Changes in cold extremes in Sweden
based on daily minimum temperatures for the period 1951-2014

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Abstract

Increases in global mean temperatures have caused the climate to change, affecting the frequency and magnitude of extreme events. Series of daily minimum temperatures for the period 1951-2014 has been analyzed in Sweden. It was found that cold extremes such as frost days, cold spells and annual minimum temperatures all show significant warming trends with a statistical significance of 90%. Frost days show a decrease of 0.4 frost days/year and days below the 10th percentile show a decrease of 0.3 days/year. Annual minimum temperatures have increased by 0.07 °C/year. There are more southerly stations than northerly showing warming trends, although they are not significant. From a societal perspective a decrease in cold extremes would indicate that wildlife, agriculture and energy sectors will have to adapt to a different climate. The Swedish society must thus consider its vulnerability and exposure within different sectors and systems and make decisions regarding climate adaptation.

1 Introduction

During the last 100 years global mean temperatures have risen causing the climate to change. As a part of a changing climate, extreme events such as extreme temperatures, heavy rainfall are also subject to changes. According to the 2013 Intergovernmental Panel on Climate Change (IPCC) report, observed trends of temperature extremes will continue [1]. These trends would indicate more frequent and severe heat waves but milder cold extremes [2-7]. From an economic, societal and ecological point of view it is thus vital to understand how extreme events will change, especially in terms of intensity and frequency.

Sweden, being an elongated country, has a varied climate depending on latitude and altitude. This variety of temperatures and weather is challenging from a societal perspective. Infrastructure must function for all weather types, energy demands changes with temperature, agriculture and wildlife must adapt to meet different weather-related challenges. The ongoing global warming have resulted in evident warming of air temperatures in Sweden (as can be seen in Figure 3). As a consequence of a changing climate, society faces a greater risk of being exposed to natural hazards such as floods and extreme temperatures.

The Swedish Meteorological and Hydrological Institute (SMHI) has made an extensive analysis of the occurrence of heat waves and their impact on the Swedish society. There is however a lack of analyses regarding the frequency of cold extremes in Sweden which is equally important. Although the issues from cold extremes are not as comprehensive as they are for heat waves they are still interesting to analyze since they too affect different aspects of society.

The aim of this report is to analyze series of daily minimum temperature data in Sweden. This analysis will then form the basis of a discussion in whether the frequency or magnitude of cold extremes has changed, how they will be affected by climate change and how this in turn will affect society, especially in terms of health, economy, agriculture, infrastructure and wildlife.

The report is structured as follows: Section 2 contains all the necessary theory needed for the reader to understand the results. Thereafter methods for retrieving and analyzing data are discussed (Section 3). Results are presented in Section 4 followed by a discussion and finally a conclusion (Section 5 and 6).

2 Background

2.1 Climate change

Climate change is defined as the long term change (i.e. decades or longer) of the weather and weather patterns in terms of precipitation, temperature and winds [8]. If the incoming solar radiation were to be larger than the outgoing radiation from the Earth, the temperature would start to increase, and decrease if the opposite was true. The amount of incoming solar radiation, the composition of gases in the atmosphere and volcanoes are all connected to the Earth’s radiation balance. Which in turn depend on the activity of the Sun, the Earth's position relative to the Sun, the amount of radiation reaching the Earth and the reflectivity from the surface and atmosphere [9]. The amount of radiation actually reaching the Earth’s surface depends on how the atmosphere and surface absorbs it. The atmosphere is quite permeable to shortwave radiation which thus can reach the Earth’s surface and warm it up.

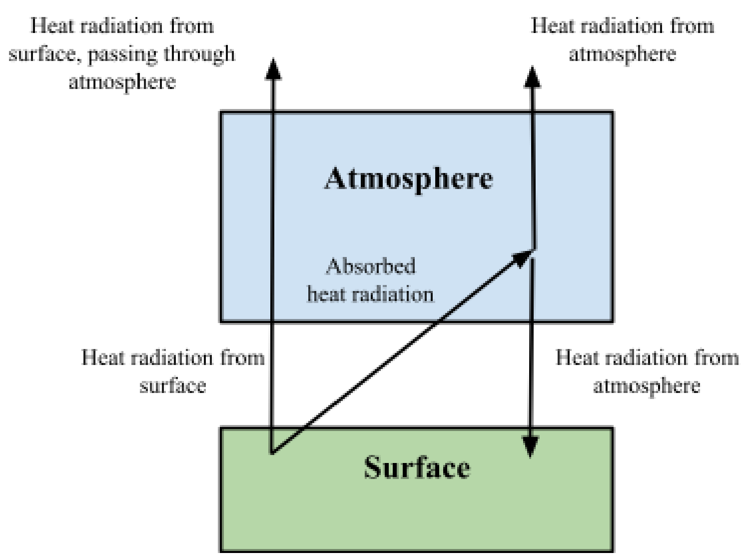

Figure 1: Adapted figure from [10] illustrating radiation and absorption in a system between the surface and atmosphere.

Figure 1 described in [10] illustrates a somewhat simplified explanation of the interaction between radiation and absorption in a system between the surface and atmosphere, assuming that they are not in thermal equilibrium. Starting with the surface, it can be assumed to behave as a blackbody with temperature T_s. Stefan-Boltzmann's’ law about the emissive power of a blackbody states that “ the total energy radiated per unit surface area of a blackbody across all wavelengths per unit time, j^*, is proportional to the fourth power of the blackbody’s temperature T”, expressed as:

$$j^* = \sigma T^4 \qquad (1)$$

Where σ is the Stefan-Boltzmann constant. The radiation from the surface then is:

$$j_s^* = \sigma T_s^4 \qquad (2)$$

In contrary to the surface, the atmosphere cannot be treated as a blackbody. Instead the atmosphere only absorb some of the incoming radiation and thus emits less energy than the surface. Given a temperature T_a and an emissivity ϵ_a, equation (1) becomes for the atmosphere:

$$j_a^* = \epsilon_a \sigma T_a^4 \qquad (3)$$

Which is the heat radiation from the atmosphere. Finally two cases are possible when radiation from the surface reaches the atmosphere. (i) The radiation passes through radiating out into space and (ii) the atmosphere absorbs the outgoing radiation. For (i) the total heat radiation becomes: $(1 - \epsilon_a)\sigma T_s^4$. For (ii) it becomes: $\epsilon_a \sigma T_s^4$. The amount of radiation radiating into space and thus leaving the system is:

$$(1 - \epsilon_a)\sigma T_s^4 + \epsilon_a \sigma T_a^4 = \sigma T_s^4 - \epsilon_a \sigma (T_s^4 - T_a^4) \qquad (4)$$

But since the temperature of the surface is higher than the temperature of the atmosphere the right hand side of equation (4) is < 0. Meaning that the heat radiation leaving the surface, equation (1), is larger than the amount of radiation leaving the system. This in turn means that the temperature at the surface rises in order to maintain the radiation balance. Thus if the amount of absorption in the atmosphere would increase the temperature would have to rise even more, and the outgoing radiation would have to increase in order to balance the radiation.

