STA4000 Final Report - Detailed Analysis
Investigation on Iceland Population Growth and Climate Change

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1 Introduction

This paper is the supplement of "STA4000 Final Report - Summary". It contains the detailed steps and evidence for the analysis of Iceland Population Growth and Climate Change.

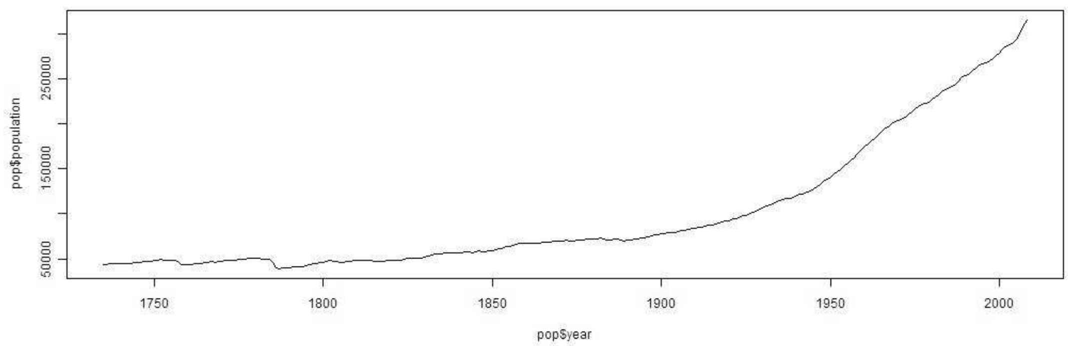
2 Data Source

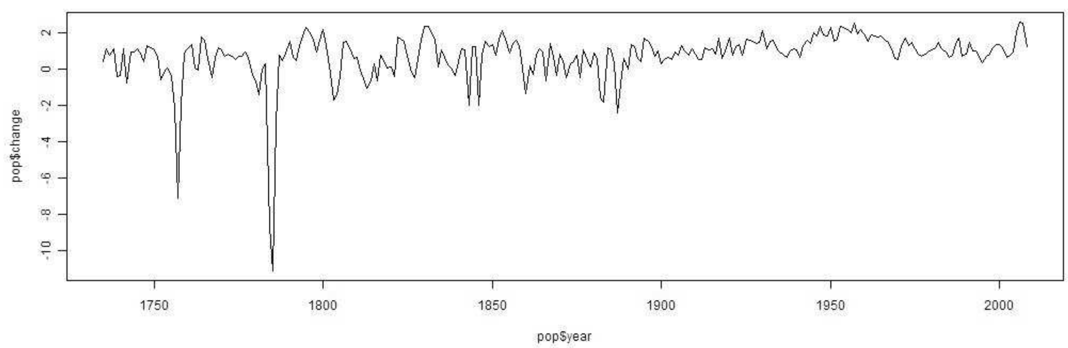
2.1 Population of Iceland

Iceland is an European island country located in the North Atlantic Ocean. It is far away from the main Europe. The first settler to Iceland is around 9th century. Iceland has a relative stable and simple population structure. Most of Icelanders are farmers and fishers.

The uninterrupted official census data in Iceland start from 1735 (Statistics Iceland official web site). The population and the growth rate (measured in percentage) are graphed below. The population in Iceland grow from 43,678 in 1735 to 78,203 in 1900 (projecting an annual growth rate of 0.36). But it has expanded 4 times during the last century (projecting an annual rate of 1.31). Mostly because of the improvement of the living standard by the modern industrialization. From the graph we also see the growth rate is less variable after 1900.

There are 16 years which the population decrease more than 1 percent in 18th and 19th century. We see 2 big population collapses (around 1756 and 1785) from the population growth graph which correspond to the history records from documentary evidence from "Milestones in Icelandic History". From 1756 to 1758, Disease and famine killed 5,000 people (10% of its population). Around 1785, the Laki volcano erupted. A great famine followed. The population continue to decease until 1787.





2.2 Climate of Iceland

There are two climatic zones in Iceland. The temperate zone in the south and the arctic zone in the north. The south coast is warmer, wetter and windier than the north. Snowfalls in winter is more common in the north than the south. The central highlands are the coldest part of the country and mostly uninhabitable. Iceland has a high concentration of active volcanoes. Among 130 volcanic mountains, 18 have erupted since 9th century.

Iceland is located near the border between the warm and cold ocean currents. The warm Irminger Current, flows along the southern and western coast. A cold East Icelandic Current (a branch of North Atlantic Drift), approaches northeast and east coasts.

Warm and cold air masses also meet near Iceland. Polar front, the boundary between moist tropical air and dry continental polar air, produce an area of instability near Iceland. Cyclones which form as disturbance on the front pass Iceland occasionally. The famous pressure center, the Icelandic Low is situated between Iceland and southern Greenland. Large pressure variations in Iceland are therefore common.

The climate of Iceland is also influence by the ice flow in the East Greenland Current. The sea ice reach the north and east coasts of Iceland in winter. But the extent of the ice flow varies from year to year and also with the time of year.

2.3 Iceland measured temperature data

The temperature data is available from GISS Surface Temperature Analysis. The measured temperature from 5 Iceland cities gave us an idea how the Iceland climate looks like for the last 150 years.

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City              Location
Akureyri          65.7 N   18.1 W
Grimsey           66.5 N   18.0 W
Teigarhorn        64.7 N   14.3 W
Vestmannaeyja     63.4 N   20.3 W
Stykkisholmur     65.1 N   22.7 W
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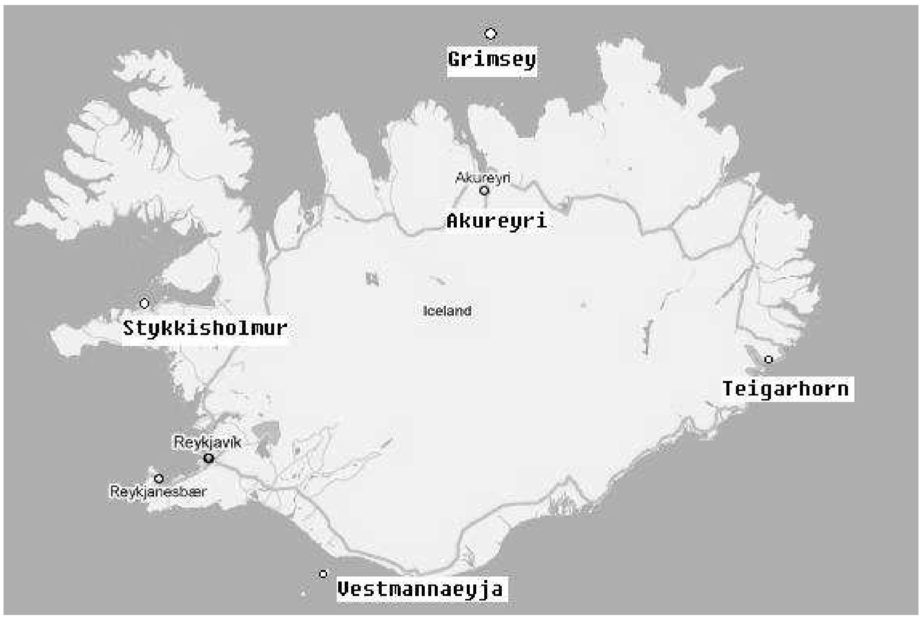


		Akureyri	Grimsey	Vestmannaeyja	Teigarhorn	Stykkisholmur
1	mean	3.17	2.43	5.57	4.15	3.42
2	standard deviation	1.03	0.94	0.57	0.87	0.71

	year	Akureyri	Grimsey	Vestmannaeyja	Teigarhorn	Stykkisholmur
year	1.00	0.46	0.32	-0.33	0.23	0.44
Akureyri	0.46	1.00	0.89	0.50	0.86	0.89
Grimsey	0.32	0.89	1.00	0.60	0.90	0.88
Vestmannaeyja	-0.33	0.50	0.60	1.00	0.73	0.53
Teigarhorn	0.23	0.86	0.90	0.73	1.00	0.77
Stykkisholmur	0.44	0.89	0.88	0.53	0.77	1.00

The highest annual temperature is seen at the south most city Vestmannaeyja, lowest at the north most city Grimsey. The weather is more variable in north and east area than to west and south area of Iceland. The correlations between measured temperatures are fairly high (0.7-0.8) between northern Iceland cities. Medium correlations (0.50, 0.60, 0.52) are found between Vestmannaeyja(south Iceland) and 3 other north Iceland cities (Akureyri, Grimsey and Stykkisholmur) which indicates south and north Iceland may belong to different weather systems.

