Icelandic Glacial Ice Volume Changes and Its Contribution to Sea Level Rise Since the Little Ice Age Maximum

Förändringar i glaciär isvolym på Island och dess bidrag till havsnivåhöjningarna sedan Lilla istidens maximum

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Abstract

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Satellite imagery and volume-area scaling are used to assess the glacier area and ice volume of Iceland from the Little Ice Age maximum to present day, obtaining a final result in sea level rise between 1890-2015. The Little Ice Age was a time of regional cooling, with glaciers reaching their maximum extent (~1890 for Iceland) with warming and glacier retreat after this period ended. Ice volume estimates are important to know due to their relevance in potential sea level rise calculations. Understanding both of these estimations for Iceland connects the impact a changing climate has on regional and global scales.

Different scaling parameters used in the volume-area scaling approach to determine ice volume and ultimately sea level equivalents highlight the range of estimates acquired and point out the need in choosing appropriate values based on glacier region. A comparison to using mass balance measurements for volume estimates is also noted, showing differences in ice volume loss over past and present time periods. The Icelandic glacier area for present day is an updated value from previous studies at 10,803 ± 83 km² and a first ever reported Icelandic Little Ice Age maximum glacier area of 12,201 ± 91 km². For potential sea level rise, it is found the most reliable estimate from the volume-area scaling assessment is 2.67 mm from the Little Ice Age maximum to present day, with a yearly contribution since 1890 of 0.02 mm.

Keywords: Iceland, Little Ice Age, sea level rise, volume-area scaling, glaciers, climate change

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Populärvetenskaplig sammanfattning

Förändringar i glaciär isvolym på Island och dess bidrag till havsnivåhöjningarna sedan Lilla istidens maximum

Stephanie Fish

Satellitbilder och volym-area skalningsmetoden användes för att uppskatta glaciärarea och isvolym på Island från Lilla istiden till nutid, för att få fram hur stor höjningen av havsnivån varit under denna tidsperiod (1890 – 2015). Den lilla istiden var en tid av regional kylning då glaciärer nådde sin maximala utsträckning (~1890 för Island) följt av en snabb reträtt efter att denna period slutade. Uppskattningen av isvolym är viktigt att veta på grund av dess relevans i potentiella beräkningar av höjningen av havsnivån. Att förstå båda dessa uppskattningar för Island är kopplat till den påverkan ett förändrat klimat har på regional och global nivå.

De olika skalparametrar som använts i volym-area skalningsmetoden för att bestämma volymer av is, och dess motsvarigheter i havsnivå, gav en rad av olika uppskattningar. Detta pekar på behovet att välja ett lämpligt parametervärde baserat på glaciärregionen. En jämförelse med att använda mätningar av massbalans för volymuppskattningar gjordes också, vilket visar skillnader i isvolymförlust över tidigare och nuvarande tidsperioder. Dagens värde på den isländska glaciärareaen är uppdaterat från tidigare studier på 10,803 ± 83 km² och den första rapporterade maximala isländska glaciärareaen från Lilla istiden på 12,201 ± 91 km². För potentiell höjning av havsnivån, har man funnit att den mest tillförlitlig uppskattning från volym-area skalningsmetoden är 2,67 mm från Lilla istidens maximum till nutid, med ett årligt bidrag sedan 1890 av 0,02 mm. (Översättning Cecilia Bayard.)

Nyckelord: Island, Lilla istiden, havsnivåhöjning, volym-area skalning, glaciärer, klimatförändringar

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1 Introduction

The glaciers of Iceland cover about 11% of the region (Bjornsson & Palsson 2008), and their mass balance sensitivities to climate change are among the highest in the world. Iceland is located at a climate boundary where the warm and saline Irminger current meets the cold East Greenland current that regulates the precipitation on Iceland and hence the mass balance of its temperate glaciers and ice caps (Hannesdottir et al. 2014). About 20% of the precipitation that falls over Iceland is received by its glaciers, storing the equivalent of 15-20 years of average annual precipitation as ice (Johannesson et al. 2006). Iceland’s glaciers are a major contributor and source for local hydropower and water uses, and any change to ice volume has a direct impact on the country.

The glaciers in Scandinavia and in particular, Iceland, reached a maximum extent in the late 1800s as a consequence of a cold climate period possibly beginning as early as the 13th century called “The Little Ice Age” (LIA). Recent literature shows the timing of this glacier maximum on Iceland mainly occurring in the late 19th century due to noted increases in global temperature after this time (Ogilvie & Jonsson 2001). Since then the glaciers have retreated, resulting in a contribution to sea level rise, although the total amount estimated varies due to differences in methods. Geomorphological traces such as end or terminal moraines are known elements that document a glacier’s previous extent. They are formed by deposited glacial debris at the end of the glacier, reflecting its past shape. By using this evidence, the LIA maximum glacial extent can be found for Iceland and elsewhere. The past volume can then be found by using a statistical approach known as volume-area scaling that relates a glacier’s volume to its area (Bahr et al. 1997). Geomorphological traces of the past and present glacial extent are identified from historical maps and mainly Landsat 8 satellite imagery in order to capture the changing landscape of Iceland from the late 19th century to present day. Satellite imagery and statistical approaches are useful tools in analyzing ice volume changes, allowing for past changes to be measured and compared to current findings in an easily accessible manner. Volume-area scaling is the most used method to estimate ice volume, as direct volume measurements of entire glacier systems are virtually impossible and/or limited (Farinotti & Huss 2013). The knowledge of ice volume is essential and needed to know for sea level rise contribution and useful, not only for Iceland but all glacier regions globally, as ice volume is known for less than 0.1% of all (~200,000) glaciers (Adhikari & Marshall 2012). By revealing glacial ice volume changes from the past to present we can detect how sensitive Iceland’s glaciers are to climate change, since current global trends indicate a warming climate causing the accelerated retreat of glaciers, effecting ocean circulation, sea level and human resources.

Iceland’s contribution to sea level rise since the LIA maximum can provide insight to future ice volume changes on Iceland, relating to the effect our changing climate has had not only on the region, but also globally. This is the first time glacial mapping of Iceland’s complete LIA extent has been established and compared to present day with the use of the volume-area scaling method to determine
sea level rise contribution over the last century. Previous studies have only accounted for a localized region of Iceland’s glaciers when reconstructing the LIA maximum, such as the southern section of Vatnajökull glacier (Hannesdottir et al. 2014) and/or have used different volume estimation methods in other location studies, such as the comparison of topography to ice thickness in the Patagonia ice fields of Chile (Glasser et al. 2011). This study method can provide a framework useful on other glacial regions for mapping and volume estimation of the past and present, since extensive glacier mapping of LIA extents is limited for Iceland and worldwide.
2 Aim

The study presented here plans to identify the total volume of water contributed to sea level rise from Iceland’s glaciers since the LIA maximum to present day. In addition, a sensitivity analysis of the volume-area scaling (VS) method used to determine the volume is discussed. Volume-area scaling volume loss rates from 1890 - 2015 are then analyzed against known annual mass balance records (converted to volume) from varying time spans for a sample size of glaciers, giving a comparison between VS volume loss rates to that of direct mass balance derived volume loss rates. A literature review of the VS method is also introduced and helpful for understanding its correct application, identifying any weaknesses and known uncertainties in further discussion. Background information on Iceland’s climate and glaciers, the Little Ice Age, mass balance and sea level rise is also provided. The following objectives are shown below.

- Present day glacier extent is mapped from Landsat 8 satellite imagery and the total area is determined which is used in the VS calculation. High resolution, pan-sharpened Landsat 8 images are then created to help identify end moraines surrounding the glacier, indicating the LIA maximum extent. Additionally, historical maps are used for reference of past extent as well. Area is then determined for the LIA maximum extent from the mapped end moraines.

- After mapping, VS results are obtained from choosing two minimum and two maximum parameters from past literature that are used in the VS equation, providing a sensitivity analysis of volume estimates for both time periods. The LIA maximum and present day glacier areas gathered from mapping are used in these calculations. From the calculated VS volume, Iceland’s contribution to sea level rise across a centennial timescale is found.

- VS results are compared to annual mass balance measurements for a subset of glaciers, highlighting similarities and differences of the two volume estimation methods across timescales.

The final results of this study are sea level rise contribution and ice volume changes that help identify the effect climate change has on Iceland and the globe. The expected results also offer understanding of the VS method and its applicability to future studies.
3 Background

3.1 Iceland’s Glaciers and Climate

Iceland, an island of 103,000 km², lies in the North Atlantic Ocean and is the largest island in this area, located close to the Arctic Circle. It has been shaped by glacial activity over the years, resulting in carved alpine landscapes, plains to the south and west regions shaped from glacial and fluvial glacial sediments, and marine coastal regions formed from glacial deposition and erosion (Björnsson & Palsson 2008). In addition to glacial activity, Iceland’s landscape is also heavily influenced from volcanoes due to its position along the Mid-Atlantic Ridge, a known active volcanic area (Einarsson & Albertsson 1988). A majority (about 60%) of the active volcanoes and geothermal areas located in Iceland are covered by ice caps. Both of these influences make Iceland a unique and beautiful landscape that is easily molded and changed from natural processes.