Sources that control the amount of radiation emitted from the surface and atmosphere are the composition of gases and aerosols in the atmosphere and the Earth's’ albedo [9]. Areas with higher albedo reflect higher amount of radiation back into space. High amount of aerosols in the atmosphere prevents radiation from reaching the surface and thus cools the surface. Greenhouse gases on the other hand, such as carbon dioxide, water vapor, ozone and methane absorb the outgoing radiation preventing it from radiating out into space.

During the last century the climate on earth has become warmer and compared to past periods the climate is changing rapidly. This rapid warming of the Earth is referred to as global warming and is very likely a consequence of human activity [11] by combustion of fossil fuels and land clearing. Global warming is the effect of increasing greenhouse gases such as carbon dioxide and methane in the atmosphere where emissions of carbon dioxide affect the greenhouse effect the most. The amount of carbon dioxide in the atmosphere has increased by around 40% since the industrialization in the 19th century [10]. As seen in Figure 2 there is an evident increase of the temperature starting in the 20th century, but an even greater increase the last 50 years.

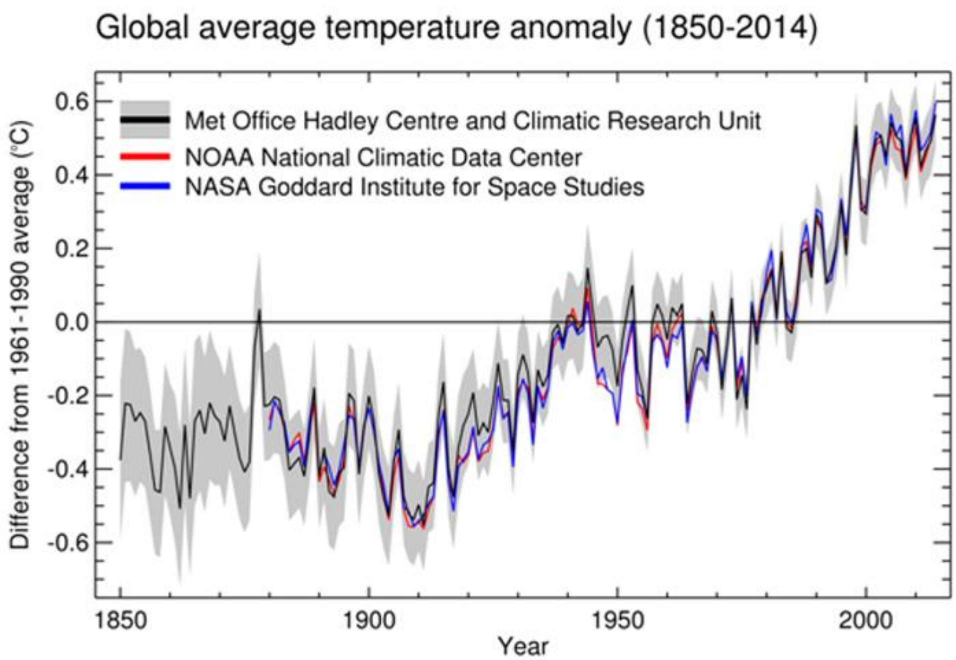

Figure 2: Global average temperature anomaly, measured at 1.25 to 2 meters above the surface level, between the years 1850-2014 compared to the 1961-1990 average temperature. Collected data sets from the UK Met Office, NOAA and NASA [12].

This increase of greenhouse gases enhances the greenhouse effect and thus affects the Earth's climate. Such a disturbance in the energy balance in turn affects the Earth's entire system. For example, both oceans and clouds react on temperature changes [13]. Warming may lead to an increase of water vapor in the atmosphere and thus enhancing the greenhouse effect. Changes in cloud cover on the other hand may increase or reduce the warming of the mean temperature depending on the type of clouds that are present [13]. Redistribution of energy within the climate system may therefore affect precipitation, sea levels, circulation patterns, temperatures, winds [10], and the occurrence of extreme weather events.

2.2 Extreme weather events

Extreme weather events such as cold spells, heat waves and droughts are often defined by various indices. Apart from also being defined as occurring rarely and lying far away from the mean, extreme weather events may also be classified by how well the society and environment withstands the strains related to them.

Studies show that temperature-related extremes are expected to change along with the ongoing global warming [2, 5, 14, 15] with more frequent and severe heat waves but milder cold extremes [2-7]. Changes in the frequency and intensity of extreme temperatures are of great importance from a societal point of view. With changing temperature extremes, specific aspects of energy demands changes. Agriculture and wildlife must adapt and the human health may be affected [4]. In different parts on Earth, society, nature and wildlife have adapted to certain climates, sudden decreases or increases of temperatures may thus become fatal.

2.3 Cold extremes

Cold extremes may be defined by various indices. In this study the focus will lie on annual minimum temperatures, annual count when at least six consecutive days of minimum temperatures are <10th percentile, annual count of days with minimum temperature <10th percentile and <0 °C.

Cold spells are characterized by a rapid fall in temperature, where the severity of the event depends on the rate at which the temperature falls and the minimum value to which it falls. These rapid drops in temperature are due to cold air masses moving in over a region. Europe gets affected when cold air masses moves in from the polar regions, causing temperatures to drop very low. This usually occurs during the winter months [16]. Since cold air masses move slowly, cold spells often lasts for several days causing damages and fatalities.

An example of a cold spell is an event that struck Europe in 2012. This extreme event brought wintry precipitation and temperatures under freezing level, reaching -39°C in some regions. During this cold spell which lasted for about one month at least 824 people died and more than 7000 had to seek medical help [17]. There were also damages to the agriculture, wildlife, infrastructure and facilities. Damages arising from cold spells such as the ones mentioned above are caused by the accompanied effects. Heavy snowfall and low temperatures affects the infrastructure. Telephone wires may fracture, water pipelines and mains can freeze.

The winter of 2009/10 brought record cold weather to large parts of Europe. In Sweden, this winter was the coldest since the middle of the 80'. Over all, this brought temperatures below zero and wintry precipitation all over the country, resulting in a long and cold winter. In some parts temperatures dropped to -40°C and up to 50 cm of snow fell. A combination of heavy wintry precipitation and strong winds (24 m/s) caused many infrastructural problems. The cause of this cold winter was a larger high pressure area with its origin over Siberia bringing strong and cold winds [18].