2.4 Iceland volcano events

Iceland has a high concentration of active volcanoes. A detailed large volcano eruptions can be downloaded from Global Volcanism Program of Smithsonian Institution website.

Volcano Name	Volcanic Subregion	Date		VEI
KATLA	Southern Iceland	1721	May 11	5?
RAEFAJ KULL	Southeastern Iceland	1727	Aug 3	4
KATLA	Southern Iceland	1755	Oct 17	5?
HEKLA	Southern Iceland	1766	Apr 5	4
GRIMSVOTN	Northeastern Iceland	1783	Jun 8	4+
HEKLA	Southern Iceland	1845	Sep 2	4
KATLA	Southern Iceland	1860	May 8	4
GRIMSVOTN	Northeastern Iceland	1873	Jan 8	4
ASKJA	Northeastern Iceland	1875	Mar 29	5
GRIMSVOTN	Northeastern Iceland	1903	May 28	4
KATLA	Southern Iceland	1918	Oct 12	4+
HEKLA	Southern Iceland	1947	Mar 29	4

VEI: The Volcanic Explosivity Index, a relative measure of the explosiveness of volcanic eruptions. The question mark on some of the VEI means the measurement may not be accurate because these volcano eruptions only have documentary evidence.

3 Reconstruct Northern Iceland Temperature

The measured temperature from Iceland is only available for the recent 150 years. But the last century coincide with the period of global warming. And the population growth is less correlated with climate change due to the improvement of the living standard by the modern industrialization. So we should focus our analysis on the pre-industrial era. And we need to find a way to reconstruct past climates of Iceland.

3.1 Introduction to Ice Core

Many scientists have tried to reconstruct the climate for Iceland. But most of the attempts are based on historical documentary like sagas, literatures, annals and some early work on geography. One of the disadvantage of using documentary evidence is it's hard to verify the reliability of the sources. Some sources even contains errors, misconceptions. And the description of the weather of Iceland is very subjective. Thus is less useful for quantitative analysis.

On the other hand, ice core from ice sheet and ice caps provides a way to build the past climatical and environmental conditions. Recent ice coring projects in Greenland and Antarctica have successfully yield climate information back to hundreds of thousands of years.

An ice core is a core sample from the accumulation of snow and ice over many years. In polar area and high mountains sufficient snow falls each year. Those places are extremely code so the snows never melt. The snow have re-crystallized and accumulates annual layers over time.

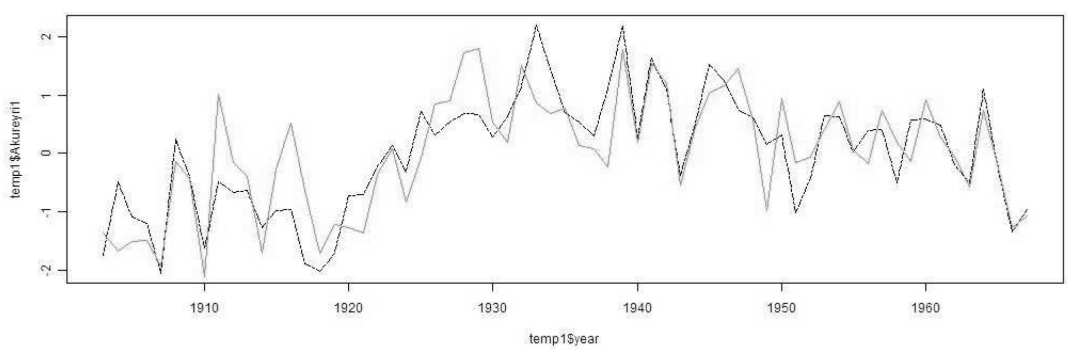
Ice core contains an abundance of information. The oxygen isotopic variation in ice core can be used to reconstruct the temperature change. The dust and air bubbles trapped in the ice provide the valuable source for the air composition in lower atmosphere. The ash layer in the ice core usually indicate a volcanic eruption. It provides a way to get a picture of the climate at past time.

By using a large hollow drill, scientists have collected thousand-meter-long ice core samples from the ice sheet. Dating the ice core is not a easy task. Shallow cores or upper parts of cores can be dated exactly by counting individual layers. Deeper ice cores are dated by seasonal variations in physical, chemical, electrical and isotope properties as layers become less visible. The dating is compared with known volcano eruptions and in other ways.

Ice cores are usually collected at polar areas and high mountains. Several major ice core sites are built in Antarctica and Greenland. There are some other ice core sites in USA, China and Peru.

3.2 Northern Iceland Measured Temperature

Although there are no ice core sites in Iceland. There are some similarity of the climate system in northern Iceland and southern Greenland. The shortest distance from Iceland to Greenland is only 290km. We also find a high correlation (0.812) between temperatures of Akureyri (north Iceland) and Angmagssalik (south west Greenland) from 1903 to 1967. The following graph is the time series of the measured temperature of Akureyri and Angmagssalik between 1903 and 1967. It also shows the temperature between these 2 cities are very similar. That provides some hope that we can use temperature pattern from south Greenland as a surrogate for Iceland.



The annual northern Iceland measured temperature is defined as the average annual temperature of 4 northern Iceland cities (Akureyri, Grimsey, Teigarhorn and Stykkisholmur):

$$t = \frac{1}{4}(t_{Akureyri} + t_{Grimsey} + t_{Teigarhorn} + t_{Stykkisholmur}) \tag{1}$$

3.3 Reconstruct temperature from Isotopic Ratio from Ice Core

One way to reconstruct temperature is to use the Isotopic variation in ice core. Ice originates by evaporation of ocean water. Ocean water is mostly $H_2^{16}O$ (normal water) and a small amounts of $H_2^{18}O$(heavy water). As air mass travels away from sea to inland place. Water is lost from air mass as precipitations. Precipitation tends to loss more heavy water as temperature become colder and the precipitation become isotopically lighter. The $\delta^{18}O$ (pronounced delta-18-O) ratio (also called oxygen isotopic ratio) is defined as the percentage change in the fraction of water which is heavy water at the sample compared to the standard mean ocean water(SMOW) baseline:

$$\delta^{18}O = \frac{(^{18}O/^{16}O)_{sample} - (^{18}O/^{16}O)_{SMOW}}{(^{18}O/^{16}O)_{SMOW}} \tag{2}$$

Empirical evidence shows the correlation between the $\delta^{18}O$ ratio and temperature is high. The correlation become stronger at lower temperature. The $\delta^{18}O$ ratio from interior regions of polar ice sheet is good for temperature reconstruction (Alley and Cuffey 2001, Cuffey et al. 1995). In tropical area the correlation is less significant because the isotopic ratio is not heavily influenced by local precipitation.

The $\delta^{18}O$ ratios are measured in ‰ scale. E.g. the value of annual $\delta^{18}O$ ratios of Crete ice core in 1974 is -38.24‰. And the $\delta^{18}O$ ratios is usually negative because the ratio of heavy water (^{18}O) in ice core is less than the ratio in the sea water.

