eruptions and reduced temperatures in the following year than any correlations between El Niño events and reduced temperatures in the following year.

2.6 USING TREE-RINGS TO ASSESS CHANGES IN CLIMATE

Tree-rings provide strong biological evidence for time scales of past environmental and climatic changes (Fritts, 1976). In temperate climates, trees grow a distinct annual ring each year. The width of the ring is a measure of how well the tree is growing – in a good year the tree will produce a wide ring and in a poor year it will produce a narrow ring. Because the trees in a specific area are subjected to similar climatic conditions, the patterns of wide and narrow rings should be similar in all the trees (Schweingruber, 1989).

Variations in tree-ring widths from one year to the next have been seen as a valuable source of chronological and climatological information for over 200 years in Europe where narrow tree-rings dating from the severe winter of 1708-

1709 were examined (see Bradley, 1999). However, Douglass (1919) is believed to be the first to fully realise the potential benefits of tree-ring analysis when he extended the rainfall record of the arid southwestern United States in the early 20th Century. Over time dendrochronology became the most accepted method of dating archaeological ruins in southwestern United States and the method eventually spread throughout the temperate world, with Huber being credited with introducing the technique to Europe (Eckstein and Pilcher, 1990). Pilcher (1996) points out that the relationship between ring widths and climate in the more temperate European climates was quickly recognised to be more complicated than in the United States. This was overcome by the development of different laboratory techniques whereby more accurate analysis was allowed through the use of oak (*Quercus*) chronologies rather than the traditional United States species of conifers (Coniferae). Dendrochronological studies were first undertaken in Ireland and Germany, with the majority of other countries on the continent eventually adopting the method. In Europe, work tended to focus on archaeological dating (dendrochronology) or climate reconstruction (dendroclimatology) (Pilcher, 1996). Since then, chronologies have been extended to over 26,000 years in length (see Reimer *et al.*, 2004) and have focused on areas as small as demesnes (see O'Sullivan and Kelly, 2006; Moir, 1999) to as large as continents and hemispheres (Moberg *et al.*, 2005; Briffa *et al.*, 2002; Jacoby and D'Arrigo, 1989).

The use of proxy data plays a significant role in the characterisation and assessment of climate variations prior to accurate instrumental records. Some reconstructions of climatic variability have employed a combination of tree-ring chronologies and other proxies (Mann *et al.*, 1999; Esper *et al.*, 2005) or specific selections of tree-ring chronologies developed in order to preserve long-term climate variability (Jacoby and D'Arrigo, 1989; Briffa, 2000). In addition to such large-scale approaches, more detailed studies of regional variations are needed to obtain insight into regionally-specific changes and driving factors (Frank and Esper, 2005). This has resulted in the examination of different tree species in an effort to determine their dendroclimatic potential, while also expanding the geographical range of tree-ring chronologies. The identification of species that can be relied upon as proxies for the reconstruction of past climates in various parts of the world is facilitating a better understanding of the diverse nature of climate, while also giving an insight into how various external forces influence weather and tree growth on a local scale.

2.6.1 The influence of volcanic eruptions on tree-ring widths

As previous sections have indicated, large-scale volcanic eruptions can have significant impacts upon climate variability. These climatological impacts can often be reflected in annual tree-ring records, above all in the more temperature-sensitive species. A reduction in temperatures of between 0.2°C and 0.5°C in the years following volcanic events (Self *et al.*, 1981) can restrict the productivity of tree-species, particularly when the temperature changes are prevalent during the growing season (Briffa *et al.*, 1998). Because precipitation is also necessary for the growth of trees, a potential post-volcanic eruption reduction in rainfall (Robock and Liu, 1994; Church *et al.*, 2005) could also negatively impact various species. However, notable changes in temperature or precipitation may not necessarily be required for tree-rings to be adversely affected in the wake of volcanic eruptions. Salzer and Hughes (2007) point out that the reduced atmospheric transparency brought about by the increased concentrations of volcanic aerosols can have a negative influence upon photosynthesis.

Villalba and Boninsegna (1989) explored the relationship between 50 tree-ring chronologies sourced in South America and ten major volcanic eruptions between 1780 and 1970. They found that the magnitude, duration, and geographical extent of the volcanically-induced tree-ring decrease in the chronologies are related to the eruption type and to the hemispheric debris distribution. However, Briffa *et al.* (1998) point out that the extent to which the strength of influence of volcano-induced temperature variability can be tested prior to the 20th Century is limited by the poor availability of volcanic and climate histories. In order to be entirely confident in results, it is necessary for volcanic and climate histories to be accurately dated. Nonetheless, Briffa *et al.* (1998) examine the evidence for volcanic forcing of Northern Hemisphere summer temperatures by comparing the mean data from a 383-site Northern

Hemisphere multi-species tree-ring chronology with indicators of large-scale volcanic activity (Dust Veil Index, Volcanic Explosivity Index and Ice-core Volcanic Index) and with the historical record of large eruptions over the past 600 years. Although Briffa *et al.* (1998) do not assume that the tree-ring data represents surface temperature flawlessly, or that all low-density values are forced by volcanic eruptions, they do believe that their results provide a thorough basis for examining the nature of volcano/temperature links over recent centuries. Besides large individual eruptions, the results show how multiple eruptions within a short time period can reduce hemisphere temperatures on decadal and multi-decadal timescales, thereby corroborating Zielinski's (2000) and Robock's (1979) theories that multiple eruptions in a short space of time are likely to have a longer-lasting impact upon climate.

Salzer and Hughes (2007) used a 5,000-year-long record to establish an association between narrow tree-rings in bristlecone pines (*Pinus longaeva* and *Pinus aristata*) from the western United States and large explosive volcanic eruptions that have been recorded in the historical volcano record and in polar ice cores. The association suggests that these eruptions produced mid-latitude summer cooling with potential effects across the Northern Hemisphere or indeed the globe. Numerous other papers have examined how post-volcanic eruption temperature changes have had an impact upon tree-ring widths: Gervais and MacDonald (2001) examined the summer temperature response of Scots pine (*Pinus sylvestris*) on the Kola Peninsula, Russia, indicating that not all volcanic eruptions result in reduced tree growth and that not all severe ring-width or temperature change is linked to volcanic activity. However, they did show that volcanism plays an important role in modulating tree-ring growth and temperature variability in the area. Grudd *et al.* (2000) used a Swedish tree-ring chronology that showed a period of severe cooling over four years around 1628 B.C. to corroborate evidence from Baillie and Munro (1988) and Kuniholm *et al.* (1996) for a volcanic eruption at that time, most likely Santorini, Greece. Hantemirov *et al.* (2004) postulated that 11 anomalously cold summers in a 1,250-year-long tree-ring series from northwest Siberia were caused by the climatic impact of volcanic eruptions.

2.6.2 Irish tree-ring studies

Quercus (oak) species are the prevailing facilitators of dendrochronological and dendroclimatological studies in Ireland because they have been dominant over large areas of Irish lowlands for the last 8,000 years (Gardiner, 1974). One of the more widespread *Quercus* species in Ireland, *Q. petraea* (Sessile oak), prefers more acidic soils that are well drained and shows a corresponding intolerance of flooding, which influences their positioning on upper slopes and hill tops. Meanwhile, *Q. robur* (English oak) has a tendency to develop on basic soils rich in nutrients, which is linked to a preference for moist clays combined with a tolerance of water logging and even flooding (Gardiner, 1974).

Precision dating through the use of tree-rings is one of the main areas within which volcanoes and Ireland are simultaneously studied. The 7,000+ year-long *Quercus*-tree-ring chronology from Northern Ireland has been used, similarly to the tephrochronological analysis in Ireland, to corroborate dates for eruptions such as that of Santorini, in the Aegean Sea (1628-1626 B.C.) (Baillie and Munro, 1988). Baillie (1990) used data from the same time period to put forward the theory that the narrowed rings in the 1620s B.C. were as a result of an eruption of Thera, again in the Aegean Sea. Moving away from the focus on volcanoes, Irish tree-ring/climate analysis in general has tended to focus on *Quercus*-based data. Pilcher and Baillie (1980) used six Irish *Quercus* chronologies to examine the climate responses of the species, while García-Suárez *et al.* (2009) use *Fagus sylvatica* (beech), *Fraxinus excelsior* (ash), *Pinus sylvestris* (Scots pine) and both *Quercus robur* (English oak) and *Quercus petraea* (Sessile oak) to reconstruct temperature, rainfall, sunshine hours and Palmer Drought Severity Index values in Northern Ireland.

Pilcher and Baillie (1980) pointed out that dendroclimatological studies in Ireland and Britain were of little merit as the *Quercus* species they examined were less sensitive to changes in climate than those that lived closer to their latitudinal limit. This dissertation will focus on yew (*T. baccata*) in order to test whether this particular species could be used as a viable alternative to the traditional *Quercus* genus. In addition to examining post-volcanic eruption ring-width disparities, the study will also explore the feasibility of using *T. baccata* to reconstruct temperature and precipitation for the length of the series and will go on to investigate the changes in these climatic elements that occurred in the years following volcanic eruptions. Consequently, this study is the first to systematically investigate the relationship between volcanic eruptions and tree-rings in Ireland, while also being the first to explore *T. baccata* as an alternative to *Quercus* in Ireland.

2.7 YEW (*TAXUS BACCATA*)

As a *T. baccata* record is central to the study, the remainder of this section will examine the various characteristics of the species and its role in dendroclimatic reconstructions. *T. baccata* is a western Atlantic species, characteristic of Irish and British rather than continental woods (Ratcliffe, 1977). However, it has a wide range throughout Europe (Jalas and Suominen, 1973), extending northwards to Norway and Sweden (*c*. 63ºN) (Vidaković, 1991), eastwards to Estonia, Poland and Turkey, and southwards to Greece (Voliotis, 1986), northern Spain (Peñalba, 1994), Portugal and into Algeria (Vidaković, 1991). A common feature in each of these areas is that climatic extremes in both winter and summer are not exceptional. In the south of its European range *T. baccata* is largely a montane tree, whereas it grows from sea level to 425 m in England and Wales and up to 470 m on Purple Mountain in Co. Kerry (Moir, 1999).

T. baccata is well suited to a mild oceanic climate and avoids areas susceptible to severe winter frosts (Godwin, 1975). The species generally prefers humid soil, but also grows where ground water levels are low. Any soil moisture shortage is offset by the high humidity of the air, or water from heavy rainfall – both features of mild oceanic climate (Moir, 1999). In Ireland and Britain, stands of *T. baccata* are generally associated with limestone slopes carrying shallow dry rendzinas (Rodwell, 1991). They also grow equally well on thin, warm chalk soils, limestone pavements and fen peats (Williamson, 1978). In Ireland, *T. baccata* occurs in several habitat types, on both sandstone and limestone bedrocks, but *T. baccata*-dominated communities are restricted to limestone pavement areas (Perrin, 2002).

T. baccata is known to be slow-growing, slow to reach maturity (*c.* 70 years), and long-lived (>1000 years) (Thomas and Polwart, 2003). Tittensor (1980), working in the South Downs, Sussex, England, found that twice as many recent as ancient woodlands contained *T. baccata*, and that the regeneration was more common in these recent woods. The ancient woodlands containing the species had few examples at canopy level and none with it as the dominant species. Combining this with the estimated young age of woodland *T. baccata,* Tittensor (1980) and others (e.g. Williamson, 1978) theorise that South Downs *T. baccata* woods are primarily the result of the abandonment of land during the last 200 years following the Napoleonic wars in the early 1800s and agricultural neglect in the 1920s. Similar expansion in Irish *T. baccata* woodlands has been seen following a cessation in grazing and human disturbance (Mitchell, 1988; Watts, 1984), although some areas, such as Reenadinna Wood in Killarney – the area under examination for the purpose of this thesis – are estimated to have developed 3,000-5,000 years ago (Mitchell, 1990).

2.7.1 Influence of weather and climate on *T. baccata*

T. baccata is tolerant of drought, with Brzeziecki and Kienast (1994) ranking the species at 2 in a 1-5 scale where 1 is very tolerant of drought. The effects of drought are seen as needles older than 2 years turning yellow from their base upwards before falling (Strouts and Winter, 1994). Watt (1926) put forward the idea that wind is important in determining the distribution of *T. baccata* in the South Downs in England, as indicated by the wind-shaping, the general limitation of the *T. baccata* woods to the valleys and from the greater and more rapid extension along sheltered slopes and to the leeward side of existing communities. *T. baccata* is intolerant of severe and prolonged frost (Skorupski and Luxton, 1998) and icy winds (Bugala, 1978). Maximum tolerance to frost occurs in mid-winter (January), declining rapidly in early spring (Brzeziecki and Kienast, 1994) when tissue is vulnerable to severe frost conditions. In Britain, Melzack and Watts (1982) found that in mid-winter damage started at -13.4ºC whereas by March this had risen to -9.6ºC in the hardiest area (south England) and -1.9ºC in the most susceptible area (northeast England). Sensitivity to frosts in early spring is understandably the crucial limiting factor in the northerly oceanic distribution in Europe of this species.

Publications examining *T. baccata* in terms of dendroclimatology are rare. An investigation into the species' potential was undertaken by Moir (1999). Here, 14 *T. baccata* trees in Hampton Court Palace in London were sampled. It was noted that February-July precipitation had a positive effect on growth, while January-February and October temperatures also influenced ring-width (specific correlation coefficients were not reported). The only coefficient in Moir's (1999) paper referred to *T. baccata*'s correlation with soil-moisture deficit (R: -0.549, P: not reported). Although a relationship between the species and climate was identified, no reconstruction of any elements was undertaken. Yadav and Singh (2002) sampled 18 *T. baccata* trees in the western Himalaya, where the 345-year-long chronology achieved its strongest correlations with mean March-June temperatures (R: -0.310 P: not significant) for the period 1898-1998. Both Yadav and Singh's (2002) and Moir's (1999) studies showed significant inter-species correlations, indicating that *T. baccata* could become an important constituent in multi-site and multi-species studies, a requirement for more successful reconstructions of past climates, particularly in areas where no single aspect of climate leads to wide or narrow tree-rings (Pilcher, 1994). This study contains the first statistically rigorous *T. baccata* reconstruction for Ireland and shows the benefit of employing the species in dendroclimatic research, particularly in Ireland.

2.7.2 Difficulties associated with using *T. baccata* in dendrochronology

While modern *T. baccata* is demonstrated to be suitable for use in dendrochronology, the need to measure a number of different radii from samples indicates that analysis from incrementally cored samples may prove inaccurate (Moir, 1999). This is because *T. baccata* is renowned for missing, or very narrow and thus easily missed rings (Thomas and Polwart, 2003). There are other pitfalls in estimating age, including, as with other tree species, old senescent trees can produce new stems from the remains of the former large trunk and appear as young trees. Grazing may also keep a tree artificially small. *T. baccata* is also known for the apparent production of large trees from the fusing of several trunks. Lowe (1897) and Williamson (1978) give examples of trunks with two or more centres surrounded by their own concentric growth. Lowe (1897) argued that the fusing of multiple stems/roots would make an individual appear older than it actually is. However, overall growth rate of the new trunk when young is unlikely to be much greater than a single tree of the same size (Thomas and Polwart, 2003). Tabbush and White (1996) argue, using rough calculations, that the coalescing of seedlings would actually make little difference to age estimates. As long as the original circle of trees was not more than 1 m in diameter, the error in subsequent age determination of the resulting 'tree' would be minor.

Difficulties in obtaining data from *T. baccata* have undoubtedly influenced the fact that only two chronology series are available from the International Tree-ring Data Bank. The chronology compiled by Bernabei and Gjerdrum (2006) was formed from 17 cores, the oldest being from 1896. This series from the Italian Alps has not been employed in any published research. The second *T. baccata* chronology, created by Kuniholm *et al.* (2006), was formed from 19 cores in Georgia and has since been utilised to cross-date other tree-ring species in the area for archaeological purposes. The start-year for this series is 1526.

The potential difficulties involved in using *T. baccata* can be overcome by selecting appropriate trees to sample, that is, those with definite single trunks. In addition, the extraction of two cores per tree greatly decreases the likelihood of missing rings. Careful cross-dating of cores will allow accurate dates to be recorded, a process that is made easier by the fact that *T. baccata* lays-down clearer rings in comparison to *Quercus* species. The long-lived nature of *T. baccata* makes it suitable for climate reconstructions, while the hardness of the wood increases the preservation potential of trees.

2.8 RESEARCH HYPOTHESES

Globally, much research relating to volcano/climate activity has focused solely on the impact of exceptional events such as the eruption of Tambora in 1815 (see Oppenheimer, 2003; Harrington, 1992), or Laki in 1783 (see Brázdil *et al.*, 2003;

Stothers, 1996). In addition, there is a tendency to examine either the global or hemispheric consequences of such events. Písek and Brázdil (2006) point out that there needs to be more attention paid to the climatic effects of large volcanic eruptions on a local scale. The general aim of this study is to assess the impact of large-scale volcanic eruptions on weather patterns and ecology in Ireland since 1800.

2.8.1 Temperatures in Ireland are altered in the months and years following volcanic eruptions, including a warmer first winter and cooler first summer after events.

Rampino *et al.* (1988), Robock (2000) and de Silva (2005) point out that the residence time for particulate matter in the atmosphere following a large-scale volcanic eruption is one to two years, something that has the potential to lower global temperatures by between 0.2^{o}C and 0.5^{o}C (Self *et al.*, 1981). The weather data of Armagh Observatory provide one of the longest and most reliable records of climate variability in Europe. Butler *et al.* (2005) calibrated and corrected air temperature records from 1796 to 2002 for any errors due to time of reading and exposure. This dataset will be analysed in three ways; firstly the 24 months following each eruption will be examined to allow the identification of a specific time-span within which temperatures are likely to be influenced. Secondly the changes in seasonal temperatures in the year of and two years following the eruptions will be assessed in order to test the theories that summer months experience cooling following large-scale volcanic eruptions (Briffa *et al*., 1998) and that winters tend to be warmer (Robock and Mao, 1992). Thirdly, correlations will be run between monthly temperatures in Armagh and Lamb's (1970) Dust Veil Index (DVI), which is one of the most representative modes of analysis of past large-scale volcanic activity (Briffa *et al.*, 1998). This will highlight whether or not the levels of particulate matter in the atmosphere can have an influence on temperatures in Armagh.

2.8.2 Volcanic matter in the atmosphere will hamper evaporation and cause reductions in precipitation levels.

Church *et al.* (2005) showed that large volcanic eruptions bring about rapid reductions in ocean heat content and global mean sea level, with the latter falling by as much as 5 mm following the eruption of Mt. Pinatubo in 1991. Volcanic aerosols in the stratosphere act to scatter incoming solar radiation, bringing about a cooling in the atmosphere and, as a consequence, a reduction in rainfall (Church *et al.*, 2005). Butler *et al.* (1998) presented standardised and corrected precipitation data for Armagh Observatory for the years 1838-1997. The precipitation data will be used in an effort to identify any particular month(s) or season(s) where precipitation levels in Armagh fall significantly following volcanic eruptions, while any change in the number of days per month within which no rain was recorded will also be compiled and examined.

2.8.3 Northeasterly, easterly, southwesterly and westerly wind directions will experience an increase in frequency in the months following volcanic eruptions.

Dawson *et al.* (1997), Kelly *et al.* (1996), Groisman (1992) and Hunt (1977) noted that, in the months following major volcanic eruptions, the Northern Hemisphere's low-latitudes experience an increased frequency of westerly winds. Dawson *et al.* (1997) also point out that, in the months following the eruption of Tambora in 1815, Edinburgh's westerly and southwesterly winds were preceded by a significant number of northeasterly and easterly airstreams. The readings from Armagh Observatory include records of the predominant wind direction for each day. This study will examine the wind regimes for Armagh in the months of, and six months following, each volcanic eruption in order to quantify what changes occurred in the wake of these events.

2.8.4 *Quercus* tree-ring widths from throughout Ireland will provide a record of post-volcanic eruption climatic downturns.

The impact of volcanic eruptions has been identified in tree-ring indices throughout the world, particularly in more temperature-sensitive species (Jones *et al.*, 1995). Drops in temperature in the summers following large-scale events are often put forward as the driving force behind particularly narrow tree-rings (Gervais and MacDonald, 2001). Ogle *et al.*'s (2005) analysis of stable carbon isotopes shows that *Quercus* growth in Co. Antrim was adversely affected in the years after the eruptions of Laki, Iceland, in 1783 and Tambora in 1815, despite temperature records remaining constant in the years analysed. The particulate matter in the atmosphere that originates from volcanic eruptions may not manifest itself through temperature change in Ireland but, as Salzer and Hughes (2007) point out, the reduced atmospheric transparency brought about by volcanic aerosols can have a negative influence upon photosynthesis.

This study will assess the impact 11 volcanic eruptions have had on *Quercus* tree-ring growth in 13 sites throughout Ireland since 1800. The results given will be formed by examining the differences that occurred in the growth indices of the year immediately before each eruption, the year of eruption, and the two years after the event. Changes in tree-ring width will also be examined in conjunction with Dust Veil Index variations over the ~200 years in question.

2.8.5 *T. baccata* is a viable study alternative to the traditional *Quercus* species when reconstructing past environments as well as post-volcanic eruption climatic downturns in Ireland.

In Ireland, dendrochronology and dendroclimatology have been dominated by the analysis of *Quercus* species (Pilcher and Hall, 1992; Baillie, 1990; Baillie and Munro, 1988; Pilcher and Baillie, 1980), with only a recent study (García-Suárez *et al.*, 2009) adopting a multi-species approach whereby *Fagus sylvatica* (beech), *Fraxinus excelsior* (ash), *Pinus sylvestris* (Scots pine) and both *Quercus robur* (English oak) and *Quercus petraea* (Sessile oak) were examined. This thesis will use *T. baccata* ring-width series from Killarney, Co. Kerry to assess the impact volcanic eruptions have had on growth and will compare any changes with those that occur in the Killarney-based *Quercus* series from the previous section. The study will also investigate the possibility of employing *T. baccata* indices in the reconstruction of temperature and precipitation as an alternative to the traditional *Quercus*-based reconstructions.

CHAPTER 3: METHODOLOGY

In order to study the impacts of past volcanic events on Irish climate, two distinct lines of inquiry were used: weather data from Armagh Observatory and Irish tree-ring records. Meteorological data have been recorded daily at Armagh Observatory since July 1795, with reliable temperature records beginning in January 1796 (Butler *et al.*, 2005). The recording of daily wind direction data also commenced on this date, while the precipitation record began in January 1838. *Quercus* series from throughout Ireland are available from the International Tree-ring Data Bank. In addition, a ~200-year-long *T. baccata* chronology was constructed to assess the response of this species to past volcano-induced changes in climate. The impact of volcanic eruptions should be identifiable in tree-ring indices, particularly in more temperature-sensitive species (Jones *et al.*, 1995).

3.1 STUDY SITES

This study employs data from various sites throughout the island of Ireland, but the main two data points are in Armagh Observatory, Co. Armagh and Reenadinna Wood in Killarney, Co. Kerry (Figure 3.1). Armagh Observatory (54°21'N; 6°38'W) lies approximately 1 km northeast of Armagh city centre. It is situated 64 m above mean sea level in an estate of natural woodland and parkland. The observatory is largely surrounded by countryside similar to that which has existed since its foundation in 1790 (Butler *et al.*, 2005). The surrounding rural environment has ensured that the observatory suffers from little or no urban micro-climatic effects (Coughlin and Butler, 1998). In addition, any urban climatic effects that did exist would be expected to be minimised as a result of the fact that the site is relatively exposed to a reasonably windy climate (Butler *et al.*, 2005).

The geomorphology of the Killarney area is diverse, something that gives rise to a wide range of forest vegetation, with the most remarkable feature being the *Taxus baccata*-dominated limestone outcrops (Kelly, 1981). Reenadinna Wood (Figure 3.2) (50°01'N; 9°31'W), located on a carboniferous limestone outcrop on

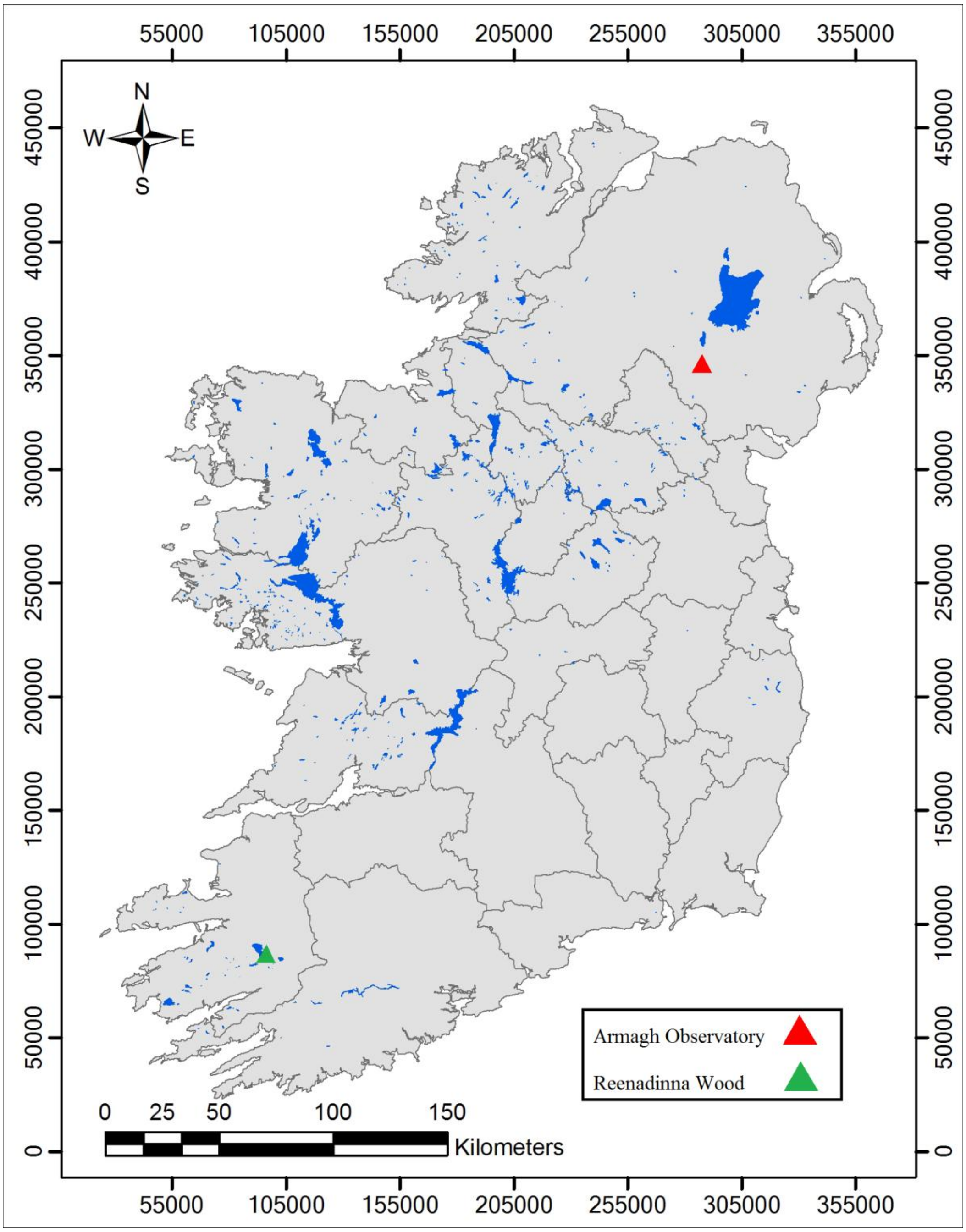


Figure 3.1: Study sites.

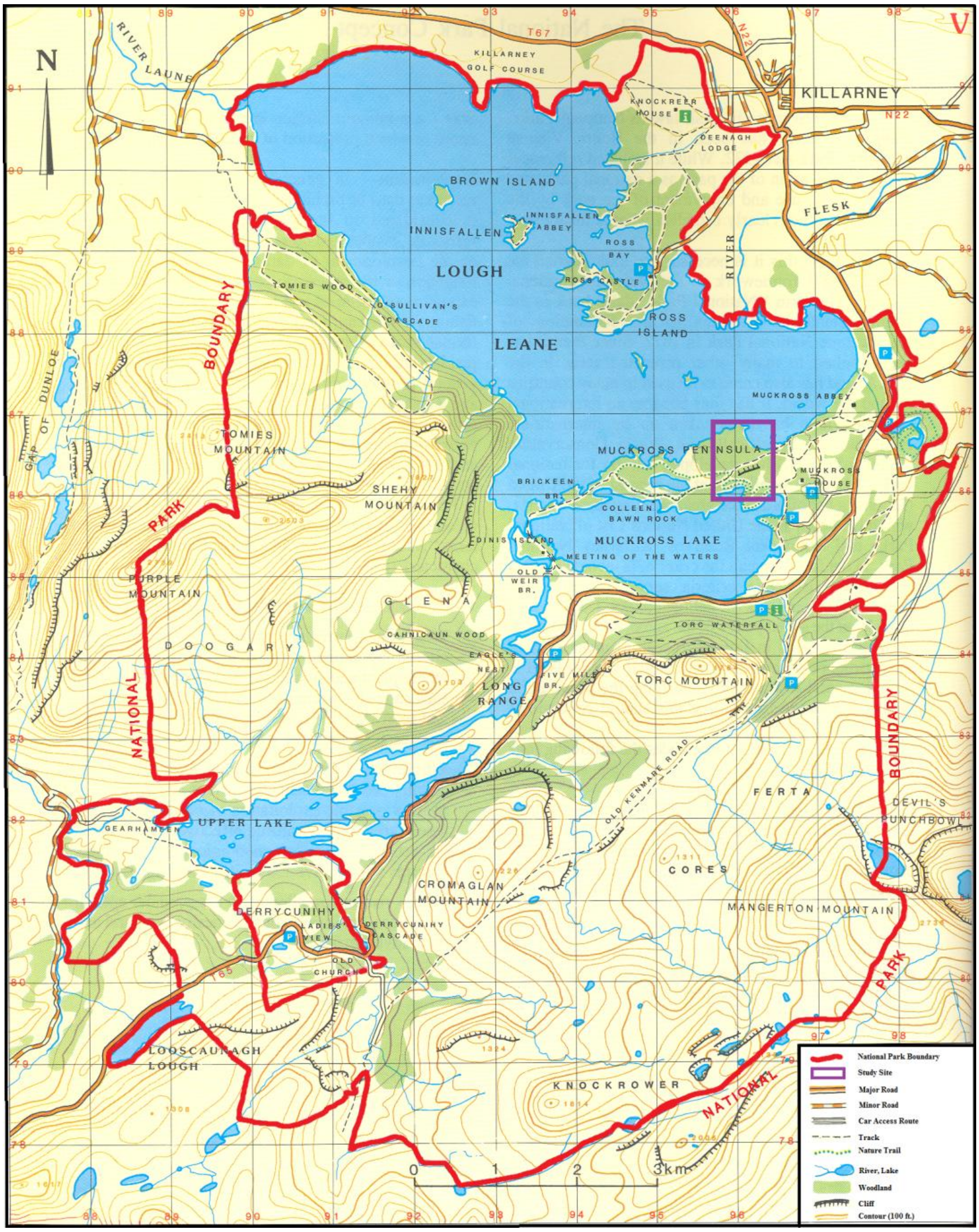


Figure 3.2: Killarney National Park and study site (Source: Office of Public Works, 1990).

Muckross Peninsula in Co. Kerry, lies approximately 4.5 km south-southwest of Killarney town. The site, part of Killarney National Park, a UNESCO Biosphere Reserve, is 20 m above sea level. It is bounded to the north by Lough Leane and by Muckross Lake to the south. The western limit of the wood lies along the geological boundary with Devonian Old Red Sandstone, while, to the east, the wood is bounded by parkland where the limestone ceases to outcrop. Mitchell (1990) showed that a significant community of *T. baccata* has existed in the area for up to 5,000 years.

Reenadinna Wood (approx. 25 ha in extent) is located on the Muckross Peninsula, Killarney, Co. Kerry and is the most extensive *T. baccata* woodland remaining in Ireland (Perrin, 2002). The shorter *T. baccata* trees on the more broken rocky terrain of the Killarney woodlands are intermingled with taller *Quercus* (mainly *Q. petraea* - Sessile oak) in the intervening soil-filled hollows. Little grows under the *T. baccata* canopy, although *Corylus avellana* (hazel) or *Ilex aquifolium* (holly) become frequent locally, with the former sometimes replacing *T. baccata* as the dominant species. The field layer is sparse, with the most common species being *Brachypodium sylvaticum* (false brome), *Fragaria vesca* (woodland strawberry), *Oxalis acetosella* (wood-sorrel), *Potentilla sterilis* (barren strawberry) and *Sanicula europaea* (wood sanicle). Unlike the *T. baccata* woodland of southern England, in Killarney there is a very dense moss cover, primarily *Thamnobryum alopecurum* (fox-tail feather-moss) and *Thuidium tamariscinum* (common tamarisk-moss) (Kelly, 1981). A general map of species distribution can be seen in Figure 3.3, while a more detailed description of the distribution and density of various species in and around Reenadinna Wood can be found in Perrin (2002).

T. baccata trees will generally grow to between 20 and 28 m in height (Thomas and Polwart, 2003). However, the stand in the Killarney woodlands has a lower canopy of between 6 and 14 m. Thomas and Polwart (2003) suggest that this is as a result of a high energy investment in defensive mechanisms which increase the resistance of wood against fungi and insect attacks. Despite its poisonous properties *T. baccata* is very susceptible to browsing and bark stripping by

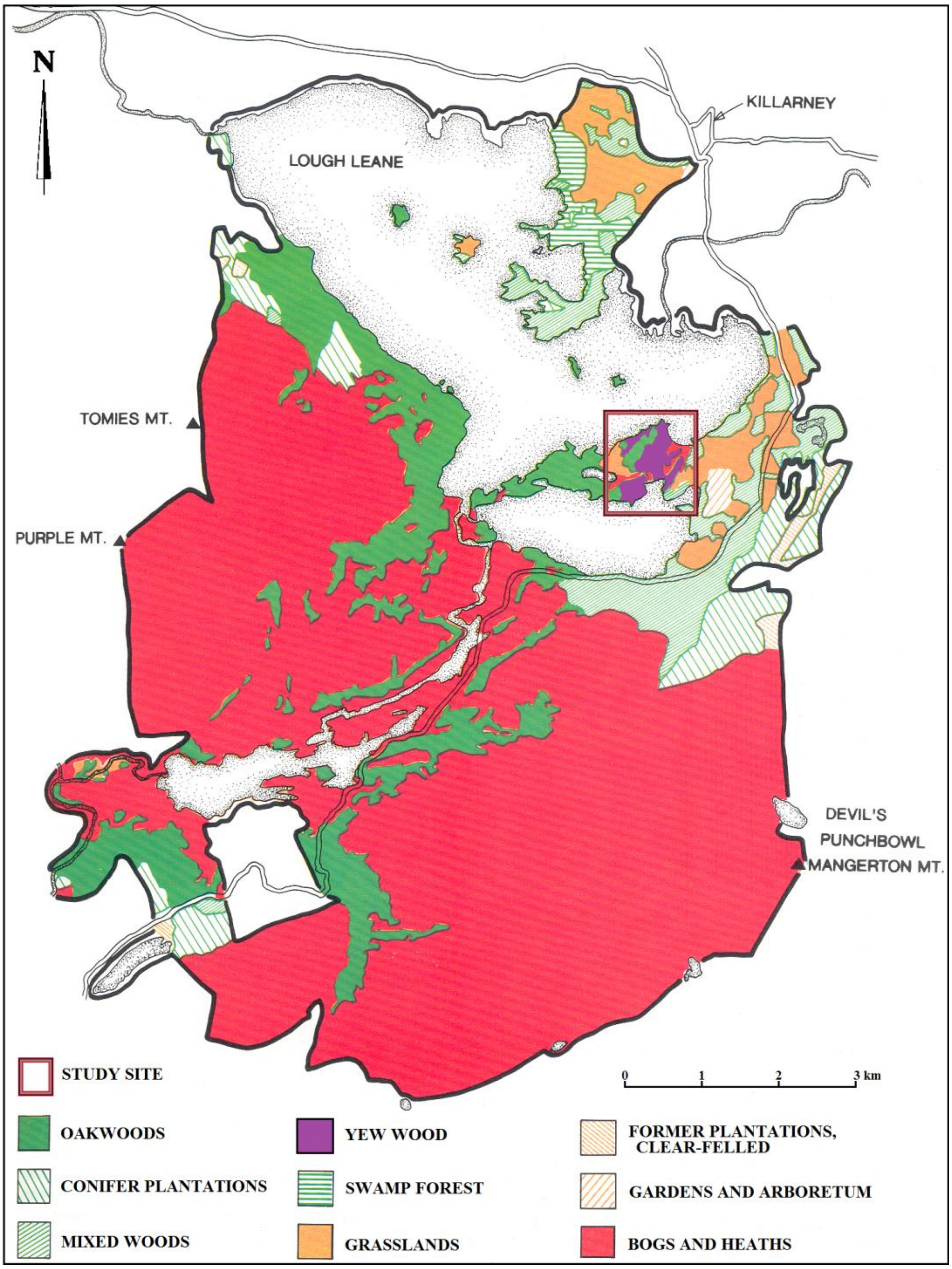
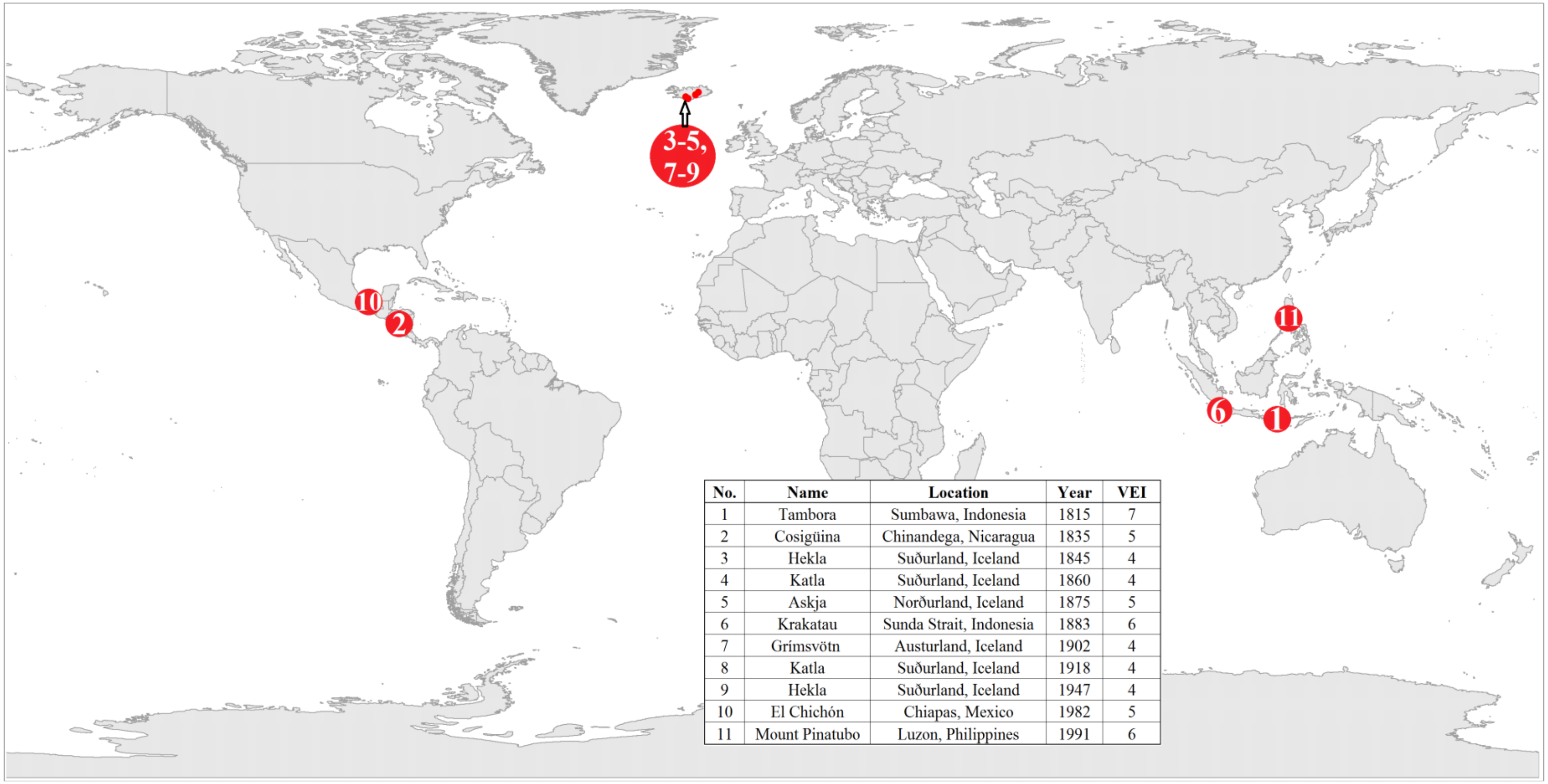


Figure 3.3: Species distribution in Killarney National Park, including study site (Source: Office of Public Works, 1990).

rabbits, hares, deer and domestic animals such as sheep and cattle (Watt, 1926; Kelly, 1981; Mitchell, 1998; Haeggström, 1990). Kelly (1975) elaborates upon this, describing *T. baccata* as one of the most grazing-sensitive species in the Killarney woodlands. However, the species is able to continue growth under severe browsing pressure (Tittensor, 1980), but it can be killed by being scoured by deer antlers, as was observed by Kelly (1975) in the Killarney woodlands. In response to this, part of Reenadinna Wood was enclosed in an effort to protect the species from browsing by deer (Perrin, 2002).

3.2 SELECTION OF RELEVANT VOLCANIC ERUPTIONS

Low-latitude volcanic eruptions that penetrate the stratosphere can have a notable impact on global climate due to the ease at which the volcanic particles are circulated in the atmosphere (Robock and Free, 1995). With the weather records from Armagh Observatory providing much of the data for this study, only low-latitude eruptions that occurred after the establishment of these records, that is January 1796, were chosen. Eruptions were narrowed-down further still when only those with a Volcanic Explosivity Index value of at least 5 (after Newhall and Self, 1982), combined with acknowledgement in literature as having an impact upon Northern Hemisphere climate, were chosen. For example, the VEI 5 eruption of Mount Agung in Bali in 1963 had a very small volume of ejecta. Four fifths of this was spread throughout the Southern Hemisphere which in turn failed to produce an effect in the Northern Hemisphere (Rampino *et al.*, 1988). Similar criteria were employed for the selection of the Icelandic eruptions. Here, eruptions since 1796, with a VEI of 4 or greater were selected (a lower VEI threshold was used here because of the proximity of Iceland to Ireland). All information regarding Volcanic Explosivity Index values was acquired from the Smithsonian Institution’s Global Volcanism Program (Siebert and Simkin, 2002). The locations of the relevant volcanoes can be seen in Figure 3.4.



No.	Name	Location	Year	VEI
1	Tambora	Sumbawa, Indonesia	1815	7
2	Cosigüina	Chinandega, Nicaragua	1835	5
3	Hekla	Suðurland, Iceland	1845	4
4	Katla	Suðurland, Iceland	1860	4
5	Askja	Norðurland, Iceland	1875	5
6	Krakatau	Sunda Strait, Indonesia	1883	6
7	Grímsvötn	Austurland, Iceland	1902	4
8	Katla	Suðurland, Iceland	1918	4
9	Hekla	Suðurland, Iceland	1947	4
10	El Chichón	Chiapas, Mexico	1982	5
11	Mount Pinatubo	Luzon, Philippines	1991	6

Figure 3.4: Name, location, year and Volcanic Explosivity Index of 11 chosen volcanic eruptions.

3.3 ARMAGH OBSERVATORY

3.3.1 Temperature recordings in Armagh Observatory

Initially temperature readings in Armagh Observatory were taken three times a day, in the morning, at noon (or sometimes 2 pm) and the evening. They were recorded both outside and inside the building with a standard thermometer. A gap in the recordings occurred from June 1st 1825 to January 1st 1833. However, Butler *et al.* (2005) used calibrated data from Dunsink Observatory near Dublin to fill this gap. For the purposes of this study, Butler *et al.*'s (2005) mean daily temperatures from Armagh Observatory for the years 1796-2007 were used to identify uncharacteristic changes in the months/seasons following volcanic eruptions.

With the 24 months following a volcanic eruption being the most important in terms of temperature change (Rampino *et al.*, 1988), the difference between individual mean monthly temperatures for 25 months (the month of the eruption and the two years following the event) and the 11-year mean monthly values centred on the eruption year was produced. The 11-year mean monthly values were formed using a symmetrical low-pass filter which acts to reduce any short-period fluctuations. Yet the low-pass nature of the analysis allows low-frequency variations (for example, long-term increases in temperature) to pass through the filter. The reverse of this method was employed by Rey *et al.* (2007) and Vaneckova *et al.* (2010) in order to identify particularly warm mean daily summer temperatures in Sydney. For the Armagh Observatory data, an 11-year mean, as opposed to a 30-year mean, was employed as the longer mean would fail to include a sufficient amount of data for the eruptions of Tambora in 1815 and Mount Pinatubo in 1991 since these occurred too close to the start and end of the dataset.

The difference, in degrees Celsius, between the individual monthly means and the 11-year monthly mean in Armagh was analysed in the context of each individual eruption, while mean values were formed in terms of five categories of eruption, namely all 11 eruptions, VEI 5-7 events, low-latitude eruptions, VEI 4 Icelandic events and all Icelandic events combined. These categories are created by amalgamating all possible combinations of volcano location and explosivity. This grouping together of events highlights the varying impacts that occur following larger or low-latitude eruptions and smaller events that took place closer to the sample site (that is, in Iceland), a process similar to that of Mitchell (1961) who used averaged results to single out volcanic signals from other fluctuations such as solar variability and carbon dioxide concentrations. For the remainder of the study, “VEI 4 events” refers to the five Icelandic VEI 4 eruptions selected, while “Icelandic events” refers to the combination of the five VEI 4 eruptions with the single VEI 5 Icelandic event.

Briffa *et al.* (1998) put forward the theory that the most intense period of cooling following volcanic eruptions occurs in the first summer after the event. In an effort to examine this in terms of the data from Armagh Observatory, the difference between the mean summer temperature for the year of an eruption (TY) as well as the two years that followed (TY+1 and TY+2) and the 11-year mean centred on the eruption year was calculated. Examining the events individually, as well as in terms of the five categories of volcanic eruption previously mentioned, allowed the identification of which summer in Armagh, if any, is likely to experience a downturn in temperatures. A similar theory of predicted change in post-volcanic eruption temperatures was proposed by Robock and Mao (1992). They presented the idea that an increase in concentrations of particulate matter and aerosols in the atmosphere acts to increase temperatures in the winter period following eruptions. Again, deviations from the 11-year mean centred on the eruption year for TY, TY+1 and TY+2 as used above highlighted when/if any increase in winter temperatures can be expected. To ensure complete seasonal coverage, the same method of analysis was also applied to mean spring and autumn temperatures in Armagh Observatory.

The next step in examining potential post-volcanic eruption temperature change in Armagh was to calculate Pearson correlation coefficients for mean seasonal temperatures and Lamb’s (1970) yearly Dust Veil Index and DVI lagged to one year. The resulting correlation coefficients were used to identify particular seasons where mean temperatures correlated well with fluctuations in DVI values. In theory, an increase in Dust Veil Index values should lead to a decrease in summer temperatures (Briffa *et al.*, 1998), producing a negative correlation coefficient. The opposite is true for winter temperatures, where values are expected to increase (Robock and Mao, 1992) in tandem with DVI. In order to ensure complete investigation into possible links between DVI and seasonal temperatures, spring and autumn values were also correlated with the index. Taking this DVI/temperature analysis a step further, correlations were run based on non-overlapping five-year averages – an effort to reduce the effect of delayed spatial responses and slight dating uncertainties (Briffa *et al.*, 1998) – between the mean temperature values for each of the four seasons and DVI values.

Both of these methods of analysis were also employed in examining Pearson correlations between seasonal temperature values in Armagh Observatory and Jones *et al.*'s (1997) extended North Atlantic Oscillation (NAO) index, as well as Hurrell's (1995) principal component (PC) winter (December-March) NAO index. Jones *et al*.'s (1997) index is a reconstruction that includes each month of the year from 1825 onwards, thus providing the longest possible record of NAO. Hurrell's (1995) PC index, as opposed to the usual station index values, is utilised as it presents the optimal representation of spatial patterns associated with NAO, particularly in the northern Atlantic area (Hurrell, 1995). This recorded index runs from 1899 onwards. It would be expected to see positive correlation coefficients between these two indices and temperature as lower NAO values generally lead to colder conditions prevailing while a high NAO index tends to correspond with warmer temperatures (Otterson *et al.*, 2001).

3.3.2 Precipitation recordings in Armagh Observatory

Daily rainfall measurements in Armagh Observatory have been measured at 9 am each morning and the amount registered entered to the previous day. For this study, total monthly precipitation in Armagh for the years 1838-2001 (García-Suárez *et al.*, 2005) was analysed in a similar fashion to the temperature data; a symmetrical low-pass filter of an 11-year mean centred on the eruption year was used to produce a mean precipitation value for each month. The difference (in percent) between individual monthly precipitation values for 24 months after eruptions was then compared to results from the 11-year mean – a method also employed by Shukla and Paolino (1983) in their analysis of summer rainfall in India. Because the precipitation dataset does not begin until 1838, there is no information available relating to the eruptions of Tambora in 1815 and Cosigüina in 1835. Nonetheless, mean precipitation values were formed in terms of the same five categories of eruption examined as regards temperature (all nine eruptions, VEI 5 and 6 events, low-latitude eruptions, Icelandic VEI 4 events and all Icelandic events combined) in order to single out the volcanic signal from other fluctuations (Mitchell, 1961).

Daily rainfall amounts (García-Suárez *et al.*, 2005) for the 24 months following volcanic events were examined whereby the number of days per month where zero precipitation was recorded in Armagh were also counted. Again, a symmetrical low-pass filter of an 11-year mean centred on the eruption year was used to produce a mean value for each month, which in turn was compared to the actual number of days per month within which no precipitation fell, while the mean results in terms of five categories of volcano were also analysed.

In an effort to investigate whether or not any particular seasons are likely to see notable changes in rainfall levels, the change in total seasonal precipitation for TY, TY+1 and TY+2 was compared to the 11-year mean centred on the eruption year, thus highlighting any atypically dry or wet periods. In addition to this, and similar to the analysis of seasonal temperature, Pearson correlations were run between total seasonal precipitation levels in Armagh Observatory and Lamb’s (1970) Dust Veil Index values, as well as Jones *et al.*’s (1997) North Atlantic Oscillation index and Hurrell’s (1995) PC based winter NAO index. With Robock and Liu (1994) pointing out that precipitation will decrease following large-scale volcanic eruptions, DVI and rainfall should, in theory, produce negative correlations. In comparison, NAO and precipitation should reveal positive correlation coefficients as a higher index value will coincide with increased rainfall in northwestern Europe (Hurrell, 1995).

3.3.3 Wind direction recordings in Armagh Observatory

The original daily weather records from Armagh Observatory were examined for the years 1796-2000 and a note was made of each recorded wind direction. A count was then made of the number of days per month within which wind blew from each of the 16 main wind rose directions. A symmetrical low-pass filter of an 11-year mean centred on the eruption year was used to formulate a mean monthly value for each of the 16 directions. As was the case in the previous two sections, notable changes were highlighted by comparing the 11-year mean values to the recorded values for each individual month. A large degree of variability in wind direction can be expected for up to 100 days after volcanic eruptions (Hunt, 1977), with other studies showing that concentrations in certain wind directions is a feature for four to five months after events (Dawson *et al.*, 1997; Kelly *et al.*, 1996; Groisman, 1992). For this reason, the analysis of post-volcanic eruption wind direction in Armagh focused on the six months following each event, concentrating firstly on the directions put forward by previous studies as being the most important (northeasterly, easterly, southwesterly and westerly) and then on the remaining 12 directions. Again, in an effort to separate signals in terms of location and size of eruptions, the data is also presented for individual eruptions, as well as in terms of mean results for all 11 events, the VEI 5-7 events, low-latitude eruptions, Icelandic VEI 4 events and all Icelandic events combined. In addition to wind direction, an examination of gale day frequency in Armagh, similar to Dawson *et al.* (1997), was undertaken but failed to produce any notable results. This is likely to be because the weather observatory in Armagh is inland, where the speed of wind is reduced by friction created between it and rough terrain. Consequently, these results are not reported here.

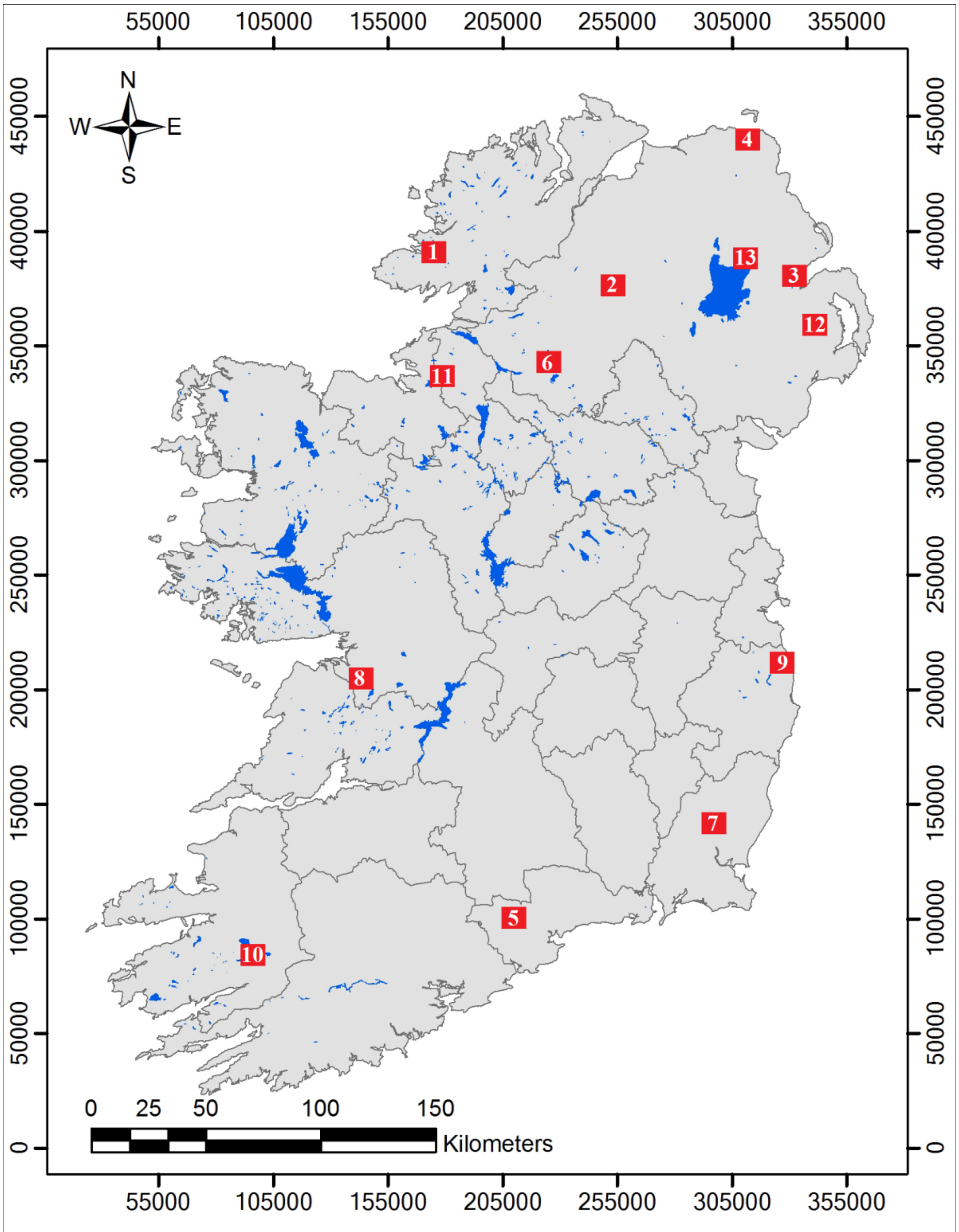
3.4 DENDROANALYSIS

This study's analysis of tree-ring indices began by examining the impact volcanic eruptions have had on 13 *Quercus* datasets from various locations on the island of Ireland. With the results in mind, it was decided to focus on another species, *Taxus baccata*, in order to examine whether or not this species reacts to potential post-volcanic eruption stress in the same way. In addition, local synoptic weather records allowed the reconstruction of temperature and precipitation data for the length of the *T. baccata* series.

3.4.1 Thirteen Irish *Quercus* series and the influence of volcanic eruptions

The International Tree-ring Data Bank, part of the National Climatic Data Centre, contains relevant tree-ring indices for 13 sites throughout the island of Ireland. All 13 series were sourced from *Quercus* species (*Q. petraea* x 12 and *Q. robur* x 1), with five coming from the southern half of the island and eight from the northern half (Figure 3.5). These indices had already been standardised using the same methodology as was employed in the standardisation of the *T. baccata* tree-ring chronology in this study (see following sections).

The majority of dendrological-based investigations into the effects of volcanic eruptions source their data from locations that are close to the latitudinal limit of the species selected (see Gervais and MacDonald, 2001; Briffa *et al.*, 1998; Villalba and Boninsegna, 1992; Lough and Fritts, 1987). The main benefit of this is that the reconstructions of temperatures from these tree-ring series are such that marginal changes in temperature values will be reflected in variations in ring-widths. This provides an ideal method of investigating the relationship between tree-growth and post-volcanic eruption climatic downturns as the reconstructed temperatures will closely follow those that prevailed in the years associated with eruptions. However, because the *Quercus* species examined in the course of this study are not close to their latitudinal limit, they are less responsive to small volcanically-induced changes in temperature. Yet combinations of volcano-related reduced temperatures, less precipitation and the presence of photosynthesis-reducing volcanic matter in the atmosphere still have the potential to be recorded in ring-widths. Consequently, it was necessary to examine variations in actual ring-widths in the aftermath of volcanic eruptions as the *Quercus* species in Ireland are unlikely to produce a high-resolution reconstruction of specific climatic phenomena (Pilcher and Baillie, 1980). A variation of the method employed by Kirchner *et al.* (1999) in their study of post Mount Pinatubo sea surface temperatures was used here to examine tree-ring indices. Kirchner *et al*.'s (1999) study simulated sea surface temperatures for the



No.	Location	Years Covered	Species	North/South
1	Ardara, Co. Donegal	1803-1978	*Q. petraea*	North
2	Barons Court, Co. Tyrone	1764-1989	*Q. petraea*	North
3	Belfast, Co. Antrim	1760-1972	*Q. petraea*	North
4	Breen Wood, Co. Antrim	1834-1988	*Q. petraea*	North
5	Cappoquin, Co. Waterford	1813-1978	*Q. petraea*	South
6	Castel Coole, Co. Fermanagh	1760-1984	*Q. petraea*	North
7	Enniscorthy, Co. Wexford	1811-1978	*Q. petraea*	South
8	Garryland Wood, Co. Galway	1841-1997	*Q. petraea*	South
9	Glen of the Downs, Co. Wicklow	1809-1978	*Q. robur*	South
10	Killarney, Co. Kerry	1809-1978	*Q. petraea*	South
11	Lough Doon, Co. Leitrim	1850-1978	*Q. petraea*	North
12	Saintfield House, Co. Down	1776-1990	*Q. petraea*	North
13	Shanes Castle, Co. Antrim	1760-1992	*Q. petraea*	North

Figure 3.5: Location, length, species and position in north/south of island of 13 tree-ring series.

two-year period following the eruption of Mount Pinatubo in 1991. The results showed summer cooling as a result of aerosol radiative forcing, and winter warming brought about by induced changes in tropospheric circulation. These results were obtained by comparing the 1991 data with that of 1992 and 1993. However, this does not take into account any changes that occurred in the year of the eruption itself compared to the previous year. For this reason, the 13 *Quercus* ring-width indices were examined by systematically comparing the differences in values that were recorded in the year immediately before an eruption (TY-1) and the year of eruption (TY), as well between TY-1 and the two years after each event (TY+1, TY+2). This showed the change in standard ring-widths that occurred in the year of, and the two years following, each of the 11 eruptions where available (some tree-ring indices were not sufficiently long to contain data relating to each of the eruptions selected for this study).

Differences in recorded weather data exist between the southern half and the northern half of Ireland. Mean yearly temperature in Valentia Observatory, Co. Kerry stands at 10.7°C (1961-1990), while in Belfast, Co. Antrim it is 9.1°C for the same time period. Total yearly precipitation at Valentia Observatory is 1,249 mm (1961-1990), whereas in Belfast it is 846 mm (1971-2001) (Met Éireann, 2010; The Met Office, 2010). With this in mind, the impact of volcanic eruptions on mean index values for the five southern indices and eight northern indices was also presented, along with an all-island average.

Pearson correlations were run between each of the 13 tree-ring series and Lamb's (1970) Dust Veil Index – an effort to highlight any similarities in fluctuations. An increase in DVI values should, in theory, coincide with a decrease in tree-ring widths as a result of a less favourable growing conditions (reduced temperature, precipitation and photosynthesis), in turn producing negative correlation coefficients. The correlations were run for the entire length of each series and for 50-year sub-groups (after Cook *et al.*, 1998). In addition, Pearson correlations were also run between the 13 tree-ring series and seasonal North Atlantic Oscillation values from Jones *et al.* (1997) and Hurrell (1995). As the NAO is a prime indicator of previous weather patterns in the North Atlantic, the aim of the correlations was to highlight to what extent, if any, the variations in NAO had on tree-ring widths in the selected sites. In order to investigate what month is most influential in terms of temperature, further correlations were run between mean monthly temperatures from Armagh Observatory and the 13 *Quercus* indices. Finally, Pearson correlations were also run between recorded total monthly precipitation in Armagh and the 13 *Quercus* indices but, because of the variable nature of precipitation from one area to another, no significant results were produced. Consequently, these coefficients were not reported.

3.4.2 Gathering *T. baccata* tree-ring data

32 healthy trees with no obvious injury or disease were selected at random from the *T. baccata* stand in Reenadinna Wood, Killarney, Co. Kerry. In 1969-1970 part of Reenadinna Wood was enclosed in an attempt to protect the species from browsing by deer (Perrin, 2002). Therefore, in order to ensure the sample was representative, trees were selected from both within and outside this deer-proof fencing (although this was eventually deemed not to have an impact upon ring-widths as the selected trees were already mature when the enclosure was constructed). The samples were taken between June and October 2007. Two cores – an effort to ensure all rings were accounted for – were taken from each tree to obtain a long-term chronology for the species. The cores were collected using a two-thread Haglöf increment borer – a precision tool designed to remove a 5.15 mm diameter core up to a depth of 305 mm from the living tree without harming it. The extremely rigid nature of the *T. baccata* species resulted in two increment borers breaking just below the threads. As a result, it was necessary to coat the borers in a layer of a combination of beeswax and a wax-based wood polish. This ensured a smoother extraction of core samples.

Standard procedures were used in preparing tree-ring cores for analysis (Stokes and Smiley, 1968; Fritts, 1976). Cores were dried, glued onto wooden mounts and sanded with successively finer sandpaper to obtain maximum ring visibility. The mounted cores were placed on a Velmex Unislide transverse table and were analysed through a Motic SMZ-140 microscope mounted on an articulating arm boom stand. Ring-widths were measured to a 0.001 mm accuracy using a

Metronics QC-10V linear encoder. Dating of samples was done visibly using a stereo-microscope and the skeleton-plot method (Stokes and Smiley, 1968). Cross-dating of trees was performed using the computer programme COFECHA (Holmes, 1986). This programme performs data quality control by checking all tree-ring measurements and locating portions within the series showing weak cross-dating or measurement errors.

3.4.3 *T. baccata* tree ring-width climate reconstruction

Cross dating for long-term chronologies was completed using a 32-year cubic smoothed spline with a 50% wavelength cut-off for filtering. Series were examined in 50-year segments with a 25-year lag. Series inter-correlation was determined using a 99% significance level Pearson correlation coefficient. To maximise the common signal within each chronology, only the most highly inter-correlated radii were retained and complacent tree-ring records were discarded (Biondi, 2001). Tree-ring widths normally contain considerable amounts of non-climatic signals that may include a biological growth trend, tree-disturbance signals, or both (Fritts, 1976).

Detrending of growth variations associated with age was accomplished using ARSTAN software (Holmes, 1992). Each series was detrended using a negative exponential curve, typical of the biological growth trend in trees (Cook *et al.*, 1990; Fritts, 1976). If this line did not provide a good fit, a linear regression line of negative slope or a horizontal line through the mean was used to detrend the ring-width series. After a curve was fitted, the actual ring-width value was divided by the curve value to obtain a dimensionless ring-width index for each series. This standard version of the chronology, created through autocorrelation, includes a large portion of the impact of prior growth (persistence) on the ring-width of the growth year. The biological persistence was removed from the standard chronology with autoregressive modelling to produce a residual chronology (Gervais, 2006; Grissino-Mayer *et al.*, 1992). Here, autocorrelation is not a part of the process, meaning that past and future index values are not considered so that each year’s index value is specific to that year. The ARSTAN chronologies contain persistence that is common and synchronous among a large portion of the tree-ring series, without including that found in only one or very few series (Pärn, 2002).

The standard, residual and ARSTAN chronologies were correlated with monthly values of mean temperature and total precipitation from Lough Leane Lakeshore Station, located in Killarney National Park. This Met Éireann synoptic station was the closest to the sample site and provided monthly data from January 1969 onwards. Simple correlation coefficients were calculated for the interval of overlap between each chronology (1969-2007) and the monthly instrumental data for the 21-month interval beginning in April of the previous year and ending with December of the current year (Blasing *et al.*, 1981), with the standard and residual indices proving more responsive than the ARSTAN index. The resulting correlations were useful in identifying particular months where precipitation and temperature are highly correlated with radial growth of *T. baccata* in Killarney, showing that mean November-April temperatures and total May-June precipitation were the best predictors of annual changes in the standard and residual ring-width series respectively. This enabled the formation of an equation that, when combined with tree ring-width variations that pre-date station records, created 200+ year-long reconstructions of temperature and precipitation for the Killarney area.

3.4.4 *T. baccata* tree ring-width/climate reconstructions and the influence of volcanic eruptions

Because the temperature and precipitation reconstructions are functions of the standard and residual indices they will quite often follow similar patterns. However, the intensity of changes within the reconstructions has the potential to be dampened or enhanced, which necessitates a separate examination of all four datasets. As a result, tree-ring width and climate reconstruction series were examined in the same manner as the 13 other Irish tree-ring indices, that is, the value for TY-1 was compared to those for the next three years (TY, TY+1 and TY+2). This gives results in terms of standard ring-width, residual ring-width, precipitation reconstructions, and temperature reconstructions, for each of the years associated with the 11 volcanic eruptions. Any notable changes in these four areas were identifiable as a result of this technique. Values for all 11 eruptions were then examined in a similar fashion to the recorded weather data from Armagh Observatory; firstly the mean of all 11 eruptions is presented, followed by the mean values for the VEI 5-7 eruptions, the Icelandic VEI 4 events, the low-latitude eruptions, and finally all Icelandic events, thus filtering out the volcanic signal from other fluctuations (Mitchell, 1961) and highlighting the varying impacts in terms of location and size of volcanic eruption.

3.4.5 *T. baccata* tree ring-widths and other indices

Pearson correlations were run between the ring-width chronologies and North Atlantic Oscillation indices (Jones *et al.*, 1997; Hurrell, 1995). Further correlations were also run between 50-year sub-groups in an effort to test stability (Cook *et. al.*, 1998). The standard and residual chronologies were then run through a Morlet wavelet analysis to determine the dominant modes of variability within the series, and how these modes vary through time (Torrence and Compo, 1998). The wavelet analysis was run using a red noise background spectrum and contour lines at 10% significance levels. This analysis offered information on the dominant periodicities within the records, and should indicate the underlying causal mechanisms by highlighting patterns of variation (Gray *et al.*, 2003).

Pearson correlations were also run between Lamb's (1970) Dust Veil Index and the standard, residual, reconstructed temperature and reconstructed precipitation values for the Killarney area. The increased DVI values in the years of and following volcanic eruptions should coincide with a narrowing of tree-ring widths due to the climatic downturns associated with post-eruption conditions. This will produce negative Pearson correlation coefficients between DVI and tree-ring indices, as well as between the reconstructed temperature and precipitation. Cook *et al.*'s (1998) method of sub-dividing Pearson correlations into 50-year segments in order to test stability was used again here. The analysis of this will highlight whether or not fluctuations in the DVI corresponded with variations in *T. baccata* ring-widths and reconstructed climatic data.

3.5 EVALUATING COMBINED PROXIES

Because this study compiled data from diverse sources, it was decided to present and evaluate all of the relevant data simultaneously. This allowed the identification of any common footprints that were left by volcanic eruptions in the recorded data. Firstly, general trends in the recorded weather data from Armagh Observatory, as well in the tree-ring data, were identified. Then combined data for each individual eruption was examined. Here, Armagh Observatory's mean seasonal temperatures, total seasonal precipitation and monthly wind direction data, as well as reconstructed temperature and precipitation from Killarney, were examined in conjunction with the various *Quercus* tree-ring indices as well as the *T. baccata* chronologies. Following that, TY-1, TY, TY+1 and TY+2 values for the various elements, barring wind direction (which was examined in relation to the six months following eruptions), were presented in terms of all volcanic eruptions, the VEI 5-7 events, the low-latitude events, Icelandic VEI 4 eruptions and all the Icelandic eruptions combined, thus allowing any longer-term common trends in the data to be readily seen as the volcanic signal is more likely to become apparent here (Mitchell, 1961). This involved collating deviations from the 11-year means for recorded temperature from Armagh Observatory in each of the four seasons, as well as their total precipitation values, mean reconstructed November to April temperatures from Killarney, total reconstructed Killarney precipitation for May-June, standard and residual *T. baccata* indices in addition to standard *Quercus* tree-ring widths for the northern half, southern half and all of Ireland.

CHAPTER 4: ARMAGH OBSERVATORY RESULTS

This chapter examines the instrumental data available in the archives of Armagh Observatory in Northern Ireland, focusing on the temperature series, precipitation levels and wind direction records.

4.1 TEMPERATURE

4.1.1 Month-to-month temperature change

Table 4.1 shows mean monthly temperatures, the 11-year mean value for each month (centred on the eruption year), and the difference in degrees Celsius between these two measurements. The 1815 Tambora (VEI 7) eruption on the island of Sumbawa in Indonesia coincided with above average temperatures in Armagh until November of that year (TM+7) where it was, on average, 1.4°C colder than the 11-year mean for that month. Of the next 13 months, 10 had colder than normal temperatures in Armagh, with the six months from February 1816 (TM+10) to July 1816 (TM+15) each containing a fall in temperatures, including -1.3°C in March and April, -1.4°C June and -1.7°C in July. November and December 1816 (TM+19, TM+20) also had reduced temperatures of -1.1°C and -0.7°C respectively.

Of the 25 months analysed in relation to the 1835 VEI 5 eruption of Cosigüina in Nicaragua, 15 had temperatures that were below the 11-year average. The first of these came in May 1835 (TM+4, -0.5°C). TM+18 to TM+24 contain the most notable, consistent falls in temperature in Armagh, including -1.5°C in July 1836 (TM+18), -1.6°C in September 1836 and -1.7°C in November of the same year. The eruption of Hekla in Iceland in September 1845 coincided with a 1.3°C fall in temperatures in comparison to the 11-year mean for that month. Only seven of the following 24 months had colder than normal conditions, including -1.3°C in September 1847 (TM+24) and -2.9°C in December 1846 (TM+15).

The VEI 4 eruption of Katla in Iceland in May 1860 was followed by seven straight months of reduced temperatures in Armagh, ranging from -0.5°C in TM+5 to -2.0°C in TM+4 and -3.1°C in TM+7. Six of the remaining 17 months

Table 4.1: Twenty-five months of temperature data (in °C) for Armagh from the months following volcanic eruptions, including the 11-year mean for each month, recorded mean monthly temperature and the difference between these two measurements.

