Complexity in crisis: The volcanic cold pulse of the 1690s and the consequences of Scotland's failure to cope

Rosanne D'Arrigo[1], Patrick Klinger[2], Timothy Newfield[3], Milos Rydval[4,5] and Rob Wilson[1,5]

[1]Lamont-Doherty Earth Observatory of Columbia University, Palisades, New York, 10964, USA

[2]Department of History, University of Kansas, Lawrence, Kansas, 66045, USA

[3]Department of History and Biology, Georgetown University, Washington, DC, 20057, USA

[4]Faculty of Forestry and Wood Sciences, Czech University of Life Sciences Prague, Kamýcká 129, Praha 6–Suchdol, Prague, 16521, Czech Republic

[5]School of Earth and Environmental Sciences, University of St. Andrews, St Andrews, FIFE, KY16 9AL, Scotland, UK

Correspondence to: Rosanne D'Arrigo (rdd@ldeo.columbia.edu)

Abstract

Recent work has linked historical crises, both regional and local, with palaeoclimatic estimates of global and hemispheric climate change. Such studies tend to underemphasize the spatiotemporal and socioeconomical disparity of human suffering and adaptive capacity as well as the complexities of past climate change. We focus herein on the effects in Scotland of a severely cold climate episode in the 1690s, associated with major tropical volcanic events including a large unidentified tropical eruption in 1695. A tree-ring based summer temperature reconstruction from the northern Cairngorms region identifies the 1690s as the coldest decade in Scotland for the last 750 years. Archival sources meanwhile reveal the 1690s as likely the worst era of crop failure, food shortage, and mortality ever documented in Scottish history. The connection appears simple - volcanic cooling triggered famine - but the drivers towards famine are far more complex. Although the unusual coldness of the 1690s was near-hemispheric in scale, it had a differential impact across north-western Europe. Within Scotland, both lowlands and highlands experienced dire conditions, but distinct factors exacerbated the suffering in each region. We integrate historical and palaeoclimatic records to explore the influence of the volcanic cold pulse of the 1690s and its consequences in Scotland. We find that while cooling temperatures characterized the regional to larger-scale climate, vulnerability and response potential were diverse and shaped by local circumstances. The Scottish crisis of the 1690s, in the context of the kingdom's failing economy, influenced investors from all parts of society, including the nobility and entire communities, to fund the ill-fated expedition to colonize Darien in modern-day Panama. The climate crisis and the colony's collapse hindered Scotland's already sluggish economy, motivating unification with England soon after. (279 Words)

1 Introduction

The decade of the 1690s is known to have been unusually cold with associated widespread crop failures, food shortages and mortality crises in many areas of Europe (Ladurie 1971, Appleby 1979, 1980, Bellettini 1987, Pfister 1988, Glaser 1993, Lamb 1995, Kington 1999, Slavin 2016, Huhtamaa and Helama 2016, Huhtamaa and Helama 2017, Alfani, Mocarelli and Stangio 2018, Camenisch and Rohr 2018, DeGroot 2018). Scotland was no exception (Tyson 1986, Dawson 2009, Cullen 2010; Klinger 2019), though some parts of northern Europe were less affected (Wrigley and Schofield 1981, Walter and Schofield 1989, Clarkson and Crawford 2001, Hoyle 2013, Dijkman 2017, Curtis and Dijkman 2017). The cooling, unusual enough that some have considered it to represent one of the peaks of the so-called Little Ice Age (LIA) in Europe (Grove 1988, Matthews and Briffa 2005), was likely predominantly forced by a cluster of volcanic events, including one of the more significant, although not the largest, eruptions of the late Holocene - the unidentified tropical event of 1695±2.5 (Sigl et al 2015, Toohey and Sigl 2017). Recent dendroclimatological studies have now affirmed that the extreme summer cooling of the late seventeenth century was near-hemispheric or hemispheric in scale (Wilson, et al. 2016). Some have gone so far as to associate the cooling of the 1690s with the tail end of the "Global Crisis", a period of political turmoil characterized by persistent war and unrest in many regions of the world with which it broadly overlapped (e.g. Parker 2013).

Exceptionally cold conditions in Scotland in the 1690s have been inferred from historical and instrumental observations, as well as paleoclimate proxies from continental Europe (e.g. Lamb 1995, Dawson 2009, Cullen 2010). Until recently, however, no purely temperature-sensitive high-resolution record existed for Scotland that could more directly corroborate the historical data and provide a long-term, quantitative perspective for the unusually cold conditions experienced in Scotland during the 1690s. Here we use a recently published tree-ring based summer temperature reconstruction for Scotland (1200-2010 CE, Rydval et al. 2017) to scrutinize, in more detail, the 1690s with respect to the temperatures of the last 800 years (**Figure 1A**). This reconstruction, termed NCAIRN, is derived from living trees and lake-preserved subfossil wood material from Scotland's northern Cairngorms region.

Recent work has linked palaeoclimatic estimates of global and hemispheric climate change with major crises in the prehistoric, Roman, medieval, and early modern eras (Gill 2000, Parker 2013, Brooke 2014, Cline 2015, Campbell 2016, Harper 2017 Weiss 2017). As engaging as they are, such large-scale analyses can understate the complexity of the causal relationships between climate and society (Haldon et al 2018, Sessa 2019). Indeed, broad-stroke histories of this sort often fail to capture the intricacies of past climate change and the marked disparity, on multiple scales, in societal vulnerability and adaptive capacity to environmental change. Here we attempt to circumvent the reductionism inherent in such interpretations. We integrate historical and palaeoclimatic records to explore the cold pulse of the 1690s and assess its consequences and reactions in Scotland. We confirm that the Scots experienced extreme cold conditions throughout the 1690s, with possibly only minimal evidence of hydroclimatic related impacts (see below). The Scots suffered more than most, with 10-15% of their population lost (ca. 100,000 people) (Flinn 1977, Tyson 1986, Cullen 2010, Dodgshon 2004, 2005), certainly more than their immediate neighbours within the British Isles, while northern

France only lost 5% (Appleby 1979, Lachiver 1991, Béaur and Chevet 2018). Within Scotland itself, both the lowlands and highlands experienced dire conditions, but with distinctive factors contributing to the suffering in each region, as we describe.

Our focused perspective emphasizes the value of more micro or regional scale analyses in understanding histories of past climate crises. This case also illuminates how the climate induced suffering of the mid-1690s, exacerbated by an already fragile economy, influenced the ill-fated Darien expedition, its subsequent failure, and the eventual Union of Scotland with England. Further, it demonstrates that not all early modern European famines were contingent on high population density, as recently claimed (Alfani and Ó Gráda 2018). The suffering experienced in both the Scottish Highlands (less populated and agriculturally marginal) and lowlands (more populated and productive) in the 1690s indicates clearly that environmental extremes and multifarious societal factors, but not population pressure, precipitated the Scottish crisis. Population pressure certainly worsened the situation in urban contexts but did not itself cause the crisis.

2 The cold pulse of the 1690s

2.1 Summer temperatures in Scotland in the 1690s in the context of the last 800 years

The climate crisis of the 1690s is almost universally understood as a period of pronounced cooling. Previously, high resolution temperature reconstructions for Northern Britain had relied on a multi-proxy approach to combine long instrumental records, historical documentary indices, tree rings and ice cores to provide spatially detailed seasonal information over much of Europe (e.g. Luterbacher et al. 2004). However, no relevant proxy data for the 1690s had originated from Scotland directly. Now however, there is a high-resolution, purely temperature-sensitive record for Scotland - the NCAIRN reconstruction (**Figure 1A**). This reconstruction is based on ring-width and latewood Blue Intensity tree-ring density data (see Rydval et al. (2017) for details) and explains 57% of the instrumental summer temperature variance for Scotland (**Figure 1B**). In order to provide a long-term perspective for the 1690s cold episode, we evaluated the NCAIRN reconstruction over its 800-year length from 1200-2010 CE (**Figure 1A** and **Table 1**). Sample replication is lower before ~1550, with associated greater uncertainty (Rydval et al. 2017), underscoring the need for additional future sampling of subfossil wood material. The maximum (1284, 1.9ºC) and minimum (1232, -2.80ºC) annual values are in this less confident period (**Table 1**) while 1698, in the more confident post-1550 period, is the 3rd coldest reconstructed value (-2.57ºC). The coldest decade in NCAIRN is 1224-1233 (-1.64ºC), followed by 1695-1704 (-1.56ºC), and then 1632-1641 (-1.47 ºC), the latter two following a protracted period of declining temperatures from the 1500s into the seventeenth century. 1612-1711 is the coldest century (-1.01ºC) and was followed by an overall return to milder summers after another cold interval in the late 1700s to early 1800s. The warmest century of the whole record is 1911-2010 (0.05ºC). The summers of the 1690s, therefore, were some of the coldest of the last ~800 years in Scotland and, significantly, they occurred at the end of a prolonged period of cooling.

The extreme nature of the 1690s can be further highlighted when compared to the seasonal, multiproxy temperature reconstructions from Luterbacher et al. (2004) for the

Scotland region (**Figure 2**). Importantly, the Luterbacher et al. (2004) dataset includes the long Central England Temperature record (CET, Parker et al. 1992 and Manley 1974), an important instrumental data source that provides UK-specific climate information through this period. The coolest decade over the 1600-1750 period is consistently around the 1690s for all four of these seasonal records from Luterbacher et al. (2004). The extreme cooling of the 1690s was therefore *not* restricted to only an expression of summer temperatures. When the accumulated temperature influence of all five records (including NCAIRN) is assessed by examining the number of records with cool years exceeding 1 standard deviation below the mean, 1698 is expressed as the combined, coldest year in Scotland (**Figure 2**).

