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The North Atlantic Oscillation and snow avalanching in Iceland

C. J. Keylock

School of Geography, University of Leeds, Leeds, West Yorkshire, UK

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[1] The number of snow avalanche cycles occurring in Iceland is correlated to a major source of variability in climate, the North Atlantic Oscillation. A new index for this oscillation is produced that reflects the cumulative effect of snow build-up in a starting zone. An analysis of the time-series for this index shows that recent avalanche tragedies in Iceland are linked to a rise in this index. Consequently, estimations of avalanche return periods and thus, avalanche hazard zones, may need re-evaluation. Because the oscillation has an impact upon climate throughout the Northern Hemisphere, this may be necessary in a number of other countries. *INDEX TERMS:* 1863 Hydrology: Snow and ice (1827); 1620 Global Change: Climate dynamics (3309); 1827 Hydrology: Glaciology (1863). **Citation:** Keylock, C. J., The North Atlantic Oscillation and snow avalanching in Iceland, *Geophys. Res. Lett.*, *30*(5), 1254, doi:10.1029/2002GL016272, 2003.

1. Introduction

[2] The North Atlantic Oscillation (NAO) is an important climate fluctuation in the Northern Hemisphere and is typically defined in terms of a standardized sea-level air pressure (SLP) difference between the Azores high and the Icelandic low [*Rogers*, 1984; *Hurrell*, 1995]. Recent works concerning the NAO are reviewed by *Greatbatch* [2000] and *Wanner et al.* [2001]. Recently, the NAO has tended towards a more positive phase [*Hurrell*, 1995] and the possibility exists that this may persist due to anthropogenic forcing of tropical sea surface temperatures, which are correlated to the NAO [*Hoerling et al.*, 2001]. A positive NAO strengthens westerlies over the Atlantic and produces a more northerly storm track, leading to wet and warm conditions in Scandinavia, with drier conditions in southern Europe [*Rogers*, 1997]. It has been shown that there is a significant positive correlation between the NAO index and monthly precipitation over Iceland [*Appenzeller et al.*, 1998] as well as precipitation in Alpine areas [*Quadrelli et al.*, 2001]. This has manifested itself in the glacial mass balance records, with a positive correlation in Scandinavia and a negative correlation in much of the Alps [*Six et al.*, 2001], although the strength of this relationship seems to be a function of continentality [*Nesje et al.*, 2000]. Although an avalanche release is not a simple function of snowfall, there would appear to be a possibility that avalanche activity is also correlated with the NAO.

[3] The possible persistence of a positive NAO is of concern to avalanche scientists in northern Europe. In Iceland, catastrophic avalanches between 1974 and 2000 have caused much personal suffering and have resulted in direct economic losses of $41 million [*Jóhannesson and Arnalds*, 2001]. It is crucial to know how changes in climate may effect avalanche return periods, which must be estimated for avalanche risk analysis and more traditional hazard zoning procedures.

[4] The relationship between meteorology and snow avalanche release is complex due to the non-linear processes that operate within a snow cover as it evolves [*McClung and Schaerer*, 1993]. Although bond development will mean that in general, snow stability increases through time, crystal metamorphism and the burial of weak layers can result in delayed avalanche release [*Birkeland et al.*, 1998]. Due to relatively low temperature gradients in the snowpack and a high frequency of major storm events compared to many Alpine regions, it might be thought that snowpack metamorphism processes are less significant for avalanche release in Iceland than in many countries. Indeed, *Björnsson* [1980] states that 80%–90% of avalanches in Iceland are directly linked to a particular set of synoptic conditions, while *De Quervain and Meister* [1987] note that in Switzerland, 25% of avalanche releases are delayed occurrences. Hence, any links between avalanching and the NAO is probably easier to demonstrate in Iceland. However, the fact that Icelandic SLP data are often used to define the NAO means that the existence of any such link is significant for the interpretation of avalanche hazard at a much wider scale.

[5] An additional difficulty with linking avalanching to climatic variables is that observations of avalanche activity have become more systematic through time. Thus, a recent increase in observed events may merely reflect improving data. However, despite these problems, links between climate and snow avalanching have been identified [*Mock and Birkeland*, 2000].

2. Data and NAO Indices

[6] The NAO index used in this study is based on a time-series of the normalized difference in SLP anomalies between Gibraltar and southwest Iceland [*Jones et al.*, 1997]. Monthly averages were used, with data from October to April used to define an avalanche season because over 95% of recorded avalanches in Iceland have occurred within this period. Avalanche occurrences were obtained from records held at the Icelandic Meteorological Office. It includes all known events as of September 1997, and also includes some additional avalanches discovered since then. Analysis in this study primarily focuses upon more recently recorded avalanches. Before the late 1960s and early 1970s only avalanches that caused fatalities or damage to property were recorded. Even today, many avalanches in Iceland still go unobserved and systematic recording of events on paths close to towns has only been in place since the late 1980s.