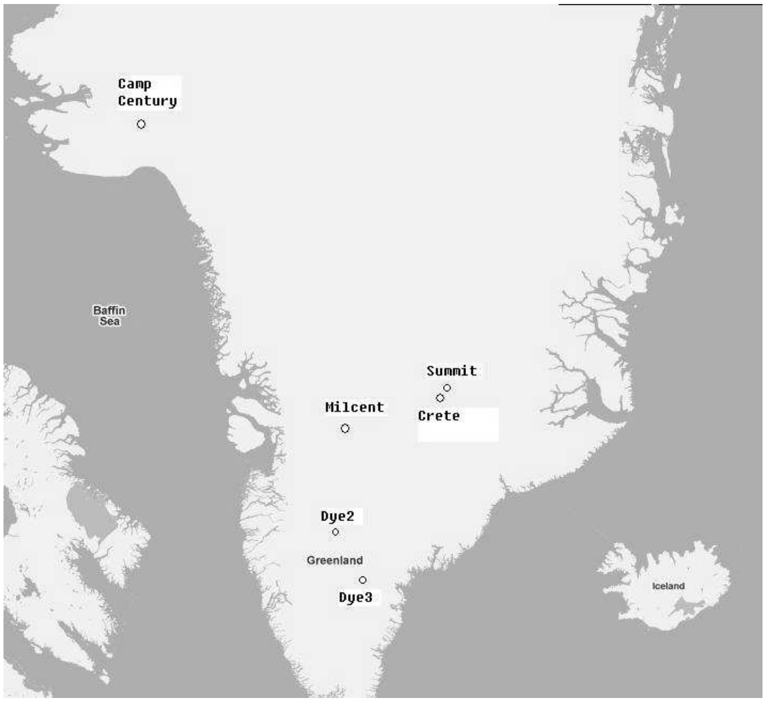
3.4 Ice Core Data from Greenland

Two projects have been funded for the research of ice core data in Greenland including the GRIP (the Greenland Ice Core Project) and GISP2 (Greenland Ice Core Project 2). The GISP project includes the collection and analysis of ice core samples from Camp Century, Milcent, Crete, Dye2, Dye3 and Summit sites. The annual average isotopic ratios ($\delta^{18}O$) can be downloaded from NOAA Palaeoclimatology website.

Some of the sites provide the ice core record up to 20 thousand years ago. But they only have 50 year average of $\delta^{18}O$ ratio. And some of them are not properly dated (in terms of years). The following ice core data will be used in our analysis since they have the annual average of $\delta^{18}O$ ratio for the recent 1000 years.

Site name	From	To	Location	Elevation
Camp Century	1242	1967	(77.10N, 61.08W)	1885 masl
Milcent Ice Core	1176	1967	(70.18N, 44.35W)	2410 masl
Crete Ice Core.	553	1974	(71.12N, 37.32W)	2850 masl
Dye-2	1742	1974	(66.48N, 46.33W)	2338 masl
Dye-3	-1899	1872	(65.11N, 43.49W)	2480 masl

Note: The 2nd and 3rd columns gives the start and end year during which the $\delta^{18}O$ ratios are available. MASL (Meters above sea level) column gives us the elevation of the ice core sites.



3.5 Which Ice Core Site Is Better in Reconstructing Northern Iceland Temperature

In this section, we try to find the $\delta^{18}O$ ratio of a ice core site which better represent the measured temperature of northern Iceland. (The $\delta^{18}O$ ratios of these ice cores have quite different patterns (See append for more detailed analysis). So we will not combine them together to model the measured northern Iceland temperature.)

The ice core data from summit and Dye-3 sites are not used for the temperature reconstruction because the year coverage is not good. This give us 4 candidate ice core sites (Crete, Dye2, Milcent and CampCentury).

The highest correlation is found between $\delta^{18}O$ from Crete ice core and measured northern Iceland temperature.

	year	Crete	Dye2	Milcent	CampCentury	temp_n_iceland
temp_n_iceland	0.50	0.33	0.06	0.24	0.14	1.00

Then we apply the following linear regression model to the measured temperature from 1884 to 1967 and corresponding ice core data:

$$t_i = \beta_0 + \delta^{18}O * \beta_1 \tag{3}$$

where t stand for measured annual average temperature of northern Iceland. $\delta^{18}O$ stand for the isotopic ratio from one ice core. The output of the model is given below:

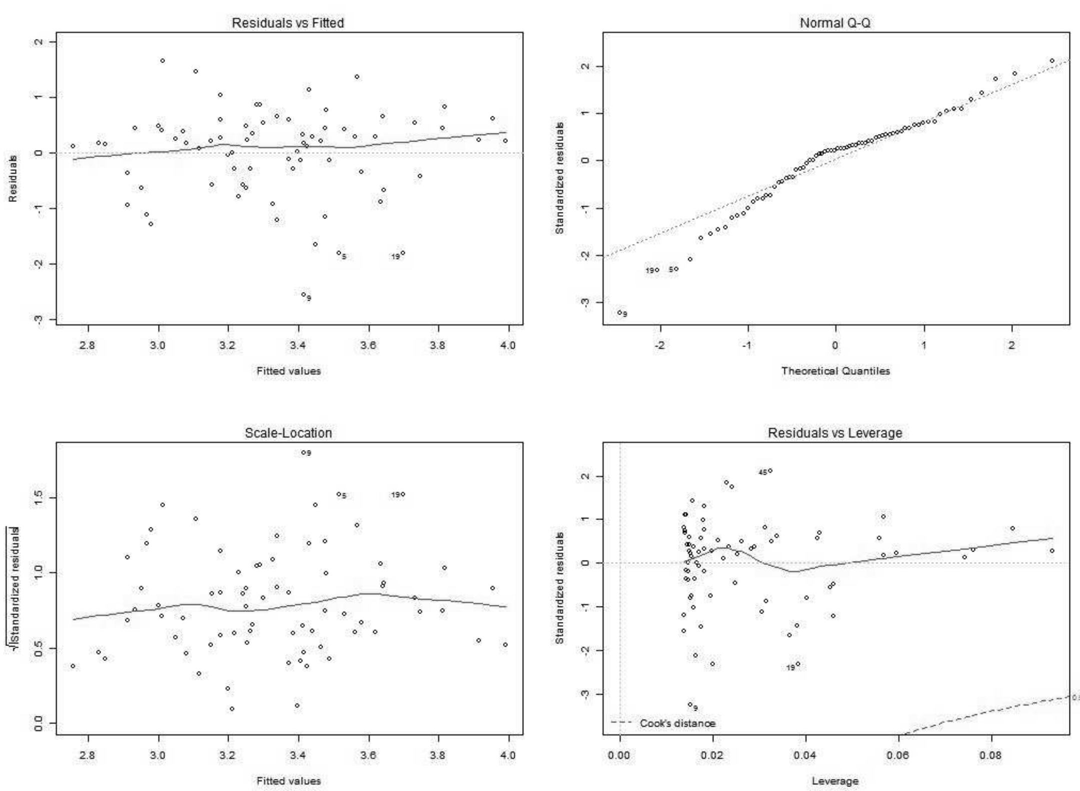
Diagnostic diagrams for the linear regression for Crete, Milcent, Dye2 and Camp Century ice cores are also included below. The model using Crete ice core data looks Normal distributed (from qq-plot) and shows constant variance residuals. The model using Milcent and Camp Century ice core data don't have constant variance residuals. The p-values for model using Dye-2 and Camp Century ice core are not significant.

