Cambridge Risk Framework

**Profile of a Macro-Catastrophe Threat Type**

Environmental Catastrophe

# Freeze

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## Profile of a Macro-Catastrophe Threat Type

# Freeze

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May 2012

**Abstract**

Extended periods of extreme cold weather have caused severe disruptions and significant economic losses to the United Kingdom and other European and North American economies in recent years. International trading networks rely on clear and timely deliveries via road, rail, sea, and air. Extreme weather limits and disrupts the flow of international trade, creating choke points that impact the global network.

This document provides an introduction and summary of the causes of the threat and an analysis of the many consequences (human, agricultural, infrastructural, commercial and social) of extended periods of extremely cold weather. A catalogue of historical events is provided, detailing the various solar, volcanic, and climatological phenomena causing the freeze, with some detailed examples illustrating the impact caused in each case. Finally, a magnitude scale is provided allowing for estimation of impact based on the number of 'freezing' degree days.

**Keywords:**

Freeze, Risk, Europe, North America, Business Interruption

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## 1 Monograph Summary

A freeze event can be defined as a climatic anomaly causing an extended period of below average temperature. Freezing conditions pose numerous direct and indirect health hazards to humans and animals, and can severely damage critical social and economic infrastructure. Effects can be immediate and prolonged, depending on the severity and length of the freezing conditions. Some freeze events last only a few hours, others last days, weeks, months, even years. Over the last 30 years in the United States, 15 freeze events have claimed over 580 lives and cost over $35billion in damages. There is no single precondition to the onset of a freeze event. Historically, periods of extreme cold have occurred as a result of diminished solar activity and increased volcanic activity, as well as the more obvious meteorological and climatological reasons.

The consequences of a freeze event are dependent on three factors: temperature, time, and type. Embedded in all three factors are the issues of vulnerability and relativity. Some geographic areas, or groups, or crop types, are more sensitive to temperature changes or are particularly vulnerable below a certain threshold. Thus, a drop below zero degrees centigrade may be a critical absolute term, equally a change relative to the mean may be more significant in determining extremity. Temperature and time are also related to type. An extended period of cold, dry weather can be devastating to a country's agricultural sector, while an extreme winter storm (with high volumes of snowfall) can decimate a country's commercial activity.

Artic (AO) and North Atlantic (NAO) Oscillation are strong indicators of the likelihood of climatologically driven extreme weather. However, they do not capture the severity or impact of the weather. In the United States, the severity of Nor'easters was previously indicated using the Northeast Snowfall Impact Scale (NESIS). The scale was then updated to the Regional Snowfall Index (RSI), and now includes population data to assess more accurately the societal impact of the snowstorm. To measure cold periods, rather than the volume of snowfall, the Met Office (UK) uses an index often referred to as Winter Cold Wave Duration, however, this fails to capture the severity of the cold weather. Other indices are calculated from the proportion of days where the daily maximum temperature falls below the coldest 10% of temperatures. In an attempt to synthesise intensity and impact, we suggest an adaptation of the degree-day calculation. Our Extreme Freeze Intensity (EFI) scale is calculated through subtracting the daily average temperature ($X_{temp} = temp_{max} – temp_{min}/2$) from the mean temperature for that climate period ($Mean_{temp}$), multiplied by the number of days where $X_{temp} < Mean_{temp}$. Although magnitude scales and impact calculations are seldom accurate, they assist in quick calculations in the assessment of socio-economic and geospatial impact from a period of extreme cold.

## 2 Definition

In simple, meteorological terms, a freeze event can be defined as a climatic anomaly causing an extended period of below average temperature. Extreme meteorological events of this nature can be defined further based on various criteria[1]. In a pure sense, an extreme freeze event occurs when the temperature (or average temperature over a period of time) lies outside the 95$^{th}$ percentile of the climatological distribution. As well as the minimum temperature, the US National Weather Service also identifies the rate of temperature fall as a criterion for determining the onset of a cold wave.

Central to definitions of freezes, cold waves, winter storms, etc. is also a consideration of impact. The benchmark for National Oceanic and Atmospheric Administration's (NOAA) definition is a temperature drop requiring increased protection to agriculture, industry, commerce, and social activities. The impact of a freeze event depends greatly on the sensitivity of those affected – something considered climatologically extreme might have little or no impact at all on one group but prove catastrophic to another.

## 3 Summary of the Threat

The threats posed by a freeze event are widespread. Freezing conditions pose numerous direct and indirect health hazards to humans and animals, and can severely damage critical social and economic infrastructure. Effects can be immediate and prolonged, depending on the severity and length of the freezing conditions. Some freeze events last only a few hours, others last days, weeks, months, even years. Over the last 30 years in the United States, 15 freeze events have claimed over 580 lives and cost over $35billion in damages.

### 3.1 Causes

There is no single precondition to the onset of a freeze event. Historically, periods of extreme cold have occurred as a result of diminished solar activity and increased volcanic activity, as well as the more obvious meteorological and climatological reasons.

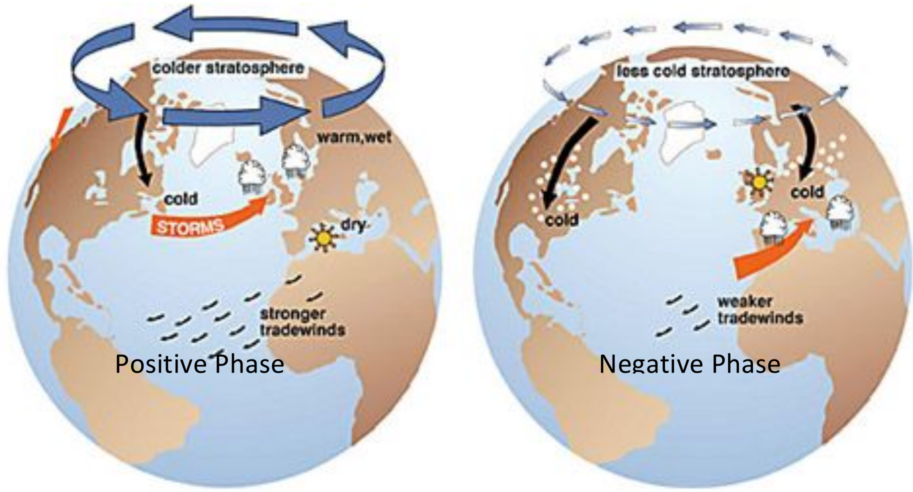
#### 3.1.1 Climatological and Meteorological causes

Weather in Northern Hemisphere depends significantly on a number of atmospheric systems. Of particular significance for Europe and North America are Polar cyclones (Arctic low pressure systems), and the interplay between the Icelandic Low (an area of permanent low pressure) and the Azores High (an area of permanent high pressure) in the North Atlantic.

Patterns in Arctic sea-level pressure variations are captured on an index called Arctic Oscillation (AO), which is related to the degree of penetration of cold air into middle latitudes and gages the strength of the Polar Vortex (see Figure 1). When surface pressure in the Artic is low, AO is said to be in a positive phase, resulting in a strong (west-to-east) jet stream that contains Arctic air in the polar region, and keeps Northern Europe relatively mild with increased precipitation. Conversely, when surface pressure is high, AO is said to be in a negative phase, resulting in weaker zonal and trade winds that allows cold, Arctic air to penetrate south into the middle latitudes (e.g., the United States and Northern Europe). Despite stochastic fluctuations, AO has become a fairly accurate weather predictor.