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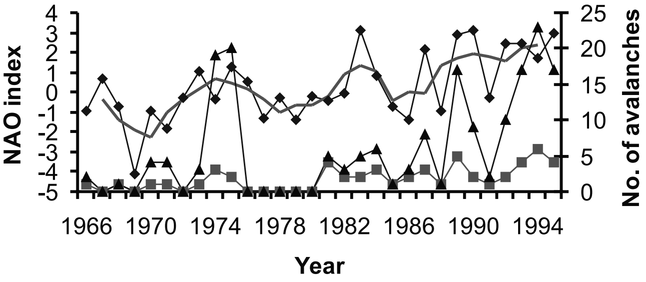

Figure 1. A comparison between an avalanche season NAO index (diamonds) its three-year running mean (heavy line) and the number of recorded avalanche cycles (squares) and events (triangles). The year *x* avalanche season lasts from October *x-1* to April *x*.

These towns tend to be coastal and are distributed throughout the country.

[7] Figure 1 shows the NAO index and the number of observed avalanche cycles and observed events from 1965–66 to 1995–96. An avalanche cycle was defined as a seven-day period within which one or more avalanches were observed. This measure was felt to be more robust with respect to the improvements in avalanche observation than the actual number of events recorded. The graph suggests a relationship between the NAO and Icelandic avalanching, with a greater propensity for avalanching during positive phases of the NAO. Rank correlations between the NAO and the number of avalanches and avalanche cycles were significant at the 1% level with values of 0.58 and 0.55 respectively. Due to the difficulties with the Icelandic avalanche data, it is encouraging to note that the correlation with the number of events increases when the events since 1982 are considered (to 0.67). In addition, the number of observed events decreases in those years with low values for the NAO index (1988 and 1991). The sixteen years with zero or one avalanche event had a median value for the NAO of −0.72, which was significantly different at the 1% level to that for years with two or more events (1.94) based on a Mann-Whitney test.

[8] The non-normalized SLP differences between Iceland and Gibraltar have increased since the 1960s for December, January, February and March, with the rise in March unprecedented in the record [*Jónsson and Miles*, 2001]. Hence, the recent increase in the NAO and associated changes in weather patterns can be related to monthly changes. A snow avalanche release occurs due to an accumulation of snow that may be deposited rapidly in a storm, or may build up more steadily. Given that avalanche releases seem to be related to positive episodes of the NAO, a new NAO index was formed that might better reflect the cumulative effect of increases in snowpack thickness:

(a) The mean and standard deviation for the October to April, monthly SLP values at Gibraltar and south-west Iceland were obtained from 1825–26 to 1994–95;

(b) SLP anomalies were produced at each time and normalized by their standard deviation;

(c) The difference in these values between Gibraltar and Iceland was found;

(d) Over an avalanche season, consecutive positive values of this NAO index were cumulated, negative values were set to zero.

[9] Figure 2 shows that between 1965–66 and 1994–95 there has been an upward trend in this cumulative NAO index (CNI). There has also been an increase in observed avalanches, which reflects the improvements in observation, but is also related to changes in the CNI. Of the 210 months displayed in Figure 2, 100 have positive values for the CNI and occur in 46 separate episodes (separated by zero values). Only 7 of 52 avalanche cycles did not occur during, or within one month of positive CNI months. Of the remaining 45 avalanche cycles, 37 occurred in the 54 months that contributed to 14 episodes with maximum CNI values greater than 4.8. Only 2 of these 14 episodes (lasting a total of 7 months) had no avalanche cycles associated with them. Of the 22 episodes (lasting 27 months) with a maximum CNI less than 2.0, only 4 avalanche cycles were recorded. From 1980–81 to 1994–95 there was a significant change ($p = 0.019$) in the median of the maximum CNI per episode compared to the period 1965–66 to 1979–80 as assessed using a Mann-Whitney test. However, the duration of these episodes has not significantly increased ($p = 0.281$).