Event		Monthly Temperature Data																								
		TM	TM+1	TM+2	TM+3	TM+4	TM+5	TM+6	TM+7	TM+8	TM+9	TM+10	TM+11	TM+12	TM+13	TM+14	TM+15	TM+16	TM+17	TM+18	TM+19	TM+20	TM+21	TM+22	TM+23	TM+24
*Apr 1815 VEI7	Month	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
	11-Year Mean Value	7.3	10.0	13.0	14.4	13.8	11.6	8.3	4.9	2.9	2.1	4.2	5.1	7.3	10.0	13.0	14.4	13.8	11.6	8.3	4.9	2.9	2.1	4.2	5.1	7.3
	Recorded Monthly Mean	8.3	13.0	14.5	15.7	15.3	13.0	9.1	3.5	1.9	3.0	3.1	3.8	6.0	9.2	11.6	12.6	14.0	11.1	9.8	3.7	2.2	4.6	5.8	5.1	7.2
	Difference (°C)	1.0	3.0	1.5	1.3	1.5	1.4	0.8	-1.4	-1.0	0.8	-1.1	-1.3	-1.3	-0.8	-1.4	-1.7	0.2	-0.5	1.4	-1.1	-0.7	2.4	1.5	0.0	-0.1
*Jan 1835 VEI5	Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan
	11-Year Mean Value	3.9	4.4	5.0	7.3	10.3	13.2	14.6	14.2	11.7	9.4	6.2	4.9	3.9	4.4	5.0	7.3	10.3	13.2	14.6	14.2	11.7	9.4	6.2	4.9	3.9
	Recorded Monthly Mean	4.2	4.8	5.8	8.2	9.9	13.1	14.4	15.4	11.6	8.0	7.0	5.4	4.5	3.7	4.4	6.5	11.2	13.4	13.1	13.0	10.2	8.1	4.5	4.0	3.7
	Difference (°C)	0.3	0.4	0.8	0.9	-0.5	-0.2	-0.2	1.2	-0.2	-1.4	0.8	0.5	0.6	-0.7	-0.6	-0.8	0.9	0.2	-1.5	-1.2	-1.6	-1.3	-1.7	-1.0	-0.2
Sept 1845 VEI4	Month	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
	11-Year Mean Value	12.4	8.6	6.7	5.0	4.0	4.6	5.8	7.9	10.8	13.3	14.1	14.0	12.4	8.6	6.7	5.0	4.0	4.6	5.8	7.9	10.8	13.3	14.1	14.0	12.4
	Recorded Monthly Mean	11.1	9.8	6.9	4.4	7.1	6.6	5.9	7.3	11.2	16.5	15.0	15.3	14.5	9.5	7.5	2.2	4.9	3.5	5.8	6.8	11.3	13.0	16.6	14.1	11.1
	Difference (°C)	-1.3	1.3	0.1	-0.7	3.0	2.0	0.1	-0.5	0.4	3.1	1.0	1.3	2.2	1.0	0.8	-2.9	0.9	-1.1	0.0	-1.0	0.5	-0.3	2.5	0.1	-1.3
May 1860 VEI4	Month	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
	11-Year Mean Value	10.6	13.4	14.6	14.5	12.4	9.4	5.7	5.0	4.0	4.1	5.3	7.8	10.6	13.4	14.6	14.5	12.4	9.4	5.7	5.0	4.0	4.1	5.3	7.8	10.6
	Recorded Monthly Mean	11.0	11.7	14.0	12.6	10.4	8.9	4.8	2.0	4.4	4.7	5.8	7.7	11.1	14.7	13.9	14.8	12.3	10.2	3.6	4.1	5.2	5.3	5.2	8.3	10.8
	Difference (°C)	0.4	-1.7	-0.6	-1.9	-2.0	-0.5	-0.9	-3.1	0.3	0.6	0.5	-0.1	0.5	1.3	-0.7	0.4	-0.1	0.8	-2.0	-0.9	1.1	1.2	-0.1	0.5	0.3
Mar 1875 VEI5	Month	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
	11-Year Mean Value	5.7	7.7	9.9	13.3	14.8	14.8	12.2	8.9	5.5	3.3	4.1	4.8	5.7	7.7	9.9	13.3	14.8	14.8	12.2	8.9	5.5	3.3	4.1	4.8	5.7
	Recorded Monthly Mean	5.7	8.9	11.3	12.8	13.9	15.4	13.8	9.2	5.2	3.9	4.8	4.3	3.7	7.2	9.8	12.9	15.4	14.8	11.8	10.9	6.6	5.6	4.8	5.7	5.1
	Difference (°C)	0.0	1.2	1.4	-0.4	-0.9	0.6	1.6	0.3	-0.3	0.6	0.7	-0.6	-2.0	-0.5	-0.1	-0.3	0.6	0.0	-0.4	2.0	1.1	2.4	0.7	0.8	-0.6
*May 1883 VEI6	Month	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
	11-Year Mean Value	9.7	12.9	14.2	14.3	11.9	8.7	5.9	3.3	3.7	4.9	5.0	7.0	9.7	12.9	14.2	14.3	11.9	8.7	5.9	3.3	3.7	4.9	5.0	7.0	9.7
	Recorded Monthly Mean	9.5	12.1	12.9	13.8	11.9	9.2	5.2	5.2	6.1	5.2	6.2	7.0	10.1	12.8	14.5	14.9	12.9	9.1	5.1	4.1	4.0	5.1	4.6	7.1	7.7
	Difference (°C)	-0.2	-0.8	-1.3	-0.4	-0.1	0.5	-0.7	1.9	2.4	0.3	1.2	0.0	0.4	-0.1	0.3	0.6	1.0	0.4	-0.8	0.8	0.3	0.2	-0.4	0.2	-2.1
Dec 1902 VEI4	Month	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	11-Year Mean Value	5.3	4.7	4.2	5.6	7.4	9.8	13.1	14.8	14.2	12.5	9.4	6.8	5.3	4.7	4.2	5.6	7.4	9.8	13.1	14.8	14.2	12.5	9.4	6.8	5.3
	Recorded Monthly Mean	5.0	3.8	7.1	5.7	6.5	10.2	12.1	13.8	13.0	12.2	9.1	6.0	3.9	4.5	3.4	4.5	7.6	9.8	12.9	14.5	13.6	12.1	9.5	6.4	5.0
	Difference (°C)	-0.2	-0.9	2.8	0.1	-0.9	0.4	-1.0	-1.0	-1.2	-0.3	-0.2	-0.8	-1.4	-0.2	-0.8	-1.1	0.2	0.0	-0.2	-0.2	-0.6	-0.4	0.1	-0.4	-0.2
Oct 1918 VEI4	Month	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
	11-Year Mean Value	9.6	6.3	4.8	4.9	5.1	5.3	7.1	10.2	12.6	14.0	14.0	12.2	9.6	6.3	4.8	4.9	5.1	5.3	7.1	10.2	12.6	14.0	14.0	12.2	9.6
	Recorded Monthly Mean	8.9	6.1	6.7	3.7	3.3	3.5	7.5	12.0	12.2	13.4	14.4	11.7	8.8	2.9	5.1	4.9	6.7	6.0	6.9	10.4	13.1	12.7	12.9	12.5	10.6
	Difference (°C)	-0.7	-0.2	1.9	-1.2	-1.8	-1.8	0.4	1.7	-0.4	-0.6	0.4	-0.5	-0.8	-3.3	0.3	0.0	1.7	0.7	-0.2	0.2	0.6	-1.3	-1.1	0.3	1.0
Mar 1947 VEI4	Month	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
	11-Year Mean Value	6.8	8.9	10.8	13.4	14.9	14.9	12.9	10.4	6.9	5.3	4.6	5.0	6.8	8.9	10.8	13.4	14.9	14.9	12.9	10.4	6.9	5.3	4.6	5.0	6.8
	Recorded Monthly Mean	3.6	8.1	11.7	13.7	14.6	17.4	13.8	11.4	7.4	5.5	4.3	5.2	8.6	8.9	10.8	12.3	14.6	14.2	13.1	10.2	9.0	6.3	6.7	7.2	6.8
	Difference (°C)	-3.2	-0.9	0.8	0.2	-0.3	2.5	0.9	1.0	0.4	0.2	-0.3	0.2	1.8	-0.1	0.0	-1.2	-0.3	-0.8	0.2	-0.2	2.1	1.0	2.1	2.2	0.0
*Mar 1982 VEI5	Month	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
	11-Year Mean Value	5.8	7.9	10.5	13.3	15.5	14.8	12.9	9.8	6.3	5.0	3.0	3.7	5.8	7.9	10.5	13.3	15.5	14.8	12.9	9.8	6.3	5.0	3.0	3.7	5.8
	Recorded Monthly Mean	6.2	9.4	10.9	14.5	16.0	14.8	13.0	9.4	6.1	4.1	5.7	2.9	7.1	6.3	10.0	13.6	18.0	17.0	13.0	9.9	7.2	6.5	2.5	4.5	5.1
	Difference (°C)	0.4	1.5	0.4	1.2	0.5	0.0	0.1	-0.4	-0.2	-0.9	2.7	-0.8	1.3	-1.6	-0.5	0.3	2.5	2.2	0.1	0.1	0.9	1.5	-0.5	0.8	-0.7
*Apr 1991 VEI6	Month	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
	11-Year Mean Value	8.1	10.9	13.7	15.7	14.9	12.5	9.9	6.8	5.1	4.9	4.5	6.5	8.1	10.9	13.7	15.7	14.9	12.5	9.9	6.8	5.1	4.9	4.5	6.5	8.1
	Recorded Monthly Mean	7.9	11.2	11.9	16.4	16.0	13.7	9.4	6.5	6.2	4.9	6.0	7.5	8.1	12.3	15.0	15.1	13.8	11.7	7.5	7.1	4.5	5.8	6.6	6.6	9.2
	Difference (°C)	-0.2	0.3	-1.8	0.7	1.1	1.2	-0.5	-0.3	1.1	0.0	1.5	1.0	0.0	1.4	1.3	-0.6	-1.1	-0.8	-2.4	0.3	-0.6	0.9	2.1	0.1	1.1

*** Denotes low-latitude eruption**

analysed here had a fall in temperatures in comparison to their 11-year mean with the most notable change, -2.0°C, coming in November 1861 (TM+18). Only 10 of the 25 months associated with the March 1875 VEI 5 Askja eruption in Iceland had reduced temperatures in Armagh, including a sustained period between February 1876 (TM+11) and June of the same year (TM+15) where changes ranged from as small as -0.1°C in May (TM+14) to -2.0°C in March (TM+12).

The VEI 6 eruption of Krakatau in Indonesia in May 1883 coincided with a -0.2°C change in temperatures that month, and was followed by further reductions in five of the next six months, peaking at -1.3°C in July (TM+2). Only five of the remaining 18 months analysed contained temperatures that were colder than the 11-year means, with the most notable changes coming in November 1884 (TM+18, -0.8°C) and May 1885 (TM+24, -2.1°C). A total of 16 months had reduced temperatures in Armagh following the December 1902 VEI 4 Grímsvötn event in Iceland. The most sustained period of change came in the 10 months from June 1903 (TM+6) and March 1904 (TM+15). The changes ranged from as little as -0.2°C in both October 1903 (TM+10) and January 1904 (TM+13) to -1.2°C in August 1903 (TM+8) and -1.4°C in December 1903 (TM+12). Five of the first six months associated with the October 1918 VEI 4 eruption of Katla in Iceland had reduced temperatures in comparison to their 11-year mean, including -1.2°C in January 1919 (TM+3) and -1.8°C in both February and March 1919. Eight of the remaining months also had mean monthly temperatures fall below their 11-year average with the most notable changes coming in TM+21 (-1.3°C) and TM+13 (-3.3°C). Eight of the months analysed in relation to the March 1947 VEI 4 eruption of Hekla in Iceland had colder than average temperatures. The largest change, -3.2°C, came in the month of the eruption and was followed by a reduction of -0.9°C in TM+1. The next most prominent change came in June 1947 (TM+15, -1.2°C).

Eight of the 24 months following the VEI 5 eruption of El Chichón in Mexico in March 1982 had reduced temperatures in Armagh Observatory. Six of these came in the eight months between October 1982 (TM+7) and May 1983

(TM+14), including -0.9°C in December 1982 and -1.6°C in April 1983. The next mean monthly temperature to be less than the 11-year average did not occur until January 1984 (TM+22, -0.5°C). The April 1991 VEI 6 eruption of Mount Pinatubo in the Philippines coincided with a -0.2°C change in temperatures that month, followed by -1.8°C in TM+2. Of the remaining 22 months examined, seven had further reductions in temperatures, including -0.8°C in September 1992 (TM+17), -1.1°C in August of the same year and -2.4°C in October 1992 (TM+18).

Figure 4.1 shows the average change in monthly temperatures in Armagh in comparison to their 11-year means. It presents the data in terms of all 11 eruptions, the VEI 5-7 eruptions, the low-latitude events, the Icelandic VEI 4 events, and all Icelandic eruptions combined. Focusing firstly on the mean changes following all 11 eruptions, the month of the event tends to contain a 0.3°C fall in temperatures in Armagh, with no other reduction coming until TM+11 (-0.1°C). TM+13 to TM+15 also tend to have colder than normal temperatures (-0.3°C, -0.1°C and -0.7°C), with further reductions coming in TM+18 (-0.5°C), TM+19 (-0.1°C) and TM+24 (-0.3°C). On average, it is not until nine months after the VEI 5-7 eruptions that Armagh has a fall in temperatures (-0.1°C) in comparison to the 11-year mean. This, however, is followed by further reductions in the five months from TM+11 to TM+15, with the most notable change, -0.4°C, coming in TM+13 and TM+15. TM+18 tends to have a -0.6°C drop in temperatures, with a fall of -0.4°C coming in TM+24

The low-latitude eruptions, on average, are followed by a -0.1°C drop in temperatures in TM+2 and again in TM+6. Of the 16 months between TM+9 and TM+24, nine contain lower than normal temperatures, including -0.4°C in each of TM+13, TM+15 and TM+24 and -0.6°C in TM+18. The month within which VEI 4 eruptions occur tends to coincide with a 1.0°C fall in temperatures in Armagh, followed by -0.5°C in TM+1, -0.7°C in TM+3 and -0.4°C in TM+4. TM+6 to TM+8 each have further reductions in temperature, including -0.4°C in TM+7. Six of the seven months between TM+13 and TM+19 also contain colder than normal conditions in Armagh, with -0.4°C in both TM+18 and TM+19, and

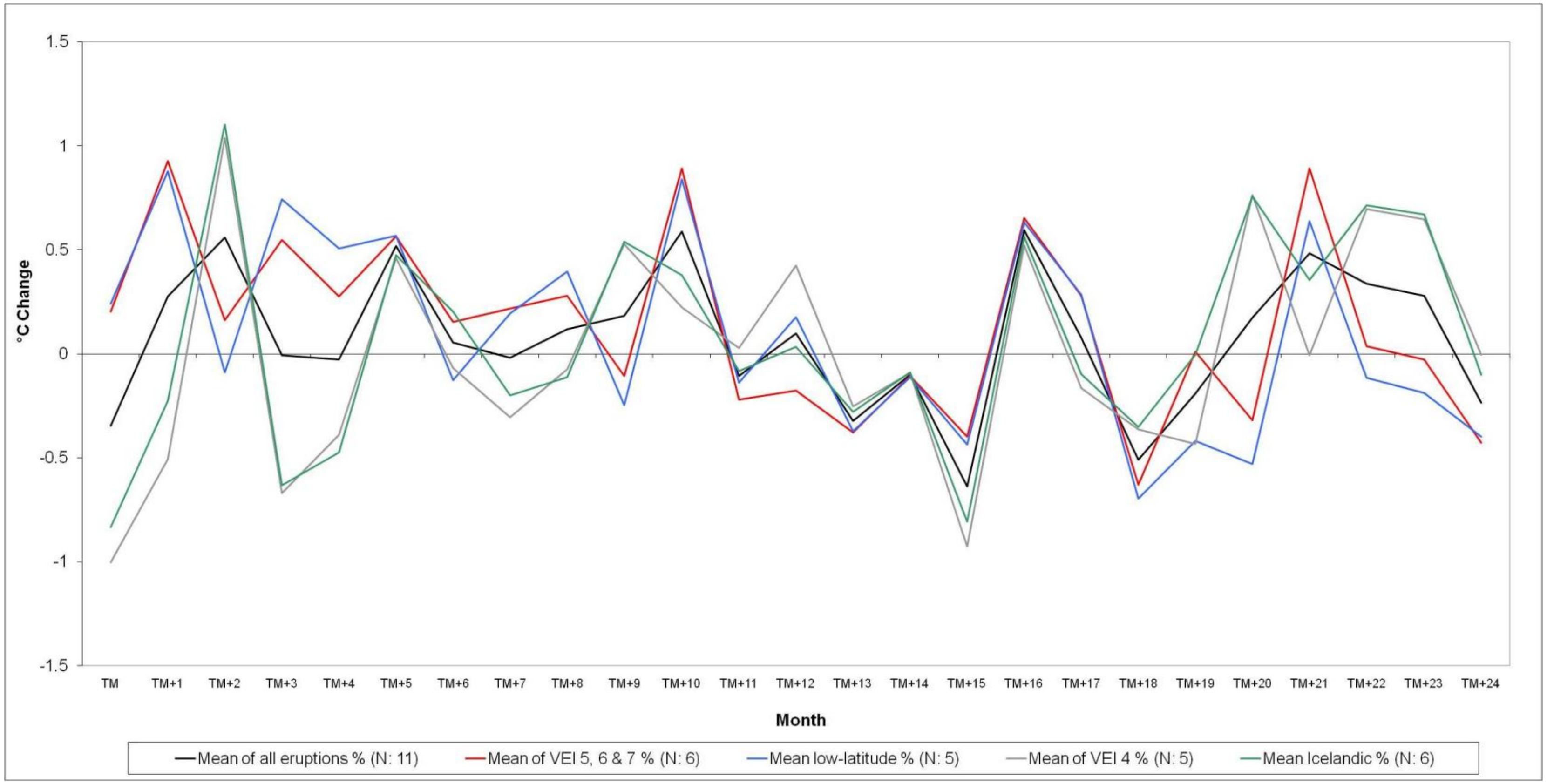


Figure 4.1: Five volcano categories showing the mean change in monthly temperatures (°C) in Armagh in comparison to 11-year mean values centred on eruption years.

-0.9°C in TM+15. On average, six of the first nine months associated with all Icelandic eruptions combined have reduced temperatures in Armagh, including -0.8°C in the month of the event, -0.5°C in TM+4 and -0.6°C in TM+3. Seven of the months from TM+11 to TM+24 also have temperatures below the 11-year mean, with values ranging from -0.1°C in TM+11, TM+14 and TM+17 to -0.8°C in TM+15.

4.1.2 Seasonal temperature change

In an effort to better assess the overall influence of volcanic eruptions on temperatures in Armagh, the difference between the mean seasonal temperatures in TY, TY+1 and TY+2 in Armagh Observatory and the 11-year mean value centred on the eruption years are presented (Tables 4.2-4.5). This allows an assessment of Briffa *et al.*'s (1998) theory that cooling occurs in the summer months following large-scale volcanic eruptions, and Robock and Mao's (1992) hypothesis of winter warming following large volcanic eruptions. Meanwhile, Figures 4.2-4.5 show the mean changes in temperature that occurred in these seasons in Armagh in terms of five categories of volcanic eruption.

Looking firstly at the winter temperature data (Table 4.2), the year of an eruption coincides with increases in temperatures on the 11-year mean on six occasions, including +1.5°C in the year of the 1845 VEI 4 Hekla and 1883 VEI 6 Krakatau eruptions and +1.0°C for the 1835 VEI 5 Cosigüina event. The decreases in temperature in TY ranged from just -0.1°C for the 1947 VEI 4 Hekla eruption to -1.3°C for the 1902 VEI 4 Grímsvötn event. The year following eruptions had an increase in winter temperatures in Armagh in 10 of the 11 cases. The more notable values include +1.0°C in TY+1 of the 1815 VEI 7 Tambora eruption, +1.4°C in the year after the 1875 VEI 5 eruption of Askja and +1.5°C in TY+1 of the 1947 VEI 4 Hekla event. The sole reduction in temperature came in the winter following the 1845 VEI 4 eruption of Hekla (-1.1°C). TY+2 had increases in winter temperatures on four occasions, the most notable being +1.0°C following the VEI 4 1860 eruption of Katla and +1.3°C in TY+2 of the 1875 VEI 5 Askja event. The decreases in temperatures on the 11-year mean ranged from -0.4°C in the second winter after the 1845 VEI 4 Hekla eruption to -0.8°C and

Table 4.2: Difference between mean Armagh Observatory winter temperatures (°C) and the 11-year mean value centred on eruption years in TY, TY+1 and TY+2 of eruptions.

Event	°C Change from 11-year Mean		
	TY	TY+1	TY+2
*Apr 1815 VEI7	-0.5	1.0	-0.9
*Jan 1835 VEI5	1.0	0.5	0.4
Sep 1845 VEI4	1.5	-1.1	-0.4
May 1860 VEI4	-0.8	0.4	1.0
Mar 1875 VEI5	0.3	1.4	1.3
*May 1883 VEI6	1.5	0.5	-0.5
Dec 1902 VEI4	-1.3	0.7	-0.8
Oct 1918 VEI4	-0.4	0.7	0.8
Mar 1947 VEI4	-0.1	1.5	0.7
*Mar 1982 VEI5	0.3	0.5	-0.7
*Apr 1991 VEI6	0.7	0.6	-0.8

*Denotes low-latitude eruption

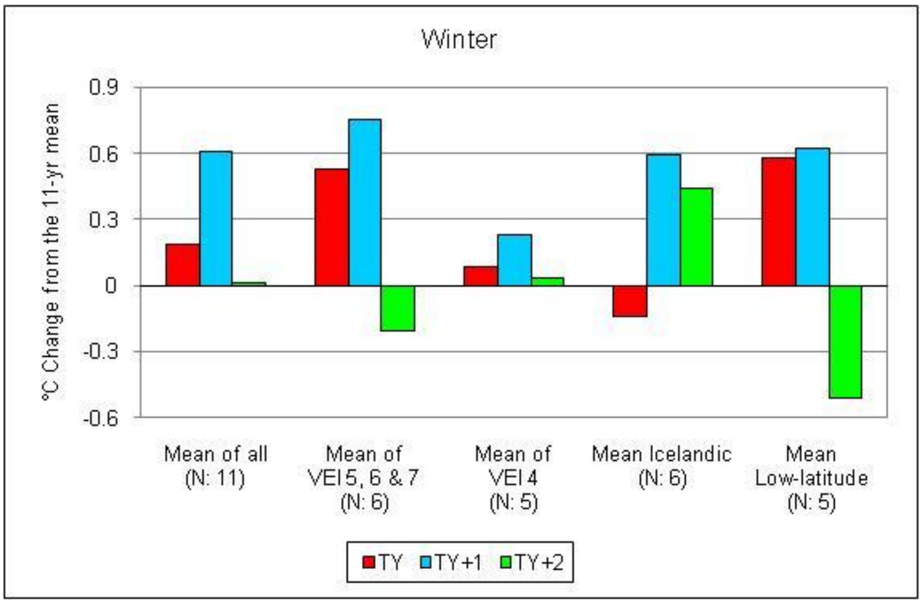


Figure 4.2: Five volcano categories indicating mean VEI- and location-specific changes in mean winter temperatures (°C) in Armagh Observatory for three years associated with eruptions.

-0.9°C following the eruptions of Mount Pinatubo (VEI 6, 1991) and Tambora (VEI 7, 1815) respectively.

Figure 4.2 shows that, on average, increases in winter temperatures can be expected in the year of and the year following any of the 11 events (+0.2°C and +0.6°C respectively), with no noticeable change coming in TY+2. The VEI 5-7 volcanic eruptions tend to be followed by an increase of +0.5°C in winter temperatures in Armagh in TY and +0.8°C in TY+1, with a decrease of -0.2°C in TY+2. The smaller VEI 4 events coincide with a +0.1°C increase in temperatures in the year of an event, followed by a further increase (+0.2°C) in TY+1 while TY+2 contains no notable change. Icelandic eruptions, in general, coincide with a decrease of -0.1°C in TY and increases of +0.6°C and +0.4°C in the following two years. Finally, the low-latitude events tend to coincide with increases in winter temperatures in TY and TY+1 (+0.6°C on both occasions), while TY+2 of these eruptions has a mean decrease of -0.5°C in Armagh.

Increases in mean spring temperatures in Armagh (Table 4.3) occurred in TY of nine of the events examined here, peaking at +1.6°C for the 1815 VEI 7 eruption of Tambora, and also included +1.1°C for the 1835 VEI 5 Cosigüina event. The two decreases in temperature values came in TY of the 1902 VEI 4 Grímsvötn eruption (-0.1°C) and the 1947 VEI 4 Hekla event (-1.1°C). Seven of the 11 eruptions examined here were followed by decreases in mean spring temperatures in Armagh in TY+1, including -0.7°C after the 1883 Krakatau event, -0.9°C following the 1875 Askja event and -1.1°C following the 1815 Tambora eruption. Six of the eruptions were followed by decreases in temperatures on the 11-year spring mean in TY+2, peaking at -1.4°C for the 1835 VEI 5 Cosigüina event, while also including -1.0°C for the 1815 VEI 7 Tambora eruption and -1.1°C for the 1875 VEI 5 Askja event.

Mean changes in spring temperature values in Armagh Observatory show much variability (Figure 4.3). The year of an eruption will, on average, coincide with an increase of +0.4°C on the 11-year mean, and will be followed by a decrease of -0.2°C in TY+1 and a further decrease of -0.3°C in TY+2. The VEI 5-7 eruptions

Table 4.3: Difference between mean Armagh Observatory spring temperatures (°C) and the 11-year mean value centred on eruption years in TY, TY+1 and TY+2 of eruptions.

Event	°C Change from 11-year Mean		
	TY	TY+1	TY+2
*Apr 1815 VEI7	1.6	-1.1	-1.0
*Jan 1835 VEI5	1.1	0.5	-1.4
Sep 1845 VEI4	0.1	-0.1	0.4
May 1860 VEI4	0.2	-0.1	0.3
Mar 1875 VEI5	0.8	-0.9	-1.1
*May 1883 VEI6	0.5	-0.7	-0.4
Dec 1902 VEI4	-0.1	-0.1	0.4
Oct 1918 VEI4	0.2	0.4	0.6
Mar 1947 VEI4	-1.1	0.6	0.1
*Mar 1982 VEI5	0.8	-0.3	-0.1
*Apr 1991 VEI6	0.6	0.0	-0.6

*Denotes low-latitude eruption

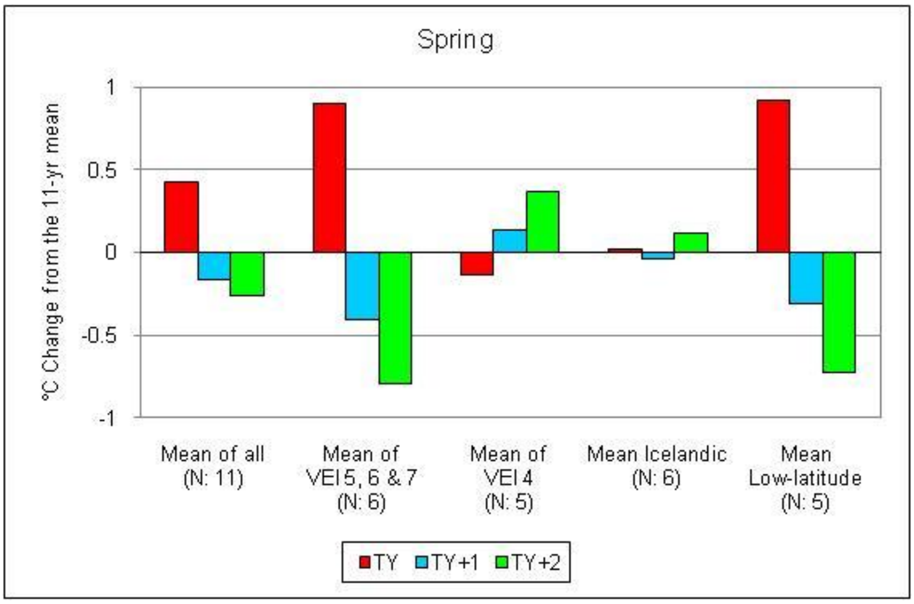


Figure 4.3: Five volcano categories indicating mean VEI- and location-specific changes in mean spring temperatures (°C) in Armagh Observatory for three years associated with eruptions.

coincide with, on average, an increase of +0.9°C in TY of eruptions, and are then followed by decreases of -0.4°C in TY+1 and -0.8°C in TY+2. The Icelandic VEI 4 eruptions have the reverse of the pattern seen in the VEI 5-7 events, with a slight decrease of -0.1°C coming in TY and increases of +0.1°C and +0.4°C in TY+1 and TY+2. The mean results in relation to all Icelandic events see a change of note only in TY+2 (+0.1°C). The low-latitude eruptions coincide with an increase in spring temperatures in TY (+0.9°C), and are followed by decreases of -0.3°C in TY+1 and -0.7°C in TY+2.

Mean summer temperatures in Armagh (Table 4.4) coincide with decreases in TY of five of the eruptions examined, including -0.8°C for the 1883 VEI 6 Krakatau event, -0.9°C for the 1902 VEI 4 eruption of Grímsvötn and -1.4°C in TY of the 1860 VEI 4 Katla event. The increases on the 11-year mean that occurred reached their peak at +1.9°C in TY of the 1845 VEI 4 Hekla event, with +1.5°C for the 1835 VEI 5 Cosigüina event and +1.4°C in the summer of the 1815 eruption of Tambora. Summer temperatures in Armagh decreased on the 11-year mean on five occasions in the year after events, including -0.7°C in TY+1 of the March 1947 VEI 4 Hekla eruption and -1.0°C following the 1815 Tambora event. The increases in temperature in this season peaked at +1.7°C following the 1982 El Chichón eruption. TY+2 of eruptions had decreases in summer temperatures on the 11-year mean on six occasions, with the most notable change coming following the 1860 eruption of Katla (-1.6°C), while decreases of -0.7°C came after the 1815 Tambora, 1845 Hekla and 1991 Mount Pinatubo eruptions. The increases in summer temperatures in TY+2 include +1.2°C after the eruption of El Chichón in 1982 and +1.9°C in TY+2 of the 1835 Cosigüina event.

The mean changes in summer temperatures in terms of location and VEI of the various eruptions (Figure 4.4) show that, in general, there tends to be an increase in temperatures in each of the three years associated with all 11 eruptions. Here, the most notable change (+0.2°C) comes in TY, with marginal increases in the following two years. The VEI 5-7 eruptions tend to coincide with increased summer temperatures of +0.4°C in the year of an event, followed by slight

Table 4.4: Difference between mean Armagh Observatory summer temperatures (°C) and the 11-year mean value centred on eruption years in TY, TY+1 and TY+2 of eruptions.

Event	°C Change from 11-year Mean		
	TY	TY+1	TY+2
*Apr 1815 VEI7	1.4	-1.0	-0.7
*Jan 1835 VEI5	1.5	0.4	1.9
Sep 1845 VEI4	1.9	0.8	-0.7
May 1860 VEI4	-1.4	0.5	-1.3
Mar 1875 VEI5	-0.3	0.1	-0.5
*May 1883 VEI6	-0.8	0.3	-0.4
Dec 1902 VEI4	-0.9	-0.2	0.4
Oct 1918 VEI4	-0.1	-0.6	0.9
Mar 1947 VEI4	0.8	-0.7	0.8
*Mar 1982 VEI5	0.6	1.7	1.2
*Apr 1991 VEI6	0.0	-0.1	-0.7

*Denotes low-latitude eruption

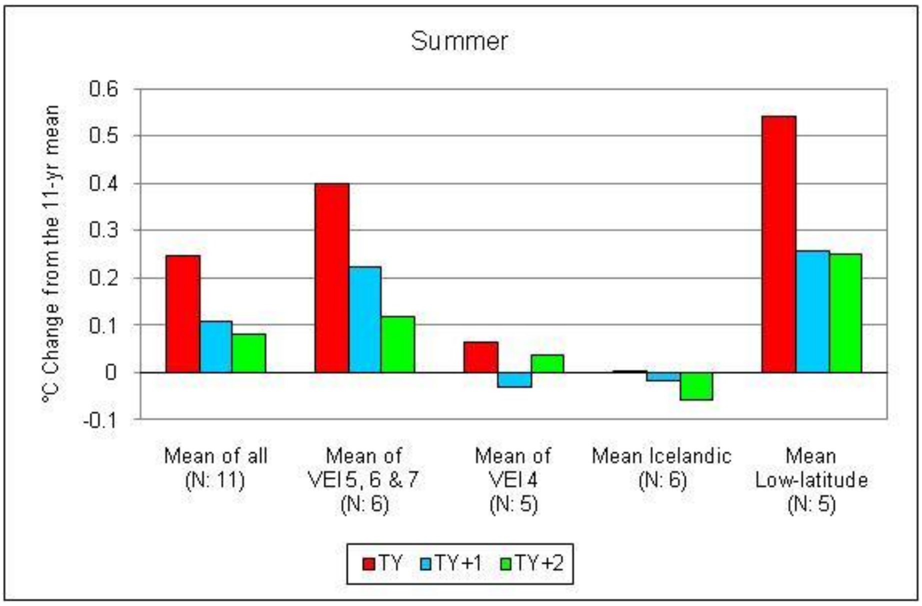


Figure 4.4: Five volcano categories indicating mean VEI- and location-specific changes in mean summer temperatures (°C) in Armagh Observatory for three years associated with eruptions.

increases of +0.2°C and +0.1°C in TY+1 and TY+2. The VEI 4 eruptions coincide with a slight increase of +0.1°C in the year of the events, followed by negligible changes in TY+1 and TY+2. On average, the Icelandic eruptions fail to make any remarkable change in mean summer temperatures in Armagh, with the most notable (-0.1°C) coming in TY+2. Finally, the low latitude eruptions tend to coincide with an increase of +0.5°C in the year of an event, followed by further increases in TY+1 (+0.3°C) and TY+2 (+0.2°C).

Autumn temperatures decreased in TY of four eruptions (Table 4.5), including -1.1°C for the VEI 4 Katla eruptions in 1860 and 1918. The increases that occurred in this year peaked at +0.8°C for the VEI 4 eruption of Hekla in 1947. Six eruptions were followed by reduced temperatures on the 11-year mean in TY+1. Here values ranged from -0.1°C for the eruption of Tambora in 1815 (VEI 7) to -1.0°C following the VEI 6 eruption of Mount Pinatubo in 1991 and -1.5°C for both the 1835 VEI 5 Cosigüina and 1918 VEI 4 Katla events. Of the increases in temperatures in TY+1, +1.4°C following the VEI 4 eruption of Hekla in 1845 was the most notable. Six of the eruptions examined were followed by decreased autumn temperatures in Armagh in TY+2, peaking at -1.8°C in the second year after the eruption of Grímsvötn in 1902, with -1.4°C in TY+2 of the 1991 Mount Pinatubo eruption. The increases in temperatures included +1.2°C following the VEI 4 eruption of Katla in 1918.

The mean changes in autumn temperatures in terms of category of volcano (Figure 4.5) show that only slight decreases tend to occur in TY of all 11 eruptions, with the maximum change (-0.2°C) coming in TY+2. The VEI 5-7 events again coincide with little change in the year of the eruptions (+0.1°C), but tend to be followed by a decrease of -0.2°C in TY+1 and a further decrease of -0.4°C in TY+2. The Icelandic VEI 4 eruptions coincide with a decrease of -0.3°C in TY, followed negligible changes in the next two years. The Icelandic eruptions, on average, coincide with a decrease of -0.2°C in TY and are followed by increases of +0.2°C in TY+1 and +0.1°C in TY+2. The low-latitude eruptions coincided with little change in TY, with more notable decreases of -0.4°C and -0.5°C coming in the next two years examined.

Table 4.5: Difference between mean Armagh Observatory autumn temperatures (°C) and the 11-year mean value centred on eruption years in TY, TY+1 and TY+2 of eruptions.

Event	°C Change from 11-year Mean		
	TY	TY+1	TY+2
*Apr 1815 VEI7	0.2	-0.1	-0.5
*Jan 1835 VEI5	-0.3	-1.5	0.5
Sep 1845 VEI4	0.1	1.4	0.5
May 1860 VEI4	-1.1	-0.3	-0.7
Mar 1875 VEI5	0.5	0.9	0.1
*May 1883 VEI6	0.0	0.3	-0.6
Dec 1902 VEI4	-0.3	-0.3	-1.8
Oct 1918 VEI4	-1.1	-1.5	1.2
Mar 1947 VEI4	0.8	0.7	1.0
*Mar 1982 VEI5	-0.2	0.3	-0.3
*Apr 1991 VEI6	0.1	-1.0	-1.4

*Denotes low-latitude eruption

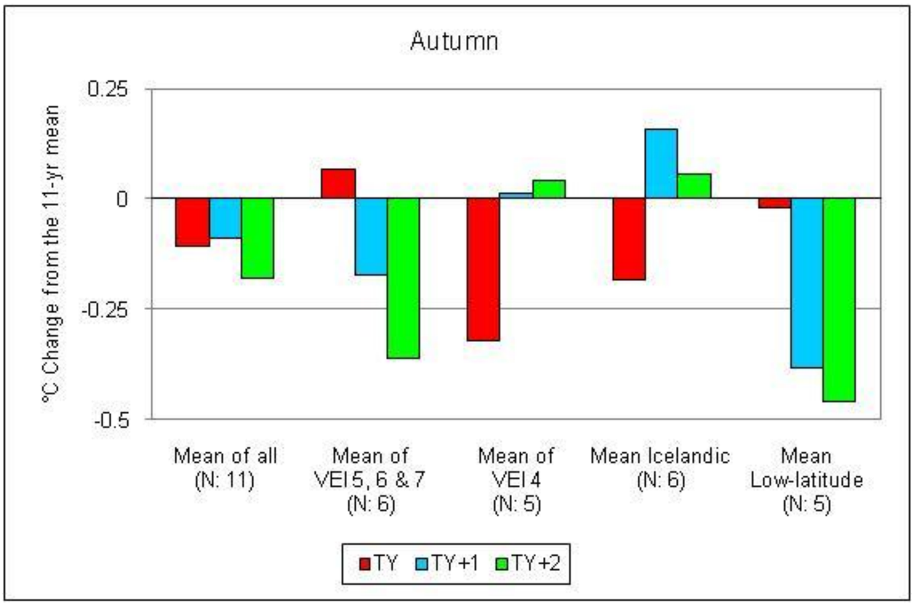


Figure 4.5: Five volcano categories indicating mean VEI- and location-specific changes in mean autumn temperatures (°C) in Armagh Observatory for three years associated with eruptions.

4.2 PRECIPITATION

For the purposes of this research the examination of post-volcanic eruption precipitation takes three forms; firstly total monthly precipitation levels in Armagh are examined for the month of each of the nine volcanic eruptions in question (precipitation measurements are not available pre-1838, thus discounting the eruptions of Tambora and Cosigüina), as well as the 24 months that followed and are compared to the 11-year monthly means centred on the eruption years. Secondly, the number of days per month, again for 25 months, within which zero precipitation was recorded, is compared to the 11-year monthly mean centred on eruption years. Both of these methods are employed in an effort to identify any particular month(s) where precipitation levels in Armagh fall significantly following volcanic eruptions. Finally, the difference between the total seasonal precipitation in TY, TY+1 and TY+2 in Armagh Observatory and the 11-year running mean value centred on each season from the eruption years is examined.

4.2.1 Month-to-month precipitation change

Table 4.6 contains 25 months of total precipitation levels, as well as the monthly 11-year mean values. It also highlights the percent difference between these two measurements. Figure 4.6 shows the mean changes in precipitation in terms of the five categories of volcano examined in relation to temperature (i.e. mean of all eruptions, mean of VEI 5 and 6 events, mean low-latitude eruptions, mean of Icelandic VEI 4 eruptions, and mean results following all Icelandic events). It was not until February 1846, five months after the eruption of Hekla in 1845, that a fall in precipitation levels was recorded in Armagh (Table 4.6). There was 33.7% decrease, while May and June 1846 (TM+11 and TM+12) had further reductions in precipitation levels by -40.5% and -32.7% respectively. Precipitation remained higher than the 11-year mean until November and December 1846, where there were falls of -4.4% and -23.5%. The highest increase in precipitation in any of the 25 months examined came in April 1847 (TM+19, +57.2%). However this was followed by persistently lower levels of rainfall for the remaining months (TM+20 to TM+24) with values ranging from -4.4% in May 1847 (TM+20) to -67.4% in August (TM+23) of the same year.

Table 4.6: Twenty-five months of precipitation data (mm) in Armagh from the months following volcanic eruptions, including the 11-year mean for each month, total monthly recorded precipitation, and the percent difference between these two recordings.

Event		Monthly Precipitation Data																								
		TM	TM+1	TM+2	TM+3	TM+4	TM+5	TM+6	TM+7	TM+8	TM+9	TM+10	TM+11	TM+12	TM+13	TM+14	TM+15	TM+16	TM+17	TM+18	TM+19	TM+20	TM+21	TM+22	TM+23	TM+24
Sep 1845 VEI4	Month	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept
	11-Year Mean Value	73.6	83.5	67.2	51.9	57.6	38.5	38.6	47.4	64.0	71.0	85.4	75.9	73.6	83.5	67.2	51.9	57.6	38.5	38.6	47.4	64.0	71.0	85.4	75.9	73.6
	Recorded Monthly Precip	79.0	112.4	72.2	68.6	67.8	25.5	53.3	63.3	38.1	47.8	95.0	100.2	97.8	119.3	64.3	38.2	74.2	27.6	40.2	74.6	61.8	54.3	31.9	25.3	54.9
	% Difference	7.3	34.5	7.4	32.1	17.8	-33.7	38.2	33.4	-40.5	-32.7	11.3	32.0	32.9	42.8	-4.4	-26.4	28.9	-28.2	4.2	57.2	-3.5	-23.5	-62.6	-66.7	-25.4
May 1860 VEI4	Month	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
	11-Year Mean Value	63.1	63.9	60.2	86.5	60.9	78.3	68.5	65.5	64.8	41.8	60.0	57.0	63.1	63.9	60.2	86.5	60.9	78.3	68.5	65.5	64.8	41.8	60.0	57.0	63.1
	Recorded Monthly Precip	78.0	95.1	35.4	126.1	22.7	56.2	46.7	54.0	50.9	43.5	105.5	29.3	16.0	120.2	105.4	142.3	102.5	69.0	81.6	54.5	118.3	24.2	76.9	70.2	108.9
	% Difference	23.6	48.8	-41.2	45.8	-62.7	-28.2	-31.9	-17.6	-21.4	4.1	75.7	-48.6	-74.6	88.1	75.1	64.6	68.3	-11.8	19.1	-16.8	82.7	-42.1	28.1	23.2	72.6
Mar 1875 VEI5	Month	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
	11-Year Mean Value	43.7	51.1	41.9	61.7	88.6	69.5	83.1	87.3	65.7	70.8	74.8	53.8	43.7	51.1	41.9	61.7	88.6	69.5	83.1	87.3	65.7	70.8	74.8	53.8	43.7
	Recorded Monthly Precip	23.7	3.6	47.3	79.4	95.3	93.2	125.7	122.5	97.2	46.6	35.6	91.7	81.2	37.9	10.7	38.4	52.0	56.3	60.0	81.7	63.9	170.2	140.2	81.5	69.6
	% Difference	-45.8	-93.0	13.0	28.6	7.6	34.0	51.3	40.3	47.9	-34.2	-52.4	70.5	85.9	-25.9	-74.4	-37.8	-41.3	-19.0	-27.8	-6.4	-2.8	140.3	87.4	51.6	59.3
*May 1883 VEI6	Month	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
	11-Year Mean Value	65.0	68.4	85.7	65.1	84.2	61.7	77.3	65.4	65.9	56.2	55.8	52.6	65.0	68.4	85.7	65.1	84.2	61.7	77.3	65.4	65.9	56.2	55.8	52.6	65.0
	Recorded Monthly Precip	50.2	68.8	56.7	72.5	125.6	78.5	99.5	52.8	113.3	88.2	70.7	49.9	76.6	23.0	91.2	59.2	72.4	81.5	61.5	90.9	54.0	78.2	43.1	57.9	41.4
	% Difference	-22.8	0.6	-33.8	11.4	49.2	27.3	28.7	-19.3	71.9	57.0	26.7	-5.1	17.8	-66.4	6.4	-9.1	-14.0	32.2	-20.4	38.9	-18.1	39.2	-22.7	10.1	-36.3
Dec 1902 VEI4	Month	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	11-Year Mean Value	70.0	65.9	59.1	62.4	59.4	75.2	67.3	57.2	103.9	63.8	70.8	72.3	70.0	65.9	59.1	62.4	59.4	75.2	67.3	57.2	103.9	63.8	70.8	72.3	70.0
	Recorded Monthly Precip	68.5	126.1	71.3	111.6	29.3	78.8	27.6	84.3	104.7	80.9	98.7	48.5	60.0	72.9	81.9	56.6	48.0	68.4	35.6	76.5	138.9	74.2	24.8	57.2	49.3
	% Difference	-2.1	91.3	20.6	78.9	-50.7	4.7	-59.0	47.5	0.8	26.8	39.5	-32.9	-14.2	10.6	38.6	-9.3	-19.2	-9.1	-47.1	33.8	33.7	16.3	-65.0	-20.9	-29.5
Oct 1918 VEI4	Month	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
	11-Year Mean Value	81.8	74.9	95.9	78.2	68.7	56.4	58.6	63.6	51.0	64.1	80.2	64.6	81.8	74.9	95.9	78.2	68.7	56.4	58.6	63.6	51.0	64.1	80.2	64.6	81.8
	Recorded Monthly Precip	98.5	105.5	90.2	104.5	23.7	61.8	30.6	45.6	52.0	15.8	82.2	80.2	37.9	48.9	155.9	104.6	62.9	81.1	73.2	75.3	60.4	76.1	48.6	58.0	136.2
	% Difference	20.4	40.9	-6.0	33.7	-65.5	9.6	-47.8	-28.3	1.9	-75.4	2.5	24.2	-53.7	-34.7	62.5	33.8	-8.5	43.8	24.9	18.5	18.3	18.7	-39.4	-10.2	66.4
Mar 1947 VEI4	Month	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
	11-Year Mean Value	50.3	54.6	54.7	70.4	79.2	90.9	81.2	71.8	74.4	90.3	87.0	48.4	50.3	54.6	54.7	70.4	79.2	90.9	81.2	71.8	74.4	90.3	87.0	48.4	50.3
	Recorded Monthly Precip	114.7	91.4	89.6	95.0	82.4	14.2	65.7	49.2	101.6	80.8	170.8	46.2	66.0	63.5	58.2	109.4	62.0	89.0	67.1	57.3	67.1	114.8	61.2	63.9	53.5
	% Difference	128.2	67.4	63.9	34.9	4.0	-84.4	-19.1	-31.5	36.5	-10.5	96.4	-4.6	31.3	16.3	6.5	55.4	-21.8	-2.1	-17.3	-20.2	-9.8	27.2	-29.6	32.0	6.4
*Mar 1982 VEI5	Month	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
	11-Year Mean Value	80.6	44.4	53.4	62.6	44.9	80.7	68.4	89.2	74.8	90.7	74.7	51.0	80.6	44.4	53.4	62.6	44.9	80.7	68.4	89.2	74.8	90.7	74.7	51.0	80.6
	Recorded Monthly Precip	101.6	9.0	30.7	79.8	15.1	64.1	69.3	101.3	131.0	114.3	76.5	34.4	79.6	60.1	67.0	40.2	15.1	32.5	67.6	92.4	28.4	111.2	127.9	94.7	65.5
	% Difference	26.1	-79.7	-42.5	27.5	-66.4	-20.5	1.4	13.5	75.2	26.0	2.4	-32.5	-1.2	35.5	25.6	-35.8	-66.4	-59.7	-1.1	3.6	-62.0	22.6	71.2	85.8	-18.7
*Apr 1991 VEI6	Month	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
	11-Year Mean Value	67.8	50.7	49.1	50.8	78.8	52.9	88.0	68.6	77.0	80.4	61.1	72.2	67.8	50.7	49.1	50.8	78.8	52.9	88.0	68.6	77.0	80.4	61.1	72.2	67.8
	Recorded Monthly Precip	90.0	6.6	57.0	19.5	26.0	39.4	82.1	84.2	59.0	40.2	95.7	70.7	36.8	52.2	59.4	146.5	64.2	47.6	101.3	63.2	90.3	17.5	39.0	82.3	129.8
	% Difference	32.7	-87.0	16.0	-61.6	-67.0	-25.5	-6.7	22.7	-23.4	-50.0	56.5	-2.1	-45.8	3.1	20.9	188.3	-18.5	-10.0	15.1	-7.9	17.2	-78.2	-36.2	13.9	91.3

*** Denotes low-latitude eruption**

The months following the 1860 eruption of Katla had notably reduced rainfall in Armagh. Eight of the 12 months following the event received less rain than was the 11-year norm. These reductions included -17.6% in December 1860 (TM+7), but went as high as -41.2% in July 1860 (TM+2), -62.7% in September 1860 (TM+4), and -74.6% in May 1861 (TM+12). The four months after May 1861 had noteworthy increases in precipitation of up to +88.1%, only to be followed by further reductions in three of the five months from October 1861 (TM+17) to February 1862 (TM+21).

March 1875, the month of the VEI 5 eruption of Askja in Iceland, contained a reduction of -45.8% in precipitation in Armagh, followed by a further reduction in April (-93%). The next seven months all had increases in precipitation values, with a maximum of +51.3% occurring in September 1875 (TM+6). December 1875 (TM+9) and January 1876 (TM+10) contained more reductions in precipitation (-34.2% and -52.4% respectively). These were followed by two months of increased precipitation, and a further eight straight months of reduced rainfall where values ranged from -2.8% in November 1876 (TM+20) to -74.4% in May 1876 (TM+14). The eruption of Krakatau in May 1883 coincided with a reduction in rainfall of -22.8% in Armagh that month, which was followed by a slight increase of just +0.6% in June, and a further fall of -33.8% in July. It was not until December 1883 (TM+7) that another reduction in precipitation occurred (-19.3%). 1884 had reduced rainfall in five months, including April (-5.1%), June (-66.4%) and November (-20.4%), with further reductions in total precipitation coming in January (TM+20), March (TM+22) and May (TM+24).

December 1902, the month of the eruption of Grímsvötn in Iceland, coincided with a reduction in precipitation in Armagh of -2.1%. This was followed by large increases in January and March 1903 (+91.3% and +78.9%). Yet these months were followed by a reduction in precipitation in April (TM+4, -50.7%) and June (TM+6, -59%). Further reductions did not occur again until November (TM+11) and December (TM+12) 1903 where levels dropped by -32.9% and -14.2% respectively. The four months between March (TM+15) and June (TM+18) 1904 again had less precipitation than the 11-year norm, with reductions including

-18.1% in April (TM+16) and -37.8% in June (TM+18). October, November and December 1904 had reductions of -65%, -20.9% and -29.5% in precipitation levels. The 13 months following the 1918 eruption of Katla coincided with precipitation values fluctuating above and below the 11-year means. The largest of the increases came in November 1918 (TM+1, +40.9%), with +33.7% occurring in January 1919. The reductions in precipitation levels tended to be more consistently prominent, with falls of -65.6% in February 1919 (TM+4), -47.8% in April 1919, -75.4% in July (TM+9) and -53.7% in October of the same year. Only three of the 10 months in 1920 examined here had reductions in rainfall levels in Armagh.

Of the 24 months following the March 1947 eruption of Hekla, 11 had reduced precipitation levels. Five of these were clustered between August 1947 (TM+5) and February 1948 (TM+11), with the most notable reduction of -84.4% occurring in the latter. The remaining six negative values came between the months of July 1948 (TM+16) and January 1949 (TM+22) but included less prominent reductions than those before, the largest being -29.6% in January 1949. Four of the five months immediately after the March 1982 eruption of El Chichón contained reduced precipitation levels, including -66.4% in July and -79.9% in April. The four remaining months in 1982 all had increases in precipitation. However seven of the 12 months in 1983 contained less rainfall than was the 11-year norm. Here values ranged from -1.1% in September (TM+18) to -59.7% in August (TM+17) and -66.4% in July 1983 (TM+16). Seven of the nine months following the eruption of Mt. Pinatubo in April 1991 also had reductions in rainfall, with most notable changes of -67% in August (TM+4) and -87% in May (TM+1). Eight of the remaining 16 months examined here had less precipitation than normal, with distinguished reductions coming in January 1992 (TM+9, -50%) and January 1993 (TM+21, -78.2%).

Figure 4.6 shows the mean percentage change in precipitation in Armagh in terms of five categories of volcano. Looking initially at the mean values for all nine eruptions, the first notable negative change comes in TM+4 where values

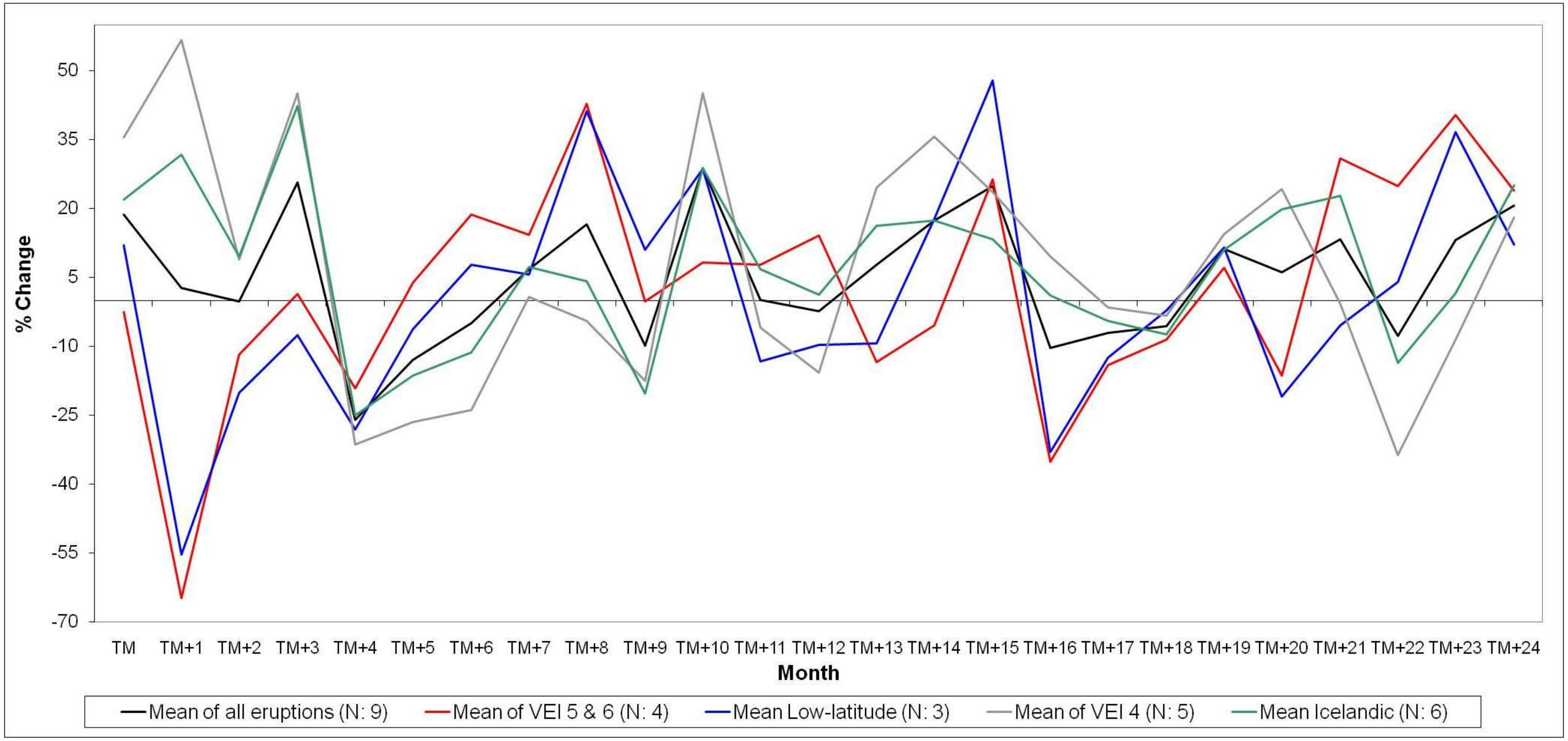


Figure 4.6: Five volcano categories showing the mean percentage change in monthly precipitation in Armagh in comparison to 11-year mean values centred on eruption years.

are reduced by 26.6%. This is followed by decreases of -12.2% in TM+5 and -5.2% in TM+6. TM+9 has a reduction of -11.8% on the 11-year mean, while six of the remaining 15 months have further reductions, with the most prominent (-13%) occurring in TM+16. The VEI 5 and 6 eruptions coincided with the largest reductions in precipitation levels. The month of the event itself has, on average, just 2.4% less precipitation, but is followed by -64.8% in TM+1 and -11.8% in TM+2. The large mean reduction in TM+1 is not the product of one significant decrease skewing the average, as reductions here include -79.9% following the eruption of El Chichón in 1982, -87% after the 1991 Mount Pinatubo event and -93% in the month after the eruption of Askja in 1875. TM+4 has a mean reduction of -19.2%, and it is not until TM+13 that another negative value occurs (-11.3%). This is followed by -11.7% in TM+14, -33.6% in TM+16, and -16.8% in both TM+17 and TM+20.

The low-latitude volcanic eruptions, on average, coincide with reduced precipitation in Armagh in each of the first five months following the event. These changes include -55.4% in TM+1 (again, a result not skewed by any one value) and -28.1% in TM+4. The months TM+11 to TM+13 have more reductions, the largest being -12.2% in the latter. Five of the six months between TM+16 and TM+21 contain less rainfall than normal, with the most notable value (-30.4%) occurring in TM+16. Eight of the nine months between TM+4 and TM+12 of Icelandic VEI 4 eruptions have a fall in precipitation levels in Armagh. The higher values come in TM+4, TM+5 and TM+6, with results of -32.5%, -24.9% and -24.3% respectively. Of the remaining 12 months examined here, only four have negative values, the peak (-33.9%) occurring in TM+22. The largest reduction in precipitation in comparison to the 11-year mean following all Icelandic volcanic eruptions tends to come in TM+4, where the mean reduction is -25.9%. Other values include -15.1% in TM+5 and -23.8% in TM+9. Overall, Figure 4.6 shows that the first month following VEI 5 and 6 eruptions, or low-latitude eruptions, is when the greatest reduction in precipitation can be expected in Armagh, while the same month coincides with the largest increase following Icelandic VEI 4 events.

4.2.2 Days with zero precipitation recorded

Table 4.7 shows the number of days per month within which no precipitation was recorded in Armagh. It compares this to the 11-year mean value for each month centred on the eruption year, while also showing the difference (in days) between these two values. Figure 4.7 goes on to show the mean change in zero-precipitation days in the months following volcanic eruptions in terms of the same five categories of volcano examined in previous sections. In October 1845, one month after the eruption of Hekla, there was a +3.2 day increase in the number of days without any precipitation in Armagh (Table 4.7). This was followed by another increase on the norm, albeit by only +0.6 days in November. Six of the eight months between May 1846 (TM+8) and December 1846 (TM+15) contained more days with zero precipitation than was the 11-year mean. These included highs of +6.1 days in December and +8.2 days in August. Five of the nine months from 1847 included for analysis here also had an increase in the number of zero-precipitation days in Armagh.

Eight of the first 13 months that followed the 1860 eruption of Katla had increases on the number of days within which no precipitation was recorded. The first of these came in July 1860 (TM+2, +3.1 days) and was followed by a further increase of +7.7 days in September (TM+4). Other notable increases included +7.1 days in December (TM+7), +4.6 days in January 1861 and +6.5% in April 1861 (TM+11). Three of the remaining 11 months also had increases in zero-precipitation days, including +7.9 days in October 1861 (TM+17). The eruption of Askja in March 1875 coincided with a +4.6 day increase in dry days in Armagh, and was followed by another increase in April, this time by +11.2 days. July (TM+4) had an increase of +3.7 days, with +3.8 days in September of the same year. The months of November to January 1876 all had increases on the 11-year mean, the most notable being +5.1 days in January (TM+10). Each of the months between May and December 1876 had increases in the number of days within which there was no precipitation recorded in Armagh. The largest increase came in May (TM+14, +10.6 days), with other notable increases occurring in July (+6.7 days), August (+5.5 days) and October (TM+19, +7.4 days).

Table 4.7: Twenty-five months of data relating to days without precipitation in Armagh following volcanic eruptions, including the 11-year mean value for each month, recorded total monthly zero-precipitation days and the difference, in days, between these records.

Event		Monthly zero-precipitation data																								
		TM	TM+1	TM+2	TM+3	TM+4	TM+5	TM+6	TM+7	TM+8	TM+9	TM+10	TM+11	TM+12	TM+13	TM+14	TM+15	TM+16	TM+17	TM+18	TM+19	TM+20	TM+21	TM+22	TM+23	TM+24
Sep 1845 VEI4	Month	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept
	11-Year Mean Value	17.3	13.8	12.4	15.9	14.9	15.7	16.7	12.8	17.3	15.9	12.8	14.8	17.3	13.8	12.4	15.9	14.9	15.7	16.7	12.8	17.3	15.9	12.8	14.8	17.3
	Recorded No. of Days	15	17	13	12	9	13	14	10	18	19	10	23	23	10	16	22	12	19	14	9	18	16	17	17	14
	Difference	-2.3	3.2	0.6	-3.9	-5.9	-2.7	-2.7	-2.8	0.7	3.1	-2.8	8.2	5.7	-3.8	3.6	6.1	-2.9	3.3	-2.7	-3.8	0.7	0.1	4.2	2.2	-3.3
May 1860 VEI4	Month	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
	11-Year Mean Value	16.4	13.3	14.9	13.4	12.3	10.1	12.4	10.9	10.4	12.3	12.5	14.5	16.4	13.3	14.9	13.4	12.3	10.1	12.4	10.9	10.4	12.3	12.5	14.5	16.4
	Recorded No. of Days	15	7	18	11	20	7	16	18	15	12	3	21	22	15	9	7	9	18	8	17	4	15	12	9	12
	Difference	-1.4	-6.3	3.1	-2.4	7.7	-3.1	3.6	7.1	4.6	-0.3	-9.5	6.5	5.6	1.7	-5.9	-6.4	-3.3	7.9	-4.4	6.1	-6.4	2.7	-0.5	-5.5	-4.4
Mar 1875 VEI5	Month	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
	11-Year Mean Value	13.4	14.8	16.4	13.7	11.3	13.5	11.2	9.6	10.0	14.1	12.2	11.2	13.4	14.8	16.4	13.7	11.3	13.5	11.2	9.6	10.0	0.0	12.2	11.2	13.4
	Recorded No. of Days	18	26	12	10	15	12	15	6	11	18	17	9	8	13	27	16	18	19	16	17	14	4	2	2	3
	Difference	4.6	11.2	-4.4	-3.7	3.7	-1.5	3.8	-3.6	1.0	3.9	4.8	-2.2	-5.4	-1.8	10.6	2.3	6.7	5.5	4.8	7.4	4.0	4.0	-10.2	-9.2	-10.4
*May 1883 VEI6	Month	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
	11-Year Mean Value	12.8	13.5	9.7	13.5	10.8	11.5	7.6	11.8	12.0	10.4	11.7	12.8	12.8	13.5	9.7	13.5	10.8	11.5	7.6	11.8	12.0	10.4	11.7	12.8	12.8
	Recorded No. of Days	11	10	12	12	8	9	2	6	5	8	7	16	13	17	9	10	7	8	4	4	10	6	11	12	8
	Difference	-1.8	-3.5	2.3	-1.5	-2.8	-2.5	-5.6	-5.8	-7.0	-2.4	-4.7	3.2	0.2	3.5	-0.7	-3.5	-3.8	-3.5	-3.6	-7.8	-2.0	-4.4	-0.7	-0.8	-4.8
Dec 1902 VEI4	Month	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	11-Year Mean Value	10.8	11.5	9.7	12.0	11.6	12.7	14.4	15.2	11.4	13.3	9.5	11.2	10.8	11.5	9.7	12.0	11.6	12.7	14.4	15.2	11.4	13.3	9.5	11.2	10.8
	Recorded No. of Days	17	13	8	5	16	14	21	12	5	13	4	14	14	11	7	4	11	19	18	14	8	16	14	9	14
	Difference	6.2	1.5	-1.7	-7.0	4.4	1.3	6.6	-3.2	-6.4	-0.3	-5.5	2.8	3.2	-0.5	-2.7	-8.0	-0.6	6.3	3.6	-1.2	-3.4	2.7	4.5	-2.2	3.2
Oct 1918 VEI4	Month	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
	11-Year Mean Value	11.7	9.5	7.6	9.1	9.5	12.6	12.5	12.8	14.9	12.5	11.7	12.4	11.7	9.5	7.6	9.1	9.5	12.6	12.5	12.8	14.9	12.5	11.7	12.4	11.7
	Recorded No. of Days	3	11	4	5	18	9	10	18	13	23	12	7	16	8	2	2	11	9	6	7	13	8	16	11	16
	Difference	-8.7	1.5	-3.6	-4.1	8.5	-3.6	-2.5	5.2	-1.9	10.5	0.3	-5.4	4.3	-1.5	-5.6	-7.1	1.5	-3.6	-6.5	-5.8	-1.9	-4.5	4.3	-1.4	4.3
Mar 1947 VEI4	Month	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
	11-Year Mean Value	14.6	12.6	14.4	12.7	12.6	11.4	10.3	13.4	11.6	8.4	9.5	11.4	14.6	12.6	14.4	12.7	12.6	11.4	10.3	13.4	11.6	8.4	9.5	11.4	14.6
	Recorded No. of Days	9	10	10	11	11	28	12	21	11	15	8	15	14	14	20	10	17	8	11	15	15	11	12	10	16
	Difference	-5.6	-2.6	-4.4	-1.7	-1.6	16.6	1.7	7.6	-0.6	6.6	-1.5	3.6	-0.6	1.4	5.6	-2.7	4.4	-3.4	0.7	1.6	3.4	2.6	2.5	-1.4	1.4
*Mar 1982 VEI5	Month	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
	11-Year Mean Value	8.0	13.2	13.1	10.9	13.6	11.5	9.7	9.3	9.9	6.6	7.4	11.8	8.0	13.2	13.1	10.9	13.6	11.5	9.7	9.3	9.9	6.6	7.4	11.8	8.0
	Recorded No. of Days	10	23	13	12	18	7	11	5	6	6	6	16	8	9	9	16	21	20	8	11	16	8	2	10	15
	Difference	2.0	9.8	-0.1	1.1	4.4	-4.5	1.3	-4.3	-3.9	-0.6	-1.4	4.2	0.0	-4.2	-4.1	5.1	7.4	8.5	-1.7	1.7	6.1	1.4	-5.4	-1.8	7.0
*Apr 1991 VEI6	Month	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
	11-Year Mean Value	11.9	16.6	15.1	12.4	11.6	14.2	11.0	10.6	12.0	8.5	9.4	8.1	11.9	16.6	15.1	12.4	11.6	14.2	11.0	10.6	12.0	8.5	9.4	8.1	11.9
	Recorded No. of Days	14	25	9	16	16	19	7	4	17	21	8	3	5	15	23	12	7	11	11	3	14	5	14	15	8
	Difference	2.1	8.4	-6.1	3.6	4.4	4.8	-4.0	-6.6	5.0	12.5	-1.4	-5.1	-6.9	-1.6	7.9	-0.4	-4.6	-3.2	0.0	-7.6	2.0	-3.5	4.6	6.9	-3.9

***Denotes low-latitude eruption**

Only four of the 25 months examined in relation to the May 1883 eruption of Krakatau contained an increase in the number of days without rain. July 1883 (TM+2, +2.3 days) was the first of these, followed by April, May and June 1884 (+3.2 days, +0.2 days, +3.5 days). December 1902, the same month as the eruption of Grímsvötn in Iceland, had a +6.2 day increase in the number of dry days in Armagh. This was followed by +1.5 days in January 1903. April, May and June had further increases in zero-precipitation days, the most prominent of which (+6.6 days) came in June 1903 (TM+6). There were then four months where fewer dry days than the 11-year means were recorded. The final two months of 1903 reverse this trend, with +2.8 days in November and +3.2 days in December (TM+11, TM+12). Five months in 1904 had increases in dry days in Armagh, the highest of which was +6.3 days in May (TM+17). Nine of the 25 months associated with the October 1918 eruption of Katla contained more days without precipitation than normal. The first of these occurred in the first month following the eruption, November 1918, where there was an increase of +1.5 days. February 1919 had an increase of +8.5 days, with +5.2 days occurring in May (TM+7) and +10.5 days in July 1919. The largest increases of the remaining months came in August and October 1920 with +4.3 days each.

It was not until August 1947, five months after the eruption of Hekla, that an increase in the number of days without rain occurred in Armagh (+16.6 days). Of the remaining 19 months examined here, 13 had further increases in dry days. These included +7.6 days in October 1947 (TM+7), +6.6 days in December of the same year, and +3.6 days in February 1948 (TM+11). March 1982, the month of the eruption of El Chichón, coincided with a two-day increase in zero-precipitation days. This was followed by +9.8 days in April 1982. Three of the remaining eight months in 1982 also had increases in dry days, the largest of which occurred in July (TM+4, +4.4 days). Seven of the months in 1983 had more dry days than the 11-year mean. Values here included +5.1 days in June (TM+15), +7.4 days in July, +8.5 days in August and +6.1 days in November 1983 (TM+20). This was followed by another increase of +7 days in March 1984 (TM+24). Five of the six months following the eruption of Mt. Pinatubo in April 1991 had more dry days than normal, including +8.4 days in May (TM+1), and

+4.8 days in September (TM+5). December and January of 1991/1992 also had an increase, with +12.5 days in the latter and +5 days in the former. Of the remaining 15 months examined, only four had an increase in zero-precipitation days in Armagh, the largest coming in June 1992 (TM+14, +7.9 days).

Figure 4.7 shows the mean change of zero-precipitation days, in terms of five categories of volcano, in the 24 months following eruptions. Looking first at the mean result for all nine eruptions, there tends to be an increase (+2.6 days) in TM+1, with a further increases in TM+4 to TM+6 (+2.5, +0.5 days and +0.2 days). It is not until TM+9 that another increase occurs (+3.7 days). Of the remaining 15 months, eight tend to have at least a slight increase in the number of dry days, the largest of which comes in TM+17 (+2 days) with +1.8 days in TM+11. The months following VEI 5 and 6 eruptions contain more notable increases, starting with the month of the eruption itself (+1.7 days), followed by +6.5 days in TM+1. TM+9 has the next large increase (+3.4 days), with the same increase in TM+14 and +2.5 days in TM+20. The three low-latitude eruptions again tend to be followed by the most prominent increase in zero-precipitation days in TM+1 (+4.9 days), with the next noteworthy result coming in TM+9 (+3.2 days). Other increases include +2 days in both TM+4 and TM+20.

The Icelandic VEI 4 eruptions tend to not be followed by an increase in the number of days without precipitation on the 11-year mean until TM+4 (+2.6 days). Six of the next eight months also have increases, including +2.8 days in TM+7, +3.9 days in TM+9, +3.2 days in TM+11 and +3.6 days in TM+12. Of the remaining four monthly increases in dry days, TM+22 (+3 days) stands out. The most notable increase in zero-precipitation days following all Icelandic eruptions combined occurs in TM+9 (+3.9 days). This is preceded by five months of less considerable increases, the highest of which is +2.8 days in TM+4. Eight of the 14 months between TM+11 and TM+24 also have increases. TM+11 contains a value of +2.3 days, with +2.1 days in TM+12 and +2.7 days in TM+17.