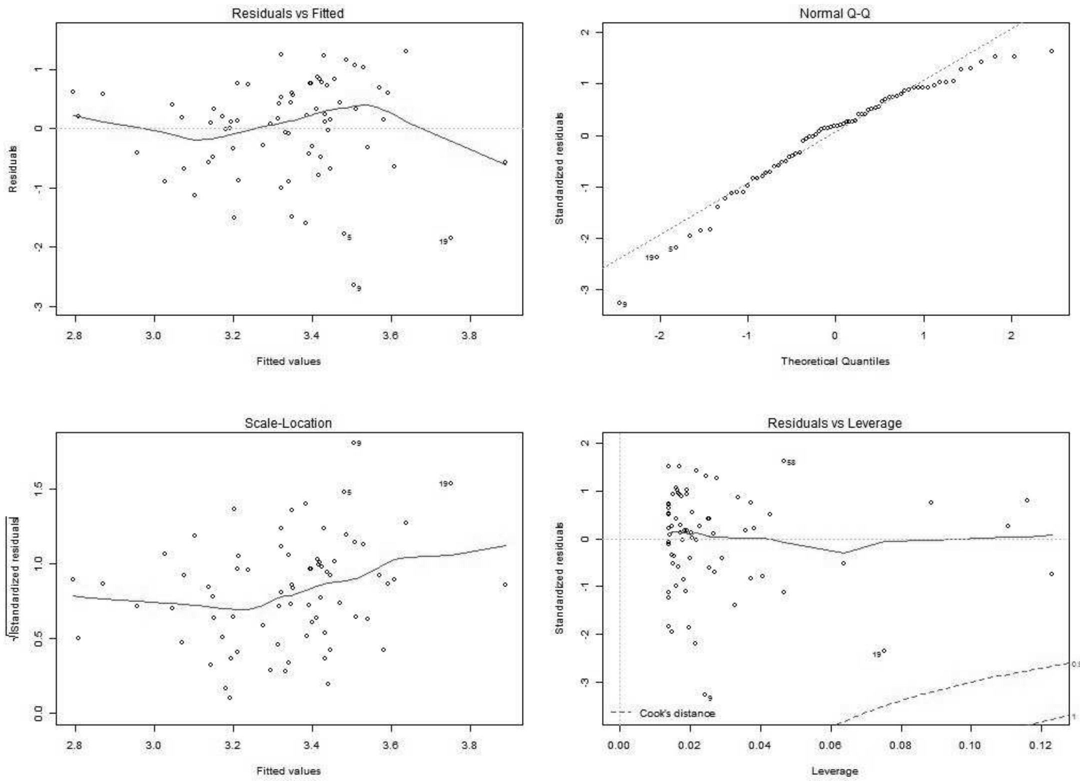
	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	12.2250	3.0173	4.05	0.0001
Crete	0.2599	0.0881	2.95	0.0043

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	7.6520	2.1003	3.64	0.0005
Milcent	0.1465	0.0711	2.06	0.0432

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	4.7205	2.6023	1.81	0.0740
Dye2	0.0536	0.1003	0.53	0.5950

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	5.8716	2.1826	2.69	0.0089
CampCentury	0.0880	0.0756	1.16	0.2481

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Residuals
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Standardized residuals
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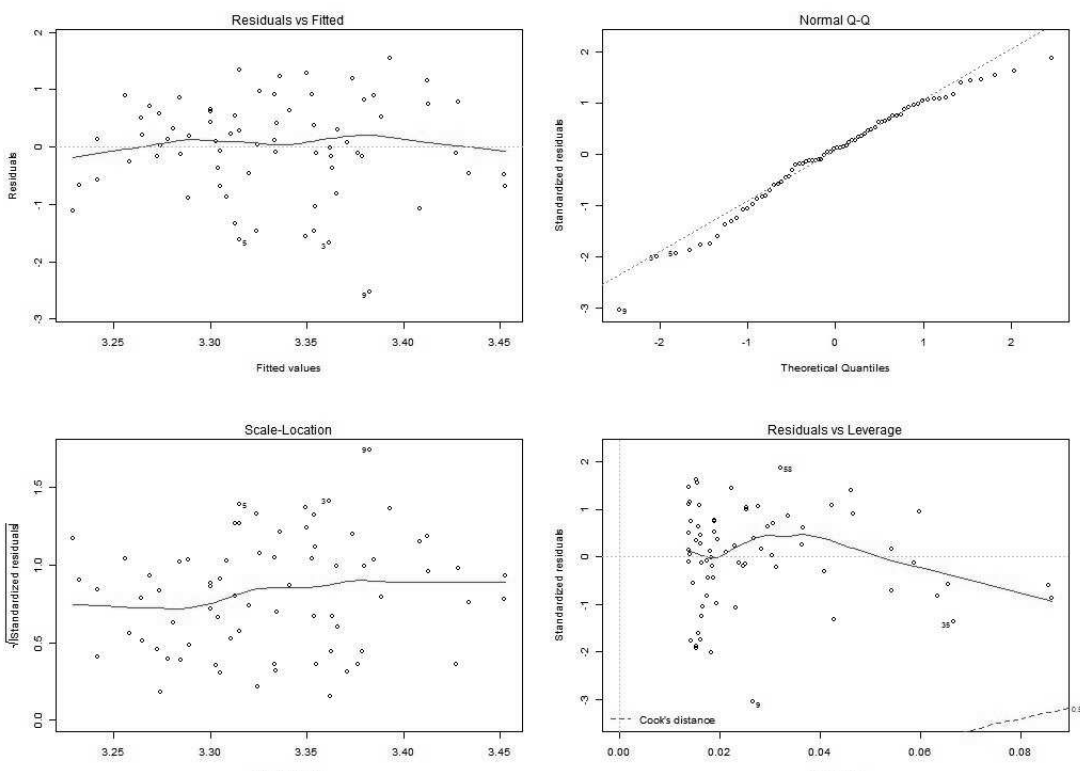
Leverage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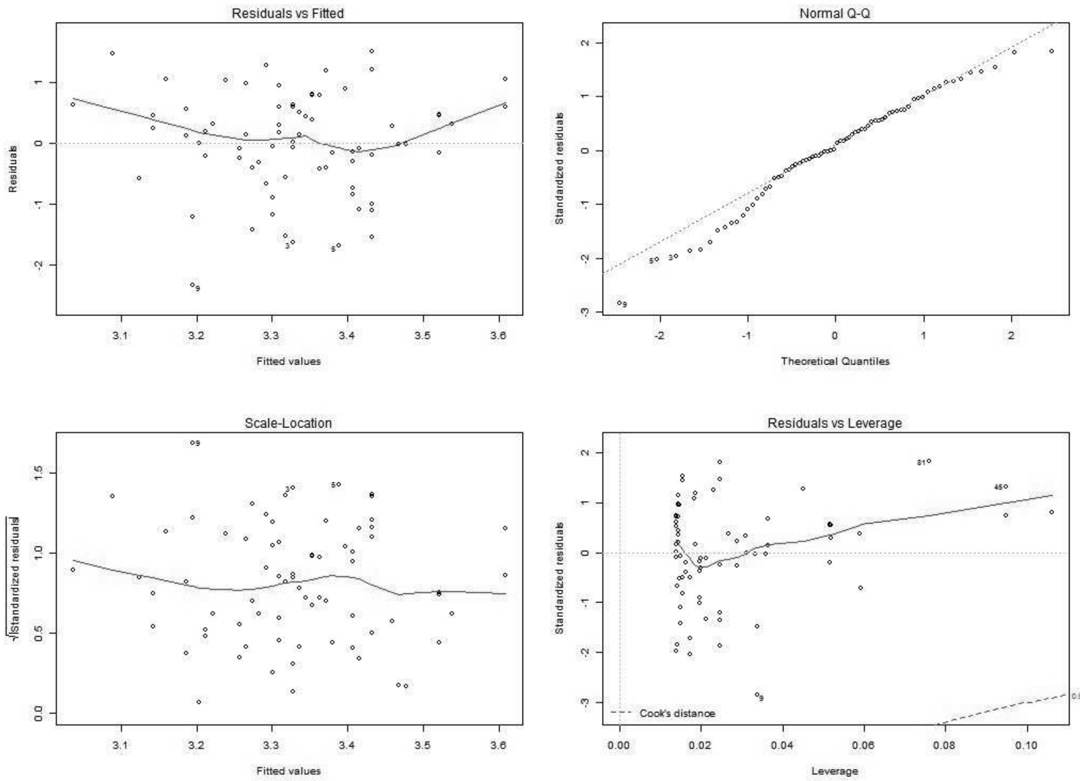


So the $\delta^{18}O$ ratio from Crete ice core is better in modeling measured temperature of northern Iceland from 1884 to 1967 because it gives the highest correlation and the most significant p-value. The equations for reconstructing temperature is:

$$t_i = 0.2599 * \delta^{18}O_i + 12.2250 \tag{4}$$

where t_i stand for northern Iceland temperature of year i. $\delta^{18}O_i$ stand for the annual average $\delta^{18}O$ ratio in Crete ice core for year i.