2.2 The 1690s cooling in a hemispheric context

Other palaeoclimatic, historical, and instrumental records for the British Isles, Europe, and elsewhere at northern latitudes corroborate the evidence found in the NCAIRN record for the exceptional coldness of the 1690s in Scotland. The spatial extent of summer cooling of the 1690s was neither limited to Scotland nor northern Europe but was virtually hemispheric in scale – at least at the mid-to-high latitudes (Esper et al. 2018).

Documentary data for mainland Europe also describe unusually low temperatures, crop failures and famine at this time, indicating that causes for these events were not merely local but interregional in extent (Lamb 1995). For example, severe food shortages were documented in Estonia, Sweden and Finland (the Great Famine, 1695-1697, Lappalainen 2012, Lappalainen 2014, Huhtamaa and Helama 2017) and throughout large stretches of western Europe (Ladurie 1971, Appleby 1979, 1980, Bellettini 1987, Pfister 1988, Glaser 1993, Lamb 1995, Kington 1999, Slavin 2016, Huhtamaa and Helama 2017, Camenisch and Rohr 2018, DeGroot 2018), but with notable exceptions for England and parts of Ireland and the Netherlands (Wrigley and Schofield 1981, Walter and Schofield 1989, Clarkson and Crawford 2001, Hoyle 2013, Dijkman 2017, Curtis and Dijkman 2017). Concurrently, more sea ice was reported in Iceland in the 1690s than in any other decade of the seventeenth century and only one "good" winter (1698) was observed there between 1694 and 1700 (Ogilvie 1992). The extent and duration of sea ice recorded off Iceland was far above average in 1694-1695 in particular (Ogilvie 1996, Devine and Wormald 2012). Ice also hindered Dutch shipping well into the summer of 1695 (Degroot 2018) and Royal Navy ships' log books for the English Channel and vicinity indicate enhanced frequency of gales between 1685-1700, albeit in the colder months (Wheeler et al. 2010).

To provide a macro-regional, albeit summer growing season biased perspective, we present the longitudinal quadrant tree-ring composite records detailed in Wilson et al. (2016) for western/eastern North America and western/eastern Eurasia (**Figure 3)** which strongly indicate that the cooling of the late seventeenth century was both near-hemispheric in nature and strongly expressed in the European (and North American) proxy records. In each of the records the coldest summer was either 1698, 1699 or 1700, strongly lending support to the argument for a volcanic cause (see next section). Finally, an ensemble plot of CMIP5 climate model runs (Wilson et al. 2016) clearly shows the same period of cooling at the end of the seventeenth century centred on 1696. There is thus broad consistency among the various palaeoclimatic, instrumental and historical records regarding the severity of cooling at the end of the 1600s. Importantly for this study, it is clear that the Scottish cooling is mirrored across much of the Northern Hemisphere and must therefore be forced by large-scale factors.

2.3 Possible causes of the 1690s cooling

The 1690s cold pulse took place during one of the coolest periods of the interval known broadly as the Little Ice Age (~1450-1850 according to Grove 1988; ~1250 according to Luterbacher et al. 2016; see also Matthews and Briffa 2005, Wilson et al. 2016) and overlaps with the latter half of the Maunder minimum, the most pronounced of recent grand solar minima (Luterbacher et al. 2001, Usoskin et al. 2015). However, recent attribution-based studies find little evidence for the sun being a direct causal influence on the cooler conditions through the 17th century (Owens et al. 2017), although such studies are sensitive to the data used.

It is possible that the cold climate conditions of the 17th century in Scotland were amplified by a shift towards a negative phase of the North Atlantic/Arctic Oscillation (NAO/AO, Shindell et al. 2001). Due to its proximity to the North Atlantic, Scotland summer temperatures are highly correlated with, and influenced by, features of the atmosphere-ocean circulation for the general region, including the summer NAO (Linderholm and Folland 2017). Comparison of NCAIRN with the summer NAO index (Folland et al. 2009) for July-August shows correlations of 0.43 and 0.60 (undifferenced and first differenced respectively - 1899-2010, $n = 111$, $p < 0.0001$). However, independent reconstructions of the summer (Linderholm and Folland (2017), winter (e.g. Cook et al. 2019) and annual/decadal (Trouet et al. 2009, Proctor et al. 2000) NAO, for example, do not indicate a significant negative phase in the 1690s, suggesting that this internal forcing mode was likely not a major influence on the extreme climate in Scotland and Scandinavia at this time. Alternatively, however, the monthly NAO reconstruction of Luterbacher et al. (2002) does indicate persistent negative NAO values from September 1694 to December 1695, and the two lowest reconstructed values for the 17th century take place in January and February 1695.

Therefore, with only a minimal NAO influence, we thus consider that the most likely explanation for the severe cold pulse felt in Scotland (**Figure 2**) and across much of the northern hemisphere (**Figure 3)** in the 1690s is volcanically forced cooling (D'Arrigo et al. 2013). As well as the seven-month-long eruption of Mount Hekla, Iceland in 1693 (starting 13 January, VEI 4; Dawson 2009, Rydval et al. 2017), two tropical eruptions, identified in sulphate layers from bipolar ice core composite records, occurred in 1693 and 1695 (Sigl et al. 2015; Toohey and Sigl 2017; Irawan et al. 2009). The apparent lagged expression of cooling observed in the northern hemispheric longitudinal quadrant tree-ring records (**Figure 3)**, could suggest a slight re-dating of these eruptions may be needed.

2.4 Hydroclimate anomalies in the 1690s

Although commonly considered solely as a period of pronounced coldness, precipitation variability also affected crop productivity in the 1690s, at least in some regions of north-western Europe. Precipitation is more spatially heterogeneous than temperature and coherent trends in hydroclimate at a hemispheric or European scale are not discernible for the 1690s (Pauling et al. 2006; Cook et al. 2015). Consideration of the societal implications of precipitation anomalies therefore demands a micro-regional perspective. This presents a substantial difficulty for Scotland, as reconstructions of past hydroclimate for early modern Scotland must be inferred from English and continental long instrumental, tree-ring and historical sources (Pauling et al. 2006; Cook et al. 2015). While archival and tree-ring data demonstrate conclusively that heavy rains, followed by drought conditions, contributed to the famine in northern France of 1693-94 (Appleby 1979, Cook et al. 2015), without a high-resolution purely hydroclimate proxy record for Scotland only tentative conclusions can be made regarding the contribution of precipitation anomalies to Scottish famine.

Within the caveats of substantial uncertainty on the reliance of mainly continental and southern English proxy archives to extrapolate across Northern Britain, the available hydroclimate reconstructions for the Scottish sector are (1) the Old World Drought Atlas (OWDA - Cook et al. 2015) which provides estimates of the summer Palmer Drought Severity Index (PDSI) – a measure of drought severity via assessing water moisture, precipitation and temperature and (2) a multi-proxy (mainly long instrumental data-sets and historical indices) spatial seasonal reconstruction of precipitation from across Europe (Pauling et al. 2006). The OWDA estimates hint at relatively dry summer conditions through the 1690s which are in some agreement with the winter and spring precipitation reconstructions from Pauling et al. (2006) although summer precipitation appears average. Only autumn precipitation appears to express wet conditions at the end of the 17th century. When the combined extreme values (< or > 1 standard deviation from the 1600-1750 mean) are examined across all 5 records, the 1690s do not stand out in any significant way (**Figure 4**). We again emphasise that no proxy data from Scotland were included in the Pauling et al. (2006) and Cook et al. (2015) studies, so any hydroclimate impacts during the 1690s can only be assessed from archival sources. As discussed below, archival evidence for precipitation extremes is spotty and does not always resonate in the aforementioned proxies. Recorded anomalies, like the summer drought conditions reported in 1695 and 1696, may have been too brief or local to register in more regional-scale indices (**Figure 4**).

3. Climate and society: Scotland and Northern Europe in the 1690s

3.1 The Scottish "Ills": Extreme weather, crop failures and famine in Scotland

As the seventeenth century drew to a close, Scotland experienced, among various socioeconomic and political challenges, the "Ills", at least five years (1695-1699/1700) of kingdom-wide dearth-like conditions and famine stemming from late harvests and crop failures suffered across much of the country (Tyson 1986, Dawson 2009, Cullen 2010, Klinger 2019). The exceptional cold pulse of the 1690s disrupted and likely shortened the growing season, adversely impacting plant health and growth in both spring and summer. Precipitation variability is less well known through this period (**Figure 4**) but likely aggravated the situation. As discussed below, the consequences were grave. Although losses certainly did not approach those of the Black Death as previously claimed (Lamb 1995; cf. Benedictow 2004), conditions were so severe that Scotland lost ca. 10-15% of its population in the mid-1690s, with a few regions losing perhaps 25% (Flinn 1977, Tyson 1986, Cullen 2010, Dodgshon 2004, 2005). Similarly, northern France lost about 5% of its population in 1693-94 through famine and associated epidemic disease

(Appleby 1979, Lachiver 1991, Béaur and Chevet 2018), and in Finland an estimated 25-to-33% of the population died through famine in 1696 (Huhtamaa and Helama 2016, Huhtamaa and Helama 2017).

Our understanding of the crop failures, food shortages and mortality crises, and the responses to those events in Scotland in the 1690s is far from perfect. NCAIRN reflects regional summer temperatures for both the highlands and the lowlands (**Figure 1**), but archival documents provide much more information for the lowlands. It is clear nevertheless that the suffering, which was unprecedented in recent memory, affected both regions.

Archival records document the crisis in some detail. They corroborate the summer coldness discernible in the NCAIRN series, suggest some precipitation extremes, and illuminate the severity of the suffering. From the lowlands we have many perspectives. For instance, in 1696 Daniel Hamilton, chamberlain of the Duke of Hamilton's lands, writing from Kinneil, Edinburgh, and Bo'ness, claimed that "there was never such difficulty of getting money since I began the world nor greater hardships for the people to live in it this 300 years, there being a general famine through the whole countrie for want of victual." This was caused by "could [cold] weather a gray frosts of which we had plentie the first three weeks of july almost every night" (D. Hamilton 1696). "Very rainie" weather was observed by Susan Hamilton, countess of Dundonald, in 1696. During the harvest in autumn, the "wind [was] always in the east [and] somewhat cold" and there was "deep snow" (Dundonald 1696 and Scrymgeour 1696). According to David Crawford, the secretary to the Duchess of Hamilton, the exceptional weather of 1696 carried through to the fall and into winter. He observed "an extraordinary great storm of frost and snow" occurring in December 1696, which damaged crops still not harvested near Berwick (Crawford 1696).