2.4 Swedish climate and geography

Sweden is situated between the Atlantic ocean to the west and large landmasses to the east. The Swedish climate is mainly influenced by a low-pressure belt with southwesterly or westerly winds bringing warm and moist air. Low pressures and fronts move along the North Atlantic polar front separating cold northern air from warmer southerly air [19]. The polar front has a great impact on prevailing weather conditions, where the temperature for instance can differ significantly depending on the side of the polar front [13]. Since low pressures are the dominating pressure systems the climate is rather rich in precipitation, especially during summer and fall [19].

Since Sweden is an elongated country the climate varies considerably depending mainly on latitude, altitude and distance to the sea. Higher latitudes and altitudes lead to a colder climate [13]. Götaland, located in southern Sweden is warm temperate and moist at the coastal areas but cold temperate inland. The average temperature for southern Sweden ranges between 0°C during winter and 16-17°C during summer [20]. The climate is also said to be cold temperate in Svealand and Norrland. Svealand is bounded by Götaland to the south and Norrland to the north. Further north at the Scandinavian Mountains the climate is polar [13]. In the north the coldest month has an average temperature of ~-15°C and 12-13°C during summer [20]. Minimum temperatures usually occur prior or at sunrise during calm and clear nights. Prevailing weather may however influence the temperature.

Along with climate change the Swedish climate has also changed, there is an evident increase of the temperature, see Figure 3, and also an increase in precipitation across the country [21].

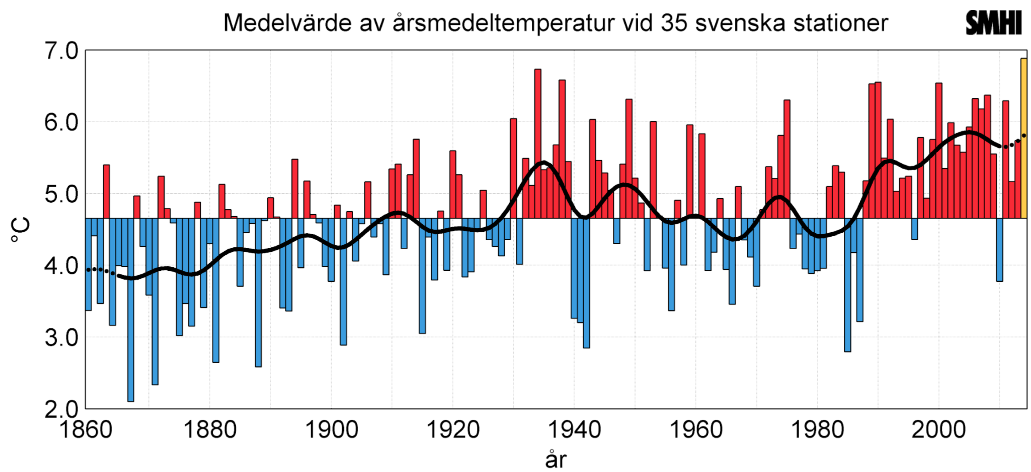

Figure 3: Swedish annual mean temperatures at 35 different meteorological stations reaching from 1860-2013 [21].

3 Method

3.1 Temperature stations and measurements

When measuring air temperatures it is important to get as precise values as possible. The Swedish Meteorological and Hydrological Institute (SMHI) therefore measures the air temperature by following the World Meteorological Organization (WMO) guidelines for meteorological observations. The temperature is thus measured at a height of 1.5-2 m above ground, preferably on a flat open space not shielded by trees or buildings [22]. It is important that thermometers are protected from direct sunlight and precipitation.

SMHI has both automatic and manual measurements stations. Nowadays however automated stations, illustrated in Figure 4, are mostly used. The air temperature at the stations is measured by electronic resistance thermometers. These thermometers consist of an electric conductor which changes its resistance as the temperature changes. A common conductor used, is platinum placed in a glass tube. The conductor is then connected to a measuring unit which measures the temperature continuously. In order to get as accurate measurements as possible the temperature is determined from the mean of the measured temperatures during the latest minute. Minimum- and maximum temperatures are determined from all values during a given period [23].

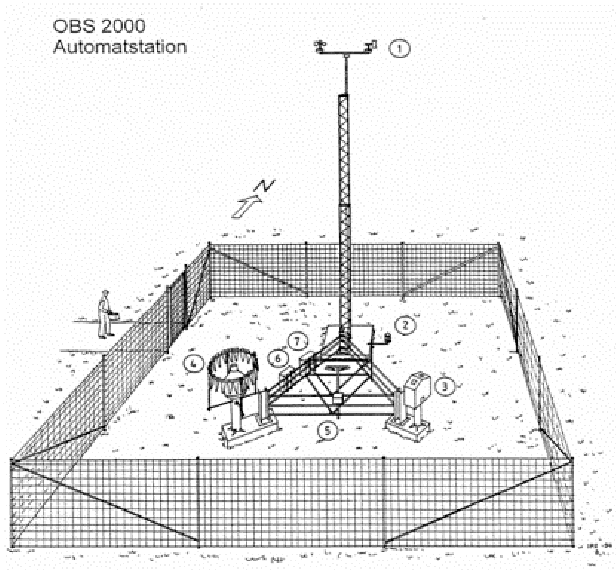

Figure 4: Illustration of an automatic station. The different parts are: (1) Anemometer (2) Humidity & temperature sensor (3) Cloud altimeter (4) Precipitation sensor (5) Present weather sensor (6) Automation centre (7) Electricity/telecom box [24].

Automatic stations collect temperature values every hour whereas a manual station only collects values two-three times a day, usually at 06, 18 and sometimes 14 UTC. Maximum- and minimum temperatures are on the other hand only collected two times a day (06 UTC and 18 UTC). The first reported value is the minimum- and maximum value valid between 18 UTC the day before and 06 UTC. The second value is valid between 06 and 18 UTC. The given maximum- and minimum temperature for a given day is thus the collected value between 18 UTC the former day and 18 UTC on the actual day [23].

SMHI has measurement stations at various locations across Sweden. However, not all stations have equally long series of measurements. It was not until 1860 that measurements began covering large parts of Sweden. There are in particular 35 stations with long series of measurements, ranging from 1860 - today. These 35 stations, illustrated in Figure 5, are thus helpful to use when analyzing temperatures and climate indicators. One can however see that there are more southerly stations, and since temperatures generally are much higher in southern Sweden the results may not be very representative geographically [25].