[1] Environmental Modeling Center, NCEP, NWS/NOAA, *Extreme Weather Events and their Probabilistic Prediction*, Presented at American Meteorological Society (AMS), January 2001

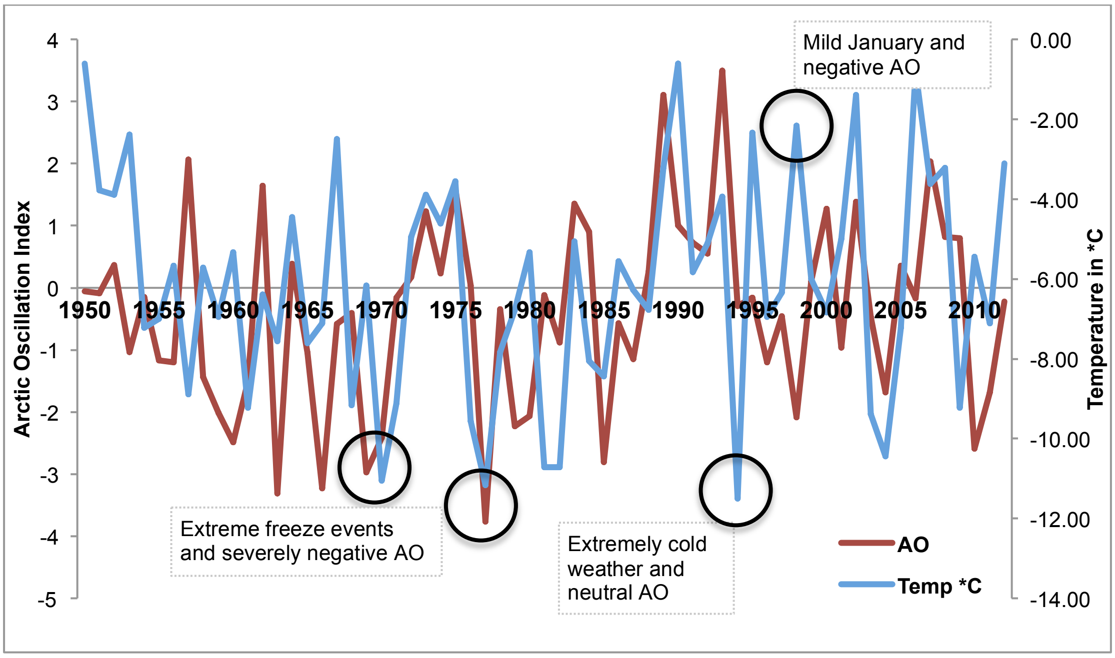
**Figure 1**: Arctic Oscillation




Source: J. Wallace, University of Washington

The NOAA regularly attributes AO to periods of extreme winter weather. However, despite strong correlations, the connection between extreme AO values and extreme weather is not always consistent (see Figure 2):

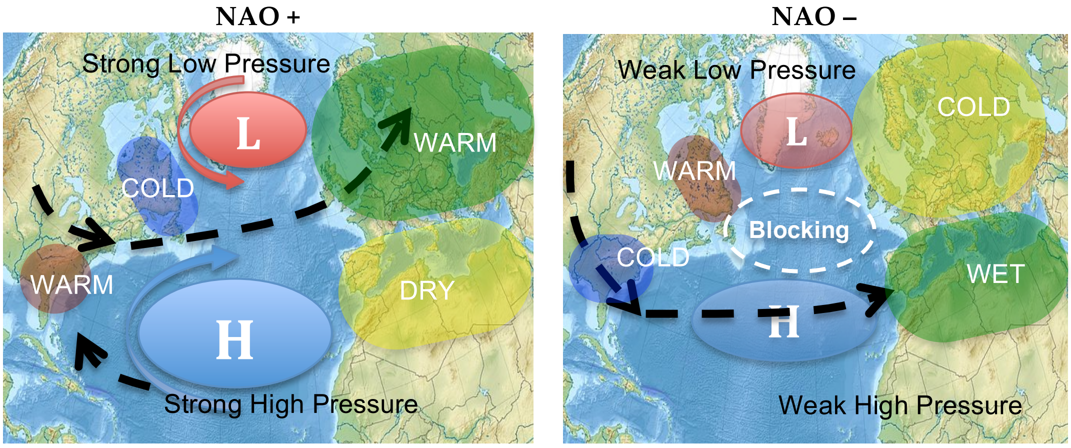
**Figure 2**: Arctic Oscillation and New York Temperature (mean *C) – 1950-2012 (January)




Related to AO is North Atlantic Oscillation (NAO), an index used to capture the variations in sea-level atmospheric pressures between permanent weather systems in the Azores and Iceland (see Figure 3). The subtle movements of the Icelandic low pressure system and the Azores high pressure system determines the strength and direction of winds and storms in the North Atlantic. When the pressure difference between the two points is large, the NAO is considered to be in a positive phase

(NAO+), and, conversely, when the pressure difference is very small the NAO is considered negative (NAO-). Typically, NAO+ results in strong westerly winds, bringing mild, wet winters to Europe. Conversely, in a low index, westerly winds are suppressed, bringing cold air from the Arctic to Northern Europe and forcing storms and wetter weather to southern Europe and North Africa. Similar effects are evident in North America. In a positive phase, warm air is pulled from the south-west up the eastern United States and southeast of Canada; in a negative phase, warm air is pulled west causing freezing arctic air from the Polar Vortex to extend as far south as Florida.

**Figure 3**: North Atlantic Oscillation (positive and negative phases)




While much of the weather experienced in the Northern Hemisphere can be linked to AO and NAO, extreme winter weather is often caused by the combination of natural meteorological events (e.g. the emergence of blocking patterns, intense cold fronts, etc.). When approaching the extremes of the meteorological phenomena, events tend to modify rather than intensify the tail of the distribution. Occasionally, however, they are exacerbated, or indeed caused by other naturally occurring phenomena.

### 3.1.2 Solar Activity

Solar activity, the level of radiation emitted from the Sun, varies very slightly. Astrophysicists suggest a 0.1% change over an 11-year period[2]. Much of this solar variation can be attributed to sunspots, which are temporary phenomena caused by magnetic disturbances to convective activity. Their occurrence is positively correlated to intense periods of solar radiation. Their absence, however, is a possible explanation (or contributing factor) for periods of global cooling, like those experienced during the 'Little Ice Age' (1400 to 1700).

### 3.1.3 Volcanic Activity

Volcanic ash has the capacity to reduce severely the capacity of solar radiation to penetrate the Earth's atmosphere. The most explosive volcanic eruptions in history been followed by periods of global cooling. The temperature drop can be as much as 4*C, and, depending on the severity and type or eruption, can last several years. For example, the eruption on Mount Tambora in 1815 triggered a period of extreme cooling (see Section 3.3.6, 1816 – A Year Without Summer).

