Climate Change Threats to one of the World's Largest Cross-Country Skiing Races

Martin Falk[1], Eva Hagsten[2]

[1] Austrian Institute of Economic Research (WIFO), Vienna, Austria

[2] University of Iceland

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Abstract

This study investigates the relationship between climate variability and the participant cancellation ratio at one of the world's oldest, longest, and largest cross-country skiing races, the Vasaloppet. This race is held in the Swedish region of Dalarna on the first Sunday of March each year. Data are based on the number of registered and starting skiers and local weather conditions (natural snow supply and temperature) for the period 1951-2016. As the dependent variable is bounded between zero and one, the fractional logit model is employed. Estimations show that a lack of natural snow significantly increases the cancellation ratio. In particular, a decline in snow depth from the average level of 57 centimetres to 30 centimetres over the sample period leads to an increase of 3.3 percentage points in the cancellation ratio. Interestingly, the dependence on natural snow has declined in absolute terms in recent years due to various adaptation practices, such as snow storage and snow production.

Keywords: Vasaloppet race, cancellation, cross-country skiing, snow conditions, climate change

1. Introduction

Cross-country (or Nordic) skiing is the oldest type of skiing that started as a means of transportation over snow-clad land. One of the most ancient skis ever found originates from the north of Sweden and is dated to more than 5,000 years old.[1] In the late 1900th century cross-country skiing developed as a sport in the north of Europe, and the first competitions took place in Norway.[2] Presently, competitions are held at all levels – national and international –on tracks of varying distances.[3] The Swedish Vasaloppet is one of the oldest, longest and largest of these races in the world, stretching 90 kilometres through the villages and wilderness of the Dalarna region. It was inaugurated in 1922 to celebrate the historical past of Sweden, specifically referring to the soon-to-be King Gustav Vasa who was chased by Danish enemies along the same route in the 16th century (although in the opposite direction). Having started with a few hundred participants, the main competition now attracts 15,800 cross-country skiers from several parts of the world on the first Sunday of March each year. In fact, a whole week is dedicated to different races, allowing a great amount of professional as well as amateur skiers to participate. The large group of participants reflects how widespread cross-country skiing is in Sweden and how attraction to the sport is surging (Skidspår, 2017). Approximately one out of five persons actively engaged in cross-country skiing during 2014-2015, with higher proportions in certain age and education classes.[4]

Sporting events of a certain scale inevitably involve cancellations and no-shows, even though the Vasaloppet makes it possible to transfer an early registration to another participant (source: www.vasaloppet.se). Despite this opportunity, entrants still cite illnesses, accidents, poor skiing conditions and other circumstances as reasons for withdrawing. In the last 70 years, an average of about 12 per cent of registered skiers did not take part in the race. On three occasions (1932, 1934 and 1990), the race was cancelled by the organisers because of a severe lack of snow and extraordinarily mild temperatures.

According to the Swedish Meteorological and Hydrological Institute (SMHI), the maximum snow depth in the period 1991-2014 was considerably lower than in the preceding years 1961-

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[1] http://www.vbm.se/sv/se-and-gora/utstallningar/skidutstallningen.html.

[2] https://www.olympic.org/cross-country-skiing.

[3] http://www.fis-ski.com/cross-country/.

[4] http://www.scb.se/hitta-statistik/statistik-efter-amne/levnadsforhallanden/levnadsforhallanden/undersokningarna-av-levnadsforhallanden-ulf-silc/pong/publikationer/fritid-2014-2015/, downloaded 2017:05.

1990 all across Sweden, except in northern Norrland (Wern 2015). Climate change scenarios for Scandinavia project a reduction in the number of days with snow coverage and a larger proportion of days with only a thin layer of snow until the end of this century (Jylhä et al. 2008). The Intergovernmental Panel on Climate Change (IPCC) (2014) concludes that global warming will be strongest in the south of Europe in summer time and in the North of Europe during winter. Its fixed location at the low elevations of southern Sweden (ranging between 170 and 370 metres above sea level) makes the Vasaloppet vulnerable to climate variability, although studies of the effects of climate change on traditional sporting events are rare. One exception is an analysis on how climate change has impacted the Eleven Cities Tour (the *Elfstedentocht*, an ice-skating race) in the Netherlands over the course of 90 years (Visser and Peterson 2009). Similarly, Scott et al. (2015) show that only half of the previous Winter Olympics locations will still have a viable climate by 2050 despite their extensive use of snowmaking equipment.

This study investigates the relationship between the cancellation ratio of the Vasaloppet and climate variability for the period 1951-2016 based on SMHI weather data and information the organiser has provided on the number of registered and starting participants (www.vasaloppet.se). The weather conditions of specific interest are snow depth and temperature. Information is derived from a detailed geographical level based on the assumption that individual behaviour relates to climate in a complex way, as suggested by Gössling and Hall (2006). To analyse the relationships, a dynamic Fractional logit model is used, which can handle the bounded nature of the cancellation ratio (it takes on values between zero and one).