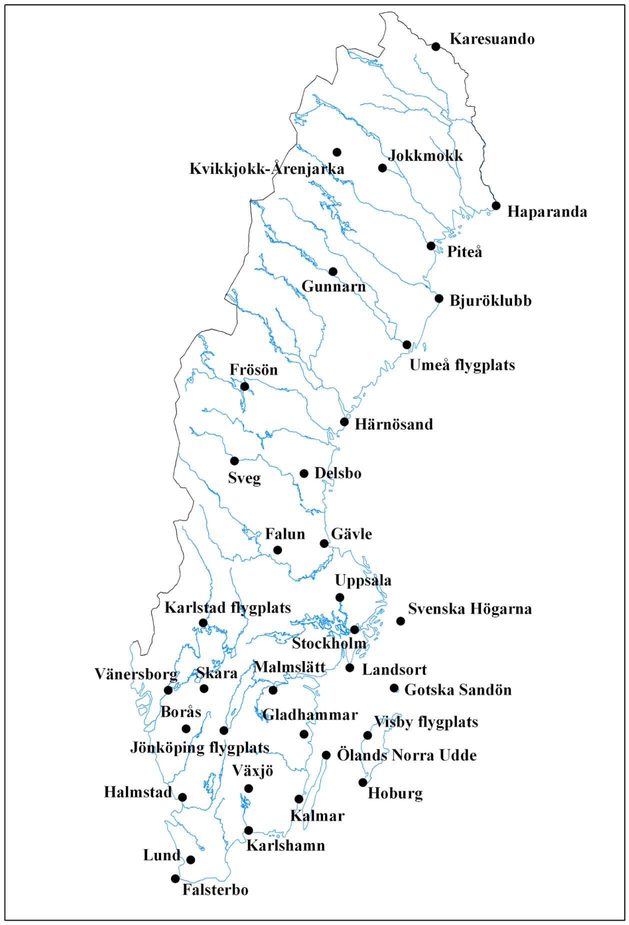

Figure 5: Geographic representation of the 35 observation stations used in this study [25].

Table 1: List of stations used in this study. Listed by their station number, location (from south-north) and data length.

Station number	Station name	Start year-end year
52230	Falsterbo	1951-2014
53430	Lund	1961-2014
62400	Halmstad	1978-2014
64130	Karlshamn	1961-2014
64510	Växjö A	1995-2014
66420	Kalmar flygplats	1994-2014
68560	Hoburg A	2009-2014

72450	Borås	1961-2014
74460	Jönköpings flygplats	1951-2014
76420	Gladhammar A	1995-2014
77210	Ölands Norra Udde A	1995-2014
78400	Visby flygplats	1951-2014
82230	Vänersborg	1961-2014
83270	Skara	1973-2014
85240	Malmslätt	1951-2014
87440	Landsort A	1995-2014
89230	Gotska Sandön A	1995-2014
93220	Karlstad flygplats	1951-2014
97510	Uppsala aut	1984-2014
98230	Stockholm A	1996-2014
99270	Svenska Högarna	1951-2014
105370	Falun-Lugnet	1951-2014
107420	Gävle A	1995-2014
116490	Delsbo A	1995-2014
124030	Sveg A	2009-2014
127380	Härnösand	1951-2014
134110	Frösön	1951-2014
140480	Umeå flygplats	1965-2014
147560	Gunnarn A	2008-2014
151280	Bjuröklubb A	1995-2014
161790	Piteå	1961-2014
163960	Haparanda A	2008-2014
167990	Kvikkjokk-	2008-2014

	Årrenjarka A	
169880	Jokkmokk	1951-2014
192840	Karesuando A	2008-2014

3.2 Retrieving and analysing data

Series of daily minimum temperature data for the 35 stations mentioned above were chosen from SMHI open data [26]. All available daily minimum temperature series were retrieved to an Excel-document through a program written in Java [27]. By investigating time series from the stations it was found that 10 stations have series starting in 1951, eight started between 1961-1990 and the rest between 1990-2009, see Table 1 for lengths of data series for each station. Since minimum temperatures began being measured much later than temperatures, some stations have very short records.

In order to analyze the occurrence and intensity of cold extremes in Sweden trends of the set of extreme temperature indices seen in Table 2 are investigated.

Table 2: Cold extreme indices listed by their term and definition.

Term	Definition
Coldest years (Sweden)	Annual average values of daily minimum temperatures
Cold spell duration	Annual count when at least six consecutive days of minimum temperatures are <10th percentile
Coldest days	Annual count of days with minimum temperature <10th percentile
Frost days	Annual count when daily minimum temperatures <0°C
Coldest year (station)	Annual minimum temperature at each station

Some of these extreme temperature indices will be analyzed for stations with long series of measurements, others for stations with different geographical placement and for all stations together, representing Sweden as one.

When analyzing the indices of Table 2 a mix of programs are used. Firstly annual minimum temperatures are listed for each station by combining the Excel functions [MIN], [IF] and [YEAR]. By then taking the average, [AVERAGE]-function, value, over the 35 stations, a list of average annual values representing Sweden is retrieved. In order to see if there are any visual trends for these two indices they are plotted and trend estimates, in the order of ℃/year, are made using a linear regression method (see Appendix 1 for MATLAB code). Corresponding error estimations are made through a program called Graphical User Interface for linear regression (REGGUI) [28]. Individual stations are also analyzed by looking at their minimum temperatures each year. Annual temperatures are analyzed by how the values have varied geographically over time and northerly stations are compared with southerly ones. In order to get as good results as possible only stations with equally long data series are compared. Secondly, when analyzing cold spell duration, coldest days and number of frost days an average of all daily minimum temperatures from all stations are taken. Thus creating a list of average daily minimum temperatures reaching from 1951-2014. Thereafter the 10th percentile of these values is calculated using the [PRCTILE]-function in MATLAB (see Appendix 1). The number of days below the 10th percentile for each year were counted using the [COUNTIF] function in Excel, which counts the number of cells from a set of values that satisfies a criterion. The same approach was used when analyzing the number of frost days, days with temperatures below 0℃, each year. Estimates of trends and uncertainties are also made with the code from Appendix 1 and REGGUI.

Furthermore it is assumed that the data has been reviewed and corrected for errors and possible inhomogeneities by SMHI [29].

4 Results

4.1 Coldest years (Sweden)

The annual lowest daily minimum temperature is analyzed by how it has varied over time. Each year one of the daily minimum temperatures will be the lowest. This value is found for each of the 35 stations and an average of this annual minimum temperature over all station is taken. The resulting values can be seen in Figure 6. In order to see if there has been any changes over the years a linear fit is applied.

Figure 6 clearly shows a positive trend indicating a warming in annual minimum temperatures, showing that minimum temperatures have risen by about 0.07°C/year, with confidence intervals of ± 0.06 °C/year (90%).