The glaciers of Iceland consist of mainly temperate or “warm-based” glaciers that are sensitive to climate fluctuations, in addition to being a main source of hydropower to the region. The location of the glaciers are dominated by Iceland’s precipitation dynamics, with much influence from the southerly winds and warm and cold currents surrounding the island (Figure 1) (Björnsson & Palsson 2008). Most of the glaciers are outlet glaciers forming from large ice caps, with a list of the main glaciers and ones used in this study described in Table 1 and regional distribution shown in Figure 2. The largest ice cap is that of Vatnajökull, where Björnsson & Palsson (2008) indicate an area of 8,300 km² but a decrease of 2.7% (83 km²) from 1998-2008. Vatnajökull is the most vulnerable to ice loss and warming compared to the others, due to its southerly location and outlet glaciers that have carved down during the LIA, creating glacial beds (ie. ground surface below the glacier) at a low elevation. Langjökull, the second largest ice cap, is also sensitive to climate changes but a recent simulated model study by Flowers et al. (2008) has indicated that it never loses its complete mass, due to its self sustaining nature from its precipitation-elevation feedback. The most recent glacier advance (LIA) can be seen from its end moraines, as is also noted on the other glaciers. Glacial monitoring of Iceland has been ongoing since the 1930s with documented changes showing correlation to climate history (ie. ice volume loss, LIA glacier advances), providing reliability of glaciers connection to climate variations (Geirsdottir et al. 2009). According to Björnsson et al. (2013), the ice caps of Iceland, if melted, would raise the sea level by 1 cm with an area of 11,000 km².
occupied by said ice caps and mountain glaciers. Currently, the highest rate of glacial meltwater into the North Atlantic Ocean from ice caps comes from Greenland, with Iceland in second (Hannesdottir et al. 2014).

Table 1. Glacier groups in relation to Figure 2 and Figure 10 with the corresponding glacier location, names and type used in this study.

<table>
<thead>
<tr>
<th>Group</th>
<th>Glacier Location</th>
<th>Glacier Name(s)</th>
<th>Glacier Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Northwest region</td>
<td>Snæfellsjökull</td>
<td>Ice cap</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Drangajökull</td>
<td>Ice cap with 3 outlet glaciers</td>
</tr>
<tr>
<td>B</td>
<td>Central North central region</td>
<td>Hofsjökull</td>
<td>Ice cap with many outlet glaciers</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Nordurlandsjöklar</td>
<td>Small region of cirque glaciers</td>
</tr>
<tr>
<td>C</td>
<td>Northeast region*</td>
<td>Austfjardajöklar</td>
<td>Small region of cirque glaciers</td>
</tr>
<tr>
<td>D</td>
<td>Southeast region</td>
<td>Vatnajökull</td>
<td>Large ice cap with many outlet (surge and non-surge) and some valley glaciers</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Snæfell</td>
<td>Small area of mountain and cirque glaciers</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tungnafellajökull</td>
<td>Ice cap</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hofsjökull</td>
<td>Ice cap</td>
</tr>
<tr>
<td>E</td>
<td>South region</td>
<td>Myrdalsjökull</td>
<td>Ice cap with outlet glaciers</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Eyjafjallajökull</td>
<td>Ice cap with outlet glaciers</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tindfjallajökull</td>
<td>Mountain glacier</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Torfajökull</td>
<td>Ice cap</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Koldaklofsjökull</td>
<td>Mountain glacier</td>
</tr>
<tr>
<td>F</td>
<td>Central western region</td>
<td>Langjökull</td>
<td>Ice cap with outlet glaciers</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Þorisdjökull</td>
<td>Ice cap</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Eiriksjökull</td>
<td>Ice cap</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hrutfellsjökull</td>
<td>Ice cap with outlet glaciers</td>
</tr>
</tbody>
</table>

*Regions where LIA glacial extent was kept the same as present day (See Data and Methodology).
Due to the vulnerability of Iceland’s temperate glaciers, it is important to understand the nature of its climate. As mentioned previously, the placement of Iceland is located where two opposing ocean surface currents meet, the warm Irminger and the cold East Greenland and its climate and glacier mass balance is regulated by the movement of these. The Irminger current brings about Iceland’s mild oceanic climate accompanied by small seasonal variations in temperature (Bjornsson & Palsson 2008). The strength of these opposing currents also influence Iceland's temperatures (Larsen et al. 2013). The average winter temperatures are around 0°C on the southern coast and the summer months around 11°C. Additionally, atmospheric circulation changes over the North Atlantic affect the high northern latitudes, where the supply of heat and moisture is controlled by this circulation change and ultimately determines the climate of neighboring landmasses and, in this case, Iceland (Kirkbride 2002). The changes in this circulation are known to be variable over time, also leading to regional glacier fluctuations (Larsen et al. 2013). The northern coast is affected by the East Greenland current, where sea ice is brought to the region. Heavy snowfall across all of Iceland is caused by tropic and arctic cyclones crossing and converging in the North Atlantic and glaciers receive a large amount of the snowfall. Annual precipitation varies quite drastically by region, with 400 mm in the north, 800mm in the southwest and 3600 mm in the southeast (Einarsson & Albertsson 1988). Iceland’s climate is known to be variable over the past 1000 years as noted from written historical documents (Ogilvie & Jonsson 2001).

Figure 2. Landsat 5 image of Iceland by the National Land Survey of Iceland showing glacier groups from Table 1 with their locations and surrounding topography. Modified and taken from Sigurdsson and Williams (2008).
3.2 The Little Ice Age

The “Little Ice Age” term was first introduced and conceived by F Mathes in 1939, describing the 4000-year Late Holocene interval where many mountain glaciers experienced advances and retreats. However, this interval is now known as the Neoglacial Period and the Little Ice Age refers to the most recent glacial expansion conventionally during the 16th-19th century, where mainly European climate was affected (Mann 2002). Colder conditions were evident as early as the 13th century with periods of sporadic warming until the end of the 19th century. This was not a time of global cooling but more indicative towards regional climate change, since the periods and timing of glacial advances differed from region to region (Mann 2002). The LIA should not be only associated with climate, but the period during which glaciers globally reached a maximum and remained at this state, as stated by J.M. Grove in Ogilvie & Jonsson (2001). As for the onset of this cool period and its causes, suggestions have been made towards volcanic eruptions causing aerosol injection to the atmosphere, a decrease in solar activity and ocean and atmospheric circulation changes (Larsen et al. 2013). It is common consensus among scholars that the coldest period of Iceland’s climate was before the 1900s. As stated in an analysis of Icelandic climate since the 19th century, Hanna et al. (2004) indicates the coldest years of Iceland were 1859 and 1866 followed by a general warming from 1871-2002 of 0.7-1.6°C, coinciding with the LIA period and global warming trends, respectively (Figure 3). The end of the LIA was noted with a large shift towards warmer temperatures and increasing precipitation (Dowdeswell et al. 1997) resulting in a general glacier recession after 1890 and even more rapidly after 1930. For Iceland in particular, 1890 is also the general consensus year as the end of the LIA and its Holocene glacier maximum (Bjornsson & Palsson 2008; Hannesdottir et al. 2014; Larsen et al. 2013).

For Iceland in particular, the Little Ice Age was the second period of glacial expansion, the first being ~500 B.C., during Neoglaciation and the onset of the Subatlantic time (Bjornsson & Palsson 2008). During the LIA, some outlet glaciers advanced as far as 10-15 km and firm lines (transition area from snow to glacial ice) in southern Iceland decreased in elevation from 1,100 m to 700 m.

![Figure 3](image-url). The Stykkisholmur location temperature series from 1830-1999. Individual bars represent a single year, with the bold line showing the 10-year running means. Icelandic climate researchers names are noted for their contributions (Ogilvie and Jonsson 2001).
computer modeling reported in Geirsdottir et al. (2009), summer temperatures would have to be 1-2°C cooler than the 1961-1990 A.D. average in order for peak ice margin to be maintained. Additionally, large glacier regions prior to the 1920s were noted to have cool summers and colder winter temperatures during this period, allowing for glacial advancement (Kirkbride 2002). In order to determine the timing of the LIA glacier maximum, sediment varve thickness and/or lichenometry methods are used to date end moraines. Likewise, borehole temperatures from bedrock and ice sheets show a cooler period prior to the 20th century (Ogilvie & Jonsson 2001). According to sediment data there were two periods of ice expansion, 1400-1550 and 1680-1890, indicating a period of warming interrupted the LIA (Larsen et al. 2013). This method using sediment data was conducted on Vatnajökull and Langjökull with results revealing a max extent in the mid to late 1800s, coinciding to other glacial expansion dates in the Alps (Hannesdottir et al. 2014). Some of the earliest studies of the LIA extent in Iceland were conducted by S. Thórarinsson in 1936 on Vatnajökull, where he indicated that some of the outermost moraines were probably from this time; using archival data, maps and other written sources (Gudmundsson 1997). Lichenometry was introduced in the 1970s and is the most commonly used technique for dating end moraines in Iceland, with modern dating indicating that glaciers were thicker and more extensive in the late 19th to early 20th century, compared to after the 1930s (Kirkbride 2002). Despite this, lichenometry dating does present some limitations. For example, there is difficulty in comparing moraines of different glaciers, as each glacier valley has different growing conditions and growth rates of lichen resulting in time estimation differences. Due to this limitation, this study, along with others (Hannesdottir et al. 2014) have relied on historical data and satellite imagery for moraine identification of the LIA glacier extent.

The warming of the 1930s-50s and the general glacial recessions marks the end of the LIA. These 20th century glacier fluctuations marked a climate transition into modern, present day, bringing high summer melt due to winter and summer warming (Kirkbride 2002). Overall, the Little Ice Age was a period of high variability on annual and decadal time scales, with below average present day temperatures and increased winter precipitation. This caused for the advancement of glaciers reaching their Holocene maximum extent in Iceland, along with advancements in other regions of the world.