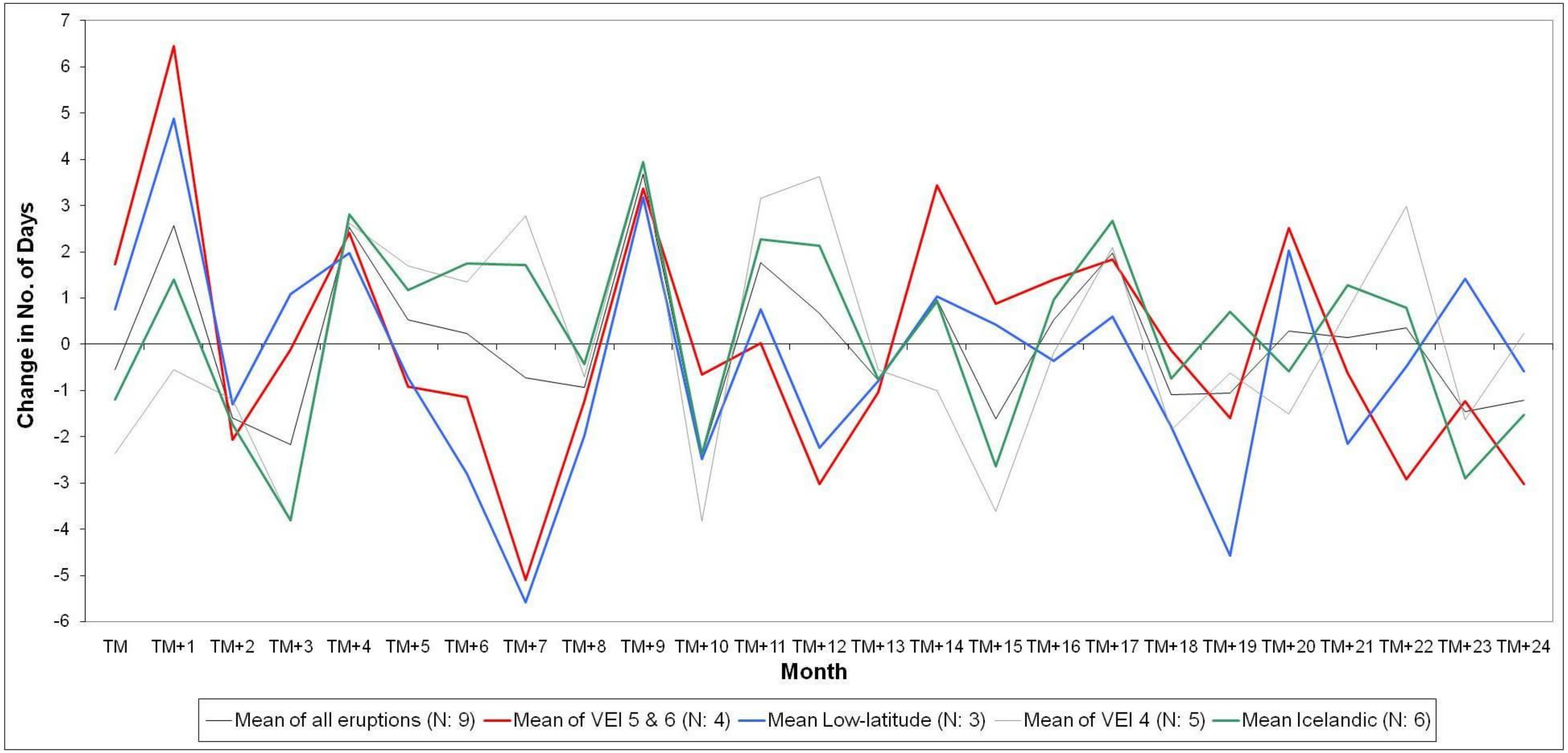


Figure 4.7: Five volcano categories showing the mean change in the number of zero-precipitation days per month in Armagh in comparison to 11-year mean values centred on eruption years.

4.2.3 Seasonal precipitation change

To further investigate the influence of volcanic eruptions on precipitation values in Armagh, Table 4.8 presents the difference, in percent, between total winter precipitation in TY, TY+1 and TY+2 in Armagh Observatory and the 11-year mean value for each season centred on eruption years. Figure 4.8 shows the mean percent changes in precipitation that occurred Armagh in TY, TY+1 and TY+2 in terms of five categories of volcanic eruption. The total winter precipitation in Armagh falls below the 11-year mean in TY of eruptions on five out of the nine cases, including reductions of -13% for the 1991 VEI 6 Mount Pinatubo event and -19.5% for the 1860 VEI 4 eruption of Katla. The four increases in total winter precipitation peaked at +37.4% for the VEI 6 eruption of Krakatau in 1883. Only two of the nine volcanic eruptions examined were followed by reductions in winter precipitation in Armagh in TY+1. Here the 1845 VEI 4 eruption of Hekla was followed by 7.3% less than the 11-year mean. The winter in TY+1 of the eruption of Mount Pinatubo had 21.9% less rain than average. The increases that occurred in TY+1 ranged from as small as +6.8% following the 1860 VEI 4 Katla event to +54.2% for the eruption of El Chichón in 1982 and +95.2% following the 1875 Askja event. Three eruptions coincided with reductions in winter precipitation in TY+2 (Katla in 1860 and 1918: -3.5% and -12%; El Chichón in 1982: -30%). The six increases that occurred peaked at +55.5% following the eruption of Mount Pinatubo in 1991.

The mean changes in precipitation seen in Figure 4.8 show that, in almost every case, an increase in winter values can be expected in all years associated with volcanic eruptions. The mean of all nine events sees a slight increase of +3% in TY, with +25% in TY+1 and +8% in TY+2. The VEI 5 and 6 events follow a similar pattern, with a small increase (+4%) in TY, followed by increases in values of +37% and +8% in the next two years. Yet again, the same pattern appears in relation to the Icelandic VEI 4 eruptions: +3% in TY, +18% in TY+1 and +8% in TY+2. The only mean decrease in total winter precipitation in Armagh Observatory, albeit a minuscule one (-0.2%), comes in the year of an Icelandic event. Four of the six eruptions associated with this result recorded a

Table 4.8: Percent difference between total Armagh Observatory winter precipitation and the 11-year mean value centred on eruption years in TY, TY+1 and TY+2 of eruptions.

Event	% Change from 11-year Mean		
	TY	TY+1	TY+2
Sep 1845 VEI4	7.2	-7.3	42.6
May 1860 VEI4	-19.5	6.8	-3.5
Mar 1875 VEI5	-13.4	95.2	3.0
***May 1883 VEI6**	37.4	20.6	3.3
Dec 1902 VEI4	-2.5	34.7	8.8
Oct 1918 VEI4	-9.8	33.5	-12.0
Mar 1947 VEI4	37.0	10.3	6.5
***Mar 1982 VEI5**	4.0	54.2	-30.0
***Apr 1991 VEI6**	-13.0	-21.9	55.5

*Denotes low-latitude eruption

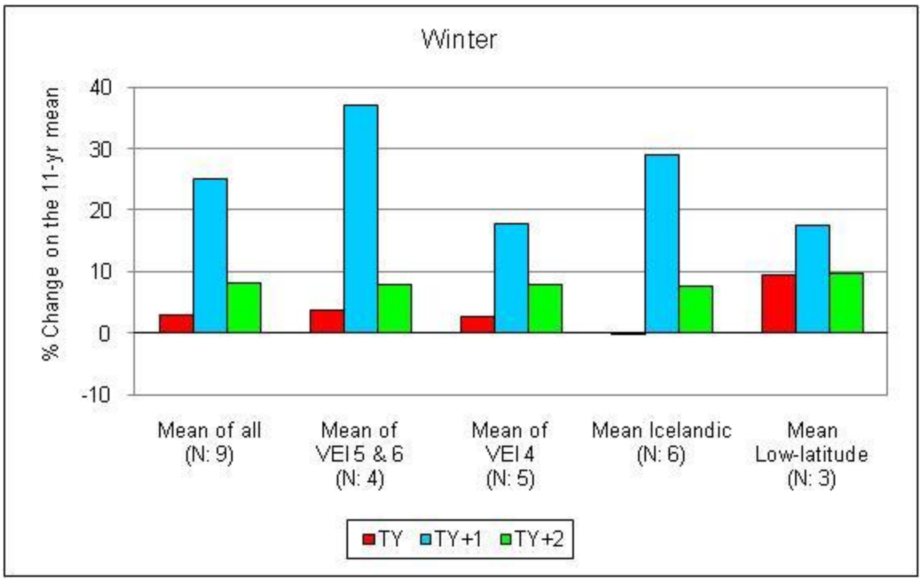


Figure 4.8: Five volcano categories indicating mean VEI- and location specific percent changes in total winter precipitation in Armagh Observatory for three years associated with eruptions.

reduction in values in TY. However, the remaining two saw sufficiently large increases to essentially cancel out the reductions linked to the other events. This minimal decrease is followed be increases of +29% and +8% in the next two years examined. The three years associated with low-latitude eruptions had three increases in total winter precipitation in Armagh, the most notable value (+18%) coming in TY+1.

Volcanic eruptions coincided with reduced total spring precipitation in Armagh on four occasions (Table 4.9), including -20.7% for the 1982 VEI 5 eruption of El Chichón and -45.4% for the 1875 VEI 5 Askja event. The increases that occurred ranged from as little as +1.3% to +85.3%, both in relation to VEI 4 Hekla eruptions in 1845 and 1947 respectively. Only three of the events analysed were followed by reduced precipitation on the 11-year mean in TY+1: -5% for the eruption of Askja in 1875, -18.9% for the 1883 Krakatau event and -12.3% for the 1902 Grímsvötn eruption. The increases were slightly more notable, with the largest, +42.1%, coming in the year after the Katla eruption in 1860. TY+2 had five reductions in total spring precipitation in Armagh Observatory, including -28.7% following the 1860 Katla event and -44.1% following the eruption of El Chichón in 1982. The five increases in TY+2 peaked at +47.7% following the 1875 Askja event.

The mean changes in total spring precipitation values in Figure 4.9 show that the only category to have a decrease in the year of an eruption is the VEI 5 and 6 events (-10%). The increases in TY are quite small, with the most notable being +12% in the year of VEI 4 Icelandic eruptions. The largest increase in TY+1 occurs, on average, following the Icelandic VEI 4 eruptions again (+19%), while all the Icelandic events together see an increase in spring precipitation of +15% with +12% following the low-latitude eruptions. The most prominent decreases in TY+2 tend to occur following the low-latitude and Icelandic VEI 4 eruptions (-8% each).

Table 4.9: Percent difference between total Armagh Observatory spring precipitation and the 11-year mean value centred on eruption years in TY, TY+1 and TY+2 of eruptions.

Event	% Change from 11-year Mean		
	TY	TY+1	TY+2
Sep 1845 VEI4	1.3	15.7	15.7
May 1860 VEI4	-16.3	42.1	-28.7
Mar 1875 VEI5	-45.4	-5.0	47.7
***May 1883 VEI6**	12.3	-18.9	11.7
Dec 1902 VEI4	11.3	-12.3	-8.6
Oct 1918 VEI4	-20.3	32.7	-17.9
Mar 1947 VEI4	85.3	17.7	-1.5
***Mar 1982 VEI5**	-20.7	15.9	-44.1
***Apr 1991 VEI6**	13.1	39.7	7.5

*Denotes low-latitude eruption

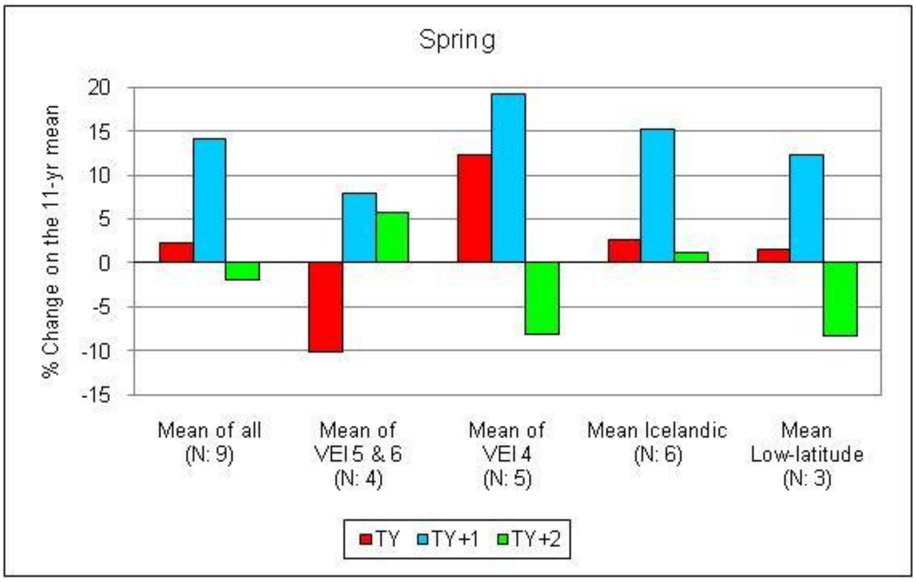


Figure 4.9: Five volcano categories indicating mean VEI- and location specific percent changes in total spring precipitation in Armagh Observatory for three years associated with eruptions.

Decreases in summer precipitation in Armagh (Table 4.10) occurred in TY in six of the nine cases examined, including -20.3% for the 1947 VEI 4 Hekla eruption, -27.6% for the VEI 4 eruption of Katla in 1918 and -42.6% for the 1991 VEI 6 Mount Pinatubo event. Five of the nine eruptions were followed by reduced precipitation in TY+1, with the most prominent values, -53.3% and -52.8%, coming in the years after the 1982 VEI 5 El Chichón and 1845 VEI 4 Hekla events. The most notable increase in any total summer precipitation value in Armagh came following 1860 eruption of Katla (+74.7%). Only four of the eruptions were followed by reduced precipitation in TY+2, with values ranging from -2% following the El Chichón eruption in 1982 to -49.3% for the eruption of Krakatau in 1883. The most notable increase in precipitation (+31.1%) came in TY+2 of the 1902 VEI 4 Grímsvötn event.

The mean changes in total summer precipitation in the years associated with volcanic eruptions (Figure 4.10) show very different results to those of the previous seasons examined. Here, reductions in precipitation can, on average, be expected following any of the nine eruptions. The largest of these changes comes in TY (-8%). The VEI 5 and 6 eruptions coincide with similar results, but with more prominent reductions on the 11-year means. TY tends have 12% less rain than normal, with -16% in TY+1 and -7% in TY+2. Of the three years associated with Icelandic VEI 4 eruptions, only the year of the event coincides with a reduction in summer precipitation (-5%). This is followed by increases of +7% in TY+1 and +6% in TY+2. An Icelandic eruption, on average, will coincide with a reduction of just -0.3% in TY, followed by an increase of the same value in TY+1, with a further increase of +6% in the following year. Finally, the low-latitude eruptions correspond to a -23% reduction in total summer precipitation values in TY, followed by -10% in TY+1 and -13% in TY+2.

Total autumn precipitation levels in Armagh (Table 4.11) show that on only three occasions did a reduction in values on the 11-year mean occur in the year of an eruption: -1.8% for the 1991 Mount Pinatubo event, -4.5% for the 1947 Hekla eruption and -39.5% for the eruption of Katla in 1860. Some of the increases in TY were more prominent, including +46.3% for the eruption of Askja in 1875

Table 4.10: Percent difference between total Armagh Observatory summer precipitation and the 11-year mean value centred on eruption years in TY, TY+1 and TY+2 of eruptions.

Event	% Change from 11-year Mean		
	TY	TY+1	TY+2
Sep 1845 VEI4	2.8	-52.8	15.6
May 1860 VEI4	21.9	74.7	19.0
Mar 1875 VEI5	21.8	-33.3	9.1
***May 1883 VEI6**	-9.7	-20.9	-49.3
Dec 1902 VEI4	-0.2	15.6	31.1
Oct 1918 VEI4	-27.6	-10.6	-8.0
Mar 1947 VEI4	-20.3	8.3	-28.9
***Mar 1982 VEI5**	-15.5	-53.3	-2.0
***Apr 1991 VEI6**	-42.6	44.4	12.8

*Denotes low-latitude eruption

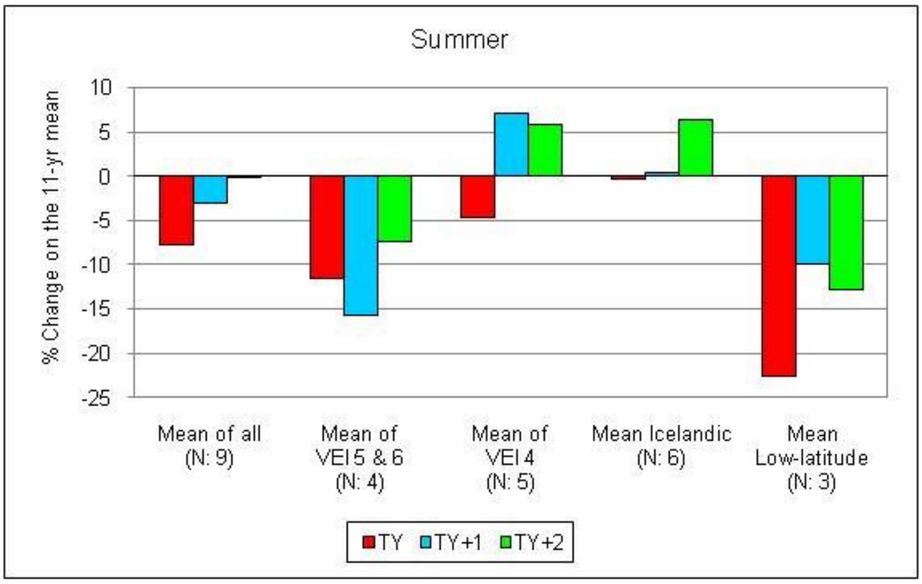


Figure 4.10: Five volcano categories indicating mean VEI- and location specific percent changes in total summer precipitation in Armagh Observatory for three years associated with eruptions.

and +54.7% for the 1918 Katla event. The trend was reversed in the year following eruptions, with six events coinciding with reductions in total autumn precipitation levels in Armagh. The more notable values include -18.9% following the eruption of El Chichón in 1982, -24.5% following the eruption of Katla in 1918 and -26.7% in TY+1 of the 1902 Grímsvötn event. The three increases in precipitation in TY+1 peaked with +25.4% following the VEI 4 eruption of Hekla in 1845. TY+2 had four reductions in total autumn precipitation values, including -6.9% for the 1845 Hekla event, -12.7% following the eruption of Mount Pinatubo in 1991 and -31.7% in the second year after the eruption of Grímsvötn in 1902. The increases in values ranged from as little as +0.9% following the 1860 Katla event to +19% following the eruption of Katla in 1918.

The mean changes in total autumn precipitation values in Armagh Observatory (Figure 4.11) display an obvious pattern in all five categories, in that an increase in precipitation will occur in the year of an eruption, and will be followed by decreases of varying intensity in the following two years. The mean of all nine eruptions gives an increase of +16% in TY, followed by decreases of -6% and -2% in the next two years. The VEI 5 and 6 events coincide with, on average, an increase of +28% in the year of an eruption, with -8% in TY+1 and -2% in TY+2. The same pattern, but to a smaller scale, is seen in the three years associated with VEI 4 and all Icelandic eruptions, with the most prominent decrease (-5%) coming in TY+1 of the latter category. The low-latitude eruptions coincide with an increase of +21% in total autumn precipitation on the 11-year mean in TY, followed by -7% in TY+1 and just -0.5% in TY+2.

Table 4.11: Percent difference between total Armagh Observatory autumn precipitation and the 11-year mean value centred on eruption years in TY, TY+1 and TY+2 of eruptions.

Event	% Change from 11-year Mean		
	TY	TY+1	TY+2
Sep 1845 VEI4	17.5	25.4	-6.9
May 1860 VEI4	-39.5	21.9	0.9
Mar 1875 VEI5	46.3	-12.9	-7.8
***May 1883 VEI6**	36.0	-3.5	4.6
Dec 1902 VEI4	7.0	-26.7	-31.7
Oct 1918 VEI4	54.7	-24.5	19.0
Mar 1947 VEI4	-4.8	-15.8	9.2
***Mar 1982 VEI5**	29.8	-18.9	6.4
***Apr 1991 VEI6**	-1.8	1.7	-12.7

*Denotes low-latitude eruption

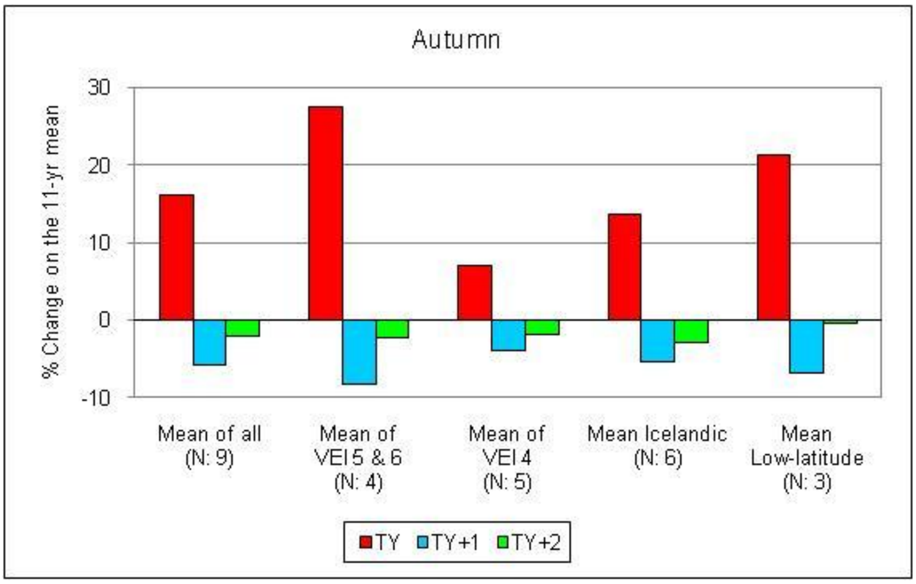


Figure 4.11: Five volcano categories indicating mean VEI- and location specific percent changes in total autumn precipitation in Armagh Observatory for three years associated with eruptions.

4.3 ARMAGH OBSERVATORY TEMPERATURE/PRECIPITATION AND INDICES OF CLIMATE VARIABILITY

Briffa *et al.* (1998) ran correlations between the mean April-September values of five Northern Hemisphere temperature series and Lamb's (1970) Dust Veil Index (DVI). For the period 1500-1990 they received an R value of -0.330 (P: 0.01). Meanwhile a correlation based on non-overlapping five-year averages – an effort to reduce the effect of delayed spatial responses and slight dating uncertainties – from 1500-1990 achieved a higher R value of -0.460 (P: 0.01). Table 4.12 contains the Pearson correlation coefficients achieved when mean seasonal temperatures and total seasonal precipitation from Armagh were correlated with Hurrell's (1995) recorded principal component North Atlantic Oscillation index for the months December to March (1899-2007), Jones *et al.*'s (1997) reconstructed seasonal NAO values (1825-2007), Lamb's (1970) Dust Veil Index (1800-2007), as well as DVI lagged to one year. Meanwhile Table 4.13 presents the Pearson correlation coefficients when Briffa *et al.*'s (1998) approach of using five-year non-overlapping averages was employed.

The most significant Pearson correlation coefficient was achieved between Jones *et al.*'s (1997) reconstructed winter NAO (December, January, February) and mean winter temperature (R: 0.694, P: 0.01), while Hurrell's (1995) recorded winter NAO produced an R value of 0.630 (P: 0.01) with winter temperatures. Precipitation in Armagh also correlates with changes in Jones *et al.*'s (1997) reconstructed North Atlantic Oscillation index, but to a less significant extent: winter precipitation R: 0.264 (P: 0.01), autumn precipitation R: 0.329 (P: 0.01). The only significant correlations between the yearly Dust Veil Index values and the weather data from Armagh came when the DVI, lagged to one year, was correlated with mean spring temperatures (R: -0.214 P: 0.01) and mean autumn temperatures (R: -0.157 P: 0.05).

Applying Briffa *et al.*'s (1998) method of correlating data with non-overlapping five-year averages produced far different results (Table 4.13). Firstly, the Jones *et al.*'s (1997) NAO and winter temperature correlation coefficients dropped to 0.552 (P: 0.01), while the same temperature data achieved a correlation of

Table 4.12: Pearson correlation coefficients between seasonal temperature and precipitation in Armagh Observatory and Hurrell’s (1995) PC based NAO values (1899-2007) and Jones *et al.*’s (1997) seasonal NAO values (1825-2007) as well as Lamb’s (1970) Dust Veil Index and DVI lagged to one year (1800-2007).

	Armagh Weather Data							
	WINTER		SPRING		SUMMER		AUTUMN	
	Temp.	**Precip.**	**Temp.**	**Precip.**	**Temp.**	**Precip.**	**Temp.**	**Precip.**
Hurrell's (1995) PC based winter NAO	0.630**	0.043	0.217*	-0.011	0.128	-0.249*	-0.048	-0.012
Jones *et al.* 's (1997) Seasonal NAO	0.694**	0.264**	0.163*	0.189*	0.102	-0.042	0.236**	0.329**
DVI	-0.113	-0.055	-0.093	0.095	0.013	-0.136	-0.138	0.021
DVI -1	-0.097	-0.030	-0.214**	0.125	-0.040	-0.140	-0.157*	-0.081

**: Correlation is significant at the 0.01 level

*: Correlation is significant at the 0.05 level

Table 4.13: Pearson correlation coefficients between five-year non-overlapping (after Briffa *et al.*, 1998) seasonal temperature and precipitation in Armagh Observatory and Hurrell's (1995) PC based NAO values (1899-2007) and Jones *et al.*'s (1997) seasonal NAO values (1825-2007) as well as Lamb's (1970) Dust Veil Index and DVI lagged to one year (1800-2007).

	Armagh Weather Data							
	WINTER		SPRING		SUMMER		AUTUMN	
	Temp.	**Precip.**	**Temp.**	**Precip.**	**Temp.**	**Precip.**	**Temp.**	**Precip.**
5-Year PC based winter NAO (Hurrell, 1995)	0.550*	-0.037	-0.058	0.140	-0.085	-0.142	-0.209	-0.505*
5-Year seasonal NAO (Jones *et al.*, 1997)	0.552**	0.142	0.326	0.427*	0.361*	-0.321	0.370*	0.264
5-Year DVI	-0.349*	-0.019	-0.375*	0.252	-0.108	-0.406*	-0.284	0.030
5-Year DVI -1	-0.329*	-0.071	-0.420**	0.263	-0.117	-0.437*	-0.281	-0.064

**: Correlation is significant at the 0.01 level

*: Correlation is significant at the 0.05 level

R: 0.550 (P: 0.05) with Hurrell’s (1995) recorded winter NAO values. The DVI, however, correlations with mean winter and spring temperatures in Armagh reached significant levels (winter R: -0.349 P: 0.05; spring R: -0.375 P: 0.05), as did summer precipitation (R: -0.406 P: 0.05). Meanwhile, the five-year non-overlapping mean values for the Dust Veil Index when lagged to one year produced significant correlations that at times surpass the influence of the North Atlantic Oscillation: winter temperature: R: -0.329 P: 0.05; spring temperature: R: -0.420 P: 0.01; summer precipitation: R: -0.437 P: 0.05.

4.4 WIND DIRECTION

For the purposes of the analysis of wind regimes in Armagh, only nine eruptions are included as there is no wind direction data available for 1835 or 1883, thus discounting the eruptions of Cosigüina and Krakatau. Tables 4.14 to 4.17 contain the number of days per month within which each of the volcano-related wind directions blew, namely northeasterly, easterly, southwesterly and westerly (see Dawson *et al.*, 1997; Kelly *et al.*, 1996; Groisman, 1992; Hunt, 1977). The tables also show the 11-year mean value for the month of each eruption and the six months after as well as the difference in days between these two measurements. Meanwhile, Figures 4.12 to 4.15 indicate the change from the norm in terms of the five categories of volcano employed in previous sections for each of the seven months analysed.

Two months associated with the eruption of Tambora in April 1815 had increased frequency in northeasterly winds, albeit by just 0.9 days in TM and 0.6 days in TM+3 (Table 4.14). None of the six months analysed following the eruption of Hekla in September 1845 had an increase in NE frequencies, while three of the months after the May 1860 Katla event did have increases, culminating in +8.2 days in TM+6. The eruption of Askja in March 1875 coincided with an increase of +1.9 days in NE winds, with three of the next six months having similar increases, the most notable of which (+2.8 days) came in TM+4. Only two months associated with the eruption of Grímsvötn in December 1902 did not have increases in NW frequency in Armagh. Of the months that did have such an increase, TM+6 was the largest (+5 days).

Table 4.14: Seven months of NE winds in Armagh (eruption month and the six following months), including an 11-year mean, the number of days per month with NE winds recorded, as well as the difference between these two measurements.

Event		Monthly Wind Direction Data						
		TM	TM+1	TM+2	TM+3	TM+4	TM+5	TM+6
*Apr 1815 VEI7	11-Year Monthly Mean	3.1	4.3	3.4	2.4	2.6	3.3	3.0
	Individual Monthly Record	4	1	3	3	1	3	3
	Difference (in Days)	0.9	-3.3	-0.4	0.6	-1.6	-0.3	0.0
Sept 1845 VEI4	11-Year Monthly Mean	2.0	2.1	1.6	1.2	1.4	1.0	2.7
	Individual Monthly Record	3	0	1	0	0	0	0
	Difference (in Days)	1.0	-2.1	-0.6	-1.2	-1.4	-1.0	-2.7
May 1860 VEI4	11-Year Monthly Mean	2.8	2.5	1.4	1.2	1.3	2.9	2.8
	Individual Monthly Record	2	3	1	0	3	2	11
	Difference (in Days)	-0.8	0.5	-0.4	-1.2	1.7	-0.9	8.2
Mar 1875 VEI5	11-Year Monthly Mean	2.1	4.4	4.2	2.7	2.2	3.5	2.5
	Individual Monthly Record	4	5	1	0	5	3	5
	Difference (in Days)	1.9	0.6	-3.2	-2.7	2.8	-0.5	2.5
Dec 1902 VEI4	11-Year Monthly Mean	1.3	0.9	1.5	2.3	2.1	2.5	4.0
	Individual Monthly Record	2	2	0	0	3	3	9
	Difference (in Days)	0.7	1.1	-1.5	-2.3	0.9	0.5	5.0
Oct 1918 VEI4	11-Year Monthly Mean	1.5	1.5	1.3	1.0	1.6	3.5	2.5
	Individual Monthly Record	3	0	0	2	4	4	1
	Difference (in Days)	1.5	-1.5	-1.3	1.0	2.4	0.5	-1.5
Mar 1947 VEI4	11-Year Monthly Mean	2.2	1.3	3.2	1.3	0.9	1.8	1.1
	Individual Monthly Record	5	2	3	3	2	7	2
	Difference (in Days)	2.8	0.7	-0.2	1.7	1.1	5.2	0.9
*Mar 1982 VEI5	11-Year Monthly Mean	1.9	2.4	1.4	2.4	1.5	0.7	0.5
	Individual Monthly Record	0	0	0	2	5	1	0
	Difference (in Days)	-1.9	-2.4	-1.4	-0.4	3.5	0.3	-0.5
*Apr 1991 VEI6	11-Year Monthly Mean	1.1	2.7	2.0	0.8	0.8	1.1	1.5
	Individual Monthly Record	1	0	1	3	1	3	2
	Difference (in Days)	-0.1	-2.7	-1.0	2.2	0.2	1.9	0.5

*Denotes low-latitude eruption

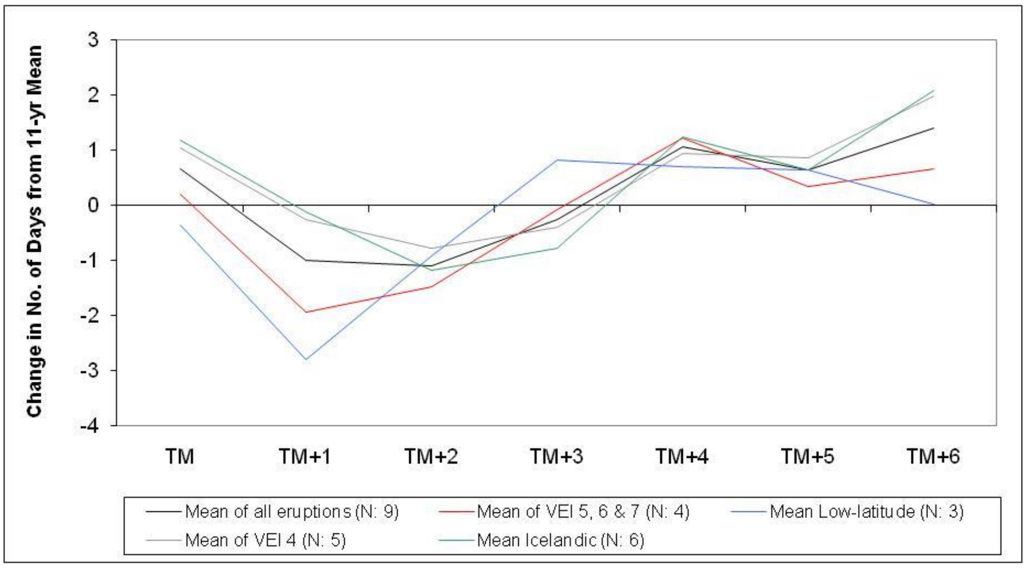


Figure 4.12: Five volcano categories showing seven months of change in NE winds in Armagh in relation to the 11-year mean.

The eruption of Katla in October 1918 coincided with an increase of +1.5 days in NE winds on the 11-year mean for that month, and was followed by further, equally slight, increases in TM+3 to TM+5. Only one month examined for the eruption of Hekla in March 1947 did not have an increase in northeasterly winds in Armagh. The most prominent increases that did occur include +2.8 days in TM and +5.2 days in TM+5. The fourth and fifth months after the eruption of El Chichón in March 1982 had increased frequencies of NE winds, with just +0.3 days in the latter and +3.5 days in the former. It was not until TM+3 of the eruption of Mount Pinatubo in 1991 that NE wind frequencies went above the 11-year mean. Here there were 2.2 days more than the average, while TM+5 and TM+6 had increases of +1.9 days and +0.5 days.

Figure 4.12 shows the mean change in NE winds in terms of volcano category over the seven months examined. The mean values for VEI 4 and Icelandic eruptions have a positive result in TM (+1 days and +1.2 days), with another slight increase (+0.2 days) in TM of VEI 5-7 events. As a result, the overall mean for the nine events also has a positive value in TM (+0.7 days). The VEI 5-7 and low-latitude eruptions both have negative values in TM+1 (-1.9 and -2.8 days), and are followed by negative values in all five categories in TM+2. Only the low-latitude events have positive results in TM+3 (+0.8 days). All five categories have increased frequencies in NE winds in TM+4 and TM+5. Looking at TM+4, the larger events have the most considerable increases, with +1.2 days for VEI 5-7 eruptions. Meanwhile the VEI 4 events have the highest value for TM+5 (+0.9 days). It is the VEI 4 and Icelandic categories that contain the most notable values in TM+6 (+2 and +2.1 days), while the VEI 5-7 eruptions coincide with +0.7 days, with no change for the low latitude events.

Five of the months associated with the April 1815 eruption of Tambora had increased frequency in E winds (Table 4.15), including +2.3 days in TM+3 and +5.6 days in TM+2. The September 1845 eruption of Hekla coincided with a 1.4 day increase in easterly wind in TM, and was followed by two further, but very slight, increases in TM+2 (+0.3 days) and TM+4 (+0.6 days). Three of the six months following the March 1860 eruption of Katla had at least some increase in

Table 4.15: Seven months of E winds in Armagh (eruption month and the six following months), including an 11-year mean, the number of days per month with E winds recorded, as well as the difference between these two measurements.

Event		Monthly Wind Direction Data						
		TM	TM+1	TM+2	TM+3	TM+4	TM+5	TM+6
*Apr 1815 VEI7	**11-Year Monthly Mean**	2.8	3.0	1.4	0.7	0.5	0.7	2.0
	Individual Monthly Record	4	5	7	3	0	1	2
	Difference (in Days)	1.2	2.0	5.6	2.3	-0.5	0.3	0.0
Sept 1845 VEI4	**11-Year Monthly Mean**	2.6	0.8	0.7	2.2	1.4	0.4	1.4
	Individual Monthly Record	4	0	1	0	2	0	0
	Difference (in Days)	1.4	-0.8	0.3	-2.2	0.6	-0.4	-1.4
May 1860 VEI4	**11-Year Monthly Mean**	3.7	1.2	0.5	0.6	0.9	2.0	2.1
	Individual Monthly Record	4	0	0	1	2	0	4
	Difference (in Days)	0.3	-1.2	-0.5	0.4	1.1	-2.0	1.9
Mar 1875 VEI5	**11-Year Monthly Mean**	3.0	4.2	2.9	2.5	0.9	2.0	1.9
	Individual Monthly Record	6	3	0	6	3	2	7
	Difference (in Days)	3.0	-1.2	-2.9	3.5	2.1	0.0	5.1
Dec 1902 VEI4	**11-Year Monthly Mean**	1.0	0.7	0.8	0.6	0.9	1.6	0.9
	Individual Monthly Record	1	0	0	0	2	2	1
	Difference (in Days)	0.0	-0.7	-0.8	-0.6	1.1	0.4	0.1
Oct 1918 VEI4	**11-Year Monthly Mean**	1.0	0.7	0.7	1.5	1.4	1.7	1.9
	Individual Monthly Record	1	0	0	2	2	2	1
	Difference (in Days)	0.0	-0.7	-0.7	0.5	0.6	0.3	-0.9
Mar 1947 VEI4	**11-Year Monthly Mean**	1.2	1.1	1.7	0.9	0.8	1.0	0.7
	Individual Monthly Record	0	0	0	1	0	2	0
	Difference (in Days)	-1.2	-1.1	-1.7	0.1	-0.8	1.0	-0.7
*Mar 1982 VEI5	**11-Year Monthly Mean**	1.1	1.5	1.2	0.7	0.4	0.5	0.1
	Individual Monthly Record	0	2	1	2	1	2	0
	Difference (in Days)	-1.1	0.5	-0.2	1.3	0.6	1.5	-0.1
*Apr 1991 VEI6	**11-Year Monthly Mean**	0.8	1.2	0.5	0.2	0.1	0.6	0.8
	Individual Monthly Record	0	0	1	0	0	1	0
	Difference (in Days)	-0.8	-1.2	0.5	-0.2	-0.1	0.4	-0.8

*Denotes low-latitude eruption

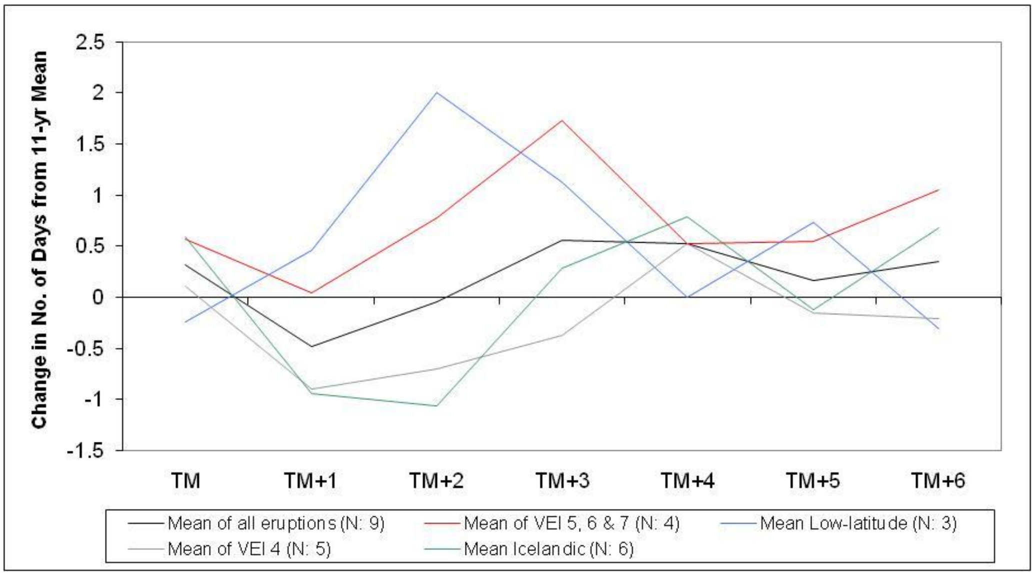


Figure 4.13: Five volcano categories showing seven months of change in E winds in Armagh in relation to the 11-year mean.

easterly winds in Armagh, the most notable of which, +1.9 days, came in TM+6. The four months of increased easterly winds associated with the May 1875 Askja event were each quite prominent, with an increase of +3 days in TM, +3.5 days in TM+3, +2.1 days in TM+4 and +5.1 days in TM+6.

It was not until four months after the December 1902 eruption of Grímsvötn that any increase on the easterly wind 11-year mean occurred in Armagh, albeit by just +1.1 days. It was followed by further less notable increases of +0.4 days in TM+5 and +0.1 days in TM+6. Similar minor increases occurred in the months after the October 1918 eruption of Katla. The largest of the three increases was by just +0.6 days in TM+4. Of the two months of increased easterly winds following the March 1947 Hekla eruption, only the +1 day increase in TM+5 stands out. Four of the five months following the eruption of El Chichón in March 1982 had increased E winds, including +1.3 days in TM+3 and +1.5 days in TM+5. Less notable increases of +0.5 days and +0.4 days came in TM+2 and TM+5 of the eruption of Mount Pinatubo in April 1991.

Figure 4.13 shows that four of the five categories of volcano had values higher than the 11-year mean in the eruption month, while low-latitude events (+0.5 days) had the only positive value in TM+1. The two categories relating to the larger eruptions had their frequency of E winds increase in TM+3 (VEI 5-7: +1.7 days; low-latitude: +1.1 days). In TM+4 the larger eruptions again had positive results (VEI 5-7: +0.5 days), while the Icelandic eruptions had the largest change (+0.8 days). The VEI 5-7 and low-latitude events become dominant once again (+0.5 and +0.7 days) in the following month. The low-latitude eruptions drop to -0.3 days below the mean in TM+6, with the mean result for the Icelandic events receiving the highest value (+0.7 days).

Table 4.16 contains the number of days within which southwesterly winds were recorded in Armagh in the months of, and the six months following, each of the nine volcanic eruptions. It was not until the sixth month after the 1815 eruption of Tambora that the number of days with SW winds went above the 11-year mean – a slight increase of just +0.4 days. The five previous months had

Table 4.16: Seven months of SW winds in Armagh (eruption month and the six following months), including an 11-year mean, the number of days per month with SW winds recorded, as well as the difference between these two measurements.

Event		Monthly Wind Direction Data						
		TM	TM+1	TM+2	TM+3	TM+4	TM+5	TM+6
*Apr 1815 VEI7	**11-Year Monthly Mean**	2.5	3.4	5.2	5.5	4.4	5.3	5.6
	Individual Monthly Record	0	2	2	2	4	5	6
	Difference (in Days)	-2.5	-1.4	-3.2	-3.5	-0.4	-0.3	0.4
Sept 1845 VEI4	**11-Year Monthly Mean**	6.7	8.8	8.2	6.7	7.8	7.4	5.6
	Individual Monthly Record	8	14	4	8	11	6	11
	Difference (in Days)	1.3	5.2	-4.2	1.3	3.2	-1.4	5.4
May 1860 VEI4	**11-Year Monthly Mean**	4.3	5.9	6.8	6.4	6.7	8.0	8.0
	Individual Monthly Record	2	9	4	7	3	11	5
	Difference (in Days)	-2.3	3.1	-2.8	0.6	-3.7	3.0	-3.0
Mar 1875 VEI5	**11-Year Monthly Mean**	7.6	3.7	5.7	6.5	7.7	7.5	6.7
	Individual Monthly Record	3	8	7	11	3	12	4
	Difference (in Days)	-4.6	4.3	1.3	4.5	-4.7	4.5	-2.7
Dec 1902 VEI4	**11-Year Monthly Mean**	8.2	9.5	6.6	6.7	5.1	4.5	4.5
	Individual Monthly Record	10	17	10	12	6	3	2
	Difference (in Days)	1.8	7.5	3.4	5.3	0.9	-1.5	-2.5
Oct 1918 VEI4	**11-Year Monthly Mean**	5.9	5.7	8.5	7.8	5.7	6.4	5.3
	Individual Monthly Record	9	9	11	6	1	8	14
	Difference (in Days)	3.1	3.3	2.5	-1.8	-4.7	1.6	8.7
Mar 1947 VEI4	**11-Year Monthly Mean**	5.7	6.1	3.4	5.1	6.1	7.7	9.0
	Individual Monthly Record	3	3	1	6	7	1	8
	Difference (in Days)	-2.7	-3.1	-2.4	0.9	0.9	-6.7	-1.0
*Mar 1982 VEI5	**11-Year Monthly Mean**	5.1	3.3	3.2	4.7	5.2	5.7	6.4
	Individual Monthly Record	7	2	5	1	5	12	8
	Difference (in Days)	1.9	-1.3	1.8	-3.7	-0.2	6.3	1.6
*Apr 1991 VEI6	**11-Year Monthly Mean**	4.5	3.6	5.0	4.5	6.0	5.0	5.5
	Individual Monthly Record	3	5	6	6	9	4	3
	Difference (in Days)	-1.5	1.4	1.0	1.5	3.0	-1.0	-2.5

*Denotes low-latitude eruption

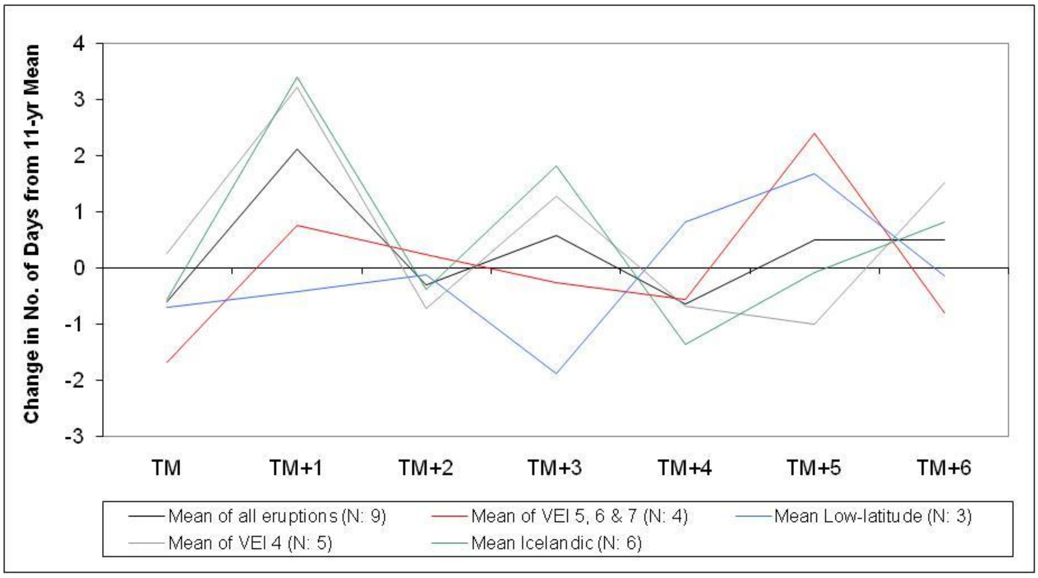


Figure 4.14: Five volcano categories showing seven months of change in SW winds in Armagh in relation to the 11-year mean.

decreases in SW winds varying from -0.3 days in TM+5 to -2.5 days in TM+3. The VEI 4 eruption of Hekla in 1845 was followed by more substantial increases in SW winds in Armagh. The most prominent of these was +5.4 days in TM+6, but also included +5.2 days in TM+1 and +3.2 days in TM+4. Three of the six months that followed the eruption of Katla in May 1860 had an increase in SW winds in Armagh, including +3.1 days in TM+1 and +3 days in TM+5. Four of the six months following the eruption of Askja in March 1875 had an increase in southwesterly winds on the 11-year mean. This included +4.3 days in TM+1, +4.5 days in TM+3 and +4.5 days in TM+5. The eruption of Grímsvötn in December 1902 was followed by four consecutive months of increased SW wind frequency in Armagh Observatory, with +7.5 days in TM+1 and +5.3 days in TM+3. Five of the seven months examined in relation to the October 1918 eruption of Katla had increases in SW winds, culminating in an increase of +8.7 days in TM+6. The two months that had any increased SW frequency following the March 1947 Hekla event (TM+3 and TM+4) did so by less than one day each. Of the seven months associated with the eruption of El Chichón in March 1982, TM+5 had the most notable increase (+6.3 days). Meanwhile, each of the four months immediately after the eruption of Mount Pinatubo in 1991 had increases in SW winds in Armagh, with only TM+4 (+3 days) providing any increase of note.

Figure 4.14 shows that, initially, it is all the Icelandic eruptions combined and VEI 4 Icelandic events that have an increase in SW wind frequency in Armagh, with +3.2 days in TM+1 for the latter and +3.4 days for the former. These two categories fall below the mean for TM+2, TM+4 and TM+5, but their TM+3 and TM+6 values are higher than any other category for those months, including +1.8 days for Icelandic events in TM+3 and +1.5 days for VEI 4 eruptions in TM+6. The most notable of three increases in SW winds following a low-latitude eruption tends to come in TM+5 (+1.7 days). The VEI 5-7 events show more change, peaking at an increase of frequency of +2.4 days in TM+5. In general, the figure shows that the largest increase in SW winds can be expected in TM+1 following Icelandic events, with the most noteworthy decrease occurring in TM+3 of low-latitude eruptions.

Table 4.17 shows the number of days within which westerly winds were recorded in the month of, and the six months following, each volcanic eruption. It also contains the 11-year mean value for each particular month, and goes on to compare these two datasets. Each of the months associated with the 1815 eruption of Tambora had, in some cases very notable, increases in the number of W wind days. These included +9.1 days, +6.2 days, +7.1 days and +12.7 days in TM+1 to TM+4. Four of the months associated with the September 1845 eruption of Hekla had increases on the mean number of W winds, the most noteworthy of which came in TM+3 (+4.6 days). Four of the six months following the eruption of Katla in May 1860 contained increased frequency in westerly winds in Armagh, with +3.5 days in TM+3, +2.5 days in TM+4 and +7 days in TM+5. Three of the months associated with the eruption of Askja in March 1875 had increases in W winds, including +3 days in TM+2 and +4 days in TM+6.

The December 1902 eruption of Grímsvötn coincided with an increase of +1.4 days in westerly winds in the month of the event, and was followed by two further, but not prominent, increases in TM+2 and TM+4. No significant increases in westerly winds occurred in the months associated with the eruption of Katla in October 1918, where each increase on the 11-year mean was less than one full day. In the months following the eruption of Hekla in March 1947, only TM+2 coincided with any increase in W winds (+0.5 days). Four of the seven months examined in relation to the March 1982 eruption of El Chichón had increased frequency in westerly winds, the most notable of which was only an increase of +1.8 days. The four months following the eruption of Mount Pinatubo in 1991 all had more days with westerly winds than the 11-year mean. However, the largest increase was just one day, coming in TM+2.

Figure 4.15, showing the change in W wind regimes on the 11-year mean in Armagh, makes it clear that, on average, the first month following low-latitude or VEI 5-7 eruptions will have the largest increases (+2.6 days for VEI 5-7 events; +3.8 days for low-latitude eruptions). The VEI 4 and Icelandic events have a

Table 4.17: Seven months of W winds in Armagh (eruption month and the six following months), including an 11-year mean, the number of days per month with W winds recorded, as well as the difference between these two measurements.

Event		Monthly Wind Direction Data						
		TM	TM+1	TM+2	TM+3	TM+4	TM+5	TM+6
*Apr 1815 VEI7	11-Year Monthly Mean	2.5	3.9	2.8	2.9	4.3	2.6	2.3
	Individual Monthly Record	7	13	9	10	17	4	4
	Difference (in Days)	4.5	9.1	6.2	7.1	12.7	1.4	1.7
Sept 1845 VEI4	11-Year Monthly Mean	2.0	2.3	3.0	2.4	2.7	4.3	2.9
	Individual Monthly Record	3	2	5	7	1	7	2
	Difference (in Days)	1.0	-0.3	2.0	4.6	-1.7	2.7	-0.9
May 1860 VEI4	11-Year Monthly Mean	3.4	3.7	4.6	4.5	3.5	3.0	3.3
	Individual Monthly Record	4	3	5	8	6	10	1
	Difference (in Days)	0.6	-0.7	0.4	3.5	2.5	7.0	-2.3
Mar 1875 VEI5	11-Year Monthly Mean	4.6	2.7	4.0	4.0	4.4	5.0	3.0
	Individual Monthly Record	4	2	7	4	5	4	7
	Difference (in Days)	-0.6	-0.7	3.0	0.0	0.6	-1.0	4.0
Dec 1902 VEI4	11-Year Monthly Mean	1.6	1.7	2.9	2.2	2.3	1.3	1.4
	Individual Monthly Record	3	0	3	2	3	0	0
	Difference (in Days)	1.4	-1.7	0.1	-0.2	0.7	-1.3	-1.4
Oct 1918 VEI4	11-Year Monthly Mean	1.6	1.8	2.5	1.6	2.2	1.7	4.2
	Individual Monthly Record	2	0	3	1	1	1	5
	Difference (in Days)	0.4	-1.8	0.5	-0.6	-1.2	-0.7	0.8
Mar 1947 VEI4	11-Year Monthly Mean	1.2	2.7	0.5	2.0	1.7	0.6	1.5
	Individual Monthly Record	1	1	1	1	0	0	1
	Difference (in Days)	-0.2	-1.7	0.5	-1.0	-1.7	-0.6	-0.5
*Mar 1982 VEI5	11-Year Monthly Mean	2.5	2.2	0.8	1.2	0.9	0.6	0.8
	Individual Monthly Record	3	4	0	0	0	2	1
	Difference (in Days)	0.5	1.8	-0.8	-1.2	-0.9	1.4	0.2
*Apr 1991 VEI6	11-Year Monthly Mean	1.1	0.6	1.0	1.1	0.5	0.9	0.5
	Individual Monthly Record	1	1	2	2	1	0	0
	Difference (in Days)	-0.1	0.4	1.0	0.9	0.5	-0.9	-0.5

*Denotes low-latitude eruption

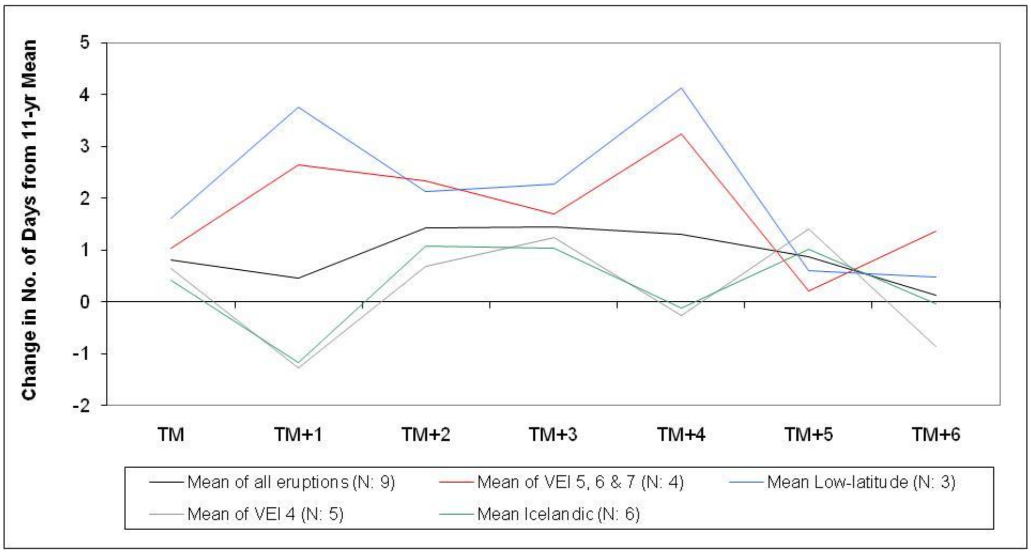


Figure 4.15: Five volcano categories showing seven months of change in W winds in Armagh in relation to the 11-year mean.

decrease in the number of days within which westerly wind blows in Armagh in TM+1 (-1.3 days and -1.2 days each). Values for all five categories stay above the mean for TM+2 and TM+3, with all Icelandic and VEI 4 Icelandic eruptions falling into negative values in TM+4. In this same month the VEI 5-7 and low-latitude eruptions increase to +3.3 days and +4.1 days. Again TM+5 has positive values for all five categories, with only the VEI 5-7 events having a notable increase in TM+6 (+1.4 days).

Having examined what are traditionally deemed to be the four most significant post-eruption wind directions, attention now turns to the remaining categories. The relevant tables and figures can be seen in Appendix 1. It is rare for any prominent increases in N winds (Table A1 and Figure A1) to occur following eruptions (+4.9 days in TM+3 of Tambora in April 1815; +5.3 days in TM+1 of Mount Pinatubo in April 1991). The mean results (Figure A1) show that it is only in TM+1 of the larger events (VEI 5-7 or low-latitude eruptions) that a notable increase occurs (+1.6 days and +2.3 days respectively). The remaining months examined tend to have values below the mean or at least remain close to it.

The mean NNE values (Table A2, Figure A2) indicate that, after an initial increase in frequency in TM, every category fell below the 11-year mean until the VEI 4 and Icelandic values moved into positive results in TM+4, with the same pattern in TM+5. Here, the most notable increase, +1.1 days, coincides with VEI 4 events. ENE winds are rare in Armagh (Table A3, Figure A3), with the vast majority of the 11-year mean values being below one day per month. As a result, the occurrence of any such day in post-eruption months gives the impression that a significant increase in frequency has taken place, most notably TM+3 of VEI 5-7 and low-latitude events and TM+4 of VEI 4 and Icelandic eruptions. A similar pattern is evident in Table A4. Again, an ESE wind is a rare occurrence in Armagh, with the months relating to the 1947 eruption of Hekla containing the most notable changes in frequency. The 11-year mean ESE value for the month of the eruption is 1.4 days, while the recorded value is six days. This is followed by a further increase of +2.1 days in TM+2. Figure A4 shows that there is a tendency for an above average frequency of ESE winds in most of the months relating to volcanic eruptions.

Fluctuations are a prominent feature of southeasterly winds in the months associated with volcanic eruptions (Table A5, Figure A5). TM+2 displays positive results for VEI 4 (+0.9 days) and Icelandic (+1 day) eruptions, while the larger events remain negative. All but the low-latitude category move below the 11-year mean in TM+3, with the same group showing positive values in TM+4 (+0.2 days). All five categories have negative values in TM+5, with the two larger categories of eruption showing positive results again in TM+6. A south-southeasterly wind is again a rare event in Armagh (Table A6 and Figure A6), with TM, TM+1 TM+2 and TM+4 of VEI 4 and Icelandic volcanic eruptions coinciding with increased frequencies, including a peak of +1 day in VEI 4 TM+1. The VEI 5-7 and low-latitude eruptions have a tendency to coincide with mainly negative values until TM+6, where the increase in frequency reaches a high of +1.1 days for low-latitude events.

Southerly wind days in Armagh (Table A7, Figure A7) stay above the mean for the first two months following an eruption. In TM+3 all five categories fall below the 11-year mean. Meanwhile TM+4 has increases in frequency in the VEI 5-7 and low-latitude categories, a pattern that repeats in TM+5 with increases of +1.8 days for the latter and +1.5 days for the former. TM+6 again has decreases in frequency for VEI 4 and Icelandic values, with further increases in the VEI 5-7 and low-latitude events (+0.4 days and +0.8 days). The volcanic eruption that precedes the greatest increase in frequency in SSW winds is Hekla (Table A8), with eleven out of the fourteen months analysed in relation to the 1845 and 1947 events containing a rise in values. The most notable increases following the 1845 event came in TM+2 (+2.2 days), TM+3 (+1.4 days) and TM+4 (+2.2 days). Five of the six months after the 1947 eruption had increased frequency, including +5 days in TM+1, +1.8 days in each of TM+2 and TM+4, with +2.3 days in TM+5 and +3.6 days in TM+6. The negligible impact of all the other eruptions is evident in Figure A8, as values vary less significantly in comparison to other wind directions. There is, however, a tendency to increase in TM+2, with all categories moving into positive values.

West-southwesterly winds (Table A9, Figure A9) vary only slightly over the time analysed. All five categories of volcano have positive values in TM, and TM+1. TM+2 has negative values throughout, while the VEI 4 and Icelandic eruptions are followed by slight increases in TM+3. All five categories record negative results in TM+4, with the larger events moving in to positive values in TM+5 (VEI 5-7: +0.8 days; low-latitude: +1.3 days). Each group falls well below the mean again in TM+6. Table A10 and Figure A10 show data relating to WNW winds in the months associated with volcanic eruptions. The VEI 5-7 and low-latitude events (Figure A10) remain below the mean for the entire time analysed. The VEI 4 and Icelandic events both have positive values in TM+2, TM+3 and TM+5, with results moving below the mean in TM+6.

Northwesterly winds almost always have a tendency to remain below the 11-year mean following volcanic eruptions (Table A11). The May 1860 Katla event is the exception to this, however, with five of the seven months analysed having an increase in frequency, including +3.2 days in TM+1 and +2.6 days in TM+2. It is in TM+2, followed by TM+4, that increases in NW wind frequencies tend to occur (see Figure A11), more specifically, in relation to VEI 5-7, VEI 4 and Icelandic eruptions, with all Icelandic events combined showing the largest increase in TM+4, albeit just +0.4 days. Values for these categories fall negative in TM+5 and remain there for TM+6. Finally, north-northwesterly winds (Table A12 and Figure A12) are another rare occurrence in Armagh, with mean increases in frequency only occurring in TM and TM+2 of VEI 5-7 and low-latitude eruptions, with a slight mean increase in TM of Icelandic eruptions.

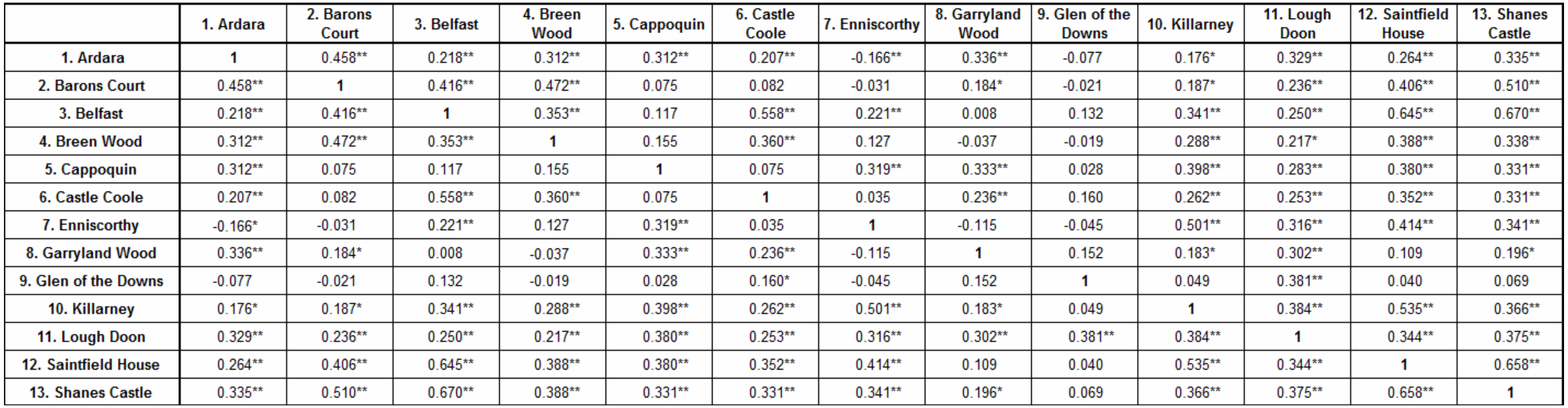
CHAPTER 5: *QUERCUS* TREE-RING RESULTS

Table 5.1 shows the intercorrelation values for all 13 tree-ring indices used in this study. The highest correlations tend to occur between series that have a close proximity to each other, with the chronologies from Belfast and Shanes Castle, both located in Co. Antrim, having an R value of 0.670 (P: 0.01) while Shanes Castle and Saintfield House in Co. Down have an R value of 0.658 (P: 0.01). However, significant correlations are also achieved between series that do not necessarily share proximity – the series in Killarney, Co. Kerry and Saintfield House have an R value of 0.535 (P: 0.01), while the same Killarney series has an R value of 0.501 (P: 0.01) with the series from Enniscorthy, Co. Wexford. Meanwhile, the series sourced at Lough Doon, Co. Leitrim has the highest number of significant correlations, with 11 of the other 12 series having R values that are significant at the 99% level, the highest being R: 0.384 with the Killarney series. The Glen of the Downs series has only one significant correlation with the other 12 series (R: 0.302 P: 0.01 with Lough Doon), while the Garryland Wood, Co. Galway series has four significant correlations, the highest of which (R: 0.336 P: 0.01) occurs with the series from Ardara, Co. Donegal, while the same Co. Galway series has an R value of 0.333 (P: 0.01) with the Cappoquin, Co. Wexford series.

5.1 TREE-RING GROWTH IN TY-1, TY, TY+1 AND TY+2 OF ERUPTIONS

This section will examine changes in tree-ring widths following the 11 volcanic eruptions under consideration. The analysis of the tree-ring indices will include examining the mean changes in growth index values in TY, TY+1 and TY+2 in terms of the series from the southern half of the island (Cappoquin, Co Waterford; Enniscorthy, Co. Wexford; Garryland Wood, Co. Galway; Glen of the Downs, Co. Wicklow; Killarney, Co. Kerry) where available, the northern half (Ardara, Co. Donegal; Barons Court, Co. Tyrone; Belfast, Co. Antrim; Breen Wood, Co. Antrim; Castle Coole, Co. Fermanagh; Lough Doon, Co. Leitrim; Saintfield House, Co. Down; Shanes Castle, Co. Antrim) where available, and the island of Ireland as a whole (combining data from each tree-

Table 5.1: Correlation values between each of the thirteen tree-ring chronologies used.



	1. Ardara	2. Barons Court	3. Belfast	4. Breen Wood	5. Cappoquin	6. Castle Coole	7. Enniscorthy	8. Garryland Wood	9. Glen of the Downs	10. Killarney	11. Lough Doon	12. Saintfield House	13. Shanes Castle
1. Ardara	**1**	0.458**	0.218**	0.312**	0.312**	0.207**	-0.166**	0.336**	-0.077	0.176*	0.329**	0.264**	0.335**
2. Barons Court	0.458**	**1**	0.416**	0.472**	0.075	0.082	-0.031	0.184*	-0.021	0.187*	0.236**	0.406**	0.510**
3. Belfast	0.218**	0.416**	**1**	0.353**	0.117	0.558**	0.221**	0.008	0.132	0.341**	0.250**	0.645**	0.670**
4. Breen Wood	0.312**	0.472**	0.353**	**1**	0.155	0.360**	0.127	-0.037	-0.019	0.288**	0.217*	0.388**	0.338**
5. Cappoquin	0.312**	0.075	0.117	0.155	**1**	0.075	0.319**	0.333**	0.028	0.398**	0.283**	0.380**	0.331**
6. Castle Coole	0.207**	0.082	0.558**	0.360**	0.075	**1**	0.035	0.236**	0.160	0.262**	0.253**	0.352**	0.331**
7. Enniscorthy	-0.166*	-0.031	0.221**	0.127	0.319**	0.035	**1**	-0.115	-0.045	0.501**	0.316**	0.414**	0.341**
8. Garryland Wood	0.336**	0.184*	0.008	-0.037	0.333**	0.236**	-0.115	**1**	0.152	0.183*	0.302**	0.109	0.196*
9. Glen of the Downs	-0.077	-0.021	0.132	-0.019	0.028	0.160*	-0.045	0.152	**1**	0.049	0.381**	0.040	0.069
10. Killarney	0.176*	0.187*	0.341**	0.288**	0.398**	0.262**	0.501**	0.183*	0.049	**1**	0.384**	0.535**	0.366**
11. Lough Doon	0.329**	0.236**	0.250**	0.217**	0.380**	0.253**	0.316**	0.302**	0.381**	0.384**	**1**	0.344**	0.375**
12. Saintfield House	0.264**	0.406**	0.645**	0.388**	0.380**	0.352**	0.414**	0.109	0.040	0.535**	0.344**	**1**	0.658**
13. Shanes Castle	0.335**	0.510**	0.670**	0.388**	0.331**	0.331**	0.341**	0.196*	0.069	0.366**	0.375**	0.658**	**1**

****. Correlation is significant at the 0.01 level**

***. Correlation is significant at the 0.05 level**

ring series). Table 5.2 contains climatic data from five weather stations in various parts of Ireland (Malin Head, Co. Donegal; Clones, Co. Monaghan; Claremorris, Co. Mayo; Rosslare, Co. Wexford; Valentia, Co. Kerry). It highlights the fact that mean temperatures in January and July can differ by almost 3°C (see Valentia and Clones mean January temperatures). Valentia and Clones again provide the biggest disparity in terms of rainfall, with 76 mm more falling in Valentia in January in comparison to Clones. Coastal and inland weather stations will obviously record different mean wind speeds – there is an average difference of 7.2 knots between Malin Head and Clones in January. Figure 5.1 shows the difference that exists between the five stations in terms of wind direction. Table 5.2 and Figure 5.1 highlight the fact that weather features differ from one end of the island of Ireland to the other, which means that growing conditions will vary from one area to the next. The analysis in this chapter will determine whether the impacts of volcanic eruptions manifest themselves better in the northern or southern half of the island as a result of these climatic disparities.

Table 5.3a shows the recorded TY-1, TY, TY+1 and TY+2 growth index values in 10 sites throughout the island of Ireland in reference to the VEI 5 eruption of Tambora in 1815, while Table 5.3b shows the difference in growth between the year before the eruption (TY-1) and the year of the eruption (TY), as well TY-1 and TY+1, and TY-1 and TY+2. Figure 5.2 shows the mean changes in growth index values in TY, TY+1 and TY+2 in terms of the northern and southern halves of the island, as well as the country as a whole. Of the 10 tree-ring series that encompass the eruption of Tambora (Table 5.3b), six had reduced ring-width in the year of the event. Here, values ranged from a very slight drop of -0.1% in Ardara, Co. Donegal, to -12.8% in Killarney and -15.8% in Shanes Castle, Co. Antrim. Seven locations had narrowed rings in 1816, the year following the eruption of Tambora. These reductions were larger than those of the previous year, including -23.4% in Barons Court, Co. Tyrone, -25.1% in Belfast, Co. Antrim and -25.7% in Castle Coole, Co. Fermanagh. The second year after the eruption coincided with reduced tree-ring growth in nine of the 10 series, with -38.4% in Barons Court, -40.6% in Shanes Castle, Co. Antrim and -53.3% in Enniscorthy, Co. Wexford. Only one location – The Glen of the Downs in Co.

Table 5.2: Climatic data from five stations in Ireland (1961-1990) (Met Éireann, 2010).

Location	Mean Temperature (Deg. C.)		Location	Mean Total Rainfall (mm)	
	Jan	Jul		Jan	Jul
1. Malin Head	5.4	13.8	1. Malin Head	114.2	71.8
2. Clones	4	14.5	2. Clones	90.8	60.3
3. Claremorris	4.3	14.3	3. Claremorris	121.1	63.4
4. Rosslare	6.1	15	4. Rosslare	94.9	50.6
5. Valentia	6.8	14.8	5. Valentia	167	73.3

Location	Wind Speed (knots)	
	Jan	Jul
1. Malin Head	17	13.2
2. Clones	9.8	6.9
3. Claremorris	10	7.5
4. Rosslare	12.9	9.5
5. Valentia	13.1	8.5

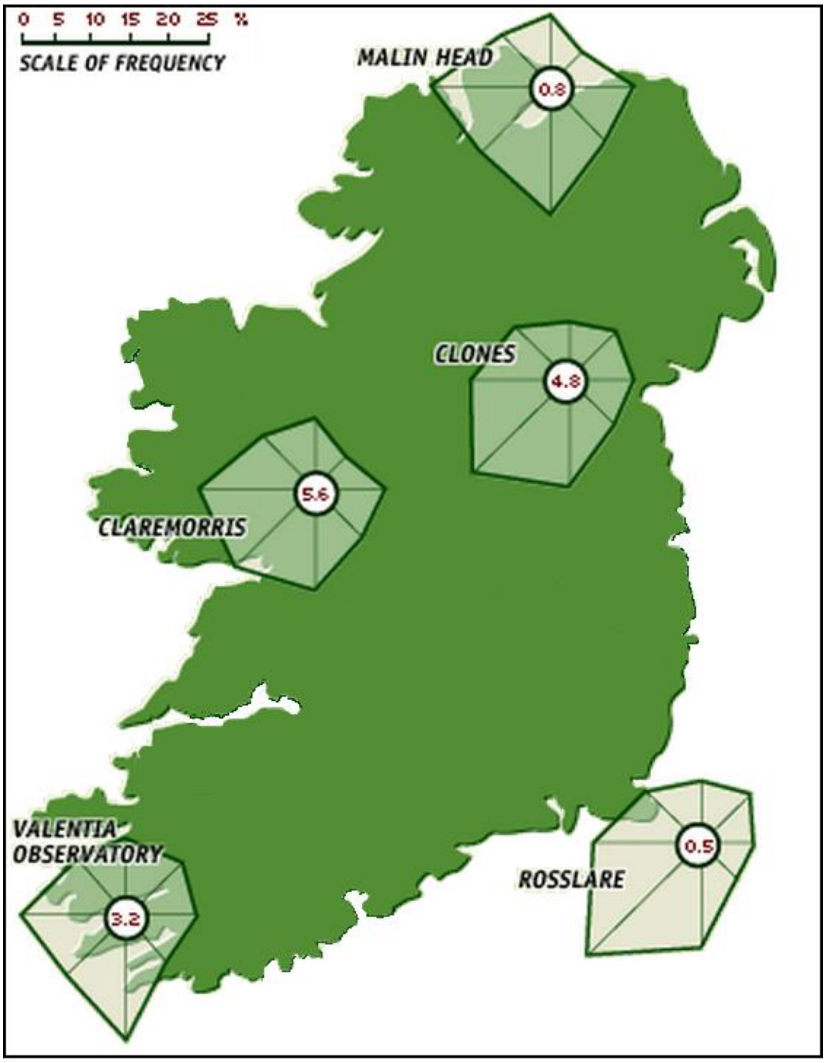


Figure 5.1: Wind direction, and percentage frequency of wind direction, in five weather stations, 1961-1990 (circled number = % calm) (Met Éireann, 2010).