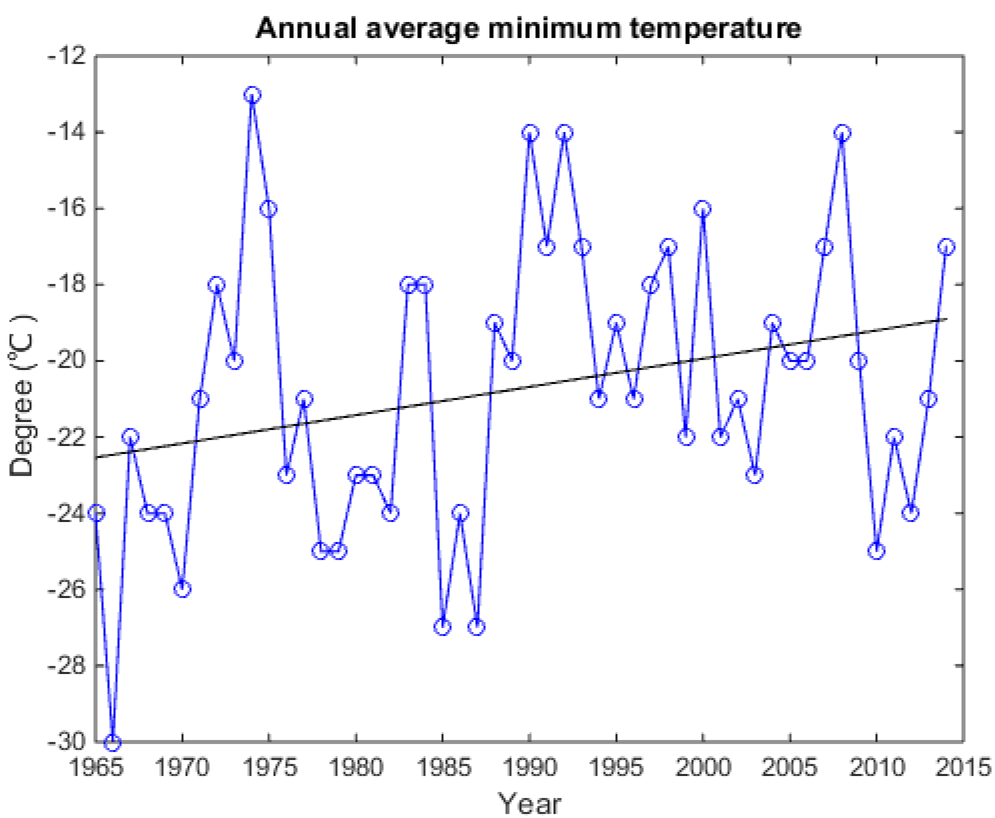

Figure 6: Representation of annual average minimum temperatures for Sweden based on an average of annual minimum temperatures from all stations for the time series between 1965-2014.

Table 3: Trend estimates for coldest year with a 90% confidence interval

Trends in °C per year
0.07±0.06

4.2 Cold spell duration and coldest days

The 10th percentile of the data set containing the average minimum temperature each day in Sweden is -8°C. The lowest 10th percentile of the data set correspond to cold extremes, the occurrence of cold extremes in Sweden over time can thus be seen in Figure 7. Here the annual count of days with temperatures below the 10th percentile is illustrated. Figure 7 shows a negative trend indicating that the number of days with cold extreme temperatures have decreased by 0.3 days/year with a confidence interval of ±0.2 days/year, 90%. Here, 2010 stands out as being the year with the highest amount of cold days compared with other years in the same time series.

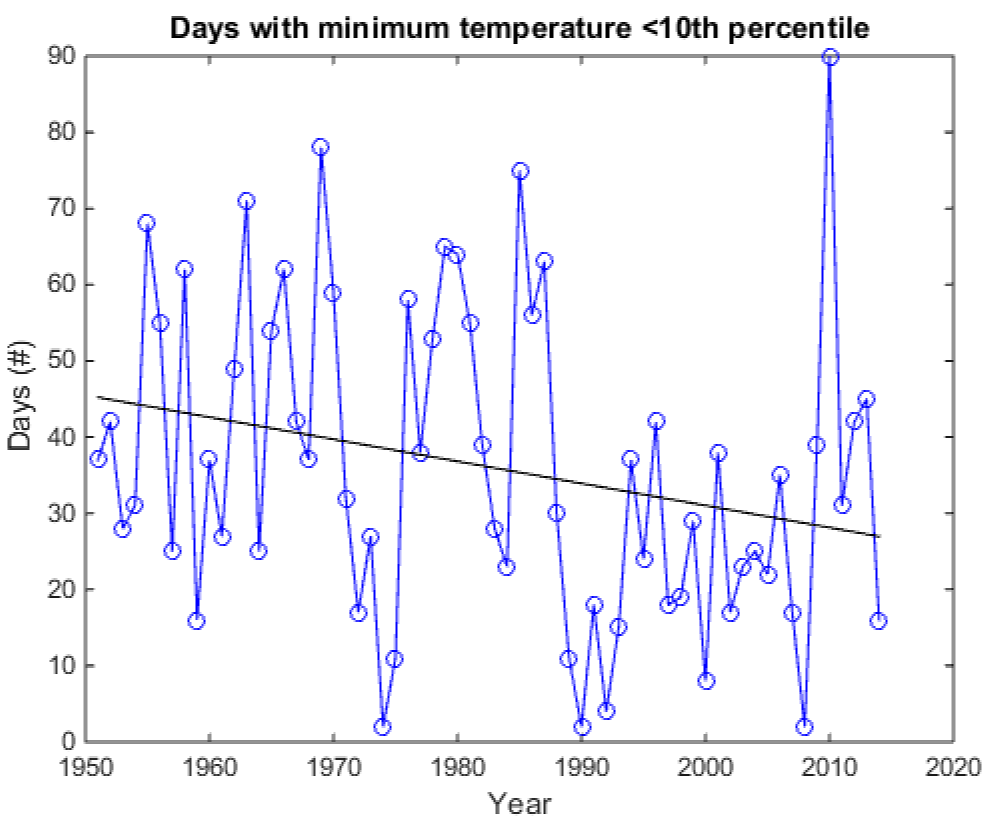

Figure 7: The 10th percentile of the average minimum temperature of each day is − 8°C. Illustrated is the annual count of days below the 10th percentile for the time series between 1951-2014.

Table 4: The 10th percentile and trend estimates for days below the 10th percentile with a 90% confidence interval.

Trends in days per year	10th percentile
-0.3±0.2	-8.0°C

Table 5 summarizes the occurrence and intensity of cold spells in Sweden for the period 1951-2014, categorized by number of cold spells, lowest measured temperature during a cold spell and longest duration, for each year. The length of cold spells are determined by counting consecutive days where temperatures were below the 10th percentile, where the minimum criteria is six consecutive days. Years that stand out in terms of temperature, duration or number of cold spells are marked red. It can be seen that during the second half of the time series the occurrence and intensity of cold spells seems to have decreased. 2010 stands out as the year with the highest amount of cold spells, with six in total. 1966 and 1987 measured the lowest temperatures and 1970 had the longest cold spell which lasted for 32 days.

