Trends in mass balance indexes connected to spatial location and precipitation

Remote sensing of 111 glaciers in the Everest region

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Preface

This Master’s thesis is Annika Burström’s degree project in Geography, at the Department of Physical Geography and Quaternary Geology, Stockholm University. The Master’s thesis comprises 30 HECs (one term of full-time studies).

Supervisor has been Hernán De Angelis at the Department of Physical Geography and Quaternary Geology, Stockholm University. Examiner has been Peter Jansson, at the Department of Physical Geography and Quaternary Geology, Stockholm University.

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Abstract

Studies of Himalayan glacial response to climatic forcing are few and a more comprehensive understanding of the relationship between the two is needed. This has been highlighted by recent controversies over future glacier change in this area. This study has therefore reviewed if there is a connection between glacier mass balance indexes and precipitation pattern in the Everest region. 111 glaciers were mapped in ArcGIS through remote sensing. Glacial total area, accumulation area as well as snowline altitudes and aspect were mapped. From this, the two mass balance indexes Accumulation Area Ratio, AAR and Area-Altitude Balance Ratios, AABR were derived. The intention was to search for patterns.

In addition to this, an expedition to parts of the study area was conducted in March to April 2011. Hundreds of photographs of snow stratigraphy, debris cover ice snouts, accumulation etc were taken. The expedition also led to an understanding of the environment and of the glaciers which was helpful for the assessment of the remote sensing results.

No pattern in glacier size, ELA, AAR or AABR was found that suggests a connection between mass balance and local precipitation pattern. The glaciers instead appear to be more sensitive to elevation. The largest glaciers and highest AAR and AABR are found at high - although not the highest - elevations.

Keywords: Everest region, remote sensing, mass balance, precipitation pattern, Accumulation Area Ratio and Area-Altitude Balance Ratios.
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1 Authors comment

The picture on the front cover was taken by me during the approach to Everest Base Camp, EBC. The nights at the EBC, spent in tents situated at the Khumbu glacier, was an unforgettable experience. The avalanches were rowing in the night and the sky felt touchable. The expedition was conducted in collaboration with Himalayan Ascent and Adventure Lovers. I would like to thank Summit Joshi, director of Himalayan Ascent, Michael Zettergren, director of Adventure Lovers as well as Ang Tsering Lama and Pasang, our guides, and of course our porters. Your expertise made this expedition an enjoyable and safe experience, very valuable for my understanding of the area and thus for this thesis.

Thank you also Hernán De Angelis, my supervisor who encouraged me to ”not drown in a glass of water” while I was panicking over some trivial matter. Your input and guidance have been much appreciated.

And of course, thank you Stefan Burström, for never ending computer support, mathematical expertise and impressive Excel mastering. Your help has been invaluable.
2 Introduction

The knowledge of Himalayan glacier behavior and present state is sparse. This has been highlighted by recent controversies about future glacier change in this area (Bolch et al, 2012). Studies of these glaciers responses to climatic forcing are few. There is a need to evaluated climate forcing on the glaciers to obtain a more comprehensive understanding of the relationship between the two (Cogley, 2011).

Glacier accumulation area and accumulation rate are connected to prevailing precipitation patterns (Sharp, 1988). Glaciers located in mountain areas have shown differences in mass balance depending on which side of the mountain range they are located at and hence their exposures to differences in the precipitation (Kulkarni, 1992; Bolch et al., 2012). A common mass balance index is the Area Accumulation Ratio, AAR (Østrem and Brugman, 1991). The connection between AAR, mass balance and precipitation has been observed in selected parts of the Himalaya (Kulkarni, 1992; Bolch et al, 2012), but the precipitation patterns impact on glacier in the Himalaya are yet to be reviewed in a deeper scale (Benn and Owen, 1998; Bolch et al, 2011; etc). The purpose for this study is therefore to investigate whether there is a connection between AAR and precipitation pattern in the Everest region and with this improve on the knowledge of glaciers in this part of the Himalaya.