### 3.1.4 Correlations & Coincidence

It is difficult to say with absolute certainty that past extreme freeze events were precipitated by purely climatological, solar, or volcanic activity. The most extreme situations occur when there is a

[2] Willson, R. C. & Hudson, H. S. *Nature* **351**, 42-44 (1991)

coincidental or causal interaction between the phenomena. Meteorological systems tend to be corrective – they usually diminish extremes (e.g. storms do not grow continuously). However, the combination of climatological, solar, and/or volcanic incidents increases the probability of meteorological events occurring in the extreme tails of the distribution.

## 3.2 Consequences

The consequences of a freeze event are dependent on three factors: temperature, time, and type. Embedded in all three factors are the issues of vulnerability and relativity. Some geographic areas, or groups, or crop types, are more sensitive to temperature changes or are particularly vulnerable below a certain threshold. Thus, a drop below zero degrees centigrade may be a critical absolute term, equally a change relative to the mean may be more significant in determining extremity. Temperature and time are also related to type. An extended period of cold, dry weather can be devastating to a country's agricultural sector, while an extreme winter storm (with high volumes of snowfall) can decimate a country's commercial activity.

### 3.2.1 Human Health Consequences

Estimates suggest that cold weather causes an additional 7700 deaths in the United States each year. Aside from the immediate, indirect casualties (which are most often travel-related), the death toll from extreme freeze events is correlated strongly to the length of cold period. Typically, the most vulnerable people (those with pre-existing medical conditions or socio-economic circumstances) are the first, and most likely, to succumb to cold temperatures. While cold conditions can exacerbate medical conditions (particularly cardio-vascular irregularities), prolonged freezes – extensive enough to affect the food supply – have resulted in widespread disease and famine.

The scale of deaths from cold-related famines is particular to the time and place of its occurrence. Health and societal advancements, particularly in terms of global trade and the development of nutritional supplements should dampen the severity of such a famine in future. However, the role of social unrest, rioting, and a general increase in criminality, are widely associated with extreme situations and can compound the severity of such situations.

### 3.2.2 Agricultural Consequences

The cost of agricultural losses can accumulate quickly. Generally, a short, extreme cold snap can devastate crops, particularly if the freeze occurs early or late in the growing season, or occurs in an area not prone to cold weather (for example, in 2007, California's orange industry lost c. $1.5 billion due to a severe cold snap in January, while the south-eastern United States lost c. $2.2 billion in citrus crops due to freezing conditions in April[3]). Livestock are more vulnerable to prolonged cold periods. Similar to humans, animals not protected from the elements, or those with medical vulnerabilities are at greater risk (for example, in April 2000, freezing conditions and snowstorms caused the deaths of thousands of newborn lambs in the UK).

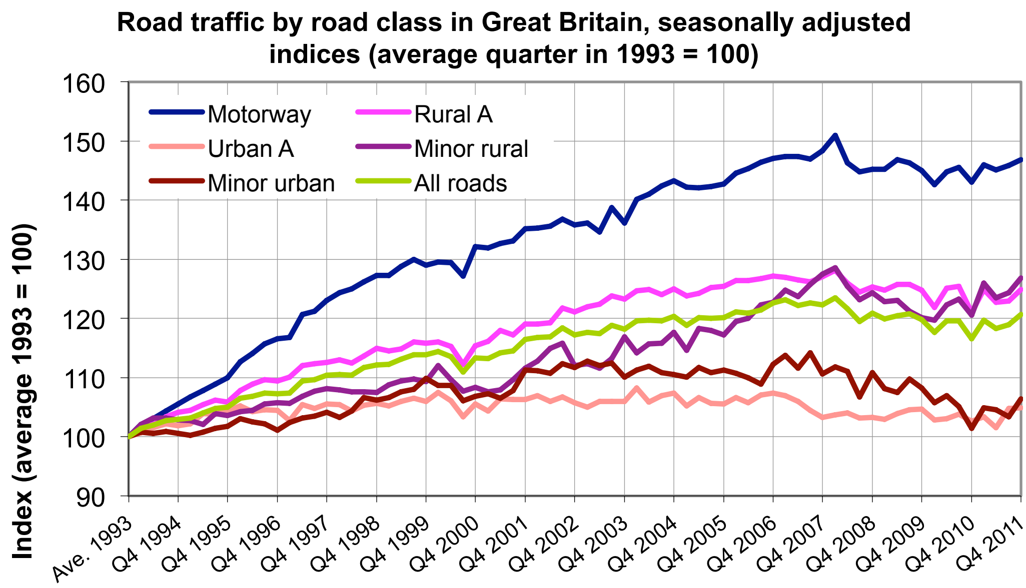
There are subsequent financial implications; citrus prices peaked historically following freeze events that damaged stocks. Rises in crop prices follow similar patterns; meat prices increase too as farmers pass on to consumers the additional costs of protecting cattle from the extreme conditions. When famine has occurred, it has been a combination of depleted food supplies, and, naturally, the increased price of the remaining supplies. The Food and Agriculture Organization of the United Nations (FAO) produces a monthly Food Price Index[4] (FFPI) that shows a strong correlation between global food prices and meteorological conditions.

[3] For more information on these two events, see NOAA Global Hazards 2007 (http://www.ncdc.noaa.gov/sotc/hazards/2007)
[4] Incorporated in the FAO Food Price Index (FFPI) are the Cereal Price Index, the Oils/Fats Price Index, the Meat Price Index, Dairy Price Index, and the Sugar Price Index; for further details see http://www.fao.org/worldfoodsituation/wfs-home/foodpricesindex/en/

### 3.2.3 Infrastructure Consequences

During the UK's 2010 freeze, the volume of road traffic activity dropped by approximately 10%. Similarly, the number of journeys reported to be 'on time' also dropped by approximately 10%. Such transportation chaos (which affected sea and air travel to a similar degree), stemmed largely from the heavy snowfall at the start of the freeze event. Typically, rural roads were closed first, with preventive measures (e.g. gritting) concentrated on motorways and main roads. Figure 4 (below) shows the seasonally adjusted dips in traffic (note particularly, the drop in Q3 2000, Q1 2010, and Q4 2010).

**Figure 4**: Road Traffic in Great Britain (1993-2011)




**Source**: Department of Transport (UK) Statistics

Airline traffic has dropped significantly during freeze events as flights are diverted or cancelled following airport closures. In the UK, in 2009-10, flights were disrupted frequently during the freezing condition between mid-December and the end of January with all major UK airports closing at some point during that period. Similar conditions prevailed between November and December 2010. Both Gatwick and Edinburgh airport were closed completely on December 1. Gatwick handled 240,500 aircraft movements (one aircraft taking off or landing) in 2010 (the 5 year average is around 260,000) - this equates to just over 700 flights per day. Edinburgh's average is around 125,000 (which equals just over 340 flights per day). Thus, between the closures at Gatwick and Edinburgh on December 1, over 1000 flights were disrupted. For Gatwick that equates to over 92,000 passengers per day, meaning that (approximately) 57,900 passengers (66%) could not fly to Europe, 12,880 (14%) could not fly long haul, and over 18,400 (20%) could not fly to UK, Eire, and other North Atlantic destinations[5].