Table 5.3a: Ten-site growth index values in TY-1, TY, TY+1 and TY+2 of April 1815 VEI 7 eruption of Tambora.

	Yearly Standard Growth Index Value			
Location	**TY-1**	**TY**	**TY+1**	**TY+2**
Ardara	1.01	1.009	1.125	0.642
Barons Court	0.998	1.021	0.764	0.615
Belfast	0.942	0.928	0.706	0.588
Breen Wood				
Cappoquin	1.121	1.047	1.727	1.058
Castle Coole	1.123	1.147	0.834	0.743
Enniscorthy	1.246	1.199	1.007	0.582
Garryland Wood				
Glen Of The Downs	0.324	0.421	0.419	1.052
Killarney Oak	1.402	1.222	1.187	1.069
Lough Doon				
Saintfield House	0.96	1.025	0.757	0.625
Shanes Castle	1.041	0.877	0.82	0.618

Table 5.3b: Percent difference between TY-1 & TY, TY-1 & TY+1 and TY-1 & TY+2 growth index values in ten sites following April 1815 VEI 7 eruption of Tambora.

	Percent Change from TY-1		
Location	**TY**	**TY+1**	**TY+2**
Ardara	-0.1	11.4	-36.4
Barons Court	2.3	-23.4	-38.4
Belfast	-1.5	-25.1	-37.6
Breen Wood			
Cappoquin	-6.6	54.1	-5.6
Castle Coole	2.1	-25.7	-33.8
Enniscorthy	-3.8	-19.2	-53.3
Garryland Wood			
Glen Of The Downs	29.9	29.3	224.7
Killarney Oak	-12.8	-15.3	-23.8
Lough Doon			
Saintfield House	6.8	-21.1	-34.9
Shanes Castle	-15.8	-21.2	-40.6

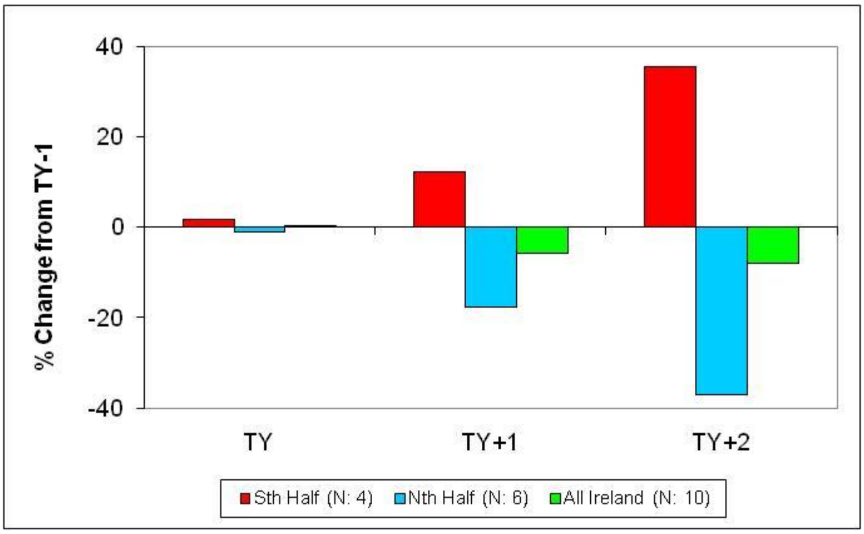


Figure 5.2: Mean changes in growth index percentage values in the southern half of the island, the northern half, and all of Ireland for three years associated with the April 1815 VEI 7 eruption of Tambora.

Wicklow – did not have reduced tree-ring widths in any of the three years analysed, while five sites had narrower rings in two of the three years, with four having reduced growth in all three years.

A difference in growth trends does exist between the northern half of the island and the southern half (Figure 5.2). In 1815, the year of the eruption of Tambora, tree-ring widths in the southern series increased slightly by +1.7%, with a reduction of -1% coming in the northern series, giving a mean all-island increase of just +0.1%. In 1816 there was, on average, a further increase in growth in southern indices (+12.2%) and a decrease in values from the northern half (-17.5%). Finally, 1817 had, on average, a decrease of -37% in tree-ring widths in the six northern series, while the four series in the southern half of the island had a mean increase of +35.5%. However, this value is skewed by the result from The Glen of the Downs (+244.7% for 1817). Discounting this value and taking a result for the remaining three locations gives a mean reduction in ring-width of -27.6%.

Table 5.4a shows tree-ring growth index values for 11 sites throughout Ireland in the years associated with the VEI 5 1835 eruption of Cosigüina. The year of the eruption coincided with reduced ring-width in nine of the 11 series examined (Table 5.4b). These values ranged from as small as -3.3% in Belfast and Enniscorthy to as large as -24.3% in The Glen of the Downs and -25.6% in Barons Court. Ten of the tree-ring series had reduced growth in TY+1. Here the changes were more prominent than the previous year, with values reaching as low as -30.9% in Castle Coole and -38% in Enniscorthy. The second year after the eruption of Cosigüina, TY+2, coincided with narrower ring-widths in six of the 11 tree-ring sites. These negative values ranged from as small as -5.5% in Saintfield House to as large as -34.7%, -34.8% and -35.3% in Ardara, Shanes Castle and Castle Coole respectively. Figure 5.3 shows that reduced tree-rings tended to be a common feature in both the southern and northern half of the island in TY (-7.7% and -10.1%) and TY+1 (-13% and -25%). However, the second year after the event had an average increase of +20.2% in the four southern tree-ring indices, while the seven sites in the northern half of the island

Table 5.4a: Eleven-site growth index values in TY-1, TY, TY+1 and TY+2 of January 1835 VEI 5 eruption of Cosigüina.

	Yearly Standard Growth Index Value			
Location	**TY-1**	**TY**	**TY+1**	**TY+2**
Ardara	0.793	0.735	0.59	0.518
Barons Court	1.039	0.773	0.842	1.503
Belfast	0.844	0.816	0.601	0.752
Breen Wood	1.438	1.322	1.067	0.985
Cappoquin	0.612	0.618	0.804	0.974
Castle Coole	1.551	1.284	1.071	1.004
Enniscorthy	0.963	0.931	0.597	1.058
Garryland Wood				
Glen Of The Downs	1.442	1.091	1.12	1.517
Killarney Oak	1.098	1.053	0.844	1.172
Lough Doon				
Saintfield House	1.178	1.256	0.956	1.113
Shanes Castle	1.345	1.137	0.994	0.877

Table 5.4b: Percent difference between TY-1 & TY, TY-1 & TY+1 and TY-1 & TY+2 growth index values in eleven sites following January 1835 VEI 5 eruption of Cosigüina.

	Percent Change from TY-1		
Location	**TY**	**TY+1**	**TY+2**
Ardara	-7.3	-25.6	-34.7
Barons Court	-25.6	-19.0	44.7
Belfast	-3.3	-28.8	-10.9
Breen Wood	-8.1	-25.8	-31.5
Cappoquin	1.0	31.4	59.2
Castle Coole	-17.2	-30.9	-35.3
Enniscorthy	-3.3	-38.0	9.9
Garryland Wood			
Glen Of The Downs	-24.3	-22.3	5.2
Killarney Oak	-4.1	-23.1	6.7
Lough Doon			
Saintfield House	6.6	-18.8	-5.5
Shanes Castle	-15.5	-26.1	-34.8

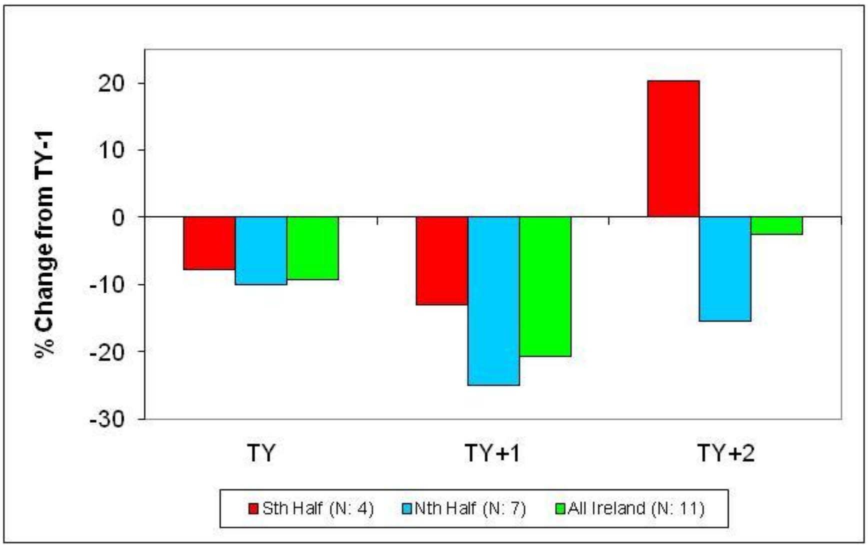


Figure 5.3: Mean changes in growth index percentage values in the southern half of the island, the northern half, and all of Ireland for three years associated with the January 1835 VEI 5 eruption of Cosigüina.

had a mean decrease of -15.4% in 1837. All four southern series had increases in values in this year, but the Cappoquin series had almost 50% more of an increase than any of the other three, in turn skewing the results. The mean increase for the three remaining southern series was +7.3%. Of the northern series, only Barons Court had an increase in values in TY+2. Discounting this series from that mean value would have produced a more notable reduction of -25.4%.

With the September 1845 VEI 4 Hekla eruption (Table 5.5a) coming after the growing season had ended, the index value for 1845 is used as TY-1, with the 1846 result acting as TY; 1847 is TY+1 with 1848 being TY+2. Table 5.5b shows the percentage change that occurred between each of the years following the event. Of the 12 series that include data for this eruption, seven had a reduction in ring-width in TY, including -13.2% in Ardara, -19% in Killarney and -27% in The Glen of the Downs (Table 5.5b). Six of the indices had narrowed rings in TY+1, ranging from -2.8% in Barons Court to -31.7% in The Glen of the Downs. Only three series had a reduction in ring-widths in TY+2, namely Castle Coole (-5.1%), Enniscorthy (-14.2%) and The Glen of the Downs (-49%). The five series from the southern half of the island had a reduction in each of the three years examined (Figure 5.4), peaking at -11.2% in TY+1. The seven series from the northern half of the island had, on average, an increase in all three years, while the mean result for Ireland as a whole shows only slight reductions in ring-widths in TY (-2.4%) and TY+1 (-0.2%), with an increase of +3.5% occurring in TY+2.

Table 5.6a contains the tree-ring index values from 13 locations pertaining to the VEI 4 eruption of Katla in 1860. Only three of the 13 series saw reduced ring-widths in TY (Table 5.6b), namely Belfast (-9.9%), Castle Coole (-15.7%) and Breen Wood (-27.9%). The increases in ring-widths in 1860 included +63.8% in Killarney and +188.3% in Garryland Wood. The year after the eruption of Katla only had one tree-ring index record narrower rings. Breen Wood followed the reduction of the previous year with a -40.6% change. The same series was one of four to have reduced growth in TY+2 (-40.3%) with the others (Belfast, Cappoquin and Castle Coole) narrowing by 9.5%, 2.2% and 8.5% respectively.

Table 5.5a: Twelve-site growth index values in TY-1, TY, TY+1 and TY+2 of September 1845 VEI 4 eruption of Hekla.

	Yearly Standard Growth Index Value			
Location	**TY-1**	**TY**	**TY+1**	**TY+2**
Ardara	1.194	1.036	1.366	1.582
Barons Court	1.233	1.246	1.199	1.28
Belfast	0.917	1.006	1.001	1.12
Breen Wood	1.32	1.287	1.663	1.39
Cappoquin	1.094	0.966	1.114	1.119
Castle Coole	1.321	1.282	1.213	1.254
Enniscorthy	0.768	0.727	0.747	0.659
Garryland Wood	1.473	1.711	1.388	1.503
Glen Of The Downs	0.917	0.669	0.626	0.468
Killarney Oak	1.13	0.915	0.933	1.346
Lough Doon				
Saintfield House	0.962	1.135	1.047	1.105
Shanes Castle	1.142	1.231	1.212	1.228

Table 5.5b: Percent difference between TY-1 & TY, TY-1 & TY+1 and TY-1 & TY+2 growth index values in twelve sites following September 1845 VEI 4 eruption of Hekla.

	Percent Change from TY-1		
Location	**TY**	**TY+1**	**TY+2**
Ardara	-13.2	14.4	32.5
Barons Court	1.1	-2.8	3.8
Belfast	9.7	9.2	22.1
Breen Wood	-2.5	26.0	5.3
Cappoquin	-11.7	1.8	2.3
Castle Coole	-3.0	-8.2	-5.1
Enniscorthy	-5.3	-2.7	-14.2
Garryland Wood	16.2	-5.8	2.0
Glen Of The Downs	-27.0	-31.7	-49.0
Killarney Oak	-19.0	-17.4	19.1
Lough Doon			
Saintfield House	18.0	8.8	14.9
Shanes Castle	7.8	6.1	7.5

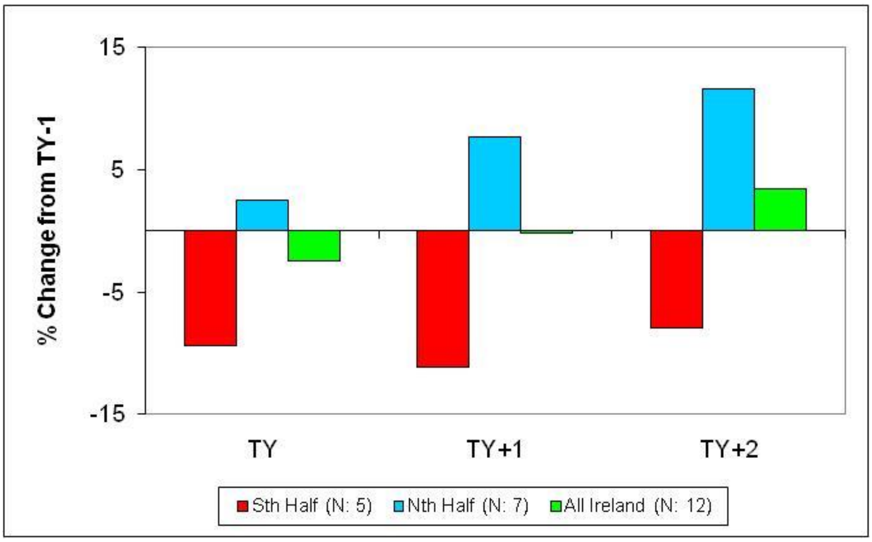


Figure 5.4: Mean changes in growth index percentage values in the southern half of the island, the northern half, and all of Ireland for three years associated with the September 1845 VEI 4 eruption of Hekla.

Table 5.6a: Thirteen-site growth index values in TY-1, TY, TY+1 and TY+2 of May 1860 VEI 4 eruption of Katla.

	Yearly Standard Growth Index Value			
Location	**TY-1**	**TY**	**TY+1**	**TY+2**
Ardara	1.098	1.358	1.417	1.577
Barons Court	1.103	1.225	1.147	1.356
Belfast	0.992	0.894	1.056	0.898
Breen Wood	1.179	0.85	0.7	0.704
Cappoquin	0.945	1.028	1	0.924
Castle Coole	1.136	0.958	1.25	1.04
Enniscorthy	0.675	0.807	0.763	0.819
Garryland Wood	0.694	2.001	2.579	1.689
Glen Of The Downs	1.114	1.394	1.385	1.657
Killarney Oak	0.658	1.078	1.21	0.872
Lough Doon	1.049	1.182	1.51	1.539
Saintfield House	0.902	0.943	1.207	1.063
Shanes Castle	0.995	1.139	1.104	1.258

Table 5.6b: Percent difference between TY-1 & TY, TY-1 & TY+1 and TY-1 & TY+2 growth index values in thirteen sites following May 1860 VEI 4 eruption of Katla.

	Percent Change from TY-1		
Location	**TY**	**TY+1**	**TY+2**
Ardara	23.7	29.1	43.6
Barons Court	11.1	4.0	22.9
Belfast	-9.9	6.5	-9.5
Breen Wood	-27.9	-40.6	-40.3
Cappoquin	8.8	5.8	-2.2
Castle Coole	-15.7	10.0	-8.5
Enniscorthy	19.6	13.0	21.3
Garryland Wood	188.3	271.6	143.4
Glen Of The Downs	25.1	24.3	48.7
Killarney Oak	63.8	83.9	32.5
Lough Doon	12.7	43.9	46.7
Saintfield House	4.5	33.8	17.8
Shanes Castle	14.5	11.0	26.4

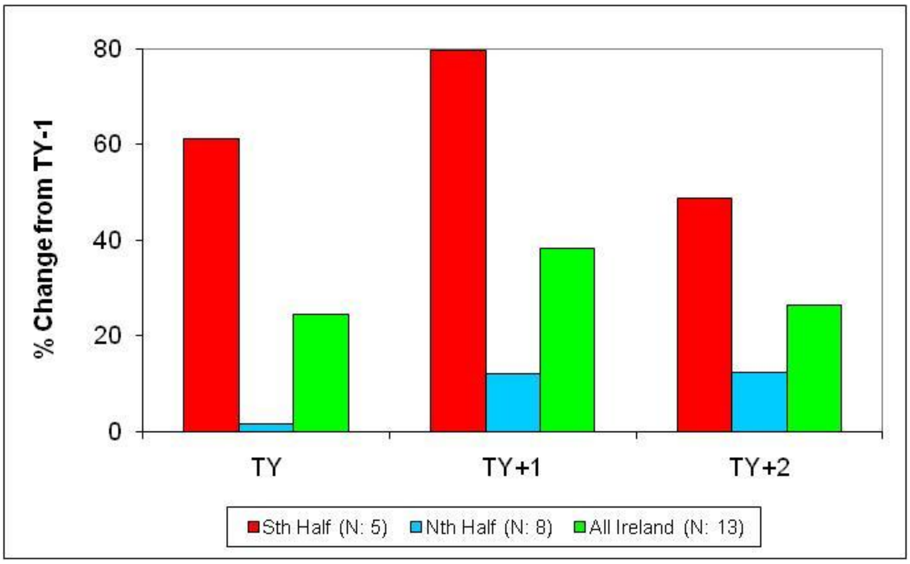


Figure 5.5: Mean changes in growth index percentage values in the southern half of the island, the northern half, and all of Ireland for three years associated with the May 1860 VEI 4 eruption of Katla.

The five southern indices (Figure 5.5) had average increases of +61.1% in TY, +79.9% in TY+1 and +48.7% in TY+2. These large changes can be attributed to the increases that occurred in Garryland Wood, where the average increase in growth over the three years studied was +201.1%. Discounting these changes would give results closer to, although still greater than, those from the northern half. Those eight series from the northern half of the island show little change in TY (+1.6%), a result that was followed by increases of +12.2% on TY+1 and +12.4% in TY+2. Again, the results from Garryland Wood could be considered to skew the mean results for the island of Ireland where the increases in growth peaked at an average of +38.2% in the second year after the eruptions.

All 13 tree-ring indices cover the eruption of Askja (VEI 5) in 1875 (Table 5.7a). Only four of the series had reduced growth in the same year as the event (Table 5.7b), including -10.8% in Garryland Wood and -20.3% in The Glen of the Downs. This number rose to nine series in TY+1. In this instance, changes ranged from small (-0.4% in Barons Court and -0.6% in Killarney) to large (-45.4% in Garryland Wood). Only two of the 13 series did not have reduced ring-widths in TY+2 (Enniscorthy and Lough Doon – both of which had increases in the previous two years). Of those that did have reductions in index values, the largest came in Ardara (-44.9%) and, again, Garryland Wood (-49.8%). Figure 5.6 highlights the fact that there was, on average, an increase in tree-ring widths in both the southern half (+13.7%) and northern half (+12%) of Ireland in TY. The possible influence of the eruption of Askja can be seen more clearly in TY+1 and TY+2, with mean reductions of -13.9% and -10.6% in the five southern series and -2.8% and -17.3% in the eight series from the northern half of Ireland. The mean impact on the island as a whole can also be seen, with reductions in ring-widths of -7.1% in TY+1 and -14.7% in TY+2.

Table 5.8a shows the tree-ring index values associated with the May 1883 VEI 6 eruption of Krakatau in Indonesia for all 13 sites on the island of Ireland. Only two of the indices did not have a reduction in ring-width in the year of the eruption (Table 5.8b), namely Cappoquin (+11%) and Garryland Wood

Table 5.7a: Thirteen-site growth index values in TY-1, TY, TY+1 and TY+2 of March 1875 VEI 5 eruption of Askja.

	Yearly Standard Growth Index Value			
Location	**TY-1**	**TY**	**TY+1**	**TY+2**
Ardara	0.97	0.94	0.878	0.534
Barons Court	0.932	1.058	0.928	0.799
Belfast	1.031	1.162	1.06	0.878
Breen Wood	0.854	1.094	0.947	0.83
Cappoquin	1.093	1.237	1.008	1.06
Castle Coole	0.867	0.795	0.718	0.672
Enniscorthy	0.933	1.643	0.954	1.176
Garryland Wood	1.237	1.103	0.675	0.621
Glen Of The Downs	0.935	0.72	0.767	0.887
Killarney Oak	1.031	1.167	1.025	0.813
Lough Doon	0.945	1.226	1.111	0.978
Saintfield House	1.008	1.13	0.829	0.802
Shanes Castle	1.168	1.303	1.062	0.908

Table 5.7b: Percent difference between TY-1 & TY, TY-1 & TY+1 and TY-1 & TY+2 growth index values in thirteen sites following March 1875 VEI 5 eruption of Askja.

	Percent Change from TY-1		
Location	**TY**	**TY+1**	**TY+2**
Ardara	-3.1	-9.5	-44.9
Barons Court	13.5	-0.4	-14.3
Belfast	12.7	2.8	-14.8
Breen Wood	28.1	10.9	-2.8
Cappoquin	13.2	-7.8	-3.0
Castle Coole	-8.3	-17.2	-22.5
Enniscorthy	76.1	2.3	26.0
Garryland Wood	-10.8	-45.4	-49.8
Glen Of The Downs	-23.0	-18.0	-5.1
Killarney Oak	13.2	-0.6	-21.1
Lough Doon	29.7	17.6	3.5
Saintfield House	12.1	-17.8	-20.4
Shanes Castle	11.6	-9.1	-22.3

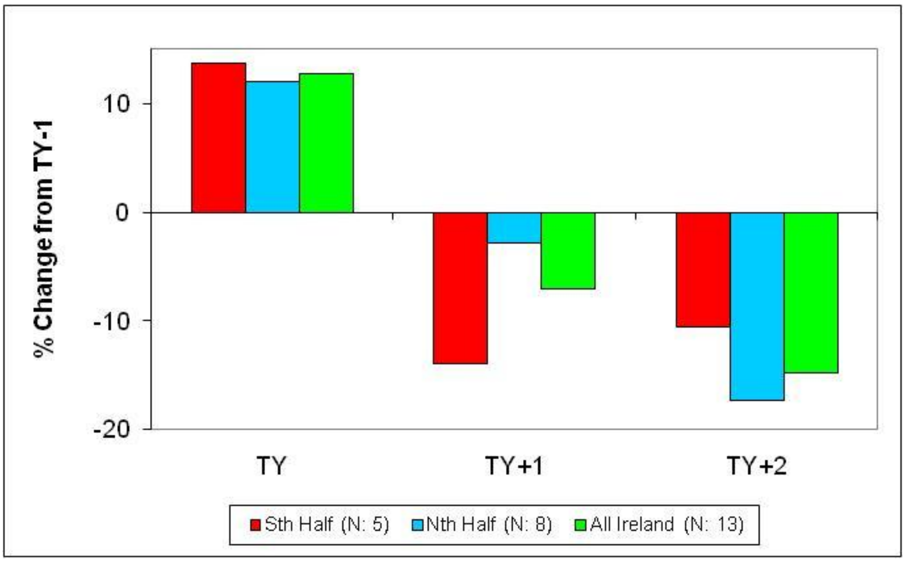


Figure 5.6: Mean changes in growth index percentage values in the southern half of the island, the northern half, and all of Ireland for three years associated with the March 1875 VEI 5 eruption of Askja.

Table 5.8a: Thirteen-site growth index values in TY-1, TY, TY+1 and TY+2 of May 1883 VEI 6 eruption of Krakatau.

	Yearly Standard Growth Index Value			
Location	**TY-1**	**TY**	**TY+1**	**TY+2**
Ardara	1.073	0.962	0.839	1.024
Barons Court	1.125	0.953	0.979	0.965
Belfast	1.165	0.976	1.044	0.866
Breen Wood	1.1	0.979	1.03	0.832
Cappoquin	0.899	0.998	1.125	0.968
Castle Coole	1.087	0.913	0.858	0.803
Enniscorthy	1.468	1.38	1.001	0.886
Garryland Wood	0.665	1.167	0.72	0.636
Glen Of The Downs	1.338	1.059	1.119	1.244
Killarney Oak	1.127	1.116	0.936	0.879
Lough Doon	1.105	1.029	0.978	0.904
Saintfield House	1.141	1.014	0.907	0.817
Shanes Castle	1.263	1.088	1.158	0.93

Table 5.8b: Percent difference between TY-1 & TY, TY-1 & TY+1 and TY-1 & TY+2 growth index values in thirteen sites following May 1883 VEI 6 eruption of Krakatau.

	Percent Change from TY-1		
Location	**TY**	**TY+1**	**TY+2**
Ardara	-10.3	-21.8	-4.6
Barons Court	-15.3	-13.0	-14.2
Belfast	-16.2	-10.4	-25.7
Breen Wood	-11.0	-6.4	-24.4
Cappoquin	11.0	25.1	7.7
Castle Coole	-16.0	-21.1	-26.1
Enniscorthy	-6.0	-31.8	-39.6
Garryland Wood	75.5	8.3	-4.4
Glen Of The Downs	-20.9	-16.4	-7.0
Killarney Oak	-1.0	-16.9	-22.0
Lough Doon	-6.9	-11.5	-18.2
Saintfield House	-11.1	-20.5	-28.4
Shanes Castle	-13.9	-8.3	-26.4

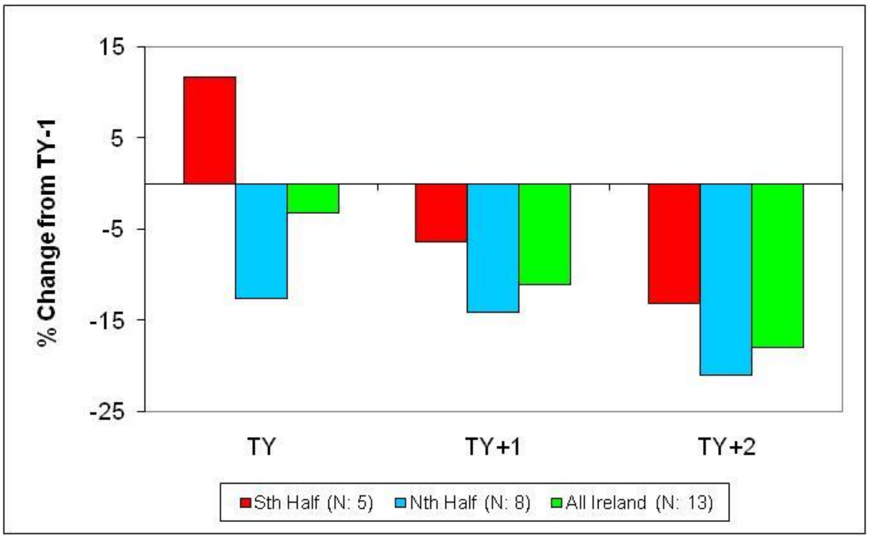


Figure 5.7: Mean changes in growth index percentage values in the southern half of the island, the northern half, and all of Ireland for three years associated with the May 1883 VEI 6 eruption of Krakatau.

(+75.5%). The remaining 11 sites had a narrowing of rings of up to -20.9% (Glen of the Downs). A narrowing of tree-rings occurred in the same 11 sites in TY+1, including -21.8% in Ardara and -31.8% in Enniscorthy. The second year after the eruption of Krakatau, 1885, coincided with reduced tree-ring growth in all but one of the sites examined. Here values ranged from as small as -4.4% in Garryland Wood – which had experienced increased growth in the previous two years – to as large as -28.4% in Saintfield House and -39.6% in Enniscorthy.

The cumulative influence of the 1883 eruption of Krakatau can be seen in Figure 5.7. The year of the eruption had, on average, increased ring-width in the southern half of the island, although this result could be considered skewed by the +75.5% increase that occurred in Garryland Wood in Co. Galway. Removing this from the analysis gives a mean reduction of -4.2% for this half of the country. All eight of the series located in the northern half of the island had reduced ring-widths in 1883, giving an average reduction of -12.6%. The year after the eruption coincided with a mean reduction in ring width of -6.3% for the five southern series and -14.1% for those in the northern half of the island. Further decreases of -13.5% and -21% occurred in the southern and northern series respectively in TY+2.

The next eruption under consideration is that of Grímsvötn in December 1902. The index values for the 13 sites can be seen in Table 5.9a, with the difference in growths in Table 5.9b. Because the eruption occurred after the growing season, the data for 1902 is used as TY-1, with results for TY coming from 1903. Only one of the tree-ring series had a narrowing in TY (Cappoquin, -7.8%). The increases in growth in this year included +47.6% in Ardara and +99.4% in Garryland Wood. None of the 13 indices recorded a narrowing of ring-widths in TY+1, with Garryland Wood again showing the most growth with an increase of +151.1% in ring-width. Three series (Cappoquin, Killarney and Shanes Castle) had reduced ring-widths of -11%, -6.5% and -21.7% respectively in TY+2. Figure 5.8 shows that the general trend of increases in tree-ring widths

Table 5.9a: Thirteen-site growth index values in TY-1, TY, TY+1 and TY+2 of December 1902 VEI 4 eruption of Grímsvötn.

	Yearly Standard Growth Index Value			
Location	**TY-1**	**TY**	**TY+1**	**TY+2**
Ardara	0.853	1.259	1.166	0.956
Barons Court	0.95	1.294	1.398	1.277
Belfast	1.012	1.228	1.142	1.012
Breen Wood	1.09	1.264	1.511	1.375
Cappoquin	0.985	0.908	1.06	0.877
Castle Coole	1.003	1.285	1.117	0.933
Enniscorthy	0.985	1.115	1.175	0.908
Garryland Wood	0.517	1.031	1.298	0.738
Glen Of The Downs	0.867	0.977	1.37	1.221
Killarney Oak	1.181	1.222	1.593	1.104
Lough Doon	0.868	0.903	1.023	0.868
Saintfield House	1.024	1.221	1.294	1.038
Shanes Castle	1.286	1.397	1.31	1.007

Table 5.9b: Percent difference between TY-1 & TY, TY-1 & TY+1 and TY-1 & TY+2 growth index values in thirteen sites following December 1902 VEI 4 eruption of Grímsvötn.

	Percent Change from TY-1		
Location	**TY**	**TY+1**	**TY+2**
Ardara	47.6	36.7	12.1
Barons Court	36.2	47.2	34.4
Belfast	21.3	12.8	0.0
Breen Wood	16.0	38.6	26.1
Cappoquin	-7.8	7.6	-11.0
Castle Coole	28.1	11.4	-7.0
Enniscorthy	13.2	19.3	-7.8
Garryland Wood	99.4	151.1	42.7
Glen Of The Downs	12.7	58.0	40.8
Killarney Oak	3.5	34.9	-6.5
Lough Doon	4.0	17.9	0.0
Saintfield House	19.2	26.4	1.4
Shanes Castle	8.6	1.9	-21.7

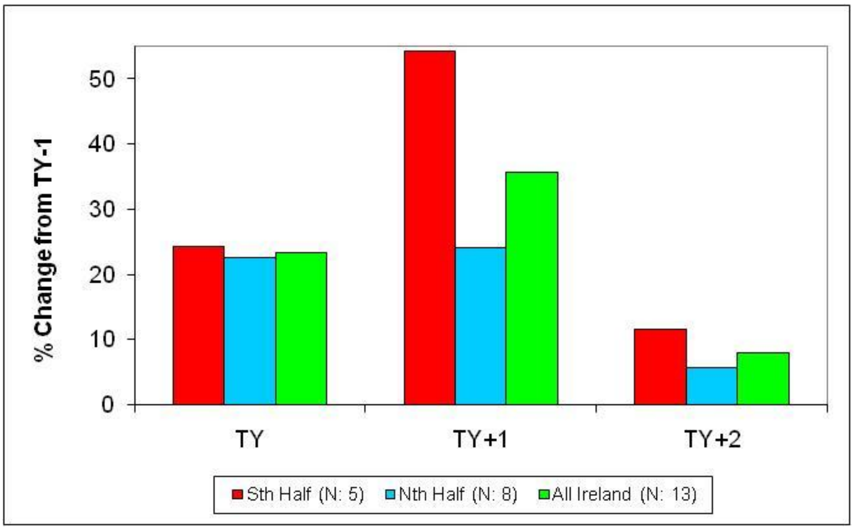


Figure 5.8: Mean changes in growth index percentage values in the southern half of the island, the northern half, and all of Ireland for three years associated with the December 1902 VEI 4 eruption of Grímsvötn.

in the years associated with the eruption of Grímsvötn in 1902 means an average increase in both the northern and southern halves of the island, peaking with an increase of +54.2% in TY+1 in the five southern series.

With the eruption of Katla in October 1918 occurring after the 1918 growing season had ended, the data for TY-1 comes from 1918, with TY being 1919 (Table 5.10a). Ten of the 13 series had a narrowing of ring-widths in TY when compared to the previous year (Table 5.10b). These reductions included results as minute as -0.2% in Shanes Castle and -1.1% in Barons Court, but went as large as -23.7% in Killarney and -24.7% in Enniscorthy. Again, 10 series had narrowed ring-widths in TY+1, including more substantial changes compared to the previous year, such as -28.9% in Lough Doon, -34.2% in Killarney and -45.7% in Breen Wood. Of the seven indices that narrowed in TY+2, those from Lough Doon (-28.9%), Killarney (-35.9%) and Breen Wood (-45.7%) were the most prominent.

The tree-ring index from The Glen of the Downs had increases in ring-width of +63.8%, +104.5% and +133.6% in the three years examined, causing the mean results from the southern half of the island (Figure 5.9) to be skewed. Discounting these changes would give mean reductions of -10.7% in TY and -11.5% in TY+2 for the four remaining southern series. With the results from The Glen of the Downs included, the five series from the southern half of the island have mean increases of +4.2%, +24.2% and +17.5% in the three years examined. The eight series from the northern half of the island of Ireland give an average decrease of -3.5% (TY), -19.2% (TY+1) and -8% (TY+2).

The tree-ring index values for the three years associated with the VEI 4 eruption of Hekla in 1947 can be seen in Table 5.11a, with the percent difference from one year to the next in Table 5.11b. This second table shows that not one of the 13 indices had a narrowing of ring-widths in TY, with increases including +36.4% in Breen Wood and +45.7% in Ardara. Nine of the series had reductions in ring-width in the first year following the eruption, with values ranging from

Table 5.10a: Thirteen-site growth index values in TY-1, TY, TY+1 and TY+2 of October 1918 VEI 4 eruption of Katla.

	Yearly Standard Growth Index Value			
Location	**TY-1**	**TY**	**TY+1**	**TY+2**
Ardara	0.804	1.028	0.79	0.977
Barons Court	1.258	1.244	0.977	1.021
Belfast	1.208	1.064	1.012	1.198
Breen Wood	1.483	1.212	0.805	0.811
Cappoquin	0.631	0.578	0.736	0.637
Castle Coole	1.037	0.969	0.918	1.077
Enniscorthy	1.102	0.83	0.93	0.66
Garryland Wood	0.632	0.721	0.944	0.816
Glen Of The Downs	0.42	0.688	0.859	0.981
Killarney Oak	0.998	0.761	0.657	0.64
Lough Doon	1.033	0.94	0.734	0.826
Saintfield House	1.131	1.029	0.969	0.957
Shanes Castle	0.957	0.955	0.833	1.06

Table 5.10b: Percent difference between TY-1 & TY, TY-1 & TY+1 and TY-1 & TY+2 growth index values in thirteen sites following October 1918 VEI 4 eruption of Katla.

	Percent Change from TY-1		
Location	**TY**	**TY+1**	**TY+2**
Ardara	27.9	-1.7	21.5
Barons Court	-1.1	-22.3	-18.8
Belfast	-11.9	-16.2	-0.8
Breen Wood	-18.3	-45.7	-45.3
Cappoquin	-8.4	16.6	1.0
Castle Coole	-6.6	-11.5	3.9
Enniscorthy	-24.7	-15.6	-40.1
Garryland Wood	14.1	49.4	29.1
Glen Of The Downs	63.8	104.5	133.6
Killarney Oak	-23.7	-34.2	-35.9
Lough Doon	-9.0	-28.9	-20.0
Saintfield House	-9.0	-14.3	-15.4
Shanes Castle	-0.2	-13.0	10.8

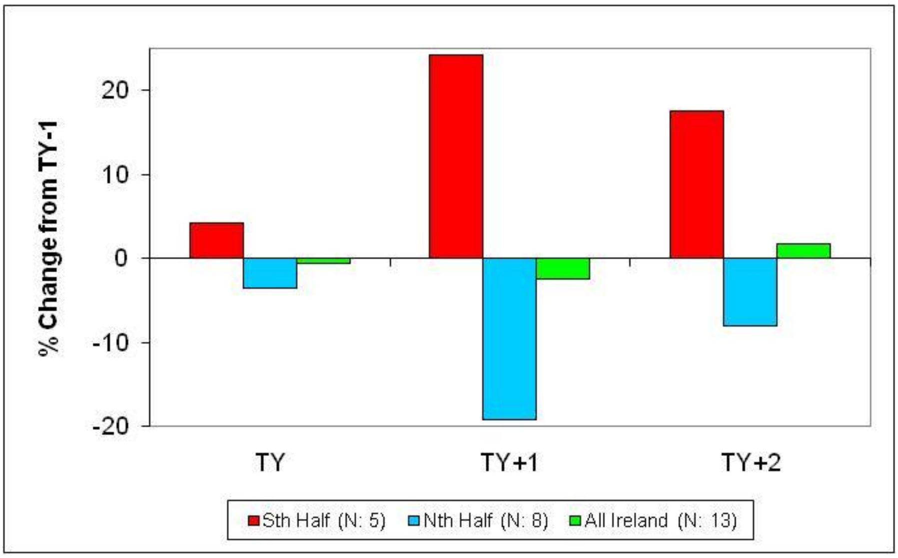


Figure 5.9: Mean changes in growth index percentage values in the southern half of the island, the northern half, and all of Ireland for three years associated with the October 1918 VEI 4 eruption of Katla.

Table 5.11a: Thirteen-site growth index values in TY-1, TY, TY+1 and TY+2 of March 1947 VEI 4 eruption of Hekla.

	Yearly Standard Growth Index Value			
Location	**TY-1**	**TY**	**TY+1**	**TY+2**
Ardara	1.045	1.523	1.183	0.867
Barons Court	1.017	1.28	0.961	0.904
Belfast	0.917	1.246	1.039	0.929
Breen Wood	1.067	1.455	0.687	0.506
Cappoquin	1.349	1.381	1.272	1.517
Castle Coole	0.957	1.29	1.015	0.889
Enniscorthy	1.119	1.468	1.102	0.769
Garryland Wood	1.705	1.757	1.225	0.812
Glen Of The Downs	0.958	1.292	1.188	1.102
Killarney Oak	1.232	1.593	1.08	0.925
Lough Doon	1.05	1.273	0.972	1.134
Saintfield House	1.097	1.388	1.076	0.968
Shanes Castle	1.154	1.404	1.076	0.874

Table 5.11b: Percent difference between TY-1 & TY, TY-1 & TY+1 and TY-1 & TY+2 growth index values in thirteen sites following March 1947 VEI 4 eruption of Hekla.

	Percent Change from TY-1		
Location	**TY**	**TY+1**	**TY+2**
Ardara	45.7	13.2	-17.0
Barons Court	25.9	-5.5	-11.1
Belfast	35.9	13.3	1.3
Breen Wood	36.4	-35.6	-52.6
Cappoquin	2.4	-5.7	12.5
Castle Coole	34.8	6.1	-7.1
Enniscorthy	31.2	-1.5	-31.3
Garryland Wood	3.0	-28.2	-52.4
Glen Of The Downs	34.9	24.0	15.0
Killarney Oak	29.3	-12.3	-24.9
Lough Doon	21.2	-7.4	8.0
Saintfield House	26.5	-1.9	-11.8
Shanes Castle	21.7	-6.8	-24.3

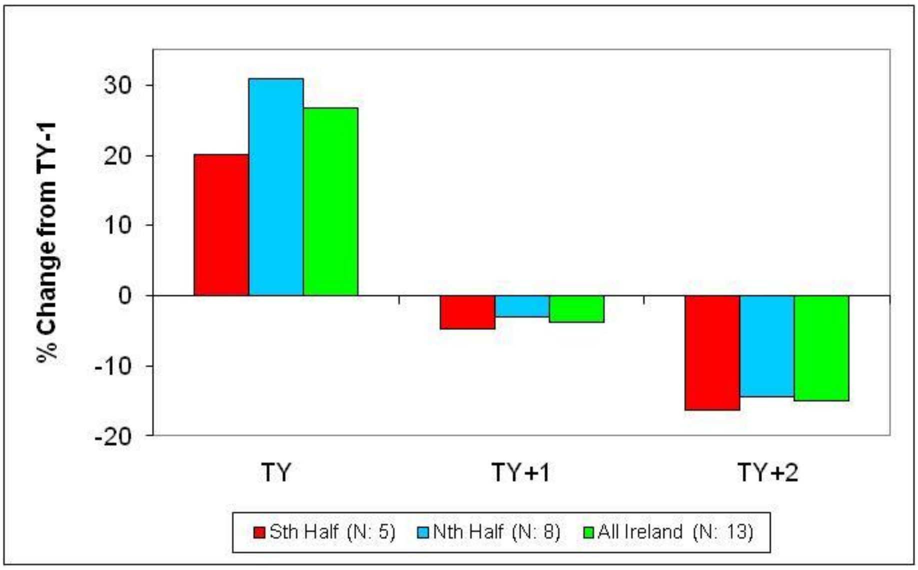


Figure 5.10: Mean changes in growth index percentage values in the southern half of the island, the northern half, and all of Ireland for three years associated with the March 1947 VEI 4 eruption of Hekla.

-1.5% and -1.9% in Enniscorthy and Saintfield House to -28.2% and -35.6% in Garryland Wood and Breen Wood. Again, nine of the indices had narrowed ring-widths in TY+2, including -31.3% in Enniscorthy, -52.4% in Garryland Wood and -52.6% in Breen Wood. Figure 5.10 reflects the fact that no series experienced a narrowing of rings in TY, with mean increases of +20.2% and +31% occurring in the southern and northern halves of the country respectively. Slight mean decreases came in TY+1 (-4.7% for the five southern series and -3.1% for the eight from the northern half). These decreased further to -16.2% (southern) and -14.3% (northern) in TY+2.

Because many of the tree-ring indices were put together in the late 1970s only six provide data relating to the VEI 5 eruption of El Chichón in Mexico in 1982 (Table 5.12a). The changes in ring-width of those that remain are in Table 5.12b. Here it can be seen that none of the six series had reduced growth in the year of the eruption, with the increases that occurred including +31.7% in Castle Coole and +33.2% in Breen Wood. Three of the six series contained narrowed ring-widths in TY+1, the largest reduction coming in Garryland Wood (-22.8%). Five of the six tree-ring indices had reduced growth in the second year after the eruption. These values ranged from a very slight narrowing of just -0.8% in Barons Court and -3% in Saintfield House, to -22.5% in Garryland Wood and -66.6% in Castle Coole.

Garryland Wood in Co. Galway is the only series from the southern section long enough to provide data for this 1982 eruption, with five existing in the northern half. Figure 5.11 shows increased ring-width in the year of the eruption in both the southern (albeit from only one series) and northern halves of the island of Ireland. The sole southern series gives a reduction of -22.8% in TY+1, while the mean change in the northern indices is an increase of +11.7% in that same year. Garryland Wood again has a decrease in TY+2 (-22.5%), while the five series from the northern half of the island contain an average decrease of -12.5%.

Only two of the 13 tree-ring series contain data pertaining to the 1991 eruption of Mount Pinatubo in the Philippines (Table 5.13a). These series are Garryland

Table 5.12a: Six-site growth index values in TY-1, TY, TY+1 and TY+2 of March 1982 VEI 5 eruption of El Chichón.

	Yearly Standard Growth Index Value			
Location	**TY-1**	**TY**	**TY+1**	**TY+2**
Ardara				
Barons Court	0.9	0.993	0.975	0.893
Belfast				
Breen Wood	0.993	1.323	1.408	1.155
Cappoquin				
Castle Coole	1.263	1.664	1.515	0.422
Enniscorthy				
Garryland Wood	1.238	1.435	0.956	0.96
Glen Of The Downs				
Killarney Oak				
Lough Doon				
Saintfield House	0.935	0.98	0.894	0.907
Shanes Castle	0.99	1.094	0.917	0.905

Table 5.12b: Percent difference between TY-1 & TY, TY-1 & TY+1 and TY-1 & TY+2 growth index values in six sites following March 1982 VEI 5 eruption of El Chichón.

	Percent Change from TY-1		
Location	**TY**	**TY+1**	**TY+2**
Ardara			
Barons Court	10.3	8.3	-0.8
Belfast			
Breen Wood	33.2	41.8	16.3
Cappoquin			
Castle Coole	31.7	20.0	-66.6
Enniscorthy			
Garryland Wood	15.9	-22.8	-22.5
Glen Of The Downs			
Killarney Oak			
Lough Doon			
Saintfield House	4.8	-4.4	-3.0
Shanes Castle	10.5	-7.4	-8.6

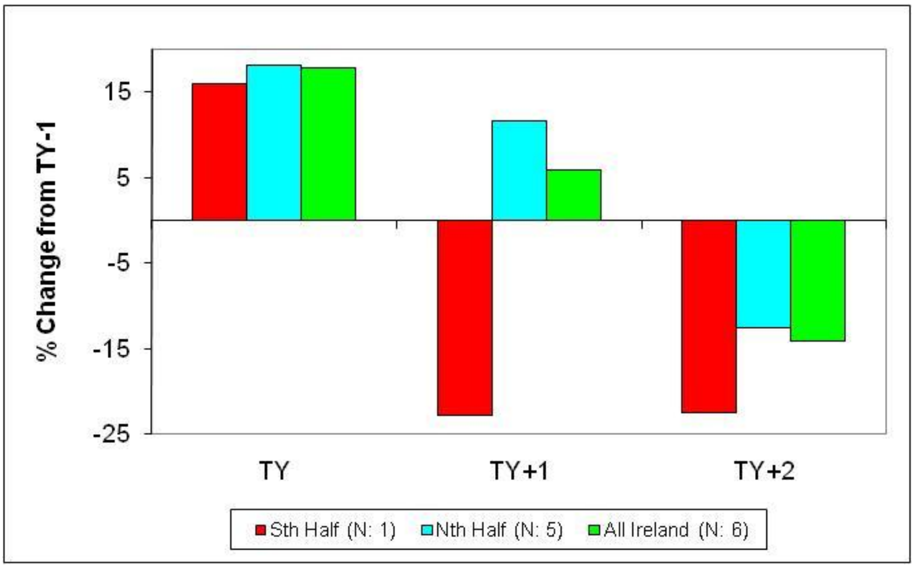


Figure 5.11: Mean changes in growth index percentage values in the southern half of the island, the northern half, and all of Ireland for three years associated with the March 1982 VEI 5 eruption of El Chichón.

Table 5.13a: Two-site growth index values in TY-1, TY, TY+1 and TY+2 of April 1991 VEI 6 eruption of Mt. Pinatubo.

	Yearly Standard Growth Index Value			
Location	**TY-1**	**TY**	**TY+1**	**TY+2**
Ardara				
Barons Court				
Belfast				
Breen Wood				
Cappoquin				
Castle Coole				
Enniscorthy				
Garryland Wood	1.203	1.425	0.845	1.077
Glen Of The Downs				
Killarney Oak				
Lough Doon				
Saintfield House				
Shanes Castle	1.467	1.265	1.075	

Table 5.13b: Percent difference between TY-1 & TY, TY-1 & TY+1 and TY-1 & TY+2 growth index values in two sites following April 1991 VEI 6 eruption of Mt. Pinatubo.

	Percent Change from TY-1		
Location	**TY**	**TY+1**	**TY+2**
Ardara			
Barons Court			
Belfast			
Breen Wood			
Cappoquin			
Castle Coole			
Enniscorthy			
Garryland Wood	18.5	-29.8	-10.5
Glen Of The Downs			
Killarney Oak			
Lough Doon			
Saintfield House			
Shanes Castle	-13.8	-26.7	

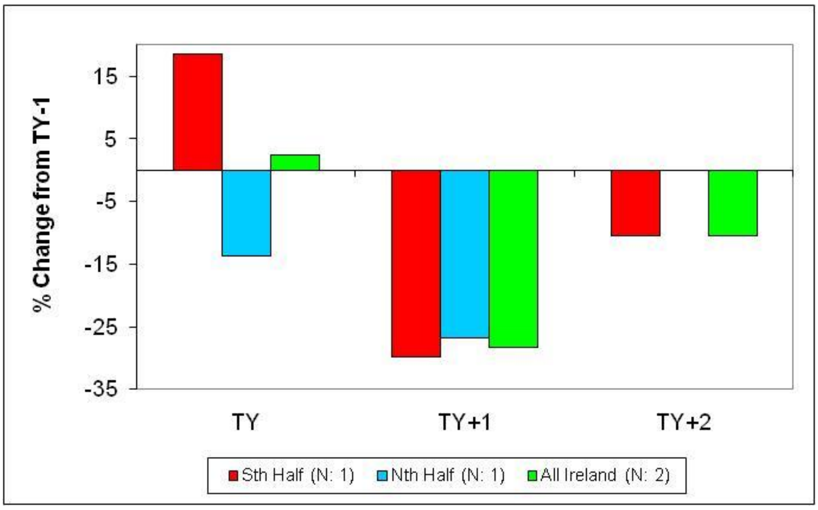


Figure 5.12: Mean changes in growth index percentage values in the southern half of the island, the northern half, and all of Ireland for three years associated with the April 1991 VEI 6 eruption of Mt. Pinatubo.

Wood and Shanes Castle (with the latter ending in 1992, meaning analysis of TY+2 is not possible). Garryland Wood had an increase in the year of the eruption (Table 5.13b), with Shanes Castle containing a reduction of -13.8%. Both series had narrowed ring-widths in 1992 (-29.8% in Garryland Wood and -26.7% in Shanes Castle). With no data available for ring-widths in TY+2 in Shanes Castle, only Garryland Wood can give any indication as to the growth trends in 1993. The result here was a narrowing of the ring-widths by -10.5%. With only two indices reaching the 1990s, the coverage of results relating to the 1991 eruption of Mount Pinatubo is less widespread than previous events. None-the-less, the data shows that TY+1 is the only year to see reduced ring-widths in both series, giving an average narrowing of -28.5% for the whole country (Figure 5.12).

5.2 MEAN TREE-RING GROWTH CHANGE

Table 5.14 shows the mean percentage change in each year's median ring-width in terms of the 13 tree-ring sites (where available). On average, five eruptions coincide with reduced ring-widths for the island as a whole in TY, with just -0.8% for Tambora in 1815, -7.3% for the 1835 eruption of Cosigüina, -2.7% for Hekla in 1845, the 1883 Krakatau event (-11%), and the eruption of Katla in 1918 (-8.4%). Eight of the eruptions were followed by reduced tree-ring index values in TY+1 in Ireland. These include -20.2% following the eruption of Tambora in 1815, -25.6% following Cosigüina in 1835 and -28.2% after the 1991 Mt. Pinatubo event. The number of eruptions that were followed by a fall in tree-ring index values remains at eight in the second year after the events. These values ranged from as little as -0.8% following the eruption of Katla in 1918 and -5.5% following Cosigüina in 1835 to -22% in the second year after the eruption of Krakatau in 1883 and -35.7% two years after the 1815 Tambora event.

Figure 5.13 shows five volcano categories that illustrate the mean change in growth in median tree-ring values for eruption years in Ireland. Looking at the mean value for all 13 events, an increase of +5.1% in tree-ring width can be expected in the year of the eruption, followed by a decrease of -6.7%% in TY+1

Table 5.14: Mean percent difference between TY-1 & TY, TY-1 & TY+1 and TY-1 & TY+2 median growth index values for thirteen sites.

	Percent Change from TY-1		
Event	**TY**	**TY+1**	**TY+2**
*Apr 1815 VEI7	-0.8	-20.2	-35.7
*Jan 1835 VEI5	-7.3	-25.6	-5.5
Sep 1845 VEI4	-2.7	-0.5	4.6
May 1860 VEI4	12.7	13.0	22.9
Mar 1875 VEI5	12.7	-7.8	-14.8
*May 1883 VEI6	-11.0	-13.0	-22.0
Dec 1902 VEI4	16.0	26.4	0.0
Oct 1918 VEI4	-8.4	-14.3	-0.8
Mar 1947 VEI4	29.3	-5.5	-11.8
*Mar 1982 VEI5	13.2	2.0	-5.8
*Apr 1991 VEI6	2.3	-28.2	-10.5

***Denotes low-latitude eruption**

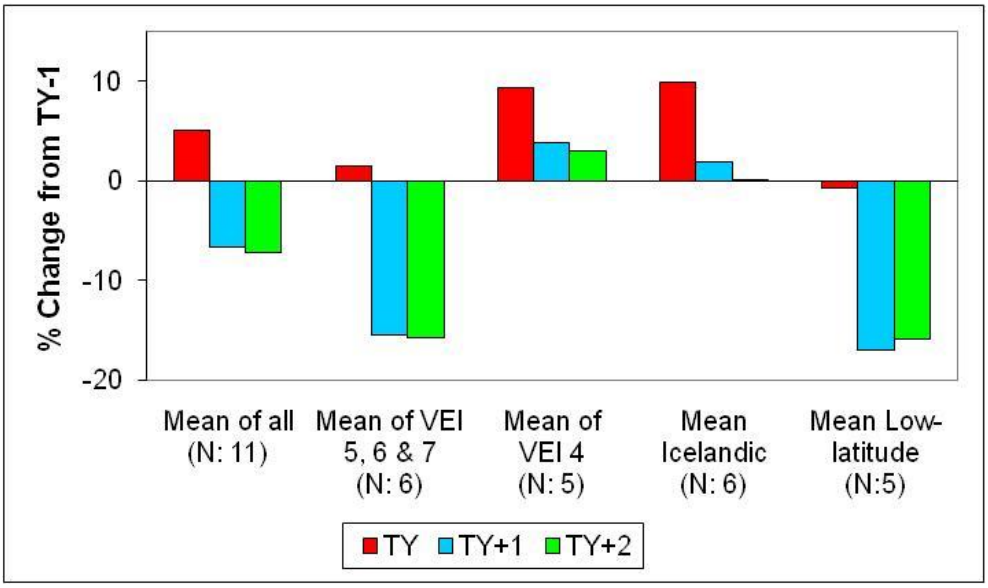


Figure 5.13: Five volcano categories indicating mean VEI- and location-specific changes in median tree-ring growth index percentage values for thirteen sites.

and a further reduction of -7.2% in TY+2. Looking more specifically at the six VEI 5-7 events, the year of the eruption tends to coincide with a very small increase in ring-widths (+1.5%), with decreases in the following two years (-15.5% in TY+1 and -15.7% for TY+2). The Icelandic VEI 4 eruptions will, on average, have an increase in all three years, with the eruption year coinciding in the largest increase (+9.4%). A similar increase (+9.9%) comes in TY of all Icelandic eruptions combined, followed by +1.9% in TY+1 and no change occurring in TY+2. The low-latitude eruptions tend to coincide with a very slight decrease (-0.7%) in TY with more prominent reductions in TY+1 (-17%) and TY+2 (-15.9%).

Table 5.15 shows the data relating to the quarter of the year within which eruptions occurred. This was undertaken in an effort to investigate what time of the year within which an eruption takes place is most likely to bring about a reduction in ring-widths. For example, an eruption in Q1 (January, February, March) could have an adverse affect on the growing season that year as a result of reduced transparency and, consequently, reduced photosynthesis (Salzer and Hughes, 2007), or eruptions later in the year may enhance growth by lessening the impact of the more harsh winter months (Robock, 2003). Of the four Q1 events, only that of Cosigüina in 1835 coincided with a mean reduction in tree-ring widths in Ireland in TY. Two of the four Q2 events (April, May, June), those of Tambora in 1815 and Krakatau in 1883, occurred in years of narrowed rings. The results for the tree-ring series show that the Q3 (July, August, September) eruption of Katla came in a year of decreased tree-ring growth, while the Q4 (October, November, December) events, Grímsvötn in 1902 and Katla in 1918, had an increase and a decrease respectively. The Q1 eruptions of Cosigüina in 1835, Askja in 1875 and Hekla in 1947 were followed by narrower rings in TY+1. Three of the four Q2 events (Tambora in 1815, Krakatau in 1883 and Mount Pinatubo in 1991) had reduced ring-widths in Ireland in TY+2, while, of the remaining Q3 and Q4 eruptions only the Q4 Grímsvötn event in 1902 was followed by wider tree-rings. All four of the Q1 eruptions coincided with reduced tree-ring widths in Ireland in TY+2. As with TY+1, the three Q2 eruptions of Tambora in 1815, Krakatau in 1883 and Mount Pinatubo in 1991

Table 5.15: Quarter within which eruption took place with +/- tree-ring growth in TY, TY+1 and TY+2 in median values for thirteen sites (N/C = No change).

Increase or Decrease in Growth When Compared to TY-1												
Event	TY				TY+1				TY+2			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
*Apr 1815 VEI7		-				-				-		
*Jan 1835 VEI5	-				-				-			
Sep 1845 VEI4			-				-				+	
May 1860 VEI4		+				+				+		
Mar 1875 VEI5	+				-				-			
*May 1883 VEI6		-				-				-		
Dec 1902 VEI4				+				+				N/C
Oct 1918 VEI4				-				-				-
Mar 1947 VEI4	+				-				-			
*Mar 1982 VEI5	+				+				-			
*Apr 1991 VEI6		+				-				-		

***Denotes low-latitude eruption**

coincided with reductions in growth. The Q3 eruption of Hekla in 1845 was followed by increased ring-widths in TY+2, with no change occurring in the second year after the Q4 eruption of Grímsvötn, and a decrease in Katla 1918 TY+2.

5.3 TREE-RING GROWTH AND INDICES OF CLIMATE VARIABILITY

5.3.1 Dust Veil Index

A high DVI value, i.e. the existence of volcanic-based particulate matter in the atmosphere, may not be marked by temperature change in Ireland, but the reduced atmospheric transparency associated with volcanic aerosols in the environment can have a negative influence upon photosynthesis. For this reason it was decided to run correlations between the Dust Veil Index and the 13 Irish tree-ring indices.

Table 5.16 shows the results received when each of the 13 tree-ring series from Ireland were correlated with Lamb's (1970) Dust Veil Index. The correlations between the DVI and the tree-ring indices were firstly run over then entire series length, and then in sub-categories of 50 years (after Cook *et al.*, 1998). Each of the correlations was also run with a DVI lag of one year in an effort to test whether or not the DVI value of the previous year had an impact upon ring-widths.

Only three of the full length tree-ring indices showed any significant correlation with the DVI, namely Ardara (R: -0.198, P: 0.01), Castle Coole (R: 0.198, P: 0.01) and Killarney (R: 0.178, P: 0.05), while the lagging of the DVI values achieved an R value of -0.190 (P: 0.05) in Ardara. The more significant and consistent correlations from throughout the tree-ring indices came from the 50 year sub-divisions, with four series providing notable correlations with DVI values for the years 1900 to 1950 (Shanes Castle: 0.433 (P: 0.01), Castle Coole: 0.362 (P: 0.01), Belfast: 0.322 (P: 0.05) and Barons Court: R: 0.291 (P: 0.05)). Breen Wood, Ardara and Castle Coole received significant results of R: 0.488

Table 5.16: Pearson correlation coefficients from Lamb's (1970) Dust Veil Index (and DVI lagged to one year) and tree-ring growth indices in thirteen sites, including full series and sub-categories (after Cook *et al.*, 1998).

Location & Species	Years Analysed	Correlation with DVI	Correlation with DVI -1	Location & Species	Years Analysed	Correlation with DVI	Correlation with DVI -1	Location & Species	Years Analysed	Correlation with DVI	Correlation with DVI -1
Ardara (*Q. petraea*)	1803-1978	-0.198**	-0.190*	Barons Court (*Q. petraea*)	1800-1989	-0.095	-0.120	Belfast (*Q. petraea*)	1800-1972	0.116	0.041
	1803-1849	-0.213	-0.187		1800-1849	-0.310	-0.136		1800-1849	0.165	-0.032
	1850-1899	-0.740	-0.150		1850-1899	0.010	0.142		1850-1899	-0.016	0.032
	1900-1949	0.570	0.181		1900-1949	0.291*	0.509**		1900-1949	0.322*	0.355*
	1950-1978	-0.379**	-0.278		1950-1989	0.239	0.137		1950-1972	-0.206	0.018
Breen Wood (*Q. petraea*)	1834-1988	0.033	0.085	Cappoquin (*Q. petraea*)	1813-1978	0.073	0.119	Castle Coole (*Q. petraea*)	1800-1984	0.198**	0.082
	1834-1849	-0.237	-0.078		1813-1849	0.147	0.306		1800-1849	-0.007	-0.149
	1850-1899	-0.144	0.012		1850-1899	0.002	-0.250		1850-1899	-0.132	-0.293*
	1900-1949	0.225	0.359*		1900-1949	-0.129	-0.179		1900-1949	0.362**	0.402**
	1950-1988	0.488**	0.293		1950-1978	0.094	0.051		1950-1984	0.365*	0.014
Enniscorthy (*Q. petraea*)	1811-1978	0.011	-0.098	Garryland Wood (*Q. petraea*)	1841-1995	0.140	-0.045	Glen of the Downs (*Q. robur*)	1809-1978	-0.020	0.097
	1811-1849	0.008	-0.138		1841-1849	0.127	-0.143		1809-1849	-0.117	0.102
	1850-1899	-0.049	-0.239		1850-1899	0.237	-0.108		1850-1899	0.016	0.097
	1900-1949	0.024	0.003		1900-1949	-0.144	-0.043		1900-1949	0.248	0.349*
	1950-1978	0.300	0.182		1950-1995	0.265	0.035		1950-1978	0.159	0.003
Killarney (*Q. petraea*)	1809-1978	0.178*	0.089	Saintfield House (*Q. petraea*)	1800-1990	0.070	-0.059	Shanes Castle (*Q. petraea*)	1800-1992	0.052	-0.056
	1809-1849	0.168	0.104		1800-1849	0.173	-0.054		1800-1849	0.085	-0.080
	1850-1899	0.127	-0.210		1850-1899	-0.039	-0.196		1850-1899	-0.114	-0.136
	1900-1949	0.251	0.260		1900-1949	0.209	0.261		1900-1949	0.433**	0.342*
	1950-1978	0.168	-0.062		1950-1990	-0.054	-0.164		1950-1992	0.216	-0.014
Lough Doon (*Q. petraea*)	1850-1978	0.086	0.041								
	1850-1899	0.059	-0.006								
	1900-1949	0.015	0.067								
	1950-1978	-0.081	-0.175								

**: Correlation is significant at the 0.01 level

*: Correlation is significant at the 0.05 level

(P: 0.01), R: -0.379 (P: 0.01) and R: 0.365 (P: 0.05) respectively when correlated with DVI values for the years 1950 to 1992. The results see both positive and negative Pearson correlation coefficients, showing that tree-ring growth patterns can sometimes mirror the increases and decreases in DVI values, displaying wider rings when DVI is increasing and narrower rings when the index is decreasing. Conversely, the tree-rings may also decrease during a time of increasing DVI values, as would be expected – a higher Dust Veil Index value suggests a downturn in photosynthesis as a result of reduced atmospheric transparency – with the rings going on to increase in width while the DVI is falling.

5.3.2 North Atlantic Oscillation

Cook *et al.* (1998) show strong correlations between NAO and tree-ring series from both eastern North America and Western Europe, with various indices achieving R^2 values as high as 0.510 (P: 0.01). Table 5.17 shows the results that were achieved when Pearson correlations were run between the 13 Irish *Quercus* tree-ring indices and Jones *et al*'s (1997) seasonal NAO values (1825-2007), as well as the results from the 50-year (where applicable) sub-groups. Of all of the correlations that were run, only one achieved a value that was significant at the 0.01 level. In this case, the Cappoquin index returned an R value of 0.212 (P: 0.01) when correlated with the full length autumn NAO index. A number of other correlations were significant at the 0.05 level, including three relating to winter NAO values (Enniscorthy: R: -0.168 P: 0.05; Lough Doon: R: -0.186 P: 0.05; Saintfield House: R: -0.158 P: 0.05). Meanwhile, the division of the data into subgroups produced few significant correlations, including autumn NAO and tree-ring index values in Cappoquin for the years 1825-1849 (R: 0.699 P: 0.01), winter NAO and tree-ring indices for 1900-1949 from Enniscorthy and Saintfield House (R: -0.422 P: 0.01; R:-0.317 P: 0.01), while the subgroup 1950 to the end of records produced significant correlations between spring NAO and Shanes Castle (R: 0.410 P: 0.01) and summer NAO and Saintfield House (R: -0.449 P: 0.01).

Table 5.17: Pearson correlation coefficients from Jones *et al.*'s (1997) North Atlantic Oscillation values (1825-2000, where applicable) and tree-ring growth indices in thirteen sites including full series and sub-categories (after Cook *et al.*, 1998).

Location & Species	Years Analysed	Correlation with Winter NAO	Correlation with Spring NAO	Correlation with Summer NAO	Correlation with Autumn NAO
Ardara (*Q. petraea*)	1825-1978	-0.027	-0.035	0.016	-0.044
	1825-1849	0.276	0.053	0.100	-0.209
	1850-1899	-0.132	-0.016	-0.118	0.133
	1900-1949	-0.321	0.000	0.017	-0.120
	1950-1978	0.015	-0.161	0.035	0.050
Barons Court (Q. *petraea*)	1825-1989	0.095	0.113	0.046	-0.121
	1825-1849	0.200	0.152	0.092	-0.293
	1850-1899	-0.090	0.206	0.041	0.142
	1900-1949	-0.017	0.189	0.086	-0.153
	1950-1989	0.048	0.075	-0.284	-0.118
Belfast (*Q. petraea*)	1825-1972	0.000	-0.019	0.043	0.000
	1825-1849	0.242	-0.180	-0.048	0.121
	1850-1899	-0.236	0.046	0.052	0.054
	1900-1949	-0.157	0.138	0.009	-0.092
	1950-1972	0.167	-0.049	0.051	0.100
Breen Wood (*Q. petraea*)	1834-1988	-0.137	-0.046	-0.037	0.014
	1834-1849	-0.126	-0.056	-0.063	0.112
	1850-1899	0.037	-0.151	0.079	0.156
	1900-1949	-0.291*	0.041	-0.014	-0.117
	1950-1988	-0.028	-0.104	-0.184	-0.080
Cappoquin (*Q. petraea*)	1825-1978	-0.119	-0.099	-0.022	0.212**
	1825-1849	-0.021	-0.093	-0.154	0.699**
	1850-1899	-0.073	-0.188	-0.051	0.100
	1900-1949	-0.338*	-0.122	0.069	0.166
	1950-1978	0.031	0.076	-0.041	-0.025
Castle Coole (*Q. petraea*)	1825-1984	-0.058	0.152	0.007	0.070
	1825-1849	0.147	-0.158	0.138	0.214
	1850-1899	-0.099	0.259	0.058	0.089
	1900-1949	-0.098	0.366	-0.075	-0.064
	1950-1984	-0.004	-0.015	-0.067	0.076
Enniscorthy (*Q. petraea*)	1825-1978	-0.168*	-0.036	-0.165*	0.162*
	1825-1849	-0.228	-0.016	-0.403*	0.429*
	1850-1899	0.033	-0.027	-0.083	0.015
	1900-1949	-0.442**	-0.099	0.027	0.252
	1950-1978	-0.149	0.098	-0.165	-0.121
Garryland Wood (*Q. petraea*)	1841-1995	-0.026	0.048	-0.025	-0.102
	1841-1849	-0.074	0.149	-0.018	-0.425
	1850-1899	-0.237	-0.059	-0.215	-0.031
	1900-1949	-0.026	0.031	0.226	0.152
	1950-1995	0.313*	0.078	0.065	-0.255
Glen of the Downs (*Q. robur*)	1825-1978	-0.020	0.008	-0.136	0.089
	1825-1849	0.095	-0.202	-0.076	0.129
	1850-1899	-0.122	0.045	-0.067	0.249
	1900-1949	0.097	0.167	-0.293*	-0.086
	1950-1978	-0.072	-0.126	-0.126	0.037
Killarney (*Q. petraea*)	1825-1978	-0.154	-0.117	-0.102	0.118
	1825-1849	0.104	-0.251	-0.179	0.381
	1850-1899	-0.245	-0.185	0.014	0.001
	1900-1949	-0.244	0.012	-0.182	0.126
	1950-1978	-0.209	-0.133	-0.070	0.011
Lough Doon (*Q. petraea*)	1850-1978	-0.186*	-0.005	-0.117	0.015
	1850-1899	-0.115	0.021	-0.246	0.022
	1900-1949	-0.205	-0.035	-0.048	-0.008
	1950-1978	-0.122	0.110	-0.073	-0.059
Saintfield House (*Q. petraea*)	1825-1990	-0.158*	0.016	-0.101	0.092
	1825-1849	0.232	-0.084	-0.237	0.286
	1850-1899	-0.175	0.089	0.055	0.149
	1900-1949	-0.371**	0.064	-0.002	-0.003
	1950-1990	-0.194	-0.024	-0.449**	0.013
Shanes Castle (*Q. petraea*)	1825-1992	-0.104	0.121	0.033	-0.031
	1825-1849	0.201	-0.152	0.072	-0.014
	1850-1899	-0.213	0.232	-0.033	-0.008
	1900-1949	-0.338*	0.118	-0.023	-0.001
	1950-1992	-0.016	0.410**	-0.009	-0.017

****: Correlation significant at the 0.01 level**
***: Correlation significant at the 0.05 level**

Pearson correlations for Hurrell's (1995) PC based winter North Atlantic Oscillation index (1899-2007) and the 13 *Quercus* indices (Table 5.18) show that these alternative NAO values produces more significant results than Jones *et al.*'s (1997) reconstructed seasonal data. Over the entire lengths of tree-ring indices, negative correlations significant at the 99th percentile were achieved on five occasions, including R: -0.377 (P: 0.01) for the Lough Doon series and R: -0.393 (P: 0.01) for the Enniscorthy index. Dividing the correlations into sub-groups produced fewer significant coefficients, but two that were achieved were stronger than those examining entire series lengths: (Enniscorthy: R: -0.404 P: 0.01; Ardara: R: -0.423 P: 0.01). The second sub-group, running from 1950 to the end of the various series, only produced two correlations significant at the 95th percentile: (Saintfield House: R: -0.363 P: 0.05; Killarney: R: -0.390 P: 0.05).

5.3.3 Armagh Observatory temperature

Table 5.19 shows the results achieved when the 13 *Quercus* indices were correlated with mean monthly temperatures from Armagh Observatory. The majority of significant correlations come between tree-ring index values and mean May temperatures, with Lough Doon (R: 0.296 P: 0.01) Castle Coole (R: 0.260 P: 0.01) and Breen Wood (R: 0.236 P: 0.01) among the strongest. With the source of the temperature data, Armagh Observatory, being situated in the north of the island, it is natural that the majority of significant correlations with tree-ring indices come with those that are also located on that area of Ireland. Each of the eight indices from the northern half of the island received correlation coefficients with mean May temperatures that were significant at least at the 95% level, while the five *Quercus* series from the southern half of Ireland failed to produce any significant correlations in that month. The only significant correlations with the southern indices came in January, when Enniscorthy's *Q. petraea* index had a negative correlation (R: -0.208 P: 0.01), and December with the *Q. petraea* index in Killarney (R: -0.216 P: 0.01).