The main contribution of the study is to show that adverse weather conditions may be a threat to events or businesses dependent on a specific climate. In this particular case, the effects of weather variability are illustrated by focusing on a traditional winter sport race with strong local and cultural ties. Besides the opportunity to use long and uninterrupted time series for the Vasaloppet and detailed data on local weather, this analysis is novel in that it stresses the increased awareness of climate among participants as well as race organisers. The approach at hand makes it possible to identify both the point in time when skiers began to react to changes in local natural snow coverage and when the organisers fully realised the severity of the situation, or had the capacity to take action in response.

In recent years, the organisers of the Vasaloppet have intensified their efforts to compensate for difficult weather conditions by adding a snowmaking facility along the route (in Oxberg) and deploying mobile snow cannons where possible (source: www.vasaloppet.se). However, the long distance of the race and the terrain make snowmaking and snow farming particularly difficult and costly. In the absence of natural snow, snowmaking requires negative temperatures over a minimum number of days and low humidity; the ground also needs to be frozen to allow the snow to be transported out to the tracks. Even when snowmaking succeeds, presumptive participants may have a preference for natural snow (as in the case of downhill skiing in Sweden; Falk and Hagsten 2016), further affecting the cancellation ratio. The success of this cross-country skiing race may thus depend on favourable climate conditions to a larger extent than in downhill skiing areas, for instance, where snowmaking is also widely used to prepare slopes, but within more limited areas and where the natural experience may be less affected by absence of snow.

2. Theoretical background and empirical model

While several studies investigate the relationship between skier visits to downhill ski resorts and snow conditions, few have focused explicitly on the implications of climate change for cross-country skiing (see Scott, Hall and Gössling 2012; Becken 2013; and Kaján and Saarinen 2013 for reviews of the related literature). Exceptions include Landauer, Pröbstl, and Haider (2012); Sælen and Ericson (2013); and Pouta, Neuvonen and Sievänen (2009). Based on a discrete choice experiment, Sælen and Ericson (2013) show that increasingly reliable snow conditions have a strong and positive effect on cross-country skiers' willingness to spend money. Finnish skiers, for instance, consider the skiing infrastructure to be a public good that should be provided for free, even when snowmaking is required (Landauer, Haider and Pröbstl-Haider 2014). Pouta, Neuvonen and Sievänen (2009) find that climate change leads to less participation in cross-country skiing, with stronger effects among females, individuals with a lower socioeconomic status, and inhabitants of larger cities. Participation in and motivation for cross-country skiing activities depend not only on snow conditions, but also on individual, socioeconomic, and demographic characteristics (Landauer et al. 2012 and 2014). In the early 2000s, cross-country skiing activities in Sweden are considered stagnate (Heberlein, Fredman and Vuorio 2002; Fredman and Heberlein 2003), but are is recently gaining in popularity, possibly due in part to the accomplishments of the Swedish national cross-country team and the increasing provision of professionally maintained tracks (Skidspår 2017).

Despite the option to transfer a Vasaloppet registration to another person, there tend to be a significant number of starting slots that are not used. Since the race places tremendous stress on the body, there are several possible reasons behind this, including sudden illness, accidents, and insufficient preparation. A survey among those who received compensation from an insurance company because they could not participate indicates that the most common reason for late cancellations is colds and other sudden illnesses.[5] This information is based on all skiing events in the week leading up to the main Vasaloppet race. However, colds are common in winter, implying other circumstances that affect cancellations.

In addition to individual reasons, external factors such as natural catastrophes, terror attacks, and unfavourable weather conditions may influence decisions to withdraw (Hajibaba, Boztuğ and Dolnicar 2016). The latter affects not only the race itself, but also the possibility to travel to the destination. Dalarna is a sparsely populated region which lacks a major airport and with the city of Sälen some 400 kilometres northwest of Stockholm. There is also no train station near Sälen (where the race starts), so most skiers must travel far to take part.

The tourism literature shows that unfavourable weather conditions can lead to an increase in the number of recreational activities cancelled during the winter (Tervo 2008). Similarly, the transportation literature shows that adverse weather conditions – specifically snow, rain, and strong winds – are one of the main reasons for travel cancellations and delays (Koetse and Rietveld 2009). Extreme weather conditions may also affect the choice of outdoor recreational activities. Based on a survey of tourism entrepreneurs in Finland, Tervo (2008) shows that three-quarters of these entrepreneurs dealt with weather-related cancellations during the previous three winter seasons. Weather conditions that can cause cancellations include extraordinarily high or low temperatures, strong winds and rain. Heavy snowfall, on the other hand, is not considered a significant cancellation factor. In particular, three-fourths of enterprises that provide cross-country skiing tracks reported cancellations due to poor or extreme winter weather (Tervo 2008). In the case of the Vasaloppet, however, temperatures seldom measure below minus 20°C on the day of the event in early March (based on SMHI data).