[5] These numbers are an approximation based on yearly flight traffic. In reality, as 14% of Gatwick's annual travel is on European Chartered flights (mostly holiday-goers), it would be rational to assume this figure to be lower for the start of December.

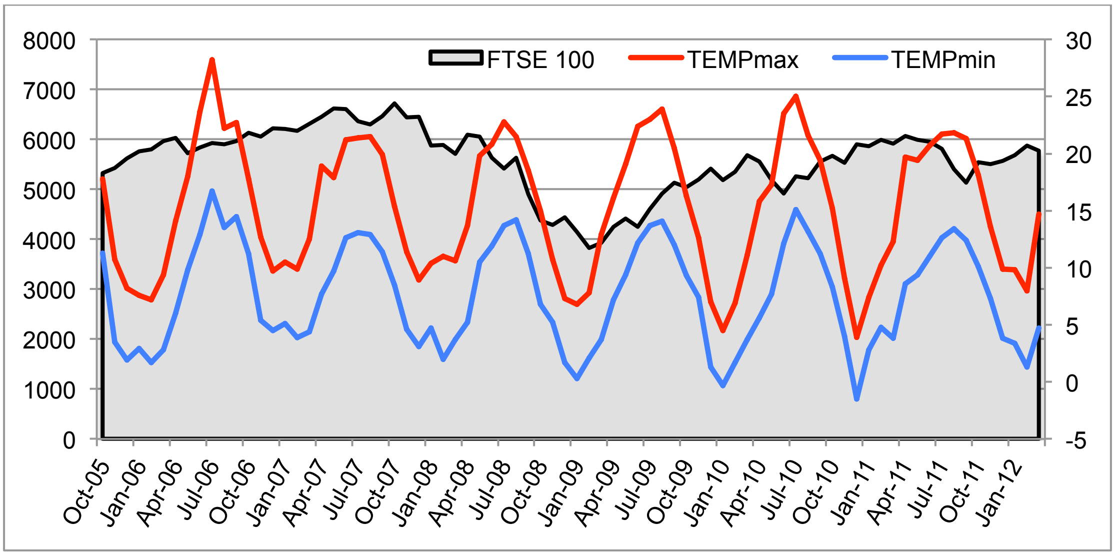
Electric rail systems are particularly vulnerable to freezing conditions as the ice forms on the cables, which then collapse under the weight. The Eurostar link between London and Paris was shut down completely on December 20. On the same day, ice on the power lines shut down services on the UKs main east coast line. Similarly, in February 2010, a 'major' Northeaster (category 3[6]) struck the United States' North-East and Mid-Atlantic region. During the 5-6 February, AMTRAK services were closed across the region.

### 3.2.4 Commercial Consequences

Estimates of the commercial cost of freeze events vary according to what indirect losses are included in calculations. Also to be considered is the distinction between loss (i.e. that which is damaged by the weather) and price change (i.e. that which is made more expensive by the weather). Costs of the 2009 freeze in the UK were estimated to be around £640 million per day. Small businesses alone are estimated to have lost over £1 billion, as approximately 20% of the workforce failed to make it in to work. In 2010-11 the loss to the economy was estimated at £1.2 billion per day, with a total cost of £13 billion. As winter in the Northern Hemisphere coincides with major western holidays, extreme weather can result in a larger than normal economic losses as people do not travel to shopping centres nor trust the delivery capacity of internet-based retailers. Retail losses due to the pre-Christmas 2009 blizzard that struck North America surpassed $2 billion.

It is difficult to assess the true economic impact of freeze event because it is partly dependent on the state of the economy at the time of occurrence. Internet commerce, though still affected by bad weather, offers consumers an alternative to travelling to shopping centres, and thus makes economic comparisons to pre 1990 freeze events difficult and inaccurate. There is also a dearth of data showing correlations between extreme cold periods and economic performance. Unfortunately, the occurrence of freezing weather during a period of economic turmoil reduces the capacity to infer any linkages between weather and the economy. Figure 5 (below) illustrates the challenges of using indices as a guide. Although small dips coincide with winter weather, particularly at December 2009 – January 2010, connecting the two variables is tenuous at best. Also, as indices like the FTSE include many industries, a period of poor weather may hurt the retail sector, but help the energy sector, resulting in a misleadingly stable picture.

**Figure 5**: FTSE 100 price and Temperature (monthly mean – max & min), 2005 - 2012




[6] Northeaster categories range from 1-5. A study of 80 storms over 120 years forms the basis of the NESIS (North East Snow Intensity Scale). Two storms have been ranked '5' or 'Extreme', eight have been ranked '4' or 'Crippling', twenty-one have been ranked '3' or 'Major', twenty-four have been ranked '2' or 'Significant', and twenty-five have been ranked '1' or 'Notable'.

#### 3.2.5 Social Consequences

Freezing conditions that disrupt normal activity can have wide-ranging political and social consequences. Prolonged road closures and delays cause frustration and anger, which is usually directed at the local and/or national governments. Forewarning of severe weather can cause panic buying and hoarding, causing an unnecessary shortage of food and water, and leading to forms of profiteering or price gouging. Some of the most severe freezes in history have been followed by periods of famine, and rioting (particularly by members of society unable to afford the inflated prices charged for basic food staples). Legal responses tend to follow: for example, in the US, the practice of price gouging is banned in 34 states[7], whereas profiteering is outlawed in the UK's Competition Act 1998.

# 4 Historical Events

## 4.1 Solar activity and freeze events

During the last 1000 years, five periods of reduced solar activity have been identified that have also coincided with periods of reduced global temperatures (see figures 4 and 5, below). Of particular historical interest for their link to extreme freeze events are the Maunder Minimum (1645-1715), and the Dalton Minimum (1790-1830).