Table 5.18: Pearson correlation coefficients from Hurrell's (1995) PC based winter North Atlantic Oscillation index (1899-2007, where applicable) and tree-ring growth indices in thirteen sites including full series and sub-categories (after Cook *et al.*, 1998).

Correlation Coefficients from Winter NAO and *Quercus* Series			
Location	**1899-2007**	**1900-1949**	**1950-1999**
Ardara	-0.202	-0.423**	0.045
Barons Court	0.073	-0.046	0.056
Belfast	0.008	-0.144	0.081
Breen Wood	-0.262*	-0.297*	-0.155
Cappaquin	-0.288**	-0.343*	-0.222
Castle Coole	-0.062	-0.104	0.054
Enniscorthy	-0.393**	-0.404**	-0.363
Garryland Wood	0.042	-0.149	0.220
Glen of the Downs	-0.066	-0.010	-0.094
Killarney	-0.329**	-0.345*	-0.390*
Lough Doon	-0.377**	-0.335*	-0.326
Saintfield House	-0.331**	-0.307*	-0.363*
Shanes Castle	-0.164	-0.321*	-0.004

****Correlation is significant at the 0.01 level**
***Correlation is significant at the 0.05 level**

Table 5.19: Pearson correlation coefficients from mean monthly temperatures in Armagh Observatory (1800-1998, where applicable) and thirteen *Quercus* indices from throughout Ireland.

Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Ardara	-0.143	-0.001	-0.023	0.075	0.190*	0.012	-0.042	0.009	-0.011	-0.018	-0.013	0.007
Barons Court	0.049	0.033	-0.068	-0.006	0.190**	0.027	-0.137	-0.001	0.057	-0.069	0.046	0.023
Belfast	-0.056	0.014	-0.145	-0.180*	0.220**	0.095	0.047	0.023	0.008	-0.018	-0.017	-0.016
Breen Wood	-0.077	-0.132	-0.172*	-0.038	0.236**	0.209**	0.177*	0.131	0.027	-0.008	0.030	-0.050
Cappoquin	-0.135	0.084	0.005	0.033	0.037	0.109	0.037	0.006	0.104	0.098	0.047	-0.072
Castle Coole	-0.179*	-0.044	-0.028	-0.013	0.260**	0.097	0.159*	0.108	0.010	0.033	-0.050	-0.096
Enniscorthy	-0.208**	0.077	-0.022	-0.008	0.062	-0.056	-0.047	0.035	0.031	0.061	-0.020	-0.159*
Garryland Wood	-0.003	-0.001	0.069	0.055	0.035	-0.094	-0.096	0.083	0.084	0.030	0.012	0.059
Glen Of The Downs	-0.049	-0.096	-0.028	-0.074	0.016	-0.068	-0.095	-0.025	-0.024	0.032	-0.016	0.011
Killarney Oak	-0.189*	-0.048	-0.180*	-0.095	0.043	-0.142	-0.055	-0.107	-0.059	-0.014	-0.013	-0.216**
Lough Doon	-0.100	-0.002	-0.006	0.135	0.296**	0.032	-0.176*	-0.028	-0.054	-0.002	-0.011	-0.103
Saintfield House	-0.121	-0.004	-0.092	0.047	0.228**	0.084	0.083	0.030	0.164*	0.112	0.091	0.078
Shanes Castle	-0.137	0.009	0.014	0.044	0.177*	0.073	0.009	0.020	0.125	0.044	0.096	-0.008

****: Correlation significant at the 0.01 level**
***: Correlation significant at the 0.05 level**

CHAPTER 6: *TAXUS BACCATA* RESULTS

This chapter will consider the viability of *T. baccata* from Reenadinna Wood in Killarney National Park, Co. Kerry, as a source of climatic information by assessing the impact of volcanic eruptions. It will do this through the analysis of *T. baccata* tree-ring widths, as well as reconstructing temperature and precipitation for the Killarney area. The chapter will go on to examine the correlations between tree-ring widths and Lamb's (1970) Dust Veil Index and will conclude by looking at North Atlantic Oscillation as another possible influence upon tree-growth.

6.1 CHRONOLOGY STATISTICS AND TREE-RING SERIES

Sampling, standard and residual chronology statistics can be seen in Table 6.1. For the standard chronology, the oldest core dated to the year 1763; however, the Subsample Signal Strength (SSS) – the increased uncertainty of a chronology when the number of its constituent core series drops in early periods (Wigley *et al.*, 1984) – goes below 0.75 in 1804. It is necessary, in this case, for six or more cores to encompass any one year in order for the series to be considered accurate. Therefore this particular chronology runs from 1805 to 2007. The mean sensitivity of the species, a measure of the impact high frequency climate variability has on the growth response (Fritts, 1976), stands at 0.161. The standard deviation is 0.210, with the first order autocorrelation of the standard *T. baccata* index in Killarney National Park at 0.5284. The SSS of the residual chronology falls below 0.75 in 1802, meaning this chronology runs from 1803 to 2007, a time period over which at least five cores are always present. The mean sensitivity here is 0.170, with a standard deviation of 0.150 and first order autocorrelation of -0.014.

Figure 6.1 and Figure 6.2 plot the standard and residual chronologies, while Table 6.2 presents the correlation coefficients achieved between the standard *T. baccata* series from Reenadinna Wood, Killarney and the 13 other tree-ring indices from various other locations in Ireland. The strongest correlation is achieved between the *T. baccata* series and the *Q. petraea* series from Killarney

Table 6.1: Killarney National Park *T. baccata* standard and residual chronology statistics.

Chronology Statistic	Standard Chronology	Residual Chronology
Total # of trees	31	31
Total # of series	58	58
Oldest sampled tree (yrs)	244	243
Full chronology interval	1763-2007	1764-2007
Full chronology interval (SSS ≥ .75)	1805-2007	1803-2007
# of trees/radii to reach SSS threshold	6	5
Series intercorrelation	0.220	0.291
Mean sensitivity	0.161	0.170
Standard deviation	0.210	0.150
First order autocorrelation	0.528	-0.014

Table 6.2: Correlation coefficients from Killarney National Park standard *T. baccata* series and 13 other Irish tree-ring series.

Location	Years Covered	Species	Correlation with *T. baccata*
1. Ardara, Co. Donegal	1803-1978	*Q. petraea*	0.075
2. Barons Court, Co. Tyrone	1764-1989	*Q. petraea*	0.127
3. Belfast, Co. Antrim	1760-1972	*Q. petraea*	0.058
4. Breen Wood, Co. Antrim	1834-1988	*Q. petraea*	-0.204*
5. Cappoquin, Co. Waterford	1813-1978	*Q. petraea*	0.054
6. Castle Coole, Co. Fermanagh	1760-1984	*Q. petraea*	-0.181*
7. Enniscorthy, Co. Wexford	1811-1978	*Q. petraea*	0.181*
8. Garryland Wood, Co. Galway	1841-1997	*Q. petraea*	0.129
9. Glen of the Downs, Co. Wicklow	1809-1978	*Q. robur*	-0.038
10. Killarney, Co. Kerry	1809-1978	*Q. petraea*	0.207**
11. Lough Doon, Co. Leitrim	1850-1978	*Q. petraea*	0.015
12. Saintfield House, Co. Down	1776-1990	*Q. petraea*	0.079
13. Shanes Castle, Co. Antrim	1760-1992	*Q. petraea*	0.099

****: Correlation significant at the 0.01 level**
***: Correlation significant at the 0.05 level**

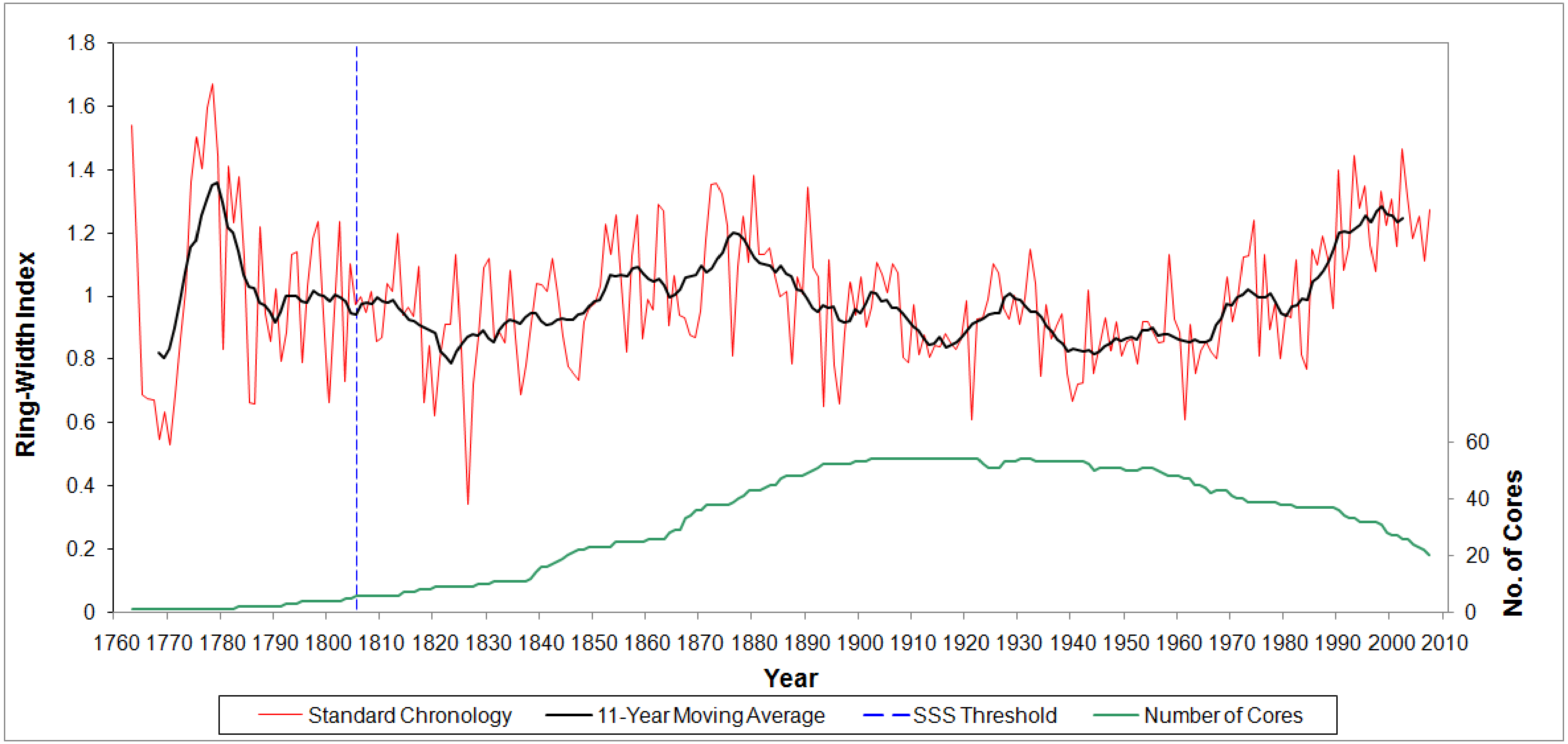


Figure 6.1: Standard *T. baccata* ring-width chronology for Killarney National Park, 1763-2007, including 11-year moving average, number of cores and the Subsample Signal Strength (SSS) threshold at 1805.

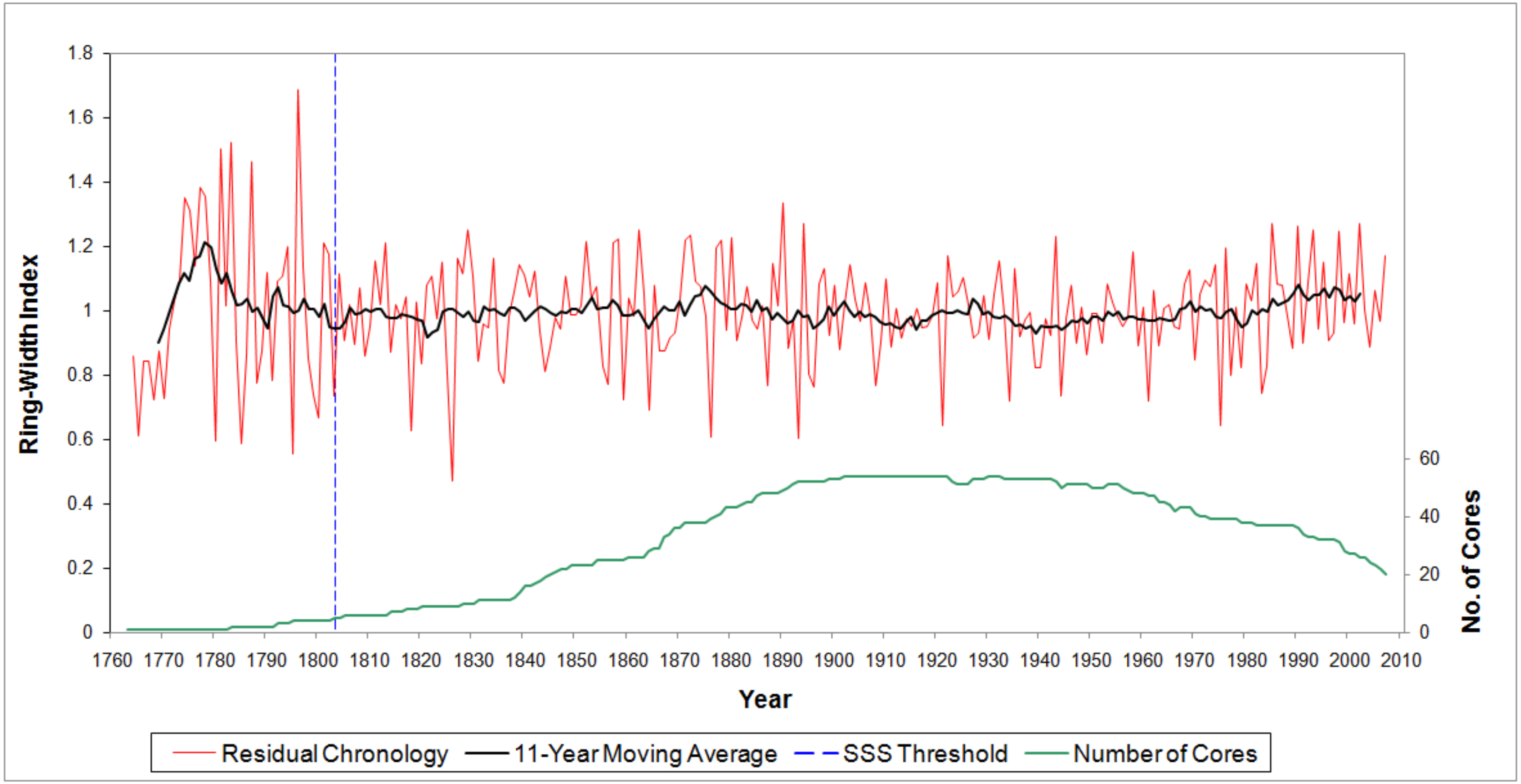


Figure 6.2: Residual T. baccata ring-width chronology for Killarney National Park, 1764-2007, including 11-year moving average, number of cores and the Subsample Signal Strength (SSS) threshold at 1803.

National Park (R: 0.207, P: 0.01). This is logical as both series would have been subjected to the same climatic conditions over their lifetime. However, the correlation is at the same time not particularly significant, implying that both species react differently to very similar climatic conditions.

6.2 RECONSTRUCTING CLIMATIC VARIABLES

6.2.1 Temperature

In order for temperature in the Killarney area to be reconstructed, correlations were run between the standard ring-width chronology and the average monthly temperatures from Lough Leane Lakeshore Station, located in Killarney National Park. This station was the closest to the sample site and provided monthly temperature data from January 1969 onwards. The results of the correlations can be seen in Table 6.3. They show that the months with the most significant influence on standard *T. baccata* ring-width in Killarney are November of the previous year to April of the current year, with two of these six months providing correlations significant at the 99% level and three at the 95% level, while combining the data for all six months gave an R^2 value of 0.366 (P: 0.01) when correlated with the standard tree-ring index. This correlation facilitated the reconstruction of mean November to April temperatures for the years 1805-2007. The equation used in this reconstruction can be seen under Table 6.3.

When compared, the observed and reconstructed temperature data for the years 1970-2007 follow similar peaks and troughs, with a general increase over time (Figure 6.3a). However, the model does tend to underestimate the fluctuations. This is a common characteristic of tree-ring models as the trees' growth responses cannot cross certain thresholds (Loaiciga *et al.*, 1993). Figure 6.3b shows the entire 202-year reconstructed temperature record, as well as an 11-year moving average. Temperatures conform to the general global trend of comparatively low values in the early 19th Century, followed by an increase from the early 20th Century onwards (Huang *et al.*, 2000; Esper *et al.*, 2002). The 11-year moving average also displays a pulse where it can be seen that temperatures will typically increase every 20-30 years and decrease again soon after.

Table 6.3: Results of correlations between mean monthly temperature values from Lough Leane lakeshore station and standard *T. baccata* tree-ring index in Killarney National Park. The bold numbers signify the months selected for the purposes of reconstructions.

Month	Correlation (Temperature)
Apr TY-1	0.122
May TY-1	0.530**
Jun TY-1	0.121
Jul TY-1	0.157
Aug TY-1	0.026
Sep TY-1	0.277
Oct TY-1	0.107
Nov TY-1	**0.436****
Dec TY-1	**0.056**
Jan	**0.390***
Feb	**0.398***
Mar	**0.551****
Apr	**0.365***
May	0.308
Jun	0.068
Jul	-0.162
Aug	0.076
Sep	0.176
Oct	-0.024
Nov	0.165

****Correlation is significant at the 0.01 level**
***Correlation is significant at the 0.05 level**

Regression Equation Employed in Reconstruction:

- $(\text{Nov-Apr Temp}) = (7.608 + 2.476 * \text{TB-std}) - (0.179 * \text{TB-std} - 1)$

Where **Nov-Apr Temp** = mean temperature values for November to April and **TB-std** = standardised *T. baccata* chronology.

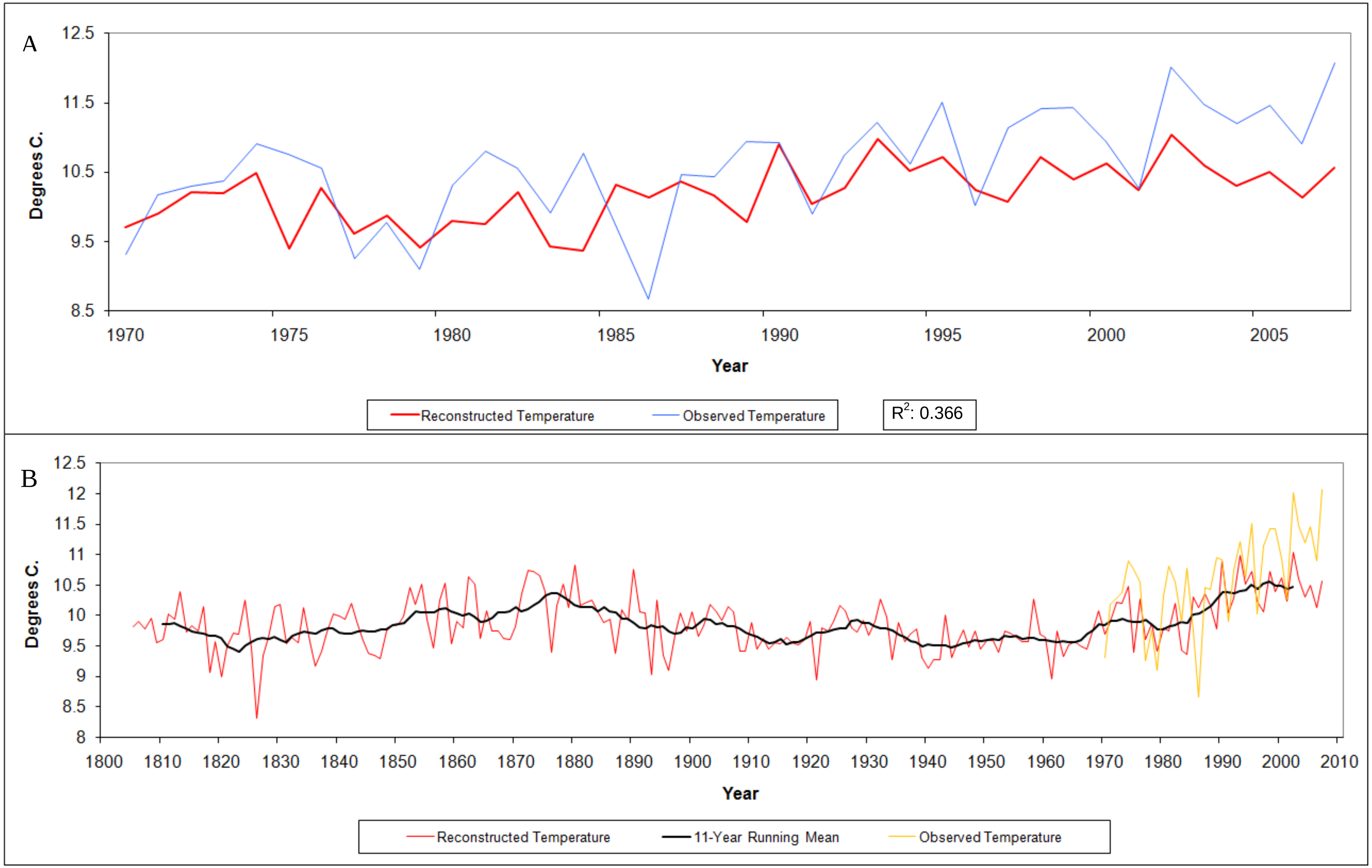


Figure 6.3: A) Reconstructed and observed mean November-April temperatures in Killarney, 1970-2007. B) Reconstructed mean November-April temperatures with an 11-year running mean, 1805-2007.

6.2.2 Precipitation

In order for precipitation values for the area to be reconstructed, correlations were run between residual *T. baccata* ring-widths and total monthly rainfall data from Lough Leane Lakeshore Station in Killarney National Park. These recorded precipitation values ran from January 1969 onwards. Because precipitation can vary so greatly from one year to the next, it is important to use the residual chronology instead of the standard chronology here as the former does not employ autocorrelation in its formulation process. Autocorrelation implies that a time series is predictable as future values are correlated with current and past values (Meko *et al.,* 1993). Discounting autocorrelation means that the correlations between precipitation and residual growth index values are produced on a year-by-year basis. The correlations between the residual and precipitation datasets can be seen in Table 6.4, where significant values were achieved on only two occasions; May and June of the current year received R values of 0.331 and 0.455 (both P: 0.01) respectively.

The correlation between combined total May-June rainfall and residual *T. baccata* ring-widths produced an R^2 value of 0.271 (P: 0.01). These results facilitated the reconstruction of total May-June precipitation in the Killarney area for the length of the residual ring-width series, i.e. 1803-2007. The equation for this reconstruction can be seen under Table 6.4. The reconstructed and observed precipitation values for the years 1969-2007 can be seen in Figure 6.4a. Similar peaks and troughs are traced by both but, as with the reconstructed temperatures for the Killarney area, the model has a propensity to undervalue the intensity of the changes. The 204-year-long precipitation reconstruction seen in Figure 6.4b shows dramatic reductions and increases in values for a number of years throughout the record, underlining the fact that precipitation can vary greatly from year to year.

Table 6.4: Results of correlations between total monthly precipitation values from Lough Leane lakeshore station and residual *T. baccata* tree-ring index in Killarney National Park. The bold numbers signify the months selected for the purposes of reconstructions.

Month	Correlation (Precipitation)
Apr TY-1	0.196
May TY-1	-0.175
Jun TY-1	-0.247
Jul TY-1	-0.038
Aug TY-1	0.061
Sep TY-1	0.002
Oct TY-1	0.038
Nov TY-1	0.099
Dec TY-1	0.073
Jan	-0.005
Feb	0.126
Mar	0.019
Apr	-0.238
May	**0.331****
Jun	**0.455****
Jul	0.134
Aug	0.197
Sep	0.014
Oct	-0.125
Nov	0.208

****Correlation is significant at the 0.01 level**

Regression Equation Employed in Reconstruction:

- (May-Jun Precip) = (-269.363+253.503 * TB-res) + (200.776 * TB-res – 1)

Where **May-Jun Precip** = total precipitation values for May to June and **TB-res** = residual *T. baccata* chronology.

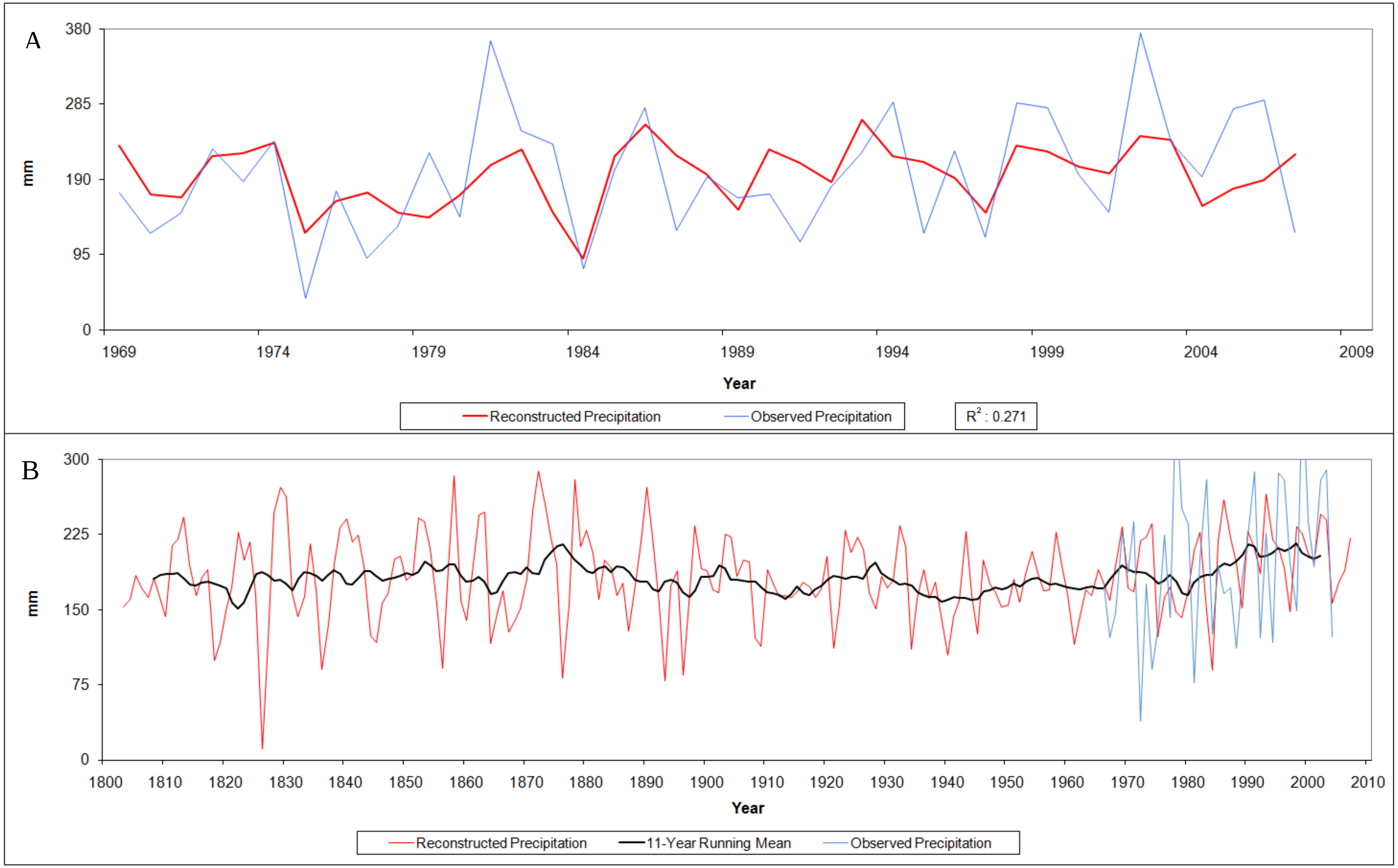


Figure 6.4: A) Reconstructed and observed total May-June precipitation in Killarney, 1969-2007. B) Reconstructed total May-June precipitation with an 11-year running mean, 1803-2007.

6.3 STANDARD *T. BACCATA* CHRONOLOGY ANALYSIS

6.3.1 Volcano-related changes in standard tree-ring index

Table 6.5a shows the recorded TY-1, TY, TY+1, and TY+2 values for the standard growth index of *T. baccata* trees in Killarney, while Table 6.5b highlights the difference in growth between the year before the eruption (TY-1) and the year of the eruption (TY), as well TY-1 and TY+1, and TY-1 and TY+2. Because the eruption of Hekla in September 1845 occurred after the growing season had ended in Killarney, the data used for TY-1 comes from the year of the event, with TY being 1846; TY+1 is 1847 and 1848 is TY+2. The same is true for the December 1902 eruption of Grímsvötn and the October 1918 Katla event.

Five of the eruptions examined coincided with reduced *T. baccata* standard ring-width in Killarney in TY (Table 6.5b). The smallest change came after the September 1845 VEI 4 eruption of Hekla (-2.8%). More noteworthy changes occurred after the March 1947 VEI 4 Hekla eruption (-11.2%) and the January 1835 VEI 5 Cosigüina eruption (-19.6%), with the largest reduction (-22.7%) coming in 1991, the year of the VEI 6 Mount Pinatubo eruption. Notably, only three of the 11 eruptions examined did not coincide with at least a slight reduced ring-width in TY+1. Those that were followed by a narrowing had values as low as -0.6% (following the 1815 VEI 7 eruption of Tambora), -1.1% after the 1947 Hekla event and -5.5% for the September 1845 Hekla eruption. The larger reductions followed the eruptions of El Chichón in 1982 (-12.6%), Mount Pinatubo in 1991 (-17.4%), Cosigüina in 1835 (-36.1%) and Askja in 1875 (-38.7%). The number of eruptions that were followed by narrowed *T. baccata* ring-widths fell to six in TY+2. The smallest negative change came after the 1883 Krakatau event (-12%). Changes of -17.4% and -17.6% came in TY+2 of the eruptions of Askja in 1875 and El Chichón in 1982. Meanwhile the two largest reductions in ring-width came two years after the eruptions of Katla in October 1918 (-26.8%) and Cosigüina in 1835 (-27.9%).

Figure 6.5 shows the mean changes in the standard ring-width chronology in terms of five volcano categories. The data relating to all 11 eruptions shows that, on average, a decrease in ring-widths can be expected in all three years analysed,

Table 6.5a: Standard *T. baccata* growth index values in TY-1, TY, TY+1 and TY+2 of eruption years in Killarney National Park.

	Yearly Standard Growth Index Value			
Event	TY-1	TY	TY+1	TY+2
*Apr 1815 VEI7	0.941	0.966	0.935	1.095
*Jan 1835 VEI5	1.082	0.870	0.691	0.780
Sept 1845 VEI4	0.777	0.755	0.734	0.917
May 1860 VEI4	0.866	0.990	0.956	1.290
Mar 1875 VEI5	1.325	1.223	0.812	1.094
*May 1883 VEI6	1.133	1.152	1.064	0.997
Dec 1902 VEI4	0.967	1.106	1.068	1.012
Oct 1918 VEI4	0.832	0.865	0.986	0.609
Mar 1947 VEI4	0.931	0.827	0.921	0.811
*Mar 1982 VEI5	0.931	1.117	0.814	0.767
*Apr 1991 VEI6	1.400	1.082	1.157	1.445

***Denotes low-latitude eruption**

Table 6.5b: Percent difference between TY-1 & TY, TY-1 & TY+1 and TY-1 & TY+2 standard *T. baccata* growth index values in Killarney National Park.

	Percent Change from TY-1		
Event	**TY**	**TY+1**	**TY+2**
*Apr 1815 VEI7	2.7	-0.6	16.4
*Jan 1835 VEI5	-19.6	-36.1	-27.9
Sept 1845 VEI4	-2.8	-5.5	18.0
May 1860 VEI4	14.3	10.4	49.0
Mar 1875 VEI5	-7.7	-38.7	-17.4
*May 1883 VEI6	1.7	-6.1	-12.0
Dec 1902 VEI4	14.4	10.4	4.7
Oct 1918 VEI4	4.0	18.5	-26.8
Mar 1947 VEI4	-11.2	-1.1	-12.9
*Mar 1982 VEI5	20.0	-12.6	-17.6
*Apr 1991 VEI6	-22.7	-17.4	3.2

***Denotes low-latitude eruption**

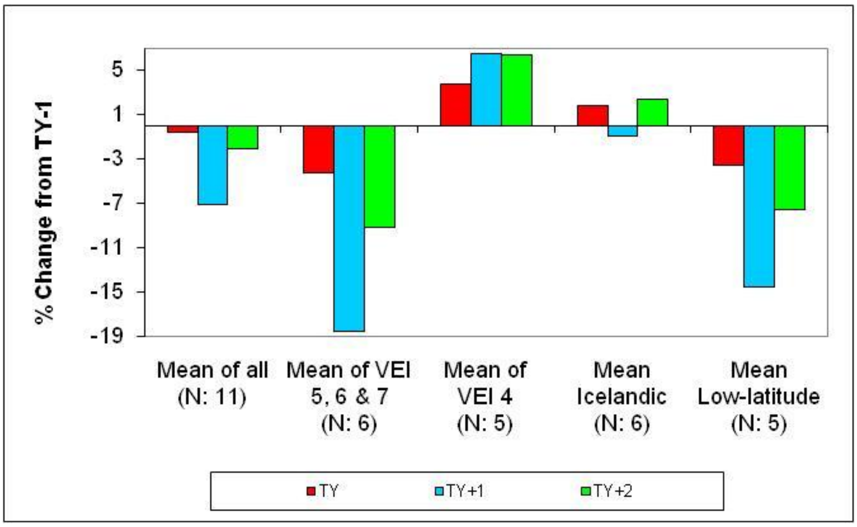


Figure 6.5: Five volcano categories indicating mean VEI- and location-specific changes in standard *T. baccata* growth index percentage values in Killarney National Park.

with just -0.6% in TY, -7.2% in TY+1 and -2.1% in TY+2. The six VEI 5-7 volcanic eruptions follow a similar pattern, peaking at -18.6% in TY+1, followed by -9.2% in TY+2. On average, none of the years associated with Icelandic VEI 4 eruptions coincide with reduced ring-widths, with increases of +3.7% in TY, +6.5% in TY+1 and +6.4% in TY+2. TY+1 is the only year related to the combined Icelandic eruptions that sees even a slight mean reduction in ring-widths (-0.9%), but this is aided by the fact that the 1875 VEI 5 Askja event coincided with a narrowing of -38.7% in this year, the largest of all the post-eruption ring-width reductions. The five low-latitude eruptions produce reductions of, on average, -4.7% in TY, -15.5% in TY+1 and -7.3% in TY+2.

In an effort to assess whether the time of the year of an eruption has an influence on *T. baccata* ring-widths in Killarney – eruptions coming before, during or after the growing season are likely to have differing influences on standard ring-width – Table 6.6 shows data relating to the quarter of the year within which the 11 eruptions occurred and whether there was an increase or decrease in standard ring-widths in the three years associated with the events. Three of the four eruptions that occurred in the first quarter of the year (January, February, March) coincided with reduced ring-width in TY, namely Cosigüina in January 1835, Askja in March 1875 and Hekla in March 1947. The eruption of Mount Pinatubo in April 1991 was the only Q2 (April, May, June) eruption to coincide with reduced ring-width in TY, with increases coming in the same years as the eruptions of Tambora in April 1815, Katla in May 1860 and Krakatau in May 1883. The single Q3 (July, August, September) eruption, that of Hekla in 1845, coincided with a decrease in *T. baccata* ring-widths in TY, while, of the two Q4 events (October, November, December), only that of Katla in October 1918 had narrowed ring-widths in the Killarney site.

All four of the Q1 volcanic eruptions were followed by reduced tree-ring widths in TY+1. Of the four Q2 events, Tambora in 1815, Krakatau in 1883 and Mount Pinatubo in 1991 all coincided with a slowing-down of standard ring growth in the first year after the eruptions. The Q3 eruption of Hekla in 1845 was followed by reduced growth, while both the Q4 events coincided with increases in growth

Table 6.6: Quarter within which eruption took place with +/- standard *T. baccata* growth in TY, TY+1 and TY+2 in Killarney National Park.

Increase or Decrease in Growth when Compared to TY-1												
Event	**TY**				**TY+1**				**TY+2**			
	Q1	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**
*Apr 1815 VEI7		+				-				+		
*Jan 1835 VEI5	-				-				-			
Sep 1845 VEI4			-				-				-	
May 1860 VEI4		+				+				+		
Mar 1875 VEI5	-				-				-			
*May 1883 VEI6		+				-				-		
Dec 1902 VEI4				+				+				+
Oct 1918 VEI4				-				+				+
Mar 1947 VEI4	-				-				-			
*Mar 1982 VEI5	+				-				-			
*Apr 1991 VEI6		-				-				+		

***Denotes low-latitude eruption**

in TY+1. For the second year in a row, all four Q1 volcanic eruptions were followed by narrowed ring-widths in TY+2. Three of the four Q2 events coincided with increases in ring-widths, with the eruption of Krakatau in 1883 providing the exception. Yet again, the Q3 1845 eruption of Hekla was followed by a reduction in *T. baccata* growth in Killarney in TY+2, while both of the Q4 events were followed by increases in ring-widths in TY+2.

6.3.2 Comparison with Killarney-based *Quercus* series

Table 6.2 presented correlations values between the standard *T. baccata* index and the 13 other tree-ring indices used in this research. With a significant correlation of 0.207 (P: 0.01) between the two Killarney-based *Q. petraea* and *T. baccata* series, Figure 6.6 compares the mean changes in ring-widths for both series in terms of the same five volcano categories examined previously. The *Q. petraea* index ends in 1978, meaning there is no data available for the final two eruptions examined, those of El Chichón in 1982 and Mount Pinatubo in 1991. Nevertheless, there are some obvious differences in growth trends. On average, the three years associated with any eruption have reduced *T. baccata* ring-widths each time, while *Q. petraea* ring-widths coincide with an increase in TY (+5.5%), a slight decrease in TY+1 (-0.1%) and a more noteworthy decrease in TY+2 (-8.4%). Both series have reduced ring-widths in all three years associated with VEI 5-7 eruptions, with the most considerable *T. baccata* change coming in TY+1 (-18.6%), while the largest *Q. petraea* change occurs in TY+2 (-15%).

The Icelandic VEI 4 eruptions have similar patterns of increases in ring-widths for both series in TY and TY+1, with the more noteworthy changes occurring in the *Q. petraea* series. This series then has a narrowing of rings in TY+2 (-3.1%) while the *T. baccata* index has another increase in ring-widths (+6.4%). The years associated with all Icelandic volcanic eruptions combined have very different reactions in the two series. The only common feature is an increase in TY (*T. baccata*: +1.8%; *Q. petraea*: +11.2%). TY+1 has a slight decrease (-1%) in *T. baccata,* and an increase of +9% in *Q. petraea.* The two series move in opposite directions in TY+2, with an increase of +2.4% in *T. baccata* and a

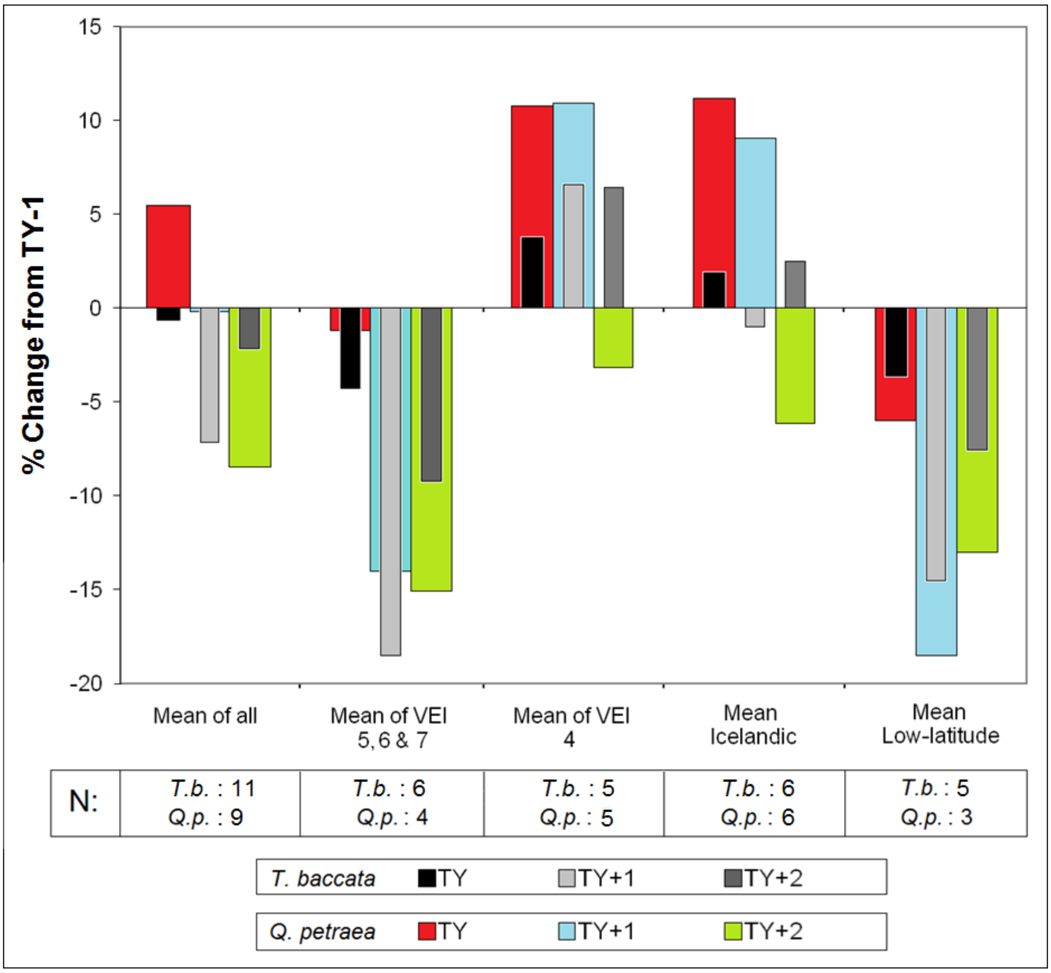


Figure 6.6: Five volcano categories comparing mean VEI- and location-specific changes in *T. baccata* and *Q. petraea* growth index values in years associated with eruptions. (*T.b.* = *T. baccata*. *Q.p.* = *Q. petraea*).

decrease of -6.1% in *Q. petraea*. Both series followed the same pattern in ring-width changes in the three years associated with low-latitude eruptions, with reductions occurring on each occasion. The most noteworthy change came in TY+1 in both instances (*T. baccata*: -14.6%; *Q. petraea*: -18.5%).

6.3.3 Reconstructed temperatures and volcanic eruptions

Table 6.7a contains the reconstructed mean November to April temperature in each of the years associated with the 11 volcanic eruptions, with the percent change is shown in Table 6.7b. Although the post-volcanic eruption trends are similar to those that occurred in the standard ring-width index, the intensity of changes within the reconstructed temperature record has the potential to be dampened or enhanced. This, in turn, necessitates a separate examination of the reconstructed temperature series. Three of the eruptions (Cosigüina in 1835, Askja in 1875 and Hekla in 1947) coincided with reduced reconstructed temperatures in all three of the years examined, with four eruptions having such reductions in two years, while one event (Katla, 1918) is followed by only one year of reduced temperatures.

Figure 6.7 shows the mean changes in reconstructed November to April temperatures in Killarney in terms of five categories of volcano. The first of these is the average change for all 11 events. Here reductions in temperatures occur in all three years examined, albeit very minor. Temperatures in TY fell by just -0.4%, followed by -2.2% in TY+1 and -0.6% in TY+2. The VEI 5-7 eruptions coincide, on average, with slightly more noteworthy changes in temperature. The five eruptions had a mean drop in temperatures of -1.6% in TY, with -5.3% in TY+1 and -2.3% in the second year after the event. The Icelandic VEI 4 eruptions tended to coincide with very small increases in all three years examined (+1%, +1.6% and +1.4% respectively), while the six Icelandic eruptions coincided with even less remarkable changes in reconstructed temperatures in Killarney, with +0.5% in TY, -0.6% in TY+1 and +0.4% in TY+2. The five low-latitude eruptions followed a similar, but less notable, pattern to the VEI 5-7 events, with decreases of -1.4% in TY, -4% in TY+1 and -1.8% in TY+2.

Table 6.7a Reconstructed mean November-April temperatures (°C) in Killarney National Park in TY-1, TY, TY+1 and TY+2 of eruption years.

	Mean November-April Temperature			
Event	TY-1	TY	TY+1	TY+2
*Apr 1815 VEI 7	9.7	9.8	9.8	10.2
*Jan 1835 VEI 5	10.1	9.6	9.2	9.4
Sept 1845 VEI 4	9.4	9.3	9.3	9.7
May 1860 VEI 4	9.5	9.9	9.8	10.6
Mar 1875 VEI 5	10.6	10.4	9.4	10.2
*May 1883 VEI 6	10.2	10.3	10.0	9.9
Dec 1902 VEI 4	9.8	10.2	10.1	9.9
Oct 1918 VEI 4	9.5	9.6	9.9	8.9
Mar 1947 VEI 4	9.8	9.5	9.7	9.5
*Mar 1982 VEI 5	9.7	10.2	9.4	9.4
*Apr 1991 VEI 6	10.9	10.0	10.3	11.0

***Denotes low-latitude eruption**

Table 6.7b: Percent difference between TY-1 & TY, TY-1 & TY+1 and TY-1 & TY+2 reconstructed mean November-April temperatures in Killarney National Park.

	Percent Change from TY-1		
Event	TY-1&TY	TY-1&TY+1	TY-1&TY+2
*Apr 1815 VEI 7	1.1	0.3	4.4
*Jan 1835 VEI 5	-5.6	-9.6	-7.1
Sept 1845 VEI 4	-0.4	-0.9	4.0
May 1860 VEI 4	4.0	2.8	11.6
Mar 1875 VEI 5	-2.3	-11.7	-4.5
*May 1883 VEI 6	0.5	-1.7	-3.2
Dec 1902 VEI 4	3.4	2.2	0.8
Oct 1918 VEI 4	0.9	4.0	-6.1
Mar 1947 VEI 4	-2.8	-0.2	-3.2
*Mar 1982 VEI 5	4.7	-3.3	-3.9
*Apr 1991 VEI 6	-7.9	-5.7	0.7

***Denotes low-latitude eruption**

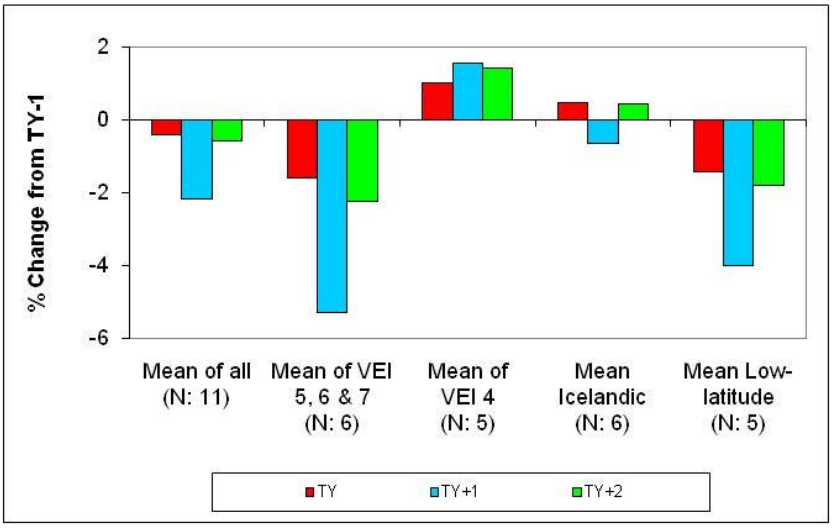


Figure 6.7: Five volcano categories indicating mean VEI- and location-specific changes in reconstructed mean November-April temperatures in Killarney National Park.

6.4 RESIDUAL *T. BACCATA* CHRONOLOGY ANALYSIS

6.4.1 Volcano-related changes in residual tree-ring index

Table 6.8a shows the residual *T. baccata* growth index values for the years associated with the 11 volcanic eruptions, with Table 6.8b containing the percent change from year to year. Four of the eruptions coincided with a narrowing of this residual chronology in TY (Cosigüina, 1835: -30.2%; Askja, 1875: -8.4%; Hekla, 1947: -16.7%; Mount Pinatubo, 1991: -28.9%). Six of the volcanic eruptions were followed by reduced residual ring-width values in TY+1, with values ranging from as low as -1% in the year after the 1883 Krakatau event to as large as -33.4% following the eruption of Cosigüina in 1835 and -43.5% in TY+1 of the 1875 Askja event. The five reductions in residual values that came in the second year after eruptions were less noteworthy in comparison to those of the previous year, with the 1947 Hekla and 1982 El Chichón events providing the largest changes (-19.9% and -19.6% respectively).

On average over the 11 eruptions, only slight changes of +2.1% and -2.2% come in TY and TY+1, with an increase of +8.4% in TY+2 (Figure 6.8). The six VEI 5-7 eruptions coincide with narrowed residual ring-widths in each of the three years, with the largest change coming in TY+1 (-18%). On average, the five Icelandic VEI 4 events had increases in residual ring-widths in all three years, as do the mean results for all six Icelandic eruptions. TY+2 provides the largest change in both cases (VEI 4: +20.3%; all Icelandic: +18.8%). The low-latitude eruptions follow the same pattern as the VEI 5-7 events, with decreases of -4.2%, -12.9% and -4.1% in the three years examined.

Table 6.9 shows data relating to the quarter of the year within which the 11 eruptions occurred and whether there was an increase or decrease in residual ring-width in the three years associated with the events. Three of the four Q1 eruptions (Cosigüina, 1835; Askja, 1875; Hekla, 1947) coincided with narrowed ring-widths in TY, while only one of the four Q2 events (Mount Pinatubo in 1991) had such a change. The remaining three eruptions from Q3 and Q4 all coincided with increases in ring-widths in TY. All four of the Q1 eruptions were followed by reduced residual index values in TY+1, while two of the four

Table 6.8a: Residual *T. baccata* growth index values in TY-1, TY, TY+1 and TY+2 of eruption years in Killarney National Park.

	Yearly Residual Growth Index Value			
Event	**TY-1**	**TY**	**TY+1**	**TY+2**
*Apr 1815 VEI 7	0.872	1.019	0.975	1.041
*Jan 1835 VEI 5	1.164	0.813	0.775	0.982
Sept 1845 VEI 4	0.81	0.885	0.979	0.943
May 1860 VEI 4	0.724	1.037	0.981	1.25
Mar 1875 VEI 5	1.073	0.983	0.606	1.196
*May 1883 VEI 6	0.979	1.075	0.969	0.942
Dec 1902 VEI 4	0.88	1.024	1.142	1.035
Oct 1918 VEI 4	0.947	0.951	0.983	1.087
Mar 1947 VEI 4	1.079	0.899	1.009	0.864
*Mar 1982 VEI 5	1.03	1.145	0.742	0.828
*Apr 1991 VEI 6	1.262	0.897	1.088	1.249

***Denotes low-latitude eruption**

Table 6.8b: Percent difference between TY-1 & TY, TY-1 & TY+1 and TY-1 & TY+2 residual *T. baccata* growth index values in Killarney National Park.

	Percent Change from TY-1		
Event	**TY-1&TY**	**TY-1&TY+1**	**TY-1&TY+2**
*Apr 1815 VEI 7	16.9	11.8	19.4
*Jan 1835 VEI 5	-30.2	-33.4	-15.6
Sept 1845 VEI 4	9.3	20.9	16.4
May 1860 VEI 4	43.2	35.5	72.7
Mar 1875 VEI 5	-8.4	-43.5	11.5
*May 1883 VEI 6	9.8	-1.0	-3.8
Dec 1902 VEI 4	16.4	29.8	17.6
Oct 1918 VEI 4	0.4	3.8	14.8
Mar 1947 VEI 4	-16.7	-6.5	-19.9
*Mar 1982 VEI 5	11.2	-28.0	-19.6
*Apr 1991 VEI 6	-28.9	-13.8	-1.0

***Denotes low-latitude eruption**

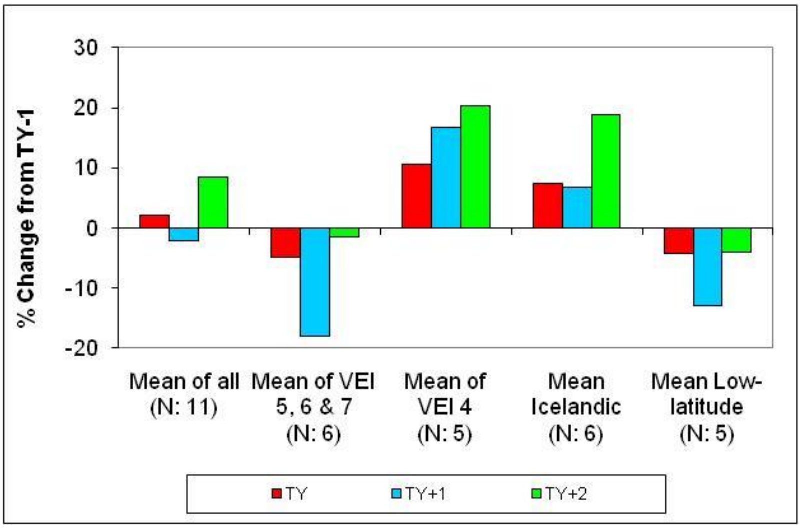


Figure 6.8: Five volcano categories indicating mean VEI- and location-specific changes in residual *T. baccata* growth index percentage values in Killarney National Park.

Table 6.9: Quarter within which eruption took place with +/- residual *T. baccata* growth in TY, TY+1 and TY+2 in Killarney National Park.

Increase or Decrease in Growth When Compared to TY-1												
Event	TY				TY+1				TY+2			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
*Apr 1815 VEI7		+				+				+		
*Jan 1835 VEI5	-				-				-			
Sep 1845 VEI4			+				+				+	
May 1860 VEI4		+				+				+		
Mar 1875 VEI5	-				-				+			
*May 1883 VEI6		+				-				-		
Dec 1902 VEI4				+				+				+
Oct 1918 VEI4				+				+				+
Mar 1947 VEI4	-				-				-			
*Mar 1982 VEI5	+				-				-			
*Apr 1991 VEI6		-				-				-		

***Denotes low-latitude eruption**

Q2 events (Krakatau in 1883 and Mount Pinatubo in 1991) had the same narrowing pattern. For the second year, all three of the Q3 and Q4 eruptions were followed by increases in ring-width in TY+1. In TY+2, of the Q1 eruptions, only Askja in 1875 was followed by an increase in residual index values. The Q2 eruptions followed the same pattern as the previous year, with decreases following the 1883 Krakatau and 1991 Mount Pinatubo events. For the third year in a row, the Q3 and Q4 eruptions coincided with increases in residual ring-widths in TY+2.

6.4.2 Reconstructed precipitation and volcanic eruptions

In an effort to investigate this possible influence of volcanic eruptions on total May-June precipitation values in Killarney National Park, Table 6.10a presents the data relating to the four years under examination for each of the 11 volcanic events, while Table 6.10b shows the year-to-year percent change. Nine of the volcanic eruptions coincided with at least a slight fall in precipitation levels in Killarney in TY, with values ranging from -2% in the year of the 1902 Grímsvötn event and -4.9% for 1845 Hekla eruption, to -15.9% in 1815, the year of the eruption of Tambora, and -21% for the 1835 Cosigüina event. The number of negatively influenced years fell to seven in TY+1. However, the changes experienced tended to be more noteworthy, including -28.9% for the eruption of El Chichón in 1982, -58.2% following the 1835 Cosigüina event and -63.2% in the first year after the eruption of Askja in 1875. Reductions in reconstructed precipitation values occurred on five occasions in TY+2, including -37.4% for the eruption of Cosigüina in 1835 and -57.2% in the second year after the 1982 El Chichón event.

The average change in precipitation for all 11 eruptions (Figure 6.9) decreases by -5.8% and -8.8% in the first two years examined, while a very slight increase of +0.3% tends to occur in TY+2. The VEI 5-7 eruptions coincide with reduced total precipitation values in all three years, including -25.9% in TY+1. The Icelandic VEI 4 eruptions tend to see a decrease in precipitation in the year of the events (-7.8%), and are followed by increases of +11.7% and +22.4% in the next two years respectively. The combined Icelandic eruptions again have a decrease

Table 6.10a: Reconstructed total May - June precipitation values (mm) in Killarney National Park TY-1, TY, TY+1 and TY+2 of eruption years.

	Total May-June Precipitation			
Event	TY-1	TY	TY+1	TY+2
*Apr 1815 VEI 7	195.0	164.0	182.4	190.3
*Jan 1835 VEI 5	215.8	170.4	90.3	135.2
Sept 1845 VEI 4	123.7	117.6	156.5	166.3
May 1860 VEI 4	159.5	138.9	187.5	244.5
Mar 1875 VEI 5	221.7	195.3	81.6	155.5
*May 1883 VEI 6	160.5	199.7	192.1	164.0
Dec 1902 VEI 4	170.4	166.9	225.7	222.3
Oct 1918 VEI 4	173.1	161.9	170.8	203.6
Mar 1947 VEI 4	199.9	175.2	166.9	152.2
*Mar 1982 VEI 5	209.0	227.7	148.6	89.5
*Apr 1991 VEI 6	227.8	211.4	186.5	265.7

***Denotes low-latitude eruption**

Table 6.10b: Percent difference between TY-1 & TY, TY-1 & TY+1 and TY-1 & TY+2 reconstructed total May - June precipitation values in Killarney National Park.

	Percent Change from TY-1		
Event	TY-1&TY	TY-1&TY+1	TY-1&TY+2
*Apr 1815 VEI 7	-15.9	-6.5	-2.4
*Jan 1835 VEI 5	-21.0	-58.2	-37.4
Sept 1845 VEI 4	-4.9	26.5	34.4
May 1860 VEI 4	-12.9	17.6	53.3
Mar 1875 VEI 5	-11.9	-63.2	-29.9
*May 1883 VEI 6	24.4	19.7	2.2
Dec 1902 VEI 4	-2.0	32.5	30.5
Oct 1918 VEI 4	-6.5	-1.3	17.6
Mar 1947 VEI 4	-12.4	-16.5	-23.8
*Mar 1982 VEI 5	9.0	-28.9	-57.2
*Apr 1991 VEI 6	-7.2	-18.1	16.6

***Denotes low-latitude eruption**

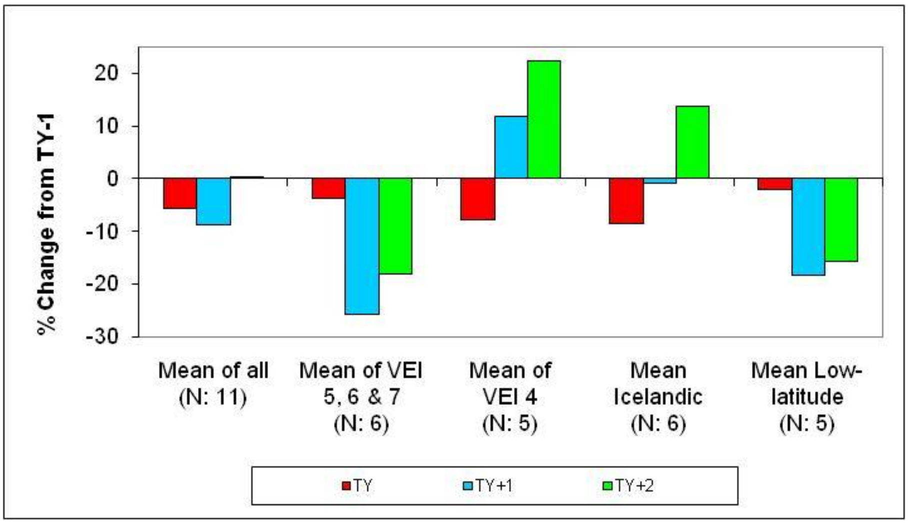


Figure 6.9: Five volcano categories indicating mean VEI- and location-specific changes in reconstructed total May - June precipitation values in Killarney National Park.

in TY (-8.4%), with another slight decrease in TY+1 (-0.7%) and an increase of +13.7% in TY+2. The low-latitude eruptions follow a similar pattern to the VEI 5-7 events, with the most prominent change occurring in TY+1 (-18.4%).

6.5 CORRELATIONS WITH LAMB'S (1970) DUST VEIL INDEX

Although correlations run in the previous chapter between DVI and other Irish tree-ring indices highlighted significant connections between the presence of volcanic ash in the atmosphere and tree growth, the examination of DVI and both standard and residual *T. baccata* chronologies in Killarney National Park (Table 6.11) fails to produce any significant correlations. The highest correlations were achieved for the years 1900 to 1949, with R values of 0.249 (P: not significant) for standard ring-width and DVI and 0.264 (P: not significant) for standard ring-width and DVI lagged to one year. Figure 6.10 shows the DVI and *T. baccata* standard and residual index values for the years 1803 to 1995 (the year up to which DVI values are available). Correlations were also run between DVI and the reconstructed temperature and precipitation values for Killarney. With the temperature and precipitation values being a function of the standard and residual indices respectively, the fact that neither produced any significant correlations with the DVI is to be expected. As with the tree-ring indices, the highest (but, in this case, not significant) correlations came with the groups of data for 1900-1949, with temperature receiving R values of 0.118 and 0.117 (P: not significant) for the DVI and DVI lagged to one year and precipitation producing R values of 0.125 and 0.189 (P: not significant) with DVI and DVI lagged to one year.

6.6 CORRELATIONS WITH NORTH ATLANTIC OSCILLATION

Figure 6.11 plots Hurrell's (1995) principal component (PC) winter NAO values along with the standard and residual *T. baccata* tree-ring index values for the years 1899-2007. When correlated with PC based winter NAO values, *T. baccata* received some significant results, with less notable correlations being achieved with Jones *et al*.'s (1997) reconstructed seasonal NAO values. In terms of Hurrell's (1995) winter NAO values for the years 1899-2007, a correlation of 0.289 (P: 0.01) was achieved with the *T. baccata* standard index, and 0.285 (P: 0.01) when the NAO was lagged to one year (Table 6.12). Following Cook *et*

Table 6.11: Correlations results for Dust Veil Index (Lamb, 1970) and DVI lagged to one year with *T. baccata* standard and residual growth indices, reconstructed temperature and reconstructed precipitation (1803-1995 and sub-categories (after Cook *et al.*, 1998)).

Years Analysed	Dust Veil Index	Standard Chronology	Residual Chronology	Reconstructed Precipitation	Reconstructed Temperature
1803-1995	DVI	0.014	-0.050	-0.026	-0.050
	DVI-1	-0.005	-0.034	-0.063	-0.036
1803-1849	DVI	-0.117	-0.173	-0.169	-0.173
	DVI-1	-0.168	-0.141	-0.221	-0.141
1850-1899	DVI	0.155	0.089	-0.081	0.089
	DVI-1	0.066	-0.021	0.039	-0.022
1900-1949	DVI	0.249	0.118	0.125	0.118
	DVI-1	0.264	0.117	0.189	0.117
1950-1995	DVI	0.192	-0.019	0.117	-0.019
	DVI-1	0.220	0.046	0.040	0.038

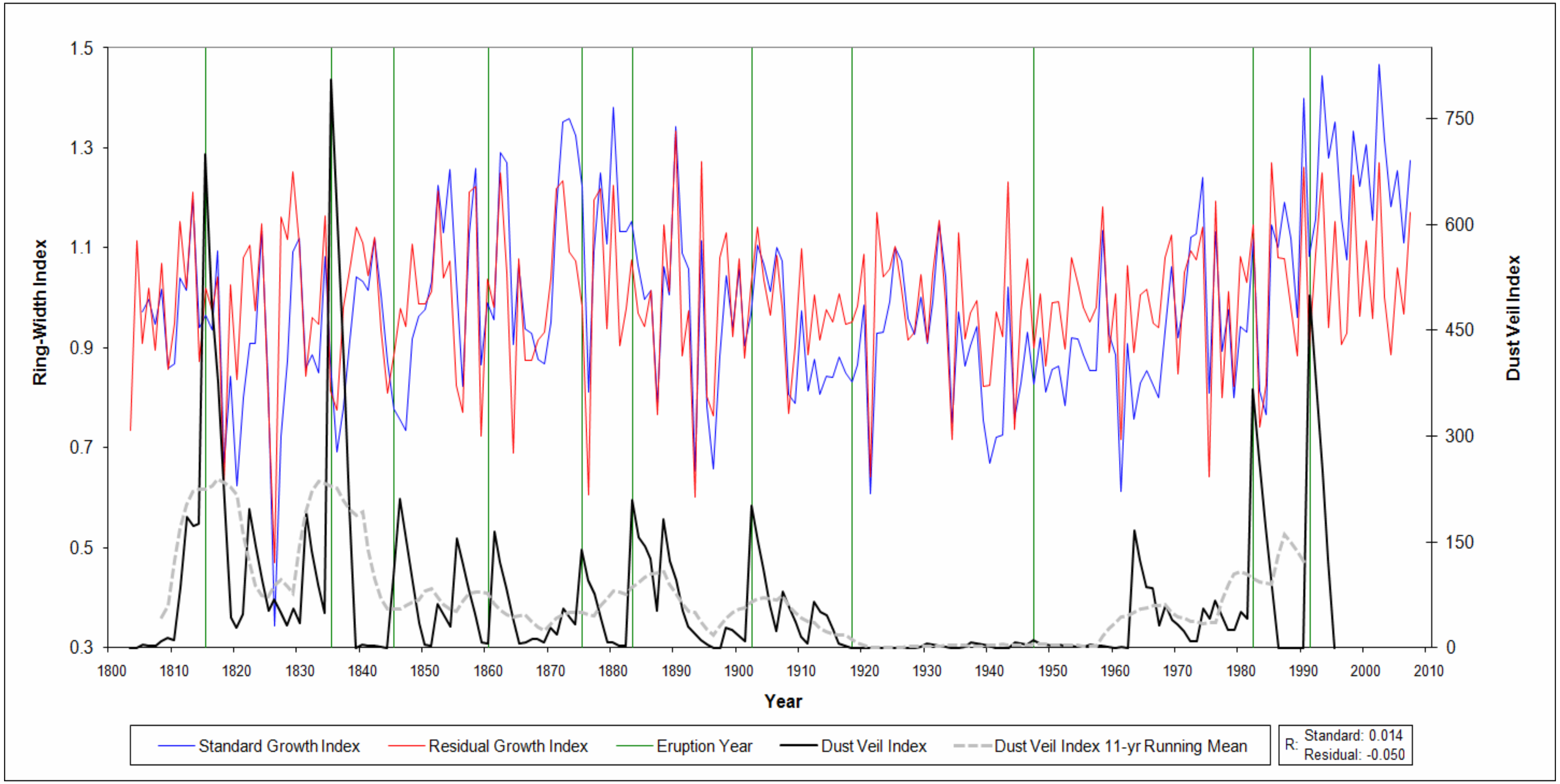


Figure 6.10: Dust Veil Index and DVI 11-year running mean with standard and residual tree-ring growth index for *T. baccata* in Killarney National Park, 1803-2007. Also included are the years the selected volcanic eruptions occurred.

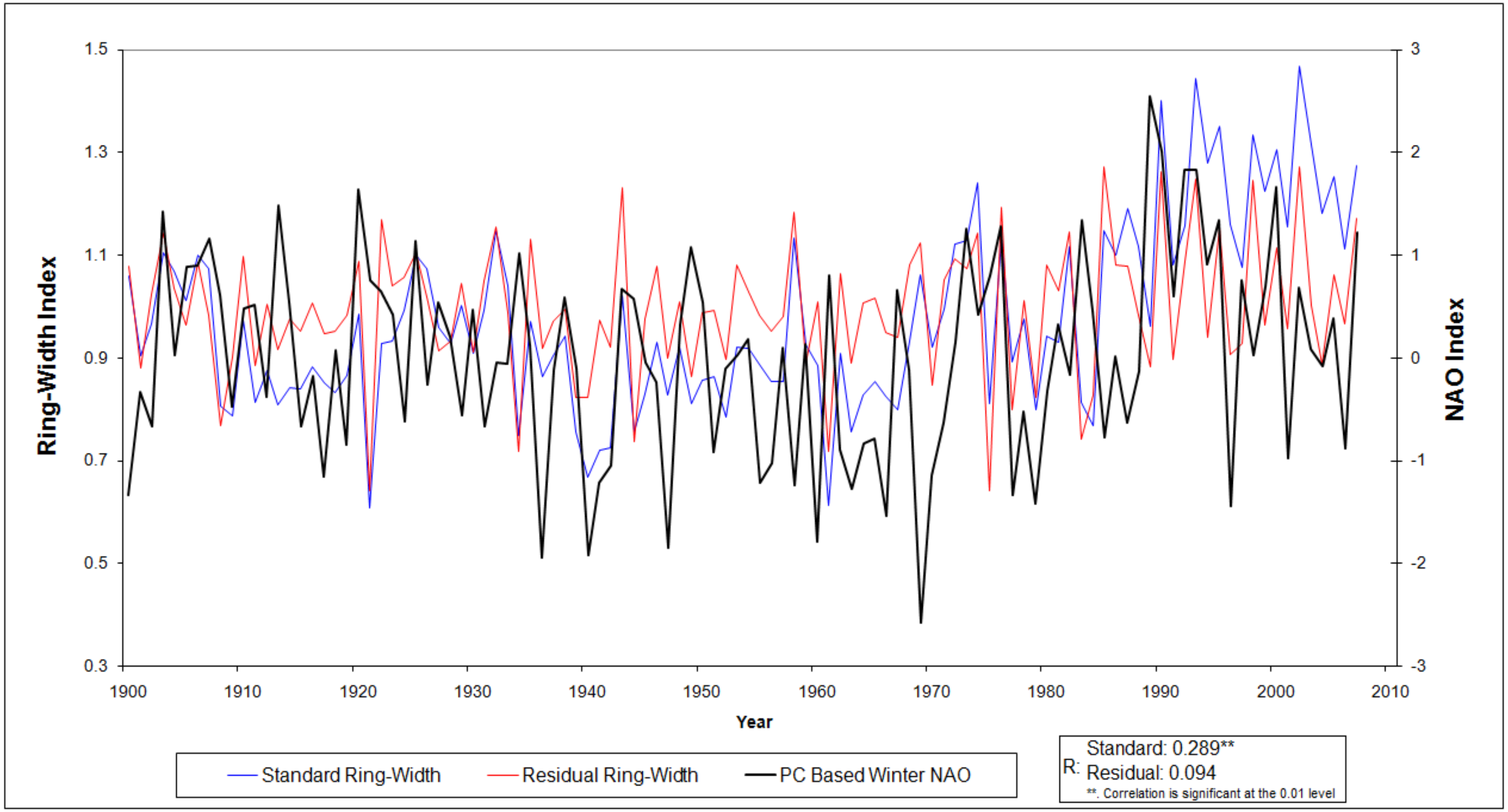


Figure 6.11: Hurrell's (1995) PC based winter North Atlantic Oscillation values with standard and residual tree-ring growth index values for *T. baccata* in Killarney National Park, 1900-2007.

Table 6.12: Pearson correlation coefficients from Hurrell's (1995) PC based winter NAO values (1899-2000) and *T. baccata* indices and reconstructions. Also included are sub-categories (after Cook *et al.*, 1998) and correlations for NAO series lagged to one year.

Correlations with Hurrell's (1995) PC based Winter NAO				
Years	**Standard Index**	**Residual Index**	**Reconstructed Temp.**	**Reconstructed Precip.**
1899-2007	0.289**	0.094	0.282**	0.097
1900-1949	0.246	0.067	0.233	0.163
1950-1999	0.335**	0.059	0.332**	0.045

Correlations with Hurrell's (1995) PC based Winter NAO (lagged to one year)				
Years	**Standard Index**	**Residual Index**	**Reconstructed Temp.**	**Reconstructed Precip.**
1899-2007	0.285**	0.065	0.275**	0.130
1900-1949	-0.040	-0.212	-0.060	-0.125
1950-1999	0.545**	0.315*	0.541**	0.355*

****Correlation is significant at the 0.01 level**
***Correlation is significant at the 0.05 level**

al.'s (1998) method of dividing the correlations into smaller sub-groups produced more significant correlations for the years 1950-1999. Here the PC based winter NAO values received an R value of 0.335 (P: 0.01) with standard *T. baccata* ring-widths, while lagging the NAO values by one year produced a higher R value of 0.545 (P: 0.01). The previous 50 years (1900-1949) failed to produce any significant correlations with the standard index. The only significant correlation with the residual index came for the years 1950-1999 when the NAO values were lagged to one year. Here an R value of 0.315 (P: 0.05) was returned.