But dire conditions had set in earlier. David Scrymgeour, of Cartmore [Gartmore], near Stirling, described the winter of 1695/96 as severe with cold temperatures and snow until April, which delayed sowing. May too was cold, but July and August were strikingly hot and dry, enough so as to damage grasses and crops (Scrymgeour 1696). Meanwhile Hugh Montgomerie, a Glasgow merchant, argued that Scotland's "extreme dearth" began in September 1695 since the "two hardest months of September and October [1695] proved so bad and unseasonable, and the cropt [sic] so defective over the whole kingdom that the nation was generally alarmed with apprehensions of a scarcity and famine." As bad as the harvest of 1695 was, to Montgomerie the harvest of 1696 appeared "much worse," especially for the poor (Montgomerie 1698). At the start of 1695, Daniel Hamilton reported from Kinneil, that the farmers had endured "a fortnight of most bitter cold weather of frost and snow" making it impossible to venture outside and preventing planting (Crawford 1695). Later that year, cattle had to be relocated for want of pasture, as there was "such a drought that it hath destroyed both grass and cowes whereby in all probability many of them will not shear this season, as for our hay we have not a load where we used to have." To make matters worse, the cut hay had started to rot because "the rain is lyke to be as excessive as the heat was (D. Hamilton 1695 (B))." In total, Hamilton estimated that they would be lucky to produce half as much hay as they had the previous year (D. Hamilton 1695 (A)).

Difficult conditions carried on into 1697, as archival records and climate proxies illustrate (**Figure 2**). Mary Campbell (Caithness), Countess of Breadalbane, who controlled both lowland and highland farms, described 1697 as having “cold misty weather such as the oldest people alive hath not seen” (Breadalbane, 1697). George Fraser, chamberlain for the earl of Mar, writing from Kildrummy near Aberdeen, meanwhile observed that the harvesting of crops throughout Scotland had been delayed in 1697 because of the intensity and frequency of storms and that “ther was never such a year seen in this countrey be any that is alive” (Fraser, 1697). A 1697 petition signed by at least 25 farmers (mainly of the Scott family) in Teviotdalehead (Roxsburghshire), protested that the state of the country had reduced them to want. They blamed the unusual summer weather for this, commenting on “the general calamity of the countrie by the blasting and frosting of the corn [grain].” The stalk retained “nothing but the shap of Bear [grain] without any kirnell att all and what had any kirnell through frost is altogether unfitt for food...” Unsurprisingly, these tenants were unable to pay their rent. They were “starving” because they used their limited grain to plant the next years’ crop rather than eating it or using it to pay rentals (National Records of Scotland 1688-1702).

Yet, the Ills were their worst in 1698, as the written sources, NCAIRN and other records (**Figure 2)** demonstrate. Like 1696 and 1697, growing conditions were poor in 1698. David Crawford claimed that “the whole country is in a bad condition… all things here are very backward, I never saw worse weather in January for frost and snow which looks like a plague for in Alendale and Leomahag they have no fother [fodder] for the beasts that labours the ground has no seed to sow what is labored. They have had a very bad years and this looks worss then any the Lord pitie it (Crawford 1698 (a)).” The planting season saw “unseasonable… storms and cold” unlike anything they had “had here since the memory of man (Caithness 1698).” Conditions failed to improve in the spring. Daniel Hamilton observed that "we hitherto have had the worst season that any living ever saw being extremely cold and dry." On June 4 snow fell and several of the hills near Hamilton had retained snow on them through June. Unsurprisingly, Daniel Hamilton wrote "our crop is generally bad and late and in both these respects worse than ever in our age." Much of the ground was barren, which also included fruits and smaller garden vegetables, and "we cannot tell whether to complain of scarcity or dearth." Even at that point, he remarked that they "are still expecting worse (D. Hamilton 1698)." The harvest again failed. 1698 is the coldest reconstructed summer in the NCAIRN reconstruction between 1600 and 1750 (**Figure 2**). In October, the country was "knee deep of snow and hard frost, and the corn's not halfe cutt down (Crawford 1698 (C))." James Hamilton commented on this early snowfall claiming that "the frost [and snow] is this day alse great as if it were December or January." The harvest was consequently "very late" and "generally a very scarce crop (J. Hamilton 1698)."

As in previous years, contemporaries could not remember more dire conditions for crops or the country. David Crawford wrote that "such bad weather and a bad cropt as is just now here as was never seie. We have constant rains and high cold winds, which with the thrie last bad years will quit[e] ruin this country (Crawford, 1698 (B))." Basil Hamilton expressed disbelief over the condition of the country in two of his accounts at the end of 1698. This was "the coldest weather," he detailed, with frosts damaging much of the unharvested grain (B. Hamilton 1698). The record of unusual cold across the lowlands carries on into 1699 and 1700, and even further at a regional level, but nationally, the worst was over by the start of 1700.

3.2 Causes and Consequences in Scotland

While some circumstances which limited adaptive capacity and facilitated the gestation of severe food shortages in the 1690s were kingdom-wide -- such as a general agricultural ‘backwardness’ and a limited crop base, the Corn Act, which encouraged the exportation of grains leaving little in reserve for insufficient harvests, and overburdened poor laws -- there were a few distinctive factors which contributed to the suffering in the lowlands and highlands. Notably, the more congested and urbanized lowlands may have experienced more morbidity and mortality, but this was not a crisis confined to urban environments or contingent on high population density. There is little evidence for population growth in the decades leading up to the crisis of the 1690s (Flinn 1977 and Cullen 2010). The combined archival and palaeoclimate records suggest that temperature extremes and multifarious societal factors led to the Scottish crisis and not population pressure, contrary to recent claims based on large-scale analysis (Alfani and Ó Gráda 2018). As noted here, sparsely populated Finland likewise suffered gravely in the 1690s.

While climatic extremes created many problems for the Scots in the 1690s, the structure of Scottish society and agriculture, actions taken by the Scottish government and recent political events allowed for the situation to unfold as it did. In the seventeenth century, Scottish agriculture was comparatively underdeveloped, and along with animal husbandry, practises were generally inferior to those of the English and Irish. For example, the Scots did not lime their soils, which were generally more acidic, on a large scale until the eighteenth century (Smout and Felton 1965, Sibbald, 1698). They also worked (for subsistence and for profit) more marginal lands than their neighbours and unlike the English they did not widely break up their agricultural production or grow subsistence crops in multiple seasons (Appleby 1979, Houston and Whyte 2005, Devine and Wormald 2012). Sir Robert Sibbald, the natural philosopher who commented extensively on seventeenth-century Scottish living conditions and history, lamented about the inferiority of Scottish agriculture and animal husbandry. He posited that this backwardness stemmed from naturally poor soils, the failure to lime them, and the Scots' inability to develop larger cattle stock (Sibbald, 1698). Poor and un-limed soils heightened their vulnerability to crisis, but no matter their size, livestock would have suffered in the 1690s. There is no extant data for livestock mortalities for this period, but cold conditions in the 1670s/80s, almost as extreme as the 1690s (**Figure 2**), caused substantial animal die-offs (Law 1695, Flinn 1977) and archival evidence for cattle exports in the 1690s suggests Scots were unable to fodder and pasture their animals (Smout 1963, Koufopoulos 2005). Not only were the Scots more prone to suffer during periods of climatic stress, but in the midst of the Ill Years the Scottish Parliament passed the 1695 "Act incouraging the exportatione of victual," more commonly referred to as the "Corn Act." The timing was exceptionally poor. The law incentivized growing for export and grain exported from Scotland in 1695 was recalled because of the failed harvest that year, but at two or three times the original price (Paterson and Bannister 1859).

There was also charity and public welfare, of course, which was essential to temper premodern famines. In Scotland during the 1690s, the responsibility for the poor fell to the church through parishioner contributions and a system of "poor laws." Yet, compared to the English system, the Scottish system was "weak and mean" and overburdened (Tyson 1986, Smout 1987, Cullen 2010). In 1699, David Crawford, the secretary to the Duchess of Hamilton, a leading political family, claimed that mortality and living conditions were much worse in many of the parishes in Scotland that had not "taken a regular course for providing their poor" (Crawford 1699). A year earlier, the politician Andrew Fletcher of Saltoun remarked on the scale of the famine and how it added an additional 100,000 poor, contributing to the failure of the poor law system (Fletcher 1698). Part of the problem was the transition from an Episcopal to a Presbyterian Church government, and the removal of the ministers that administered Scottish poor relief, only a few years prior to the onset of famine and dearth-like conditions. Ultimately, this denuded the quantity, and upset the distribution, of resources for the poor. To the south, comparatively stable English poor laws and structures for poor relief proved successful in helping to prevent lean harvests from devolving into a full-fledged famine (Flinn 1977, Cullen 2010, Hoyle 2013). Likewise, religious conflicts and rebellions, which had plagued the Scottish economy prior to the crisis (in the 1680s and 1689-91 especially), heightened the vulnerability of the Scots' to crop failure and food shortage. To cope, many emigrated to other parts of Europe and the American colonies (Cullen 2010).