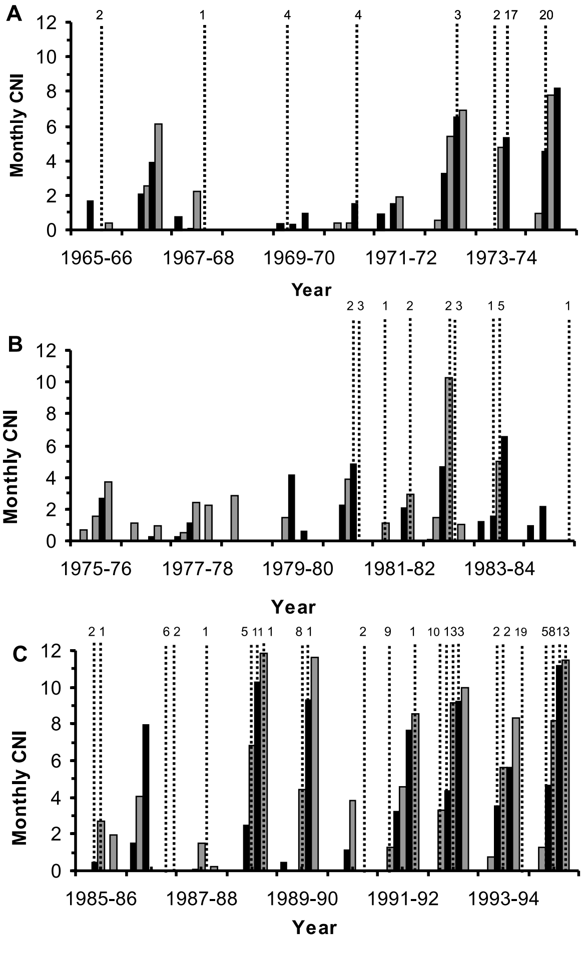

Figure 2. Values for the CNI index for the months October–April from 1965–66 to 1974–75 (a), 1975–76 to 1984–85 (b) and 1985–86 to 1994–95 (c). A vertical line indicates an avalanche cycle and the number above the line indicates the number of recorded events during that cycle.

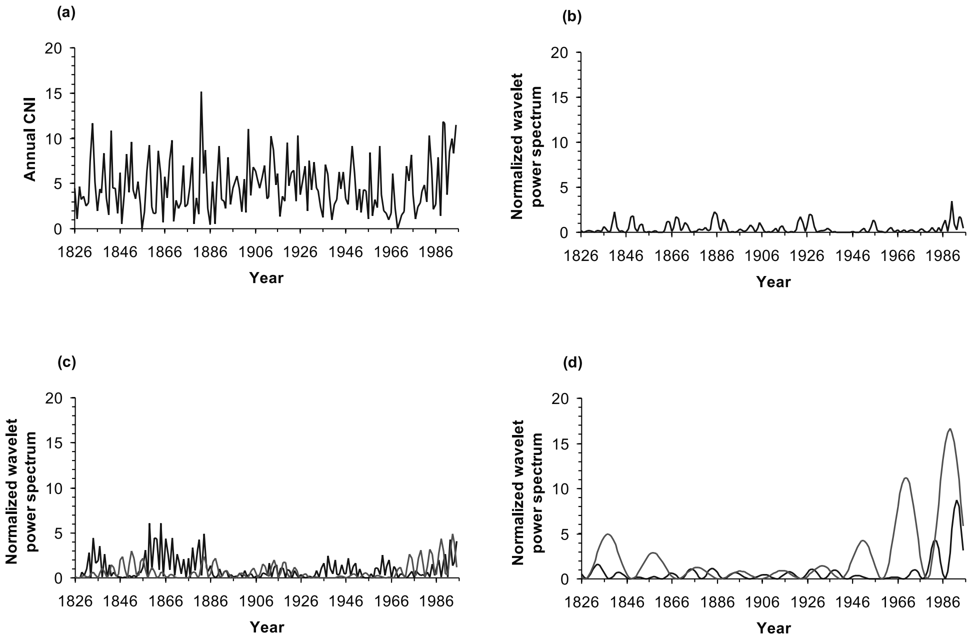

Figure 3. Continuous wavelet decomposition of the avalanche season maximum CNI. (a) contains the original signal, (b) shows the wavelet power spectrum normalized by the signal variance at the two year scale, (c) shows the spectra for the four year (black) and eight year (gray) scales, (d) shows the spectra for the sixteen year (black) and thirty-two year (gray) scales.

[10] The avalanche season maximum CNI is a better predictor of avalanching than the NAO index displayed in Figure 1. A binary logistic regression using in turn, the annual maximum CNI and NAO, was used to predict years with zero or one avalanche cycle (category 1) and those with more than one (category 2). The results were insensitive to the choice of link function. The effectiveness of the models was tested by forming 224 pairs from the 16 values in category 1 and 14 values in category 2, and checking that the element of each pair that belonged to category 1 was predicted to do so. The model formed from the NAO had an 86% success rate, compared to 93% for the CNI. Rank correlations between the NAO and avalanche cycles per year (R = 0.59), as well as avalanche events per year (R = 0.60) were weaker than equivalent correlations for the CNI (R = 0.68 and R = 0.72, respectively).