Some significant associations were also produced when Hurrell's (1995) PC based winter NAO values were correlated with the reconstructed temperature and precipitation values for Killarney. This NAO index showed a correlation of 0.282 (P: 0.01) with reconstructed mean November to April temperatures, while a lag of one year produced an R value of 0.275 (P: 0.01). Correlations for the years 1900 to 1949 failed to reveal any significant results. However, PC based winter NAO values and reconstructed temperatures for 1950 to 1999 gave an R value of 0.332 (P: 0.01), with 0.541 (P: 0.01) when lagged to one year. Less significant correlations were achieved when examining PC based winter NAO and reconstructed precipitation as this reconstruction was achieved using the residual chronology. However, the years 1950 to 1999 produced an R value of 0.355 (P: 0.05) when correlated with PC based winter NAO values lagged to one year.

Jones *et al.*'s (1997) reconstructed seasonal NAO values rarely produced any correlation coefficients of note with the *T. baccata* series or reconstructions, be it in terms of NAO, NAO lagged to one year, or sub-division of 50-year segments (Table 6.13). NAO values for winter (1900-1949) produced correlations significant at the 95th percentile with the standard index (R: 0.310 P: 0.05) as well as the reconstructed precipitation (R: 0.301 P: 0.05), while autumn NAO values from the current year have a negative influence on the same two datasets: (standard index: R: -0.321 P: 0.05; reconstructed temperature: R: -0.324 P: 0.05). Lagging the seasonal NAO values by one year does produce some more notable

Table 6.13: Pearson correlation coefficients from Jones *et al.*'s (1997) seasonal NAO values (1825-2000) and *T. baccata* indices and reconstructions. Also included are sub-categories (after Cook *et al.*, 1998) and correlations for NAO series lagged to one year.

Correlations with Jones *et al*.'s (1997) Seasonal NAO Reconstructions					
Season/Years		Standard Index	Residual Index	Reconstructed Temp.	Reconstructed Precip.
Winter	1825-2007	0.147	0.104	0.151*	0.072
	1825-1849	0.293	0.174	0.295	0.235
	1850-1899	0.073	0.114	0.085	0.054
	1900-1949	0.310*	0.264	0.301*	0.236
	1950-1999	0.168	-0.016	0.166	-0.086
Spring	1825-2007	-0.011	0.044	-0.003	0.052
	1825-1849	0.172	0.078	0.179	0.124
	1850-1899	-0.060	0.079	-0.047	-0.043
	1900-1949	0.079	0.049	0.076	0.095
	1950-1999	0.025	0.011	0.026	0.145
Summer	1825-2007	-0.057	-0.104	-0.049	-0.141
	1825-1849	-0.291	-0.398	-0.289	-0.300
	1850-1899	-0.225	-0.201	-0.216	-0.253
	1900-1949	0.197	0.276	0.223	0.241
	1950-1999	0.006	-0.026	0.012	-0.130
Autumn	1825-2007	-0.037	0.004	-0.030	0.010
	1825-1849	-0.058	-0.117	-0.048	-0.060
	1850-1899	0.170	0.113	0.184	0.185
	1900-1949	0.041	0.055	0.049	0.060
	1950-1999	-0.321*	-0.189	-0.324*	-0.133

Correlations with Jones *et al*.'s (1997) Seasonal NAO Reconstructions (lagged to one year)					
Season/Years		Standard Index	Residual Index	Reconstructed Temp.	Reconstructed Precip.
Winter	1825-2007	0.100	0.007	0.107	0.079
	1825-1849	0.043	-0.198	0.071	-0.004
	1850-1899	-0.068	-0.052	-.070	0.036
	1900-1949	0.136	-0.070	0.101	0.150
	1950-1999	0.374**	0.247	0.365**	0.231
Spring	1825-2007	-0.103	-0.094	-0.113	-0.049
	1825-1849	-0.016	-0.148	-0.032	-0.043
	1850-1899	-0.134	-0.064	-0.133	-0.005
	1900-1949	-0.145	-0.211	-0.178	-0.155
	1950-1999	0.025	0.013	0.021	0.022
Summer	1825-2007	-0.064	-0.041	-0.065	-0.109
	1825-1849	-0.420*	-0.216	-0.431*	-0.420*
	1850-1899	-0.108	0.070	-0.085	-0.076
	1900-1949	-0.136	-0.273	-0.148	-0.055
	1950-1999	0.148	0.110	0.141	0.078
Autumn	1825-2007	-0.133	-0.118	-0.131	-0.098
	1825-1849	-0.214	-0.174	-0.239	-0.141
	1850-1899	-0.102	-0.216	-0.120	-0.051
	1900-1949	-0.053	-0.078	-0.041	-0.027
	1950-1999	-0.255	-0.044	-0.232	-0.188

****Correlation is significant at the 0.01 level**
***Correlation is significant at the 0.05 level**

correlations, particularly in relation to winter values for 1950-1999: (standard index: R: 0.374 P: 0.01; reconstructed temperature: R: 0.365 P: 0.01). In addition, summer NAO values from the previous year had a negative influence on growth for the period 1825-1849 (standard index: R: -0.420 P: 0.05; reconstructed temperature: R: -0.431, P: 0.05; reconstructed precipitation: R: -0.420 P: 0.05).

Morlet wavelet analysis was performed on the standard and residual *T. baccata* chronologies to ascertain the dominant modes of variability within the time series and how these modes vary through time (Torrence and Compo, 1998). Both chronologies exhibit variability similar to NAO frequencies pre-1900, demonstrated by the contour lines between the four and eight year periodicity in the wavelet power spectrum in Figure 6.12b and particularly in Figure 6.13b. The wavelet power spectrum indicates such a periodicity here because the nature of the residual chronology means that each year's growth is assessed on its own merit, in that the influence of previous years is not included. Consequently, the periodicity of an external forcing factor such as NAO, which can vary greatly from year-to-year, is likely to be more prevalent in the residual index than the standard. Meanwhile, the global wavelet (Figure 6.12c and Figure 6.13c) comes close to the line of significance centred on the eight year mark in both cases, corresponding well with Rogers' (1984) theory that the NAO index is characterised by a periodicity of 7.3-8.0 years. Both the wavelet power spectrum and global wavelet for the residual chronology (Figure 6.13b and c) show a further periodicity, which is displayed at short intervals throughout the series, at just over two years, in-keeping with Schneider and Schonwiese's (1989) report of significant spectral power between 1.7 and 2.2 years in NAO data.

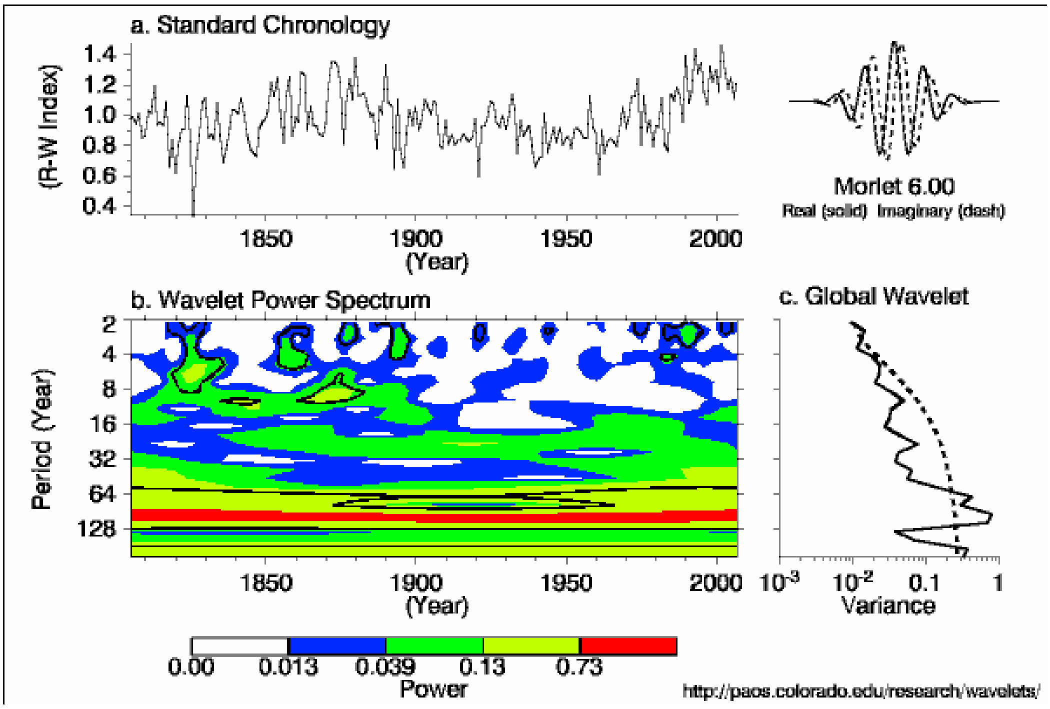


Figure 6.12: (a) *T. baccata* standard ring-width chronology. (b) Wavelet power spectrum. The contour levels are chosen so that 75%, 50%, 25%, and 5% of the wavelet power is above each level, respectively. Black contour is the 10% significance level, using a red-noise (autoregressive lag1) background spectrum. (c) The global wavelet power spectrum (black line). The dashed line is the significance for the global wavelet spectrum, assuming the same significance level and background spectrum as in (b). See Torrence and Compo (1998) for a detailed guide to wavelet graphs.

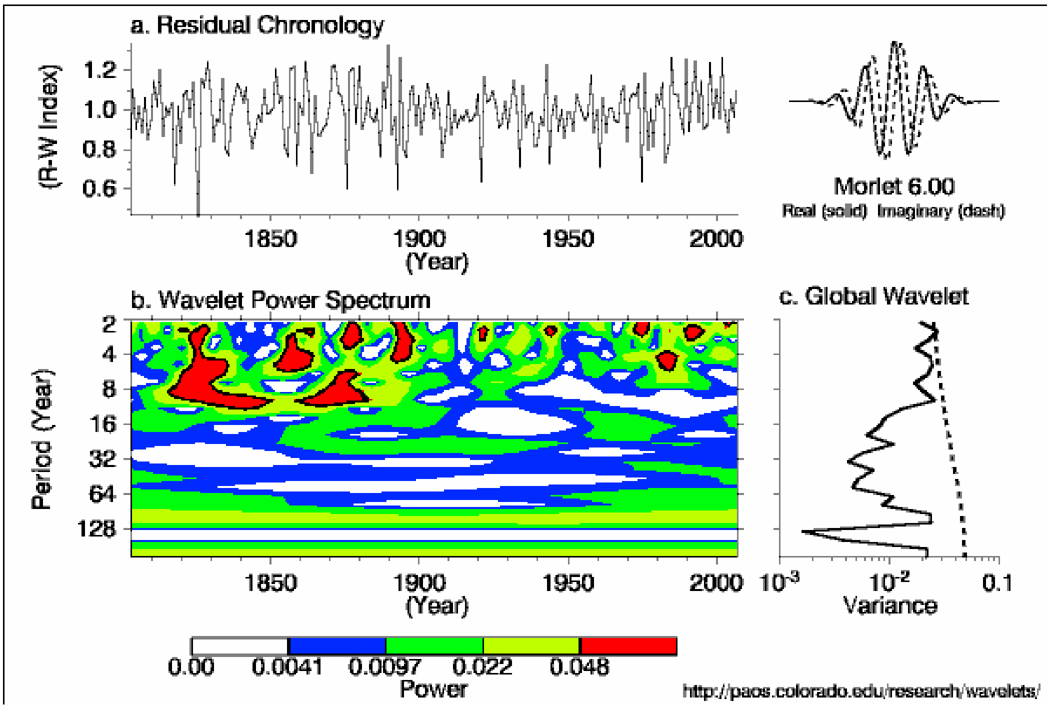


Figure 6.13: (a) *T. baccata* residual ring-width chronology. (b) Wavelet power spectrum. The contour levels are chosen so that 75%, 50%, 25%, and 5% of the wavelet power is above each level, respectively. Black contour is the 10% significance level, using a red-noise (autoregressive lag1) background spectrum. (c) The global wavelet power spectrum (black line). The dashed line is the significance for the global wavelet spectrum, assuming the same significance level and background spectrum as in (b). See Torrence and Compo (1998) for a detailed guide to wavelet graphs.

CHAPTER 7: COMBINED PROXY EVALUATION

The objective of this thesis was to determine the extent large-scale low-latitude volcanic eruptions and lesser Iceland-based events have had on the climate and ecology of Ireland over the past ~200 years. In order to assess these interactions, the results chapters were each the culmination of different techniques. Consequently, it is important to combine the records in a more comprehensive synthesis whereby more general patterns of post-volcanic eruption weather phenomena can be presented. By combining the results of the archive-based climate data with the dendroecological trends and dendroclimatic reconstructions, a deeper understanding of volcano-climate interactions in Ireland is developed. This chapter will begin by identifying trends in the data gathered before comparing the results garnered in relation to each individual eruption, and will conclude by presenting an evaluation of the various proxies in terms of five categories of volcano.

7.1 TRENDS IN RECORDED WEATHER DATA

The weather records from Armagh Observatory show that large-scale volcanic eruptions can have a marked impact on climate regimes in Ireland. The most notable and consistent drops in temperature values in the months after the larger eruptions (i.e. the VEI 5-7 and low-latitude events) come between TM+11 and TM+20. This study has also shown that the winters in the year of and the year following larger scale VEI 5-7 and low-latitude eruptions are likely to experience warmer than usual temperatures in Armagh, while the records show very little change in TY+1 summer temperatures, regardless of the VEI value or location of eruption. However, autumn and, to a greater extent, spring temperatures are negatively impacted upon in TY+1 and TY+2 of the VEI 5-7 and low-latitude eruptions.

The precipitation data from Armagh Observatory shows that the first month after large-scale VEI 5-6 eruptions tends to experience the most notable reduction in values (-64.86%), with -55.4% in TM+1 of low-latitude events. The biggest contrast from one month to the next following VEI 5-6 eruptions occurs between

TM+15 (+37.7%) and TM+16 (-30.4%). The VEI 4 and Icelandic eruptions stay above the 11-year mean for precipitation values for the first three months, with the highest of any of the values produced (+55.3%) coming in TM+1 of the Icelandic VEI 4 eruptions. Between TM+9 and TM+21, values fluctuated above and below the mean, but seldom to any great extent.

The only persistent increases that occur in the number of days where zero precipitation falls following the VEI 5-6 eruptions comes between TM+14 and TM+17, with the former providing the largest change (+4 days). The low-latitude eruptions follow an almost identical pattern to the VEI 5-6 events throughout. Of the 11 months that did see an increase in zero-precipitation days in Armagh following low-latitude eruptions, TM+1 provided the largest value (+4.9 days), as it did with the VEI 5-6 events (+6.5 days). The VEI 4 and Icelandic eruptions persistently see more dry days in Armagh in comparison to the larger eruptions. Winter in TY+1 of eruptions, particularly VEI 5-6 events, is likely to see an increase in rainfall in Armagh, while autumn records for TY show a similar increase throughout the five mean categories of volcano. The summer months are those likely to experience the most prominent decrease in precipitation, more noticeably in relation to VEI 5-6 and low-latitude events. Finally, spring precipitation levels in Armagh tend to fluctuate in the three years associated with eruptions. However, one common trait in each of the five categories of volcano examined is a slight increase in values in TY+1.

Using the North Atlantic Oscillation and the Dust Veil Index to examine fluctuations in seasonal temperature and precipitation values in Armagh Observatory shows that winter, autumn and, to a lesser extent, spring are the seasons where NAO has its strongest influence upon temperature and precipitation, while only spring temperatures reveal any notable correlation with DVI values (lagged to one year). However, looking at the Pearson correlations from the perspective of non-overlapping five-year means produces significant correlations between DVI and winter temperatures, spring temperatures, as well as summer precipitation.

The analysis of the wind direction data from Armagh Observatory shows that the first month following VEI 5-7 and low-latitude eruptions contains considerable increases in westerly winds, while the same month sees notable decreases in westerly winds following VEI 4 and Icelandic events. The direction that does increase in TM+1 of VEI 4 and Icelandic eruptions is southwest. The increase in westerly wind in TM+1 of VEI 5-7 and low-latitude events is replaced by easterly wind in TM+2 and TM+3, with southerly winds becoming dominant in TM+4 and TM+5. These same two months see similar scale increases in northeasterly winds following VEI 4 and Icelandic eruptions.

7.2 TRENDS IN TREE-RING DATA

7.2.1 *Quercus*

Seven of the 13 *Quercus* series had reduced growth in the year of VEI 5-7 events, a figure that increases to 10 in both TY+1 and TY+2. Results for the low-latitude eruptions increase to nine series with narrower ring-widths in TY, 11 in TY+1 and 10 in TY+2. The Icelandic VEI 4 eruptions coincide with increased tree-ring widths in all but one of the 13 series in TY, while only two series had reduced growth in TY+1, with four in TY+2. Again, only one of the series had narrowed ring-widths in relation to mean results for all Icelandic eruptions combined, while four of the tree-ring indices had reduced growth in TY+1 of Icelandic events, rising to seven in TY+2.

The Pearson correlations between tree-ring widths and, perhaps the best indicator of volcanic activity, Lamb's (1970) Dust Veil Index supports the idea that eruptions can have an impact upon growth. Correlation coefficients for the entire lengths of tree-ring indices and the DVI rarely show significant result, but the breaking-down of series into 50 year sub-groups proved successful. The formation of these sub-groups allows the better identification of correlations between ring-widths and specific periods of volcanic activity. Meanwhile, correlations between the 13 tree-ring indices and NAO values highlighted the fact that winter and autumn are the seasons within which variations in NAO are most likely to manifest in tree-ring widths in Ireland, while Pearson correlations with mean monthly temperatures in Armagh showed that the indices, particularly those from the northern half of Ireland (due to their proximity to Armagh), are positively influenced by temperatures in May.

7.2.2 *T. baccata*

Decreases in ring-width occurred, on average, in all three years examined in relation to VEI 5-7 eruptions and low-latitude events, with the most prominent reduction coming in TY+1 in both instances. The smaller-scale Icelandic VEI 4 eruptions coincided with increases in ring-width in each of the three years, while the addition of data from the 1875 VEI 5 Askja event, giving combined results for all Icelandic eruptions, led to mean increases in TY and TY+2, with a slight decrease in TY+1. The residual ring-width index showed similar patterns to the standard index with mean negative changes in all three of the years associated with the larger VEI 5-7 and low-latitude eruptions. What are quite different to the standard chronology are the larger increases in ring-widths that occur in the years examined for the Icelandic VEI 4 and all Icelandic eruptions combined.

The *T. baccata* analysis showed that the species is sensitive to temperature change in the colder months of the year (November to April), and to precipitation in the months of May and June. The reason for November to April temperatures being important is likely to be related to extensions of growing seasons. Warmer temperatures in the months towards the end of the year will result in longer growing seasons, while increases in values in the first few months of the year will bring about an earlier growing season. The influence of precipitation in May-June is likely to stem from fact that, in Killarney, the *T. baccata* stand is growing on a limestone area which will result in significant draining of the thin layer of soil that exists. A consequence of this is that there is little storage potential for precipitation, meaning what does fall will have a more immediate impact, particularly in the height of the growing season.

The temperature reconstructions show that reduced mean November to April values can be expected in all three years associated with VEI 5-7 and low-latitude eruptions, with increases in three years associated with Icelandic VEI 4 eruptions and in two of the three years examined for all Icelandic events combined. Similar changes in values are experienced in terms of total reconstructed precipitation for the months of May and June in Killarney, with, on average, decreases in all three years associated with eruptions with marked decreases in TY+1 of VEI 5-7 and low-latitude events. Such changes in precipitation levels, particularly during the growing season, as indicated in this research, are likely to adversely affect the development of *T. baccata* in Killarney National Park. Increases in precipitation tend to occur in two of the three years examined for VEI 4 events, with two years of slight decreases coming in TY and TY+1 and an increase in TY+2 of all Icelandic eruptions combined.

Lamb's (1970) Dust Veil Index fails to produce any significant correlations with changes in *T. baccata* ring-width in Killarney. The highest – but not significant – R values were achieved with the standard index for the sub-group of years 1900-1949, as was the case with the *Quercus* series from throughout Ireland. Low correlation values for tree-ring width and DVI had a knock-on affect for any correlations between reconstructed temperature and precipitation as these datasets were a product of the tree-ring indices. There were, however, more significant results when the *T. baccata* ring-width index was correlated with Hurrell's (1995) principal component based winter North Atlantic Oscillation values. Here it was obvious that the NAO has a significant influence on the standardised growth patterns of *T. baccata* and, by association, the connection between NAO and reconstructed temperatures could be seen.

7.3 INDIVIDUAL ERUPTIONS

7.3.1 Tambora: Sumbawa, Indonesia. April 1815. VEI 7.

The eruption of Tambora in 1815 did not coincide with reduced temperatures in any season in Armagh Observatory that year, a feature that had no effect on the various tree-ring series and species examined. However, temperatures fell by between -1.0°C and -1.4°C below the 11-year average for a number of months around one year following the eruption of Tambora. In 1816, all four seasons had temperatures that were colder than the previous year, while the reconstructed precipitation levels from Killarney National Park indicate a reduction of 34 mm in rainfall that year in comparison to 1815. Such a persistent change in conditions would be expected to bring about ecological changes, something that was a feature in many parts of Ireland with a narrowing of ring-widths in eight of the 10 *Quercus* series in comparison to the index value for the previous year, as well as in the standard and residual *T. baccata* index. Growing season temperatures and reconstructed precipitation levels remained low in 1817, which translated into narrowed ring-widths in all of the *Q. petraea* tree-ring series when compared to 1816. Conversely, the *T. baccata* series showed signs of recovery this year, while the *Q. robur* series from the Glen of the Downs seemed to thrive in these conditions.

7.3.2 Cosigüina: Chinandega, Nicaragua. January 1835. VEI 5.

The Cosigüina eruption in 1835 occurred early in the year, giving the particulate matter enough time to spread throughout the Northern Hemisphere and influence temperatures in Armagh during the 1835 growing season – spring and autumn temperatures dropped, while summer values remained stable. The reconstructed temperatures and precipitation from Killarney also show a downward trend in that year, which coincided with reductions in both the standard and residual *T. baccata* chronologies. Narrowing of ring-widths was also a feature in nine of the 11 *Quercus* series examined (although some of these changes were marginal). The year after the eruption coincided with reduced temperatures in spring (-0.3°C), summer (-0.8°C) and autumn (-1.5°C) in Armagh when compared to 1835, while the reconstructed temperatures and precipitation values in Killarney show the same downturn. A notable consequence of this back-to-back decline in growing season conditions was a prominent reduction of ring widths in eight of the 11 *Quercus* series, with a similar narrowing occurring in both the standard and residual *T. baccata* series. Temperatures remained low in the winter and spring of 1837, whereas summer and autumn improved. This coincided with a recovery of ring-width values in all of the *Quercus* series from the southern half of the island of Ireland, as well as the *T. baccata* indices (also in the south), while four of the seven series from the northern half of Ireland continued to experience a decline in values.

7.3.3 Hekla: Suðurland, Iceland. September 1845. VEI 4.

The eruption of Hekla in 1845 was followed by increases in temperatures in each of the four seasons in Armagh in 1846, while recorded precipitation levels increased in all but the summer (-54 mm). Reconstructed mean November to April temperatures in Killarney fell very slightly in this time period, while reconstructed May-June precipitation increased. Mean seasonal temperatures in Armagh Observatory decreased in 1847 in comparison to the previous year, while only spring had a rise in precipitation levels (+22 mm). In Killarney, both reconstructed temperature and precipitation had an increase at this time. Fluctuations in weather conditions did occur in the months following this eruption of Hekla, but these, for the most part, did not translate into any significant changes in tree-ring widths throughout Ireland. Any decreases, barring those of *Q. robur* in the Glen of the Downs and, to a lesser extent, *Q. petraea* in Killarney, were minor and are likely to be associated with the year-to-year variations in index values brought about by local disturbances. The *Q. robur* series from the Glen of the Downs recorded the most notable narrowing of rings in each year examined. All other series had only slight variations in ring-widths.

7.3.4 Katla: Suðurland, Iceland. May 1860. VEI 4.

Temperatures in Armagh Observatory remained persistently lower than normal for the first seven months after the eruption of Katla, while precipitation levels were lower than average for five of these months. However, this only coincided with reduced ring-widths in two of the 13 *Quercus* indices as well as the *T. baccata* standard index. Temperatures in 1861 increased on the previous year's values in each of the four seasons, while the reconstructed temperatures also rose. Meanwhile winter (-33 mm) and spring (-16 mm) precipitation fell slightly, but increased notably in summer (+113 mm) and autumn (+128 mm). These conditions resulted in increases in the majority of tree-ring indices throughout Ireland, while those that decreased did so only slightly. Meanwhile, a fall in Armagh's spring (-0.3°C), summer (-1.8°C) and autumn (-0.4°C) temperatures in 1862, combined with a reduction in precipitation in summer and autumn, failed to bring about any very notable changes in ring-widths, regardless of species or location. One exception in the tree-ring series came in Breen Wood where large reductions in ring-width occurred in the first two years examined, with a minor recovery in the third. With trees prospering in other locations, the persistent negative growth in Breen Wood is likely to be a result of local ecological disturbances.

7.3.5 Askja: Norðurland, Iceland. March 1875. VEI 5.

The only persistent reductions in temperature in Armagh Observatory following the eruption of Askja came between February and June of 1876 (mean change of -0.6°C), while the months of April to September of the same year had, on average, 40 mm less rainfall per month than the norm. In addition to this, the reconstructed temperatures and precipitation levels from Killarney were reduced at this time. This resulted in negative growth in both the standard and residual *T. baccata* indices, as well as 12 of the 13 *Quercus* series (all *Q. petraea*). However, many of these changes in ring-widths tended to be quite minor. Precipitation increased in all four seasons in Armagh in 1877, while only winter had an increase in temperature (+1.1°C). The reconstructions from Killarney show increases on the previous year in both temperature and precipitation. In this year, 10 of the 13 *Quercus* series had a narrowing of ring-widths, while the *T. baccata* indices had increases. The three *Quercus* indices that contained positive growth in 1877 were located in the southern half of the island of Ireland.

7.3.6 Krakatau: Sunda Strait, Indonesia. May 1883. VEI 6.

Monthly temperatures in Armagh Observatory were below average for the majority of the year following the eruption of Krakatau in May 1883, while precipitation levels were quite varied. The seasonal results show decreases in all but autumn temperatures (+0.3°C), while precipitation in spring (-107 mm) and summer (-53 mm) was notably reduced. In Killarney, both reconstructed temperatures and precipitation increased in 1883. This coincided with increases in the standard and residual *T. baccata* indices, while all but two of the 13 *Quercus* series had a narrowing of ring-widths in 1883. Temperatures increased in all four seasons in Armagh in the following year, while only spring had an increase in precipitation. This is mirrored by the increase in reconstructed May-June precipitation in Killarney. Warmer conditions, however, did not result in wider ring-widths as seven of the 13 *Quercus* series had a downturn in growth, while the remaining recoveries in growth were only slight. The standard and residual *T. baccata* series also narrowed in this year. Meanwhile, temperatures in Armagh Observatory in 1885 fell in all four seasons when compared to 1884's records, as was the case for the reconstructed mean November-April temperatures in Killarney. In addition, precipitation levels fell in winter (-32 mm), spring (-55 mm) and summer (-62 mm) in Armagh, as well as May-June in Killarney (-28 mm). The general downward trend of weather in 1885 resulted in only two tree-ring series having an increase in values in comparison to the previous year. All other indices, regardless of species or location, had narrower ring-widths in 1885.

7.3.7 Grímsvötn: Austurland, Iceland. December 1902. VEI 4.

The eruption of Grímsvötn in 1902 was followed by lower than normal temperatures in Armagh Observatory for much of 1903 and 1904, while precipitation levels tended to increase. The reconstructed precipitation levels in Killarney had an increase in 1903, which resulted in wider residual *T. baccata* ring-widths. Meanwhile reduced reconstructed temperatures coincide with a narrowing of the standard index in Killarney. Persistently lower temperatures in Armagh usually correspond with widespread narrowing of tree-ring indices for the *Quercus* data. However, the negative changes in climate do not translate into a downturn in growth, with only the Cappoquin series having a narrowing of ring-widths in 1903, while four series had slight downturns in 1904. Meanwhile all 13 *Quercus* indices recorded a decrease in values in 1905.

7.3.8 Katla: Suðurland, Iceland. October 1918. VEI 4.

There were slight decreases in temperatures in all four seasons in Armagh in 1919. Meanwhile, summer (-23 mm) and autumn (-175 mm) precipitation levels were more notably reduced, as was the reconstructed precipitation record in Killarney. The conditions in Killarney coincided with increases in *T. baccata* standard and residual ring-widths. However, only three of the 13 *Quercus* indices had such positive growth. Nonetheless, many of the reductions in ring-width that did occur were minor and could be associated with local influences. In Armagh, 1920 recorded increased temperatures in comparison to the previous year in all but summer (-0.4°C), while precipitation increased throughout. These conditions coincided with more notable decreases in growth in eight of the 13 *Quercus* indices, while both the standard and residual *T. baccata* series increased. The following year had increased temperatures in all seasons in Armagh, while only summer recorded a slight increase in precipitation (+6 mm). This corresponded with five *Quercus* series having narrowed growth in comparison to the previous year while others recorded slight recoveries. One distinguishing aspect of the various tree-ring series was the constant positive growth in the Glen of the Downs. The increases in precipitation, particularly in the year after the eruption, could explain the series thriving at this stage as this species (*Q. robur*) is known to be tolerant of flooding.

7.3.9 Hekla: Suðurland, Iceland. March 1947. VEI 4.

Temperatures in Armagh Observatory decreased in spring 1947 in comparison to the previous year. This was the season within which the eruption of Hekla took place. However, the following four seasons, as far as summer 1948, all had temperatures that were above the previous year's values. Precipitation, in comparison, fluctuated more notably with decreases in summer (-86 mm) and autumn (-77 mm) 1947 followed by decreases in spring (-108 mm) and autumn (-25 mm) 1948. In Killarney, the temperature and precipitation reconstructions recorded decreases in values in 1947, with only the latter following this trend in 1948. These reconstructions came in years of decreased standard and residual *T. baccata* values in 1947 and increases on these in 1948. Meanwhile, all 13 *Quercus* indices had an increase in growth in 1947, but these were followed by decreases in each series in 1948. Increases in temperatures occurred in 1949 in Armagh Observatory in all but spring (-0.5°C), while autumn was the only season to coincide with increased precipitation (+57 mm). This year had decreases in standard and residual *T. baccata* indices in Killarney. Meanwhile, only two *Quercus* series showed a recovery from the widespread decreases in ring-width in 1947, with the remaining 11 indices continuing to display progressively narrower rings.

7.3.10 El Chichón: Chiapas, Mexico. March 1982. VEI 5.

Summer (+0.6°C) and autumn (+0.3°C) temperature records in Armagh Observatory increased in 1982 when compared to 1981, with slight decreases coming in the precipitation values for these seasons. Meanwhile, the reconstructed temperature and precipitation records both contained increases in values in the year of the eruption of El Chichón. As a consequence, the standard and residual *T. baccata* indices had positive growth at this time, while the six *Quercus* indices that are long enough to extend into the 1980s also had increases in growth. Winter, summer and autumn temperatures increased in Armagh in 1983, as did winter and spring precipitation. However, both reconstructed temperature and precipitation fell in comparison to the previous year in Killarney. Consequently, both of the *T. baccata* indices decreased in value in 1983, as did five of the six southern *Quercus* series. Of the four seasons in Armagh in 1984, summer (-0.5°C) and autumn (-0.7°C) temperatures were reduced in comparison to 1983, while spring precipitation was the only negative value recorded (-107 mm). Nonetheless, four *Quercus* indices lay down narrower rings in comparison to the previous year, while the *T. baccata* indices were divided – the standard index decreased in value while the residual series recovered from the narrowness of the previous year.

7.3.11 Mount Pinatubo: Luzon, Philippines. April 1991. VEI 6.

The eruption of Mount Pinatubo was followed by reduced temperatures (-0.2°C) and precipitation (-89 mm) in Armagh Observatory in the summer of that year, with the following autumn and winter also recording reductions in these values when compared to 1990. The reconstructed temperature and precipitation records in Killarney had reductions in 1991, which coincided with a narrowing of tree-ring widths. Only two of the *Quercus* series were long enough to include this eruption, with tree-rings in Shanes Castle in 1991 being narrower than the previous year, and Garryland Wood having an increase in ring-width. Meanwhile both series recorded narrower rings in 1992. The following year had colder temperatures in Armagh for all four seasons in comparison to 1992, while winter (-19 mm), summer (-57 mm) and autumn (-30 mm) all recorded less precipitation than the previous year. Garryland Wood was the only *Quercus* series to provide a value for this year, indicating an increase in ring-widths on the previous year's values, a feature of both the standard and residual *T. baccata* indices.

7.4 COMBINED RESULTS

7.4.1 Mean results for all volcanic eruptions

Figure 7.1 shows the average changes in variables in comparison to the 11-year means following all 11 eruptions (where available). The year of an eruption will see above-average temperatures in all seasons but autumn (-0.1°C), while the same year only sees reduced precipitation levels in autumn (-15 mm). The generally warmer and wetter conditions in TY coincide with increases in *Quercus* ring-widths throughout Ireland. However, the reconstructed November to April temperatures and May-June precipitation values from Killarney indicate a downturn in conditions, which also sees a narrowing of *T. baccata* ring-widths. The year following an eruption, on average, sees warmer than usual temperatures in winter (+0.5°C), with a further slight increase in summer, yet colder temperatures prevail in spring and autumn. An increase in spring precipitation (+23 mm) is followed by decreases in summer (-13 mm) and autumn (-13 mm), while the reconstructed temperatures and precipitation from Killarney also tend to have below average levels. These downturns in climatic conditions coincide with narrowing of tree-rings regardless of species or location on the island of Ireland. The second year after an eruption has below average temperatures in all but summer (Figure 7.1C), where values remain slightly above the 11-year mean, while only winter has an above average level of precipitation (+11 mm). These conditions coincide with reduced *Quercus* ring-widths in both the northern and southern half of Ireland. However, the *T. baccata* series recover from the previous year's growth downturn. The examination of wind patterns in Armagh (Figure 7.1P) shows an increase in those of a westerly direction in all seven months under consideration, while northeasterly values also increase between the fourth and sixth month after an eruption.

The combination of all proxy evidence shows that that Robock and Mao's (1992) theory of warming in the first winter following an eruption is a feature of the Armagh Observatory records, while the idea of colder temperatures in the first

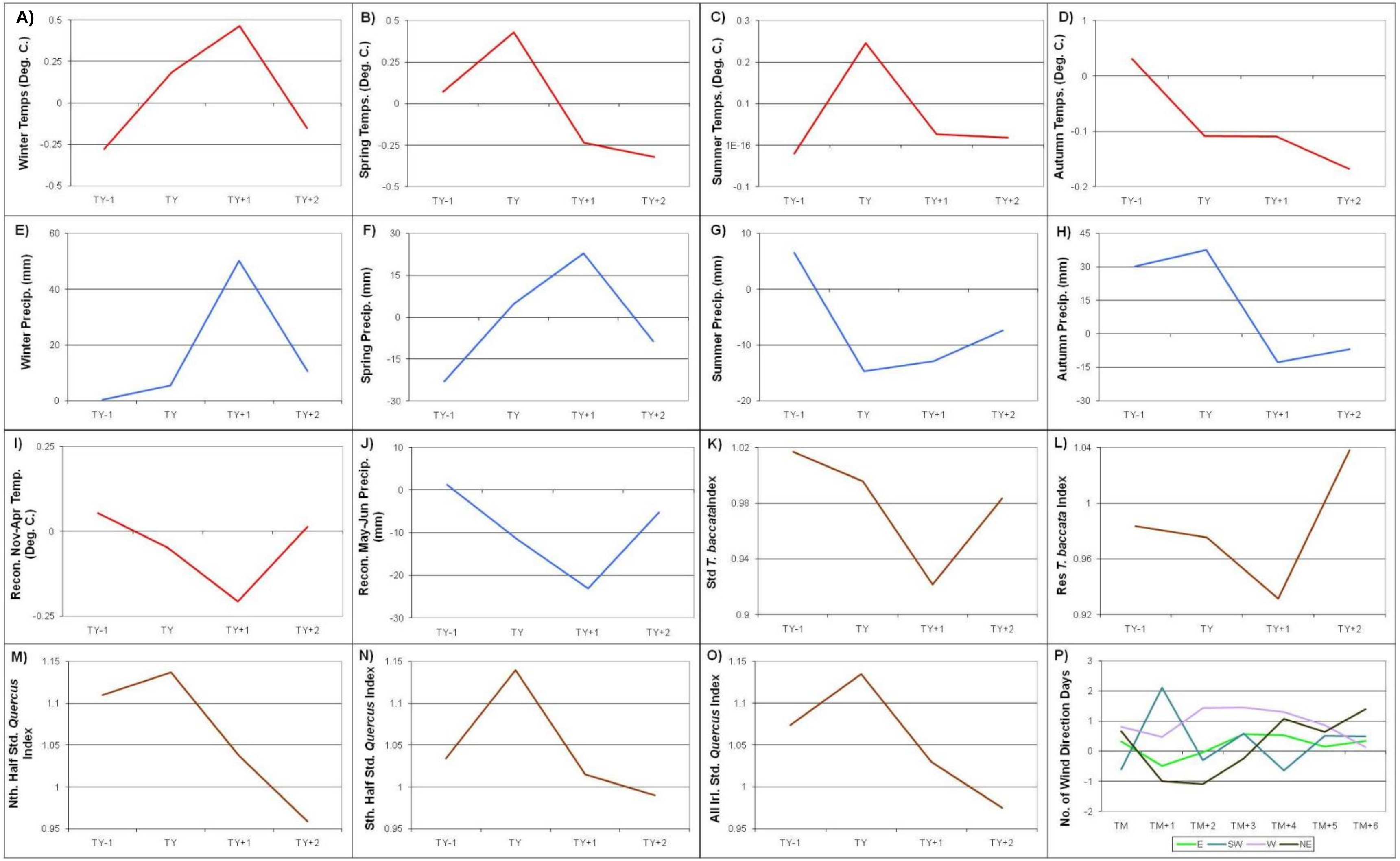


Figure 7.1: Four years of results for all 11 eruptions. Weather data refers to deviations from 11-year means. A-D): Winter, summer, spring and autumn temperatures in Armagh. E-H): Winter, summer, spring and autumn precipitation in Armagh. I): Reconstructed Nov-Apr temperatures in Killarney. J): Reconstructed May-June precipitation in Killarney. K-L): Standard and residual *T. baccata* index from Killarney. M-O): Mean *Quercus* tree-ring index for the northern half, southern half and all of Ireland. P): Seven months of change in number of days of NE, E, SW, W wind direction in Armagh.

summer after an eruption, put forward by Briffa *et al.* (1998) is not evident. A plausible explanation for this is that volcanic signals may not manifest themselves on a local scale as strongly as they do on a hemispheric or global scale due to local effects and circulation patterns. Meanwhile, precipitation tends to display increases in values, as opposed to the decreases in precipitation values for two to three years following an eruption put forward by Church *et al.* (2005), Gillett *et al.* (2004) and Robock and Liu (1994). With downturns in tree-ring indices prevalent throughout the series and locations examined, it is evident that, for the most part, the proxies studied do contain records of post-volcanic eruption trends.

7.4.2 Mean results for VEI 5, 6 and 7 volcanic eruptions

Figure 7.2 shows the mean changes in variables in the years associated with VEI 5, 6 and 7 volcanic eruptions (where available). An eruption with a VEI of between 5 and 7, on average, comes in a year of increased temperatures on the 11-year mean in all four seasons in Armagh Observatory, including +0.9°C in spring. However, spring and summer had less than average precipitation, while the reconstructed May-June precipitation from Killarney remained at the mean. These conditions coincided with narrowed *T. baccata* ring-widths, with the *Quercus* series from the northern half of the island following suit (Figure 7.2M). In contrast, the mean *Quercus* series from the southern half of Ireland will, on average, have an increase in growth in comparison to the previous year. The year following a VEI 5-7 eruption will have above-average winter temperatures (+0.5°C), with summer values dropping to just above the mean. However, mean spring and autumn temperatures both have below-average results, including -0.6°C in the former. An increase in winter (+75 mm) and spring (+12 mm) precipitation is offset by decreases in the following two seasons, something that coincides with notable reductions in tree-ring widths throughout Ireland in each of the species examined.

Below-average temperatures in all four seasons are a feature of the second year after an eruption, with only winter experiencing an increase in precipitation

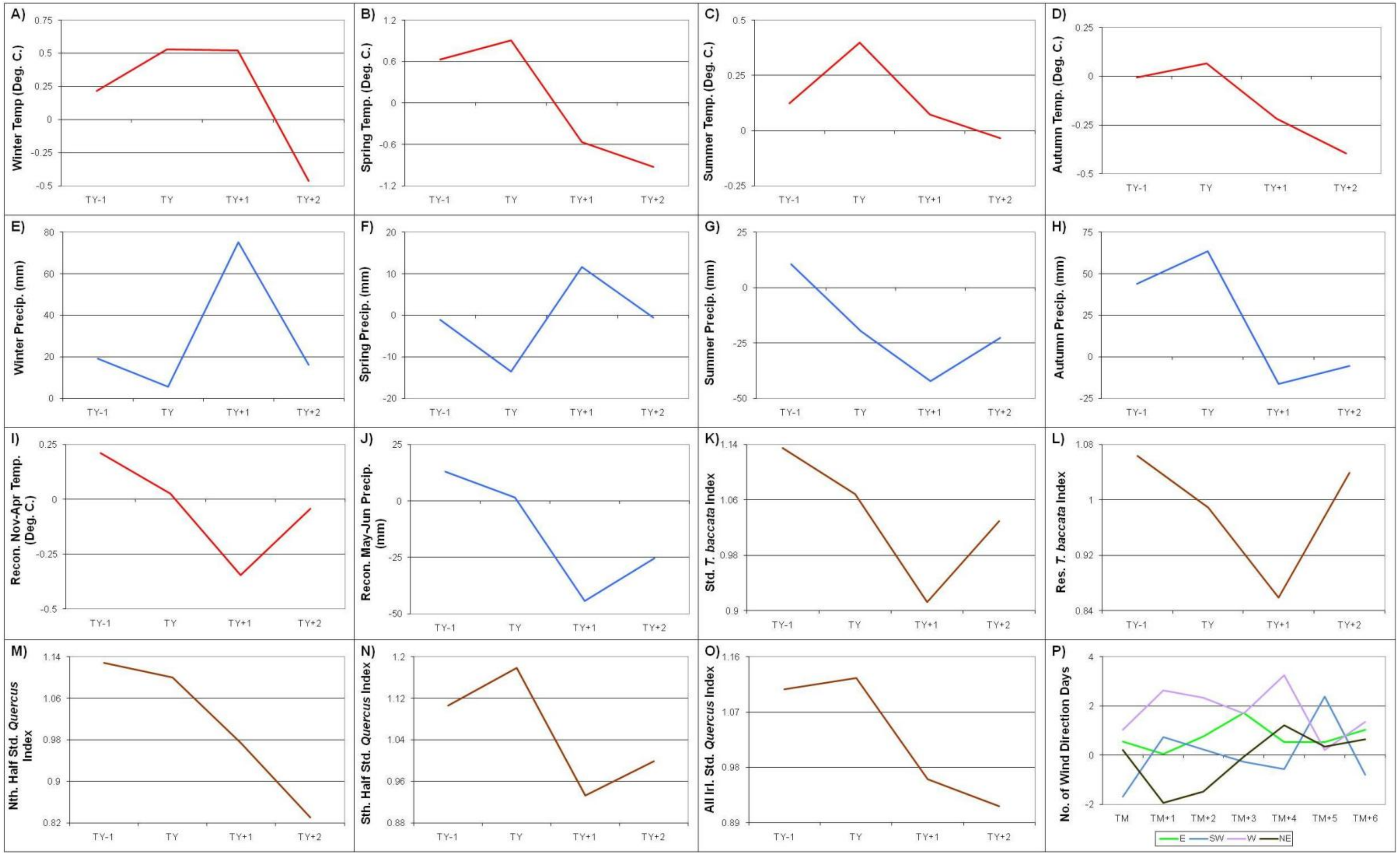


Figure 7.2: Four years of results for all VEI 5-7 eruptions. Weather data refers to deviations from 11-year means. A-D): Winter, spring, summer and autumn temperatures in Armagh. E-H): Winter, spring, summer and autumn precipitation in Armagh. I): Reconstructed Nov-Apr temperatures in Killarney. J): Reconstructed May-June precipitation in Killarney. K-L): Standard and residual *T. baccata* index from Killarney. M-O): Mean *Quercus* tree-ring index for the northern half, southern half and all of Ireland. P): Number of days of NE, E, SW, W wind direction in Armagh.

levels (+16 mm; Figure 7.2E). Meanwhile, the reconstructed precipitation and temperatures from Killarney also remain below the 11-year mean. However, these conditions do not restrict the growth of the *Quercus* and *T. baccata* series in the southern half of Ireland as ring-widths recover in comparison to the previous year. In contrast, ring-widths continue to narrow in the mean *Q. petraea* series from the northern half of Ireland. In the seven months of wind direction examined, the most prominent trend is seen in the increase in westerly winds, with those from an easterly direction also featuring more than average. This particular group of eruptions should result in the most obvious volcano-induced footprint appearing in the proxy records examined. With consistent decreases in temperature and precipitation, as well as obvious downturns in *T. baccata* and *Quercus* growth throughout Ireland, the impact of VEI 5, 6 and 7 events has undoubtedly been recorded in the data studied.

7.4.3 Mean results for low-latitude volcanic eruptions

Figure 7.3 shows the mean changes in the various elements following low-latitude volcanic eruptions (where available). A low-latitude event will see increases in temperatures in winter, spring and summer in the year of the event, with a fall of just -0.1°C coming in autumn. Only summer sees less precipitation than the 11-year average (-42 mm), while the reconstructed temperatures and precipitation both remain just above the mean in TY (Figure 7.3I and J). However, this does not prevent a narrowing of *T. baccata* ring-widths in comparison to the previous year, with a similar reduction coming in the *Q. petraea* series from the northern half of the island of Ireland. Winter and summer temperatures are slightly above the norm in the year after an eruption, with the spring and autumn values falling -0.5°C and -0.4°C respectively below the mean, while summer and autumn precipitation values are also below average. A consequence of this is that tree-ring index values, regardless of location or species, all see a reduction in the year after a low-latitude eruption.

Only summer temperatures and winter precipitation are above the 11-year mean

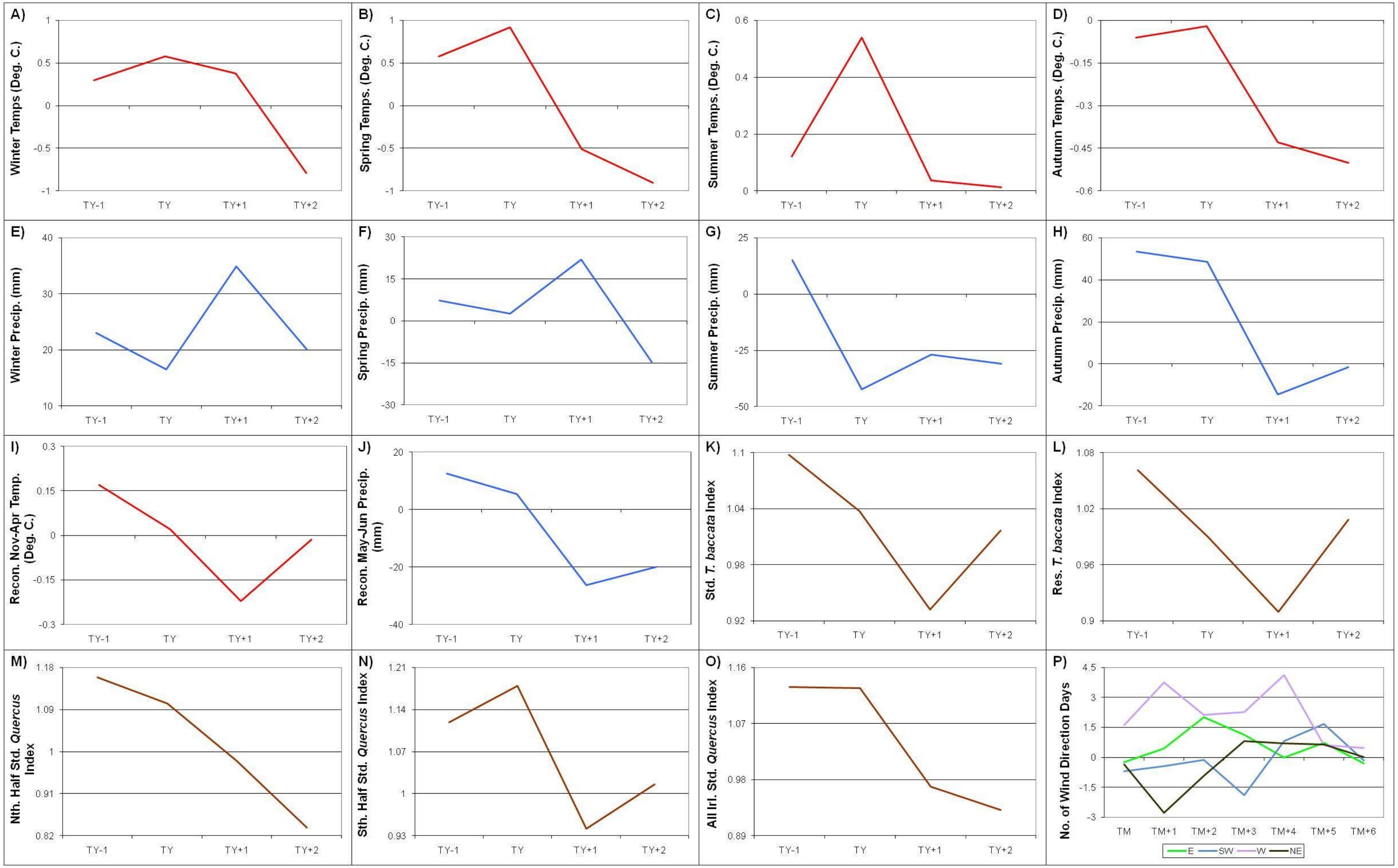


Figure 7.3: Four years of results for all low-latitude eruptions. Weather data refers to deviations from 11-year means. A-D): Winter, spring, summer and autumn temperatures in Armagh. E-H): Winter, spring, summer and autumn precipitation in Armagh. I): Reconstructed Nov-Apr temperatures in Killarney. J): Reconstructed May-June precipitation in Killarney. K-L): Standard and residual *T. baccata* index from Killarney. M-O): Mean *Quercus* tree-ring index for the northern half, southern half and all of Ireland. P): Number of days of NE, E, SW, W wind direction in Armagh.

in the second year after an event, while the reconstructed temperatures and precipitation from Killarney remain below average. However, this does not lead to the continuation of the trend of narrowing ring-widths in the southern half of Ireland. Instead, both the *T. baccata* and *Quercus* series have an increase in values, while the mean *Q. petraea* series values for the northern half of Ireland has a further year of negative growth (Figure 7.3M). The wind direction data shows that westerly winds will feature strongly in the wake of a VEI 5, 6 or 7 volcanic eruption, while southwesterly winds will remain below average for the first four months examined. As with the VEI 5-7 events, the low-latitude eruptions have left a notable impression on the proxies examined, including year after year reductions in temperature, as well as sharp decreases in ring-widths.

7.4.4 Mean results for Icelandic VEI 4 volcanic eruptions

Figure 7.4 shows the mean results relating to Icelandic VEI 4 volcanic eruptions (where available). Here, it can be seen that minor temperature increases can be expected in winter and summer in the year of an eruption, with both spring (-0.1°C) and autumn (-0.3°C) having below average values. Only summer sees less precipitation (-11 mm) than the 11-year mean. Although the reconstructed temperatures and precipitation from Killarney are below average in the year of a VEI 4 eruption, the standard and residual *T. baccata* ring-width series both have an increase in values in this year, as do the various *Quercus* series from throughout Ireland. In the year after an eruption, the above-average temperatures in all but summer, where only a very minor decrease occurs, are joined by increases in precipitation in all but autumn (-10 mm). These conditions coincide with increases in *T. baccata* ring-widths, as well as the mean *Quercus* series for the southern half of Ireland. The *Q. petraea* value for the northern half, however, records a decline in ring-width in TY+1 (Figure 7.4M).

The standard *T. baccata* index, as well as the *Quercus* series from both north and south, records a narrowing of ring-widths in the second year after a VEI 4 eruption. In this year, spring and autumn have below average precipitation, while spring (+0.4°C), summer (+0.1°C) and autumn (+0.1°C) temperatures rise

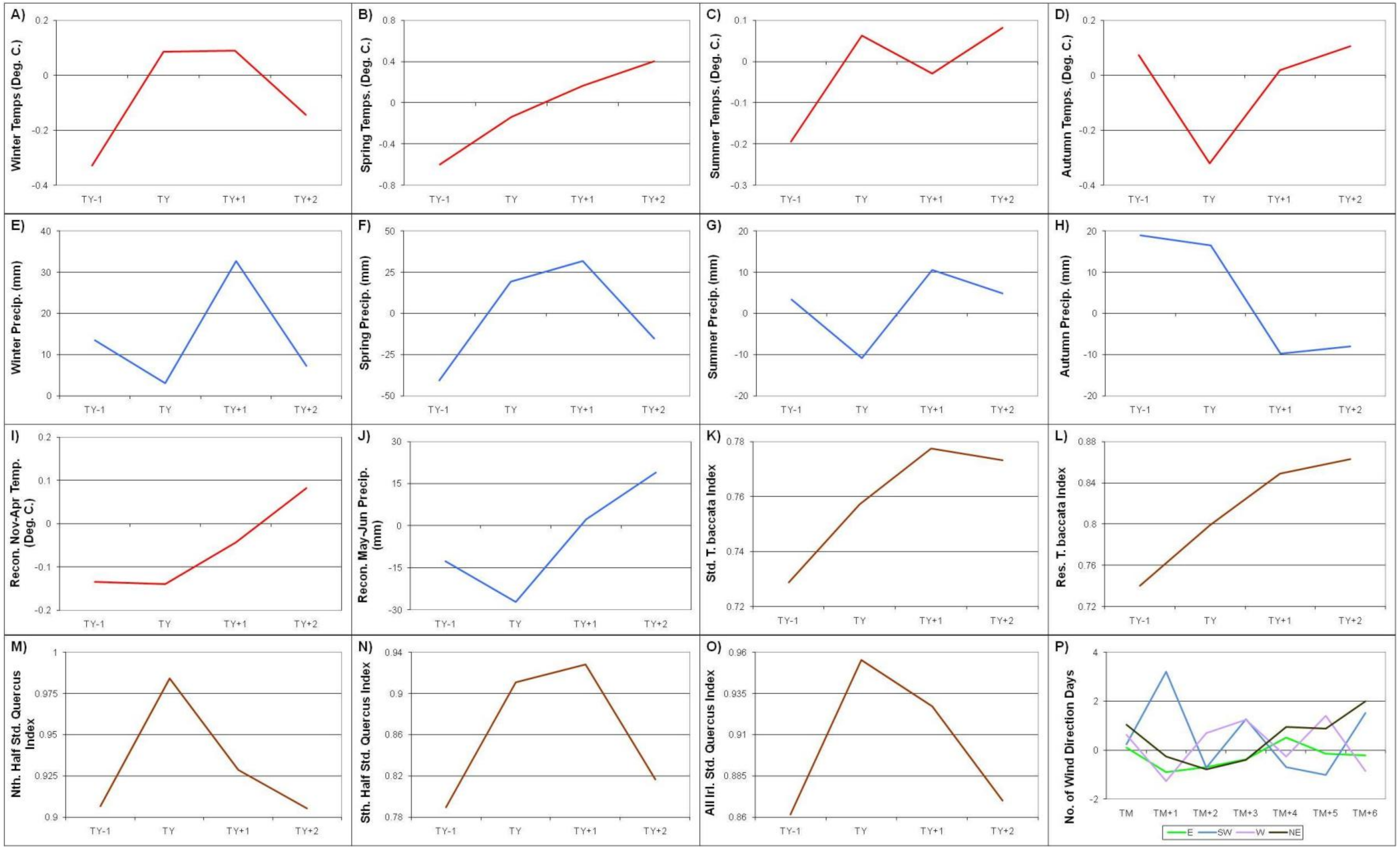


Figure 7.4: Four years of results for Icelandic VEI 4 eruptions. Weather data refers to deviations from 11-year means. A-D): Winter, spring, summer and autumn temperatures in Armagh. E-H): Winter, spring, summer and autumn precipitation in Armagh. I): Reconstructed Nov-Apr temperatures in Killarney. J): Reconstructed May-June precipitation in Killarney. K-L): Standard and residual *T. baccata* index from Killarney. M-O): Mean *Quercus* tree-ring index for the northern half, southern half and all of Ireland. P): Number of days of NE, E, SW, W wind direction in Armagh.

above their 11-year means. The wind direction data shows a notable increase in southwesterly values in the month after an eruption, while westerly winds go on to increase in TM+3 and TM+5 (Figure 7.4P). In a stark contrast to the larger VEI 5-7 and low-latitude eruptions, the Icelandic VEI 4 events do not leave a notable impression on the various proxies examined in the course of this study. What little temperature changes that do occur are likely to take the form of increases, with changes in precipitation values being only minor. Meanwhile the various ring-width indices contain strong growth values in the year of, and year following, these small-scale volcanic eruptions.

7.4.5 Mean results for all Icelandic volcanic eruptions combined

The final category to be examined relates to the mean results for all volcanic eruptions that occurred in Iceland (Figure 7.5). Here, a -0.8°C reduction on the 11-year winter mean temperature is followed by imperceptible changes in spring and summer, while autumn returns to colder than normal conditions. Very little change in precipitation occurs until autumn in the year of an Icelandic eruption (+32 mm), while the reconstructed temperatures and precipitation values record slightly below-average values during this year. With no dramatic changes in weather conditions, it is no surprise that all of the various tree-ring series, from both north and south Ireland, see increases in ring-widths in the year of an Icelandic eruption. The year following an event has above average temperatures in all four seasons, while precipitation only goes slightly below the 11-year mean in summer and autumn (Figure 7.5G and H). In spite of quite normal climatic conditions persisting during this time, the *T. baccata* and *Quercus* indices all have a decrease in values in comparison to the previous year. The *T. baccata* standard and residual series have increases in TY+2, while he mean results for the *Quercus* series see continued reduction in ring-widths. This comes in a year when temperatures remain above-average, but not overly-so, throughout the year. Only spring and autumn precipitation having a slight reduction in values. Meanwhile, westerly winds become the dominant winds in the months following an Icelandic eruption, with southwesterlies also featuring often (Figure 7.5P). As was the case for the VEI 4 eruptions, the variations in

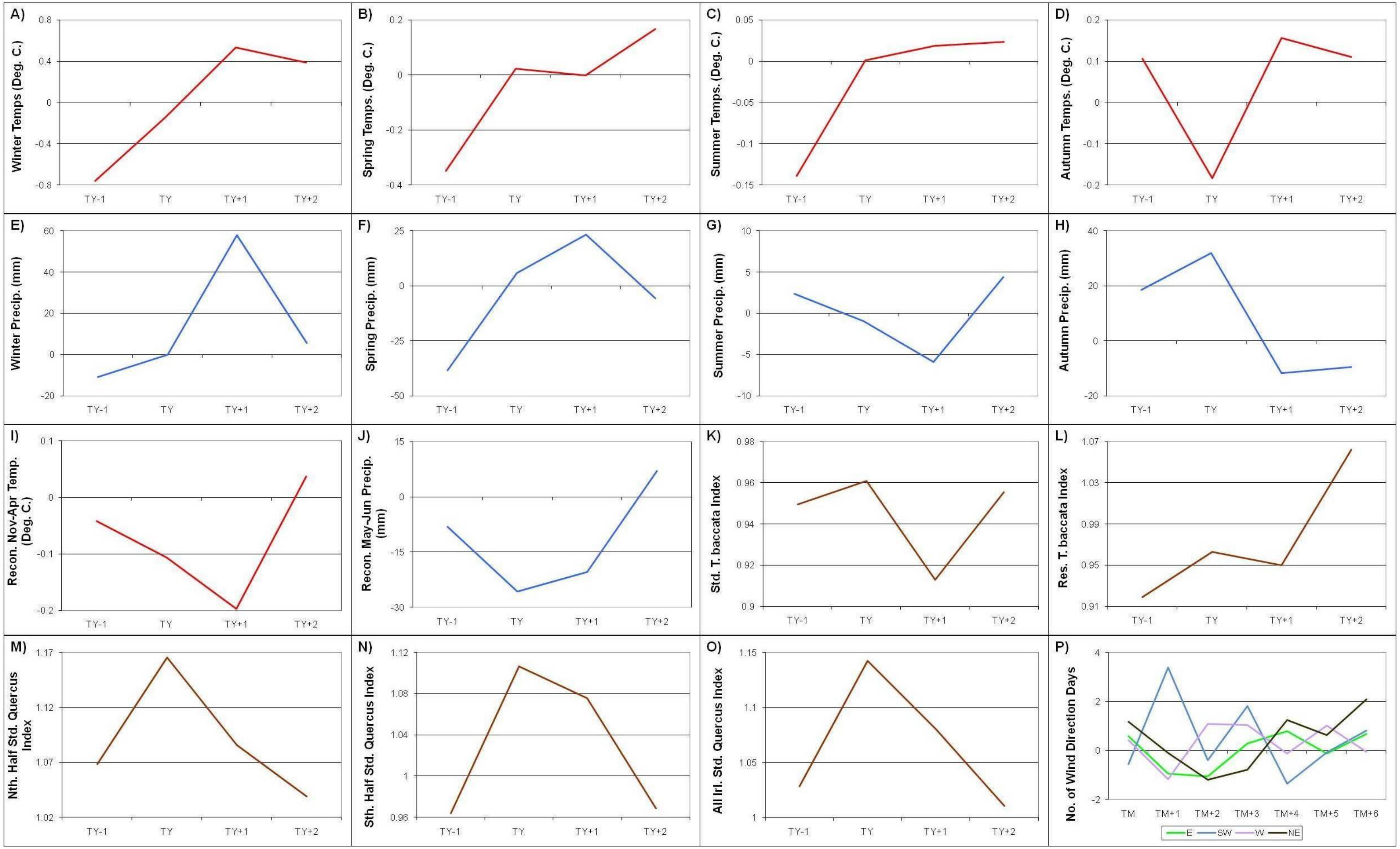


Figure 7.5: Four years of results for Icelandic eruptions. Weather data refers to deviations from 11-year means. A-D): Winter, spring, summer and autumn temperatures in Armagh. E-H): Winter, spring, summer and autumn precipitation in Armagh. I): Reconstructed Nov-Apr temperatures in Killarney. J): Reconstructed May-June precipitation in Killarney. K-L): Standard and residual *T. baccata* index from Killarney. M-O): Mean *Quercus* tree-ring index for the northern half, southern half and all of Ireland. P): Number of days of NE, E, SW, W wind direction in Armagh.

proxy evidence in the wake of Icelandic eruptions are, for the most part, slight. The inclusion of the VEI 5 eruption of Askja results in only minor changes in temperature and precipitation in comparison to the mean values for the VEI 4 eruptions, yet the *Quercus* and *T. baccata* indices do have a more notable reduction in values in the year following an event. The addition of the various data relating to the wake of the VEI 4 events acted to mask the influence of this larger eruption.

CHAPTER 8: DISCUSSION AND CONCLUSIONS

This study set out to assess the impact of volcanic eruptions on the climate and ecology of Ireland. Perhaps the predominant weakness here is the fact that larger-scale volcanic eruptions with a Volcanic Explosivity Index value of 5, 6 or 7 will, on average, only occur every ~50, ~100 and ~1000 years respectively (Siebert and Simkin, 2002). However, five of these larger-scale low-latitude events still took place within the timeframe provided by the data examined. Iceland, one of the most volcanically active locations in the world, also provided one VEI 5 event, as well as five VEI 4 eruptions. Individual analysis of the aftermaths of these 11 eruptions showed that reactions in terms of climate and ecology varied in intensity. Grouping eruptions in terms of VEI value and location and calculating the mean changes in the variables examined allowed a broader picture to emerge and allows the impact of volcanic eruptions to be separated from other fluctuations such as solar variability and carbon dioxide concentrations. In these instances, one outlier can easily skew the average results, but combining these individual examples with the remaining events did not result in any disproportionate trends emerging – the large-scale eruptions were still followed by a downturn in climatic and ecological variables while the smaller Icelandic VEI 4 events saw little, if any, influence manifest in the data. Consequently, the grouping together of eruptions in such a manner certainly proved fruitful as the obvious disparities in data relating to the wake of large- and small-scale eruptions that would be expected to emerge were still evident.

The identification of post-volcanic eruption abnormalities within the various climatic elements was made possible by examining month-to-month and seasonal changes in comparison to the 11-year mean. The assessment of such changes is quite often done by comparing recorded data with mean values for the years 1961-1990. With the data being examined in this study extending to 1800, comparing individual months/seasons to the 11-year mean was deemed more appropriate. The predominant reason for this was that the data relating to the 30-year mean for 1961-1990, particularly in reference to temperature, would have put more emphasis on the changes that occurred following the earlier eruptions under examination; for example, the comparison of warmer 20th Century temperatures to the downturn in spring temperatures following the 1815 eruption of Tambora is likely to suggest a more considerable change occurred than was actually the case. Utilising an 11-year mean meant that the most dominant shorter-term influence on climate variability – sunspot cycles – was reduced, in turn allowing easier detection of eruption-related impacts.

The method used in examining year-to-year variations in tree-ring widths in the wake of eruptions also proved successful as obvious disparities between growth in the year before an event and the three years that followed were evident in relation to the larger eruptions, regardless of species or location on the island of Ireland. One disadvantage of employing dendroclimatology in Irish-based research is that the various tree species that grow here are rarely, if ever, at the maximum extent of their latitudinal limit. Species that are in such a position will respond very readily to changes in a dominant limiting factor such as temperature. However, in Ireland, no one element prevails in the promotion or restriction of tree-growth. Quite often temperature, precipitation, light, competition between species, availability of nutrients as well as the influence of other organisms such as insect attacks or animal grazing can notably impact tree-growth. As a result, it can be difficult to pinpoint how a change in one single element can have a consequence for growth. Nonetheless, this study did show that volcanic eruptions, particularly the high-magnitude low-latitude events, do have an impact upon tree growth in Ireland. Perhaps future Irish dendroclimatological studies will identify a species whose productivity is more responsive to factors that are also influenced by volcanic eruptions, in turn facilitating a better understanding of the interaction between such events and tree growth.

8.1 RESEARCH HYPOTHESES

8.1.1 Temperatures in Ireland are altered in the months and years following volcanic eruptions, including a warmer first winter and cooler first summer after events.

The relative proximity of Ireland to Iceland results in an impact upon temperature in the months immediately after an Icelandic VEI 4 eruption. A reduction in temperature values is likely to be as a result of the presence of volcanic ash in the troposphere, as opposed to volcanic aerosols in the stratosphere (Robock, 2000). This layer of ash acts to increase the albedo of the atmosphere, in turn reducing temperatures at the surface level below. Icelandic volcanic eruptions are often not violent enough to inject matter into the upper layers of the atmosphere. Only one of the six events studied here had a VEI of 5 or more, meaning only this eruption was strong enough to penetrate deep into the stratosphere (Newhall and Self, 1982). As a result, the material that is ejected in the process of the majority of Icelandic eruptions will only remain suspended in the air for a relatively short period of time as it will eventually be too heavy to be held aloft. The prevailing winds from Northern Europe will tend to move any volcanic matter in a southerly direction, thus increasing the likelihood of at least short-term volcano-induced weather phenomena in the area of Ireland, Britain and Northern/Northwestern continental Europe. Notable negative deviations from the 11-year mean of between 0.7°C and 3.2°C came in the month of, or the month following, five of the six Icelandic eruptions. The sixth event was that of Askja in 1875, the largest of the Icelandic eruptions examined (VEI 5). The matter ejected here would have been propelled higher into the atmosphere, thus masking the influence of prevailing surface winds from its dispersal and allowing an even distribution of matter in a more stable area of the atmosphere (de Silva, 2005).

The fact that the weaker eruptions will result in volcanic matter falling back to earth within a short period of time means that there are no long-term effects on temperatures in Ireland. Therefore, theories of warmer first winters and colder first summers in the year of and the year following an eruption are not an issue, as is evidenced by the recorded and reconstructed temperature data. The average changes witnessed in comparison to the 11-year means are marginal for Icelandic VEI 4 events, remaining within ±0.1°C in the relevant seasons.

The opposite is true for high-magnitude volcanic eruptions from the lower latitudes. The systematic examination of month-to-month temperatures in Ireland shows that an immediate impact upon temperatures is highly unlikely because of the distance between the location of the volcanoes involved and Ireland. However, with eruptions creating an enhanced pole-to-equator temperature gradient (Robock, 2003), four out of the five events studied here coincide with temperatures in the first winter being above the 11-year mean. The only event not to coincide with a warmer first winter was Tambora in 1815, but this came at a time when Luterbacher *et al*.'s (2002) reconstructed North Atlantic Oscillation values were negative. A consequence of this phase of NAO would be the settling of cold air over Northwestern Europe, thus potentially overriding the warming influence of volcanic matter in the atmosphere. The remaining low-latitude events were followed by positive NAO values in the winter after an eruption. Although, in theory, large-scale low-latitude volcanic eruptions will produce higher than normal temperatures in the first winter after an event, positive NAO values will bring about the same result for Ireland, making the influence of eruptions difficult to distinguish from that of NAO.

The existence of volcanic matter in the atmosphere is also known to cause temperatures to fall in the summer of the year following an eruption (Robock, 2003). This is the case for two of the five low-latitude eruptions examined in this study, while three coincide with temperatures in Armagh Observatory falling below the 11-year mean in spring of the year after an event. All of these changes come regardless of the influence of North Atlantic Oscillation, with both negative and positive values recorded in the various seasons. Robock and Mao's (1995) theory of the most intense period of cooling coming roughly one year after an eruption is, for the most part, not applicable to Ireland as only two of the five low-latitude eruptions were followed by notable below-average temperatures in the 10 to 14 month period after an event. Changes in temperature at this time, be they increases or decreases, cannot be attributed to North Atlantic Oscillation values either as warmer and colder than average temperatures come during periods of both positive and negative phases of NAO. Therefore, this result strengthens Písek and Brázdil's (2006) argument for the necessity to examine local-level post-volcanic eruption climatic trends as micro-scale influences such as circulation patterns could result in different trends becoming prevalent.

The negative influence of low-latitude eruptions is greater in spring temperatures than any other season. This was evidenced by the significant Pearson correlation coefficient achieved between Lamb's (1970) Dust Veil Index, lagged to one year, and mean spring temperatures. Three out of five low-latitude eruptions were followed by a reduction on 11-year mean values during spring in the year after the event. The negative changes in temperature ranged from -0.3°C to -1.1°C. These reductions came during positive and negative North Atlantic Oscillation values. The 1835 eruption of Cosigüina was followed by a +0.5°C increase in spring temperatures in 1836, while the fifth low-latitude eruption, that of Mount Pinatubo in 1991, was followed by a mean spring temperature that was equal to the 11-year mean value. However, the influence of the eruption is likely to have been negated by the very strong positive NAO value that prevailed during the spring of 1992. Reduced mean spring temperatures in the second year after an eruption were a feature in Armagh in all five cases, with the most notable reduction of -1.4°C coming following the Cosigüina event. The Pearson correlation coefficients achieved when non-overlapping five-year averages for Jones *et al*.'s (1997) and Hurrell's (1995) NAO indices as well as DVI (lagged to one year) were run with mean spring temperatures showed that, on a scale broader than simply year-to-year (that is, five year intervals), the Dust Veil Index has only marginally less influence than North Atlantic Oscillation. This is because the utilisation of the non-overlapping averages shows that the effects of volcanic eruptions can linger for more than one year.

Finally, autumn temperatures are almost as consistently negatively influenced as spring values, but the changes that take place tend to be of a lesser extent. Three of the five low-latitude eruptions were followed by decreases in mean autumn temperatures in the year after the event, with changes ranging from -0.1°C to

-1.5°C. These reductions in mean temperatures came during phases of marginally positive and negative NAO. This suggests that a more important factor here is the presence of volcanic matter in the atmosphere, an idea supported by the fact that a significant negative Pearson correlation coefficient was achieved between the Dust Veil Index and mean autumn temperatures. The second year after eruptions show more widespread reductions in mean autumn temperatures, with four out of the five events being followed by colder conditions, the largest change being -1.4°C following the eruption of Mount Pinatubo in 1991. However, each of these reductions occurred during a negative phase of NAO, with the value following the Mount Pinatubo event undoubtedly being influenced by the lowest NAO values since 1933. Meanwhile the sole increase in mean temperatures came during a strongly positive phase of NAO in 1837, two years after the eruption of Cosigüina, suggesting that the influence of volcanic matter over autumn temperatures may have faded in the second year after an eruption, or has been mirrored by NAO in these five cases.