3.3 Highland contexts

We know less about the crisis in the highlands, but it is nonetheless clear that in the relatively remote and marginal and upland areas agriculture had several inherent disadvantages. The growing season was generally shorter; crops, like barley-like bere, for example, went in one month later and were harvested one month earlier than in the rest of the country (Dodgshon 2004). This limited the crop varieties that could be grown. Oats (*Avena strigosa*) were an option, though they were not favoured everywhere. More intense highland winds were known to shake their crop seeds close to the harvest. They liked cool-wet summers and therefore suffered greatly in the cold and perhaps drier conditions of the 1690s. Many growers preferred four-row bere (sometimes bear, beir, or beer), a grain better suited for shorter growing seasons and windy areas. Nevertheless, all crops grown in marginal highland areas yielded less than in the rest of the country at a ratio between 2.5 and 4 to 1 compared to 3 or 5 to 1 (Dodgshon 2004, Smout 1987). The situation was such that a single crop failure could impel highland farmers to utilize seed crop for their subsistence, reducing their subsequent yields.

Andrew Fletcher, writing at the end of the seventeenth century, claimed that Scottish tenants grew crops too frequently in “to [too] remote places, and at unseasonable times”, indicating much marginal land was then brought under the plow (Fletcher 1698). He even referred to the highlands as a central location of the poor in Scotland. Similarly, Robert Sibbald observed that “a vast deal of ground [was] now tilled and labored that was before pasture (Sibbald 1698).” Modern historians have confirmed that the cultivation of marginal land was widespread in the seventeenth century (Flinn 1977).

Resting land was a common practice in Scotland during the seventeenth century. Land could be fallowed for a growing season to help replenish soils and increase yields, or to restore fields damaged by overuse, grazing, drought, flooding, or even conflict. Resting, naturally, resulted in agricultural and revenue losses. Exchequer records, which provide insight into the Crown’s land revenues, although spotty, indicate that ‘rests’ were particularly common in marginal and highland shires, especially in northern and western Scotland (Shetland, Orkney, Caithness, Ross, and the western isles) and that lands were rested often during the Ill Years (**Table 2**).

George Mackenzie [McKenzie], a tax collector (subtacksman) of the northern shires provided a vivid account of these marginal lands in 1697. In his petition to the Lord Chancellor and Commissioners of Treasury and Exchequer, he attempted to explain the tax losses he recorded as a consequence of six months of famine in 1697: "there was great scarcity and dearth in most shyres of the kingdom yet the northern shyres hade it to the degree of famine." McKenzie also argued that prices had been excessive for some time. The highlands had indeed suffered worse inflation. In his words, prices were "very ordinarie" in "the south and west" but "are excessive in the north." He lamented that even if people could have afforded grain (bear, bere) there was none to be had, as the harvest had failed. He claimed that taxes needed to be put in arrears to allow tenants to pay them back in time because the "loss of the subtacksman is vast." Consequently, losses would soon increase by three times, he posited, because no one would be left to pay taxes (Mackenzie 1697). Table 2 reports 'rest'-related losses in years for which we have information, shortly before the Ills and in the midst of the crisis. The total losses recorded in 1697, which either reflect damages sustained in that year alone or possibly across 1695-97 (Mackenzie 1697), are nearly double the losses recorded for 1687-89 combined.

The harvest of 1698 was likewise poor in the highlands because of extreme weather. John Campbell wrote that "desolation is universal in the Highlands, Lord help it…. The weather is so tempestuous that there is nather meall nor men can be sent up to yow till it setle[.] make what shift you can till then." The situation was such that he was "out of humour (Campbell 1698)."

3.4 The Darien expedition

The dire economic conditions from the crisis of the 1690s was also one of several motivators for investment into the ill-fated Darien expedition in 1696-98 (Cullen 2010, Prebble 2000, Edwards 2007, Miller 2016, Paul 2016). An initial five ships set out on a four-and-a-half-month-long journey on 12 July 1698. The scheme's goal was to establish a Scottish colony on the Isthmus of Panama (**Figure 1C**). The expectation, from the plans developed by William Paterson, was that this colony would serve as a gateway to the riches of the Orient, by connecting the Atlantic and Pacific Oceans (a premodern Panama Canal), in the hope of boosting the Scottish economy and increasing its global standing independent of England. This catastrophic venture, to what is still one of the most isolated regions of the American tropics, now the Darién Gap, was finally abandoned in March 1700 when upwards of one third of Scotland's wealth sank into the swamps (Prebble 2000, Whatley 2014), and many of the 2,500 would-be colonists perished or deserted the isthmus. Mosquito-borne diseases, likely falciparum malaria and yellow fever, with which the colonists would have been only faintly, if at all, acquainted, may have contributed to the demise of the venture (McNeil 2010), though many were already unwell upon arrival. As the marquees of Tweeddale and the earl of Panmure, two investors of the expedition and Scottish peers, observed, many volunteered to take part to escape the Ills and famine, but they instead found a scarcity of healthy settlers and supplies (Tweeddale 1699 and Panmure 1699). In any case, the Company of Scotland records suggest that poor communication between New and Old Edinburgh, ineffective leadership at both ends, and Spanish attacks on the nascent settlement played a critical role in the expedition's collapse (Royal Bank of Scotland, Insh 1932, Prebble 2000). However, the anomalous climate of the 1690s was also a significant factor in the colony's demise. Failed and failing harvests in Scotland repeatedly delayed resupply ships in 1699 and 1700 and finding alternative sources of grain for the colony proved difficult (Klinger 2019). As such, both the expedition and its failure illustrate the complex interaction of climatic and environmental factors with geopolitical and social efforts to cope with catastrophe.

4. Conclusions

We have integrated historical and palaeoclimatic records to explore the impacts of the cold pulse of the 1690s, one of the most severe climatic events and human disasters of the Little Ice Age in Scotland. Our perspective is supported by archival and multi-proxy paleoclimate records, as well as NCAIRN, an 800-year long tree-ring based summer temperature reconstruction specific to Scotland (Rydval et al. 2017). NCAIRN is part of a growing network of such data from multiple regions around the northern hemisphere (Wilson et al. 2016) which provide a quantitative and spatial perspective for the unusually cold conditions experienced in Scotland during the 1690s.

The NCAIRN reconstruction identifies 1695-1704 as the coldest decade of the last 750 years. Of several potential causes for the mid-1690s cold pulse, two tropical volcanic eruptions in 1693 and 1695 (Sigl et al 2015, Toohey and Sigl 2017) likely forced the summer cooling discernible in Scotland, across northern Europe and the northern hemisphere more broadly. Although attention to the extreme climate of the 1690s has focused almost solely on cooling, pronounced coldness may not alone have defined the decade. The evidence for summer [and winter] cooling in Scotland is stronger, but as yet there is no high-resolution purely hydroclimate record for Scotland (although a multi-proxy approach does identify concurrent precipitation anomalies in north-western Europe). To what degree hydroclimatic variability contributed to the Scottish Ills is still, however, an open question.

Recent histories of climate crises have tended to link palaeoclimatic estimates of global or hemispheric climate change with events occurring on much smaller scales, such as wars, famines, epidemics and population declines (Parker 2013, Brooke 2014, Campbell 2016, Harper 2017). This scholarship tends to underemphasize the complexity of climate change and the spatiotemporal and socioeconomical inconsistency of human suffering experienced following extreme climatic events. In focusing on Scotland in particular, and north-western Europe in general in the 1690s, we have emphasized that despite large-scale cooling, there was significant disparity in suffering and adaptive capacity. Scots endured a great crisis, but many across north-western Europe, including their closest neighbours, did not. Our focussed perspective underlines the importance of considering multiple climate variables as well as regional and local circumstances if we are to understand the complexity and impacts of, in this case, volcanic climate forcing. Climatic conditions in Scotland and England were similarly poor in the 1690s, but the choices made by each government, in some cases many years prior to the anomalous climatic conditions, and in others during the immediate build up to the crisis, did not take into account the state of the agrarian regime which determined the vulnerability of each country. England fared well, but tens of thousands died in Scotland.

The Scots' crisis influenced the Darien expedition as well as its failure. Together the Ills, the colony's collapse, and Scotland's subsequent economic depression motivated the Scottish Parliament's decision to end its independence and join the United Kingdom in 1707. Many (but not all) Scottish parliamentarians voted for union, thinking it was in the Scotland's best interest, be it financially, politically or socially. In this way, Scotland could benefit from England's international trade and political strength, as well as its social structures and systems, which undeniably helped England avert famine in the 1690s and limit the effects of later crop failures.

Scotland underwent wide-scale agricultural improvement only in the mid eighteenth century (Whyte 2001 and Kidd 2005), but access to English grain markets and poor relief curbed food shortages after the union. When cold weather again damaged crops in 1708-09 and the early 1740s, English grain imports prevented famine (Klinger 2019 and Post 1984), and despite prolonged cold conditions from the mid eighteenth to the beginning of the nineteenth centuries (**Figure 2**), Scotland did not suffer another major subsistence crisis. Notably, the very large eruption of Laki in 1783-84 (Sigl et al 2015, Toohey and Sigl 2017) contributed to a cold pulse that worsened the Highlands Crisis of 1782-84, but did not cause large-scale mortality (Cullen 2019), as did the crisis of the 1690s. Although the radical cultural changes enforced upon Scotland after the final Jacobite rising in 1745 should not be overlooked, nor the impacts of the following period of Highland Clearances (Devine and Wormald 2012), the 1690s do seem to provide a cautionary tale suggesting that a country's resilience to a complex amalgam of natural (climatic or otherwise) and geopolitical factors are more easily buffered when part of a larger union. Current UK politicians should heed such lessons from the past.