3. Analysis of the Cumulative NAO Index

[11] Figure 3 shows the CNI signal for the period 1825–26 to 1994–1995, together with a wavelet decomposition using a Morlet wavelet. Similar results to those shown were obtained using other wavelets. Figure 3a indicates that the CNI has had a similar upward trend since the 1970s as other NAO indices [*Hurrell*, 1995; *Jónsson and Miles*, 2001]. The wavelet analysis indicates that this trend is seen most clearly in the lower frequency behavior of the CNI (Figures 3c and 3d). Although the record used here is too short to demonstrate periodicities at 32 years, the results are in broad agreement with similar analyses of proxy records [*Wanner et al.*, 2001]. A notable feature of the four year scale component of the signal (Figure 3c) is a high energy period from the early 1830s to the early 1890s, followed by a reduction in variance until the 1980s. This effect manifests itself in the CNI signal. A set of Siegel-Tukey tests for difference in variance were applied to the signal in Figure 3a isolating in turn, consecutive segments of record with lengths from 8 to 130 years duration at all possible locations in the series. The period with the greatest difference in variance compared to the rest of the record (significant at $p < 0.01$) was for a segment with a reduced variance from 1891 to 1955. Thus, there has been a recent upward trend in the CNI at low frequencies, coupled to an increase in the energy at higher frequencies.

4. Discussion

[12] An important feature in Figure 3a is the peak in the CNI in the 1880s. This is larger than any equivalent feature in more conventional NAO indices and seems to have been a localized phenomenon, with little expression in the low frequency signals (Figure 3d). Of the 66 avalanche events occurring in Iceland between 1825–26 and 1965–66 for which data were available, eleven occurred between 1884 and 1894. Lichenometric data show that in southern Norway, a peak in avalanche activity occurred somewhere between 1850–1900 [*McCarroll et al.*, 1995]. The main peak in 1882 pre-dates the eruption of Krakatoa in 1883 and the rise in wavelet power from 1854 post-dates by nine years a major eruption of Hekla in Iceland. This lack of correlation with volcanic processes raises the possibility that this event is connected to the traditional dates for the termination of the Little Ice Age. The more recent rising trend, which has a low frequency expression, is of great cause for concern. Avalanche hazard zoning or risk mapping is based on the determination of avalanche return periods from historic data. The links between the CNI and avalanche activity demonstrated in this work, coupled to the rising recent trend in various NAO indices suggests that current avalanche hazard zones may need to be revised.

This is not just an issue for Iceland as the NAO has a hemispheric expression.

[13] It is important to note that not all avalanche cycles are linked to the index described here. For example, from 1879–80 to 1929–30 eleven years have annual maximum CNI values greater than 7.0 and ten years have values less than 3.0. Sixteen years have recorded avalanche events, of which seven have CNI values greater than 7.0 and just one year has a CNI value less than 3.0. However, it was in February of this year (1885) that a major avalanche event in Seyðisfjörður destroyed several buildings and caused a number of fatalities. It would appear that in this case, more local conditions were crucial. An index based on pressure differences between east and west Iceland from 1873 onwards yields its greatest negative value (representing strong northerly winds) for this month (T. Jónsson, personal communication, 2002). These northerly winds may have contributed to snow loading in avalanche starting zones in a similar manner to the more northerly storm tracks associated with positive values for the NAO.

[14] Avalanche risk and hazard zoning requires an assessment of the frequency of avalanche occurrence and an evaluation of probable damage [*Keylock and Barbolini*, 2001], which is linked to the forces exerted by the avalanche. Avalanches that travel further will have, in general, greater velocities and thus, higher impact pressures, at a particular location in the run-out zone of the avalanche path. Hence, data on run-out distance provide an indirect method of evaluating peak pressures. To compare avalanche travel distances from different paths it is necessary to non-dimensionalize these distances. Although there are sophisticated methods for this [e.g., *Dade and Huppert*, 1998] these require more information than is usually available from historical events. Hence, this study used the runout ratio approach, which has been adopted in a number of studies in the avalanche literature [e.g., *Keylock et al.*, 1999]. The travel distance of individual avalanches was independent of the CNI. A rank correlation is insignificant at the 10% level. Such a result tentatively leads to the conclusion that (in Iceland at least) the NAO is not affecting the distribution of avalanche sizes and hence, travel distances. Instead, positive values of the NAO increase the number of avalanche cycles, but the avalanches are drawn from the same population of events.

5. Summary

[15] Any connection between the NAO and snow avalanching is of great importance because, if the recent rise in the NAO continues, there are likely to be increasing fatalities from snow avalanches in Iceland. A cumulative NAO index appears to exhibit a closer relationship to avalanche activity than the standard index. The implication for hazard and risk zoning is that the effective return period of particular run-out distances may be set to decrease in Iceland and perhaps other areas in northern Europe. Because there is no significant correlation between the NAO and run-out distance, the historical record is still a legitimate source of information for estimating avalanche travel distances.

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C. J. Keylock, School of Geography, University of Leeds, Woodhouse Lane, Leeds, West Yorkshire LS2 9JT, UK. (c.keylock@geog.leeds.ac.uk)