8.1.2 Volcanic matter in the atmosphere will hamper evaporation and cause reductions in precipitation levels.

The idea that rainfall levels will be reduced in the wake of a volcanic eruption refers to low-latitude events that spread particulate matter in the atmosphere. This acts to inhibit evaporation, particularly in areas just north of the equator. In turn, the amount of water vapour in the atmosphere will be limited (Robock and Liu, 1994). Precipitation data exists for only three of the five low-latitude eruptions referred to in this study. Of these, the eruptions of Krakatau in 1883 and El Chichón in 1982 were both followed by reductions in precipitation in the summer of the eruption year, as well as each of the two summers that followed. The third eruption, that of Mount Pinatubo in 1991, coincided with reduced summer precipitation levels only in 1991. These changes in precipitation are unlikely to be as a result of phases of North Atlantic Oscillation as notable reductions occurred during strongly positive and negative periods. The idea that low-latitude volcanic eruptions will coincide with reduced precipitation in the summer of the event is supported by the fact that a significant negative Pearson correlation coefficient was achieved between Lamb’s (1970) Dust Veil Index and total summer precipitation values.

One common feature of the three low-latitude eruptions that coincided with reduced rainfall was that they all occurred in spring. This implies that the volcanic aerosols had spread sufficiently northwards to restrict Irish precipitation levels, with July being negatively affected in all three cases while August had reductions on two occasions. The months of August and September also had reduced rainfall levels in the year after each of the three eruptions, while June and July reductions occurred in the year after the 1883 Krakatau and 1982 El Chichón events. The number of days per month within which rain occurs is not necessarily reduced in the wake of these eruptions, showing that, although day-to-day precipitation is still likely, it is the change in the amount of rain that is important here with reductions of between -8 mm and -106 mm per month in the summer months following low-latitude eruptions. Meanwhile, the declines in these monthly precipitation values cannot be accounted for by phases of North Atlantic Oscillation as, again, they coincide with both strongly positive and strongly negative periods of NAO.

As with the temperature discussion in the previous section, the likelihood of a smaller Icelandic eruption inhibiting precipitation levels beyond a number of months is slim due to the inability of the majority of events to inject particulate matter into the stratosphere, an action that would greatly reduce the possibility of matter descending back to ground level (Newhall and Self, 1982). Unlike temperature, no definite long-term pattern of reductions in precipitation is discernable following Icelandic events. However, four of the five VEI 4 eruptions are followed by an increase in precipitation in the month of the event, while all five are followed by increases of between +35% and +91% on the 11-year mean in the first month after the onset. These increases occur regardless of the time of year, or whether the North Atlantic Oscillation is in a positive or negative phase. Meanwhile, the number of days within which zero precipitation fell had reductions in the same months as four of the five VEI 4 events, again suggesting an increase in precipitation levels. The ability of volcanic aerosols to create condensation nuclei (Baker *et al.*, 1995) could be the reason for increased precipitation as the particulate matter ejected by VEI 4 eruptions tends to be restricted to the troposphere (Newhall and Self, 1982), the area of the atmosphere within which the vast majority of weather takes place. This idea is further supported by the fact that the single VEI 5 Icelandic event, that of Askja in 1875, coincided with reductions of -46% and -93% in precipitation in the month of and the month following the eruption. Here, as with the low-latitude eruptions examined, the particulate matter reached higher into the atmosphere, thus greatly reducing the likelihood of volcanic aerosols causing water vapour to condense into rain while also restricting the amount of evaporation taking place.

8.1.3 Northeasterly, easterly, southwesterly and westerly wind directions will experience an increase in frequency in the months following volcanic eruptions.

The alteration of mean sea level pressure following large-scale low-latitude volcanic eruptions will act to strengthen westerly winds in the North Atlantic region (Kelly *et al.*, 1996). Wind data from Armagh Observatory was available for three such eruptions. The systematic analysis of these wind direction records showed that the month of and the two months following low-latitude events did have an increase in westerly winds, but also in northerly and north-northwesterly directions. Hunt (1977) indicated that, between 50 and 100 days after large-scale volcanic eruptions, easterly winds will become dominant in the northern hemisphere. This is certainly the case in the third month following an eruption, as easterly, southeasterly and northeasterly winds tend to prevail. The final three months vary between south, southwest and southeast directions, implying the influence of the volcanic eruptions may have subsided as the natural prevailing winds for Ireland are a more common feature than in the previous months.

Each of the three low-latitude eruptions examined occurred in the March-April period of the year, while North Atlantic Oscillation values varied over the relevant months. A positive phase of NAO will coincide with an increase in westerly winds, while a negative phase sees these winds suppressed (Dawson *et al.*, 2002). Simultaneous analysis of monthly North Atlantic Oscillation values and dominant wind directions shows that, in the months following low-latitude volcanic eruptions, positive NAO does not necessarily correspond to a prevailing westerly wind. Instead, the results are quite variable – a feature of post-volcanic eruption wind regimes (Hunt, 1977). To emphasise this more so, the dominant directions put forward by Dawson *et al.* (1997), Kelly *et al.* (1996), Groisman (1992) and Hunt (1977) as being closely-related to volcanic events are more likely to prevail at various times in the months following eruptions. These notable directions do include southwesterly winds, the prevailing wind direction for Ireland. It would be expected to see these winds to feature regardless of the influence of a volcanic eruption. However, the fact that their frequency increases on the 11-year mean, combined with increases in other notable wind directions – easterly and northeasterly – underlines the volcano-induced influence that is most noticeably prevalent in the first five months following an eruption.

The wind regimes in the months following the lower-magnitude Icelandic events do not display what are deemed to be volcano-related changes. The prevailing southwesterly winds remain dominant in the months after the Icelandic VEI 4 volcanic eruptions, while southerlies and south-southwesterlies also feature heavily. Although a characteristic of post-volcanic eruption changes in weather patterns (Dawson *et al.*, 1997), southwesterly winds are likely to feature heavily in any month in Ireland. However, unlike the low-latitude eruptions, these winds persist throughout each of the months examined in the wake of the Icelandic VEI 4 eruptions and are rarely replaced by the other winds closely associated with volcanic events, namely easterlies and northeasterlies. North Atlantic Oscillation is more likely to have an influence on wind regimes than Icelandic VEI 4 eruptions. Positive NAO values, for the most part, did coincide with southwesterly and westerly winds dominating while negative NAO phases, a feature of which is the suppression of westerly winds, occurred at a time when northerly and northeasterly wind directions were prevalent.

The solitary VEI 5 Icelandic eruption coincided with a notable increase in easterly winds in four of the six months following the eruptions. Three of these months contain negative NAO values, which suggests the normal pattern of wind could have been altered by North Atlantic Oscillation alone. However, in all of the months examined in the wake of VEI 4 eruptions, a notable increase in easterly winds did not occur once, regardless of whether the NAO was in a positive or negative phase. Southwesterlies and westerlies dominate in the remaining two months after the VEI 5 eruption. Again, being the prevailing winds in Ireland, these were likely to feature regardless of the influence of the eruption of Askja in Iceland in 1875. However, their frequency is above the 11-year mean for the months in question, suggesting their occurrence may well be volcanically-related.

8.1.4 *Quercus* tree-ring widths from throughout Ireland will provide a record of post-volcanic eruption climatic downturns.

Many complicated factors interact to influence tree-ring widths. Temperature and precipitation are two of the primary constituents, but so too are light, competition and other natural disturbances such as insect outbreaks and animal grazing. Meanwhile, a factor such as temperature, which limits growth at a particular time of year, can have little or no influence at another time of year – a warm spring could encourage growth earlier than usual; a hot summer could restrict growth by limiting the amount of moisture available; yet during the dormant winter period, persistent freezing temperatures will have no effect on any particular process (Fritts, 1976). It is for these reasons that the use of tree-ring indices to examine specific changes in the past can sometimes be difficult as limiting factors vary from month to month. In spite of this, the obvious changes in *Q. petraea* and *Q. robur* growth patterns in the wake of volcanic eruptions confirm the idea that these species will provide a record of past volcanic events. This indicates that the eruptions forced sufficient change in the relevant limiting factors at vital times of the year.

The North Atlantic Oscillation is a high-quality indicator of variability in temperatures and precipitation (Dawson *et al.*, 2002). The autumn NAO values received more significant positive correlations with the 13 *Quercus* indices than any other season, while a number of less significant negative correlations were achieved with winter NAO values. However, Pearson correlation coefficients from the tree-ring indices and mean monthly temperatures in Armagh showed that May is more often than not the most significant month in terms of a positive influence. With previous sections showing the negative influence of low-latitude eruptions is more prevalent in spring temperatures than any other season, volcanically-induced reductions in May temperatures, in turn, are likely to have a negative effect on tree-ring growth.

Reductions in autumn temperatures are likely following eruptions, with correlations also showing that fluctuations in the North Atlantic Oscillation are linked with variations in these temperatures, implying that the NAO could potentially mask the effect of volcanic eruptions in autumn. However, the NAO has considerably less influence on spring temperatures, the season displaying the influence of volcanic eruptions more than any other. Therefore the largest volcanically-induced impact upon temperatures comes at a time when values are most important for the productivity of *Quercus* species, thus increasing the likelihood of a narrowing of ring-widths in the wake of volcanic eruptions. Meanwhile, 5-year non-overlapping correlations between NAO and DVI with tree-ring widths show that, in a broader sense, the Dust Veil Index achieves stronger and more significant results than North Atlantic Oscillation. With large-scale volcanic eruptions producing particulate matter that can be maintained in the atmosphere for two to three years (Robock, 2000; de Silva, 2005), their influence on tree-rings will manifest over more than just one growing season (LaMarche and Hirschboek, 1984). This is supported by the fact that, following all five low-latitude eruptions examined in this study, at least two years of back-to-back reductions in mean ring-widths occurred.

The Icelandic VEI 4 eruptions are very much divided in two in terms of when they occurred. Two of the events came in March and May, while the remaining three occurred in September, October and December. Previous discussions have shown that the month of, or the month following, a VEI 4 Icelandic eruption will result in notable decreases in temperatures in Ireland. However, in the case of the spring eruptions, the onset of this reduction in temperature has very little adverse effect on tree-growth, showing that the Icelandic VEI 4 eruptions failed to force these temperatures to such an extent that they became a limiting factor in *Quercus* growth. In fact, an increase in ring-width is more likely following these events. Meanwhile, with both positive and negative phases of North Atlantic Oscillation being prevalent during these increases in ring-widths, it is unlikely that the changes can be attributed to NAO. One common feature is an increase on the 11-year mean precipitation values in the months of, and month following, both spring eruptions. This implies that, of all the factors that combine to encourage tree growth, an increase in precipitation is likely to outweigh a notable decrease in temperature during the growing season, in turn allowing growth to continue unscathed, and indeed thrive.

It is difficult to attribute downturns in tree-ring widths to the three Icelandic VEI 4 eruptions that occurred after the growing season as their influence on temperature and precipitation is short-lived. Therefore, smaller-scale Icelandic volcanic eruptions that occur later in the year fail to see their influence upon various elements vital for tree-growth persist for long enough to produce a downturn. The single VEI 5 event, however, was followed by *Quercus* growth patterns in Ireland similar to those that came in the wake of the low-latitude events. Here, extensive reductions in ring-widths occurred throughout the island of Ireland in each of the two years following the event, making it the only Icelandic eruption to see back-to-back years of notably narrowed ring-widths.

The clear geographical division between the eight *Quercus* series in the northern half of Ireland and the five in the south coincides with different reactions in the wake of volcanic eruptions. Although the mean *Quercus* series changes from the north and south of Ireland show similar patterns of decreasing ring-widths in the two years after large-scale low-latitude volcanic eruptions, the degree to which these reductions occur differs with less notable narrowing coming in the south. A plausible explanation for this lies in the differences that exist between climatic conditions in the north and the south. The higher temperatures in the south of Ireland, brought about for the most part by the influence of the North Atlantic Drift, will result in a longer growing season in this area. Four out of five low-latitude eruptions coinciding with increased temperatures in the first winter after the events. As a result the *Q. petraea* series from the southern half of Ireland are likely to have begun growing earlier than normal, only for this growth to be curtailed by the impact of particularly cold spring temperatures in the year after the eruptions. Warmer winter temperatures persisted in the second year after these eruptions, thus lessening the impact of the colder spring temperatures that again dominated the following season. Differences between the northern and southern halves also exist in the wake of the smaller-scale Icelandic eruptions that occurred in spring. However, in this instance, it is a case of the mean *Quercus* series from the south having a more notable increase in ring-width in the year of the eruption in comparison to increase in the north. The favourable growing conditions following these eruptions are more pronounced in the southern half of the island.

8.1.5 *T. baccata* is a viable study alternative to the traditional *Quercus* species when reconstructing past environments as well as post-volcanic eruption climatic downturns in Ireland.

8.1.5 (i) Reconstructing past environments.

In Ireland, García-Suárez *et al.* (2009) showed that various combinations of beech (*Fagus sylvatica*), ash (*Fraxinus excelsior*) and oak (both *Q. robur* and *Q. petraea*) were best suited to reconstructing climatic variables such as temperature, precipitation and sunshine at certain times of the year. For decades, dendroclimatic studies in Ireland had been dominated by the use of *Quercus* species, with García-Suárez *et al.* (2009) pointing out that never before had a formal examination of any other species been undertaken in Ireland. This thesis shows that another species, *T. baccata*, is a further possible source of climatic data that can be utilised in the reconstruction of past environments. The benefit of employing a variety of species in climate reconstructions is that different tree species are more sensitive to certain climatic parameters at particular times of the year.

Combined results for the months of May-July dominated García-Suárez *et al.*’s (2009) reconstructions, with October-November of the previous year also featuring. Correlations between *T. baccata* and total May-June precipitation returned an R value of 0.52 (P: 0.01; or R^2: 0.271 P: 0.01), which compares favourably with the three species García-Suárez *et al.* (2009) correlated with total May-July rainfall, being surpassed only by *F. Excelsior* (R: 0.58 P: 0.01). Meanwhile, *T. baccata*'s correlation with mean November-April temperatures (R: 0.60 P: 0.01; or R^2: 0.366 P: 0.01) exceeds those reported by García-Suárez *et al.* (2009), each of which involved combinations of species; the grouping of *F. sylvatica, F. excelsior* and *Q. petraea* produced an R value of 0.59 (P: 0.01) with mean May-July maximum temperatures (García-Suárez *et al.*, 2009).

The reconstructions provided by *T. baccata* cover, in terms of temperature, November of the previous year to April of the current year, while precipitation is best correlated with May-June of the current year. The correlation coefficients achieved compare very favourably to others for the species; Moir (1999) indicated that February-July precipitation had a positive effect on *T. baccata* growth in London, while January-February and October temperatures also influenced ring-width. Yet Moir (1999) failed to specifically state the results. Yadav and Singh (2002) did report the correlation coefficient they achieved between *T. baccata* and mean March-June temperatures in the Himalaya, but the relationship was not considerable (R: -0.310 P: not significant).

8.1.5 (ii) Post-volcanic eruption downturns in *T. baccata* growth.

The obvious disparities that occurred in the *T. baccata* growth indices in the years that followed low-latitude volcanic eruptions and the smaller-scale Icelandic events suggest that this species will suffer more of a downturn in growth following large-scale eruptions, as was the case with the *Quercus* species. Both the standard and residual chronologies are useful in their own ways here. The latter shows the ring-width values devoid of the influence of the previous years' growth, thus allowing each year to be examined independently, while the former indicates the likelihood of volcanically-induced change persisting over a number of years due to the inclusion of a large portion of the impact of prior growth. All five of the low-latitude events occurred in the first five months of the year, with the indication being that a change in ring-widths is less likely in the year of an eruption (occurring on two occasions), while the first year after an event will see the largest downturn in *T. baccata* growth.

With volcano-related climatic declines not being prominent until spring of the year after an eruption, it is natural that an impact upon *T. baccata* ring-width is not seen until then. Correlations showed that the months of November of the previous year to April of the current year are most important in terms of temperature's influence upon ring-width, while May-June precipitation in the current year was more important than any other period. However, with low-latitude eruptions being, more often than not, immediately followed by an increase in winter temperatures, the equally prevalent reduction in spring temperatures is more influential in the onset of a decrease in ring-width. The warmer winters in the aftermath of the eruptions may well have encouraged *T. baccata* growth, but, similar to the *Quercus* situation, the abrupt downturn in spring temperatures would have become the dominant limiting factor in growth, an idea supported by Brzeziecki and Kienast (1994) who point out that *T. baccata*'s tolerance for frost decreases rapidly in spring. Meanwhile, only one low-latitude eruption was followed by a reduction in spring and summer precipitation values, the time at which rainfall is most important for *T. baccata* growth. With Brzeziecki & Kienast (1994) stating that the species is quite tolerant of drought, the reductions in rainfall failed to bring about a negative reaction in the chronology.

Although neither the standard nor the residual *T. baccata* indices produced significant correlations with the Dust Veil Index, the presence of volcanic matter in the atmosphere, acting to reduce transparency and, in turn, photosynthesis, combined with volcanically-induced colder spring temperatures have led to decreasing ring-widths being dominant features in the years following large-scale low-latitude volcanic eruptions. The correlations between *T. baccata* ring-widths and Lamb's (1970) DVI show atypical positive values. In theory, an increase in DVI will lead to a decrease in ring-widths. This is true for *T. baccata*, but the timing of the changes results in positive correlations, possibly as a result of ring-widths following the same pattern as the Dust Veil Index. The largest reduction in ring-widths comes in the year following a low-latitude volcanic eruption. This occurs in a year where the DVI value is also decreasing, having reached a peak in the previous year, that is, the year of an eruption. As the DVI continues to decrease so too do tree-ring widths, thus producing positive Pearson correlation coefficients.

As was the case with the *Quercus* species, *T. baccata* is unlikely to have any notable changes in growth in the years associated with the smaller-scale VEI 4 Icelandic volcanic eruptions. Of the two that occurred during the growing season, one coincided with a reduction in *T. baccata* index values, while the other had an increase. NAO values during the decrease were predominantly positive, which would bring cooler summers and milder winters (Dawson *et al.*, 2002), while a negative phase persisted during the increase in ring-widths. These phases of NAO correspond well with the reconstructed temperatures for the relevant periods, suggesting that the changes in *T. baccata* ring-widths were more related to variations in North Atlantic Oscillation than smaller-scale Icelandic volcanic eruptions, a feature supported by the significant positive Pearson correlation coefficients between Hurrell's (1995) NAO values and *T. baccata* ring-width. The Icelandic VEI 4 eruptions that occurred in the second half of the year failed to coincide with any notable changes in *T. baccata* ring-widths at any stage. In spite of the fact that the correlations between temperature and growth showed that values from November to April are important, the cooler temperatures that came directly in the aftermath of the Icelandic eruptions were not enough to trigger a limiting of *T. baccata* growth. Any changes in precipitation would not have persisted for long enough to affect the most important period for growth (May-June). Meanwhile, the single VEI 5 eruption in Iceland followed a similar pattern to the large-scale low-latitude events – a slight reduction in the year of the event, followed by very notable narrowing in the following year. As with the low-latitude eruptions, this event came in the first half of the year and would have propelled volcanic matter deep into the stratosphere, thus allowing the material to persist in the atmosphere for a longer period when compared to the smaller VEI 4 Icelandic eruptions. As a result, an alteration to the growth trend did not occur to any great extent until a year later. This change in growth is seen in terms of both the standard and residual *T. baccata* indices and was, again, more likely to be as a result of a reduction in transparency due to increased concentrations of volcanic matter in the stratosphere.

With the *T. baccata* series and the *Q. petraea* series from Killarney both growing in close proximity, they are subjected to the same fluctuations in climatic variables throughout the year. Yet the *Q. petraea* is more responsive to post-volcanic eruption conditions, with more notable reductions in ring-widths occurring in each of the three years associated with low-latitude events. Meanwhile the increases in growth in the wake of the smaller-scale Icelandic eruptions are also more pronounced in this series as opposed to *T. baccata*. Both species show positive correlations with spring temperatures and in turn see downturns in growth as a result of the colder temperatures, coupled with the increased concentrations of transparency-reducing volcanic matter in the atmosphere, that come in the wake of low-latitude eruptions. However *T. baccata*'s ability to endure all but the most severe reductions in rainfall (Brzeziecki & Kienast, 1994) suggests that this third potential volcanically-induced limiting factor had less of an impact in the species, or that the species simply reacts less negatively to post-eruption conditions when compared to *Quercus.*

8.2 SUMMARY AND SUGGESTIONS FOR FUTURE RESEARCH

8.2.1 Climate data

Temperatures in Ireland are influenced in the wake of a volcanic eruption, but the catalysts and timescales depend upon the location and severity of the volcanic events. Smaller-scale Icelandic eruptions are likely to lead to colder temperatures in the month of or the month immediately following an eruption as the volcanic ash in the troposphere acts to intercept energy from the sun. The larger-scale eruptions coincide with changes on a longer timescale, with warmer first winters being very probable. The mechanism that produces this warming is an enhanced polar vortex caused by stratospheric warming in the tropics. This occurs as a result of the absorption of solar radiation by volcanic aerosols (Graf *et al.*, 1993). The changes in stratospheric winds associated with this also filter down to the troposphere, bringing about altered wind patterns in this layer of the atmosphere. In the lower latitudes, the direct effect of reducing the solar flux results in cooling. However, in higher latitudes around Ireland, the dynamical effect produces winter warming due to weakened solar insolation (Robock and Mao, 1992).

Colder summers in the year after an eruption are possible, but in Ireland the impact is more widespread in autumn and, in particular spring, the season that achieves the strongest Pearson correlation coefficient with Lamb's (1970) Dust Veil Index. This spring cooling, according to Stenchikov *et al.* (2002), is as a result of substantial changes in ozone levels following strong explosive volcanic eruptions. Ozone absorbs solar UV radiation, and radiates and absorbs thermal IR radiation. Volcanically-induced depletions in ozone levels cause cooling in higher latitudes in spring because of a decrease in UV absorption. The net contribution from the IR effect is smaller and as a result the most notable period of cooling tends to occur in spring (Stenchikov *et al.* 2002).

The influence of volcanic matter on precipitation in Ireland varies greatly, in terms of both level of rainfall and timescale, depending on the strength of the eruption. Smaller-scale eruptions from Iceland act to increase rainfall levels in the immediate aftermath of an event as their injection of matter into the troposphere encourages the creation of condensation nuclei. Meanwhile, the higher-magnitude events that propel material further into the atmosphere see their negative influence on precipitation manifesting in summer months, particularly if the eruption occurred earlier in the same year. These instances are a consequence of a reduction in ocean heat content. This reduction leads to a decrease in evaporation as a result of increased concentrations of volcanic matter in the atmosphere which act to reflect solar energy back into space (Church *et al.*, 2005). Rainfall is likely to remain a feature of day-to-day weather. However, a reduction in the amount recorded, combined with correlations between DVI and summer precipitation, is what emphasises the interaction between large-scale eruptions and rainfall.

The proposed increases in northeasterly, easterly, southwesterly and westerly frequencies (Dawson *et al.*, 1997; Kelly *et al.*, 1996; Groisman, 1992; Hunt, 1977) are certainly evident in the months following the VEI 5, 6 and 7 volcanic eruptions examined. The increased concentrations of volcanic matter in the atmosphere following these large-scale events lead to a decline in low-latitude jet stream wind intensity (Hunt, 1977). This is caused by a reduction in latent heat brought about by the increased atmospheric albedo associated with volcanic aerosols. The decline in wind intensity also coincides with an increase in variability in terms of direction (Hunt, 1977). In comparison, Ireland's prevailing southwesterly and the closely-associated westerly winds continue to dominate in the months following the smaller VEI 4 Icelandic-based eruptions, suggesting that an alteration in frequency will not feature in the wake of these events.

8.2.2 Tree-ring data

It is likely to be the case that Icelandic VEI 4 volcanic eruptions fail to have a negative impact upon *Quercus* tree-ring widths in Ireland. It is more feasible that the particulate matter injected into the stratosphere by higher-magnitude eruptions, in Iceland or at low-latitudes, has a damaging effect on tree growth through one of, or a combination of, two ways: firstly, the particulate matter acts to reduce atmospheric transparency, thus having a negative influence on photosynthesis (Salzer and Hughes, 2007). Secondly, the reduction of ozone associated with volcanic matter in the atmosphere brings about lower temperatures than normal in spring and autumn and can hinder growth (Briffa *et al*, 2004). The more notable and more common decreases in ring-width values in the years following the VEI 5-7 eruptions compare very favourably to the seemingly haphazard variations in ring-widths that come in the wake of Icelandic VEI 4 events – changes that are more likely to be a consequence of local influencing factors or simply a result of year-to-year noise in the datasets. The mean changes in ring-widths come in the form of increases in the three years associated with Icelandic VEI 4 eruptions, while the VEI 5-7 events are dominated by reductions in values in the first and second year after eruptions, with more notable changes tending to occur in the northern half of the island of Ireland. The less notable changes in the southern half of Ireland are likely to be a consequence of the milder climate that persists here as a result of, for the most part, the North Atlantic Drift. Although volcanically-induced colder spring temperatures are likely to dominate throughout the island of Ireland, the winter warming associated with the same events has the potential to encourage early growth in the southern half, thereby facilitating at least some productivity before the onset of growth-restricting colder conditions in the following season.

Similar to the *Quercus* species examined in the course of this study, *T. baccata* shows a reduction in growth in the wake of high-magnitude volcanic eruptions, while the smaller-scale Icelandic events mostly fail to impact upon growth. Although a volcanically-induced reduction in precipitation alone is unlikely to notably limit growth due to the specie's high tolerance of drought (Brzeziecki & Kienast, 1994), *T. baccata* will still be negatively impacted upon as a result of the combination of the reduced summer precipitation, the colder temperatures that dominate in spring, and the increased concentrations of volcanic matter in the atmosphere causing a reduction in photosynthesis.

T. baccata is a long-lived species, with potential to survive more than 1000 years (Thomas and Polwart, 2003). Dendroclimatic reconstructions in Ireland are very limited because of the lack of long-term chronologies for species other than *Quercus*. The extension of the *T. baccata* chronology and reconstructions, as well as the significant inter-species correlation with other species (Yadav and Singh, 2002; Moir, 1999), indicates that *T. baccata* could become an important constituent in multi-site and multi-species studies of past environments. The fact that only two *T. baccata* chronologies are available from the International Tree-ring Data Bank suggests that the potential benefits of *T. baccata* are not necessarily recognised, something that may be a consequence of the difficulties in attaining useable cores from the species. In addition, the cores used to create the *T. baccata* series in this research did not contain missing or very narrow rings – a potential weakness of the species, as indicated by Thomas and Polwart (2003).

8.2.3 Further research

Although previous publications have focused on Irish storm patterns associated with North Atlantic Oscillation (Dawson *et al.*, 2004; Dawson *et al.*, 2002), little emphasis has been given to the overall influence of NAO on the climate and weather of Ireland. Fowler and Kilsby (2001), for example, examined seasonal variations in NAO values and their correlations with precipitation in Yorkshire, England; Trigo *et al.* (2004) looked at the interaction between NAO and precipitation, river flow and water resources in the Iberian Peninsula; and Livingstone and Dokulil (2001) examined 80 years of temperature change in eight locations in Austria with reference to seasonal NAO values. Similar examinations of the interactions between NAO and Irish climate variability will lead to a better understanding of how NAO influences weather patterns here. In terms of precipitation, this can be achieved by correlating multi-site precipitation values with monthly/seasonal NAO values (Fowler and Kilsby, 2001), or by correlating monthly river flow records with NAO values (Trigo *et al.*, 2004). Meanwhile, similar analysis of monthly/seasonal temperature records with NAO values would facilitate a deeper understanding of the interaction between the two elements. The North Atlantic Oscillation is the dominant influential factor on the climate of Northwestern Europe. A better understanding of this influence on an Irish scale, from month to month and season to season, would enable in-depth analysis of abrupt changes in weather and climate that occur at more variable intervals, such as the influence of high-magnitude volcanic eruptions.

El Niño Southern Oscillation (ENSO) is a further climatic signal that should be investigated. Because the climatic response to ENSO is of the same amplitude and timescale as volcanic responses (Robock and Mao, 1995), it would be beneficial to seek to separate them to examine the volcanic signal. Low frequency variations in temperature datasets can be removed by employing high-pass Lanczos filtering (Duchon, 1979), a technique that is important when long-term trends can interfere with short-term regional signals. High-frequency signals (i.e. ENSO) can be removed by establishing a relationship between ENSO and surface temperature variations by calculating correlations between Ropelewski and Jones' (1987) Southern Oscillation Index (SOI) and surface temperature anomalies for each three-month season. SOI should lead land surface air temperature anomalies by one season, producing an appropriate lag for correlation calculations (Robock and Mao, 1995). The correlations can then be used to establish a linear regression relationship between high-frequency temperature anomalies and the SOI series which, in turn, can be used to remove the ENSO signals from the high-frequency temperature variations. Because ENSO-related patterns will differ from case to case and are not related to temperature in a simple linear fashion, it is impossible to completely remove the ENSO signal using this method (Robock and Mao, 1995). However, it does allow a more accurate representation of post-eruption temperature change by greatly reducing the influence of ENSO.

The long-lived nature of the *T. baccata* species presents the potential to expand the chronology further than the ~200 years produced in the course of this research. Although Reenadinna Wood in Killarney National Park, the study site employed here, is the most extensive *T. baccata* stand in Ireland, other stands were identified by Perrin (2002) in The Burren, Co. Clare; Garryland Wood, Co. Galway; St. John’s Wood in Co. Roscommon; and The Rocks of Clorhane, Co. Offaly. Meanwhile, individual examples can be found in estates and graveyards throughout the country where some trees could be up to 2,000 years old (Perrin, 2002). A multi-site approach to extending the *T. baccata* chronology could lead to a longer series, in turn facilitating the reconstruction of climatic elements further into the past. Such an extension of the *T. baccata* chronology would also strengthen multi-species approaches to the examination to past environmental change. Significant inter-species correlations (Yadav and Singh, 2002; Moir, 1999) indicate the potential for *T. baccata* to assume an important role in the study of environmental change. The multi-species study undertaken by Garcia-Suarez *et al.* (2010) highlighted the benefits of this approach in Ireland. The incorporation of more species such as *T. baccata* would add to the strength of any results garnered. This study has shown the reliability of *T. baccata*, indicating that future dendroclimatological studies in Ireland should include this species.

8.3 CONCLUSIONS

This study has shown that the climate of Ireland will respond in the wake of volcanic eruptions, with the severity and location of the events playing integral roles in determining a timescale and degree of impact. This, in turn, has consequences for growth of both *T. baccata* and *Quercus* species on the island. In order for such conclusions to be made, it was necessary to develop an understanding of how eruptions are likely to impact upon the variables examined. The majority of studies relate to continental or even hemispheric impacts. However, this study has shown that such examinations are also possible on the local scale.

The research has shown that the weather records from Armagh Observatory contain footprints left by volcanic eruptions over the last ~200 years. This study was the first to combine the systematic examination of the various elements available in these Armagh records and apply them all in a detailed study. Although much work had previously been undertaken by those in Armagh Observatory in terms of calibrating the temperature and precipitation data, very little analysis of trends or anomalies has been carried out. This study is also the first to undertake such a detailed examination of the aftermath of eruptions and go on to identify trends and patterns that are likely following, in general, high-magnitude low-latitude volcanic eruptions or lesser Icelandic events. Because the approach to this investigation was quite novel, many of the methods of analysis employed were adapted from other studies not necessarily focusing on volcanically-induced climatic changes, but changes in climate nonetheless. Yet, the approach proved successful as the post-eruption adjustments and trends identified are clear.

Less than 30 years ago, dendroclimatological research in Ireland was deemed to be of little value because *Quercus* species are not as responsive to changes in climate here as they are in other locations. However, this study has shown that a movement away from the traditional *Quercus* species as the focus of attention is undoubtedly a fruitful exercise. In terms of climatic reconstructions of mean November-April temperatures and total May-June precipitation, *T. baccata* proved to be on par with, and at times exceeded, other species that have only recently been examined for their dendroclimatological potential, something that bodes well for future dendrological-based reconstructions of climatic variability in Ireland. The correlations with climatic variables proved to be stronger in the Killarney-based *T. baccata* series than any other published *T. baccata* series in the world, while the reconstruction of these variables are a first for the species. Meanwhile, the use of the species to identify downturns in environmental conditions in the years following volcanic eruptions was also a success. The detailed analysis of volcanic footprints recorded in the weather data – reductions in both spring temperatures and summer precipitation levels – facilitated a better understanding of why the impacts of these events are also seen in tree-ring widths.

Although tree growth in Ireland is a factor of numerous variables, volcanically-induced alterations in temperature and to a lesser extent precipitation, as well as photosynthesis-inhibiting increased concentrations of volcanic matter in the atmosphere at vital times of the year for growth (i.e. spring and summer) will result in downturns in growth in *T. baccata*, with impacts also seen in *Q. petraea* and *Q. robur*. The degree to which these impacts are recorded will vary, even over a relatively small geographical area such as Ireland, with obvious disparities between the reactions of the species in the northern half and the southern half of the island. The severity of the eruption is the most important aspect in the onset of a downturn in growth, as a Volcanic Explosivity Index value of 5 or more is necessary for the matter to persist in the atmosphere for long enough to bring about a change in growth patterns. Consequently, the majority of Icelandic eruptions, that is, those with a VEI of 4 or less, are highly unlikely to result in an impact upon tree-growth in Ireland.

The combination of climatological and ecological examinations compliment each other by putting forward assessments of different aspects of post-volcanic eruption conditions at various temporal and spatial resolutions. With tree ecology being largely a function of climatic conditions, each of these separate aspects combines to improve our understanding of post-volcanic eruption conditions in

Ireland and outlines what changes can be expected in climate and tree-growth in the future when similar-sized events recur. It also indicates that it is important to be aware of the potential of abrupt changes in climate that will come-about as a result of more catastrophic eruptions that periodically occur.

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APPENDIX I

Table A1: Seven months of N winds in Armagh (eruption month and the six following months), including an 11-year mean, the number of days per month with N winds recorded, as well as the difference between these two measurements.

Event		Monthly Wind Direction Data						
		TM	TM+1	TM+2	TM+3	TM+4	TM+5	TM+6
*Apr 1815 VEI7	11-Year Monthly Mean	2.0	1.5	1.2	2.1	1.5	0.4	0.6
	Individual Monthly Record	5	1	1	7	1	0	0
	Difference (in Days)	3.0	-0.5	-0.2	4.9	-0.5	-0.4	-0.6
Sept 1845 VEI4	11-Year Monthly Mean	2.9	2.6	1.6	1.4	0.9	1.6	2.8
	Individual Monthly Record	3	0	1	2	0	0	5
	Difference (in Days)	0.1	-2.6	-0.6	0.6	-0.9	-1.6	2.2
May 1860 VEI4	11-Year Monthly Mean	2.5	1.9	3.1	2.2	1.3	1.5	1.1
	Individual Monthly Record	0	0	2	2	3	0	0
	Difference (in Days)	-2.5	-1.9	-1.1	-0.2	1.7	-1.5	-1.1
Mar 1875 VEI5	11-Year Monthly Mean	2.5	3.4	4.7	2.5	2.2	2.5	1.9
	Individual Monthly Record	1	3	3	2	2	2	0
	Difference (in Days)	-1.5	-0.4	-1.7	-0.5	-0.2	-0.5	-1.9
Dec 1902 VEI4	11-Year Monthly Mean	0.8	1.2	1.5	2.6	2.1	2.3	2.3
	Individual Monthly Record	0	2	0	1	2	2	3
	Difference (in Days)	-0.8	0.8	-1.5	-1.6	-0.1	-0.3	0.7
Oct 1918 VEI4	11-Year Monthly Mean	1.0	0.8	1.0	0.6	0.7	1.7	3.0
	Individual Monthly Record	2	0	1	0	2	0	3
	Difference (in Days)	1.0	-0.8	0.0	-0.6	1.3	-1.7	0.0
Mar 1947 VEI4	11-Year Monthly Mean	0.9	1.0	1.8	1.8	1.5	1.3	1.1
	Individual Monthly Record	0	1	1	0	0	2	0
	Difference (in Days)	-0.9	0.0	-0.8	-1.8	-1.5	0.7	-1.1
*Mar 1982 VEI5	11-Year Monthly Mean	2.3	3.8	3.9	2.1	2.0	2.1	1.5
	Individual Monthly Record	1	6	0	0	3	0	0
	Difference (in Days)	-1.3	2.2	-3.9	-2.1	1.0	-2.1	-1.5
*Apr 1991 VEI6	11-Year Monthly Mean	2.9	2.7	2.2	1.6	2.3	1.9	1.3
	Individual Monthly Record	3	8	2	0	1	1	1
	Difference (in Days)	0.1	5.3	-0.2	-1.6	-1.3	-0.9	-0.3

*Denotes low-latitude eruption

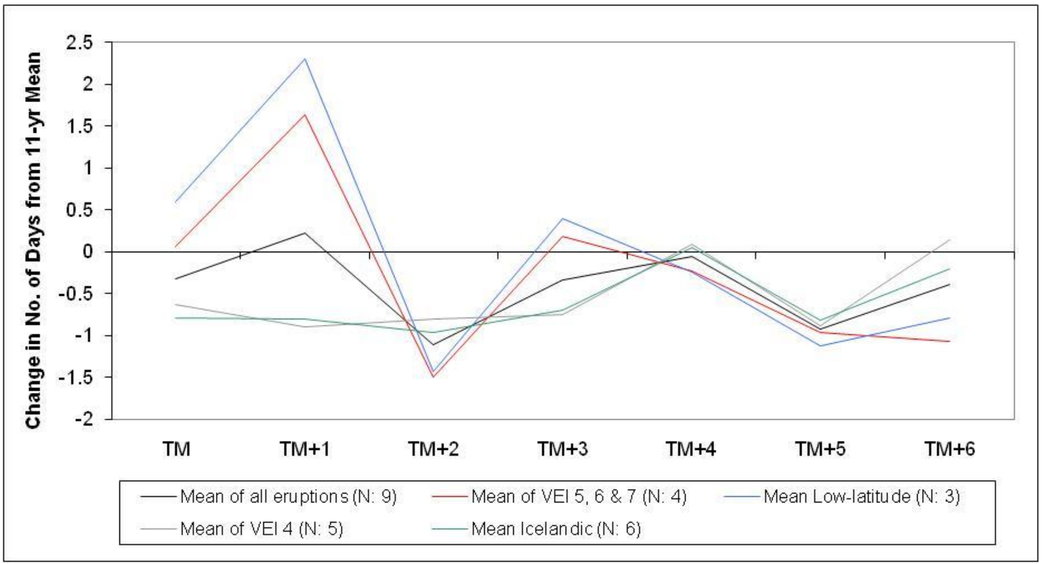

Figure A1: Five volcano categories showing seven months of change in N winds in Armagh in relation to the 11-year mean.

Table A2: Seven months of NNE winds in Armagh (eruption month and the six following months), including an 11-year mean, the number of days per month with NNE winds recorded, as well as the difference between these two measurements.

Event		Monthly Wind Direction Data						
		TM	TM+1	TM+2	TM+3	TM+4	TM+5	TM+6
*Apr 1815 VEI7	11-Year Monthly Mean	1.5	1.6	1.8	0.7	1.0	1.2	1.5
	Individual Monthly Record	0	0	0	0	0	0	0
	Difference (in Days)	-1.5	-1.6	-1.8	-0.7	-1.0	-1.2	-1.5
Sept 1845 VEI4	11-Year Monthly Mean	0.8	1.3	0.3	0.4	0.4	0.4	0.9
	Individual Monthly Record	0	1	0	0	0	1	0
	Difference (in Days)	-0.8	-0.3	-0.3	-0.4	-0.4	0.6	-0.9
May 1860 VEI4	11-Year Monthly Mean	0.5	0.4	0.9	0.6	0.6	0.8	0.4
	Individual Monthly Record	0	0	0	0	2	0	1
	Difference (in Days)	-0.5	-0.4	-0.9	-0.6	1.4	-0.8	0.6
Mar 1875 VEI5	11-Year Monthly Mean	0.4	0.7	0.3	0.3	0.4	0.5	0.2
	Individual Monthly Record	1	0	0	0	1	1	0
	Difference (in Days)	0.6	-0.7	-0.3	-0.3	0.6	0.5	-0.2
Dec 1902 VEI4	11-Year Monthly Mean	0.5	0.5	0.7	1.3	1.2	1.8	1.5
	Individual Monthly Record	0	0	0	0	0	4	3
	Difference (in Days)	-0.5	-0.5	-0.7	-1.3	-1.2	2.2	1.5
Oct 1918 VEI4	11-Year Monthly Mean	0.2	0.5	0.3	0.3	0.5	1.0	1.5
	Individual Monthly Record	0	0	0	1	0	0	1
	Difference (in Days)	-0.2	-0.5	-0.3	0.7	-0.5	-1.0	-0.5
Mar 1947 VEI4	11-Year Monthly Mean	1.0	1.1	2.8	1.6	1.1	1.5	1.0
	Individual Monthly Record	5	1	0	1	3	6	1
	Difference (in Days)	4.0	-0.1	-2.8	-0.6	1.9	4.5	0.0
*Mar 1982 VEI5	11-Year Monthly Mean	0.2	0.7	1.0	0.8	0.4	0.2	0.2
	Individual Monthly Record	1	1	0	0	0	1	0
	Difference (in Days)	0.8	0.3	-1.0	-0.8	-0.4	0.8	-0.2
*Apr 1991 VEI6	11-Year Monthly Mean	1.0	2.3	1.0	0.5	0.6	1.2	1.1
	Individual Monthly Record	4	3	0	0	0	0	0
	Difference (in Days)	3.0	0.7	-1.0	-0.5	-0.6	-1.2	-1.1

*Denotes low-latitude eruption

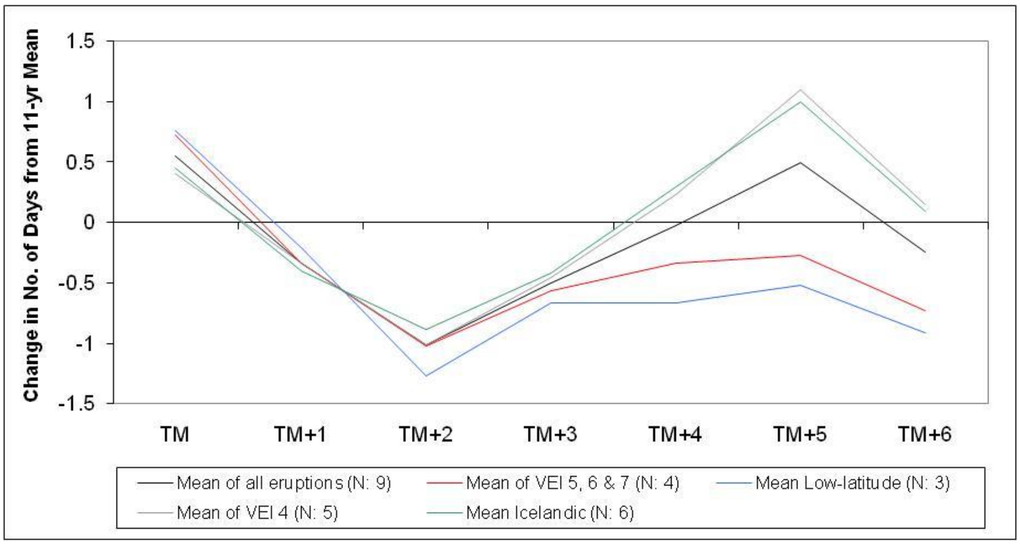

Figure A2: Five volcano categories showing seven months of change in NNE winds in Armagh in relation to the 11-year mean.

Table A3: Seven months of ENE winds in Armagh (eruption month and the six following months), including an 11-year mean, the number of days per month with ENE winds recorded, as well as the difference between these two measurements.

Event		Monthly Wind Direction Data						
		TM	TM+1	TM+2	TM+3	TM+4	TM+5	TM+6
*Apr 1815 VEI7	11-Year Monthly Mean	1.3	0.8	0.2	0.6	0.8	0.2	0.9
	Individual Monthly Record	0	0	1	0	0	1	0
	Difference (in Days)	-1.3	-0.8	0.8	-0.6	-0.8	0.8	-0.9
Sept 1845 VEI4	11-Year Monthly Mean	0.4	0.2	0.6	0.2	0.0	0.3	0.5
	Individual Monthly Record	0	1	0	0	0	0	0
	Difference (in Days)	-0.4	0.8	-0.6	-0.2	0.0	-0.3	-0.5
May 1860 VEI4	11-Year Monthly Mean	0.5	0.5	0.2	0.1	0.2	0.5	0.5
	Individual Monthly Record	0	0	0	0	0	0	2
	Difference (in Days)	-0.5	-0.5	-0.2	-0.1	-0.2	-0.5	1.5
Mar 1875 VEI5	11-Year Monthly Mean	0.4	0.5	0.2	0.4	0.0	0.5	0.1
	Individual Monthly Record	0	0	0	0	0	1	0
	Difference (in Days)	-0.4	-0.5	-0.2	-0.4	0.0	0.5	-0.1
Dec 1902 VEI4	11-Year Monthly Mean	0.7	0.3	0.4	1.0	1.4	2.1	1.2
	Individual Monthly Record	1	1	0	1	0	4	1
	Difference (in Days)	0.3	0.7	-0.4	0.0	-1.4	1.9	-0.2
Oct 1918 VEI4	11-Year Monthly Mean	0.5	0.4	0.6	0.5	0.7	1.4	1.2
	Individual Monthly Record	1	0	0	1	3	2	0
	Difference (in Days)	0.5	-0.4	-0.6	0.5	2.3	0.6	-1.2
Mar 1947 VEI4	11-Year Monthly Mean	1.0	1.3	1.5	0.6	0.2	0.5	0.4
	Individual Monthly Record	0	2	1	0	1	0	0
	Difference (in Days)	-1.0	0.7	-0.5	-0.6	0.8	-0.5	-0.4
*Mar 1982 VEI5	11-Year Monthly Mean	0.1	0.6	0.7	1.0	0.3	0.4	0.0
	Individual Monthly Record	0	0	0	1	1	0	0
	Difference (in Days)	-0.1	-0.6	-0.7	0.0	0.7	-0.4	0.0
*Apr 1991 VEI6	11-Year Monthly Mean	0.5	0.5	0.5	0.3	0.5	0.3	0.4
	Individual Monthly Record	1	1	0	2	0	0	1
	Difference (in Days)	0.5	0.5	-0.5	1.7	-0.5	-0.3	0.6

*Denotes low-latitude eruption

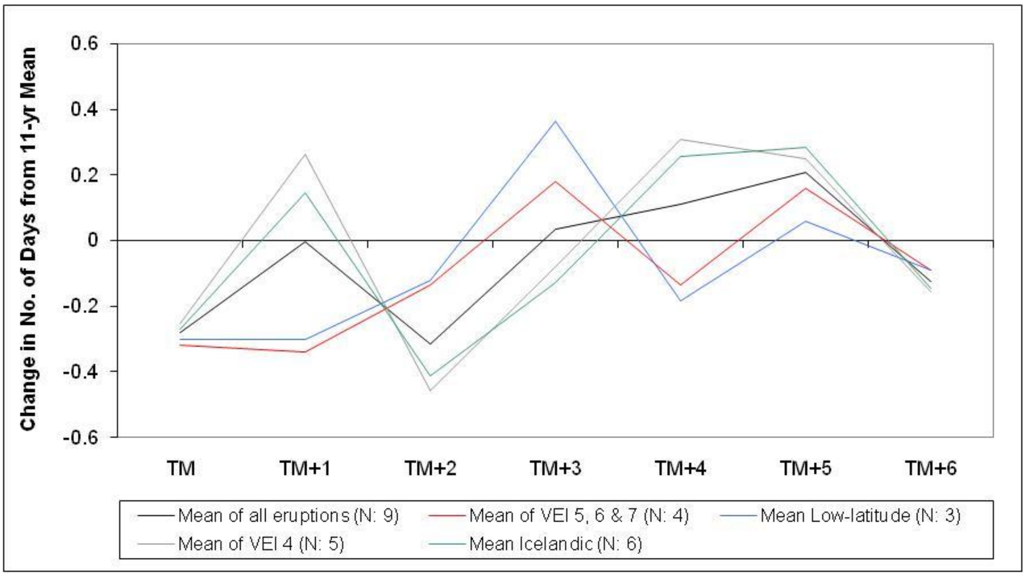

Figure A3: Five volcano categories showing seven months of change in ENE winds in Armagh in relation to the 11-year mean.

Table A4: Seven months of ESE winds in Armagh (eruption month and the six following months), including an 11-year mean, the number of days per month with ESE winds recorded, as well as the difference between these two measurements.

Event		Monthly Wind Direction Data						
		TM	TM+1	TM+2	TM+3	TM+4	TM+5	TM+6
*Apr 1815 VEI7	11-Year Monthly Mean	0.5	0.5	0.5	0.2	0.2	0.3	0.7
	Individual Monthly Record	1	0	0	0	0	0	1
	Difference (in Days)	0.5	-0.5	-0.5	-0.2	-0.2	-0.3	0.3
Sept 1845 VEI4	11-Year Monthly Mean	0.7	0.6	0.2	0.8	0.5	0.0	0.3
	Individual Monthly Record	0	0	1	0	0	0	1
	Difference (in Days)	-0.7	-0.6	0.8	-0.8	-0.5	0.0	0.7
May 1860 VEI4	11-Year Monthly Mean	0.4	0.3	0.1	0.4	0.4	0.6	0.4
	Individual Monthly Record	0	1	1	1	1	0	1
	Difference (in Days)	-0.4	0.7	0.9	0.6	0.6	-0.6	0.6
Mar 1875 VEI5	11-Year Monthly Mean	0.4	0.3	0.4	0.2	0.0	0.5	0.2
	Individual Monthly Record	0	0	0	1	0	0	1
	Difference (in Days)	-0.4	-0.3	-0.4	0.8	0.0	-0.5	0.8
Dec 1902 VEI4	11-Year Monthly Mean	1.5	0.5	0.2	0.5	0.2	1.0	0.7
	Individual Monthly Record	0	0	0	1	0	1	1
	Difference (in Days)	-1.5	-0.5	-0.2	0.5	-0.2	0.0	0.3
Oct 1918 VEI4	11-Year Monthly Mean	0.8	0.5	0.5	1.3	0.9	1.3	0.8
	Individual Monthly Record	0	0	1	0	2	1	0
	Difference (in Days)	-0.8	-0.5	0.5	-1.3	1.1	-0.3	-0.8
Mar 1947 VEI4	11-Year Monthly Mean	1.4	0.5	1.9	0.5	0.3	0.6	0.5
	Individual Monthly Record	6	0	4	0	1	2	0
	Difference (in Days)	4.6	-0.5	2.1	-0.5	0.7	1.4	-0.5
*Mar 1982 VEI5	11-Year Monthly Mean	0.3	0.8	0.9	0.8	0.2	0.3	0.5
	Individual Monthly Record	0	0	2	2	1	0	1
	Difference (in Days)	-0.3	-0.8	1.1	1.2	0.8	-0.3	0.5
*Apr 1991 VEI6	11-Year Monthly Mean	0.5	0.3	0.5	0.1	0.0	0.3	0.4
	Individual Monthly Record	0	0	0	0	0	2	0
	Difference (in Days)	-0.5	-0.3	-0.5	-0.1	0.0	1.7	-0.4

*Denotes low-latitude eruption

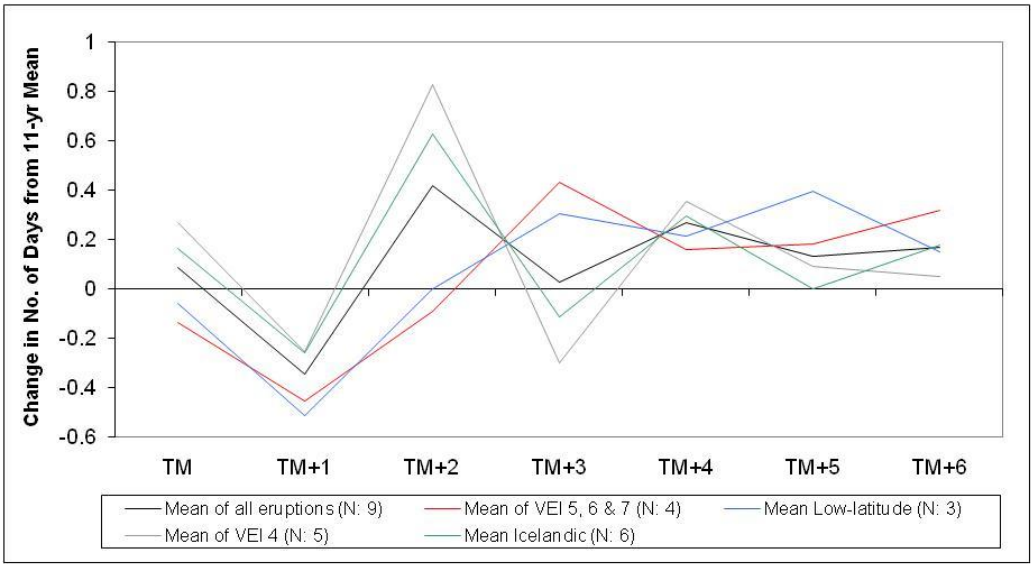

Figure A4: Five volcano categories showing seven months of change in ESE winds in Armagh in relation to the 11-year mean.

Table A5: Seven months of SE winds in Armagh (eruption month and the six following months), including an 11-year mean, the number of days per month with SE winds recorded, as well as the difference between these two measurements.

Event		Monthly Wind Direction Data						
		TM	TM+1	TM+2	TM+3	TM+4	TM+5	TM+6
*Apr 1815 VEI7	**11-Year Monthly Mean**	1.2	1.8	1.5	1.7	1.5	1.8	1.7
	Individual Monthly Record	1	2	1	0	0	1	2
	Difference (in Days)	-0.2	0.2	-0.5	-1.7	-1.5	-0.8	0.3
Sept 1845 VEI4	**11-Year Monthly Mean**	1.4	1.2	1.7	1.2	2.0	0.8	2.6
	Individual Monthly Record	0	0	0	1	4	1	3
	Difference (in Days)	-1.4	-1.2	-1.7	-0.2	2.0	0.2	0.4
May 1860 VEI4	**11-Year Monthly Mean**	2.5	2.1	1.2	1.4	2.4	2.2	1.0
	Individual Monthly Record	5	3	4	0	2	1	1
	Difference (in Days)	2.5	0.9	2.8	-1.4	-0.4	-1.2	0.0
Mar 1875 VEI5	**11-Year Monthly Mean**	2.3	3.1	1.6	1.2	1.7	1.6	1.1
	Individual Monthly Record	1	2	3	0	1	2	1
	Difference (in Days)	-1.3	-1.1	1.4	-1.2	-0.7	0.4	-0.1
Dec 1902 VEI4	**11-Year Monthly Mean**	0.7	1.6	1.4	1.2	2.2	1.9	2.3
	Individual Monthly Record	1	4	1	0	0	1	2
	Difference (in Days)	0.3	2.4	-0.4	-1.2	-2.2	-0.9	-0.3
Oct 1918 VEI4	**11-Year Monthly Mean**	2.3	1.7	0.8	1.1	2.3	1.5	1.2
	Individual Monthly Record	0	3	0	1	2	1	0
	Difference (in Days)	-2.3	1.3	-0.8	-0.1	-0.3	-0.5	-1.2
Mar 1947 VEI4	**11-Year Monthly Mean**	1.4	1.0	2.3	0.7	1.3	1.4	1.3
	Individual Monthly Record	1	0	7	1	1	0	1
	Difference (in Days)	-0.4	-1.0	4.7	0.3	-0.3	-1.4	-0.3
*Mar 1982 VEI5	**11-Year Monthly Mean**	1.7	2.8	4.7	2.7	1.6	1.4	2.3
	Individual Monthly Record	0	2	2	5	3	1	3
	Difference (in Days)	-1.7	-0.8	-2.7	2.3	1.4	-0.4	0.7
*Apr 1991 VEI6	**11-Year Monthly Mean**	1.7	2.5	0.9	1.3	0.4	0.8	1.0
	Individual Monthly Record	4	0	1	1	1	0	2
	Difference (in Days)	2.3	-2.5	0.1	-0.3	0.6	-0.8	1.0

*Denotes low-latitude eruption

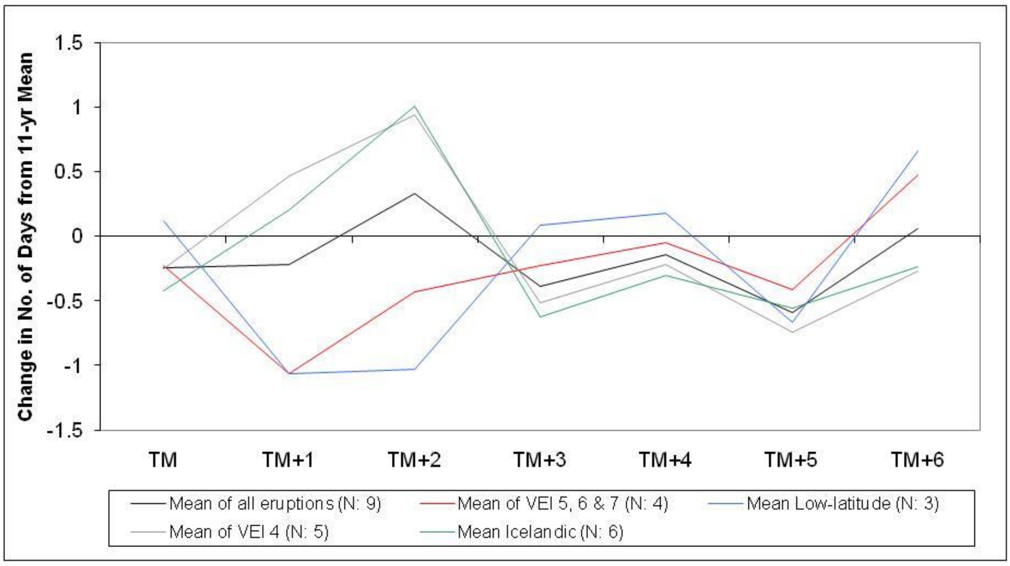

Figure A5: Five volcano categories showing seven months of change in SE winds in Armagh in relation to the 11-year mean.

Table A6: Seven months of SSE winds in Armagh (eruption month and the six following months), including an 11-year mean, the number of days per month with SSE winds recorded, as well as the difference between these two measurements.

Event		Monthly Wind Direction Data						
		TM	TM+1	TM+2	TM+3	TM+4	TM+5	TM+6
*Apr 1815 VEI7	**11-Year Monthly Mean**	0.5	0.9	0.4	0.5	0.5	1.3	1.3
	Individual Monthly Record	0	1	0	0	0	1	4
	Difference (in Days)	-0.5	0.1	-0.4	-0.5	-0.5	-0.3	2.7
Sept 1845 VEI4	**11-Year Monthly Mean**	0.9	0.6	0.6	1.0	1.4	0.1	1.0
	Individual Monthly Record	1	2	2	0	1	0	1
	Difference (in Days)	0.1	1.4	1.4	-1.0	-0.4	-0.1	0.0
May 1860 VEI4	**11-Year Monthly Mean**	0.6	0.9	0.4	0.5	0.5	0.6	1.0
	Individual Monthly Record	1	1	1	0	0	0	0
	Difference (in Days)	0.4	0.1	0.6	-0.5	-0.5	-0.6	-1.0
Mar 1875 VEI5	**11-Year Monthly Mean**	0.5	0.3	0.3	0.4	0.3	0.5	0.4
	Individual Monthly Record	2	0	0	0	1	0	0
	Difference (in Days)	1.5	-0.3	-0.3	-0.4	0.7	-0.5	-0.4
Dec 1902 VEI4	**11-Year Monthly Mean**	2.1	1.2	0.9	1.3	1.5	1.3	1.8
	Individual Monthly Record	4	2	0	1	0	1	4
	Difference (in Days)	1.9	0.8	-0.9	-0.3	-1.5	-0.3	2.2
Oct 1918 VEI4	**11-Year Monthly Mean**	1.1	1.4	0.8	1.0	1.0	1.2	0.4
	Individual Monthly Record	1	3	2	1	5	1	0
	Difference (in Days)	-0.1	1.6	1.2	0.0	4.0	-0.2	-0.4
Mar 1947 VEI4	**11-Year Monthly Mean**	2.1	0.8	1.1	0.8	0.7	0.7	0.6
	Individual Monthly Record	2	2	1	1	2	1	0
	Difference (in Days)	-0.1	1.2	-0.1	0.2	1.3	0.3	-0.6
*Mar 1982 VEI5	**11-Year Monthly Mean**	1.8	0.3	2.5	0.8	1.8	1.5	2.3
	Individual Monthly Record	2	1	3	3	1	0	4
	Difference (in Days)	0.2	0.7	0.5	2.2	-0.8	-1.5	1.7
*Apr 1991 VEI6	**11-Year Monthly Mean**	1.6	1.7	1.8	1.4	1.5	1.5	1.3
	Individual Monthly Record	0	0	0	0	1	0	0
	Difference (in Days)	-1.6	-1.7	-1.8	-1.4	-0.5	-1.5	-1.3

*Denotes low-latitude eruption

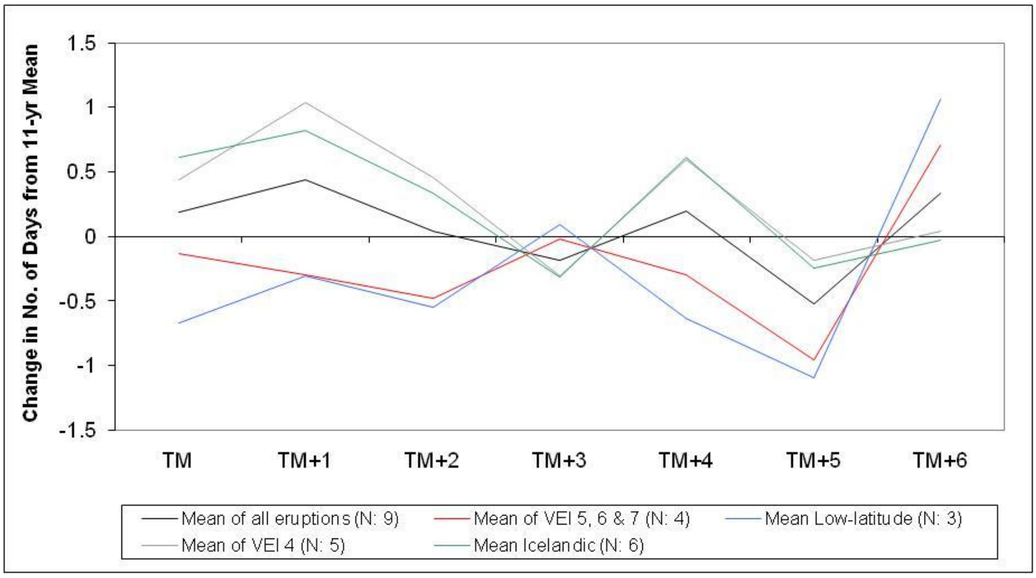

Figure A6: Five volcano categories showing seven months of change in SSE winds in Armagh in relation to the 11-year mean.

Table A7: Seven months of S winds in Armagh (eruption month and the six following months), including an 11-year mean, the number of days per month with S winds recorded, as well as the difference between these two measurements.

Event		Monthly Wind Direction Data						
		TM	TM+1	TM+2	TM+3	TM+4	TM+5	TM+6
*Apr 1815 VEI7	11-Year Monthly Mean	0.8	0.9	0.5	0.5	0.9	1.0	1.1
	Individual Monthly Record	2	2	1	0	3	4	6
	Difference (in Days)	1.2	1.1	0.5	-0.5	2.1	3.0	4.9
Sept 1845 VEI4	11-Year Monthly Mean	2.7	4.3	4.6	7.1	6.5	4.9	3.5
	Individual Monthly Record	1	4	5	5	4	6	3
	Difference (in Days)	-1.7	-0.3	0.4	-2.1	-2.5	1.1	-0.5
May 1860 VEI4	11-Year Monthly Mean	3.6	2.7	1.9	3.2	4.6	2.5	3.9
	Individual Monthly Record	7	2	0	0	5	2	3
	Difference (in Days)	3.4	-0.7	-1.9	-3.2	0.4	-0.5	-0.9
Mar 1875 VEI5	11-Year Monthly Mean	3.4	4.2	2.9	5.5	5.3	2.4	4.5
	Individual Monthly Record	2	5	7	5	4	3	4
	Difference (in Days)	-1.4	0.8	4.1	-0.5	-1.3	0.6	-0.5
Dec 1902 VEI4	11-Year Monthly Mean	4.0	3.8	2.7	3.3	2.2	3.0	2.6
	Individual Monthly Record	3	3	4	2	4	3	0
	Difference (in Days)	-1.0	-0.8	1.3	-1.3	1.8	0.0	-2.6
Oct 1918 VEI4	11-Year Monthly Mean	5.6	4.5	5.1	6.5	3.7	2.9	1.6
	Individual Monthly Record	3	5	4	4	3	2	0
	Difference (in Days)	-2.6	0.5	-1.1	-2.5	-0.7	-0.9	-1.6
Mar 1947 VEI4	11-Year Monthly Mean	3.5	2.4	2.4	3.0	3.2	2.5	2.7
	Individual Monthly Record	4	6	6	8	3	2	4
	Difference (in Days)	0.5	3.6	3.6	5.0	-0.2	-0.5	1.3
*Mar 1982 VEI5	11-Year Monthly Mean	4.8	2.9	3.8	4.2	5.8	6.0	6.1
	Individual Monthly Record	6	3	8	6	5	2	4
	Difference (in Days)	1.2	0.1	4.2	1.8	-0.8	-4.0	-2.1
*Apr 1991 VEI6	11-Year Monthly Mean	4.7	3.4	4.4	7.2	7.5	5.6	6.5
	Individual Monthly Record	6	0	1	6	9	12	6
	Difference (in Days)	1.3	-3.4	-3.4	-1.2	1.5	6.4	-0.5

*Denotes low-latitude eruption

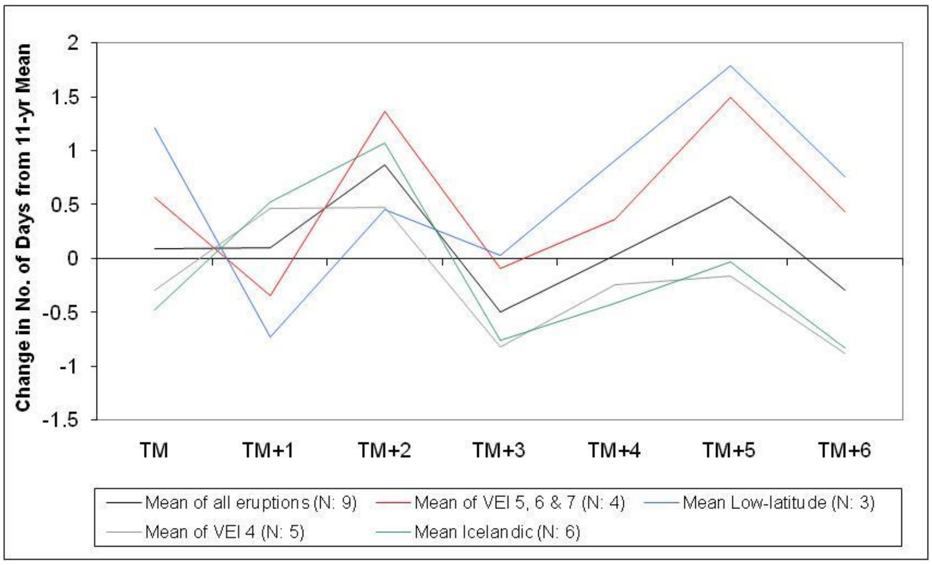

Figure A7: Five volcano categories showing seven months of change in S winds in Armagh in relation to the 11-year mean.

Table A8: Seven months of SSW winds in Armagh (eruption month and the six following months), including an 11-year mean, the number of days per month with SSW winds recorded, as well as the difference between these two measurements.

Event		Monthly Wind Direction Data						
		TM	TM+1	TM+2	TM+3	TM+4	TM+5	TM+6
*Apr 1815 VEI7	11-Year Monthly Mean	0.7	0.7	0.6	1.4	0.5	2.0	1.1
	Individual Monthly Record	0	1	1	0	0	6	0
	Difference (in Days)	-0.7	0.3	0.4	-1.4	-0.5	4.0	-1.1
Sept 1845 VEI4	11-Year Monthly Mean	1.7	1.7	1.8	2.6	2.8	1.6	1.6
	Individual Monthly Record	2	2	4	4	5	1	2
	Difference (in Days)	0.3	0.3	2.2	1.4	2.2	-0.6	0.4
May 1860 VEI4	11-Year Monthly Mean	1.4	1.4	1.0	2.8	1.8	1.7	1.5
	Individual Monthly Record	1	0	1	3	0	2	0
	Difference (in Days)	-0.4	-1.4	0.0	0.2	-1.8	0.3	-1.5
Mar 1875 VEI5	11-Year Monthly Mean	0.6	0.3	0.5	0.3	1.5	0.7	1.3
	Individual Monthly Record	1	0	0	0	0	0	1
	Difference (in Days)	0.4	-0.3	-0.5	-0.3	-1.5	-0.7	-0.3
Dec 1902 VEI4	11-Year Monthly Mean	5.4	6.0	3.8	3.3	2.5	2.2	1.5
	Individual Monthly Record	1	0	7	5	2	1	2
	Difference (in Days)	-4.4	-6.0	3.2	1.7	-0.5	-1.2	0.5
Oct 1918 VEI4	11-Year Monthly Mean	4.2	5.4	5.0	3.8	4.2	2.5	1.4
	Individual Monthly Record	5	5	4	5	1	3	0
	Difference (in Days)	0.8	-0.4	-1.0	1.2	-3.2	0.5	-1.4
Mar 1947 VEI4	11-Year Monthly Mean	3.8	4.0	2.2	3.4	3.2	2.7	4.4
	Individual Monthly Record	1	9	4	3	5	5	8
	Difference (in Days)	-2.8	5.0	1.8	-0.4	1.8	2.3	3.6
*Mar 1982 VEI5	11-Year Monthly Mean	2.1	1.6	2.0	2.5	4.6	4.4	4.4
	Individual Monthly Record	3	0	3	1	2	0	5
	Difference (in Days)	0.9	-1.6	1.0	-1.5	-2.6	-4.4	0.6
*Apr 1991 VEI6	11-Year Monthly Mean	2.9	2.5	2.5	5.3	6.5	4.4	4.7
	Individual Monthly Record	2	3	2	0	3	3	1
	Difference (in Days)	-0.9	0.5	-0.5	-5.3	-3.5	-1.4	-3.7

*Denotes low-latitude eruption

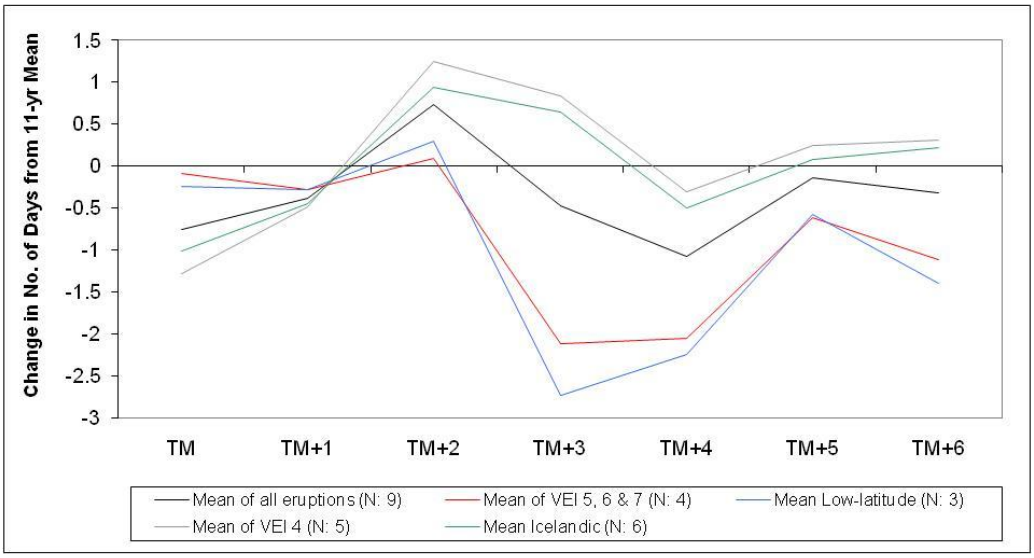

Figure A8: Five volcano categories showing seven months of change in SSW winds in Armagh in relation to the 11-year mean.