3.3 Iceland’s Mass Balance

Annual mass balance measurements have been ongoing on Iceland’s major ice caps of Hofsjökull, Vatnajökull, Langjökull and Drangajökull since the 1990s, providing information of meltwater contribution (Bjornsson & Palsson 2008). The mass balance sensitivity of Iceland’s ice caps are among the highest in the world and the amount of glacial meltwater contributed to the North Atlantic is the greatest and twice of that of Svalbard (Bjornsson et al. 2013). Past mass loss was little in the beginning of the 20th century and peaked after 1925, possibly due to the ice caps response times to climate warming after the end of the LIA. Climatic influences greatly impact the variability of mass
loss and smaller glaciers and ice caps are more affected by warming as seen in Iceland. This mass loss was mainly the cause of high summer temperatures resulting in high summer melt, as no long-term precipitation changes were noted (Bjornsson & Palsson 2008). In addition, a longer melting season, warm winters causing less precipitation as snowfall and lower albedo due to a thinner snowpack also contributed (Bjornsson et al. 2013). Impacts to mass balance directly result to impacts in ice volume, as volume loss or gain can be detected from the conversion of the sum of annual mass balance measurements over a given time period.

3.4 Volume-area Scaling

3.4.1 The Theory

As a practical basis for estimating ice volume, volume-area scaling uses statistically valid relationships to other known variables, such as surface area, to determine ice volume and in the end sea level rise contribution. Since glacier area can be measured directly more easily than volume, and surface area data is more abundant, the application of VS is useful and readily applied to estimate sea level rise from glacial and ice cap area changes. This makes is the most widely applied approach for global-scale glacier inventories to assess glacial volume (Adhikari & Marshall 2012). It has been used since the 1970s as a traditional approach to estimate ice volume, followed by being an expanded and confirmed theory by Bahr et al. (1997) who showed the physical basis of the relationship by an analysis of 144 glaciers. This was not before Chen & Ohmura (1990) used the method to first estimate and suggest 63 alpine glacier ice volumes from the 1870s-1970s. VS is a power law and is an analytical scaling technique that is based on principles of dimensional analysis. It is a theoretical scaling analysis of mass and momentum showing that the volume of a glacier can be related by a power law to observed surface area (Bahr et al. 1996). In simplification, the accumulation area ratio of a glacier is linked to its mass balance profile, which is then related to the volume and surface area relationship. Coincidentally, the surface area is raised to a power, with volume and mean thickness being estimated based on area distributions (Meier & Bahr 1996). The use of the power law for the scaling of glaciers is not a new and unproven concept but shares a theoretical basis of the analysis of other landforms (Bahr et al. 2015). The power law equation is represented as:

\[ V = cA^\gamma \]  

where \( V \) = volume, \( A \) = surface area of the glacier or ice cap and the empirical variables of \( c \) = power law coefficient and \( \gamma \) = power exponent. The power law coefficient \( c \) is a variable parameter and represents the magnitude of volume for a glacier in units of \( \text{m}^{3\text{-}2\gamma} \), and \( \gamma \) is a fixed constant that represents the degree by which \( V \) scales with \( A \) (Adhikari & Marshall 2012). The dimensionless parameters that differ from glacier to glacier represents the variations that comes from \( c \), due to the
parameters being statistically similar but not identical (Bahr et al. 2015). The variable $c$ is not treated as a constant, having a distribution of possible values. The variation associated in the scaling constant $c$ is 40% of $c$, or in other words, the standard deviation of the probability density function for $c$ is about 40% of the mean of the distribution (Radic & Hock 2010). In comparison to $\gamma$, the exponents in for example, the Reynolds flow equation, are fixed by physics and so is $\gamma$ fixed by the physics of glaciers. The associated error for the scaling exponent $\gamma$ is the difference between the empirical (1.36) and theorized (1.375) value found from Bahr et al. (1997) and Bahr (1997b) respectively.

The theory behind VS suggests it not to be applied to a single glacier, but for a sample size of glaciers varying in type and size. The application can be used on only one glacier, however the resulting volume will be one order of magnitude accurate or errors up to 50%, due to the $c$ coefficient not being established for single glaciers, but for an ensemble instead (Bahr et al. 2015). Additionally, the equation does not work sufficiently well on parts or individual branches of a glacier or glaciers draining to multiple outlets, but even so can provide a volume estimate with associated error. It also does not assume shallow ice approximation or steady state conditions of a glacier.

3.4.2 Practical Applications and Literature Coefficients

Chen & Ohmura (1990) first delved into the VS relationship by improving the accuracy of ice volume from ice thickness depth measurements of seismic and radio-echo soundings. From the volume data of 63 mountain glaciers, they found that $c = 0.2055 \ m^3 \cdot 2\gamma$ and $\gamma = 1.357$, with a squared correlation coefficient $r^2 = 0.96$ (Figure 4). These coefficients were utilized to calculate present ice volume using the World Glacier Inventory (WGI) data and eventually assessed volume change of the Alps from 1870s-1970s. Their study initially improved the VS method due to the availability of volume data, but its physical basis was expanded even further by Bahr et al. (1997), to include variables not only for glaciers, but ice caps as well. This improvement by Bahr et al. (1997) was due to the inclusion of derived closure parameters for the scaling behavior of a glacier; such as glacier widths, slopes, side drag and mass balance, ultimately linking unknown ice volumes to observed ice surface characteristics. Taking on previous methods from volume estimates of radio echo soundings, Bahr et al. (1997, 1997b) showed that $V$ was proportional to $A$ from 144 glaciers, where $\gamma = 1.36$ (Figure 5). For ice caps and ice sheets, $\gamma = 1.25$ (initially derived by Paterson (1972) study of Laurentide ice sheet volumes) and $c = 0.191 \ m^3 \cdot 2\gamma$. For a more in depth analysis

![Figure 4.](image)

Figure 4. Chen and Ohmura (1990) figure showing the relationship between volume (km$^3$) and surface area (km$^2$) of a mountain glacier, based on an inventory of 63 mountain glaciers. $r$: correlation coefficient, $s_e$: standard deviation of the residuals. From this, VS coefficients of $c$ and $\gamma$ are derived.
of how the $\gamma$ exponent and $c$ coefficient values were calculated and derived from this physical analysis with the inclusion of the scaling closure parameters, reference to Bahr et al. (2015) is recommended. Ultimately, these two studies presented the basis of recent literature in finding ice volume estimates regionally and globally and offered research into identifying other coefficients.

A study conducted by Adhikari & Marshall (2012) randomly modelled 280 steady state valley glaciers in a high order 3D flow model and found $\gamma = 1.46$, a higher estimate falling outside the theoretical limits due to the model’s differences in glacial mechanics. The model also found $c = 0.27 \text{ m}^{3-2\gamma}$, with an $R^2 = 0.95$, a lower correlation than Bahr et al. (1997), however the $c$ coefficient is relatively equivalent to the standard $0.2055 \text{ m}^{3-2\gamma}$ (Adhikari & Marshall 2012). The study showed how different modelled topographic features affect the volume-area relationship, indicating that glacier shape and slope are drivers of volume. A host of studies have used $c = 1.7026 \text{ m}^{3-2\gamma}$ for the scaling of ice caps, with a corresponding $\gamma = 1.25$ (Radic & Hock 2010; Radic et al. 2014; Slangen & van de Wal 2011) making them the commonly used chosen variables for ice caps. However, a comparison of five Icelandic ice caps volume to surface area by Johannesson (2009) indicated $c$ as $0.219 \text{ m}^{3-2\gamma}$. Additionally, the $\gamma$ exponent for ice caps has been represented as 1.22 when the relationship of volume versus area for ice caps larger than 200 km$^2$ was found (Meier & Bahr 1996). The differences in $\gamma$ between glaciers and ice caps represents how a glacier grows or shrinks, since a glacier is controlled by a valley’s shape, where with an ice cap the bedrock topography is submerged and has little to no influence on the closure conditions (parameters) (Bahr et al. 2015). The scaling exponent $\gamma = 1.56$ has been derived from 37 synthetic steady state glaciers in a 1-D ice flow model by Radic et al. (2007) and differs from Bahr et al. (1997) by 14%. The glacier data was derived from empirical data and simplified geometry was used due to the 1-D model, so some deviation was expected. A compile of sensitivity experiments was also done through the model, showing that smaller glaciers < 20 km$^2$ are more sensitive to the choice of scaling parameter.

The studies presented here show the differences of scaling variables for the $c$ coefficient and $\gamma$ exponent, from either modelling or with empirical data, giving emphasis that past literature is not always in agreement with one another. Previous studies finding past and present ice volume estimates for Iceland using ice cap and/or glacier scaling parameters are more closely analyzed and compared to this study’s findings in the Discussion. The $c$ coefficient is not a constant and is supposed to vary due to glacier type and its characteristics, however $0.2055 \text{ m}^{3-2\gamma}$ is the widely used value for glaciers and $1.7026 \text{ m}^{3-2\gamma}$ for ice caps. Additionally, values for the $\gamma$ exponent should be set as a constant for either
a glacier or ice cap and commonly seen in literature as 1.36 and 1.25 respectively, as any deviation from these values requires changes to the established closure parameters found by Bahr et al. (1997).

3.5 Applicability of Volume-area Scaling

Knowledge of volume is needed to know in order to estimate sea level rise contribution and volume-area scaling helps with this need and is a common method for estimation. A review of VS by Bahr et al. was done recently in 2015, where they accessed the validity and use of how previous studies applied the VS method in estimating volume and/or sea level rise. Problems were addressed and assumptions were clarified, which will be discussed here along with a brief overview of its advantages and disadvantages.

3.5.1 Advantages and Disadvantages

The primary advantage is its easy applicability to estimating volume. Field investigations are not normally needed in order to use the equation, as area data is readily available through glacier databases such as the World Glacier Inventory, Randolph Glacier Inventory or remote sensing measurements, although not updated frequently. The approach used in this study is also a viable option in order to obtain up to date area measurements for the calculation (i.e. satellite imagery analysis and end moraine identification). In regards to modeling, it is seen that models may not be more accurate than volume-area scaling. Using VS as an alternative approach to ice flow modeling for glacier changes in the future show agreement with estimates from VS to that of ice flow models (Radic et al. 2007). Testing the validity of VS using a numerical ice flow model that establishes a volume-area relation has shown that a retreating glacier under non steady state conditions is not more than 20% smaller in volume than the estimated value from VS (van de Wal & Wild 2001). Moreover, VS allows the ability to calculate volume without the need of physical computations such as bed topography, ice thickness and microclimate that are needed for flowline models (Slangen & van de Wal 2011). Using such models is hard to do on a global scale, therefore VS fulfills this need by only needing relatively simply inputs such as length or area in relation to its volume.