**Figure 6**: Solar Activity Events

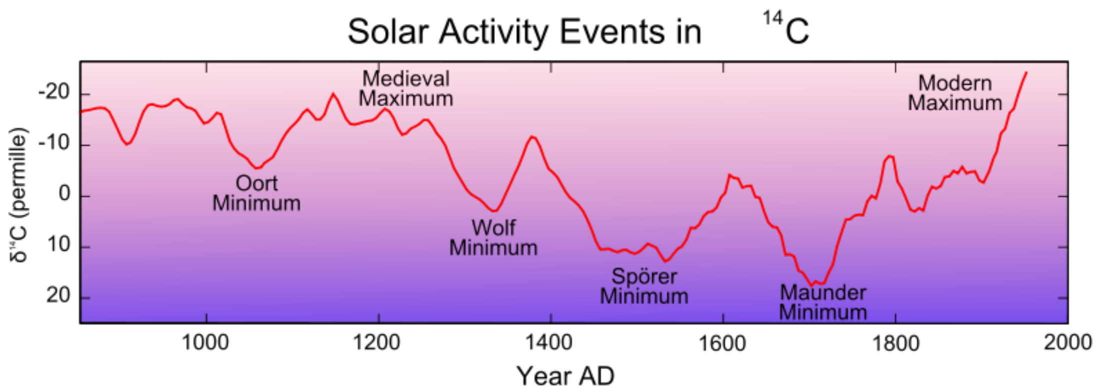
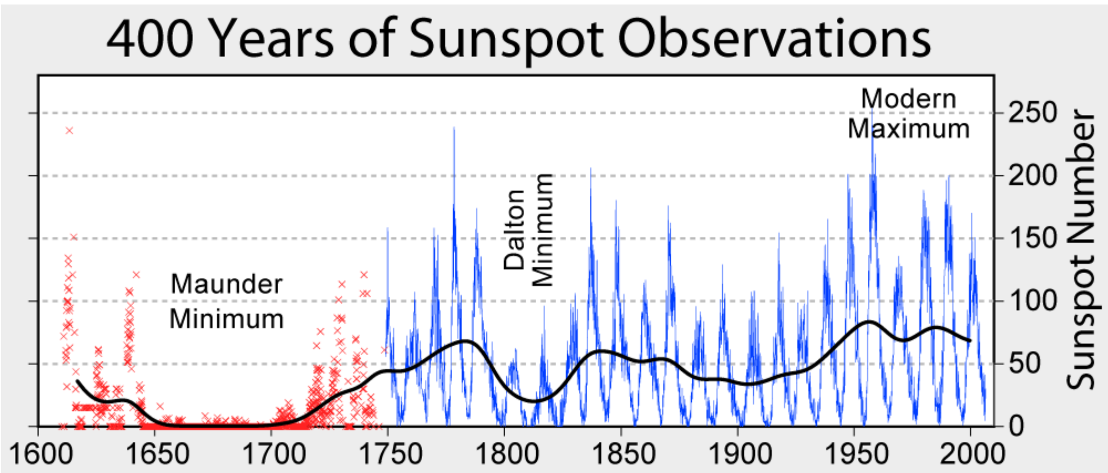



**Figure 7**: 400 Years of Sunspot Observations




[7] Zwolinski, Matt, The Ethics of Price Gouging. Business Ethics Quarterly, Vol. 18, No. 3, pp. 347-378, July 2008.

The Maunder Minimum was a period of extremely few sunspots. It occurred at the mid- and coldest-point in the Little Ice Age and enhanced the impact of climatological phenomena (see, Irish famine of 1740, section X). The Dalton Minimum occurred some 150 years later and coincided with some of the coldest and most abnormal weather in recent history. 1816 is often referred to as the year without summer, and although it occurred during the Dalton Minimum (and was perhaps exacerbated by it), the cause of such climatic anomalies was thought to have been primarily the result of extreme volcanic activity.

**Table 1**: Volcanic Explosivity Index (VEI)

| VEI | Description | Tephra Volume ($m^3$) | Plume Height (km) | Frequency | Examples |
|---|---|---|---|---|---|
| **0** | Gentle | $< 1x10^4$ | < 0.1 | Constant | Kīlauea,<br>Piton de la Fournaise |
| **1** | Effusive | $> 1x10^4$ | 0.1 – 1 | 12 / 1 | Stromboli<br>Nyiragongo (2002) |
| **2** | Explosive | $> 1x10^6$ | 1 – 5 | 1 / 1 | Galeras (1993)<br>Sinabung (2010) |
| **3** | Explosive | $> 1x10^7$ | 3 – 15 | 1 / 5 | Nevado del Ruiz (1985)<br>Soufriere Hills (1995) |
| **4** | Cataclysmic | $> 1x10^8$ | 0 – 25 | 1 / 10 | Pelee (1902)<br>Eyjafjallajokull (2010) |
| **5** | Cataclysmic | $> 1x10^9$ | > 25 | 1 / 100 | Vesuvius (79CE)<br>St Helens (1980) |
| **6** | Paroxysmal | $> 1x10^{10}$ | > 25 | 1 / 500 | Krakatoa (1883)<br>Pinatubo (1991) |
| **7** | Colossal | $> 1x10^{11}$ | > 25 | 1 / 1000 | Thera (1600BCE)<br>Tambora (1815) |
| **8** | Colossal | $> 1x10^{12}$ | > 25 | 1 / 100,000 | Yellowstone (640,000BP)<br>Toba (74,000BP) |

## 4.2 Volcanic activity and freeze events

Although not without its shortcomings, the Volcanic Explosivity Index (VEI) is a method of measurement used to rank eruptions[8]. Table 1 presents a brief overview of the index[9], and Table 2 presents some examples of cool periods that followed major eruptions. Supervolcanic eruptions like Yellowstone or Lake Toba are world-changing events. Lake Toba has been linked to 10-year volcanic winter that triggered a glacial cycle and reduced the human population by 80%. These supervolcanoes erupt approximately every million years, and thus fall well outside our 1 in a 1000 benchmark (hence their omission from Table 2).

[8] Newhall, C. G., and S. Self (1982), The Volcanic Explosivity Index (VEI) An Estimate of Explosive Magnitude for Historical Volcanism, *J. Geophys. Res.*, *87*(C2), 1231–1238

[9] For a thorough description of volcanic eruption data, please see the Smithsonian's Global Volcanic Program (http://www.volcano.si.edu/world/eruptioncriteria.cfm, accessed March 15 2012)

**Table 2**: Volcanoes triggering decrease in global temperature

| Year | Volcano | Description |
|---|---|---|
| 535 | Krakatoa<br>Tierra Blanca Joven<br>Rabual | It is speculated that one of these volcanoes erupted with a VEI >6. Historical reports note the lack of sunlight, the dense fog (tephra), and failure of crops. Scientific data from marine sediment supports a massive volcanic eruption. |
| 1315 | Kaharoa | The great European famine was triggered by a universal crop failure in 1316. Millions of deaths due to famine and disease were noted across the whole of Northern Europe. The period was marked further by the increase in criminal activity and social unrest, culminating in rebellion against the church and state. |
| 1600 | Huaynaputina | Russia experienced its worst ever famine between 1601 and 1603, with a third of its citizens dying, as exceptionally cold winters decimated agriculture across Northern and Eastern Europe and Asia. |
| 1815 | Tambora | The Year Without a Summer (see section 3.3.6) |
| 1883 | Krakatoa | Global temperatures decreased significantly in the four years after the eruption. The winters of 1887 and 1888 were particularly bad as record snowfall was recorded worldwide. |
| 1991 | Pinatubo | For 2-3 years following the eruption, global temperatures dropped. In 1992 and 1993 North America experienced two of the worst winter storms in recorded history. |

As is seen from the two tables, eruptions of a VEI magnitude greater than 4, essentially those that exhibit a Plinian eruption (the spewing of tephra into the atmosphere), result in a substantial stratospheric injection and can affect temperatures significantly. For example, the 1815 eruption of Mount Tambora had a significant and well-documented impact on the weather in the years that followed (see Year Without a Summer 1816, section 3.3.6).

## 4.3 Historical Examples

The UK and North America have been subject to several periods of extreme cold over the past 700 years. The following tables show a short summary of significant periods from the past 400 years. Freeze events prior to the mid-19th century occurred during the end of the little ice age – a period of low solar activity, while most of the 20th century freezes are linked to periods of extreme lows in the AO and NAO indices.