Table 5: Cold spells. Annual count when at least six consecutive days of minimum temperatures <10th percentile. Listed by year, number of cold spells, minimum temperature and longest duration.

Year	Cold spells (#)	T_{min} (°C)	Longest Duration (days)	Year	Cold spells (#)	T_{min} (°C)	Longest Duration (days)
1951	2	-13.7	7	1967	4	-19.3	12
1952	2	-13.5	10	1968	2	-21.2	14
1953	2	-19.6	11	1969	4	-21.7	24
1954	2	-18.1	13	1970	3	-23.1	32
1955	4	-18.6	19	1971	2	-17.5	10
1956	3	-24.6	24	1972	1	-12.5	7
1957	1	-13.3	7	1973	2	-19.6	7
1958	5	-19.3	13	1974	-	-	-
1959	1	-16.5	8	1975	-	-	-
1960	3	-15.9	15	1976	3	-20.1	18
1961	1	-15.4	9	1977	3	-15.6	10

1962	3	-16.7	10	1978	4	-21.9	18
1963	4	-21.3	21	1979	4	-22.4	23
1964	1	-16.7	10	1980	3	-21.6	21
1965	3	-19.1	13	1981	2	-20.7	17
1966	4	-26.5	20	1982	3	-22.8	12

Year	Cold spells (#)	T_{min} (°C)	Longest Duration (days)	Year	Cold spells (#)	T_{min} (°C)	Longest Duration (days)
1983	1	-12.8	6	1999	2	-16.3	7
1984	1	-14.1	10	2000	-	-	-
1985	5	-25.2	23	2001	2	-18.1	11
1986	3	-19.5	28	2002	-	-	-
1987	2	-26.5	21	2003	1	-22.1	8
1988	1	-16.5	6	2004	-	-	-
1989	1	-19.1	9	2005	1	-15.9	8
1990	-	-	-	2006	2	-17.9	12
1991	1	-12.9	9	2007	1	-13.3	7
1992	-	-	-	2008	-	-	-
1993	-	-	-	2009	3	-14.4	13
1994	3	-17.6	11	2010	6	-20.9	21
1995	1	-17.7	13	2011	1	-19.0	17
1996	3	-18.4	13	2012	2	-22.3	14
1997	1	-13.4	6	2013	3	-16.9	16
1998	-	-	-	2014	-	-	-

4.3 Frost days

Frost days are defined by days with temperature <0°C. By counting the number of days when the average daily minimum temperature is below 0°C the occurrence over time can be analyzed. In Figure 8 it is shown that the total number of frost days in Sweden has decreased by about 0.4 days/year with a confidence interval of ±0.2 days/year, 90%. 2014 being the hottest year so far in Europe, as can also be seen in Figure 1 and 3, also had the fewest number of frost days since the beginning of the data set in 1951. This result is also consistent with Figure 7. For example 2010 where one can see an increase in frost days, could be correlated with the amount of cold spells and extreme cold days that year.

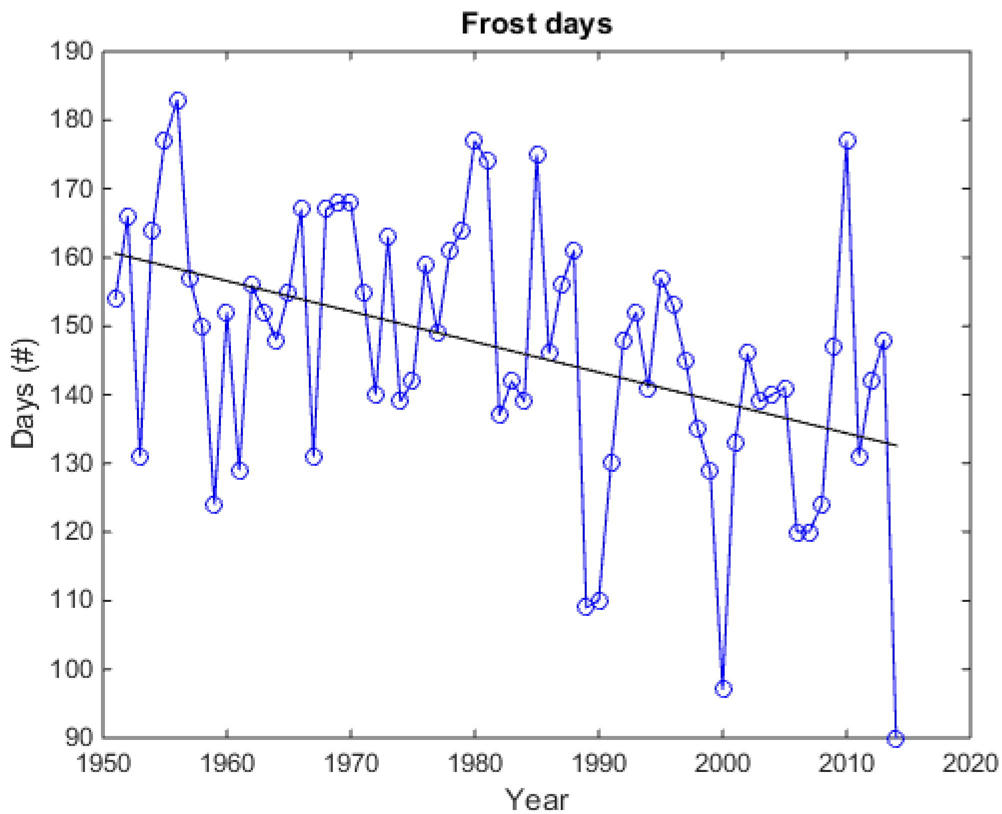

Figure 8: Illustrated is the annual count of days with temperatures below 0℃ in Sweden for the time series between 1951-2014.

Table 6: Trend estimates for frost days with a 90% confidence interval.

Trends in days per year
-0.4±0.2

4.4 Coldest year (Station)

Figure 9 show trends for the annual minimum temperature for Falsterbo and Jokkmokk. These are compared because of their geographical placement, Falsterbo is situated in southern Sweden and Jokkmokk in the north. From Figure 9 Falsterbo show a positive trend whereas Jokkmokk show a negative trend. Indicating that annual minimum temperatures are increasing in Falsterbo and decreasing in Jokkmokk. It is interesting to examine if temperatures are generally decreasing in the north. Trends have therefore been made for all stations, which is shown in Table 7.

In Figure 9, Falsterbo show a warming (positive) trend and Jokkmokk a cooling (negative) trend. But since the confidence interval suggests that the temperature trends might have been either positive or negative it is not possible to say anything about the statistical significance of these trends.