Table A9: Seven months of WSW winds in Armagh (eruption month and the six following months), including an 11-year mean, the number of days per month with WSW winds recorded, as well as the difference between these two measurements.

Event		Monthly Wind Direction Data						
		TM	TM+1	TM+2	TM+3	TM+4	TM+5	TM+6
*Apr 1815 VEI7	11-Year Monthly Mean	2.0	1.6	1.8	2.1	2.0	2.0	2.4
	Individual Monthly Record	0	1	0	0	1	2	0
	Difference (in Days)	-2.0	-0.6	-1.8	-2.1	-1.0	0.0	-2.4
Sept 1845 VEI4	11-Year Monthly Mean	0.9	1.1	1.6	0.6	1.0	1.8	1.0
	Individual Monthly Record	1	1	1	2	1	1	1
	Difference (in Days)	0.1	-0.1	-0.6	1.4	0.0	-0.8	0.0
May 1860 VEI4	11-Year Monthly Mean	1.1	1.2	2.3	1.8	2.1	1.1	0.9
	Individual Monthly Record	2	0	2	1	0	0	0
	Difference (in Days)	0.9	-1.2	-0.3	-0.8	-2.1	-1.1	-0.9
Mar 1875 VEI5	11-Year Monthly Mean	0.3	0.4	0.5	0.5	0.5	0.9	0.5
	Individual Monthly Record	0	0	0	0	0	0	0
	Difference (in Days)	-0.3	-0.4	-0.5	-0.5	-0.5	-0.9	-0.5
Dec 1902 VEI4	11-Year Monthly Mean	1.5	1.6	2.3	1.8	1.9	2.1	1.5
	Individual Monthly Record	4	0	2	2	0	5	2
	Difference (in Days)	2.5	-1.6	-0.3	0.2	-1.9	2.9	0.5
Oct 1918 VEI4	11-Year Monthly Mean	1.4	1.3	0.7	1.8	1.2	1.2	0.8
	Individual Monthly Record	2	3	1	4	1	1	0
	Difference (in Days)	0.6	1.7	0.3	2.2	-0.2	-0.2	-0.8
Mar 1947 VEI4	11-Year Monthly Mean	1.2	1.5	0.5	1.2	2.3	1.6	0.7
	Individual Monthly Record	2	3	0	0	1	0	0
	Difference (in Days)	0.8	1.5	-0.5	-1.2	-1.3	-1.6	-0.7
*Mar 1982 VEI5	11-Year Monthly Mean	2.1	1.0	0.5	0.6	0.7	1.3	0.8
	Individual Monthly Record	4	3	1	0	1	6	0
	Difference (in Days)	1.9	2.0	0.5	-0.6	0.3	4.7	-0.8
*Apr 1991 VEI6	11-Year Monthly Mean	0.5	0.4	0.5	0.9	0.9	0.7	0.4
	Individual Monthly Record	1	0	1	3	1	0	0
	Difference (in Days)	0.5	-0.4	0.5	2.1	0.1	-0.7	-0.4

*Denotes low-latitude eruption

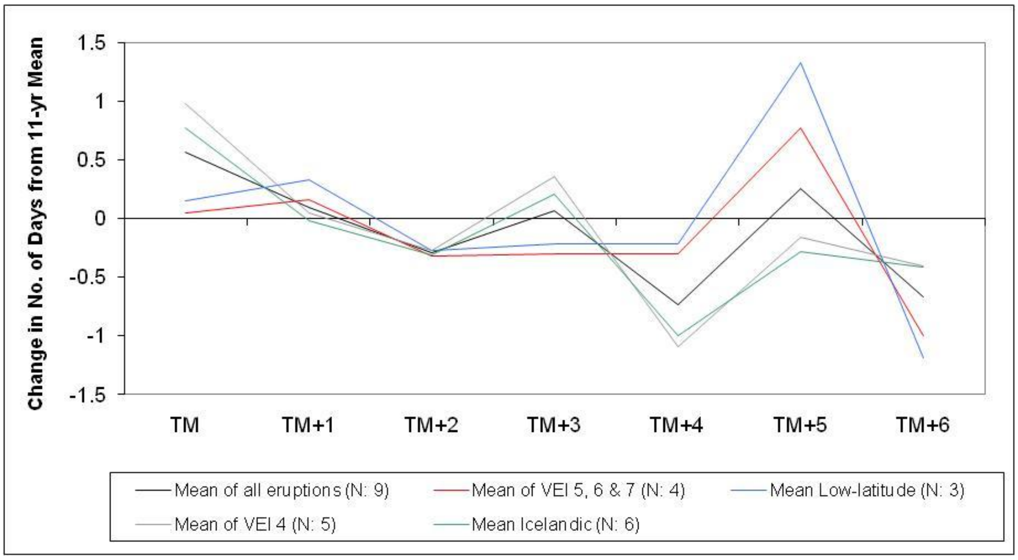

Figure A9: Five volcano categories showing seven months of change in WSW winds in Armagh in relation to the 11-year mean.

Table A10: Seven months of WNW winds in Armagh (eruption month and the six following months), including an 11-year mean, the number of days per month with WNW winds recorded, as well as the difference between these two measurements.

Event		Monthly Wind Direction Data						
		TM	TM+1	TM+2	TM+3	TM+4	TM+5	TM+6
*Apr 1815 VEI7	**11-Year Monthly Mean**	2.1	1.2	1.8	2.9	2.7	2.3	2.1
	Individual Monthly Record	0	0	0	2	1	0	0
	Difference (in Days)	-2.1	-1.2	-1.8	-0.9	-1.7	-2.3	-2.1
Sept 1845 VEI4	**11-Year Monthly Mean**	0.8	0.6	0.3	0.2	0.2	0.5	0.7
	Individual Monthly Record	0	0	0	0	0	2	0
	Difference (in Days)	-0.8	-0.6	-0.3	-0.2	-0.2	1.5	-0.7
May 1860 VEI4	**11-Year Monthly Mean**	0.8	0.8	0.9	0.9	1.1	0.7	0.5
	Individual Monthly Record	0	0	1	3	0	1	0
	Difference (in Days)	-0.8	-0.8	0.1	2.1	-1.1	0.3	-0.5
Mar 1875 VEI5	**11-Year Monthly Mean**	0.4	0.1	0.3	0.3	0.6	0.4	0.2
	Individual Monthly Record	0	0	0	0	1	0	0
	Difference (in Days)	-0.4	-0.1	-0.3	-0.3	0.4	-0.4	-0.2
Dec 1902 VEI4	**11-Year Monthly Mean**	0.5	0.2	0.9	0.7	2.4	0.6	0.8
	Individual Monthly Record	1	0	0	3	4	0	0
	Difference (in Days)	0.5	-0.2	-0.9	2.3	1.6	-0.6	-0.8
Oct 1918 VEI4	**11-Year Monthly Mean**	0.8	0.6	1.1	0.5	0.1	1.0	1.3
	Individual Monthly Record	1	1	3	0	0	1	1
	Difference (in Days)	0.2	0.4	1.9	-0.5	-0.1	0.0	-0.3
Mar 1947 VEI4	**11-Year Monthly Mean**	1.2	1.5	1.4	1.9	2.2	2.1	1.5
	Individual Monthly Record	0	0	2	3	2	2	1
	Difference (in Days)	-1.2	-1.5	0.6	1.1	-0.2	-0.1	-0.5
*Mar 1982 VEI5	**11-Year Monthly Mean**	0.2	0.1	0.1	0.0	0.0	0.0	0.1
	Individual Monthly Record	0	1	0	0	0	0	0
	Difference (in Days)	-0.2	0.9	-0.1	0.0	0.0	0.0	-0.1
*Apr 1991 VEI6	**11-Year Monthly Mean**	0.2	0.4	0.5	0.5	0.4	0.0	0.0
	Individual Monthly Record	1	0	1	0	0	0	0
	Difference (in Days)	0.8	-0.4	0.5	-0.5	-0.4	0.0	0.0

*Denotes low-latitude eruption

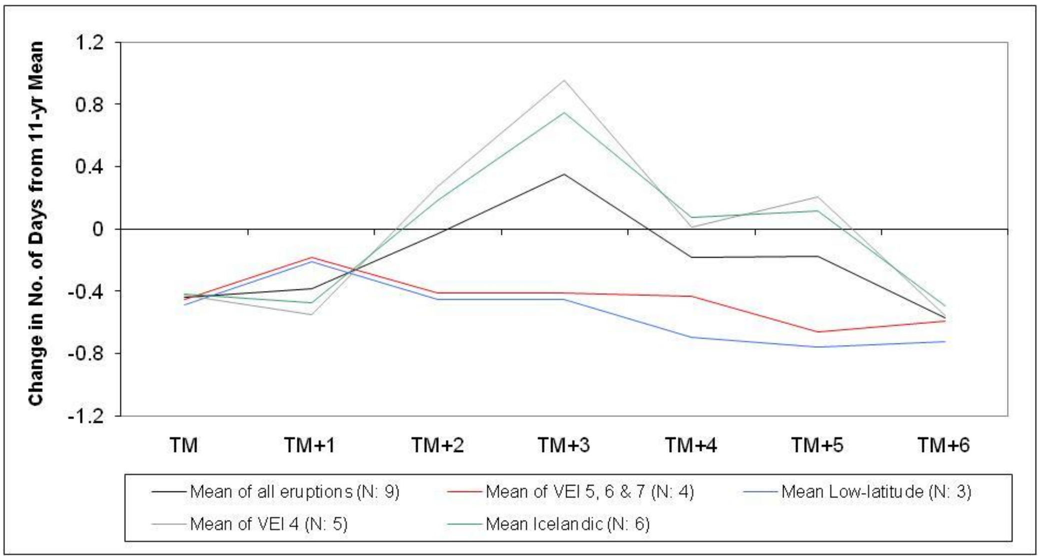

Figure A10: Five volcano categories showing seven months of change in WNW winds in Armagh in relation to the 11-year mean.

Table A11: Seven months of NW winds in Armagh (eruption month and the six following months), including an 11-year mean, the number of days per month with NW winds recorded, as well as the difference between these two measurements.

Event		Monthly Wind Direction Data						
		TM	TM+1	TM+2	TM+3	TM+4	TM+5	TM+6
*Apr 1815 VEI7	**11-Year Monthly Mean**	4.8	3.5	5.7	5.0	6.2	4.3	3.5
	Individual Monthly Record	4	2	3	2	2	2	1
	Difference (in Days)	-0.8	-1.5	-2.7	-3.0	-4.2	-2.3	-2.5
Sept 1845 VEI4	**11-Year Monthly Mean**	2.6	1.8	2.1	1.2	0.8	2.4	2.2
	Individual Monthly Record	2	0	0	1	1	1	2
	Difference (in Days)	-0.6	-1.8	-2.1	-0.2	0.2	-1.4	-0.2
May 1860 VEI4	**11-Year Monthly Mean**	2.5	3.8	4.4	3.5	2.5	2.0	2.0
	Individual Monthly Record	3	7	7	4	3	2	1
	Difference (in Days)	0.5	3.2	2.6	0.5	0.5	0.0	-1.0
Mar 1875 VEI5	**11-Year Monthly Mean**	2.2	1.8	2.5	2.7	2.9	2.4	2.9
	Individual Monthly Record	4	2	3	1	4	1	0
	Difference (in Days)	1.8	0.2	0.5	-1.7	1.1	-1.4	-2.9
Dec 1902 VEI4	**11-Year Monthly Mean**	0.6	0.5	0.9	1.0	1.2	1.0	1.4
	Individual Monthly Record	0	0	1	1	3	0	0
	Difference (in Days)	-0.6	-0.5	0.1	0.0	1.8	-1.0	-1.4
Oct 1918 VEI4	**11-Year Monthly Mean**	1.1	0.5	0.5	0.7	0.5	0.7	1.9
	Individual Monthly Record	0	0	0	1	0	3	2
	Difference (in Days)	-1.1	-0.5	-0.5	0.3	-0.5	2.3	0.1
Mar 1947 VEI4	**11-Year Monthly Mean**	2.0	1.7	1.7	2.6	3.8	2.5	1.5
	Individual Monthly Record	1	0	0	0	3	1	2
	Difference (in Days)	-1.0	-1.7	-1.7	-2.6	-0.8	-1.5	0.5
*Mar 1982 VEI5	**11-Year Monthly Mean**	1.4	1.2	1.0	0.7	0.3	0.6	0.5
	Individual Monthly Record	1	2	3	0	0	0	0
	Difference (in Days)	-0.4	0.8	2.0	-0.7	-0.3	-0.6	-0.5
*Apr 1991 VEI6	**11-Year Monthly Mean**	1.5	0.6	1.5	0.9	0.5	0.6	0.5
	Individual Monthly Record	2	0	2	0	0	0	1
	Difference (in Days)	0.5	-0.6	0.5	-0.9	-0.5	-0.6	0.5

*Denotes low-latitude eruption

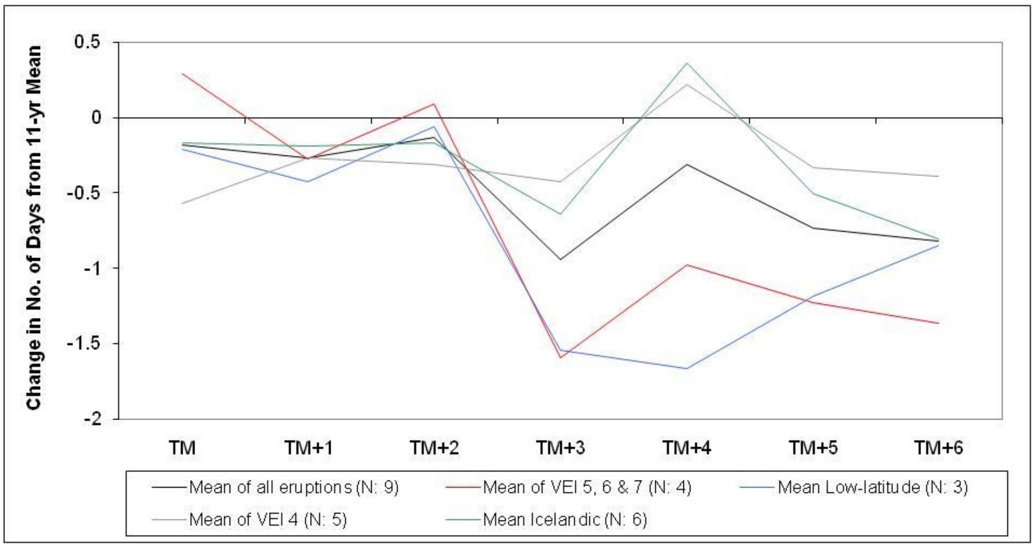

Figure A11: Five volcano categories showing seven months of change in NW winds in Armagh in relation to the 11-year mean.

Table A12: Seven months of NNW winds in Armagh (eruption month and the six following months), including an 11-year mean, the number of days per month with NNW winds recorded, as well as the difference between these two measurements.

Event		Monthly Wind Direction Data						
		TM	TM+1	TM+2	TM+3	TM+4	TM+5	TM+6
*Apr 1815 VEI7	11-Year Monthly Mean	1.5	1.4	1.3	1.4	1.3	1.2	0.8
	Individual Monthly Record	2	0	1	0	0	0	1
	Difference (in Days)	0.5	-1.4	-0.3	-1.4	-1.3	-1.2	0.2
Sept 1845 VEI4	11-Year Monthly Mean	0.7	0.2	0.4	0.4	0.0	0.5	1.2
	Individual Monthly Record	0	0	0	0	0	2	0
	Difference (in Days)	-0.7	-0.2	-0.4	-0.4	0.0	1.5	-1.2
May 1860 VEI4	11-Year Monthly Mean	0.4	0.5	1.3	0.8	0.2	0.7	0.7
	Individual Monthly Record	0	1	2	1	0	0	0
	Difference (in Days)	-0.4	0.5	0.7	0.2	-0.2	-0.7	-0.7
Mar 1875 VEI5	11-Year Monthly Mean	0.4	0.1	0.1	0.2	0.5	0.1	0.2
	Individual Monthly Record	2	0	0	0	1	0	0
	Difference (in Days)	1.6	-0.1	-0.1	-0.2	0.5	-0.1	-0.2
Dec 1902 VEI4	11-Year Monthly Mean	0.3	0.6	0.4	1.2	0.6	1.4	1.5
	Individual Monthly Record	0	0	0	0	1	1	0
	Difference (in Days)	-0.3	-0.6	-0.4	-1.2	0.4	-0.4	-1.5
Oct 1918 VEI4	11-Year Monthly Mean	0.4	0.3	0.5	0.3	0.5	0.7	0.9
	Individual Monthly Record	1	1	1	0	0	1	2
	Difference (in Days)	0.6	0.7	0.5	-0.3	-0.5	0.3	1.1
Mar 1947 VEI4	11-Year Monthly Mean	0.3	1.2	1.9	1.6	1.4	1.3	1.3
	Individual Monthly Record	0	0	0	2	0	0	2
	Difference (in Days)	-0.3	-1.2	-1.9	0.4	-1.4	-1.3	0.7
*Mar 1982 VEI5	11-Year Monthly Mean	0.7	0.5	0.5	0.2	0.5	0.2	0.0
	Individual Monthly Record	2	0	0	0	0	0	0
	Difference (in Days)	1.3	-0.5	-0.5	-0.2	-0.5	-0.2	0.0
*Apr 1991 VEI6	11-Year Monthly Mean	0.5	0.5	1.3	0.1	0.2	0.5	0.4
	Individual Monthly Record	0	0	5	0	0	0	0
	Difference (in Days)	-0.5	-0.5	3.7	-0.1	-0.2	-0.5	-0.4

*Denotes low-latitude eruption

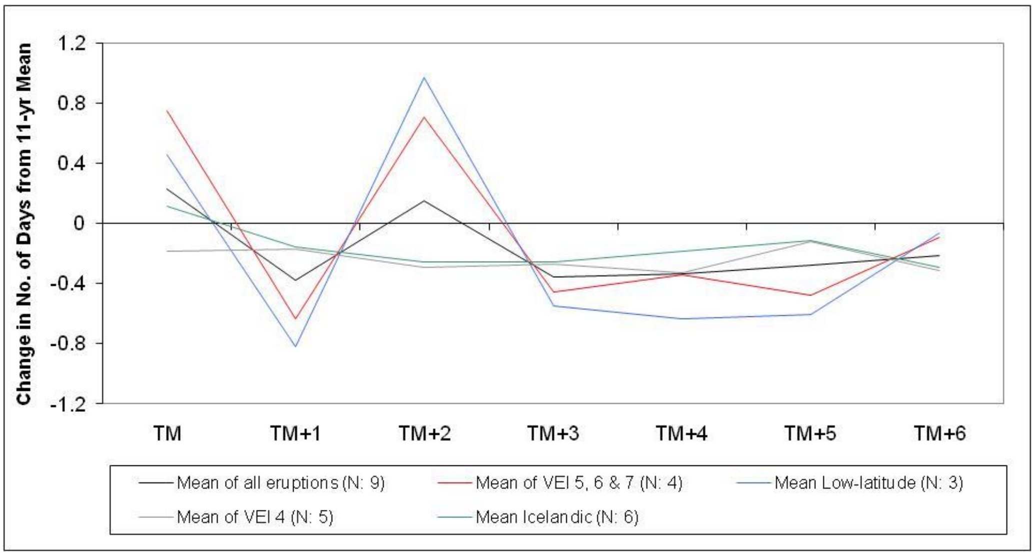

Figure A12: Five volcano categories showing seven months of change in NNW winds in Armagh in relation to the 11-year mean.

APPENDIX II

Figure B1: ***T. baccata*** **tree in Reenadinna Wood, Killarney National Park, with 5.15 mm two-thread Haglöf increment borer.**
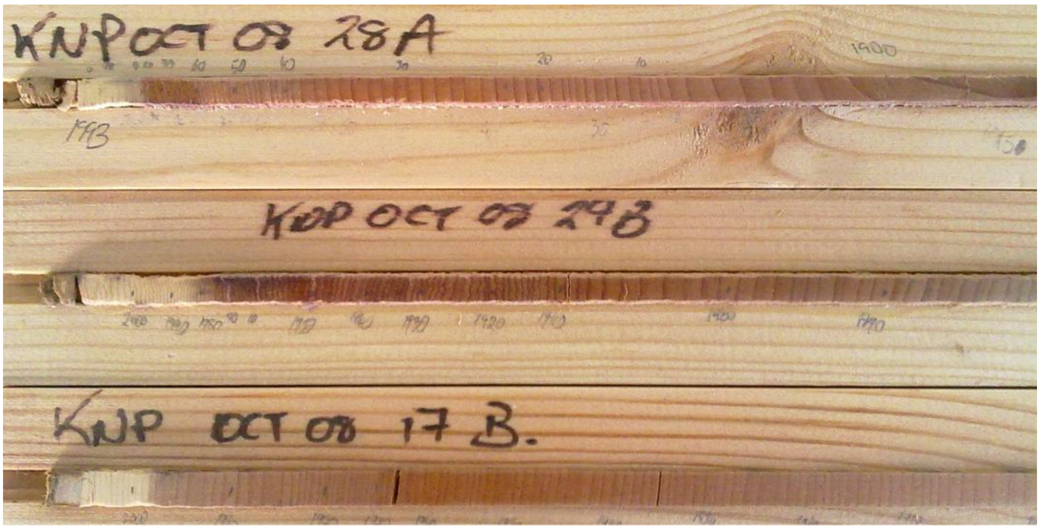
Figure B2: Mounted and sanded *T. baccata* cores.

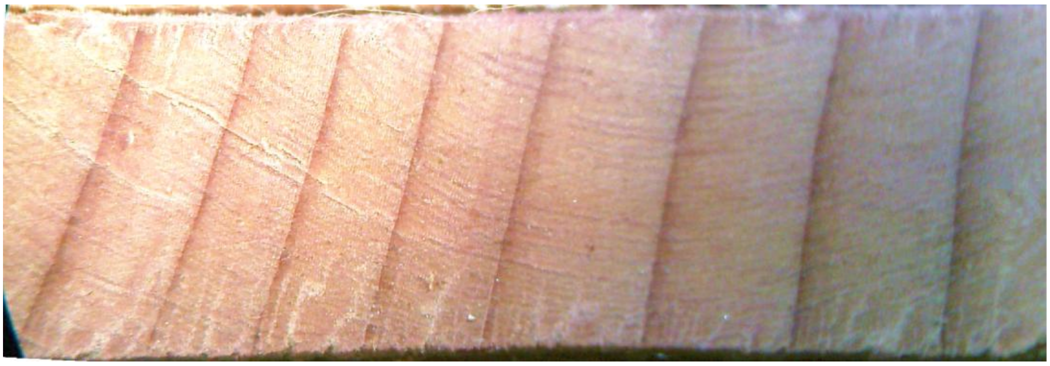

Figure B3: *T. baccata* core magnified 10x.

Table B1: Killarney National Park *T. baccata* raw measurements.

KTB01A	1865	401	428	397	368	322					
KTB01A	1870	511	411	377	294	351	447	371	430	397	478
KTB01A	1880	803	409	353	487	433	330	431	246	326	274
KTB01A	1890	370	244	236	196	320	239	156	234	274	161
KTB01A	1900	216	111	118	157	114	117	161	136	111	115
KTB01A	1910	154	96	134	112	123	107	119	82	84	90
KTB01A	1920	97	54	83	73	88	83	79	65	54	64
KTB01A	1930	56	58	84	96	53	84	78	102	93	64
KTB01A	1940	55	77	66	145	73	75	68	61	56	46
KTB01A	1950	51	43	37	55	56	52	54	53	54	35
KTB01A	1960	53	999								
KTB01B	1864	297	293	261	221	238	240				
KTB01B	1870	240	301	306	233	171	144	174	260	312	232
KTB01B	1880	334	278	286	314	377	364	377	209	375	373
KTB01B	1890	433	282	288	179	200	143	94	125	165	161
KTB01B	1900	253	184	187	172	152	143	194	323	237	195
KTB01B	1910	218	236	242	170	192	152	170	115	107	109
KTB01B	1920	108	52	102	83	95	66	62	62	53	56
KTB01B	1930	44	79	118	135	82	119	106	128	153	122
KTB01B	1940	96	90	75	119	72	93	79	70	61	49
KTB01B	1950	70	74	49	60	60	59	54	56	86	66
KTB01B	1960	55	33	48	28	44	40	36	21	41	34
KTB01B	1970	36	49	56	53	68	51	77	57	80	60
KTB01B	1980	108	93	133	55	61	87	64	45	49	75
KTB01B	1990	133	102	107	102	169	148	163	170	80	98
KTB01B	2000	118	39	141	111	84	75	77	94	999	
KTB02A	1831	154	177	212	226	133	66	73	69	213	
KTB02A	1840	313	286	375	248	247	209	262	237	549	463

KTB02A	1850	390	328	286	329	360	332	238	293	281	126
KTB02A	1860	151	157	251	222	152	255	226	160	124	120
KTB02A	1870	131	167	172	189	177	209	130	200	284	224
KTB02A	1880	272	256	268	257	298	261	213	271	220	120
KTB02A	1890	180	172	152	102	136	87	63	103	126	118
KTB02A	1900	106	118	107	101	92	76	74	76	57	69
KTB02A	1910	76	60	58	65	80	64	64	80	78	88
KTB02A	1920	88	47	85	71	97	100	128	116	114	124
KTB02A	1930	71	112	118	89	52	68	66	60	71	57
KTB02A	1940	36	42	39	60	50	60	82	66	72	60
KTB02A	1950	59	52	55	70	73	80	78	999		
KTB02B	1849	319									
KTB02B	1850	359	320	285	239	274	263	176	404	367	194
KTB02B	1860	248	206	312	228	145	317	229	172	161	132
KTB02B	1870	145	192	207	206	247	231	152	216	231	144
KTB02B	1880	200	248	264	267	226	163	141	149	172	143
KTB02B	1890	203	211	189	96	189	107	65	121	124	128
KTB02B	1900	152	111	143	138	115	86	99	126	91	89
KTB02B	1910	106	71	88	86	90	93	91	130	115	99
KTB02B	1920	115	70	89	87	87	123	139	104	124	114
KTB02B	1930	112	114	91	105	68	95	78	72	64	96
KTB02B	1940	69	71	78	78	78	96	81	61	73	47
KTB02B	1950	85	68	67	88	85	99	105	72	93	108
KTB02B	1960	200	81	86	999						
KTB03A	1840	225	303	1204	877	899	535	532	363	138	441
KTB03A	1850	541	398	308	255	248	199	170	205	219	130
KTB03A	1860	145	144	194	179	152	127	117	109	154	112
KTB03A	1870	111	115	126	148	141	123	68	106	110	102
KTB03A	1880	137	108	109	101	88	82	76	53	85	66

KTB03A	1890	94	71	79	70	102	64	52	68	106	89
KTB03A	1900	107	74	66	52	51	43	54	47	36	40
KTB03A	1910	72	67	49	56	62	55	49	43	44	43
KTB03A	1920	48	20	56	45	58	54	56	51	45	50
KTB03A	1930	33	55	68	54	35	55	46	53	61	47
KTB03A	1940	35	53	39	47	24	32	34	38	35	21
KTB03A	1950	32	52	32	41	46	50	999			
KTB03B	1845	183	263	294	329	222					
KTB03B	1850	210	166	240	234	217	237	273	290	374	350
KTB03B	1860	382	271	209	174	173	186	179	186	248	258
KTB03B	1870	234	209	158	177	229	256	139	101	79	110
KTB03B	1880	145	136	115	116	118	122	95	100	122	135
KTB03B	1890	152	131	137	82	120	94	102	109	86	89
KTB03B	1900	47	55	62	63	37	86	88	97	73	67
KTB03B	1910	120	71	122	110	86	73	100	124	115	79
KTB03B	1920	63	44	60	40	34	33	29	43	31	31
KTB03B	1930	25	21	38	33	22	31	27	30	26	41
KTB03B	1940	39	31	34	50	40	42	27	42	53	60
KTB03B	1950	40	31	35	0	38	73	46	63	60	48
KTB03B	1960	45	29	27	38	32	43	44	46	43	68
KTB03B	1970	81	77	55	48	49	17	48	49	51	42
KTB03B	1980	40	56	49	37	48	46	46	33	47	33
KTB03B	1990	31	31	52	72	72	55	39	42	72	44
KTB03B	2000	55	75	46	43	38	54	58	53	999	
KTB04A	1839	367									
KTB04A	1840	389	387	301	260	219	228	295	253	322	317
KTB04A	1850	322	343	372	336	288	217	175	194	202	136
KTB04A	1860	199	235	425	493	346	361	333	276	254	221
KTB04A	1870	223	269	294	302	298	232	140	176	165	168

KTB04A	1880	230	169	258	218	168	184	146	108	152	144
KTB04A	1890	247	189	202	142	241	169	152	155	146	115
KTB04A	1900	132	109	121	159	146	152	151	150	86	91
KTB04A	1910	98	74	93	83	106	124	112	96	83	76
KTB04A	1920	106	50	90	87	124	113	121	101	71	58
KTB04A	1930	56	69	60	56	41	57	44	51	67	42
KTB04A	1940	32	38	44	94	40	54	52	49	60	48
KTB04A	1950	37	43	42	44	46	52	44	60	77	72
KTB04A	1960	69	51	53	51	63	71	73	72	99	109
KTB04A	1970	85	91	82	90	102	60	82	63	66	57
KTB04A	1980	52	69	73	65	35	66	68	60	72	54
KTB04A	1990	82	60	65	84	77	108	79	63	81	70
KTB04A	2000	97	83	127	97	73	76	50	85	999	
KTB04B	1814	88	99	77	61	44	49				
KTB04B	1820	52	75	132	124	120	88	36	88	137	151
KTB04B	1830	179	154	177	139	170	160	172	173	224	270
KTB04B	1840	317	417	384	266	153	116	103	109	174	173
KTB04B	1850	198	361	456	528	458	288	169	174	181	124
KTB04B	1860	136	201	240	195	202	221	202	179	166	165
KTB04B	1870	149	145	189	212	248	252	138	222	227	219
KTB04B	1880	311	321	277	279	218	181	165	116	172	137
KTB04B	1890	207	146	154	86	165	125	111	103	103	71
KTB04B	1900	103	64	67	89	95	95	98	106	71	74
KTB04B	1910	92	75	89	68	58	103	97	89	80	71
KTB04B	1920	110	46	95	107	123	125	132	106	86	78
KTB04B	1930	62	78	65	63	38	59	51	60	67	40
KTB04B	1940	29	36	35	79	41	58	61	69	60	48
KTB04B	1950	36	38	39	47	50	55	50	58	68	58
KTB04B	1960	68	49	52	53	75	70	67	59	72	70

KTB04B	1970	59	66	75	96	109	73	78	62	61	56
KTB04B	1980	63	82	75	77	41	88	105	90	118	71
KTB04B	1990	94	76	94	111	101	117	87	77	120	76
KTB04B	2000	67	109	99	65	70	57	69	33	999	
KTB05A	1892	31	31	73	50	42	49	56	43		
KTB05A	1900	62	42	34	23	49	40	39	37	44	42
KTB05A	1910	46	32	33	40	33	53	50	35	39	38
KTB05A	1920	44	36	32	33	30	30	37	31	32	33
KTB05A	1930	32	37	33	36	26	37	38	36	31	27
KTB05A	1940	25	34	33	45	33	50	44	37	46	45
KTB05A	1950	46	42	54	57	63	84	68	57	70	78
KTB05A	1960	79	55	60	73	74	60	53	62	65	115
KTB05A	1970	72	65	53	81	81	58	61	38	62	41
KTB05A	1980	43	41	57	40	44	52	39	84	58	65
KTB05A	1990	154	79	78	57	39	93	58	63	67	40
KTB05A	2000	76	42	72	97	999					
KTB05B	1795	355	365	398	605	506					
KTB05B	1800	360	513	475	332	399	407	391	340	373	269
KTB05B	1810	270	318	336	347	312	324	275	268	172	182
KTB05B	1820	143	164	144	130	111	85	42	87	95	103
KTB05B	1830	119	152	166	161	201	180	148	165	192	193
KTB05B	1840	157	160	167	182	138	134	122	147	194	165
KTB05B	1850	142	158	175	145	149	192	158	233	309	232
KTB05B	1860	238	190	232	214	144	167	136	123	120	105
KTB05B	1870	120	167	193	182	166	188	122	116	112	125
KTB05B	1880	181	121	133	99	87	85	68	50	71	73
KTB05B	1890	94	85	73	52	81	64	47	52	61	43
KTB05B	1900	50	44	46	36	48	55	50	48	37	48
KTB05B	1910	52	48	37	47	43	41	45	46	61	64

KTB05B	1920	76	38	62	64	70	78	84	67	61	74
KTB05B	1930	54	62	54	57	45	52	50	53	49	28
KTB05B	1940	34	49	45	56	30	41	42	38	38	39
KTB05B	1950	41	34	33	40	44	44	46	45	50	44
KTB05B	1960	42	33	32	29	29	33	36	23	23	30
KTB05B	1970	27	31	42	41	48	36	58	45	47	41
KTB05B	1980	44	49	54	51	33	56	47	44	50	43
KTB05B	1990	46	41	39	39	38	45	43	37	43	38
KTB05B	2000	43	36	44	37	33	35	38	47	999	
KTB06A	1803	182	285	275	231	215	238	205			
KTB06A	1810	207	236	241	284	268	288	261	305	204	258
KTB06A	1820	202	233	205	259	285	248	87	183	181	154
KTB06A	1830	187	155	130	97	139	111	88	98	100	120
KTB06A	1840	121	115	119	117	75	64	67	68	114	106
KTB06A	1850	116	139	158	164	189	139	109	144	121	71
KTB06A	1860	73	99	98	133	72	66	60	59	58	55
KTB06A	1870	75	139	156	174	133	124	70	105	144	107
KTB06A	1880	107	71	101	176	176	150	149	81	103	127
KTB06A	1890	134	107	111	72	130	77	49	69	95	89
KTB06A	1900	90	73	87	100	105	91	89	77	60	58
KTB06A	1910	64	62	74	60	82	77	88	106	75	57
KTB06A	1920	79	41	66	61	58	84	79	83	92	92
KTB06A	1930	57	64	52	48	18	38	46	60	46	24
KTB06A	1940	18	18	18	29	18	37	39	35	46	32
KTB06A	1950	35	28	35	38	37	30	37	75	999	
KTB06B	1792	370	443	356	320	308	360	287	248		
KTB06B	1800	147	246	383	263	265	250	199	167	182	138
KTB06B	1810	132	180	177	167	131	131	132	135	73	67
KTB06B	1820	58	81	113	112	117	106	52	88	105	123

KTB06B	1830	154	144	107	92	121	88	57	47	51	61
KTB06B	1840	75	82	78	70	52	64	59	75	110	118
KTB06B	1850	124	144	165	151	170	147	100	160	102	26
KTB06B	1860	37	43	99	108	86	97	55	48	42	41
KTB06B	1870	62	133	133	146	205	257	172	254	308	107
KTB06B	1880	228	210	205	318	296	261	265	155	149	109
KTB06B	1890	137	152	144	79	143	162	119	98	135	121
KTB06B	1900	144	118	118	98	98	97	91	94	87	65
KTB06B	1910	69	71	70	43	85	57	61	57	60	47
KTB06B	1920	62	32	63	50	58	54	56	36	51	54
KTB06B	1930	32	42	34	30	20	28	26	31	33	24
KTB06B	1940	30	39	39	32	38	36	55	28	34	36
KTB06B	1950	40	48	54	37	46	47	52	42	39	32
KTB06B	1960	36	35	50	48	43	46	46	56	82	78
KTB06B	1970	117	999								
KTB07A	1871	1005	767	676	664	279	218	538	625	532	
KTB07A	1880	583	491	461	446	452	407	402	353	428	459
KTB07A	1890	523	457	477	349	490	367	298	342	417	379
KTB07A	1900	370	289	332	346	324	321	351	353	246	197
KTB07A	1910	272	232	199	122	177	119	131	130	119	152
KTB07A	1920	216	145	145	135	102	135	132	89	77	71
KTB07A	1930	51	51	41	27	23	42	32	27	23	20
KTB07A	1940	20	14	17	19	15	20	20	14	16	19
KTB07A	1950	17	14	11	17	13	17	21	21	27	14
KTB07A	1960	23	10	29	14	16	16	13	20	28	21
KTB07A	1970	19	38	66	999						
KTB07B	1885	748	732	490	527	503					
KTB07B	1890	592	436	443	327	558	456	307	320	387	306
KTB07B	1900	401	318	329	358	323	292	321	298	260	220

KTB07B	1910	246	223	202	158	180	152	158	163	166	167
KTB07B	1920	181	143	181	168	186	181	203	184	164	181
KTB07B	1930	148	147	159	165	127	152	134	136	131	104
KTB07B	1940	94	99	92	124	83	89	90	99	116	87
KTB07B	1950	103	112	90	113	105	99	102	61	90	67
KTB07B	1960	85	33	73	74	72	73	63	82	75	93
KTB07B	1970	71	69	64	59	52	40	46	54	43	999
KTB08A	1820	176	195	191	219	309	203	109	280	307	337
KTB08A	1830	343	243	248	233	276	207	150	182	205	150
KTB08A	1840	152	278	296	234	252	264	308	256	265	280
KTB08A	1850	229	249	350	255	330	231	159	238	244	159
KTB08A	1860	152	134	197	161	111	113	125	137	126	93
KTB08A	1870	126	153	234	237	178	181	117	156	203	156
KTB08A	1880	202	183	170	145	173	159	136	83	139	141
KTB08A	1890	180	136	139	78	125	97	81	101	107	102
KTB08A	1900	117	78	97	104	112	91	84	77	63	67
KTB08A	1910	62	66	67	62	71	62	84	84	103	96
KTB08A	1920	96	61	91	83	88	94	89	69	76	77
KTB08A	1930	68	75	87	82	60	83	59	65	68	52
KTB08A	1940	49	58	52	62	31	48	46	50	62	55
KTB08A	1950	51	46	50	51	43	54	51	54	59	48
KTB08A	1960	61	46	49	46	56	68	52	54	52	59
KTB08A	1970	45	49	62	62	63	51	75	57	60	47
KTB08A	1980	42	54	48	48	50	72	56	57	58	53
KTB08A	1990	84	57	59	73	58	76	66	49	58	64
KTB08A	2000	71	79	64	61	60	60	56	65	999	
KTB08B	1805	278	349	319	255	248					
KTB08B	1810	234	212	152	250	177	231	172	230	115	166
KTB08B	1820	132	219	124	105	160	110	50	129	141	207

KTB08B	1830	214	87	98	108	180	118	89	97	123	104
KTB08B	1840	92	169	64	37	40	53	44	46	38	46
KTB08B	1850	34	58	83	88	133	101	76	146	150	95
KTB08B	1860	101	91	79	59	56	59	53	40	39	34
KTB08B	1870	104	101	116	121	147	133	79	108	139	99
KTB08B	1880	143	143	122	116	130	100	111	77	112	125
KTB08B	1890	171	111	125	67	117	79	82	90	113	115
KTB08B	1900	148	98	128	166	159	136	150	124	107	114
KTB08B	1910	145	127	110	100	119	110	129	127	141	131
KTB08B	1920	131	88	125	127	129	142	131	90	107	103
KTB08B	1930	82	98	117	111	76	108	81	92	100	83
KTB08B	1940	66	79	85	97	61	77	76	77	75	70
KTB08B	1950	66	70	64	69	77	78	73	74	75	67
KTB08B	1960	78	61	73	56	72	70	69	57	64	71
KTB08B	1970	53	55	66	65	63	46	70	51	63	48
KTB08B	1980	60	63	83	60	44	68	91	92	91	90
KTB08B	1990	87	109	86	96	84	57	64	64	66	80
KTB08B	2000	94	96	90	103	83	81	85	78	999	
KTB09A	1890	228	170	192	50	75	123	68	53	92	61
KTB09A	1900	47	41	28	29	26	32	24	35	28	24
KTB09A	1910	30	34	23	21	29	21	21	27	31	24
KTB09A	1920	21	17	8	9	22	24	27	34	36	41
KTB09A	1930	43	44	48	42	30	41	38	37	44	31
KTB09A	1940	21	28	26	39	26	30	37	29	27	26
KTB09A	1950	25	26	22	25	24	30	23	34	37	50
KTB09A	1960	40	29	35	35	58	71	73	44	43	57
KTB09A	1970	40	41	52	58	62	53	58	39	64	55
KTB09A	1980	63	66	88	81	70	101	106	115	116	73
KTB09A	1990	90	77	113	136	125	110	79	68	86	75

KTB09A	2000	90	69	96	91	86	81	72	90	999	
KTB09B	1844	209	265	284	169	279	254				
KTB09B	1850	298	490	414	408	354	202	115	87	163	154
KTB09B	1860	207	284	498	572	362	353	206	181	183	154
KTB09B	1870	147	198	296	292	283	337	240	248	319	255
KTB09B	1880	312	232	231	226	176	144	135	91	135	127
KTB09B	1890	217	182	180	181	148	76	84	179	254	185
KTB09B	1900	203	129	132	154	182	139	161	161	118	100
KTB09B	1910	92	99	108	101	90	85	95	88	88	78
KTB09B	1920	137	60	69	79	87	140	130	100	79	80
KTB09B	1930	60	60	62	55	50	81	61	66	64	45
KTB09B	1940	34	41	38	59	37	46	53	43	47	43
KTB09B	1950	33	44	37	43	37	33	36	37	38	26
KTB09B	1960	22	19	29	22	29	38	31	29	40	48
KTB09B	1970	48	59	73	84	74	39	60	52	58	44
KTB09B	1980	57	64	82	47	29	52	59	44	43	36
KTB09B	1990	35	39	41	53	58	66	53	41	55	38
KTB09B	2000	39	30	46	40	32	41	29	28	999	
KTB10A	1783	388	383	250	144	436	322	228			
KTB10A	1790	266	191	207	232	306	172	416	408	311	198
KTB10A	1800	149	173	222	132	193	116	107	96	97	87
KTB10A	1810	84	120	107	143	117	88	101	91	46	87
KTB10A	1820	65	59	125	119	159	114	41	72	94	175
KTB10A	1830	141	133	157	181	197	126	103	122	215	242
KTB10A	1840	250	239	258	235	187	176	73	86	100	85
KTB10A	1850	107	122	185	141	161	121	102	125	197	128
KTB10A	1860	154	115	171	173	98	133	99	92	68	81
KTB10A	1870	145	219	249	243	306	255	123	122	97	91
KTB10A	1880	79	92	52	53	54	62	45	34	74	75

KTB10A	1890	105	113	99	22	73	48	43	77	95	97
KTB10A	1900	107	70	99	91	72	75	83	86	71	94
KTB10A	1910	95	89	70	71	65	76	96	104	97	97
KTB10A	1920	111	71	118	105	110	110	108	84	73	86
KTB10A	1930	57	76	80	84	48	84	67	54	63	36
KTB10A	1940	37	43	38	78	999					
KTB10B	1763	454	335	199	193	190	154	176			
KTB10B	1770	146	189	234	274	362	395	366	412	427	366
KTB10B	1780	209	351	303	401	263	133	203	229	177	205
KTB10B	1790	240	192	241	258	251	144	240	255	189	116
KTB10B	1800	92	120	124	120	165	161	202	221	251	200
KTB10B	1810	201	255	237	279	207	173	200	185	112	176
KTB10B	1820	92	107	184	178	190	166	37	98	122	195
KTB10B	1830	172	158	164	145	156	129	86	95	138	178
KTB10B	1840	175	169	167	144	95	95	43	93	100	115
KTB10B	1850	116	117	162	136	172	154	112	135	189	133
KTB10B	1860	154	95	188	203	119	105	99	87	68	80
KTB10B	1870	112	137	181	158	146	120	67	75	66	114
KTB10B	1880	132	152	90	92	91	95	107	76	124	102
KTB10B	1890	178	143	118	18	81	46	36	73	72	75
KTB10B	1900	97	60	75	76	63	64	59	62	52	52
KTB10B	1910	64	50	55	55	58	51	71	64	52	66
KTB10B	1920	75	36	57	64	999					
KTB11A	1885	419	864	627	572	533					
KTB11A	1890	589	440	595	499	423	272	202	283	328	336
KTB11A	1900	345	451	480	408	400	489	525	419	210	140
KTB11A	1910	177	128	187	103	139	158	157	142	184	165
KTB11A	1920	174	123	148	205	202	198	184	178	169	202
KTB11A	1930	162	117	107	72	34	64	63	78	81	58

KTB11A	1940	50	50	46	78	40	51	60	70	68	38
KTB11A	1950	55	54	47	72	61	46	60	92	89	54
KTB11A	1960	48	21	54	999						
KTB11B	1888	324	129								
KTB11B	1890	132	326	379	319	423	101	103	172	360	513
KTB11B	1900	410	397	271	271	222	273	237	337	321	259
KTB11B	1910	323	290	296	269	300	254	250	186	119	151
KTB11B	1920	133	62	71	151	112	145	114	106	106	85
KTB11B	1930	65	80	80	115	63	90	82	67	85	73
KTB11B	1940	38	26	37	34	16	19	23	12	10	15
KTB11B	1950	17	9	5	13	10	23	10	15	19	35
KTB11B	1960	34	24	41	40	41	63	72	47	52	41
KTB11B	1970	999									
KTB12A	1945	248	158	173	688	498					
KTB12A	1950	390	251	180	218	197	174	130	121	512	688
KTB12A	1960	717	590	356	236	194	255	322	258	249	302
KTB12A	1970	225	180	162	168	151	43	55	53	91	55
KTB12A	1980	85	40	61	26	16	37	55	46	30	20
KTB12A	1990	30	23	21	13	20	18	18	24	32	999
KTB13A	1927	514	405	368							
KTB13A	1930	297	253	235	194	169	121	96	60	58	24
KTB13A	1940	22	37	51	107	75	76	84	80	107	52
KTB13A	1950	66	67	66	77	91	78	83	89	170	192
KTB13A	1960	227	184	144	94	75	50	22	37	51	91
KTB13A	1970	146	231	181	180	164	123	152	99	90	58
KTB13A	1980	69	38	65	42	57	67	76	85	57	51
KTB13A	1990	56	38	30	31	24	23	25	38	30	65
KTB13A	2000	66	72	59	50	72	999				
KTB13B	1876	207	356	279	259						

KTB13B	1880	169	138	161	123	140	194	97	206	227	248
KTB13B	1890	210	187	45	75	178	124	110	154	170	105
KTB13B	1900	100	53	59	100	95	60	106	80	54	63
KTB13B	1910	80	67	94	77	78	89	66	60	53	58
KTB13B	1920	74	31	59	66	107	100	120	104	105	118
KTB13B	1930	142	148	192	142	89	148	90	125	153	135
KTB13B	1940	101	130	103	160	94	133	119	133	120	66
KTB13B	1950	74	82	63	73	84	71	62	92	138	75
KTB13B	1960	79	41	81	108	86	65	95	83	87	71
KTB13B	1970	49	51	80	73	89	43	56	31	34	28
KTB13B	1980	37	52	59	40	29	65	71	82	66	56
KTB13B	1990	67	48	40	55	52	53	35	36	66	999
KTB14A	1877	529	194	285							
KTB14A	1880	358	217	209	102	132	158	141	130	326	185
KTB14A	1890	240	317	197	229	136	73	34	57	66	49
KTB14A	1900	64	59	91	141	63	44	86	62	49	44
KTB14A	1910	69	45	46	65	64	47	50	52	44	49
KTB14A	1920	88	67	114	147	180	180	184	101	82	147
KTB14A	1930	139	178	237	197	108	213	198	204	144	214
KTB14A	1940	62	64	113	180	77	115	131	82	91	64
KTB14A	1950	104	83	80	74	90	66	55	53	98	44
KTB14A	1960	47	27	78	54	41	29	44	24	34	37
KTB14A	1970	27	33	62	72	76	41	68	45	61	47
KTB14A	1980	58	56	61	39	24	45	49	32	31	32
KTB14A	1990	37	30	46	72	41	39	34	40	70	63
KTB14A	2000	54	33	80	56	35	31	49	49	999	
KTB14B	1926	36	26	37	61						
KTB14B	1930	50	62	115	137	91	133	155	104	92	90
KTB14B	1940	32	42	30	35	16	17	51	47	74	39

KTB14B	1950	53	58	85	78	122	50	36	28	100	45
KTB14B	1960	46	25	42	25	29	34	38	22	33	43
KTB14B	1970	25	36	55	72	92	33	54	30	41	31
KTB14B	1980	60	50	84	41	46	97	74	67	75	61
KTB14B	1990	96	66	59	99	73	999				
KTB15A	1842	248	223	199	196	203	189	239	198		
KTB15A	1850	199	177	182	183	150	115	103	261	278	193
KTB15A	1860	220	238	229	190	138	182	156	184	155	211
KTB15A	1870	222	300	329	288	281	244	164	221	256	189
KTB15A	1880	208	177	232	212	215	160	149	185	163	159
KTB15A	1890	219	142	110	60	175	185	140	191	209	181
KTB15A	1900	167	193	192	208	152	148	147	117	86	91
KTB15A	1910	76	79	74	82	71	71	96	84	75	94
KTB15A	1920	68	70	94	99	106	114	102	105	120	116
KTB15A	1930	111	124	160	115	80	118	96	103	105	114
KTB15A	1940	68	88	87	100	66	63	92	64	78	80
KTB15A	1950	71	78	57	85	64	69	63	54	82	37
KTB15A	1960	41	33	77	41	67	58	57	56	55	45
KTB15A	1970	48	65	66	64	62	38	63	42	63	51
KTB15A	1980	73	41	58	37	25	47	59	62	33	32
KTB15A	1990	43	44	42	45	35	38	48	47	61	34
KTB15A	2000	47	43	83	54	47	55	55	61	999	
KTB15B	1817	445	312	279							
KTB15B	1820	239	258	270	239	263	168	81	107	157	174
KTB15B	1830	178	132	109	126	150	176	153	201	164	233
KTB15B	1840	252	170	196	206	151	166	193	135	142	174
KTB15B	1850	110	102	95	105	109	94	68	120	135	77
KTB15B	1860	111	117	138	109	91	96	73	75	104	138
KTB15B	1870	145	77	194	195	273	226	160	258	221	147

KTB15B	1880	191	139	160	141	116	134	130	99	102	142
KTB15B	1890	183	136	116	75	146	96	78	94	104	85
KTB15B	1900	126	91	114	134	86	99	93	85	59	68
KTB15B	1910	75	78	85	80	72	52	52	49	48	66
KTB15B	1920	55	41	69	66	66	59	51	43	57	61
KTB15B	1930	58	59	72	62	48	67	59	51	38	26
KTB15B	1940	25	37	44	57	50	43	58	51	54	49
KTB15B	1950	51	53	45	62	63	51	52	61	52	25
KTB15B	1960	35	35	40	28	36	42	21	26	34	22
KTB15B	1970	23	35	32	34	39	24	54	34	49	26
KTB15B	1980	39	28	26	16	15	32	35	26	11	13
KTB15B	1990	16	999								
KTB17A	1881	379	264	244	166	117	182	263	458	507	
KTB17A	1890	499	412	331	152	213	228	176	243	262	235
KTB17A	1900	264	223	206	244	196	198	186	121	102	106
KTB17A	1910	128	92	95	86	97	126	109	124	105	91
KTB17A	1920	109	121	121	103	104	104	107	91	92	85
KTB17A	1930	101	123	146	69	47	61	115	90	78	59
KTB17A	1940	52	68	48	91	61	65	66	50	58	54
KTB17A	1950	50	83	60	71	67	63	47	69	86	73
KTB17A	1960	78	47	69	56	58	65	51	63	90	80
KTB17A	1970	71	73	94	105	133	89	106	75	79	70
KTB17A	1980	57	61	83	66	69	83	92	89	73	68
KTB17A	1990	84	66	69	85	67	49	80	70	43	97
KTB17A	2000	82	89	48	84	82	69	46	78	999	
KTB17B	1891	286	240	170	257	324	244	262	256	213	
KTB17B	1900	252	241	232	259	212	196	182	142	116	108
KTB17B	1910	150	144	164	145	154	154	159	111	112	100
KTB17B	1920	123	114	119	150	160	236	198	172	135	116

KTB17B	1930	154	150	146	117	93	108	116	123	132	144
KTB17B	1940	138	147	151	207	139	135	124	96	125	154
KTB17B	1950	118	143	125	134	98	89	86	146	138	98
KTB17B	1960	125	88	101	132	116	73	75	20	24	22
KTB17B	1970	29	47	79	69	95	79	90	69	70	71
KTB17B	1980	55	74	113	78	91	98	141	262	193	167
KTB17B	1990	196	135	149	218	161	190	111	90	108	100
KTB17B	2000	98	72	95	73	78	86	76	86	999	
KTB18A	1840	104	88	178	182	162	120	109	91	95	92
KTB18A	1850	90	97	125	117	141	208	198	233	321	269
KTB18A	1860	278	289	317	387	322	357	273	261	188	128
KTB18A	1870	96	177	192	192	181	225	161	260	292	232
KTB18A	1880	241	155	151	103	30	68	105	55	80	74
KTB18A	1890	143	84	96	38	150	110	69	88	85	79
KTB18A	1900	79	43	65	88	108	74	93	58	30	31
KTB18A	1910	36	34	33	37	31	43	48	38	43	49
KTB18A	1920	76	26	55	48	87	81	88	56	45	40
KTB18A	1930	34	44	47	49	22	41	34	32	31	25
KTB18A	1940	17	22	23	33	15	27	37	27	28	17
KTB18A	1950	20	17	18	33	20	17	21	30	42	26
KTB18A	1960	8	7	10	9	17	15	15	14	24	23
KTB18A	1970	32	46	57	73	43	34	31	36	31	22
KTB18A	1980	25	32	32	28	30	55	35	53	67	45
KTB18A	1990	42	33	46	39	46	49	40	33	999	
KTB18B	1828	196	219								
KTB18B	1830	173	119	136	166	196	120	131	145	140	118
KTB18B	1840	99	85	150	198	169	134	131	152	197	194
KTB18B	1850	177	163	193	214	195	150	192	309	410	364
KTB18B	1860	417	431	378	339	248	306	253	228	163	191

KTB18B	1870	147	251	244	181	160	150	79	140	137	118
KTB18B	1880	129	113	94	149	132	134	118	12	43	27
KTB18B	1890	82	25	31	12	41	10	9	28	23	26
KTB18B	1900	33	15	31	38	43	27	37	25	14	24
KTB18B	1910	28	23	34	26	15	24	29	25	23	29
KTB18B	1920	49	16	38	32	54	41	40	32	35	43
KTB18B	1930	37	37	40	45	25	49	39	48	47	30
KTB18B	1940	27	29	20	25	15	25	32	25	20	16
KTB18B	1950	18	13	17	18	25	30	29	28	36	33
KTB18B	1960	29	28	29	20	22	31	16	22	25	32
KTB18B	1970	21	27	32	34	40	22	60	29	35	23
KTB18B	1980	31	32	37	25	19	37	37	32	35	24
KTB18B	1990	28	26	32	31	27	33	29	30	28	28
KTB18B	2000	999									
KTB19A	1946	247	268	294	271						
KTB19A	1950	240	308	337	225	263	347	320	247	247	225
KTB19A	1960	183	134	136	104	115	129	206	212	209	251
KTB19A	1970	279	276	271	235	251	97	220	129	262	331
KTB19A	1980	306	319	265	202	183	146	181	208	243	225
KTB19A	1990	238	246	321	297	254	252	292	311	252	245
KTB19A	2000	107	113	999							
KTB20A	1967	178	198	177							
KTB20A	1970	73	63	43	42	14	18	28	37	38	26
KTB20A	1980	31	28	62	29	40	72	57	69	41	34
KTB20A	1990	65	43	75	42	36	40	39	34	84	49
KTB20A	2000	52	37	56	37	36	39	31	57	999	
KTB20B	1867	531	518	353							
KTB20B	1870	466	497	482	569	487	378	473	477	327	538
KTB20B	1880	371	304	270	300	226	180	151	213	184	214

KTB20B	1890	198	184	42	37	153	110	79	115	203	166
KTB20B	1900	154	80	138	153	119	80	100	127	74	69
KTB20B	1910	104	68	67	57	70	50	44	62	47	54
KTB20B	1920	54	19	48	999						
KTB21A	1890	652	550	590	469	487	357	335	297	273	229
KTB21A	1900	290	320	401	364	315	250	329	281	153	241
KTB21A	1910	387	231	217	176	184	207	193	153	164	137
KTB21A	1920	105	90	164	103	97	84	108	63	73	90
KTB21A	1930	106	88	88	110	54	52	36	50	72	38
KTB21A	1940	52	28	36	59	50	35	59	30	34	39
KTB21A	1950	34	32	35	27	39	27	14	10	17	21
KTB21A	1960	44	12	14	13	16	999				
KTB21B	1839	327									
KTB21B	1840	401	280	186	172	151	86	90	61	64	96
KTB21B	1850	144	153	282	314	341	177	158	136	157	91
KTB21B	1860	113	115	94	54	66	113	207	360	398	251
KTB21B	1870	531	529	569	465	447	483	179	231	374	362
KTB21B	1880	361	272	277	215	181	143	178	64	108	89
KTB21B	1890	130	96	106	31	59	32	21	46	30	14
KTB21B	1900	15	19	29	41	44	39	63	51	43	42
KTB21B	1910	66	44	58	47	35	50	34	31	19	23
KTB21B	1920	23	32	11	34	29	19	9	24	33	30
KTB21B	1930	47	59	44	999						
KTB22A	1844	78	71	53	57	82	96				
KTB22A	1850	118	122	211	327	307	224	175	108	93	65
KTB22A	1860	73	59	68	115	118	110	109	49	35	89
KTB22A	1870	192	217	286	391	446	332	160	252	426	569
KTB22A	1880	527	433	276	304	361	304	230	234	999	
KTB22B	1902	23	21	21	17	30	17	11	9		

KTB22B	1910	20	6	7	17	8	10	10	33	9	28
KTB22B	1920	59	28	30	16	25	32	26	29	21	22
KTB22B	1930	28	72	94	55	43	39	125	72	76	63
KTB22B	1940	71	64	63	56	9	53	70	100	122	84
KTB22B	1950	111	141	249	225	289	244	308	95	69	138
KTB22B	1960	149	166	205	75	97	77	107	109	204	163
KTB22B	1970	94	74	87	70	107	85	98	71	95	64
KTB22B	1980	70	96	999							
KTB23A	1927	546	386	369							
KTB23A	1930	292	258	251	203	188	142	105	64	54	28
KTB23A	1940	23	36	50	105	81	71	87	82	106	54
KTB23A	1950	66	67	66	80	102	81	83	91	169	185
KTB23A	1960	223	191	140	95	68	45	20	35	50	89
KTB23A	1970	141	239	183	181	161	127	156	105	83	50
KTB23A	1980	57	38	61	42	55	61	79	84	56	57
KTB23A	1990	58	35	32	30	28	22	25	12	17	15
KTB23A	2000	25	62	64	82	60	47	74	43	999	
KTB23B	1886	173	162	222	257						
KTB23B	1890	364	346	224	77	99	100	99	166	155	113
KTB23B	1900	98	122	121	190	284	256	234	182	90	71
KTB23B	1910	105	79	86	74	62	42	61	49	39	29
KTB23B	1920	33	18	51	49	62	110	85	102	103	117
KTB23B	1930	99	106	122	84	52	57	52	38	36	18
KTB23B	1940	17	37	48	79	53	61	72	36	34	20
KTB23B	1950	43	45	50	83	57	38	49	39	68	35
KTB23B	1960	51	30	36	30	31	28	25	38	35	40
KTB23B	1970	41	41	36	52	53	36	34	30	31	30
KTB23B	1980	39	28	33	45	54	65	42	81	80	61
KTB23B	1990	119	103	82	118	101	109	96	147	165	112

KTB23B	2000	101	76	133	99	112	128	999			
KTB24A	1854	185	116	72	85	87	169				
KTB24A	1860	136	148	326	227	102	211	228	338	233	424
KTB24A	1870	316	881	393	421	362	361	260	310	382	296
KTB24A	1880	343	179	191	183	139	157	203	143	211	198
KTB24A	1890	218	181	143	67	116	98	49	107	98	65
KTB24A	1900	64	49	43	54	57	61	77	77	56	81
KTB24A	1910	55	50	61	47	43	43	51	68	60	51
KTB24A	1920	54	27	63	36	38	28	38	32	50	33
KTB24A	1930	33	60	79	59	46	73	58	58	50	52
KTB24A	1940	30	37	34	29	15	15	19	12	10	22
KTB24A	1950	999									
KTB24B	1868	762	964								
KTB24B	1870	653	661	440	475	615	519	277	426	499	368
KTB24B	1880	461	302	361	398	359	299	274	176	243	209
KTB24B	1890	235	189	139	61	98	67	46	77	79	52
KTB24B	1900	62	49	52	90	112	142	148	120	71	94
KTB24B	1910	68	53	59	54	40	30	28	17	35	33
KTB24B	1920	49	40	67	46	50	45	54	43	36	30
KTB24B	1930	39	51	67	69	47	63	48	44	47	35
KTB24B	1940	21	25	30	41	28	26	36	19	27	34
KTB24B	1950	44	35	35	33	26	30	36	8	18	10
KTB24B	1960	9	12	30	34	22	29	37	43	33	41
KTB24B	1970	999									
KTB25A	1869	262									
KTB25A	1870	270	266	396	393	402	285	364	230	254	267
KTB25A	1880	406	285	306	366	263	203	189	142	149	118
KTB25A	1890	222	141	155	105	150	109	89	165	214	205
KTB25A	1900	212	194	215	216	242	212	213	187	155	107

KTB25A	1910	159	136	153	111	140	128	114	123	106	96
KTB25A	1920	87	52	72	71	100	77	81	56	49	75
KTB25A	1930	38	52	79	83	66	82	88	84	95	69
KTB25A	1940	51	51	52	84	70	75	89	71	85	59
KTB25A	1950	69	58	51	61	49	61	66	49	59	75
KTB25A	1960	78	34	79	56	67	68	73	65	72	75
KTB25A	1970	61	85	85	108	107	16	96	77	113	89
KTB25A	1980	93	88	84	46	42	78	65	55	52	62
KTB25A	1990	71	60	59	72	71	72	56	57	72	60
KTB25A	2000	70	61	69	74	999					
KTB25B	1864	266	335	176	385	194	144				
KTB25B	1870	291	339	434	435	349	274	160	202	195	189
KTB25B	1880	239	231	237	248	222	150	168	145	151	175
KTB25B	1890	244	162	152	98	137	120	97	120	129	102
KTB25B	1900	112	92	109	110	87	81	80	75	48	52
KTB25B	1910	45	50	42	46	36	35	22	25	25	22
KTB25B	1920	17	11	19	14	15	6	10	8	9	8
KTB25B	1930	11	10	15	10	6	12	8	9	7	6
KTB25B	1940	6	9	13	18	18	16	22	14	12	8
KTB25B	1950	14	14	13	15	19	20	16	8	32	26
KTB25B	1960	23	12	43	48	48	40	41	30	25	56
KTB25B	1970	43	74	69	104	93	74	67	40	43	59
KTB25B	1980	80	95	74	80	69	72	121	136	120	89
KTB25B	1990	94	103	115	87	83	83	83	80	69	79
KTB25B	2000	73	70	999							
KTB26A	1846	177	171	248	326						
KTB26A	1850	239	235	238	259	290	200	129	203	270	224
KTB26A	1860	219	241	240	299	211	231	219	227	236	170
KTB26A	1870	164	177	204	195	144	138	75	82	106	76

KTB26A	1880	117	100	128	118	117	117	94	66	92	77
KTB26A	1890	96	75	79	37	78	44	58	66	90	76
KTB26A	1900	105	89	94	114	98	100	91	124	94	102
KTB26A	1910	105	108	108	101	108	94	72	83	107	114
KTB26A	1920	88	75	112	112	117	149	119	89	77	75
KTB26A	1930	89	81	111	112	82	97	67	54	61	56
KTB26A	1940	55	52	48	73	48	45	60	66	59	65
KTB26A	1950	47	48	53	57	45	54	42	25	44	35
KTB26A	1960	63	37	35	14	19	44	34	52	67	48
KTB26A	1970	999									
KTB26B	1847	161	228	227							
KTB26B	1850	198	253	277	279	235	178	130	225	253	225
KTB26B	1860	217	232	249	292	241	254	258	261	220	211
KTB26B	1870	149	128	168	179	180	140	77	99	106	114
KTB26B	1880	162	138	86	68	65	74	80	68	68	60
KTB26B	1890	101	80	91	40	75	52	53	36	62	77
KTB26B	1900	73	51	68	75	78	66	96	93	75	86
KTB26B	1910	118	78	63	68	77	77	69	60	77	77
KTB26B	1920	55	46	57	78	82	127	121	106	83	104
KTB26B	1930	80	57	108	107	66	91	56	50	42	33
KTB26B	1940	45	36	37	55	33	30	33	40	56	65
KTB26B	1950	53	58	47	59	42	53	44	31	40	59
KTB26B	1960	89	52	64	52	62	71	79	84	77	68
KTB26B	1970	48	49	60	50	52	45	70	44	46	48
KTB26B	1980	43	41	54	53	47	60	58	69	74	71
KTB26B	1990	80	66	60	69	59	77	61	49	63	71
KTB26B	2000	79	69	86	77	66	55	56	999		
KTB27A	1883	344	292	286	200	217	247	379			
KTB27A	1890	258	176	141	60	142	52	116	201	208	152

KTB27A	1900	143	140	91	117	112	87	113	104	72	65
KTB27A	1910	71	55	83	122	104	135	139	80	100	77
KTB27A	1920	94	52	109	93	70	111	96	98	61	72
KTB27A	1930	61	50	58	50	42	63	56	46	55	47
KTB27A	1940	39	49	54	96	76	60	60	52	50	47
KTB27A	1950	45	32	29	68	52	47	57	56	63	42
KTB27A	1960	44	29	53	41	59	56	44	40	44	37
KTB27A	1970	36	43	52	86	78	49	63	56	56	46
KTB27A	1980	36	33	32	20	43	55	50	59	64	58
KTB27A	1990	110	96	133	170	154	140	101	79	112	131
KTB27A	2000	106	86	108	93	85	101	65	999		
KTB27B	1867	118	186	135							
KTB27B	1870	153	116	88	98	116	48	28	123	132	72
KTB27B	1880	95	126	117	126	161	170	204	168	229	238
KTB27B	1890	246	183	160	49	110	35	55	96	115	118
KTB27B	1900	122	129	88	79	101	105	148	157	142	139
KTB27B	1910	159	156	180	202	215	168	158	127	131	93
KTB27B	1920	167	62	83	152	122	93	93	80	65	77
KTB27B	1930	70	82	57	81	63	58	87	90	90	63
KTB27B	1940	65	35	30	56	84	74	59	84	57	81
KTB27B	1950	81	75	62	45	65	55	36	60	86	77
KTB27B	1960	47	29	16	31	28	36	999			
KTB28A	1901	513	343	345	420	397	376	252	148	114	
KTB28A	1910	152	139	198	134	169	141	128	99	93	176
KTB28A	1920	181	163	174	260	204	247	192	231	200	204
KTB28A	1930	183	172	198	239	175	178	176	195	133	71
KTB28A	1940	70	82	78	144	64	85	64	42	45	31
KTB28A	1950	41	54	46	68	51	71	57	51	59	45
KTB28A	1960	58	45	65	46	59	56	45	34	39	69

KTB28A	1970	31	22	24	22	30	35	32	26	20	31
KTB28A	1980	26	27	65	37	23	25	44	108	87	96
KTB28A	1990	91	83	40	89	999					
KTB28B	1882	941	657	673	615	445	454	311	259		
KTB28B	1890	348	492	554	413	482	377	248	158	161	168
KTB28B	1900	141	133	156	283	399	394	357	354	289	335
KTB28B	1910	240	209	166	176	258	234	250	207	150	138
KTB28B	1920	125	32	82	109	42	36	61	76	62	105
KTB28B	1930	58	38	33	19	26	12	18	29	19	36
KTB28B	1940	29	30	24	41	36	23	39	15	11	15
KTB28B	1950	999									
KTB29A	1871	619	585	361	198	182	126	219	182	205	
KTB29A	1880	241	232	192	217	151	162	227	103	239	161
KTB29A	1890	208	139	159	57	165	74	67	81	67	87
KTB29A	1900	116	85	93	119	79	85	143	95	64	45
KTB29A	1910	58	47	45	35	17	22	28	23	23	31
KTB29A	1920	39	12	58	37	34	46	34	50	27	23
KTB29A	1930	15	34	23	21	16	25	26	21	33	24
KTB29A	1940	35	21	17	999						
KTB29B	1869	229									
KTB29B	1870	115	281	204	191	205	212	162	72	350	218
KTB29B	1880	222	165	179	225	212	217	298	198	260	197
KTB29B	1890	301	197	234	119	233	169	191	252	268	247
KTB29B	1900	273	234	262	292	327	280	241	218	144	145
KTB29B	1910	151	104	118	98	73	83	82	103	76	98
KTB29B	1920	103	55	105	133	120	138	138	88	80	77
KTB29B	1930	97	86	94	68	66	103	78	106	63	60
KTB29B	1940	32	54	39	99	63	74	92	83	90	100
KTB29B	1950	111	74	53	81	76	67	75	73	89	70

KTB29B	1960	57	25	50	28	45	41	32	30	41	27
KTB29B	1970	31	43	53	42	54	21	44	46	47	24
KTB29B	1980	43	51	40	31	30	44	44	46	45	49
KTB29B	1990	54	46	54	57	45	59	48	53	68	68
KTB29B	2000	86	85	101	101	78	98	80	104	999	
KTB30A	1867	361	352	386							
KTB30A	1870	305	397	280	396	411	387	239	294	423	321
KTB30A	1880	330	242	189	227	162	110	149	89	88	34
KTB30A	1890	25	24	36	27	41	54	44	53	62	81
KTB30A	1900	99	106	106	121	101	96	89	70	64	54
KTB30A	1910	47	40	57	65	77	107	113	111	118	106
KTB30A	1920	100	59	71	70	94	117	121	131	151	168
KTB30A	1930	140	130	163	159	87	122	116	106	102	108
KTB30A	1940	85	96	100	116	97	100	999			
KTB30B	1867	275	299	423							
KTB30B	1870	313	498	694	711	449	252	142	171	246	268
KTB30B	1880	313	249	202	245	168	138	172	90	61	57
KTB30B	1890	67	57	57	39	52	43	33	41	60	57
KTB30B	1900	60	76	72	93	97	104	95	101	103	99
KTB30B	1910	98	94	92	80	78	82	93	102	104	98
KTB30B	1920	79	45	58	72	75	89	84	75	81	80
KTB30B	1930	87	89	96	89	59	84	61	79	82	84
KTB30B	1940	76	80	64	77	67	72	84	83	83	67
KTB30B	1950	63	84	56	42	39	38	43	52	82	84
KTB30B	1960	60	40	62	67	42	53	55	62	76	101
KTB30B	1970	107	67	103	53	94	86	89	74	62	36
KTB30B	1980	52	55	66	37	56	68	51	70	34	41
KTB30B	1990	31	24	29	33	41	60	45	68	77	65
KTB30B	2000	59	51	62	61	45	50	45	49	999	

KTB31A	1893	192	293	247	137	234	266	208			
KTB31A	1900	189	246	236	268	245	180	176	144	100	75
KTB31A	1910	72	48	54	48	21	10	16	29	35	63
KTB31A	1920	66	42	81	88	112	88	51	25	56	50
KTB31A	1930	47	58	59	54	33	44	25	27	36	21
KTB31A	1940	34	56	31	29	22	26	29	26	21	19
KTB31A	1950	19	25	16	28	34	29	25	25	27	13
KTB31A	1960	7	9	15	6	18	21	17	12	19	23
KTB31A	1970	17	27	25	16	19	15	26	17	17	5
KTB31A	1980	21	14	10	5	6	34	11	35	38	18
KTB31A	1990	999									
KTB32A	1860	425	239	234	134	38	96	39	110	107	131
KTB32A	1870	244	410	327	190	240	76	34	181	228	141
KTB32A	1880	116	92	118	196	163	168	158	73	141	129
KTB32A	1890	235	137	147	44	179	93	46	71	66	77
KTB32A	1900	91	58	44	82	107	84	89	94	52	45
KTB32A	1910	95	53	61	43	36	23	47	37	11	45
KTB32A	1920	60	27	61	999						