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[5] DOKTORN.com "Var tionde åkare kommer inte till start i Vasaloppet – förkylning vanligaste orsaken". http://www.doktorn.com/artikel/var-tionde-åkare-kommer-inte-till-start-i-vasaloppet-–-förkylning-vanligaste-orsaken. Downloaded 2016:11.

Besides high temperatures, lack of natural snow is a serious dilemma for the Vasaloppet organisers. Sufficient natural snow is considered a necessity for most snow-based winter sport activities, and producing and transporting snow is expensive. Several studies using data at the daily level or for the total season show that natural snow conditions significantly affect demand for downhill skiing (Hamilton, Brown and Keim 2007; Moen and Fredman 2007; Shih, Nicholls and Holecek 2009; Steiger 2011; Gonseth 2013; Damm, Köberl and Prettenthaler. 2014; Falk and Hagsten 2016). The magnitude of this relationship varies widely depending on the respective location (elevation and latitude), time span, frequency of data (daily, monthly or annual data) and use of adaptation methods. Few studies have employed data over a longer time period. One exception is Töglhofer, Eigner and Prettenthaler (2011), who use data covering 35 years. They find that the magnitude of the relationship between tourism demand and snow depth in winter sport destinations is relatively low and decreasing over time (Töglhofer, Eigner and Prettenthaler 2011).

Climate change is a concern with regard to snow-based winter activities not only in North America and continental Europe, but also in the Nordic countries (Moen and Fredman 2007; Brouder and Lundmark 2011; Tervo-Kankare 2011; Tervo-Kankare, Hall and Saarinen 2013; Haanpää, Juhola and Landauer 2015). Corresponding climate change scenarios project a decline in both the number of days with snow coverage and snow depth itself. The largest absolute effects are expected in the Alps and on the western slope of the Scandinavian mountains (Jylhä et al. 2008). Evidence for Alpine ski areas indicates that climate change is reducing the length of the snow season (Steiger 2010). However, snowmaking is regarded as a robust remedy in the longer run, provided that temperatures do not increase too significantly (Pons et al. 2015).

Temperature may have an indirect effect on withdrawals from the Vasaloppet if higher temperatures reduce the likelihood that sufficient snow (whether natural or fabricated) is available for the race. Englin and Moeltner (2004) show that lower daily temperatures lead to an increase in skier visits.

The magnitude of the relationship between participation in snow-based winter sport activities and snow conditions may be dependent on the type of activity in question. According to a survey of winter sport tourists, downhill skiing and ice sport activities are least dependent on natural snowfall (Tervo 2008). This is because ski resorts are typically equipped with snowmaking facilities. In comparing different snow-based winter sport activities, Loomis and

Crespi (1999) find that visitors' sensitivity to weather conditions is most pronounced for cross-country skiing activities. This relates to the fact that snowmaking is less widespread among operators of cross-country skiing areas (Neuvonen et al. 2015). A minimum snow depth of 20 centimetres is often regarded as sufficient (Tervo 2008; Neuvonen et al. 2015), but a race of the Vasaloppet's magnitude tends to require more.[6] Based on the existing literature, external weather factors such as lack of snow or unusually high temperatures are expected to affect the cancellation ratio at the Vasaloppet. Therefore, time varying coefficient models are suitable to employ as well. To account for persistence in the cancellation ratio, a partial adjustment model is specified:

$$CR_t = \alpha_0 + \alpha_1 CR_{t-1} + \alpha_2 \, ln SNOWDEPTH_t + \alpha_3 TEMP_t + \alpha_4 Trend + \alpha_5 D1990 + \varepsilon_t ,$$

where *CR* is the cancellation ratio, defined as 1 minus the ratio of starting to registered skiers, and t=1951, …, 2016. *SNOWDEPTH* reflects the average snow depth recorded in the week preceding the Vasaloppet, *TEMP* measures average temperature over the same period and *ln* is the natural logarithm. Two alternative measures of snow conditions are used: Snow depth in centimetres and the number of days with a minimum snow layer of 30 centimetres. The latter measure is often seen as superior to average snow depth (Marty 2008). *Trend* is the annual time trend that represents changes in the cancellation ratio over time other than variations in weather conditions and *D1990* is a dummy variable for the year 1990 when the Vasaloppet race was cancelled. The equation can also be specified with the squared term of snow depth since it is possible that the benefits of additional snow decrease as the layer increases. In order to account for lagged effects, the cancellation ratio, temperature and snow depth from the respective previous year can be included. Lagged reactions to weather conditions are a common finding in the literature (Rosselló-Nadal 2014).