In terms of limitations, the calculating of volume for glaciers on a global scale could vary, based on the differences of estimates between ice caps and glacier coefficients. Using glacier coefficients will result in higher volume estimations based on the value set for the γ exponent being higher than for ice caps. This is based on the characteristics of how valley or mountain glaciers are shaped and the way they lose mass, due to the confinement of the ice and shape of the glacier forming to the valley or mountain sides (i.e. controlled by topography). Hence the ice caps γ exponent is a lower value, since ice caps are not controlled by their topography as it has little to no influence on its ice geometry, resulting in less volume storage (Bahr et al. 2015). Diverse variables have also been used in studies for either the c coefficient or γ exponent as discussed, resulting in different estimations and causing a
debate on whether it is useful. VS causes larger errors when applied to a single glacier in the range of 50-200% (Grinsted 2013) and greater uncertainties when applied to a smaller sample glacier size (<100) or very large (>4,000) (Farinotti & Huss 2013). The main source of error arises from the extrapolation of scaling relationships and then applying that to entire glacier complexes. For instance, using a single glacier complex in Arctic Canada versus subdividing it, resulted in an 80% larger volume for the single complex (Grinsted 2013).

3.5.2 Assumptions Clarified and Future Advances
In the review of Bahr et al. (2015) the correct use of the VS method was described in order to alleviate past discrepancies between studies applying the theory. The review states the appropriate variables to use for each ice cap and glacier volume estimation. For instance, the correctly specified value of $\gamma = 1.375$ for glaciers and treated as a constant is addressed. With ice caps, using $\gamma = 1.25$ is deemed appropriate, as it was mentioned that choosing $\gamma = 1.22$ requires negative values for the mass balance scaling exponent when deriving the final VS equation. These set $\gamma$ exponents are not a function of time and do not vary, yet $V, A$ and $c$ can vary in both time and space; allowing for the method to be applied to nonequilibrium conditions. Stated previously, VS is to be applied to a population of glaciers and not individual, unless errors are accounted for or the $c$ coefficient has been established. The method gives an accurate estimate to the volume of a system of glaciers, based on the law of large numbers, since the sum of many glacier volumes, even if errors in $c$ are significant, will show an acceptable estimate of total volume (Bahr et al. 2015).

The VS method is not a perfect method, and advancements are needed. Time dependence is poorly understood as well as the behavior of the $c$ coefficient (Bahr et al. 2015). Furthermore, better data used in the equations to delineate ice caps from glaciers would be useful. Despite this, estimating volume using this approach helps with the need to understand sea level rise contribution. The widely applicable nature of the method, whether regional or globally gives volume estimates that are statistically representative (Adhikari & Marshall 2012) and help with this need.

3.6 Sea level Rise
The theory of volume-area scaling is of importance to the topic of sea level rise (SLR), since estimations of ice volume is one method required in order to determine glacial meltwater contribution and its impact. Sea level rise is of current and future concern for Iceland and also globally, due to the continual melting of glaciers causing fresh water being inputted into streams and ultimately the ocean, raising levels and also changing ocean salinity (Johannesson et al. 2006). To date, the melting of glaciers is considered the second largest contributor to sea level rise in the 20th century, after ocean thermal expansion (Radic et al. 2007). The determination of global sea level rise comes from the estimate of global ice volume and having an understanding of regional (for this study, Iceland) or
global impacts to ocean levels is important. Past, present and future knowledge of ice volume is relied upon for sea level rise estimates and water resource implications. Polar regions and its meltwater contribution from its ice caps and glaciers account for more than half of the SLR estimate, making it a very sensitive area to change (Hannesdottir et al. 2015). Current estimates of global sea level rise by Huss & Farinotti (2012) (not taking into account the Antarctic and Greenland ice sheets) show an $0.43 \pm 0.06$ m rise from all mountain and ice caps, whereas Radic & Hock’s (2010) estimate from scaling relationships is $0.60$ m. Iceland’s current estimated sea level equivalent has also varied, anywhere from 8.7 mm to 12 mm, yet this study aims to present a comparison and usable VS estimate based off of new glacial area data for both present day and since the Little Ice Age maximum (Grinsted 2013 and Radic & Hock 2010). Analyzing these two time periods shows the importance of ice volume and ultimately sea level rise contributions from Iceland, indicating a yearly estimate to rise that has been ongoing since 1890.
4 Data and Methodology

4.1 Satellite Imagery and Mapping

The use of satellite imagery data was the main method in determining the present and LIA maximum extent of Icelandic glaciers. Landsat 8 satellite imagery provided by NASA and the United States Geological Survey (USGS) are high-resolution images (30 m) compiled of various spectral bands and gathered every 16 days over the entire earth. The Earth Explorer computer database tool (USGS Products) offers access to said images for downloading. This study acquired all spectral band images from the Earth Explorer tool that encompassed all of Iceland, in the coordinate system WGS 1984 UTM Zone 28N and 27N. Due to the overcast and cloudy nature of Iceland, the best images were chosen from July – September 2015 that showed minimal cloud coverage in order to clearly identify glaciers. When referring to “present day” it is hereby meant by this time (2015). After the images were selected and downloaded, in order to correctly identify glacial bodies versus land or water mass, bands 7, 5 and 3 from the received images were compiled to make composite images (a total of six) in ArcGIS, for the whole of Iceland, with a full rendition of all images seen in Figure 6. This band configuration was chosen to enhance false colors and make ice easily visible from terrain. Each of the six images of the fully compiled result was used for mapping and glacier identification during the study, as some provided less cloud and/or snow cover of certain regions compared to others. The composite images and further steps to identify present and LIA glacier extents and its area were completed in ArcGIS, with Figure 7 showing the step-by-step processes of the main methods.
In order to correctly identify current glaciers from snow masses and when cloud cover was an issue, USGS glacier maps and outlines taken from Sigurdsson and Williams (2008) that identified all Icelandic glaciers were referenced (Figure 8). A supervised classification of the band 7, 5, and 3 images was done in order to identify present glacier outlines from terrain, then from these additional modifications of the outlines. For LIA extent, historical maps (1:50,000) from the 1904 Danish General Staff mapping expedition were georeferenced and used as validation for glacier outlines on the select ones that were available from the expedition (Figure 9). The maps were based on trigonometrical geodetic surveys completed during the summers from 1902-1904 and are representative of 1890 LIA extents, as extensive retreat was not noted until after the 1930s (Hannesdottir et al. 2014). They included southern Vatnajökull and all of Eyjafjallajökull, Tindfjallajökull, Snaefellsjökull and Drangajökull. Pan-sharpened images with a resolution of 15 m were additionally helpful in the identification of end moraines for the LIA extent mapping, along with “natural” or “true color” images formed of bands 4, 3 and 2. The pan-sharpened images consisted of using the initially made composite images of bands 7, 5 and 3 with an additional band 8 image to create the final pan-sharpened image for each of the six glacier regions. When the Danish General Staff maps were not used for reference in determining the LIA extent, the most recent identifiable end moraine was, found in the pan-sharpened and/or “natural” image. For consistency, this was identified
as the end moraine closest to the glacier, as moraines further out may have been from previous advances. For this study, only the main glacier regions were included in determining the LIA maximum extent as noted in Table 1 previously. The small cirque glaciers in the north parts of Iceland (Group B and all of Group C) retained their present day area for LIA volume-area scaling estimation, as it was difficult to identify end moraines from the “natural” composite and/or pan-sharpened images for the small glaciers. The glaciers studied were kept in the same groups shown in Table 1, based on their location and region, for easier organization of area calculations.

**Figure 7.** Description of ArcGIS steps completed to identify glacier extents and area for the present day and the LIA.

- The six band 7, 5, and 3 images were clipped to the outline of Iceland, using Icelandic Land Survey ArcGIS data
- All clipped images were reclassified, distinguishing glaciers from land, ocean/water and clouds
- Land, ocean/water and cloud data were removed, leaving only glacier data for digitizing
- Glacier outlines for the present extent were examined more closely for fine tuning and corrections
- A copy of the finished present day glacier extents were made for all groups. LIA extent was mapped from these by end moraine identification and historical maps referencing
- Finished outlines were used to find the total area for present day and LIA extents by calculating geometry for each glacier group

To assess the errors on the calculated areas from the digitization, I repeated the steps shown in Figure 7, for a series of five times for Group A and Group F glaciers (7 glaciers total). These glaciers were chosen for the error calculations based on their representation of larger and smaller ice caps. The standard deviations of Group A and F glacier areas were found from the five digitizing runs and from that the average standard deviation for area. This process accounted for 11% of the total Icelandic glacier area and is considered an error representation during the mapping and digitizing process of glacier outlines. Therefore a simplified linear scaling up was completed, where the percent error of the standard deviation for the two groups was found based off of each corresponding original area from the main study. This percent error for Groups A and F glaciers was then scaled up by the total area of all glaciers in Iceland, for the present and LIA extents, resulting in errors in area for each time period. Other possible error sources from the use of satellite imagery for glacial extents and end moraine identification are noted further in the Discussion.
Figure 8. Example of one of the USGS glacier outlines used for glacier identification and reference for present day glacier outlines.