This means a increase of 1‰ of $\delta^{18}O$ in Crete ice core is corresponding to 0.2599°C increase of northern Iceland temperature from 1884 to 1967.

We then plug in the $\delta^{18}O$ in Crete ice core data from 1700 to 1885 to this equation to reconstruct past northern Iceland temperature for 18th and 19th century.

More discussions on reconstruct temperature by linear model can be found in the appendix.

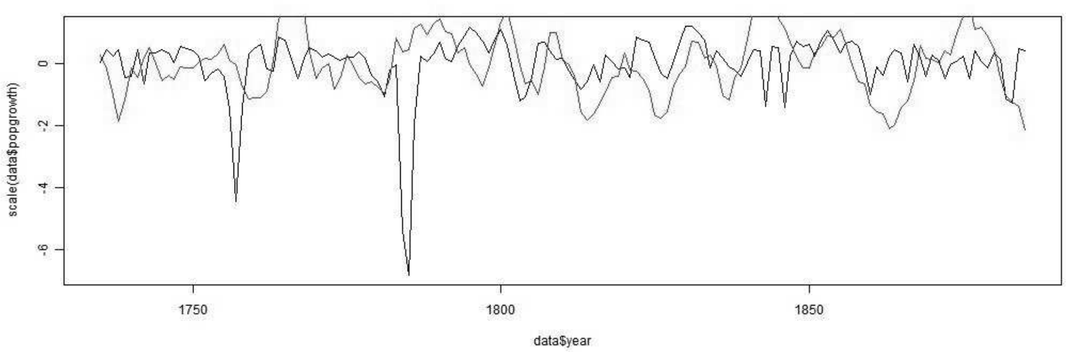
4 Analysis of Iceland population growth

With the reconstructed northern Iceland temperature from 1700 to 1885, we are able to do the analysis on Iceland population growth for the pre-industrialization periods.

We choose a 150 period (from 1735 to 1885) to do the analysis.

4.1 Initial investigation of the data

The following figures represent the standardized population growth and 5 year moving average of the reconstructed temperature from 1735 to 1885. The biggest drops of population growth on around 1757 and 1785 were due to 2 volcano eruptions. The population growth and temperature share the similar increase and decrease patterns. It looks like both the volcano eruptions and the temperature has some effect on the population growth rate.



Note: The 5 year moving average temperature of year n is defined as

$$t_{n,ma5} = \frac{1}{5} \sum_{i=n-4}^{n} t_i \tag{5}$$

where t_i stand for the annual temperature of year i. It measured the average temperature in the last 5 years.

4.2 Model by using Volcano Events as Factors

There are 7 big volcano eruptions from 1735 to 1860.

Volcano Name	Volcanic Subregion	Date	VEI
KATLA	Southern Iceland	1755 Oct 17	5?
HEKLA	Southern Iceland	1766 Apr 5	4
GRIMSVOTN	Northeastern Iceland	1783 Jun 8	4+
HEKLA	Southern Iceland	1845 Sep 2	4
KATLA	Southern Iceland	1860 May 8	4
GRIMSVOTN	Northeastern Iceland	1873 Jan 8	4
ASKJA	Northeastern Iceland	1875 Mar 29	5

We found the biggest population growth rate drop all happened within the 5 years of the volcano eruption. So first we tried to use indicator to identify post-volcano-eruption years. E.g. For the volcano eruption on 1755, the volcano indicator for 1755, 1756, 1757, 1758, 1759 is set to 1.

We try to model the population growth with both the temperature and the volcano events. We are not sure if the temperature and volcano eruptions are related to each other (i.e. volcano eruptions may cause temperature drop). So we include interactions between temperature and volcano indicator to the model. We also include the year in the model because the temperature may increasing/decease with time. So we start with the following full (3-way) interaction model:

$$\begin{aligned} popgrowth = {} & \beta_0 * vind * t * year + \beta_1 * vind * t + \beta_2 * vind * year + \beta_3 * t * year \\ & + \beta_4 * volind + \beta_5 * t + \beta_6 * year + \beta_7 \end{aligned}$$

	year	pop	popgrowth	post-volcano 5 years indicator
22	1756	48620	-2.09	1
23	1757	47602	-7.13	1
50	1784	49753	-8.69	1
51	1785	45428	-11.11	1
52	1786	40381	-2.95	1
112	1846	58677	-2.01	1

where popgrowth stand for population growth rate, vind stand for post-volcano years indicator, t stand for reconstructed temperature (or its moving average) in a particular year.

The model selection strategy is:

- start from the full 3-way interaction linear model
- drop 3-way interaction if not significant
- redo regression on full 2-way interaction linear model
- drop the most insignificant term (drop one term at a time)
- if the interaction terms are significant, use this model as the final model even some of the non-interaction terms are not significant.
- or if all interaction terms are all removed from model. drop the insignificant term (one at a time) until all terms left are significant and use it as the final model

The final model for using 5 post volcano year indicator is as follow: The 2-way interaction

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-3.4850	6.6613	-0.52	0.6017
temp_ma5	1.5244	0.9073	1.68	0.0951
factor(volcano5years)1	-41.0366	11.8223	-3.47	0.0007
year	-0.0005	0.0033	-0.15	0.8819
factor(volcano5years)1:year	0.0218	0.0065	3.34	0.0010

term for volcano indicator and year is significant (0.0010). The model suggests the volcano eruptions and year together are related to population growth rate. By looking into the data, 2 the big volcano eruptions in 18th century (1755 and 1783) caused large population growth drops (-7.13 in 1757, -8.69 in 1784, -11.11 in 1785) in Iceland. But the volcano eruptions from 19th century only caused minor population drops in Iceland.

We also tried to use indicator for 4 post volcano years and get the following final model: The 3-way interaction term for temperature, volcano indicator and year is significant (0.0193) which suggest all 3 variables together are related to population growth.

But we found the model is not very stable by using different post-volcano years indicator. It make us think this model may not be good for the data set. Volcano eruptions are rare events. The effect of volcano also depend on its locations and severity measured by VEIs. The VEI measurement from 18th century may not be reliable because we only have documentary evidence at that time. The effect of volcano events on population growth rate is changing

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-33.0923	150.6015	-0.22	0.8264
temp_ma5	10.6132	46.0508	0.23	0.8181
factor(volcano4years)1	-782.7903	302.1951	-2.59	0.0106
year	0.0156	0.0827	0.19	0.8508
temp_ma5:factor(volcano4years)1	214.8324	89.8905	2.39	0.0182
temp_ma5:year	-0.0049	0.0253	-0.20	0.8456
factor(volcano4years)1:year	0.4219	0.1647	2.56	0.0114
temp_ma5:factor(volcano4years)1:year	-0.1159	0.0490	-2.37	0.0193

over time (perhaps because people have more knowledge of volcano and have better shelters to protect themselves). So the effect of volcano events can not be captured in the model in a systematical way. So it may be wise to just remove the data in post volcano years from the model.