The cancellation ratio is a proportion whose values are bounded between zero and one (or zero and 100 per cent) by definition. This requires a share equation regression method such as the (two-limit) Tobit model. However, the Tobit model is not appropriate in this case because values exactly on the boundaries are observed (no cancellations in 1952 and no race in 1990). Applying the OLS estimator to the linear specification may generate predicted values that are

[6] Based on correspondence with the providers of cross-country tracks in Sweden. For optimal race conditions, 20 centimetres of snow depth is not sufficient.

outside the range of zero to one. Therefore, the Fractional logit model developed by Papke and Wooldridge (1996) is applied:

$$E(CR_t|X_t) = G(X_t\beta) = \frac{exp(X_t\beta)}{1 + exp(X_t\beta)},$$

where E is the expected value, t denotes time and CR_t the cancellation ratio that takes on values in the interval $[0 \leq CR_t \leq 1]$. G is the logit link-function with binomial distribution, which guarantees the boundaries of the dependent variable. A vector of explanatory variables, X_t, includes weather conditions in the week before the race. The model can be estimated using the Quasi-maximum likelihood method, with heteroscedasticity-robust asymptotic variance.

The relationship between weather and cancellations may vary over time and adaptation measures could reduce the correlation between cancellations and snow depth. In order to test for the stability of the weather variables, rolling regression methods are used. This is a valid method to detect structural breaks when variables are stationary, which the cancellation ratio and the weather indicators are assumed to be (i.e. means and variances do not change over time).

3. Data and descriptive statistics

The data at hand originates from several different sources. Information on daily temperatures and snow depth is provided by SMHI. Values are drawn from weather stations along or near the Vasaloppet route (in Mora, Sälen, Evertsberg and Malung). The length of the time series available for snow depth and temperature data vary across these stations: Snow depth data for Sälen is available for the period 1966-2007, while information for Malung has been continuous since the station was established in 1951. Temperature data for Mora is available for the periods 1951-1993 and 1995-2016. Because of these gaps, this study has also investigated the correlations between the weather indicators measured by the different stations at hand. They range between 0.83 and 0.98 and are all highly significant (information available in online supplement, Table A). This means that the Sälen data can be interpolated with information on snow depth from Malung and Evertsberg for the missing years and the information gap for Mora can be filled with data from Malung.

Snow depth data are available at daily intervals, whereas temperatures are measured several times per day. This information is aggregated to weekly averages (temperature at noon each day). Two indicators of snow coverage are used: average snow depth in centimetres and a dummy variable equal to one if the minimum level of snow depth in the week before the race was 30 centimetres or more. Although commonly the snow richest time of the year, Sälen has seen its average snow depth in the first week of March decline from 60 centimetres in the 1950s and 1960s to about 53 centimetres in the period 1990-2009 and to 45 centimetres since 2010 (source: SMHI, snow depth data for Sälen, own calculations).[7] In response, the organisers have intensified their snow hamstring and snowmaking efforts to ensure that the Vasaloppet can take place.

Figure 1: The Vasaloppet itinerary

Source: http://www.vasaloppet.se/

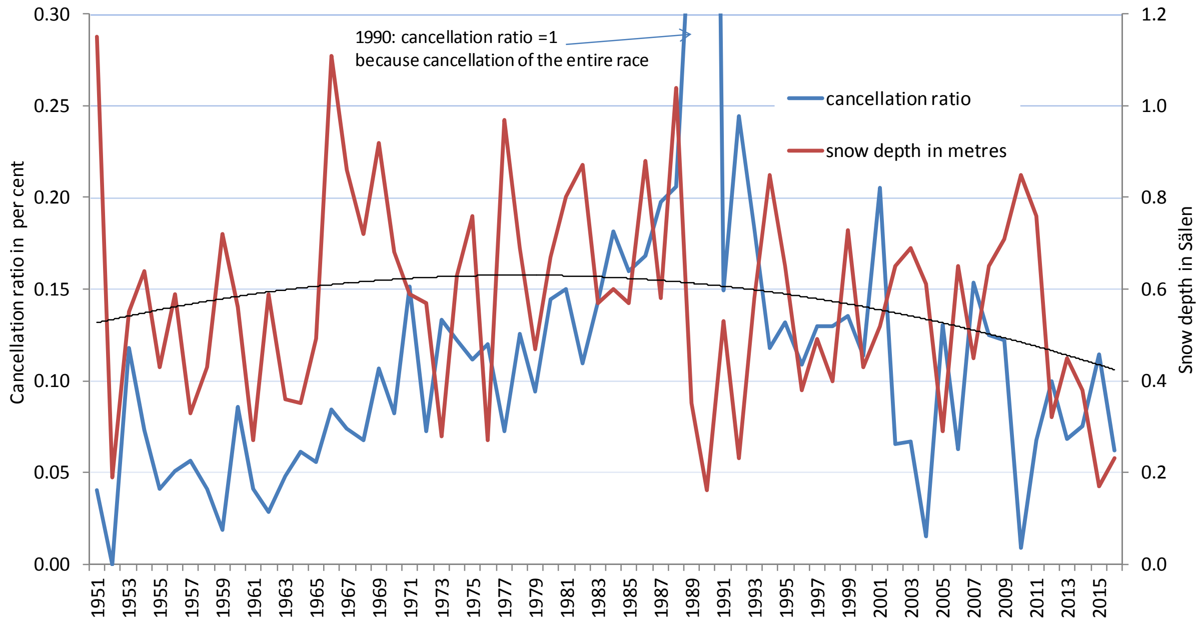
Event organizers have provided information on the number of registered and actual starting participants in the Vasaloppet. The number of participants has steadily increased from a few hundred in the 1930s to 15,000 in recent years. This is mainly related to an increase in the maximum number of participants. The 90 kilometres' race starts in Sälen and ends in Mora in the province of Dalarna (see Figure 1). The majority of Vasaloppet participants are from Sweden or neighbouring countries.