Acknowledgements: We thank the National Science Foundation Paleoclimatological Perspectives on Climatic Change (P2C2) program, including grant nos. AGS-1502150 and AGS 1502224. The Scottish Pine Project (http://www.st-andrews.ac.uk/~rjsw/ScottishPine/) acknowledges funding through the EU project “Millennium” (017008-2), Leverhulme Trust project “RELiC: Reconstructing 8000 years of Environmental and Landscape change in the Cairngorms (F/00 268/BG)”, and the NERC project “SCOT2K:Reconstructing 2000 years of Scottish climate from tree rings (NE/ K003097/1). MR acknowledges funding through the EVA4.0 project (CZ.02.1.01/0.0/0.0/16_019/0000803). RDD and RW conceived the paper and developed early drafts. M.R. and R. W. generated the tree-ring data. Historians PK and TN helped frame the paper and wrote the sections of historical context. They thank the CCHRI.princeton.edu for intellectual support. We also thank the Society of Antiquaries of Scotland, the Strathmartine Trust, and the Hall Center for the Humanities. None of the authors have competing interests. Lamont-Doherty Earth Observatory Contribution No. 0000.

References

Alfani, G. and C. Ó Gráda. 2018. The timing and causes of famines in Europe. Nature Sustainability 1: 283-288.

Alfani, G., L. Mocarelli, D. Strangio, Italy in G. Alfani and C. Ó Gráda eds., 2018. Famines in European History. Cambridge University Press, Cambridge: 25-47.

Appleby, A. 1979. Grain prices and subsistence crises in England and France, 1590-1740. Journal of Economic History 39: 865-887.

Appleby, A. 1980. Epidemics and famine in the little ice age. Journal of Interdisciplinary History 10: 643-663.

Béaur, G., J.-M. Chevet, France in in G. Alfani and C. Ó Gráda eds., Famines in European History. 2018. Cambridge University Press, Cambridge: 73-100.

Bellettini, A. 1987. La popolazione italiana. Un profilo storico. Torino, Einaudi.

Benedictow, O. 2004. The black death, 1346-1353: A complete history. Boydell and Brewer, Woodbridge.

Breadalbane, Countess, 1697. [N]ational [R]ecrods of [S]cotland, GD40/2/7/73, Countess of Breadalbane to Lady Lothian, 27 Dec. 1697.

Briffa, K., Jones, P., Schweingruber, F. and Osborn, T. 1998. Influence of volcanic eruptions on Northern Hemisphere summer temperature over the past 600 years. Nature 393: 450-455.

Brooke, J. 2014. Climate Change and the Course of Global History: A Rough Journey (Cambridge Press).

Caithness, L. 1698. NRS, GD40/9/113, Taymouth, to her sister, the countess of Lothian, 13 Apr. 1698.

Camenisch C. and C. Rohr. 2018. When the weather turned bad: The research of climate impacts on society and economy during the little ice age in Europe, an overview. Geographical Research Letters 44: 99-114.

Campbell, B. 2016. The great transition: Climate, disease and society in the late-medieval world. Cambridge University Press, UK.

Campbell, J. 1698. NRS, GD170/629, Taymouth, to Barcaldine, his chamberlain, 23 Mar. 1698.

Campbell, J. 1698. NRS, GD170/629, Taymouth, to Barcaldine, his chamberlain, 12 Dec. 1698.

Clarkson, L. and M. Crawford. 2001. Feast and famine: A history of food and nutrition in Ireland, 1500-1920. Oxford University Press.

Cline, E. 2015. 1177 B.C. The Year Civilization Collapsed. Princeton University Press.

Cook, E.R., R. Seager, Y. Kushnir, K. Briffa, U. Buntgen, D. Frank, P. Krusic et al. 2015. Old World megadroughts and pluvials during the Common Era. Science Advances Vol. 1, no. 10, e1500561

Cook, E.R., Kushnir, Y., Smerdon, J.E., Williams, A.P., Anchukaitis, K.J. and Wahl, E.R., 2019. A Euro-Mediterranean tree-ring reconstruction of the winter NAO index since 910 CE. Climate Dynamics, pp.1-14.

Cowtan, K., and Way, R. 2014. Coverage bias in the HadCRUT4 temperature series and its impact on recent temperature trends. Quarterly Journal of the Royal Meteorological Society 140.683: 1935-1944.

Crawford, D. 1695. NRS, GD406/1/4011, Hamilton, to the earl of Arran, 7 Jan. 1695.

Crawford, D. 1696. NRS, GD406/1/4111, Belford, to the earl of Arran, 6 Dec. 1696.

Crawford, D. 1698 (A). NRS, GD406/1/4245, Hamilton, To the earl of Arran, 30 Apr. 1698.

Crawford, D. 1698 (B). NRS, GD406/1/4269, Hamilton, to the duke of Hamilton, 3 Oct. 1698.

Crawford, D. 1698 (C). NRS, GD406/1/4268, Hamilton, to the duke of Hamilton, 24 Oct. 1698.

Crawford, D. 1699. NRS, GD406/1/4402, [David Crawford], Edinburgh, to the duke of Hamilton, 8 Jun. 1699.

Cullen, K. 2010. Famine in Scotland: the “Ill” Years of the 1690s, Edinburgh University Press.

Cullen, K. 2019. For the Good of the Empire, or the Relief of the Poor? Motivations for British Government Provision of Famine Relief in Scotland, 1783-4. Northern Scotland 10: 132-156.

Curtis, D. and J. Dijkman. 2017. The escape from famine in the northern Netherlands: A reconsideration using the 1690s harvest failures and a broader northwest European perspective. The Seventeenth Century. doi.org/10.1080/0268117X.1410494.

D'Arrigo, R., Wilson, R. and Anchukaitis, K. 2013. Volcanic cooling signal in tree-ring temperature records for the past millennium. JGR-Atmospheres DOI: 10.1002/jgrd.50692.

Dawson, A. 2009. So Foul and Fair a Day: A History of Scotland's Weather and Climate, Birlinn, Edinburgh.

Degroot, D. 2018. Climate change and society in the 15^{th} to 18^{th} centuries. WIREs Climate Change. In press.

Devine, T. and Wormald, J., Eds. 2012.The Oxford Handbook of Modern Scottish history, Oxford University Press, Oxford, UK.

Dijkman, J. 2017. Bread for the poor: Poor relief and the mitigation of the food crises of the 1590s and 1690s in Berkel, Holland. in D. Collet and M. Schuh eds., Famines during the ‘little ice age’ (1300-1800). Springer, Switzerland.

Dodghson, R. 2004. Coping with Risk: Subsistence Crises in the Scottish Highlands and Islands, 1600-1800. Rural History 15: 1-25.

Dodghson, R. 2005. The Little Ice Age in the Scottish Highlands and Islands: documenting Its human impact. Scottish Geographical Journal, 121: 321-337.

Drummond, John and John Oswald. 1689. NRS, E95/50, Lists of rests or debts due by shires and burghs for supply and excise 1 Nov. 1687-1 Feb. 1689, given up by John Oswald and John Drummond, receivers-general.

Dundonald, S. 1696. NRS, GD406/1/6385, Belford, to the earl of Arran, 10 Dec. 1696.

Edwards, N. 2007. Caledonia's Last Stand: In Search of the Lost Scots of Darien, Edinburgh: Luath Press, ISBN 978-1-905222-84-1.

Esper J., St. George S., Anchukaitis K., D’Arrigo R., Ljungqvist F., Luterbacher J., Schneider L., Stoffel M., Wilson R., Büntgen U. 2018. Large-scale, millennial-length temperature reconstructions from tree-rings. Dendrochronologia 50, 81-90.

Fletcher, A. 1698. Two Discourses Concerning the Affairs of Scotland, Written in the

Year 1698, Edinburgh.

Flinn, M. 1977. Scottish Population History from the 17th Century to the 1930s Cambridge: Cambridge University Press, 1977.

Folland, C., et al. 2009.The Summer North Atlantic Oscillation: Past, present, and future. J. Climate 22: 1082–1103.

Fraser, G. 1697. NRS, GD124/15/205, Letter to Robert Allen from George Fraser, 4 Jan. 1697.

Gill, R. 2000. The Great Maya Droughts: Water, Life, and Death. University of New Mexico.

Glaser, R. 1993. Wetter, witterung, umwelt: Aufzeichnungen und daten aus Franken, Sachsen, Sachsen-Anhalt und Thüringen, 1500-1699. Würzburg: Geographisches Inst. der Univ. Würzburg.

Grove, J. 1988. The Little Ice Age, Methuen, London.

Haldon, J., Mordechai, L., Newfield, T., Chase, A., Izebski, A., Guzowski, P., Labuhn, I. and Roberts, N. 2018. History Meets Palaeoscience: Consilience and Collaboration in Studying Past Societal Responses to Environmental Change. PNAS, 115: 3210-3218.

Hamilton, B. 1698. NRS, GD406/1/6442, Holyroodhouse, to the duke of Hamilton, 15 Nov. 1698.

Hamilton, D. 1695 (A). NRS, GD406/1/3999, Kinneil, to the earl of Arran, 14 Jun. 1695.

Hamilton, D. 1695 (B). NRS, GD406/1/3998, Kinneil, to Lord Basil Hamilton, 12 Jul. 1695.

Hamilton, D. 1696. NRS, GD406/1/4128, Edinburgh, to the earl of Arran, 7 Aug. 1696.

Hamilton, D. 1698. NRS, GD406/1/4344, Kinneil, to William Hamilton of Wishaw, 20 Jun. 1698.

Hamilton, J. 1698. NRS, GD406/1/10886, Edinburgh, to the duke of Hamilton, 29 Oct. 1698.

Harper, K. 2017. The fate of Rome: Climate, disease, and the end of antiquity. Princeton University Press, USA.

Houston, R. A. and Whyte, I. D., Scottish Society, 1500–1800. Cambridge University Press, 2005.

Hoyle, R. 2013. Why was there no crisis in England in the 1690s? in R. Hoyle ed., The Farmer in England, 1650-1980 (Routledge, London): 69-100.

Huhtamaa, H., and Helama, S. 2016. Reconstructing crop yield variability in Finland: long-term perspective of the cultivation history on the agricultural periphery since AD 760. The Holocene doi: 10.1177/0959683616646188.