4.3 Model by Exclude Post Volcano Years

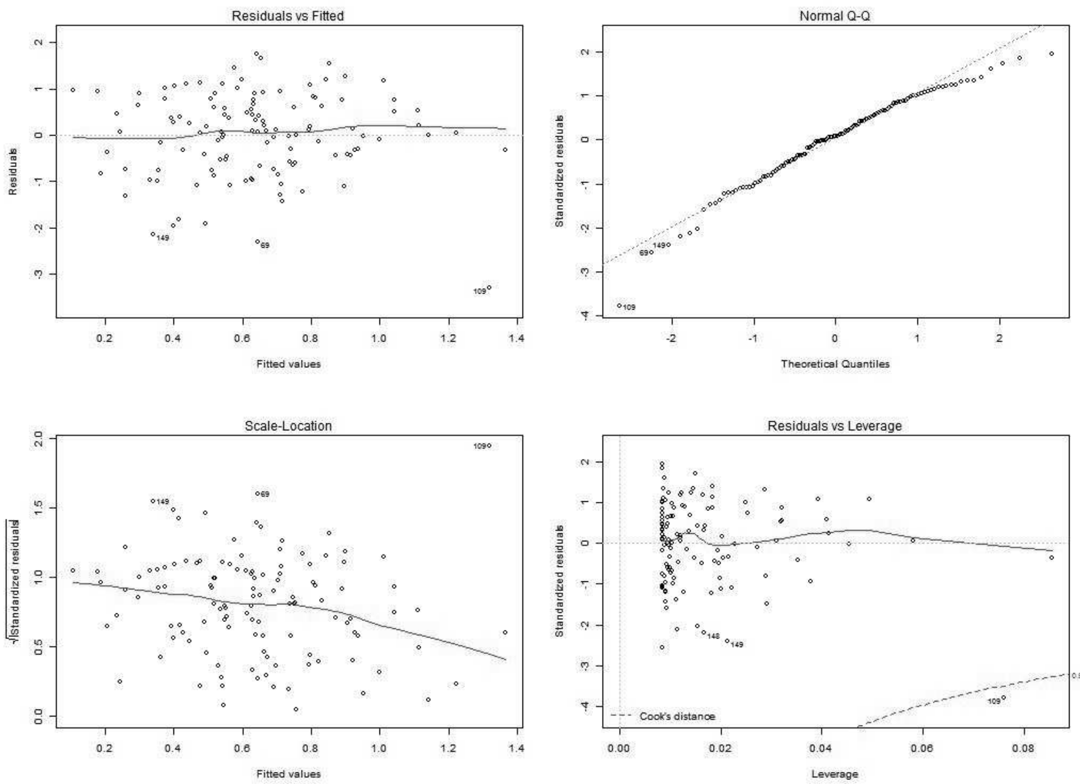
This lead us to excluding post 5 volcano years from the data. So the question is can we still find some relationship between population growth rate and Iceland temperature during normal years (years without volcano eruptions)?

We try a linear regression on the following model:

$$popgrowth = \beta_0 * year * t + \beta_1 * year + \beta_2 * t + \beta_3 \tag{6}$$

We tried the model on the 5 year moving average of the temperature. We start with full interaction model and use the same model selection strategy from the previous section. The year term is removed because of non-significant p-value. The output of final model are shown below:

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-5.5092	2.1252	-2.59	0.0107
temp_ma5	1.8682	0.6454	2.89	0.0045



The diagnostic of the model is good. The residuals have constant variance. The qq-plot also shows the 5 years moving average of reconstructed temperature is Normally distributed.

But is it a coincidence that 5 year moving average is related to population growth rate? We go back to the data and found the 2 to 10 years moving average are all correlated (range from 0.18 to 0.31) to the population growth rate. This means the population growth was related to the reconstructed temperature int the past few years.

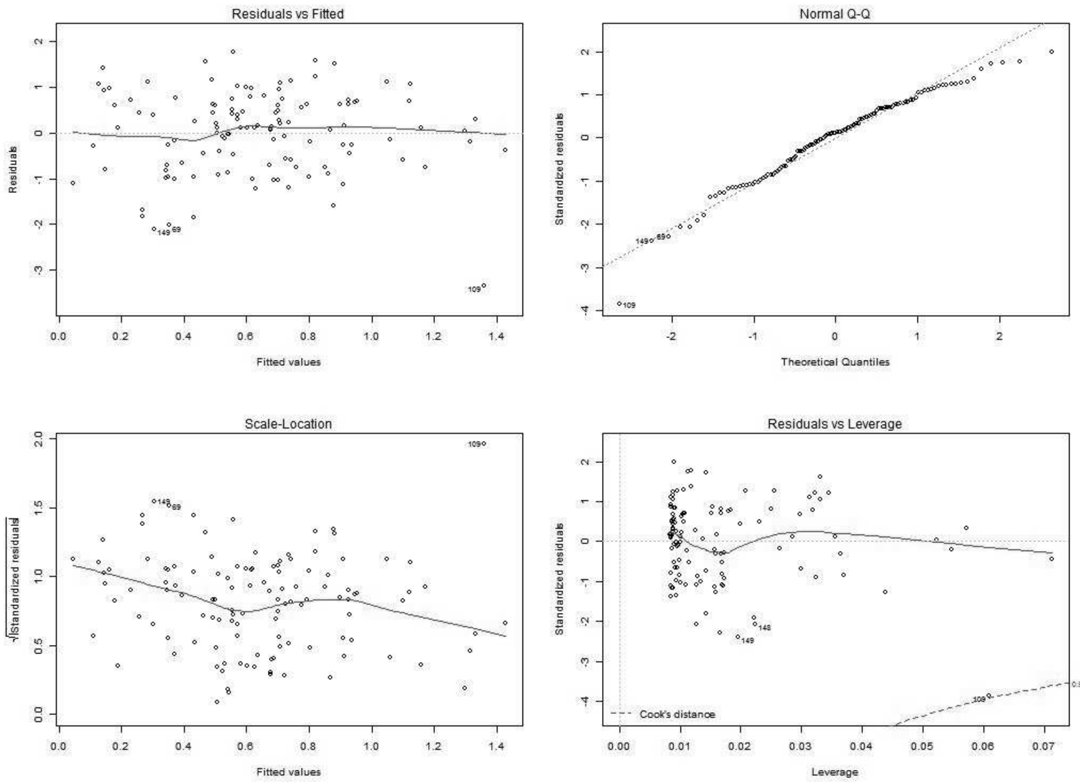
	popgrowth	temp	temp_ma2	temp_ma3	temp_ma4	temp_ma5
popgrowth	1.00	0.10	0.22	0.30	0.31	0.26

	popgrowth	temp_ma6	temp_ma7	temp_ma8	temp_ma9	temp_ma10
popgrowth	1.00	0.21	0.18	0.18	0.19	0.20

And we did some futher check on the model by trying different moving averages (3 to 6 moving averages) of reconstructed temperature, excluding 4 or 5 post volcano years, applying the model to the data in all 150 years (from 1735 to 1885) as well as first and second 75 years. All the results gives significant (or close to significant) p-values and similar coefficients (between 1.4 to 2.0). Which confirms the model is good for the data set. (See detailed regression output in the appendix).

We choose 4 year moving average by excluding 5 post volcano years from 1735 to 1885 as our final model because it give the highest correlation (0.31) and the most significant p-value(0.0006).

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-5.7614	1.8151	-3.17	0.0019
temp_ma4	1.9441	0.5509	3.53	0.0006



The equation between population growth rate and 4 year moving average is

$$popgrowth_n = 1.9441 * t_{n,ma4} - 5.7614 \tag{7}$$

4.4 Explanation of the model output

We found a some association between the Iceland population growth between volcano events and temperature fluctuation from 1730 to 1860.

The volcano eruption have a big impact of the population drop. The biggest population drop all happened during the 5 years after each volcano eruption.

In normal years (excluding 5 post-volcano eruption years), the population growth rate fluctuate with the temperature. As the 4 years moving average of the reconstructed temperature increase (or decrease) by 1 degree, the annual population growth rate increase (or decrease) by 1.9441%.