Figure 2 depicts the evolution of snow conditions alongside the cancellation ratio at the Vasaloppet. Over the past three or four decades, a negative relationship is evident between snow depth and cancellations: Lower-than-average levels of snow depth (1989, 1990, 1992 and 2015) go hand in hand with a higher-than-average cancellation ratio. This clearly

[7] Average snow depth in Sälen by decade: 1950s: 56 cm, 1960s: 62 cm, 1970s: 59 cm, 1980s: 69cm, 1990s: 50 cm, 2000s: 57cm and 2010s: 45 cm (Source: SMHI).

indicates that the cancellation ratio increases in winter seasons marked by a lack of snow. Bivariate relationships must be interpreted with caution, however, and the 1990 race was cancelled by the organisers. Meanwhile, it is interesting to note that despite lower-than-average snow depths in early March between 2013 and 2016, the cancellation ratio did not increase. This is likely related to the organisers' intensive efforts to secure their snow supplies through snow farming, snowmaking and snow storage.

Figure 2: Vasaloppet cancellation ratio (non-participants to registered participants) vis-à-vis snow depth (in metres)



Source: Snow depth data from SMHI and cancellation data from Vasaloppet.

4. Empirical results

The results obtained from the Fractional logit model show that there is a significant relationship between the cancellation ratio at the Vasaloppet and natural snow conditions in the area for the period 1980-2016. (Table 1). However, this relationship does not hold for the overall period (1951-2016) indicating that snow depth is only relevant for cancellations in the past three decades. In addition, effects of temperatures are not significantly different from zero. The lagged coefficient of the cancellation ratio exhibits a link almost as weak, implying that current cancellations are not dependent on what happened in the previous year.

Table 1: Relationship between snow depth and Vasaloppet cancellations

	(i) Main: Fractional logit estimates			
	(a) Specification with dummy variable for snow depth			
	1980-2016		1951-2016	
	m.e.	z-stat	m.e.	z-stat
Cancellation ratio (t-1)	0.019	0.69	0.101**	1.99
Snow depth≥30 cm (t), dummy	-0.043***	-3.05	-0.003	-0.14
Temperature (t)	0.002	0.57	-0.001	-0.48
Year 1990, dummy	1.970***	12.49	1.629***	12.84
Time trend	-0.004***	-4.05	0.001**	2.42
Number of observations	37		66	
Log pseudo likelihood	-9.84		-16.14	
Pseudo R^2	0.90		0.79	
	(b) Specification with snow depth measured in centimetres			
	1980-2016		1951-2016	
	m.e.	z-stat	m.e.	z-stat
Cancellation ratio (t-1)	0.021	0.74	0.102*	1.95
ln Snow depth in cm (t)	-0.070***	-2.80	-0.005	-0.30
Temperature (t)	-0.001	-0.25	-0.001	-0.61
Year, 1990, dummy	1.783***	12.52	1.634***	13.09
Time trend	-0.004***	-4.70	0.001**	2.24
Number of observations	37		66	
Log pseudo likelihood	-9.77		-15.96	
Pseudo R^2	0.92		0.79	
	(ii) Robustness: OLS estimates			
	1980-2016		1980-2016	
	Coeff.	t-stat	Coeff.	t-stat
Cancellation ratio (t-1)	0.018	0.50	0.019	0.50
Snow depth ≥30 cm (t), dummy	-0.045**	-2.47		
ln Snow depth in cm (t)			-0.067**	-2.55
Temperature (t)	0.002	0.58	0.000	-0.07
Year 1990, dummy	0.786***	28.04	0.747***	17.95
Time trend	-0.004***	-3.75	-0.004***	-4.25
Constant	7.954***	3.81	8.855***	4.30
Number of observations	37		37	
R^2	0.84		0.80	
Durbin alternative test for autocorrelation (p)	0.22		0.68	
	(iii) Robustness: Betafit estimates			
	1980-2016		1980-2016	
	m.e.	z-stat	m.e.	z-stat
Cancellation ratio (t-1)	0.019	0.78	0.022	0.50
Snow depth >=30 cm (t), dummy	-0.047***	-3.56		
ln Snow depth in cm (t)			-0.071***	-3.33
Temperature (t)	0.003	0.86	0.000	-0.15
Year 1990, dummy	0.569***	15.42	0.536***	5.90
Time trend	-0.004***	-4.53	-0.004***	-5.73
Number of observations	37		37	
Pseudo R^2	0.89		0.91	