Figure 9. One of the 1904 Danish General Staff maps used as a mapping reference for the Little Ice Age extent. Eyjafjallajökull is shown here.
4.2 Volume-area Scaling Assessment

The sum of the area results for all glacial groups from the ArcGIS mapping were used in Equation 1 to determine total ice volume of present day and LIA maximum. Scaling variables for separately calculating ice cap volume (i.e. using the parameter sets of ice caps for all of Iceland’s glaciers) with the total area result and the same for glacier volume (i.e. using the parameter sets of glaciers for all of Iceland’s glaciers) were used. This provided results of current total ice volume and ultimately volume loss from LIA to present day (1890 - 2015), giving a range of possible ice volume estimates from using the ice caps and glacier scaling parameters. The variables for the $c$ coefficient and $\gamma$ exponent that were chosen to conduct the sensitivity assessment are described in Table 2. Four sensitivity runs were calculated for the ice caps and glacier coefficients: Run 1 = $\gamma$ max, $c$ max; Run 2 = $\gamma$ max, $c$ min; Run 3 = $\gamma$ min, $c$ max and Run 4 = $\gamma$ min, $c$ min. The maximum and minimum value of $\gamma$ for ice caps and glaciers were selected based on commonly used and reliable values found from past literature and the same was done for $c$. Based on this, Run 1 for ice caps and glacier assessments is seen as the standard run, where the common scaling parameters seen in literature were used (ice caps: $\gamma$ = 1.25, $c$ = 1.7026 m$^{3.27}$ and glaciers: $\gamma$ = 1.375, $c$ = 0.2055 m$^{3.27}$). Error for the ice volume estimates at each sensitivity run were found using the error of propagation calculation, that also takes into account the area error found previously.

The maximum value of $\gamma$ for glaciers (1.375) was taken from Chen and Ohmura (1990) initial study of 63 mountain glaciers, as mentioned previously, and the minimum value (1.36) chosen from Bahr et al. (1997) based upon theory. The maximum $c$ coefficient 0.2055 m$^{3.27}$ for glaciers is considered the global average (Bahr et al. 2015) and used in various studies (Chen and Ohmura 1990; Radic & Hock 2010 and Radic et al. 2014). The minimum $c$ value (0.191 m$^{3.27}$) was chosen from Bahr et. al (1997) based on theory. For ice caps, the $\gamma$ maximum value 1.25 is considered the appropriate value and commonly used (Bahr et al. 2015; Radic et al. 2010 and 2014) and also used here. The minimum $\gamma$ value of 1.22 was taken from Meier and Bahr (1996). A maximum $c$ value of 1.7026 m$^{3.27}$ for ice caps was chosen and is also the standard value. For the minimum $c$ value of ice caps, 0.219 m$^{3.27}$ was used, taken from a study of Icelandic ice caps by Johannsson (2009). For errors in the $\gamma$ exponent, the difference from the chosen maximum and minimum (Table 2) was used for an error value of 0.03 for ice caps and 0.015 for glaciers in the error propagation. Errors in the $c$ value were not accounted for as it is a scaling parameter that is dependent upon the glacier.

Upon completing the total ice volume calculations for Iceland using ice cap and glacier variables, the volume loss over a 125 year time span from the end of the LIA to present day (1890-2015) was established by taking the difference between them. Likewise, the main result of contribution to sea level rise (assuming an ocean area of $3.62 \times 10^8$ km$^2$) is also given in yearly contribution for each sensitivity run.
Table 2. The chosen $c$ and $\gamma$ (gamma) variables used in the VS sensitivity analysis for estimating Iceland’s ice volume using ice cap and glacier variables, for the present and LIA maximum extent.

<table>
<thead>
<tr>
<th>VS Variable</th>
<th>Ice Caps</th>
<th>Glaciers</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_{\text{maximum}}$</td>
<td>1.7026 m$^{3-2\gamma}$</td>
<td>0.2055 m$^{3-2\gamma}$</td>
</tr>
<tr>
<td>$c_{\text{minimum}}$</td>
<td>0.219 m$^{3-2\gamma}$</td>
<td>0.191 m$^{3-2\gamma}$</td>
</tr>
</tbody>
</table>

4.3 Mass Balance Comparison

After the ice volume estimates from VS were found, a comparison of yearly ice volume loss estimates using direct mass balance data was sought. This process involved gathering available mass balance data for all of Iceland from the World Glacier Monitoring Service (WGMS 2015, and earlier reports). In order to correlate the correct glacier sections on my mapping to that of the WGMS mass balance glacier sections, the glacier flow basins in ArcGIS were found using ASTER DEMs (digital elevation models) gathered from the Earth Explorer USGS web tool (USGS Products). The ice cap and glacier sections where volume loss rates were estimated and compared using VS and mass balance measurements were from areas of Vatnajökull, Hofsjökull and all of Langjökull.

Firstly, once my glacier outlines were correlated to WGMS sections, the present and LIA area for each one was calculated in ArcGIS and then used in the VS equation to find ice volume loss rates for the sections. The coefficients used for this calculation were the standard ones: ice caps: $\gamma = 1.25$, $c = 1.7026$ m$^{3-2\gamma}$ and glaciers: $\gamma = 1.375$, $c = 0.2055$ m$^{3-2\gamma}$. The difference of LIA to present day ice volumes from the VS calculation provided the final results of yearly ice volume loss rates from 1890 – 2015, for the same glacier sections chosen from the WGMS direct mass balance data, which had been converted to volume by using the net mass balance. The total volume sum was divided by its corresponding time span, that varied depending on the glacier section for when the mass balance data was measured. The results gave a comparison between two time spans, showing rates of yearly volume loss between 1890 – 2015 and more recent time spans from mass balance records, highlighting the differences of yearly ice volume rate loss.
5 Results

In this chapter, results are presented in the same order as listed in the data and methodology section, beginning with glacial extent results. Distinct images for each glacier group can be seen in more detail in Appendix 2 for documentation of the LIA and present day glacier areas, as exact area results from the LIA and present day are described in Table 2. All ice volume results are presented for each time period, along with total volume and yearly results during the period of 1890 – 2015. Sea level rise is also presented in the same manner. Mass balance obtained volume results compared to VS results are shown, in addition to the location of the correlated ice caps and glacier sections.

5.1 Little Ice Age Maximum and Present Glacier Extent

From the ArcGIS mapping of Iceland’s glaciers, the LIA and present glacial extent was established. As previously stated, the glaciers were separated into groups for easier organization during analysis (Figure 10). The corresponding area found from each group is shown in Table 3, with the total and two comparison areas from the World Glacier Inventory (WGI) from 2012 that is based on the Icelandic Inventory provided by Sigurdsson and Arendt in 2008 and revised by Radic & Hock (2010) global inventory; and the Randolph Glacier Inventory (RGI) version 5.0 from 2015. However, the area cited for Iceland in this inventory is from 2012. My present day total Icelandic glacial area was 10,803 km², less than what has been previously estimated. The LIA area estimate was 12,201 km². The error calculated from the five runs for Group A and Group F glaciers was ± 36 km² for present extent and ± 91 km² for the LIA.
Table 2. Glacier groups and their total glacial area (in km²) from satellite imagery and GIS mapping analysis of present day (2015) and LIA extent (1890). Also reported for comparison is Iceland’s total glacier area from WGI and RGI data.

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Present Day Area</td>
<td>223</td>
<td>1,077</td>
<td>7</td>
<td>7,884</td>
<td>631</td>
<td>981</td>
<td>10,803 ± 36</td>
<td>11,005 ± 821</td>
<td>11,060</td>
</tr>
<tr>
<td>LIA Area</td>
<td>274</td>
<td>1,220</td>
<td>7</td>
<td>8,668</td>
<td>830</td>
<td>1,202</td>
<td>12,201 ± 91</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Part of Group B (northern region) and all of Group C area calculations were minimal and for very small cirque glaciers. LIA extent unidentifiable via mapping, therefore kept as the same area as present day.
An example of one group (Group D) and its LIA and present glacier extents are shown in Figure 11. The Group D glaciers and mainly the large ice cap of Vatnajökull, located in southeast Iceland, had the greatest area reduction of Icelandic glaciers since 1890. Present day area is 7,884 km² and an LIA maximum of 8,668 km². The 1904 historical maps of the Danish General Staff were referenced for LIA mapping in the southern region but also end moraines were highly visible on the satellite images.

Figure 11. Group D glacier (Vatnajökull) comparison of the present day glacier extent and the Little Ice Age Maximum outline.
In Figure 12 it is identifiable that the present day area has been markedly reduced from the LIA maximum for Vatnajökull glacier and its outlet regions. For comparison to other recent glacial outlines, the 2012 RGI extent is seen in pink.
5.2 Volume-area Scaling Sensitivity Runs

Tables 3 and 4 indicate the ice volume results obtained from the four volume-area scaling sensitivity runs using ice caps and glacier coefficients. The highest overall ice volume results came from Run 1 (γ max, c max) and the lowest result from Run 4 (γ min, c min) for both ice caps and glacier runs and for each time period, as expected. As mentioned, Run 1 was seen as the standard run in all sensitivity runs, using the common scaling parameters of \( c = 1.7026 \text{ m}^3 \text{-2γ} \) and γ = 1.25 for ice caps and \( c = 0.2055 \text{ m}^3 \text{-2γ} \) and γ = 1.375 for glaciers.