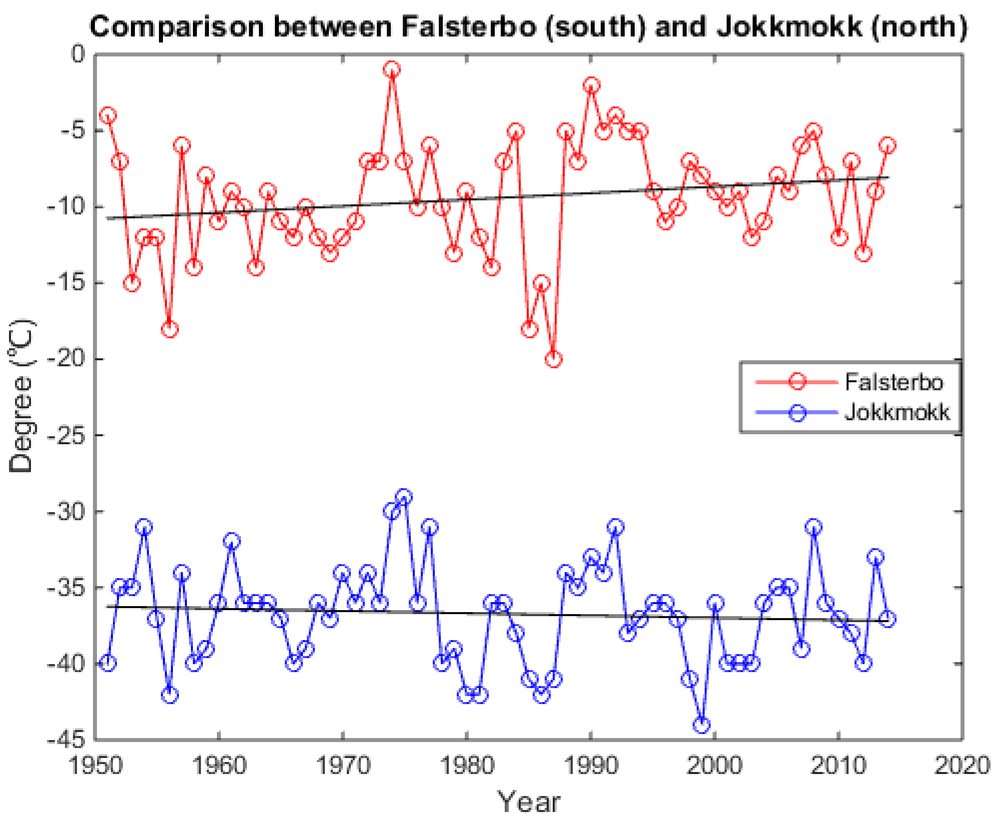

Figure 9: Comparison of the annual minimum temperatures at Falsterbo and Jokkmokk for the period 1951-2014.

Table 7 show trend estimates for annual minimum temperatures for each station in °C/year. Stations where there seems to be a negative trend are marked with blue. There seems to be more northerly stations with negative trends than southerly stations, however not exclusively. Station 105370 (in italic) showed some errors during calculations and should therefore not be treated as a correct result. Trends shown in Table 7 do however not have statistically significant values due to the same issues as above, large confidence intervals. Hoburg (station 68560) shows the largest warming trend (marked red) and Gunnarn A (station 147560) shows the largest cooling trend. However, the warming- and cooling trends may not be significant.

Table 7: Table of trend estimates for annual minimum temperatures for each station (sorted from south-north) with a 90% confidence interval.

Station number	Trend in °C per year	Station number	Trend in °C per year	Station number	Trend in °C per year
52230	0.0±0,0	82230	0.0±0.1	124030	0.5±1.3
53430	0.0±0.1	83270	0.0±0.1	127380	0.0±0.0
62400	0.1±0.1	85240	0.0±0.0	134110	0.1±0.0
64130	0.0±0.1	87440	0.1±0.2	140480	0.1±0.1
64510	0.3±0.2	89230	0.0±0.2	147560	-0.6±1.8
66420	0.1±0.3	93220	0.1±0.1	151280	-0.1±0.3
68560	0.4±1.6	97510	0.0±0.2	161790	0.1±0.1
72450	0.1±0.1	98230	0.0±0.3	163960	-1.6±2.1
74460	-0.1±0.1	99270	0.1±0.1	167990	-0.9±1.2
76420	0.1±0.3	105370	*-0.2±0.1*	169880	0.0±0.0
77210	0.0±0.2	107420	-0.2±0.2	192840	-1.4±0.7
78400	0.0±0.0	116490	-0.1±0.2		

5 Discussion

Results indicate that Sweden has indeed experienced a significant warming trend in cold extremes well in agreement with other regional and global studies [15, 30].

Annual average minimum temperatures have been examined, Figure 6. The period 1965-2014 show a warming trend of 0.07 °C/year with a 90% confidence interval. The period of 1965-2014 was chosen in order to eliminate large variations of the data and thus be able to find an eventual trend. The aim of this report is to analyze whether the frequency or magnitude of cold extremes has changed. Figures 8 and 9 shows similar results. Over all, days with temperatures below the 10th percentile has decreased indicating that days are getting warmer. Results show trends of -0.3 days/year with a 90% confidence interval of ±0.2 for the entire period of 1951-2014. Regarding the magnitude and frequency of cold spells, seen in Table 5, cold spells during the last 30 years seems to have decreased in both magnitude and frequency compared to the first half. Together with the overall increase of temperatures in Sweden, number of frost days have decreased by 0.4 days/year covering the whole period of 1951-2014. The above results all show a statistically significant warming in cold extremes in Sweden. Although the evident warming of cold extremes is consistent with results in [2-7] this study doesn't say much about the magnitude of cold extremes in general.

The choice of stations and their length of data series affect the results in many ways. Firstly it is important to have in mind that the results are not geographically representative due to the uneven placement of stations. As can be seen in Figure 5, there are more southerly stations and since temperatures are generally higher in southern Sweden results may be somehow misleading. In this study however the choice of stations were made due to their long series of measurements. Neither has the local climate of the individual stations been accounted for. Local weather and the environmental surroundings may be one of the reasons why some stations, Table 7, show different (negative) tendencies than others. In order to sort out questions regarding changes in cold extremes geographically southern Sweden has been compared with northern, Figure 9 and Table 7. Although it is not possible to say that the trends are significant, northern Sweden seems to have more stations showing negative trends. In Table 5 lengths of all data series for each station can be seen, 10 stations have series starting in 1951, eight started between 1961-1990 and the rest between 1990-2009. When doing analyses such as the ones in this study it is important to reflect over the limitations occurring from short records. Random variability may indicate larger temporary trends when looking at shorter time series [31]. Random variability may however also affect longer time series but the effect may not be as comprehensive. When looking at changes in climate it is thus very important to use longer time series in order to avoid short-term fluctuations. Random variability is one of the reasons why the period 1965-2014 was used in section 4.1 instead of 1951-2014, since trends may be difficult to determine when the variability is large.