Notes: The dependent variable of the Fractional logit and OLS models is the cancellation ratio. The STATA GLM command with the logit link and the binomial distribution is used to estimate the Fractional logit model. In the Betafit model, the cancellation ratio (CR) is transformed in accordance with the formula ((CR*36)+0.5)/37). The Betafit model is estimated by Maximum likelihood with heteroscedasticity consistent standard errors. The STATA Betafit command is employed. T- and z-values (t-stat, z-stat) are based on heteroscedasticity consistent standard errors and (m.e) is short for marginal effect. Asterisks ***, ** and * denote significance at the 1, 5 and 10 per cent levels, respectively.

The time trend is significant and negative for the subsample starting from 1980, and positive and significant for the earlier years. This could relate to the Vasaloppet's progression from its early years – which saw an incremental rise in the maximum participants allowed – to the more developed and established iterations of the race.

Lagged values for temperature and snow depth are not significant at conventional levels and thus are not included in the final specification. The goodness of fit for the second subsample is quite reasonable overall, with a pseudo R-squared of 0.90. Augmented Dickey-Fuller tests show that the cancellation ratio, snow depth and temperatures are all stationary at the one per cent level. This indicates that the variables have constant mean and variance over time and thus no spurious relationships can be expected.[8]

The negative coefficient for snow depth in the more recent subsample indicates that a lack of natural snow increases the number of cancellations among a given number of registered participants. This relationship is robust when the alternative indicator of snow conditions – a dummy variable pertaining to the minimum level of 30 centimetres – is used (with a marginal effect of -0.043). Using the marginal effect of -0.07, an example can be calculated in which snow depth is assumed to decrease from the average level over the sample period (57 centimetres) to 30 centimetres (which is anecdotally considered to be the minimum level for a good cross-country track). This 48 per cent decline would lead to an increase in the cancellation ratio of 3.3 percentage points (= -0.07 times 48 per cent).

Additional insights into the effect on the cancellation ratio may be reached by calculating the predicted probability at different levels of snow depth, adjusted for other significant covariates, the time trend and with a dummy variable for 1990. The predicted cancellation ratio varies between 22 per cent for low levels of snow depth (25 cm) and nine per cent for high levels (more than one metre) (Figure 3). This leads to the conclusion that the magnitude of the relationship between the cancellation ratio and snow depth is not negligible, indicating that cross-country skiing competitions may be even more vulnerable to climate changes than downhill skiing competitions.

The results of the rolling regressions with a fixed 30-year window shed further light on the relationships between the cancellation ratio and snow depth. The first sample is drawn from the period 1951-1980, and the last from 1987-2016.