Table 3. Volume-area scaling ice cap sensitivity run results, showing present glacier volume (2015) and LIA extent (1890) in km³. Run 1 = γ max, c max; Run 2 = γ max, c min; Run 3 = γ min, c max and Run 4 = γ min, c min

<table>
<thead>
<tr>
<th>Sensitivity Run (Ice caps)</th>
<th>Parameters Used</th>
<th>Present Day Volume</th>
<th>LIA Volume</th>
<th>Yearly Volume Loss (1890-2015)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (standard)</td>
<td>γ = 1.25, c = 1.7026</td>
<td>5,930 ± 25</td>
<td>6,904 ± 64</td>
<td>8 ± 1</td>
</tr>
<tr>
<td>2</td>
<td>γ = 1.25, c = 0.219</td>
<td>763 ± 3</td>
<td>888 ± 8</td>
<td>1 ± 0.1</td>
</tr>
<tr>
<td>3</td>
<td>γ = 1.22, c = 1.7026</td>
<td>2,965 ± 12</td>
<td>3,440 ± 31</td>
<td>4 ± 0.4</td>
</tr>
<tr>
<td>4</td>
<td>γ = 1.22, c = 0.219</td>
<td>381 ± 2</td>
<td>442 ± 4</td>
<td>0.49 ± 0.04</td>
</tr>
</tbody>
</table>

The volume range between Run 1 (the highest volume estimate) and Run 4 (the lowest volume estimate) for present day is 5,549 ± 23 km³ and 6,462 ± 60 km³ for the LIA. The range for yearly volume loss between the same Run 1 and Run 4 is 7.5 ± 1 km³, both ranges indicating a large spread of estimations.
Table 4. Volume-area scaling glacier sensitivity run results, showing present glacier volume (2015) and LIA extent (1890) in km$^3$. Run 1 = $\gamma$ max, c max; Run 2 = $\gamma$ max, c min; Run 3 = $\gamma$ min, c max and Run 4 = $\gamma$ min, c min.

<table>
<thead>
<tr>
<th>Sensitivity Run (Glaciers)</th>
<th>Parameters Used</th>
<th>Present Day Volume</th>
<th>LIA Volume</th>
<th>Yearly Volume Loss (1890-2015)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (standard)</td>
<td>$\gamma = 1.375, c = 0.2055$</td>
<td>12,851 ± 59</td>
<td>15,192 ± 156</td>
<td>19 ± 2</td>
</tr>
<tr>
<td>2</td>
<td>$\gamma = 1.375, c = 0.191$</td>
<td>11,944 ± 55</td>
<td>14,120 ± 145</td>
<td>17 ± 2</td>
</tr>
<tr>
<td>3</td>
<td>$\gamma = 1.36, c = 0.2055$</td>
<td>9,087 ± 14</td>
<td>10,723 ± 109</td>
<td>13 ± 1</td>
</tr>
<tr>
<td>4</td>
<td>$\gamma = 1.36, c = 0.191$</td>
<td>8,446 ± 38</td>
<td>9,966 ± 101</td>
<td>12 ± 1</td>
</tr>
</tbody>
</table>

In Table 4, the glacier coefficients used in volume-area scaling indicate results following the similar pattern demonstrated in Table 3, where the highest and lowest ice volumes for both time periods are seen in Runs 1 and 4 respectively. However, the volume estimates for each run using the glacier parameters are greater for each time period. The range for present day volume estimates is 4,405 ± 21 km$^3$ and 5,226 ± 55 km$^3$ for the LIA. The range for using glacier parameters to estimate ice volumes for each time period are smaller compared to using the ice cap parameters. For yearly volume loss, the range is 7 ± 1 km$^3$, also smaller than the ice cap scaling.

5.2.1 Sea Level Equivalents and Contribution

Global sea level equivalents (SLE) were calculated following the volume results for ice caps and glacier sensitivity runs. Present day and LIA are shown and represent the equivalent global sea level rise if all of the ice melted during each corresponding period. The difference from LIA to present day shows the estimated effect on sea level rise of post LIA ice loss and then the suggested yearly contribution for the time span.
Table 5. Sea-level equivalent results (mm) obtained from ice cap volume-area scaling sensitivity runs for the present day and LIA glacier extent (1890-2015). The last column shows the yearly sea level contribution since the LIA maximum (1890). Run 1 = γ max, c max; Run 2 = γ max, c min; Run 3 = γ min, c max and Run 4 = γ min, c min

<table>
<thead>
<tr>
<th>Sensitivity Run</th>
<th>Total SLE: Present Day (mm)</th>
<th>Total SLE: LIA (mm)</th>
<th>SLE: LIA to Present Day (mm)</th>
<th>SLE: Yearly Contribution (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (standard)</td>
<td>16.4</td>
<td>19.07</td>
<td>2.67</td>
<td>0.02</td>
</tr>
<tr>
<td>2</td>
<td>2.11</td>
<td>2.45</td>
<td>0.34</td>
<td>0.003</td>
</tr>
<tr>
<td>3</td>
<td>8.19</td>
<td>9.50</td>
<td>1.31</td>
<td>0.01</td>
</tr>
<tr>
<td>4</td>
<td>1.0</td>
<td>1.22</td>
<td>0.22</td>
<td>0.0018</td>
</tr>
</tbody>
</table>

Similar patterns are again seen with sea level equivalent results for ice cap and glacier scaling in Table 5 and 6, with Runs 1 and 4 producing the highest and lowest values. The range of estimates using ice cap scaling parameters for SLE in present day is 15.4 mm and 17.85 mm for the LIA. Contribution to sea level rise from the LIA to present has a range of 2.45 mm and the yearly contribution range is 0.02 mm. Using glacier scaling parameters, a range of 12.17 mm and 14.44 mm for present and LIA SLE, is shown respectively (Table 6). The range for total contribution to sea level rise from 1890-2015 is 2.27 mm and the yearly contribution range is 0.02 mm. As suggested, the SLE estimates are lower using the ice cap coefficients, yet with a larger range than the glacier scaling. For yearly contribution, the range is similar with both scaling methods.
Table 6. Sea level equivalent results (mm) obtained from glacier volume-area scaling sensitivity runs for the present day and LIA glacier extent (1890-2015). The last column shows the yearly sea level contribution since the LIA maximum (1890). Run 1 = γ max, c max; Run 2 = γ max, c min; Run 3 = γ min, c max and Run 4 = γ min, c min

<table>
<thead>
<tr>
<th>Sensitivity Run (Glaciers)</th>
<th>Total SLE: Present Day (mm)</th>
<th>Total SLE: LIA (mm)</th>
<th>SLE: LIA to Present Day (mm)</th>
<th>SLE: Yearly Contribution (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (standard)</td>
<td>35.50</td>
<td>41.97</td>
<td>6.47</td>
<td>0.05</td>
</tr>
<tr>
<td>2</td>
<td>33</td>
<td>39</td>
<td>6.01</td>
<td>0.05</td>
</tr>
<tr>
<td>3</td>
<td>25.10</td>
<td>29.62</td>
<td>4.52</td>
<td>0.04</td>
</tr>
<tr>
<td>4</td>
<td>23.33</td>
<td>27.53</td>
<td>4.20</td>
<td>0.03</td>
</tr>
</tbody>
</table>

5.3 Volume-area Scaling vs. Mass Balance

When volume-area scaling and sea level equivalents were identified, a comparison to yearly volume loss rates using direct mass balance measurements for a select sample of glaciers was completed. The correlated glacier regions from my satellite imagery and the WGMS mass balance data locations are illustrated in Figure 13 for Vatnajökull in southeast Iceland. The following map (Figure 14) indicates the other glacier regions in central Iceland used as well (Hofsjökull and Langjökull). The present day and LIA area extent were found for glaciers that direct mass balance measurements existed for, in order to compare VS estimates to volume estimates derived from the WGMS mass balance data.
Figure 13. The four Vatnajökull sample outlet or surge-type glaciers showing present and LIA glacier extent, used in the mass balance and volume-area scaling comparison.
Figure 14. Langjökull ice caps and sample Hofsjökull glaciers showing present and LIA maximum extent, used in the mass balance and volume-area scaling comparison.
After the areas were found for each time period, they were then entered into the VS equation to determine volume loss estimates for each named glacier. Mainly the glacier parameters set were used in the equation, since most of the sample selections were outlet glaciers. Langjökull was the only one treated as an ice cap and used ice cap variables since mass balance data was available as a whole for this region. Table 7 shows the results of the VS yearly volume loss estimates for the selected glaciers, along with the derived volume loss estimates from mass balance measurements.

Table 7. Mass balance yearly volume loss of various years noted and volume-area scaling volume loss (1890-2015) comparison, in km³/year.

<table>
<thead>
<tr>
<th>Selected Outlet Glaciers/Ice Caps</th>
<th>Mass Balance Yearly Volume Loss Rate</th>
<th>VS Yearly Volume Loss Rate (1890-2015)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Langjökull (Ice Cap)</td>
<td>1.308 (1997-2013)</td>
<td>0.647</td>
</tr>
<tr>
<td>Bruarjökull</td>
<td>0.755 (1994-2013)</td>
<td>1.001</td>
</tr>
<tr>
<td>Dyngjujökull</td>
<td>0.402 (1994-97, 2005-2013)</td>
<td>0.321</td>
</tr>
<tr>
<td>Kölduksvislar</td>
<td>0.217 (1995-2013)</td>
<td>0.104</td>
</tr>
<tr>
<td>Hofsjökull E</td>
<td>0.145 (1989-2014)</td>
<td>0.076</td>
</tr>
<tr>
<td>Hofsjökull SW</td>
<td>0.047 (1990-2014)</td>
<td>0.002</td>
</tr>
<tr>
<td>Hofsjökull N</td>
<td>0.049 (1988-2014)</td>
<td>0.053</td>
</tr>
</tbody>
</table>
The results indicate yearly volume loss has been greater during the recent time spans listed, gathered from the mass balance data, compared to yearly loss from the LIA to present. It is seen that one glacier, Bruarjökull, located on northern Vatnajökull (Figure 16), has a higher VS calculated yearly loss from 1890 to 2015. Hofsjökull N is also noted as slightly higher VS volume loss for the same time period.