**Table 3**: Notable Freeze Events (UK since 1680)

| Year | Description |
|---|---|
| 1683-84 | Thames frozen for 2 months. Ground frozen up to 1m across all of England. Average winter temperature -1.2°C. |
| 1694-95 | Extreme cold temperature (-23°C) and 5 weeks of heavy snowfall, 25cm of ice lasting until mid-April. |
| 1739-40 | One of the most severe winters on record. Snow and extreme freezing temperatures (-24°C) persist for over 2 months. |
| 1813-14 | Heaviest snow in 300 years, followed by severe frost lasting 2 months. Travel hampered by floating ice and severe fog. |
| 1875-76 | Heavy snowfall from December to April across England (>0.5m in places). |
| 1946-47 | One of the worst winters on record for snowfall. Snow fell in January and lasted until March. Blizzard conditions across the UK. |
| 1962-63 | Heavy snowfall recorded from November to March. Blizzards cause widespread drifting. One of Britain's worst winters. |
| 2010-11 | Coldest December in 100 years, and significant snowfall lasts on the ground for 6 weeks. |

**Table 4**: Notable Freeze Events (US since 1880)

| Year | Description |
|---|---|
| 1888 | One of the worst blizzards in US history. Over 1m of snow fell in 3 days, winds of 50mph created drifts exceeding 15m in NE US. |
| 1899 | Massive blizzard sweeps across the United States (from Florida to Maine), temperatures drop to -35°C, and almost 1m of snow falls. |
| 1936 | One of the most intense cold waves in US history lasting 3 months and extending across most of the country. Midwest temperatures reach as low as -50°C. |
| 1976-78 | Two consecutive winters of extremely low temperatures and blizzards. Blizzard of 1977 caused 10m drifts and was followed by temperatures as low as -22°C. The 1978 cold wave lasts over 3 months, temperatures in Midwest US coldest on record. A Nor'easter blizzard in 1978 was one of the worst experienced in New England. |
| 1983 | Coldest December on record for the United States. Cold snap, driven down from Canada and blocked by the Rockies, lasted for 2 weeks. |
| 1993 | Massive storm blankets the Eastern US (26 states) and Canada in snow. One of the worst blizzards in history. 13 cubic miles of snowfall. |

### 4.3.1 Europe 1316

The great famine on 1315-1317 was caused by prolonged periods of extreme weather (specifically, cool, wet summers and freezing winters), which resulted in widespread crop failures across Northern Europe. Populations had risen sharply during the previous 300 years as an extended period of global warming helped produce bountiful crop yields and reduced the number of cold-related deaths. The change coincided with a decrease in solar activity (the Wolf Minimum) and the plinian eruption of Kaharoa in 1314 (+/- 12yrs). It is unknown if the eruption of Kaharoa in New Zealand triggered the famine, was a connected or exacerbating force, or had minimal (or no) impact.

Unusually heavy rain in the spring and summer of 1315 decimated crop yields (the plant-to-harvest ration dropped to 1:2 – more than three times worse than in previous years, and fractional compared to a modern yield of 1:30). The crop failure set in motion a chain of cascading failure. Livestock feed was greatly reduced, and food prices rose dramatically. After a year of bad weather and general malnourishment, diseases like pneumonia and tuberculosis spread wildly, killing 10-25% of the population. Food stocks would not return to normal for almost a decade, and by that time, the criminalisation (there was widespread theft, rape and murder) and starvation of society had cast doubt over the authority of the Catholic Church and of the capacity of the ruling governments.

### 4.3.2 Russia 1601-1603

The eruption of Huaynaputina (Peru) in 1600 may have triggered two exceptionally cold winters that triggered widespread social change, including the overthrow of Russia's reigning tsar[10]. There are records of poor weather and crop failure across the world, with 1601 cited as being the coldest year in the Northern Hemisphere in 600 years. In Russia, the government response of giving food and money to impoverished citizens exacerbated the impact of the crop failures and famine. People travelled to the capital in search of hand outs, causing economic disruption, the dissolution of rural communities, elevated tensions in the crowded city, and irreversible political turmoil. It is estimated that over 2 million Russians (over a third of the population) died from starvation.

[10] "1600 Eruption Caused Global Disruption", *Geology Times*, 25 April 2008, accessed 24 March 2012

#### 4.3.3 Ireland 1740[11]

The Maunder minimum, a period of extremely low solar activity, was the last extensive cold period of the Little Ice Age (1400-1800). Shortly after the minimum's passing, a prolonged period of bad weather struck Europe in December 1739. Ireland was hit particularly hard as exceptionally cold winters in 1739 and 1740, and cool summers until September 1741 decimated crops and caused 13-20% excess mortality. Snowfall was minimal but temperatures were low enough to cause rivers and lakes to freeze in January. Fuel supplies dropped as coal ferries from England and Wales could not access the quays, causing an immediate spike in retail prices. The production of many foodstuff and other products was restricted as water-powered equipment (e.g. Mills) froze. The start of the famine was began with the ruin of potatoes (one of two food staples), which, having ripened the previous autumn, froze.

While the frost eased in the spring of 1740, a period of cool, dry weather followed. The drought decimated sheep and cattle populations, and destroyed much of the seeds sown the previous autumn. With potatoes scarce, grain prices skyrocketed. Rural villages emptied as starving citizens descended on the major towns. Social unrest increased, riots broke out, and hording and profiteering were rampant. International skirmishes restricted the import of necessary aid, and the export of goods critical to the economy.

A meagre harvest was compounded by blizzards through October and November. A temporary thaw, and massive rainstorm, caused flooding throughout the country. Freezing temperatures returned a day later, causing lakes and waterways to ice over. Shortly thereafter another quick thaw saw more flooding and damage as ice blocks wrecked vessels moored on the Liffey River. It was not until summer 1741 that the famine started to subside. Ships from America brought grain, a mixed harvest, and a 13-20% drop in population helped alleviate the food crisis. The ill effects of such events, however, affected Ireland for decades afterwards.

#### 4.3.4 Year without Summer 1816

A historic low period of solar activity, known as the Dalton Minimum, and the eruption of Mount Tambora (Indionesia) in 1815, were likely causes in a drop in global temperatures that damaged crops and agriculture and resulted in over 200,000 extra deaths in Europe in 1816. Mount Tambora was classified as a colossal eruption (VEI = 7), a 1 in 1000 event, and occurred shortly after four other volcanoes erupted (all VEI > 4). The volcanic activity created a thick layer of atmospheric dust that prevented the already diminished solar radiation from penetrating.

The volcanic dust created a fog that lasted much of spring and summer. Frost in May and June was reported in the North-eastern United States; and river ice was observed in Pennsylvania. Cold weather and heavy rainfall damaged crops across Europe. Similar damage was reported in China and India. In all countries that experienced such extreme weather, food shortages (and price increases) preceded mass starvation, malnutrition, rioting, disease and death.

The effects were widespread, but depending on local crop dependence, affected some communities more than others. The New England area was particularly hard hit. As a result, many farmers who lost entire crops moved southwest, beginning the population of the American heartland.