The above results in changes of temperature extremes may however depend on the given definition. One way to improve the analysis would be to use smaller percentiles in order to separate extremes from daily distribution. Instead of defining a cold extreme as lying below the 10 percentile one might use the 5th. It would also be beneficial to use same metrics as in other studies when studying extremes when it comes to percentiles and indices so that comparisons between different studies have higher accuracy and comparability [32].

Sweden has a rather cold climate, warming of the climate may thus bring unexpected weather conditions which in turn could cause problems. But on the other hand, decreasing cold extremes is also beneficial since extreme events often affect society and ecosystems negatively. A milder climate would for example not cause great damages to infrastructure and agriculture (although some insect pests might benefit from less cold extremes) and thus be beneficial from an economical perspective. However, a decrease in cold extremes may lead to a different way of living. By no longer investing in sectors that normally needs support when cold spells strikes things could go wrong when they eventually strike. Warming of the climate would also require redistributions within the energy sector as demands would change. As shown by [2-7] although cold extremes might be getting milder, warm events are getting more extreme. From a societal perspective it is thus important to discuss vulnerability and exposure within different sectors and systems. It's crucial to understand how extreme events are changing and to what extent in order to eliminate the risks accompanied by them and prepare societies for their impacts on human and natural systems.

6 Conclusion

In conclusion there has been a significant warming since at least 1965 and a clear decrease in frost- and extreme cold days. Whether or not this warming has anything to do with anthropogenic emissions is not covered in this study but it is strongly indicated that this warming is correlated with the ongoing global warming. The Swedish society must thus consider its vulnerability and exposure within various sectors and systems and take decisions regarding climate adaptation. Knowledge about extreme events in terms of frequency and magnitude is crucial to societies since extreme events caught by surprise usually causes more damage. Sweden is facing a period of fewer and milder cold extremes but might also be experiencing more extreme warm events. Knowledge about changing extremes is useful for climate adaptation in order to prevent and reduce the societal vulnerability associated with the Swedish climate.

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Appendix 1

Codes and files available at:
https://drive.google.com/folderview?id=0BxER55NFDVKnfnJsM0NldFZXVUpvUDdRZXlJRGFkOC1KZ1JIaTFHdk9tSzRsNWJZOFhYTmc&usp=sharing

```
clear all
clc
%%
load Sverige65.txt
load year1965.txt

y1= Sverige61(:,1);
x=year1961(:,1);

xm=mean(x); % mean value of x
y1m=mean(y1); % mean value of y

c1=sum((x-xm).*(y1-y1m));
d1=sum((x-xm).^2);

a1=c1/d1 % a value of the equation (least square estimate eq)(trend)
b1=y1m-(a1*xm);% b value of the equation (least square estimate eq)
y1s=b1+(a1*x); % the linear regression equation

e1i=y1-y1s; % the residual
SSE1=sum(e1i.^2); % sum of squared residuals
se1=sqrt(SSE1/(62)); % square root of the variance
sa1=se1*sqrt(1/d1) % standard error in a
%sb=se*sqrt((1/4/+((xm^2)/d)))% standard error in b

plot(x,y1,'b')
hold on
plot(x,y1,'b-o')
hold on
plot(x,y1s,'k')
hold off

reggui(x,y1); %REGGUI - GraphicalUserInterface for linear regression
              % Copyright 1999 Joakim Lübeck
```

```
%%
load frostdagar.txt
load year.txt

y2=frostdagar(:,1);
x=year(:,1);

xm=mean(x); % mean value of x
y2m=mean(y2); % mean value of y

c2=sum((x-xm).*(y2-y2m));
d2=sum((x-xm).^2);

a2=c2/d2 % a value of the equation (least square estimate eq)(trend)
b2=y2m-(a2*xm);% b value of the equation (least square estimate eq)
y2s=b2+(a2*x); % the linear regression equation

e2i=y2-y2s; % the residual
SSE2=sum(e2i.^2); % sum of squared residuals
se2=sqrt(SSE2/(62)); % square root of the variance
sa2=se2*sqrt(1/d2) % standard error in a
%sb=se*sqrt((1/4/+((xm^2)/d)))% standard error in b

plot(x,y2,'b')
hold on
plot(x,y2,'b-o')
hold on
plot(x,y2s,'k')
hold off

reggui(x,y2); % REGGUI - GraphicalUserInterface for linear regression
              % Copyright 1999 Joakim Lübeck

%%
load coldextreme.txt
load year.txt

y3=coldextreme(:,1);
x=year(:,1);

xm=mean(x); % mean value of x
y3m=mean(y3); % mean value of y

c3=sum((x-xm).*(y3-y3m));
d3=sum((x-xm).^2);

a3=c3/d3 % a value of the equation (least square estimate eq)(trend)
b3=y3m-(a3*xm);% b value of the equation (least square estimate eq)
```

```
y3s=b3+(a3*x); % the linear regression equation

e3i=y3-y3s; % the residual
SSE3=sum(e3i.^2); % sum of squared residuals
se3=sqrt(SSE3/(62)); % square root of the variance
sa3=se3*sqrt(1/d3) % standard error in a
%sb=se*sqrt((1/4/+((xm^2)/d)))% standard error in b

plot(x,y3,'b')
hold on
plot(x,y3,'b-o')
hold on
plot(x,y3s,'k')
hold off
reggui(x,y3); % REGGUI - GraphicalUserInterface for linear regression
              % Copyright 1999 Joakim Lübeck

%%
load medeldag.txt

y=medeldag(:,1);

P=prctile(y,10) %gives the 10th percentile in y

%%
load falsterbo.txt
load jokkmokk.txt
load year.txt

x=year(:,1);
f=falsterbo(:,1);
j=jokkmokk(:,1);

xm=mean(x); % mean value of x
fm=mean(f); % mean value of y

cf=sum((x-xm).*(f-fm));
df=sum((x-xm).^2);

af=cf/df % a value of the equation (least square estimate eq)(trend)
bf=fm-(af*xm);% b value of the equation (least square estimate eq)
yfs=bf+(af*x); % the linear regression equation

jm=mean(j); % mean value of y

cj=sum((x-xm).*(j-jm));
dj=sum((x-xm).^2);
```

```
aj=cj/dj % a value of the equation (least square estimate eq)(trend)
bj=jm-(aj*xm);% b value of the equation (least square estimate eq)
yjs=bj+(aj*x); % the linear regression equation

figure
plot(x,f,'r-o',x,j,'b-o',x,yfs,'k',x,yjs,'k')
legend('Falsterbo','Jokkmokk')
```