6 Discussion

6.1 Present Day Results: Comparisons to Previous Studies

6.1.1 Glacial Area

Since the LIA, the glacial area of Iceland has been reduced, however the reported present day area varies across sources. This variation may be due to lack of data, measuring techniques or simply the year when the area was calculated, as recent studies have been sparse. My result for present glacier area, $10,803 \pm 36 \text{ km}^2$ is less than any other reported sources found and the most current. For example, Farinotti & Huss (2013) and Grinsted (2013) used data from the WG I that was gathered in 2010. This WGI data was revised for Icelandic glaciers by Radic & Hock (2010) and estimated the glacial area to $11,005 \pm 821 \text{ km}^2$. Before this, no data for Icelandic glacier area existed in the database. The other main database of RGI reported an area of $11,060 \text{ km}^2$ from 2012. As seen in Figure 10 for southern Vatnajökull, the RGI extent varies from my present day, showing a greater area. The RGI is a working dataset with the outlines of all glaciers (except for Antarctica and Greenland), yet it is not often quality checked and some locations have a lack of data and information, such as the source of imagery used and date collected, providing uncertainty (Huss & Farinotti 2012).

The errors associated with my area calculation may be due to the differences in glacier area calculation methodology from others. Despite that, how the main databases of WGI and RGI constructed their glacier outlines is also from satellite imagery, yet the exact process of each contributor is unknown. Determining the area of my study was a step-by-step process, with possible errors for each step. Differentiating perennial snow cover from ice was a main issue, especially for Group E glaciers, even with the pan-sharpened images contrasting the two. Due to the nature of Iceland often being cloudy choosing images that provided little to no cloud cover, along with minimal snow cover for a clear glacier extent identification, proved problematic. Reclassing the satellite imagery to separate ice from land, water and sometimes clouds also introduced error, as it was done multiple times for various regions and choosing the best classification to show glacier coverage may have differed. After the reclassing, the main process of “cleaning up” and digitizing the glacier outlines was tedious and subjective choices during digitization may have altered results. However, in this study, much care and time was given for correctly outlining glacier extent when digitizing, in addition to referencing other sources (ie. historical maps, USGS outlines). The end result suggests an
accurate glacier area representation, with the found associated errors from doing the process over repeatedly on a few regions and scaling up.

### 6.1.2 Ice Volume

Ice volume estimates for Iceland and the globe are usually derived from volume-area scaling. The sensitivity test of volume-area scaling used in this study was an assessment in order to show the differences in results one would get based off the value and type (ice caps or glaciers) of variable used. Choosing reliable variables to produce accurate results relies heavily on the type of area being studied, especially when looking at regional scales. Past results of ice volume for Iceland include the area used from WGI and RGI, so my ice volume results vary to some past literature. Radic & Hock’s (2010) study that contributed the Icelandic glacier area of 11,005 ± 821 km$^2$ obtained an ice volume of 4,889 ± 2,224 km$^3$ from volume-area scaling, using the ice cap variables of $c = 1.7026 m^{3-2\gamma}$ and $\gamma = 1.25$. My result of 5,930 ± 25 km$^3$ falls within Radic & Hock’s (2010) range for present day using the same ice cap variables, as seen in Run 1 present day ice volume (Table 3), with a 9% relative difference. In contrast, a recent study by Radic et al. (2014) showed an ice volume result of 2,655 km$^3$ using similar area data (11,058 km$^2$) and the same VS coefficients from Radic & Hock (2010) noted above. This difference is due to Radic et al. (2014) using the lower bound ice volume estimate from the 2010 study, which is lower than my estimation bounds. The lower volume result from Radic et al, (2014) compared to my findings may be due to differences in error estimations of area and volume. Similar area uncertainties to mine for both studies were mentioned (i.e. interpretation of the glacial boundary) and the choice of scaling exponents was also emphasized, citing the need for more direct measurements in order to constrain the parameters (Radic & Hock 2010). For instance in my volume results, it is seen when different scaling parameters are chosen, for example keeping the $c$ coefficient set at 1.7026 m$^{3-2\gamma}$ yet changing the $\gamma$ value to 1.22, the result changes drastically to 2,965 ± 12 km$^3$. This indicates the effect and importance the power exponent $\gamma$ has on the outcome, as changes to $c$ have a lesser impact and also ties back onto how power law equations work. Nonetheless, this effect is more noticeable in the volume results using the glacier variables (Table 4). The effect $\gamma$ has on the outcomes is not as evident in my results for using ice caps variables for all runs, most likely due to the large difference in the chosen $c$ maximum and minimum (1.7026 m$^{3-2\gamma}$ and 0.219 m$^{3-2\gamma}$, respectively) and a smaller $\gamma$ exponent. A second $c$ variable for ice caps was hard to come by as only one study, Johannesson (2009), used a different value of $c = 0.219 m^{3-2\gamma}$ from the standard $c = 1.7026 m^{3-2\gamma}$. This also relates to the larger range of ice volume seen for each of the four runs using ice caps variables, as using glacier variables showed a smaller range between results. As is it seen when calculating ice volume for Iceland, most of the studies assume Iceland’s glaciers as ice caps and use the corresponding parameters of $\gamma = 1.25$ and $1.7026 m^{3-2\gamma}$, even though Iceland consists of mountain, cirque and outlet type glaciers as well. However, the majority of the glacial area of Iceland are ice caps, so assuming this may not add a significant error to the ice volume estimate.
A method other than VS was applied by Huss & Farinotti (2012) to determine ice volume using the reported RGI glacier area for Iceland. Their method involved a physically based approach using terrain elevation models validated against 300 known ice thickness measurements that were represented in the regions of RGI glaciers. They then used a region specific thickness-area scaling function, with \( \gamma \) exponents lower than previously published (0.375 for glaciers and 0.25 for ice caps). Their result was \( 4,441 \pm 370 \text{ km}^3 \), showing only a 4% relative difference from Radic & Hock’s (2010) estimate, with my results of \( 5,930 \pm 25 \text{ km}^3 \), using the ice cap Run 1 standard variables, showing a 14% difference. This method by Huss & Farinotti (2012) provided a new way in determining ice volume based on glacial characteristics, yet the uncertainties are still considerable, due to the lack of ice thickness measurements regionally and globally.

### 6.1.3 Sea Level Equivalent

Results of present day sea level equivalents indicate higher results for glacier coefficients compared to ice caps, as previously seen in ice volume results as well. Since the overall SLR is determined from the ice volume results, it comes as no surprise that the results correspond this way. Again, this underlines the range of SLE results one can achieve based on the value and type of coefficient used for the initial ice volume calculations of a chosen region. Grinsted (2013) who used RGI and WGI area data in determining SLE for various regions along with the VS approach found the result to be 8.7 mm and 8.9 mm (respectively) for Iceland. These results relate more closely to my present day SLE of 8.19 mm (Table 5, Run 3) using the ice cap variables of \( c = 1.7026 \text{ m}^{3-2\gamma} \) and \( \gamma = 1.22 \). This differs from the standard use of \( \gamma = 1.25 \) and \( c = 1.7026 \text{ m}^{3-2\gamma} \) (Run 1) for ice caps, and is due to Grinsted (2013) using her own obtained \( \gamma \) value of 1.23 for ice caps, resulting in the similar values to Run 3. Looking at Run 1 for ice caps (Table 5), my result of 16.4 mm is a slightly higher estimate from other studies who also used the same variables of \( \gamma = 1.25 \) and \( c = 1.7026 \text{ m}^{3-2\gamma} \) in the volume determination. For instance, Radic & Hock (2010) estimated SLE of Iceland is 12 ± 6 mm, nevertheless, my estimate does fall within their uncertainty range. The aboved mentioned study by Huss & Farinotti (2012) using a method other than VS, obtained an SLE of 11 ± .9 mm, falling inbetween my results from Run 1 and Run 3 in Table 5. The difference in methods between my study and theirs may account for this.

As it is seen, the results of my sensitivity analysis for ice volume and sea level equivalents for present day more closely correspond to previous studies when using the ice cap variables of \( \gamma = 1.25 \) and \( c = 1.7026 \text{ m}^{3-2\gamma} \). Therefore, it is of my interpretation that these values are the best to use when analyzing ice volume and sea level equivalent for Iceland specifically, with a result of 16.4 mm SLE. The use of the \( c \) minimum (0.219 m\(^{3-2\gamma}\)) for ice caps provides a large underestimation of the results for ice volume and SLE, even when paired with the \( \gamma \) maximum and minimum and do not agree with any other past studies. Furthermore, no past studies put to use the glacier variables when analyzing Iceland, as it provides an overestimation for ice volume and sea level equivalent. This is the result of
Iceland mainly being comprised of ice caps and the specified ice cap volume-area scaling variables should be used accordingly.

6.2 Reconstructing the LIA

The final result of the glacial extent for all of Iceland at the LIA maximum is the first of its kind reported at 12,201 ± 91 km$^2$. Other studies have only reconstructed the LIA for outlet glaciers on southern Vatnajökull (Bradwell et al. 2006 and Hannesdottir et al. 2014) or parts of Langjökull (Palsson et al. 2012). The same error and uncertainties from the establishment of the present day area are representative for the LIA extent, however an additional error source includes end moraine identification that varied for each glacier group. Some areas were harder to distinguish end moraines from others, as mountainous regions, cloud or snow cover were present in some. The aid of the 1904 Danish General Staff maps helped in this regard, however these maps were not available for all of Iceland. Errors in georeferencing the historical maps in order to align with Landsat 8 images may have also occurred, but were aimed to be limited with the help of georeferencing tools in ArcGIS and the alignment of multiple landmark points on both Landsat 8 images and 1904 maps were used.