5 Conclusions

The $\delta^{18}O$ ratio in the ice core is a good source to reflect past climate. But this ratio is also affected by other factors (elevation of the sites, source of the precipitation) beside the temperature. The $\delta^{18}O$ ratio need to be calibrated to the measured temperature in order to be used quantitatively. The relationship between the $\delta^{18}O$ ratio and the temperature may be much complicated than a linear equation. But a linear relationship may be enough for our analysis purpose.

We found south Greenland and northern Iceland belong to the same climate system. By assuming a linear relationship between $\delta^{18}O$ ratio of the Greenland ice core and the northern Iceland temperature. We successfully reconstructed northern Iceland temperature from beginning of the 17th century.

The Iceland population grow continuously and the growth become much stable after industrialization. The largest population drop in Iceland history are all caused by volcano eruptions. The volcano eruptions has much bigger impact to population growth in 18th century than later years. During normal years (without the effect from volcano eruptions) the population growth rate fluctuate with the reconstructed temperature from the last few years.

Our statistics model, proxy records (Ice core) is related to climate. But they need to be calibrate to the measured temperature in order to be used quantitatively. But the measured temperature is only available for the last 150 years which make it very difficult to build our calibration model.

6 Appendix

6.1 Analysis of Greenland Ice Core Data from 1242 to 1872

This section analyze the $\delta^{18}O$ ratio of 4 ice core from Greenland.

		CampCentury	Milcent	Dye3	Crete
1	mean	-29.43	-29.69	-28.00	-34.18
2	standard deviation	1.12	1.01	0.96	1.01

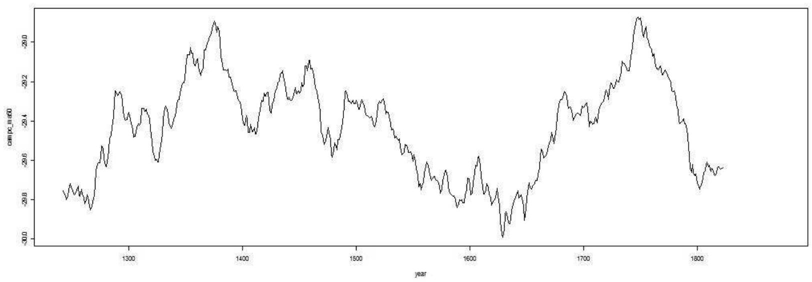
	year	CampCentury	Milcent	Dye3	Crete
year	1.000	-0.010	0.084	-0.011	-0.038
CampCentury	-0.010	1.000	-0.022	-0.096	0.008
Milcent	0.084	-0.022	1.000	0.119	0.297
Dye3	-0.011	-0.096	0.119	1.000	0.232
Crete	-0.038	0.008	0.297	0.232	1.000

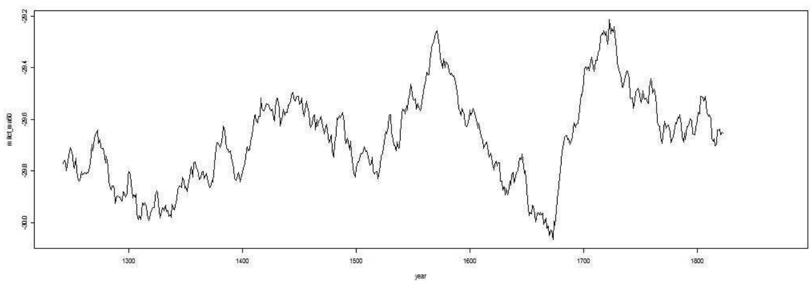
$\delta^{18}O$ of ice core from camp century site (north Greenland) has close to zero correlations with all other sites from south Greenland. It implies different weather systems of north and south Greenland. $\delta^{18}O$ of ice cores from 3 sites in south Iceland are higher (0.297, 0.232 and 0.118). Even $\delta^{18}O$ from the closest sites (Milcent and Crete) only have 0.297 correlation.

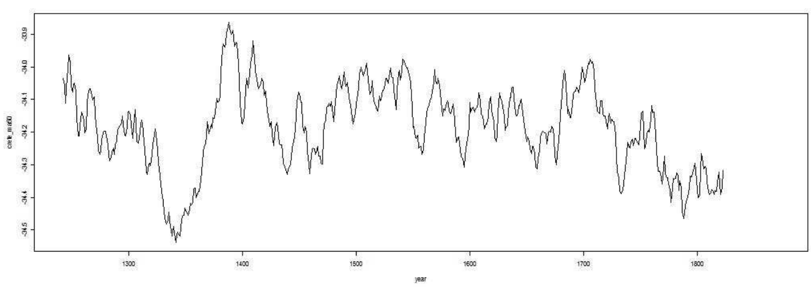
The 50 year moving average of $\delta^{18}O$ ratio of 4 Greenland ice core samples are graphed on the next page (Camp Century, Milcent, Dye3 and Crete). We are not able find similar patterns from the graphs. The isotopic ratios continue to drop from 1400 to 1630 on graph of Camp Century but the trends not seen on all other sites. The lowest isotopic ratio is seen around 1640 on Camp Century graph and Milcent graph but not see on other 2 graphs. The isotopic ratio from Crete ice core is quite stable after a big hike on 1400. There are 3 big drops in isotopic ratios of Dye-3 ice cores (1420, 1500, 1600) but we don't see similar drops in other ice core graphs.

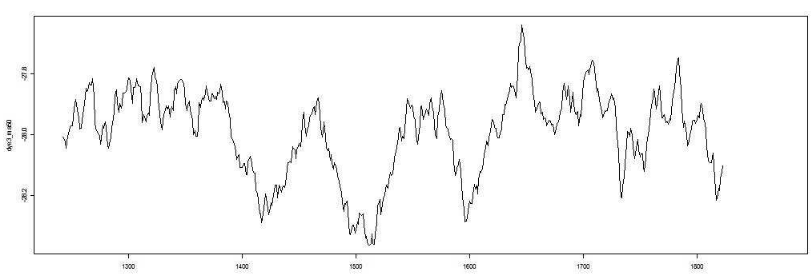
The big difference in the patterns of isotopic ratios of the 4 ice cores maybe because the ice core sites are built in highest mountains with different elevations in addition to the locations of the sites. Crete has MASL (Meters above sea level) 2850 (highest place in Greenland). Milcent has MASL 2410, Dye-3 2480 and Camp Century 1885. So even the sites are close to each other (e.g. Milcent and Crete), they may have different trends.

Also the ice core contains the precipitation from the air. If different ice core site have different source of precipitation, their isotopic ratios may not be the same.









6.2 Is Linear Regression Good Enough to Reconstruct Northern Iceland Temperature from Greenland Ice Core Data

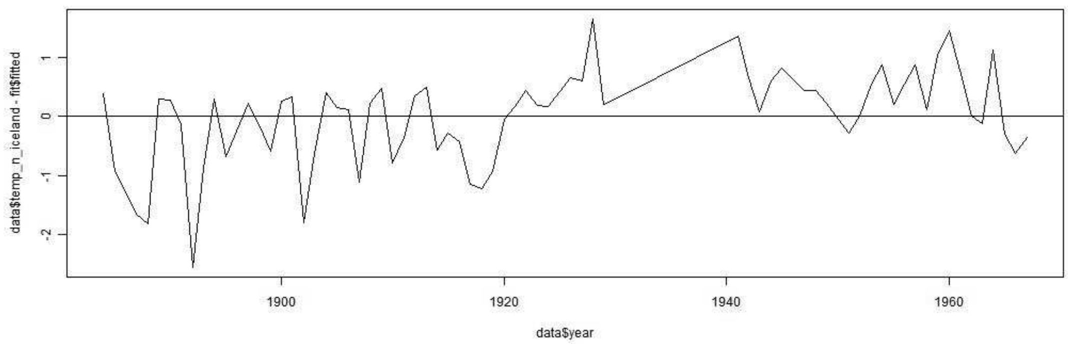
In the paper, we tried a simple regression to reconstruct the northern Iceland temperature from Greenland ice core data: Then we apply the following linear regression model to the measured temperature from 1884 to 1967 and corresponding $\delta^{18}O$ ratio of ice core:

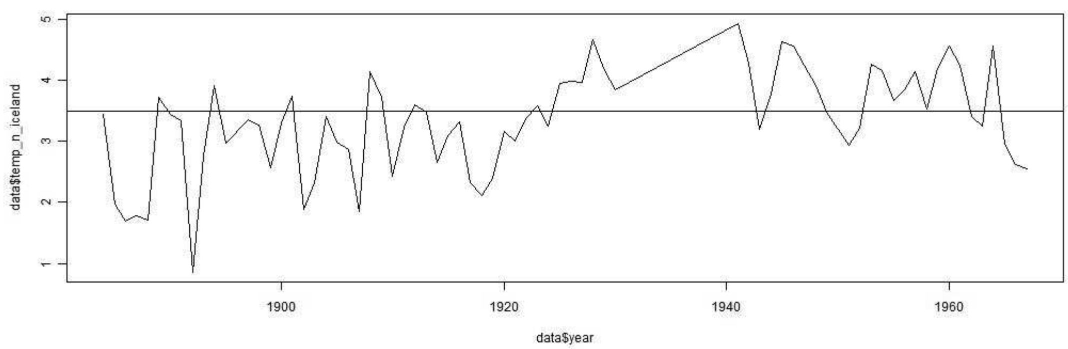
$$t_i = \beta_0 + \delta^{18}O * \beta_1 \tag{8}$$

The initial check of the model looks good. The residuals have constant variance. The qq plot also looks ok which confirm the data is Normal distributed. But the time series of the residuals (first figure below) indicate the residuals has different patterns before 1930 and after 1940. The residuals (measured temperature - fitted temperature by the linear model) are generally negative before 1930 and positive after 1940. The second figure (time series of

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	12.2250	3.0173	4.05	0.0001
Crete	0.2599	0.0881	2.95	0.0043

the measured northern Iceland temperature) also indicates the temperature before 1930 are less than 3.5 degree and greater than 3.5 after 1940.





We also split the data into 2 periods and try the same linear model on both data sets. The outputs are listed below:

Crete and Milcent data after 1940 give significant p-values. Neither of Dye2 data give significant p-values. Camp Century data before 1930 gives significant p-value.

There is an overall temperature increase in northern Iceland after 1940. But we didn't see a corresponding change of isotopic ratio from the Greenland ice core data (the 3rd figure shows the time series of Greenland Ice core in the same period).

The models give different p-values and coefficients by applying to first and second half of the data.

This suggest the relation between ice core and temperature during this period may be much more complicated than a simple linear regression.

But this conclusion will not invalid our analysis on population growth with reconstructed temperature. Because we are only using linear regression model to reconstruct temperature and doing analysis on population growth. Thus any linear relationship will give the same correlations and linear regression significance. The only difference will be the coefficients.

Crete 1884 to 1967

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	12.2250	3.0173	4.05	0.0001
Crete	0.2599	0.0881	2.95	0.0043

Crete 1884 to 1930

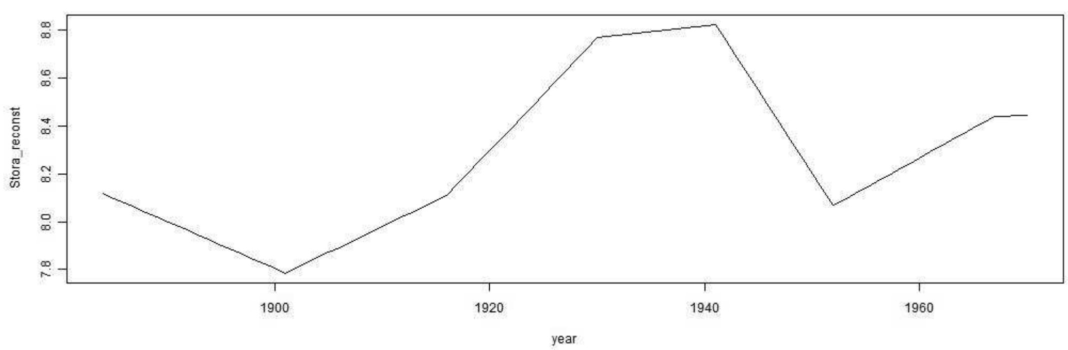
	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	7.4195	3.6798	2.02	0.0499
Crete	0.1270	0.1071	1.19	0.2421

Crete 1940 to 1967

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	18.1288	3.7742	4.80	0.0001
Crete	0.4210	0.1110	3.79	0.0009

6.3 Reconstructed Temperature from Sediment Data

The reconstructed Iceland temperature from sediment data by Stora is also available. As we can see from the time series graph below, the time series of the reconstructed temperature shows a long term trend of the temperature instead of the year to year fluctuation.



The reconstructed temperature is higher than the measured annual average temperature of Iceland cites (As it's claimed as reconstructing the summer temperature of Iceland).

	mean	standard deviation
Stora_reconst	8.21	0.27
Akureyri	3.17	1.03
Grimsey	2.43	0.94
Vestmannaeyja	5.57	0.57
Teigarhorn	4.15	0.87
Stykkisholmur	3.42	0.71
temp_n_iceland	3.29	0.84
temp_iceland	3.75	0.75

So we will not use the reconstructed temperature from Stora for our analysis.

6.4 Verify Linear Regression Model on Population Growth and Temperature by Excluding Post Volcano Years

To check the robustness of the model, we apply different combination of data the model and found not much difference in terms of p-values and coefficients.

- different year range: 1735 to 1885, 1735 to 1810 and 1811 to 1885
- 3, 4, 5, 6 moving average of annual temperature
- excluding 4 or 5 post volcano eruptions years

excluding 5 post volcano years	(from 1735 to 1885)			
	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-4.5942	1.5503	-2.96	0.0037
temp_ma3	1.5880	0.4699	3.38	0.0010

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-5.7614	1.8151	-3.17	0.0019
temp_ma4	1.9441	0.5509	3.53	0.0006

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-5.5092	2.1252	-2.59	0.0107
temp_ma5	1.8682	0.6454	2.89	0.0045

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-4.9724	2.4226	-2.05	0.0424
temp_ma6	1.7044	0.7356	2.32	0.0222

excluding 4 post volcano years	(from 1735 to 1885)			
	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-4.0674	1.4830	-2.74	0.0070
temp_ma3	1.4329	0.4499	3.18	0.0018

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-5.1527	1.7469	-2.95	0.0038
temp_ma4	1.7640	0.5306	3.32	0.0012

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-4.7079	2.0230	-2.33	0.0216
temp_ma5	1.6285	0.6145	2.65	0.0091

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-4.1471	2.2917	-1.81	0.0728
temp_ma6	1.4573	0.6959	2.09	0.0383

excluding 5 post volcano years	(from 1735 to 1810)			
	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-4.7475	2.0282	-2.34	0.0225
temp_ma3	1.6447	0.6122	2.69	0.0092

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-5.6446	2.5499	-2.21	0.0305
temp_ma4	1.9189	0.7712	2.49	0.0155

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-5.2846	3.1033	-1.70	0.0936
temp_ma5	1.8105	0.9391	1.93	0.0585

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-4.9431	3.5674	-1.39	0.1708
temp_ma6	1.7053	1.0786	1.58	0.1189

excluding 5 post volcano years	(from 1811 to 1885)			
	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-3.6752	1.3338	-2.76	0.0067
temp_ma3	1.3906	0.4006	3.47	0.0007

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-4.7738	1.4575	-3.28	0.0013
temp_ma4	1.7230	0.4384	3.93	0.0001

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-4.8132	1.5687	-3.07	0.0026
temp_ma5	1.7356	0.4721	3.68	0.0003

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-4.9432	1.6989	-2.91	0.0042
temp_ma6	1.7753	0.5115	3.47	0.0007

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