Huhtamaa, H. and S. Helama. 2017. Distant Impact: Tropical volcanic eruptions and climate-driven agricultural crises in seventeenth-century Ostrobothnia, Finland. Journal of Historical Geography 57: 40-51.

Insh, George Pratt. 1932. The Company of Scotland Trading to Africa and the Indies. C. Scribner's Sons.

Irawan, D.; et al. 2009. Hydrogeochemistry of volcanic hydrogeology based on cluster analysis of Mount Ciremai, West Java, Indonesia, J. of Hydrology 376: 221-234.

Jones, P., and Lister, D. 2004. The development of monthly temperature series for Scotland and Northern Ireland, Int. J. Climatol., 24: 569–590.

Kidd, C. 2005. “Eighteenth Century Scotland and the Three Unions” in T.C. Smout. ed. Anglo-Scottish Relations From 1603-1900. Oxford University Press. Oxford: 171-188.

Kington, J. 1999. The severe winter of 1697/98. Weather : 43-49.

Klinger, P., 2019. The Climate of Union: An Environmental History of the Anglo-Scottish Union c.1660-1707. Doctoral Dissertation, University of Kansas.

Koufopoulos, A. J. 2005. The Cattle Trades of Scotland, 1603-1745. University of Edinburgh.

Lachiver, M. 1991. Les années de misère: La famine au temps du Grand Roy 1680-1720. Paris, Fayard.

Ladurie, E. 1971. Times of Feast, Times of Famine: A History of Climate since the Year 1000. Doubleday, NY.

Lamb, H. 1995. Climate, History and the Modern World, Routledge, London.

Lappalainen, M. 2012. Jumalan vihan ruoska: Suuri nälänhätä Suomessa 1695–1697. Helsinki: Siltala.

Lappalainen, M. 2014. Death and disease during the great Finnish famine, 1695-1697. Scandinavian Journal of History 39: 425-447.

Law, R. 1819 [1695] Memorialls or The Memorable Things That Fell Out Within This Island of Brittain from 1683 to 1684. A. Constable and Co. Edinburgh.

Linderholm, H.W. and Folland, C.K., 2017. Summer North Atlantic Oscillation (SNAO) variability on decadal to palaeoclimate time scales. Past Global Changes Magazine, 25(1), 57-60.

Luterbacher, J.; et al. 2001. The Late Maunder Minimum (1675–1715) – A key period for studying decadal scale climatic change in Europe. Climatic Change. 49 (4): 441–462. doi:10.1023/A:1010667524422.1.

Luterbacher, J., Dietrich, D., Xoplaki, E., Grosjean, M. and Wanner, H., 2004. European seasonal and annual temperature variability, trends, and extremes since 1500. Science, 303(5663), pp.1499-1503.

Luterbacher, J., Werner, J.P., Smerdon, J.E., Fernández-Donado, L., González-Rouco, F.J., Barriopedro, D., Ljungqvist, F.C., Büntgen, U., Zorita, E., Wagner, S. and Esper, J., 2016. European summer temperatures since Roman times. Environmental Research Letters, 11(2). doi:10.1088/1748-9326/11/2/024001

Mackenzie, G. 1697. NRS, GD26/7/439, Representation and Petition to the Lord Chancellor and Commissioners of Treasury and Exchequer.

Manley, G., 1974. Central England temperatures: monthly means 1659 to 1973. Quarterly Journal of the Royal Meteorological Society, 100(425), pp.389-405.

Matthews, J.A. and Briffa, K.R., 2005. The ‘Little Ice Age’: Re-evaluation of an evolving concept. Geografiska Annaler: Series A, Physical Geography, 87(1), pp.17-36.

McNeill, J. R. 2010. Mosquito Empires: Ecology and War in the Greater Caribbean, 1620-1914. Cambridge University Press.

Miller, K. 2016. The Darien scheme: debunking the myth of Scotland’s ill-fated colonization attempt. MA thesis, Wright State University.

Montgomerie, H. 1698. NRS, GD3/10/4/1, Papers of Hugh Montgomerie.

Morice, C., Kennedy, J., Rayner, N. and Jones, P. 2012. Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: The HadCRUT4 dataset, J. Geophys. Res., 117, D08101, doi:10.1029/2011JD017187.

National Records of Scotland. Tacks and Related Papers, 1688-1702. Edinburgh.

Ogilvie, A. 1992. “Documentary Evidence for Changes in the Cliamte of Iceland, A.D. 1500-1800” in R. Bradley and P. Jones. eds. Climate Since AD 1500. Routledge. London: 92-117.

Ogilvie, A. 1996. Sea-ice conditions off the coasts of Iceland AD 1601–1850 with special reference to part of the Maunder Minimum period (1675–1715). AmS-Varia 25: 9-12.

Owens, M.J., Lockwood, M., Hawkins, E., Usoskin, I., Jones, G.S., Barnard, L., Schurer, A. and Fasullo, J., 2017. The Maunder minimum and the Little Ice Age: an update from recent reconstructions and climate simulations. Journal of Space Weather and Space Climate, 7, p.A33.

Panmure, M. 1699. National Records of Scotland, GD406/1/4379, Edinburgh, to the duke of Hamilton, 6 Apr. 1699.

Parker, G. 2013. Global Crisis: War, Climate change and catastrophe in the 17th century Yale Univ Press, New Haven.

Parker, D., Legg, T. and C. Folland. C. 1992. A new daily Central England temperature series, 1772-1991. Int. J. Climatol. 13: 317-342.

Paterson, W. and S. Bannister. 1859. The Writings of William Paterson ... Founder of the Bank of England, and of the Darien Colony Vol. 1. Judd & Glass, London.

Paul, H. 2016. The Darien Scheme and Anglophobia in Scotland. Economics Division, University of Southampton, UK.

Pauling, A., Luterbacher, J., Casty, C. and Wanner, H., 2006. Five hundred years of gridded high-resolution precipitation reconstructions over Europe and the connection to large-scale circulation. Climate dynamics, 26(4), pp.387-405.

Pfister, C. 1988. Klimageschichte der Schweiz 1525–1860: Das klima der Schweiz von 1525–1860 und seine bedeutung in der geschichte von bevölkerung und landwirtschaft. Bern: Paul Haupt.

Post, J. 1984. Climatic Variability and the European Mortality Wave of the Early 1740s. Journal of Interdisciplinary History, 15(1), 1-30.

Prebble, J. 2000. Darien: The Scottish Dream of Empire. Edinburgh: Birlinn.

Proctor, C., A. Baker, W. Barnes, and M. Gilmour. 2000. A thousand year speleothem proxy record of North Atlantic climate from Scotland. Climate Dynamics 16: 815-820.

Royal Bank of Scotland. Journals of the court of directors of the Company of Scotland Trading to Africa and the Indies, 1696-1707.

Rydval, M., Loader, N.J., Gunnarson, B.E., Druckenbrod, D.L., Linderholm, H.W., Moreton, S.G., Wood, C.V. and Wilson, R., 2017. Reconstructing 800 years of summer temperatures in Scotland from tree rings. Climate Dynamics, 49(9-10), pp.2951-2974. doi:10.1007/s00382-016-3478-8.

Scrymgeour, D. 1696. NRS, GD224/605/1, Volume Containing an account of some memorable things.

Sessa, K. 2019. The new environmental fall of Rome: A methodological consideration. Journal of Late Antiquity. 12: 211–255.

Shindell, D., Schmidt, G., Mann, M., Rind, D., and Waple, A. 2001. Solar forcing of regional climate change during the Maunder Minimum. Science 294: 2149-2152.

Sibbald, R. Discourse Anent the Improvements May be Made in Scotland. 1698.

Sigl, M., et al. 2015. Timing and climate forcing of volcanic eruptions for the past 2500 years. Nature: doi:10.1038/nature14565.

Slavin, P. 2016. Climate and famines: A historical reassessment. WIREs Climate Change 7: 433-447.

Smout, T.C. 1963. Scottish Trade on the Eve of Union, 1660-1707. Oliver & Boyd. London.

Smout, T.C. 1987. A History of the Scottish People 1560-1830. Collins, London.

Smout, T. C. and A. Fenton. 1965. Scottish Agriculture Before the Improvers: An

Exploration. The Agriculture History Review 13:73-93.

Toohey, M. and Sigl, M., 2017. Volcanic stratospheric sulfur injections and aerosol optical depth from 500 BCE to 1900 CE. Earth System Science Data, 9(2), pp.809-831.

Trouet, V., J. Esper, N. Graham, A. Baker, J. Scourse and D. Frank, 2009. Persistent positive North Atlantic Oscillation mode dominated the Medieval Climate Anomaly. Science 324: 78-80.

Tweeddale, J. 1699. NRS, GD406/1/4415, Edinburgh, to the duke of Hamilton, 15 Jun. 1699.

Tyson, R. 1986. "Famine in Aberdeenshire, 1695-1699: Anatomy of a Crisis." in D. Stevenson. ed. From Lairds to Louns: Country and Burgh Life in Aberdeen, 1600-1800. Aberdeen University Press. Aberdeen: 32-52.

Usoskin, I.G., Arlt, R., Asvestari, E., Hawkins, E., Käpylä, M., Kovaltsov, G.A., Krivova, N., Lockwood, M., Mursula, K., O'Reilly, J. and Owens, M., 2015. The Maunder minimum (1645–1715) was indeed a grand minimum: A reassessment of multiple datasets. Astronomy & Astrophysics, 581, p.A95.

Walter, J. and R. Schofield. 1989. Famine, disease and crisis mortality in early modern society. in J. Walter and R. Schofield eds., Disease and the Social Order in Early Modern Society. Cambridge University Press, 1989: 1-74.

Weiss, H. 2017. Megadrought and Collapse: From Early Agriculture to Angkor. Oxford University Press.

Whatley, C. 2014. The Scots and the Union: Then and Now. Oxford University Press.