Remote sensing techniques were used to map 111 glaciers. The mappings were based on NASAs Landsat TM and ETM+ satellite images from 5 January 2002, 3 January 2007 and 9 April 2010. The total area, the accumulation area and the snowlines for all 111 glaciers in each year were mapped in ArcGIS.

As this study progressed, a connection between AAR and regional trends in precipitation pattern was however not detected. The concept of AAR seemed to be too basic to use in this case. The Area-Altitude Balance Ratios, AABR a glacier index that accounts for glacier hypsometry (Furbish and Andrews, 1984) were therefore introduced to the study. AABR is not as widely used as AAR (Rea, 2009). The intention
was therefore to firstly see if this index was at all possible to use in this area and secondly, if AABR could not be used in a conventional way, could the results indicate other valuable insights?

AABR considers the ablation and accumulation gradients contribution to the mass balance (Rea, 2009). The study thus carried on with mappings of the glaciers total elevations and the snowlines elevations. The study area is extremely rugged and the elevations as well as the gradients of the slopes are diverse. The elevations were derived from an Advanced Spaceborne Thermal Emission and Reflection Radiometer Digital Elevation Map, ASTER DEM.

Snowline elevations and glacier aspects for all glaciers were also mapped. The results were plotted against longitude and latitude in order to search for trends.

A five week long field expedition in March-April 2011 to parts of the study area was conducted as well. The intention for the expedition was to collect snow density samplings and to observe the snow line positions. This however proved hard to accomplish at the site. Instead hundreds of photographs of snow stratigraphy, debris covered ice snouts, accumulation etc were taken.
3 Background

The area chosen for this study is located at the boarder of Nepal and Tibet, China at 28° 16’N - 27° 38´ N, 86° 24´ E-87° 11´ E and is about 5720 km² (Figure 1). A satellite image of the area is presented in Figure 2.

![Map of the study area](image)

*Figure 1. Map over the study area. The study area is indicated in orange in the main map and with an arrow and orange dot in the world map (modified map from Benn and Owen, 1998 and from www.freeworldmaps.net, 2011-12).*

The area includes the Goddess of the Sky; the Sagarmāthā, as it is referred to in Nepalese, or the Mother Goddess of the Universe; the Qomolangma, as the Tibetan calls it. In the west it is most commonly known as Mount Everest (Howes, 2001). The topographic character of this area is shown by the vast difference in the minimum elevation of around 2000 m a.s.l. and the maximum elevation of 8850 m a.s.l. (Figure 3).
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Figure 2. Color composite of the study area. The image is derived from band 5, 4, and 3 from the Landsat TM satellite. Mt Everest is marked with a green dot. Images acquired 9 April, 2010.

Figure 3. An example of the topography in the area. The picture shows the northwest view from the top of Lobuche East. Pumori 7161 m a.s.l, Kala Pattar 5643 m a.s.l, Mt Everest 8850 m a.s.l, Lothse 8516 m a.s.l and Nuptse 7861 m a.s.l are all visible. The Khumbu Icefall, with its debrised snout, flows below the mountains. Picture taken at 27°57’21”N, 86°47’38”E, elevation 5974 m a.s.l, 17 April, 2011 by A. Burström during the expedition.
The 111 mapped glaciers in this study are distributed on both sides of the mountain range. This should allow for a diverse area with changes in precipitation patterns. Precipitation patterns are strongly influenced by topography (Anders et al., 2006). The southern slopes of Sagarmāthā in Nepal should present a wetter climate than the northernmost part of the study area due to the precipitation shadow that the mountain range fuels (Benn and Owen, 1998). The mapping is shown in Figure 4.