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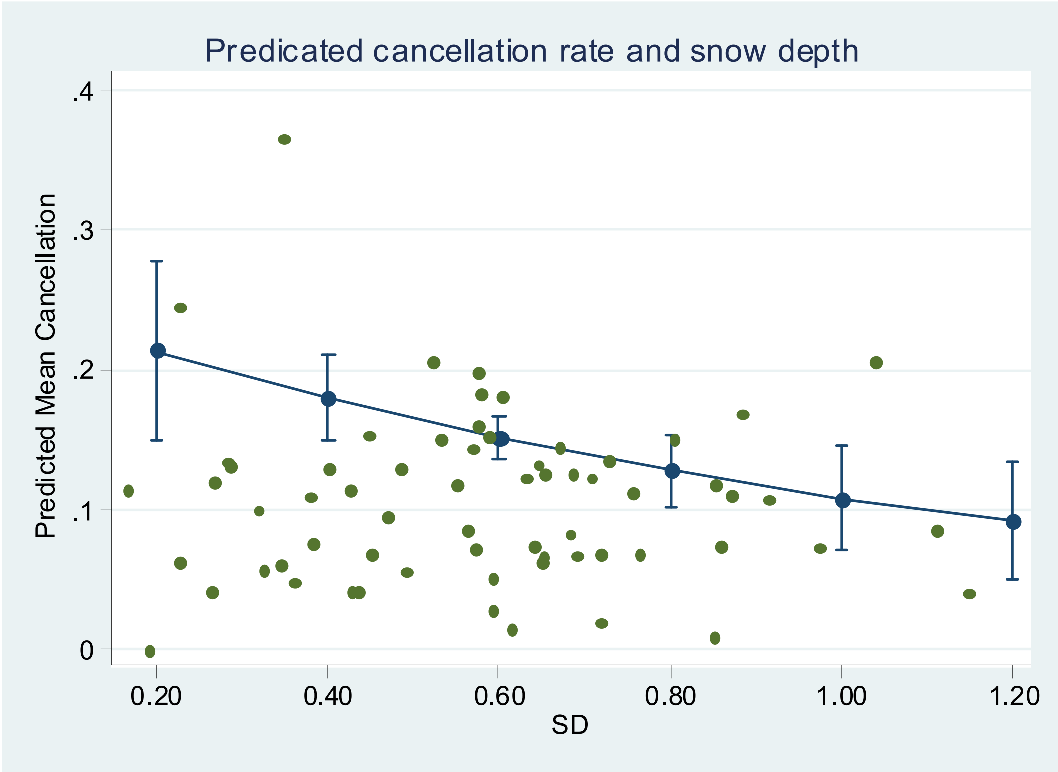
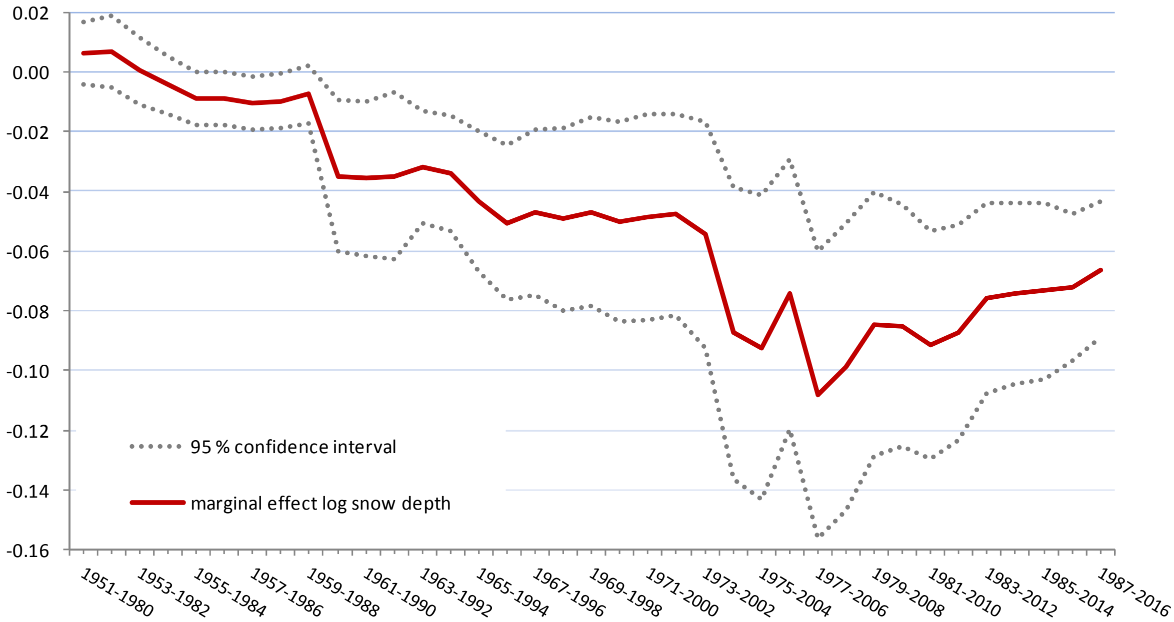
[8] The test statistics for the cancellation ratio, logarithm of snow depth and temperatures are -4.381, -6.507 and -7.095 with MacKinnon p-values of <0.01. Time trend is not significant and thus excluded from the ADF tests.

Figure 3: Predicted cancellation probability at different levels of snow depth



Notes: Predicted probability is calculated based on the Fractional logit model with level of snow depth (SD) rather than the logarithm of snow depth. The sample is based on the period 1980-2016. Data for the cancellation ratio equal to one has been excluded.

Figure 4: Stability of the marginal effect of the cancellation ratio with respect to snow depth



Notes: Marginal effects are based on the rolling regression approach applied to the Fractional logit model.

The results show that the association varies over time: It is highly sensitive to natural snow conditions in the rolling subsamples from 1961-1990 and onwards, but independent of snow depth for the samples ending in the late 1980s (Figure 4). Thus, the rolling regression results indicate that the end of the 1980s was the turning point in the relationship. From the 1990s onwards, the sensitivity of the cancellation ratio – measured as the marginal effect – increases in absolute terms. In the earlier periods (1961-1990 and 1965-1994), poor snow conditions in early March had relatively little effect on the cancellation ratio. However, the marginal effect steadily increases in absolute terms up until the sample for 1983-2012, and then declines afterwards. The weakening of the relationship between cancellations and snow depth may be attributable to the intensive efforts of the Vasaloppet's organisers to produce snow. A similar result is found for the relationship between overnight stays and winter tourism demand for Austrian destinations during the period 1972-2007 (Töglhofer, Eigner and Prettenthaler 2011).