Wheeler, D., Garcia-Herrera, R., Wilkinson, C., and Ward, C. 2010. Atmospheric circulation and storminess derived from Royal Navy logbooks: 1685-1750. Climatic Change: 101: 257-280.

Whyte, I. D. . 2001. “Economy: primary sector: 1 Agriculture to 1770s” in M. Lynch. ed. The Oxford Companion to Scottish History. Oxford University Press, Oxford.

Wilson, R., et al. 2016. Last millennium Northern Hemisphere summer temperatures from tree rings: Part I: the long term context. Quaternary Science Reviews 134: 1-18.

Wrigley, E. and R. Schofield. 1981. The population history of England, 1541-1871. Edward Arnold, London.

Figures and Tables

Years	Cold	Anomaly	Warm	Anomaly
1	1232	-2.80	1284	1.96
2	1782	-2.71	1285	1.67
3	**1698**	**-2.57**	1307	1.55
4	1799	-2.51	1310	1.45
5	1227	-2.49	1282	1.34
6	**1639**	**-2.23**	2010	1.33
7	**1667**	**-2.23**	2003	1.31
8	1441	-2.05	1859	1.20
9	1202	-2.04	1990	1.18
10	**1696**	**-2.03**	1949	1.18
Decades				
1	1224-1233	-1.64	1303-1312	0.98
2	**1695-1704**	**-1.56**	1279-1288	0.96
3	**1632-1641**	**-1.47**	2001-1010	0.63
Centuries				
1	**1612-1711**	**-1.01**	1911-2010	0.05

Table 1: Top ten (annual), three (decadal) and centennial cold and warm periods in NCAIRN. Temperature anomaly values are with respect to the mean of 1961-1990. 17th century values bolded.

Location	**Losses 1687-89**	**Losses 1697**
Orkney and Shetland	13038	7148
Caithness	2594	3428
Sutherland	1711	1376
Ross	6173	13857
Inverness	7822	4734
Cromarty	0	115
Murray and Nairn	1889	9832
Banff	6697	10941
Aberdeen	9918	37988
Dundee Town	N/A	7848
Forfar Shyre	8685	15864
Kinkardy	2242	7761
Total	60769	120892

Table 2: Agricultural losses before and in the midst of the Ills. John Drummond's record of Crown agricultural revenue losses for years 1687-89 is presented in column two (Drummond 1689). George McKenzie's report of Crown agricultural revenue losses suffered in the "northern Shyres" is presented in column three. Note McKenzie's tallies may reflect losses sustained following six months of famine in 1697 or possibly losses accumulated over the course of the mid-1690s, likely 1695-97 (Mackenzie 1697). Although reported by different authors using different temporal scales, the latter of which is somewhat unclear, Drummond and McKenzie's records do illuminate the extent of agricultural losses from rests suffered during the 1690s in several locations. Losses increased significantly in at least eight of these 12 locations between the late 1680s and the late 1690s. If the losses reported by McKenzie do in fact reflect damages sustained in 1697 alone, they were clearly catastrophic.

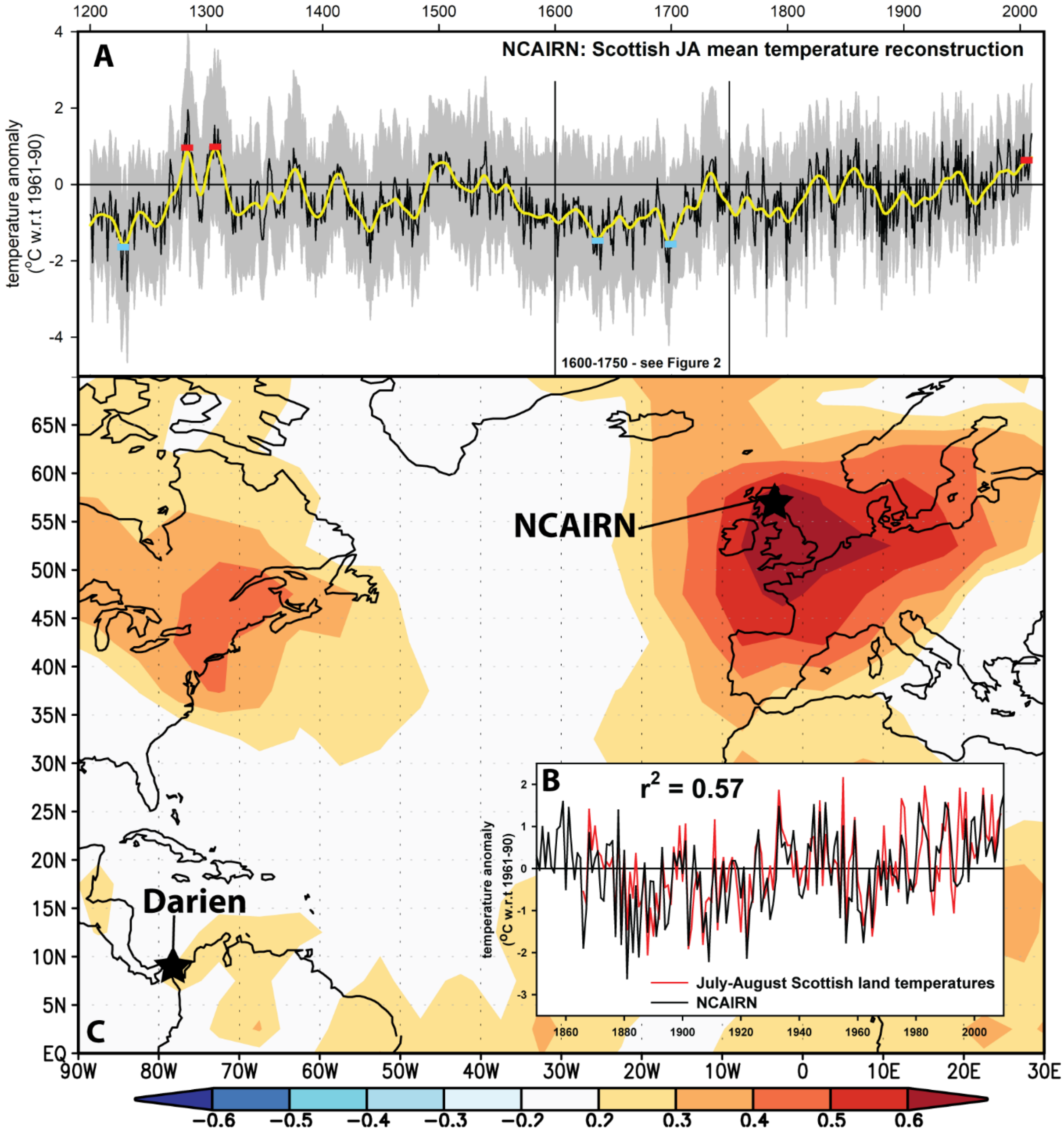

Figure 1. **A:** Scottish NCAIRN reconstruction (Rydval et al. 2017) of July-August Scottish mainland temperatures (Jones and Lister 2004). The three coldest and warmest decades are highlighted in blue and red, respectively (see **Table 1**). Yellow line is smoothed 20-year low pass filtered version; gray lines are error bars. **B:** Calibration between NCAIRN and Scottish mainland mean July-August temperatures (Jones and Lister 2004). **C:** Spatial correlations (1850-2010) between the NCAIRN reconstruction (Rydval et al. (2017)) and July-August mean temperatures (HadCRUT4 (Morice et al. (2012), with Cowtan and Way (2014) infill). Black stars denote the NCAIRN study region (northern Cairngorms, Scotland) and Darien, Panama.