![Figure 4. The 111 mapped glacier. The yellow areas represents the accumulation areas and the green the ablation areas, the black line illustrates the ELA (see section 4.1). Mapping from 2002, image acquired in 5 Jan, 2002.](image)

3.1.1 The glaciers in the study area

The glaciers are summer-accumulation type glaciers; they receive almost all precipitation from the summer monsoon. Ablation is mainly regulated by air temperature and is therefore highest during the warmest months. These glaciers
therefore have a concurring ablation and accumulation period and they are hence termed non-maximum type of balance rate glaciers. This means that they do not have a specific stage when they have a glacier maximum which occurs in glacier that has a non-concurring ablation and ablation period (Ageta and Higuchi, 1984). It is however important to remember that even though glacier accumulation is foremost regulated by precipitation, accumulation could also be received by blowing snow and avalanches. The dominate accumulation factor; precipitation, avalanching or windblown snow, varies from glacier to glacier (Benn and Owen, 1998). The Khumbu Glacier for example (Figure 5) located at the southwest slope of Mt Everest at 28° 00´ N, 86° 52´ E, has been estimated to gain 2,8 times as much accumulation from avalanching as from precipitation (Inoue, 1977).

Figure 5. The Khumbu Glacier Icefall as it flows down the slopes of Mt Everest. Picture taken at Everest Base Camp at 28° 0’ 16” N, 86° 51’ 23” E, elevation 5322 m a.s.l., 15 April, 2011, by A. Burström during the expedition.
Other glaciers in this area have a similar accumulation pattern due to the character of this area; the elevation differences, steepness of mountain walls etc (Benn and Lehmkuhl, 2000).

Most of the glaciers have a wide accumulation area. The ablation area is narrower and eventually tapers off completely (Benn and Lehmkuhl, 2002). Most of the glaciers also have debris-covered snouts (Figure 6). The debris is delivered from mountain weathering from the steep mountain walls (Figure 7; Benn and Owen, 1998). The debris-covered area is relatively small compared to the total glacier area in most of the mapped glaciers, since the lower part of the glacier often is narrow. The debris cover is also reduced with altitude. The debris is transported down to the glacier terminus by the down-slope movement of the glacier. The particle size and the distribution of the debris are highly diverse. Small dust-size particles up to house sized blocks can be found (Figure 8). The coverage also ranges from minimal occurrence to complete coverage of the glacier tongue (Paul et al, 2003). Observation at the Khumbu glaciers shows that ablation at the debris-covered terminus is nonexistent from the insulation. The ablation increases with elevation linearly up to the elevation with maximum ablation (Inoue and Yoshida, 1980). Debris free glaciers normally have an AAR between 0.5 and 0.8 and debris covered glacier usually have an AAR between 0.3 and 0.5. This is also the commonly known AAR for Himalayan glaciers (Benn and Evans, 2010).

![Image](image_url)

*Figure 6. The debris covered snouts of Lhotse Shar Glacier and Imja Glacier as they meet before entering the glacier lake Imja Tso. Picture taken at 27° 54’ 8” N, 86° 54’ 55” E, elevation 5128 m a.s.l., 19 April, 2011, by A. Burström during the expedition.*
Figure 7. Talus debris at the Khumbu glacier. The orange tents is part of the Everest Base Camp. Picture taken at 28° 0’ 7” N, 86° 51’ 7” E, elevation 5297 m a.s.l, 13 April, 2011, by A. Burström during the expedition.

Figure 8. A glacier table the size of an expedition tent at Mt Everest Base Camp, EBC. EBC is located at the debris-covered part of the Khumbu glacier. Picture taken at 28° 0’ 16” N, 86° 51’ 22” E, elevation 5310 m a.s.l., 19 April, by A. Burström during the expedition.
Mass balance measurements in Himalaya glacier are sparse and also unestablished (Cogely, 2011). There is only one appropriate measurement for estimating mean glacier thickness. Glacier volume cannot be measured directly over regional scales due to the character of the area. This must instead be modeled (Bolch et al, 2012). The availability of DTMs (see section 5.2.1) allows for regional mass balance to be estimated, but only a handful of mass balance estimations has been conducted using this technique and additional regional mass balance estimations need to be done (Bolch et al, 2011).

3.2 Precipitation and topography

Mountains are physical barriers; they interfere with the vertical stratification of the air masses as they act as sources or sinks of heat. In larges mountain ranges the rain shadow effect has a profound and firmly established impact on the precipitation pattern; it fuels increased precipitation on the windward side of the mountain range (Anders et al, 2006).