#### 4.3.5 North America 1993

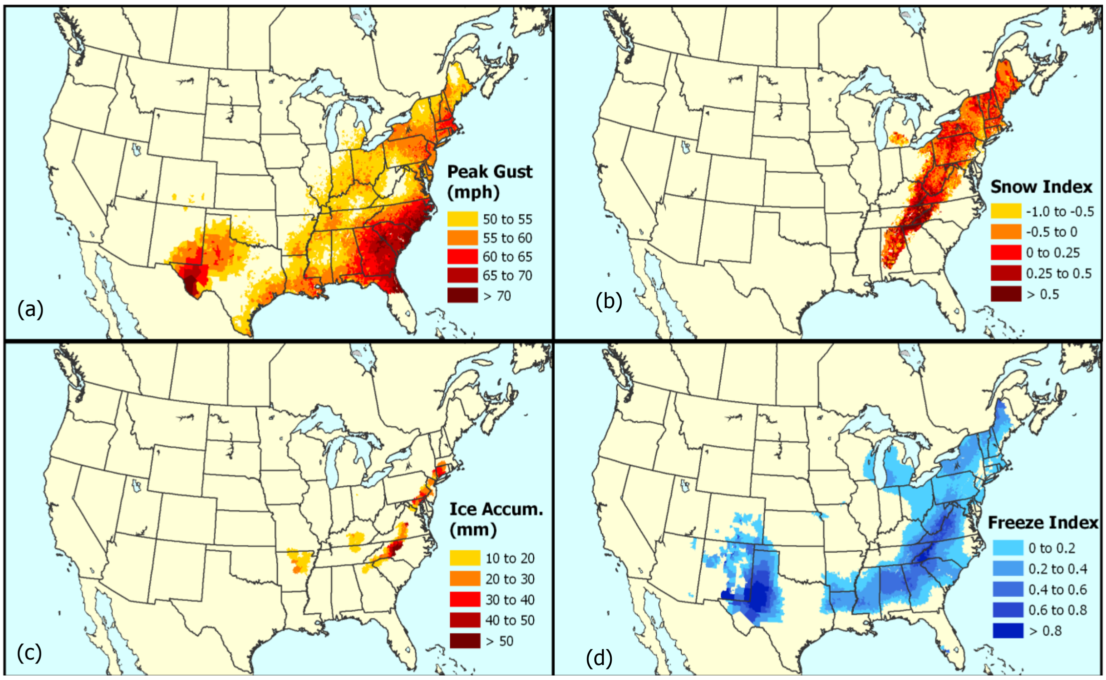
The extra-tropical storm that struck the United States' East coast in March 1993 is often referred to as the 'Storm of the Century'. The storm, which lasted three days, claimed 100-310 deaths and caused between $5-6 billion in damage (with insured losses of nearly $2 billion). The cyclone, which started in the Gulf of Mexico, made landfall west of Tallahassee, creating a 3.7 metre storm surge. A squall

[11] See David Dickson, *Arctic Ireland: The Extraordinary Story of the Great Frost and Forgotten Famine of 1740-1741* (Belfast, 1997).

line to the south of the storm, over Cuba, killed 10 and caused $1 billion of damage. Meanwhile, the squall line to the north caused multiple thunderstorms and tornadoes across Florida. As the storm moved northeast, the rain turned to snow, blanketing the United States: record snowfall of 127cm was reported in North Carolina (along with record winds of over 101mph), 109cm in Syracuse, NY. Further east, Philadelphia, New York, and Boston, experienced only a foot of snow before the precipitation turned to ice pellets as temperatures dropped to -12*C. Record low temperatures were recorded in 68 cities across 18 states.

It is estimated that over three million people were without power during the storm. Approximately 25% of all flights were cancelled during the storm, and every airport on the eastern seaboard closed at some stage during the March 12-14 period. In terms of economic impact, 25% of the losses were sustained in Florida (mostly due to Tornado and high wind damage). RMS[12] produced a range of insured losses (projecting the 1993 storm onto a 2008 model); out of the total damage as 37% due to Snow, 26% due to Wind, 21% due to Tornadoes, 11% due to Ice, and 5% due to Freezing Temperatures.

**Figure 8 –** Hazard Footprint: 1993 Superstorm




**Source**: RMS Special Report (2008): The 1998 Ice Storm: 10-year retrospective. RMS reconstruction model of 1993 superstorm showing a) 3-second peak gust windspeed in mph; b) snowfall as an index from its deviation from climatological conditions; c) ice thickness in millimetres; and d) index of temperature deviation from climatological conditions.

Although the storm is often referred to as the 'Storm of the Century', similar meteorological events occur with a greater than 1 in 100 return period. The storm itself is similar in scale and devastation to the Great Blizzards of 1888 and 1899, and, to a lesser extent, the Nor'easters of January 1996, and December 2003). In 130 years of NWS data, a category 5 storm on the NOAA's NESIS (North East Snowfall Impact Scale) has occurred twice (1993 and 1996), although the economic and human impact was far less in 1996. Accordingly, the NOAA now use a Regional Snowfall Index (RSI) to make results more regionally relative (e.g. 6 inches of snowfall in Florida, has a far greater impact that 12

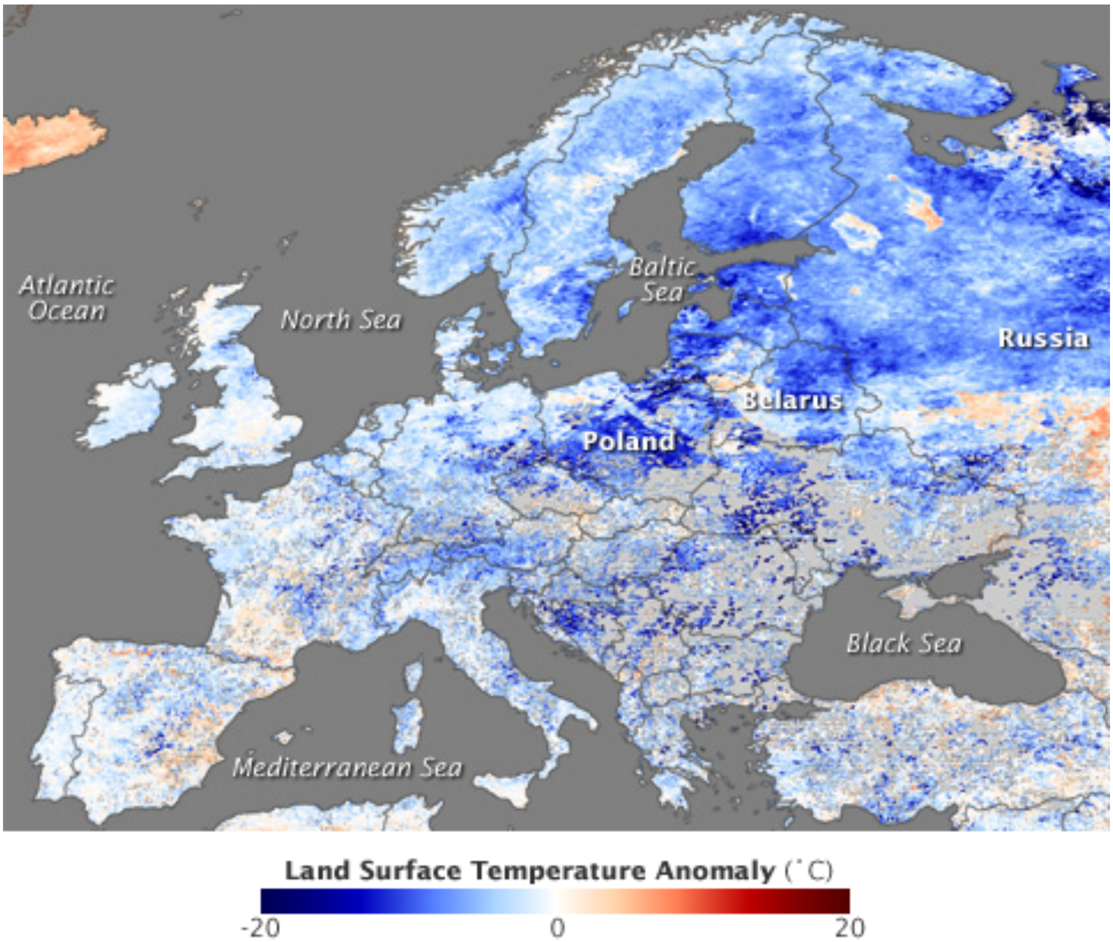
[12] Risk Management Solutions (RMS), 2008. The 1993 Superstorm: 15-year Retrospective. http://www.rms.com/publications