Unfortunately, improved snowmaking capacity and related preparations do not come without additional costs. Between 2012 and 2017, the registration fee for the race increased from SEK 1,280 to 1,690 – an annual rise of 5.9 per cent on average, clearly more than the overall inflation rate and increases in the cost of other winter activities, including the price of ski lift tickets, for instance. As suggested by Landauer, Haider and Pröbstl-Haider (2014) there could be a ceiling for what skiers are willing to pay for being able to ski or take part in cross-country competitions, which is an additional threat to the race. Between 2000 and 2012, prices rose moderately by an average of 2.7 per cent per year. Meanwhile, snowmaking itself is also dependent on optimal weather conditions: According to the Vasaloppet's organisers, 30 days of temperatures at least five degrees below zero with low humidity are required. In the last 20 years, these climate conditions occurred every second year on average (information available in online supplement, Table B).

This study includes several robustness checks to assess the sensitivity of its results. First, a simpler estimation technique is used: OLS. The semi-elasticity calculated using this approach is -0.067, quite similar to the marginal effects obtained from the Fractional logit model (-0.070; Table 1, Main specification, alternative "a".). This indicates that the bias of the OLS estimator is relatively small. Second, the Fractional logit estimator is originally developed for cross-sectional data with a relatively large sample size, although the exact lower limit is unclear. Because of this the *Betafit* model has also been employed. This model transforms values of the dependent variable away from the boundaries to the span within $(0<CR<1)$. Smithson and Verkuilen (2006) suggest the following transformation formula: $(CR_t \times (n-1)+0.5) \times n$, where *n* is the sample size. When estimated by use of Maximum likelihood, results of similar magnitudes and significance levels appear for snow depth indicators (Table 1, Specification "iii"), but with somewhat smaller standard errors than in the Fractional logit estimation. Both the Fractional logit and the Betafit model are also estimated with 1990 excluded, the year when the Vasaloppet was cancelled by the organisers (implying a cancellation ratio of 1). This leads to similar and still significant estimates, although the magnitude of the snow depth coefficient is larger when the observation for year 1990 is included (estimation results available in online supplement, Table C). This indicates that the relationship between the cancellation ratio and weather conditions is not driven by influential observations, but technically it is sensitive to how the year 1990, when the Vasaloppet race was cancelled, is treated. Third, economic variables such as GDP growth, household consumption, oil prices and the inflation rate (originating from Statistics Sweden) have been tested as indicators of the business cycle as well as transportation costs, indicating willingness to travel, although none of these variables meet conventional levels of significance and thus are excluded in the final specifications.

5. Conclusions

This study investigates the relationship between the cancellation ratio at the Vasaloppet race in Sweden and weather factors such as snow conditions and temperatures over the last seven decades. The results obtained from a Fractional logit model show that a lack of natural snow has led to significant increases in the cancellation ratio. Overall, the magnitude of the relationship is substantial and varies over time: The dependence of cancellations on natural snow conditions is initially non-existent, but increases between 1990 and 2010 before entering a slight decline, possibly related to improved snow-making and storage facilities. Thus, the results reveal an increased awareness of climate change among both participants and organisers.

Given the results, it is natural to ask what the implications of climate change for future iterations of the Vasaloppet could be. Climate change is expected to bring higher temperatures and a decline in the amount and duration of snow as well as in the number of days with snowfall. Winters with less natural snow will lead to an increase in the Vasaloppet's cancellation ratio. The finding that the dependence of cancellations on natural snow depth has declined of late indicates that the use of snowmaking facilities, snow farming and other adaptation methods is effective, but very likely to be costly. However, adaptation is only long-lasting if the fabricated snow is of satisfactory quality. In addition, the effort to work around one environmental issue creates another: Extensive snowmaking may be at odds with long-term ecological sustainability, for example (De Jong 2015). In the case of the Vasaloppet, the race's route is not near main roads, which likely makes snowmaking facilities and the transportation of snow both difficult and expensive. Such costs may prove too much for the organisers to bear in the long run, and these expenses will need to be passed on to participants or other willing actors, for instance sponsors. At the moment, it remains unclear whether this will be justifiable in the long term. By their nature, heavy snowmaking and snow transportation are not particularly environmentally friendly practices. A similar discussion is under way regarding the costs and benefits of further investments in snowmaking facilities in low-elevation downhill skiing areas (Damm et al. 2014). Given the historical ties at hand, relocating the Vasaloppet to another geographical area – in the same manner as the Eleven Cities Tour in the Netherlands – does not seem to be an option.

A presumptive closure of the Vasaloppet race would have far-fetching effects not only on the region, where extensive businesses related to the competition have been established, but also on the sport. The race attracts large groups of amateurs as well as professionals and the organisers collaborate with several cross-country centres in Sweden that provide training facilities and coaching specifically for the race.[9] From a managerial perspective, activities, or a whole industry, built around a core that is not fully controllable (in this case, snow supply of satisfactory quality) is a risky venture.

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[9] http://www.vasaloppet.se/om-oss/vara-partners/officiella-vasaloppscenter/.

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