However, the connection between spatial patterns of precipitation and topography is complex and not only connected to precipitation shadow. Anders et al have considered how topography interacts with the atmosphere in other ways than the fueling of precipitation shadow. Air can, for example, be blocked or diverted around the mountain range. Or the airflow could stir up internal waves in the atmospheres vertical density stratification. Mountains also have the ability to heat the air above them which will fuel upwelling of colder air from lower elevations. This in turn will trigger condensation and convections on the slopes. The atmospheres interaction with the mountains is determined by the incoming air velocity, the airs vertical profiles of temperature and the airs moisture content. This interaction is also dependent of the mountains topology; the length, width, and height of the mountain are important factors (Anders et al, 2006).

3.2.1 The climate of the study area

The study area receives about 80% of its annual precipitation in June to September from the South Asian monsoon (Ageta and Higuchi, 1984). The moisture is derived from the Indian Ocean and advected northwards by the southwestern monsoon. The summer precipitation decreases sharply as it travels from south to north across the mountain
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range. This leads to that the precipitation is rather high in Nepal. When the winds advance into Tibet the precipitation is reduced. The precipitation is lowest in the westernmost part of the Tibetan Plateau (Figure 9; Benn and Owen, 1998).

The winters are dry and cold. The winds also take a different path in the winter than in the summer (Figure 10; Benn and Owen 1998; Ageta and Higuchi, 1984).

Figure 9. Summer wind pattern in the Himalaya. The solid arrows indicate airflow at about 3000 m a.s.l and the dashed arrows that at about 600 m a.s.l. The dotted area lies above 6000 m a.s.l (Benn and Owen, 1998).

Figure 10. Winter wind pattern in the Himalaya. The solid arrows indicate airflow at about 3000 m a.s.l. and the dashed arrows that at about 600 m a.s.l. The dotted area lies above 6000 m a.s.l. (Benn and Owen, 1998).
Long-term precipitation patterns in the Himalaya are not well documented due to the constrains in precipitation measurement. It is only recently that satellite radar has been possibly to use for this. Earlier rain-gauge was the dominant method of precipitation measuring. Rain-gauges network are not dense enough to cover up for variability in precipitation over spatial scales of tens of kilometers. And in the Himalaya, precipitation and topography can vary substantially over such scales (Anders et al, 2006).

In 2006, approximate annual precipitation over the Himalaya was estimated with Tropical Rainfall Measuring Mission, TRMM satellite radar data. The spatial resolution used for this was 10 km. The overall pattern in the Himalaya was notably stable from year to year. A clear precipitation gradient from the north to the south was visible. A more subtile gradient from the east to the west were also detected (Figure 11; Anders et al, 2006).

The study by Anders et al implies that the Himalayan precipitation pattern has a very strong connection to the topography since the topography was the only real stable constant from year to year. Incoming air masses can vary significant in every event. This indicates that the factors mentioned in section 2.1 may not have significant impact at precipitation in this area (Anders et al, 2006). However, studies of orographic precipitation in the Himalaya has shown large gradient in seasonal precipitation which were not solely related to elevation. Differences has also been detected in the diurnal monsoon precipitation pattern at high (<2000 m a.s.l.) and low (>2000 m a.s.l) elevations. These differences have been related to daytime upslope winds that during night switch to weak downslope winds (Barros et al., 2000; Barros and Lang, 2003). The minimum elevation of the glacier in this study is at 4100 m a.s.l and hence may therefore not be affected by this. Also, a study of the mass balance of the Khumbu glacier indicates that there are no precipitation gradients over elevations of 5850 m a.s.l (Inohue, 1977) which further support this theory.
Figure 11. A four year annual spatial precipitation map of Himalaya, estimated from TRMM (Anders et al, 2006), note that the study area is located at 28° 16˝:27° 38´ N, 86° 24´ E:87° 11´ E.
3.3 Glaciers and climate

The linkages between glaciers and climate have been the focus of many studies (Furbish and Andrews, 1984). There are two parts in the problem of connecting glacier with climate; these are due to how glacier responds to external influences. Firstly, glaciers are to be considered as dynamic boundaries over which mass and energy are exchanged with the atmosphere. This produces temporal and spatial change in the glacier mass balance. Secondly, all dynamics, no matter the cause, in the ice body will lead to changes in the glacier geometry (Kuhn, 1981).