For comparison, similar strategies to the methods here have been used when reconstructing the LIA in Iceland and also parts of the Patagonia ice fields in Chile. The southeast outlet glaciers LIA extent of Vatnajökull in Iceland were estimated by Hannesdottir et al. (2014) using the same process of identifying geomorphological features as seen in this study. The end moraines are known to represent the LIA maximum, as they have been dated to roughly the late 19th century from lichenometry. In addition, the same 1904 Danish General Staff maps were used as reference by Hannesdottir et al. (2014). Similar extents between this study and theirs were found due to the large presence of geological traces (i.e. end moraines). In the Patagonia ice fields, Glasser et al. (2011) again used a similar method in determining glacier extents for present and LIA maximum. Landsat images from 2002 or later were analyzed and LIA extents were noted by the presence of end moraines seen in the images. When multiple end moraines or trimlines were present, the one closest to the glacier was chosen to give minimal error. Both of these studies emphasize the use of geomorphological features in identifying past glacier extents and the processes are practical for future studies.

6.2.1 Ice Volume and Sea Level Rise since the LIA

The ice volume and resulting sea level rise estimates obtained from volume-area scaling are the first of its kind reported for all of Iceland’s glaciers since the Little Ice Age maximum of 1890. Comparable results to this study are not available as only present day volume and contribution to sea level is usually found. Likewise, the only other study using a similar method in determining LIA extent and global sea level rise contribution since then was the Glasser et al. (2011) study of the Patagonia ice
fields. Yet, volume-area scaling was not used in their approach, as ice volume was found from the difference between the created LIA glacial maps and DEM topography.

Keeping in part with the previous interpretation that the ice cap variables of $c = 1.7026$ m$^3$ and $\gamma = 1.25$ are best to use when deducing ice volume (Table 3, Run 1), the same will be said for LIA volume and the resulting sea level equivalent. Therefore, the ice volume loss of Iceland since the LIA to present day has been $974.26 \pm 89.07$ km$^3$, with a yearly loss of $7.79 \pm 0.71$ km$^3$ from 1890 to 2015. Potential sea level rise of this time span is $2.67$ mm and a yearly contribution of $0.02$ mm a year since 1890. In contrast to the north Patagonian ice fields of $103 \pm 20.7$ km$^3$ ice volume loss since 1870 and a sea level contribution of $0.0018 \pm 0.0004$ mm. This lower amount of ice loss suggested for the Patagonia ice fields might be due to the fact mostly mountain glaciers were analyzed compared to the ice caps of Iceland, along with differences in total volume and/or regional differences. Also, the lower sea level contribution could also be from this, as well as the longer time span from 1870. Even so, both necessitate the need for investigating ice volume since the LIA in order to get a historical perspective to present day changes, as the melting of glaciers across the globe is expected to contribute vastly to sea level rise this century.

### 6.3 Comparison of Mass Balance to Volume-area Scaling

Mass balance derived volume estimates from the selected glaciers shown in Table 7 aimed to provide a relation between the volume losses during the varying time span of said glaciers (i.e. Langjökull data from 1997 - 2013) to that of volume-area scaling results during the LIA to now. The majority of the glaciers sampled showed a greater yearly volume loss during later time spans compared to the LIA to present. This may point to increased mass and volume loss presently, as a result from warming temperatures. Two of the selected glaciers had a larger yearly volume loss during 1890-2015, those of Bruarjökull located on northern Vatnajökull and Hofsjökull N, a northern section of Hofsjökull (Figure 14 and 15). They are both considered outlet and surge type glaciers, possibly giving reason as to why volume loss has been greater over the longer time span of the LIA to present (Bjornsson & Palsson 2008). It is also important to note that the time spans do vary considerably between the mass balance obtained volume results and VS results, as well as applying the VS method to parts of a glacier which can produce errors in estimation. Yet despite this, it is evident that the mass loss and hence volume loss during current time spans have been negative. Documented frontal variations of the selected glaciers extents would have been more sufficient to use in order to compare volume loss, as frontal variation data dates back further in Iceland. The data obtained by the WGMS for Iceland was not adequate to use for this, as the required frontal area data was missing.

### 6.4 Climate Change Effects on Iceland’s Glaciers
The estimation of ice volume is of great importance, especially in Iceland, due to its contribution to regional water resources and global implications of sea level rise. Water balance is also affected by changes in ice volume, affecting water supply and river runoff, riparian ecology and climate feedbacks (Meier & Bahr 1996). The changing climate impacts these resources, caused by the reduction of mass and volume of Iceland’s glaciers, due to increased warming. Since after the LIA, warming has been consistent not only affecting sea level rise, but a rising ocean salinity due to the increase of glacial meltwater affecting ocean circulation in the North Atlantic (Johannesson et al. 2006). Iceland is an important location for the study of the North Atlantic climate change since it’s located between atmospheric and oceanic polar fronts (Bradwell et al. 2006). Future climate models for Iceland show the projection of an estimated 25-35% volume loss of ice caps within 50 years and only small glaciers located on the highest peaks will be around after 150-200 years (Bjornsson & Palsson 2008). Glaciers have been ongoingly retreating from their Little Ice Age maximum, with ice caps and alpine glaciers responding the quickest to changes in temperature, indicating their high sensitivity to climate change. Iceland’s climate is known to be variable over the years, although since the 1990s warming in Iceland has been 3-4 times higher compared to the average warming of the Northern Hemisphere during the same period (Hannesdottir et al. 2015). This increased warming has been greater than the rise in precipitation and has resulted in a negative mass balance of most arctic glaciers since the end of the LIA (Dowdeswell et al. 1997). Current continual warm temperatures across Iceland and the globe only affect ice volume in a negative way, resulting in a increasing trend to sea level rise. Knowing present and past volume changes as represented in this study are useful because of this, as the trend indicates a loss of volume since the LIA that has contributed to sea level rise.
7 Conclusion

Icelandic ice volume changes and its contribution to sea level rise from the Little Ice Age maximum (~1890) was presented in this study, discussing the knowledge of volume-area scaling as an applied method and climate change implications. Landsat 8 satellite imagery offered high-resolution images in order to examine geomorphological features, particularly end moraines, for identification of glaciers LIA maximum extent on Iceland. Historical maps from the 1904 Danish General Staff expedition offered validation and referencing for some glaciers of their LIA extent and used in addition to end moraines sourcing. Present day glacier extent (~2015) also used Landsat 8 imagery, to digitize the present day outlines in ArcGIS to determine an updated area. Using multiple parameters shown in previous literature, the volume-area scaling method was critiqued and analyzed for ice volume determination of Iceland, giving an array of ice volumes for present day and LIA extent along with sea level rise values. A comparison of volumes calculated using mass balance data against volume-area scaling also focused on showing differences between yearly volume loss rates of present time spans and that since the LIA. The applicability of volume-area scaling and its shortcomings were addressed, citing the need in choosing appropriate variables of the $c$ coefficient and $\gamma$ exponent for accurate estimations. Additionally, climate change on Iceland and its effect on its glaciers pointed out the necessity for understanding past, present and future ice volume changes.

Present day glacier area on Iceland was found to be 10,803 ± 36 km$^2$, an updated value from past World Glacier Inventory and Randolph Glacier Inventory data. Similar methods for finding area were used with my study and those of the inventories. Little Ice Age maximum glacier area was 12,201 ± 91 km$^2$, being first reported in this study, as other past research has only accounted for specific glaciers on Iceland. Relevant variables in the volume-area scaling calculation for ice volume estimations were chosen as $c = 1.7026 \text{ m}^{3-2\gamma}$ and $\gamma = 1.25$, for Iceland and relate to ice caps. These variables are often used in past studies for ice cap volume estimations and as Iceland is mainly consisted of ice caps, the chosen variables were justified. From this, present day ice volume of Iceland is 5,930 ± 25 km$^3$ and an LIA volume of 6,904 ± 64 km$^3$, with a yearly volume loss of 8 ± 1 km$^3$ since 1890. Sea level rise contribution from the volume estimates was found at 2.67 mm since 1890 and a yearly contribution of 0.02 mm. The significance of these findings shows that ice volume loss in Iceland has been ongoing since glaciers were at their maximum, caused by the high sensitivity these temperate glaciers have to climate fluctuations, due to its unique location between a climate boundary. Iceland’s contribution to sea level rise in the North Atlantic is only second to that of Greenland’s because of this and its regional resources are affected by ice volume changes.

Research into sea level rise has currently been of importance based on our warming global climate, however many studies focus on larger glacier regions or a global perspective. The importance of sea level rise is not only globally but also regionally, and future studies into the main impacts sea level rise would have on Iceland in particular are needed. Additional research looking into the maximum
glacier extent during the Little Ice Age for Iceland would be beneficial, as comparisons to other studies for this region are not available for total glacier area during this time period. Ice volume measurements are required for glacier modeling and sea level rise estimates and future insight into Iceland’s ice volume may provide more specific input into how Iceland’s glaciers are changing. This study and method provides a basis for future applications that can be used for other glacier regions, to understand past and present glacier areas, ice volumes and contributions to sea level rise.
8 Acknowledgments

I would like to thank the continual and ongoing support that my advisor, Rickard, has given to me throughout the process. He was always readily available and willing to help, no questions asked. I thank him greatly. Thanks are also given to the WGMS, who provided all Icelandic mass balance measurements to me upon request. Also, the help of my peers and friends giving advice during the thesis process and working together to help one another out when we could was greatly beneficial. Thanks to all.
9 References


Appendix 1: Supplemental Maps

The following maps are from the USGS and 1904 Danish General Staff that were referenced and used during mapping of the glacier outlines for present day and LIA extent.
Appendix 2: Glacier Extents

The following maps show some of the present day and LIA glacier extents of the glacial groups for Iceland, except Group C (very small region of cirque glaciers) and Group D (shown in the results).

**Group A: Snaefellsjökull**
Group A: Drangajökull
Group B: Hofsjökull
**Group E:** Clockwise from bottom left: Eyjafjallajökull, Tindfjallajökull, Kaldaklofsjökull, Torfajökull and Myrdalsjökull
**Group F:** Clockwise from bottom left: Þorísjökull, Eiríksjökull, Langjökull and Hrutfellsjökull