inches of snowfall in Vermont). Considering the blizzards at the latter part of the 19th century, and more recent (albeit weaker) storms, a North American meteorological event like the one experienced in 1993, has an approximate 1 in 30 year return period[13].

#### 4.3.6 Historical example: Europe 2009-2010

A negative NAO, caused by a high pressure system over Greenland and Iceland, and a degree of cyclogenesis from North American storms, brought an extended period of cold weather to much of Northern Europe. In the UK, snow began falling on December 16th 2009, and freezing conditions lasted until late January 2010.

**Figure 9** – European Temperature Map (December 2009)




**Source**: NASA Earth Observatory

In the UK, road conditions were reported as the worst in 20 years, as snowfall and freezing temperatures overwhelmed the local authorities' capacity to plough and salt roads. The combination of snow, extremely low temperatures, the more snowfall on ice, and so forth, continued for weeks, causing unprecedented numbers of minor injuries (fractures, sprains, bruising, etc.) as a result of falls and other weather related accidents. The Department of Health estimated a possible 40,000 excess deaths because of the cold weather. Insurance estimates cost the freeze at almost £700 million per

[13] RMS also advocate a return period of 30-years, based on a winter storm catastrophe model which uses a stochastic event set based on 30,000 years of winter storm activity.

day, as people were unable to travel to work or shopping centres, and natural gas usage increased to record levels (up 25% to 455m cubic meters). This cost also includes the closure of international and national airports, as well as the train delays occurring throughout the UK, and connecting European services.

## 5 Magnitude Scales

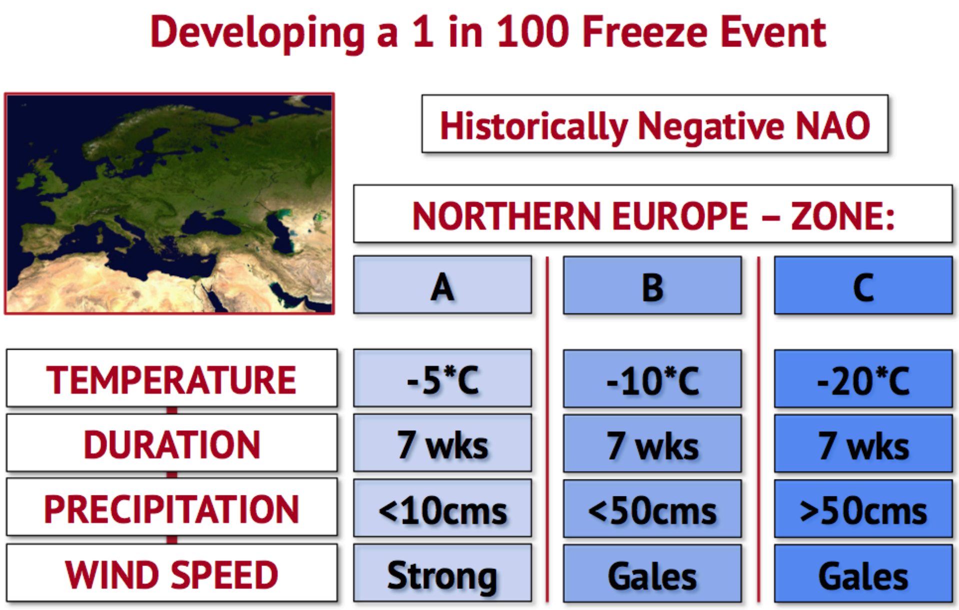
Artic (AO) and North Atlantic (NAO) Oscillation are strong indicators of the likelihood of climatologically driven extreme weather. However, they do not capture the severity or impact of the weather. In the United States, the severity of Nor'easters was previously indicated using the Northeast Snowfall Impact Scale (NESIS). The scale was then updated to the Regional Snowfall Index (RSI), and now includes population data to assess more accurately the societal impact of the snowstorm.

The Met Office uses an index often referred to as Winter Cold Wave Duration. The number is derived from counting the number of days with minimum temperatures more than 3*C below the daily mean (for the same climate period between 1961-1990) for more than five consecutive days. This does not capture the severity of the cold weather. Other indices are calculated from the proportion of days where the daily maximum temperature falls below the coldest 10% of temperatures during the same climate period over a 20-year average (known as TX10P).

In an attempt to synthesise intensity and impact, we suggest an adaptation of the degree-day calculation. Our Extreme Freeze Intensity (EFI) scale is calculated through subtracting the daily temperature ($X_{temp}$) from the mean temperature for that climate period ($Mean_{temp}$), multiplied by the number of days where $X_{temp} < Mean_{temp}$. To fit a 1-10 scale, the number is then divided by. So, if the mean temperature for January is 3*C and the recorded temperature is -10*C for 30 days, the EFI is 3-(-10) x 30 / 100 = 13 x 30 / 100 = 390 / 100 = 3.9.

From the climatological and socio-economic impact data, we can derive a 1in100 scenario. Within such a scenario we develop three zones of severity:

**Figure 10**: Developing a freeze severity impact scale




**Source**: Centre for Risk Studies, University of Cambridge

Using our EFI, Zone A is ranked at 2.45, Zone B is ranked at 4.9, and Zone C is ranked at 9.8. The impact of this freeze has been calculated as the following:

**Table 5**: 1in100 Freeze impact on Northern Europe

| NORTHERN EUROPE | | | |
|---|---|---|---|
| **Factor** | **Zone A** | **Zone B** | **Zone C** |
| **Human** | 5% | 10% | 15% |
| **Economic** | -0.2% GDP | -0.5% GDP | -1.0% |
| **Industry Activity** | **15%** | **20%** | **25%** |
| **Transportation** | | | |
| **Road** | 10% | 25% | 50% |
| **Rail (delays)** | 12% (40%) | 20% (60%) | 30% (80%) |
| **Air Travel** | 10% | 20% | 30% |
| **Sea Travel** | 5% | 10% | 25% |

**Source**: Centre for Risk Studies, University of Cambridge

Magnitude scales and Impact calculations are unreliable and slightly speculative endeavours, however they aid the framing for quick calculations in the assessment of socio-economic and geospatial impact.