The three most prominent climatic forcings are air temperature, precipitation and radiation balance. These influences the mass balance equally much and simplifications are therefore incorrect to make. Mass balances changes can thus not easily be used as climate indicators, or the other way around. Changes in for example glacial terminus can be due to all of the above forcings, or just one. The relative ELA, the budget gradient and the annual accumulation are useful parameters for assessing glacier regimes in different climates. Observations of varying ELA (see section 4.1) is most useful when assessing climatic fluctuations (Kuhn, 1981).

Avalanche fed glaciers at high elevations in the Karakoram and northwestern Himalaya have shown diverging behavior. They have retreaded in a slower pace or even advanced. This is a result of that the accumulation area on avalanche fed glaciers does not change notably when the ELA rises (Bolch et al, 2012). This means that Kuhn`s statement of measurements of ELA fluctuations is the best index for climatic fluctuations (Kuhn, 1981) does not necessarily apply here. The mass balance of this type of glaciers is complex. Summer accumulation glaciers are for example generally more vulnerable to changes in the temperature than winter-accumulation–type glaciers. Increased temperature directly reduces solid precipitation i.e. snow accumulation. The surface albedo is also lowered when the snow cover in the summer is absent. This extends the ablation period and melting is further increased (Bolch et al, 2012).

Due to the complexity of the linkages between glacier and climate, and other external factors, there are only certain links that have been explained for; although there are probably many other linkages that have been involved in the glacier response (Furbish
and Andrews, 1984). Understanding of climate forcing on Himalayan glaciers is needed to obtain a more comprehensive understanding of this relationship (Cogely, 2011). For example, previous mass loss estimation have been reassessed and found to be overestimated about ten times. Mass balance times series also shows that there was a large interannual variability between 2003 and 2010. The variations are believed to be uncharacteristic for a longer time span (Jacob et al, 2012). This suggests that there could have been shift in the precipitation during this time since mass balance is connected to mass balance. But Anders et al. show that precipitation was stable, Figure 11 (Anders et al, 2006). This readily proves Kuhn’s point that climate input not easily can be translated into glacier response (Kuhn, 1981).
4 Glacier parameters

The mapped features of the glaciers in this study are the total area of the glacier, the accumulation area and the snowline. The concepts equilibrium line, EL, equilibrium line altitude, ELA, accumulation area ratio, AAR, area-altitude balance ration, AABR and glacier aspect are also used.

4.1 Snowline and equilibrium line

The edge of last year’s snow cover forms the glacier snowline. This line is possible to distinguish in satellite images because snow reflectance is high. The reflectance of the melting snow and ice in the ablation zone are usually lower (Cheung-Wai Chan et al., 2009). The area above the snow line indicates the accumulation area and the area below the snowline indicates the ablation area (Sharp, 1988). The EL is a theoretical line which divides the net accumulation-area and the net ablation-area of the glacier. The glaciers mass balance is zero at the EL (Paterson, 1994). The EL often corresponds to the snowline, but this is only true for glacier with an insignificant internal accumulation. However, there are few glaciers that have a substantial internal accumulation although this can be hard to prove (Østrem and Brugman, 1991). The ELA is the average elevation of the EL (Paterson, 1994). A glacier with a zero annual mass balance will display a steady state ELA, but this state rarely occurs in nature. Glaciers are always out of equilibrium with climate, the annual ELA provide an indicator as to how much (Benn and Lehmkuhl, 2000).

4.2 Accumulation area ratio

AAR is the ratio between the accumulation area and the glaciers total area. The AAR is fairly easy to obtain from a satellite image if the snowline and the lower limit of the glacier are clearly visible. AAR is derived by digitalizing the glacier total area and its
transient snowline with the help of an images analysis system, for example ArcGIS (Østrem and Brugman, 1991). The total ablation area as well as the total accumulation area is then calculated. From this, the AAR can easily be established with the equation

\[ AAR = \frac{A_c}{A_t} = \frac{A_c}{A_c + A_b} \]

were \( A_t \) is the total area, \( A_c \) is the accumulation area and \( A_b \) is the ablation area of the glacier (Benn and Evans, 2010). AAR will vary from year to year depending on the mass balance of the glacier. If the steady-state AAR of a glacier is to be obtained the glacier mass-balance needs to be monitored for several years (Kulkarni, 1992).