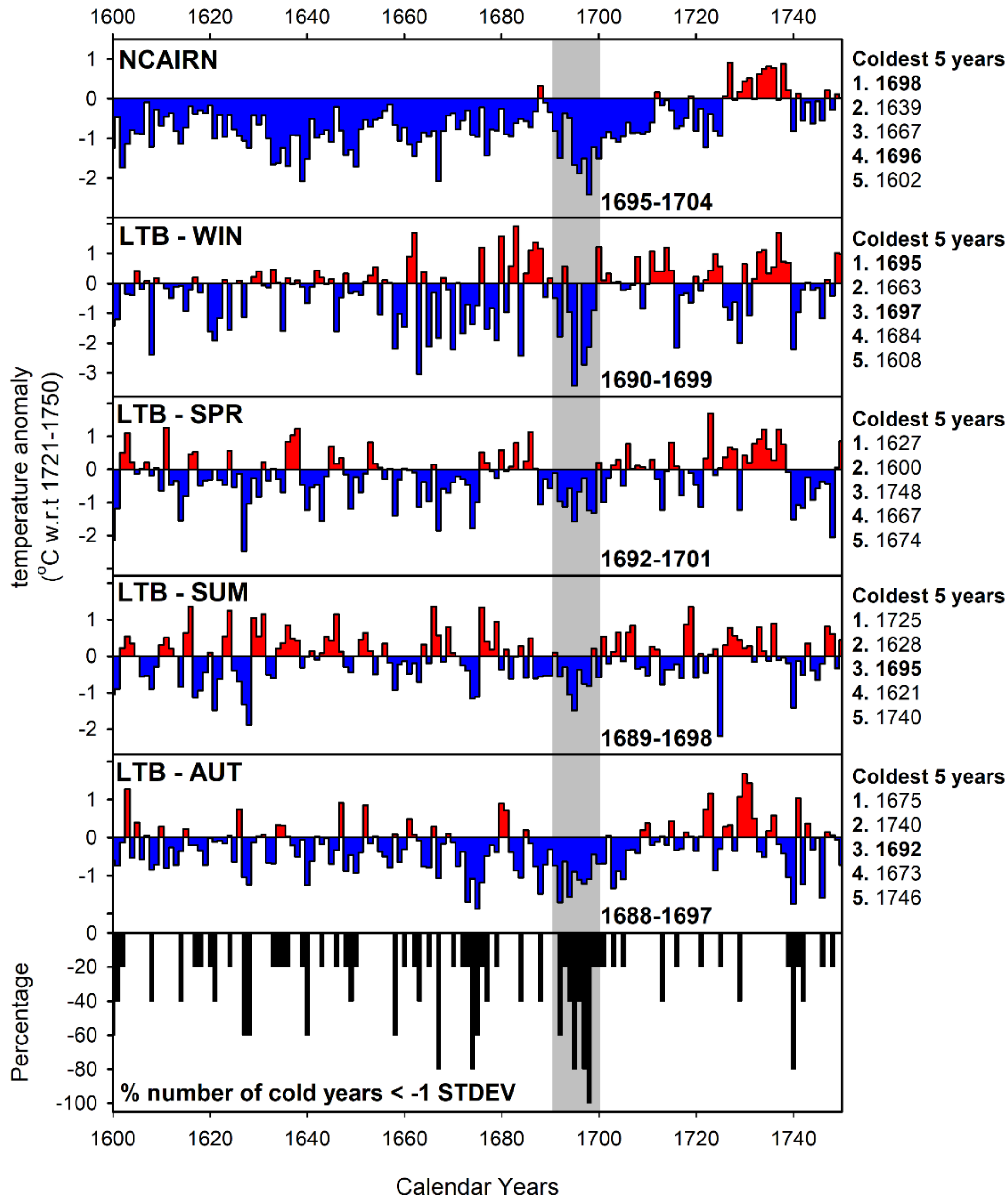

Figure 2. Comparison (1600-1750) between NCAIRN (Rydval et al. 2017) and the four temperature seasons relevant to Scotland from Luterbacher et al. (2004). The temperature series are expressed as anomalies with respect to 1721-1750. The coldest decade over the 1600-1750 period is detailed on each panel while the top 5 coldest years are listed on the right. Cold years within the 1690s are bolded. The lower histogram denotes the % number of seasonal records (NCAIRN + Luterbacher et al. 2004) that express cold seasonal values 1 standard deviation below the 1600-1750 mean. The 1690-1700 period is highlighted in grey.

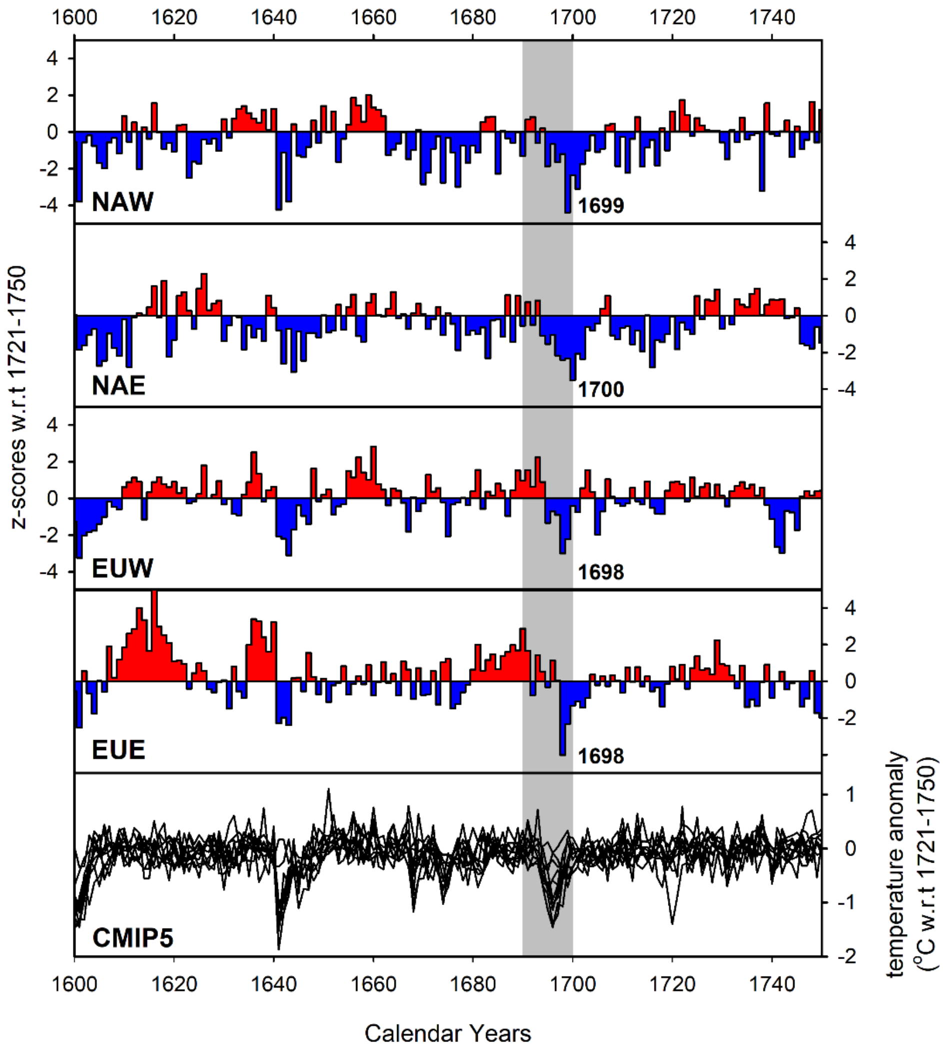

Figure 3: Longitude quadrant composite mean series (Wilson et al. 2016) for the latitudinal band 40-70ºN for western North America (NAW - 170ºW – 100ºW); eastern North America (NAE - 100ºW – 10ºW); Western Eurasia (EUW - 10ºW – 80ºE) and eastern Eurasia (EUE - 80ºW – 170ºW). The series have been normalized to z-scores w.r.t. the 1721-1750 period and the coldest anomaly within the 1690s is indicated. The lower panel shows an ensemble of CMIP5 model runs (see Wilson et al. 2016 for details) which are expressed as temperature anomalies with respect to 1721-1750. The 1690-1700 period is highlighted in grey.

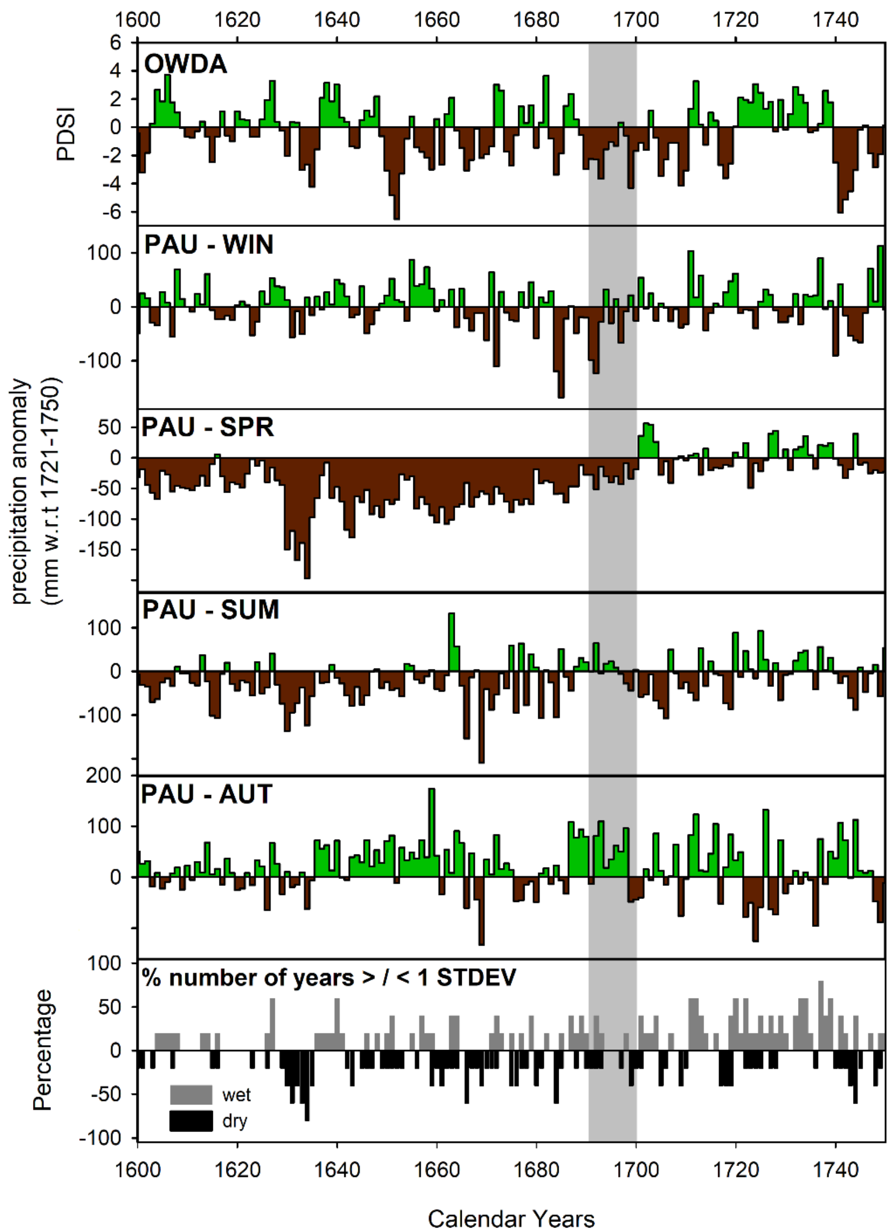

Figure 4. Hydroclimate gridded proxies for the Scottish region. From upper to lower: June-August scPDSI tree-ring reconstruction (Cook et al. 2015); Season precipitation reconstructions of Winter through to Autumn derived from multi-proxy sources (Pauling et al. 2006). The lower histograms denote the % number of records (Cook et al. 2015 + Luterbacher et al. 2004) that express both dry and wet seasonal values > or < 1 standard deviation from the 1600-1750 mean. The 1690-1700 period is highlighted in grey.