Under equilibrium conditions the AAR method assumes that the accumulation area accounts for a fixed ratio of the total area (Rea, 2009). AAR does however not consider variations in glacier shape or glaciers hypsometry. Specific AAR values can consequently not be used as estimations for ELA. A glacier with a narrow accumulation area and broad snout will have a relatively small AAR and a glacier with a wide accumulation area and a narrow snout will have a larger AAR, but their ELA could be the same. However, AAR estimations over altitudinal range could still be a good indicator of area distribution (Benn and Evans, 2010).

Debris covered glaciers tend to have an AAR of 0.3 to 0.5. This is also the general AAR given for glaciers in the Himalaya (Benn and Evans, 2010). Unmantled glacier often have a higher AAR, around 0.5 to 0.8 due to the fact that debris covered glacier tend to be longer than unmantled glacier. The debris cover reduces the glacier ablation since it insulates the ice. The glacier therefore needs to compensate for lost ablation in order to maintain equilibrium mass balance and the ablation area will thus increase (Menzies, 1995).

In this study annual AAR has been used. Annual AAR is the AAR at the end of the mass balance year. The mass balance year is the time span corresponding to one calendar year which the annual mass balance refers to (Cogley et al., 2011).
4.3 Area-altitude balance ratio

AABR is a glacier index that, as opposed to AAR, accounts for glacier hypsometry. It also considers the ablation and accumulation gradients contribution to the mass balance (Rea, 2009). The index were first referred to as the Balance Ratio Methods (Furbish and Andrews, 1984), but was more recently renamed the Area-Altitude Balance Ratio, AABR by Osmaston in 2005 (Osmaston, 2005).

Due to the complexity of climate and glacier response, there have been attempts to isolate climatic causes in order to analyze what glacial response they spur. The development of AABR is such an attempt. Furbish and Andrews examined how valley topography was linked to long-term glacier response through the distribution of surface area over elevation and the distribution of mass balance over elevation. They point out that the output of the first aspect of the problem, in this case mass balance, is often taken as input for treatment of the ice dynamic. This means that we often treat changes in the climate as equivalent to changes in accumulation or ablation. Topography as a factor is therefore often overseen. But the topography is in fact a major player, it produces local variations in mass input and energy balance. The relief of the glacier floor will also restrict the flow, surface gradient and thickness of the ice body (Furbish and Andrews, 1984).

The AABR is based on the fact that a glacier in equilibrium will have the same total annual accumulation above the ELA as the total annual ablation below the ELA. This relation can be expressed as

\[ \bar{b}_{nb} A_b = \bar{b}_{nc} A_c \]

were \( \bar{b}_{nb} \) and \( \bar{b}_{nc} \) are the average net annual mass balance in the ablation area and accumulation area, respectively, and \( A_b \) and \( A_c \) are their respective areas (Furbish and Andrews, 1984; Rea, 2009; Benn and Evans, 2010).

In order to calculate AABR, one basic assumption must be made; ablation and the accumulation gradients are assumed to be linear (Furbish and Andrews, 1984). AABR is calculated by
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\[ AABR = \frac{b_{nab}}{b_{nac}} = \frac{\bar{z}_{ac}A_{ac}}{\bar{z}_{ab}A_{ab}} \]

where, \( b_{nab} \) and \( b_{nac} \) are the net mass balance gradients in the ablation and accumulation zones respectively, \( \bar{z}_{ac} \) and \( \bar{z}_{ab} \) are the area-weighted mean altitudes, measured positive from the ELA, of the accumulation and ablation areas respectively. \( A_{ac} \) and \( A_{ab} \) are the areas of the accumulation and ablation areas respectively (Furbish and Andrew, 1984; Rea, 2009). Thus in AABR, the mass balance contribution is weight against the ELA. This means that with increased altitude over the ELA, a unit area will provide greater accumulation. Below the ELA the ratio is reversed, hence a unit area will account for greater ablation with decreasing altitude below the ELA (Rea, 2009).

AABR could be used to more accurately infer the regime of glaciers in different climatic zones. AAR is uncertain for this use since it implicitly presumes conformity in both glacier shape and glacier regime (Furbish and Andrew, 1984; Benn and Evans, 2010). AABR vary with local climate. Low ablation will give low AABR, and hence high ablation will give high AABR. Rea have calculated representative AABR for a suite of different glaciers types located in different climatic zones (Rea, 2009). A glacier with equivalent accumulation and ablation gradients will render an AABR of 1. This would be typical for polar glaciers which are subject to low temperatures over the altitudinal range of the glacier. Glaciers with high ablation year around, thus giving high AABR, is adherent to tropical glaciers which are located in warmer areas (or calving glaciers although they do not submit to linear ablation). Mid-latitude maritime glaciers which have high summer ablation rates have AABR around 1.8 to 2.2 meaning that the ablation gradient is 1.8 to 2.2 times greater than the accumulation gradient.

It is noteworthy that high AABR means that the glacier has high ablation per unit area compared to the accumulation per unit area, and not necessarily that the total ablation is higher than the total accumulation. AABR indicate the ratio between accumulation and ablation and not the overall glacier state. The global AABR were estimated to be 1.75 ± 0.71. AABR for Himalayan glacier were not calculated in this study (Rea, 2009).
4.4 Aspect

The importance of glacial slope aspect has been verified by several studies. Both solar radiation and precipitation shadow can vary substantially due to aspect. At local scale the aspect can therefore exert a strong influence over glacial location, snowline and mass balance. In high relief terrain the snow line altitude can vary by hundreds of meters (Benn and Lehmkuhl, 2000; Benn and Evans, 2010).
5 Method

5.1 Expedition

A five week long expedition to selected parts of the study area was conducted by A. Burström in March to April in 2011. The expedition was concentrated to the Solukhumbu region, 27° 41’ 0” N:27° 59’ 0” N, 86° 43’ 0” E: 86° 56’ 0” E, in Nepal. Covering the entire study area at just one expedition was not possible to do due to the extent of the study area. The Solukhumbu region was chosen for logistical reason. The Solukhumbu region is relatively accessible compared to other parts of the study area.

One main intention for the expedition was to collect snow density samplings on selected glaciers. At the site however it became apparent that this was not possible to conduct due to physical constrains. Observations of snowline elevation were also attempted but proved difficult because of recent snowfalls.

The expedition resulted in hundreds of photographs and on-site experience of the study area which should not be underestimated, especially in this particular area which is rather unique in its character.

5.2 Remote sensing

Remote sensing offers a unique possibility to extensively and frequently observe glacier in remote areas (Albert, 2002). A study of this kind would not be possible to conduct trough fieldwork since these glaciers are not easily accessible due to their location and exposure to potential hazardous events.

5.2.1 Data

Remote measuring of snow and ice calls for a spatial resolution of tens of meters in mountain areas. Landsat Thematic Mapper, TM, offers the required resolution as well as
a good spectral cover. This is necessary in order to classify different land-cover types (Albert, 2002). The Landsat TM is produced by National Aeronautics and Space Administration, NASA and the United States Geological Survey, USGS. For this study, Landsat satellites 5 and 7 equipped with the Thematic Mapper and the Enhanced Thematic Mapper Plus, ETM+, were selected.

Desirable images to use for this kind of studies are from the end of the ablation season since they best display the accurate snowline (Albert, 2002). The end of the ablation season is regarded as the time before the year’s first precipitation. For most glaciers, this occurs in the very end of fall, before the first snow falls. For this area however, where accumulation and ablation occurs simultaneous during summer, this occurs before the summer monsoon begins in June (Ageta and Higuchi, 1984). Hence May would be a good month to use. May however tend to be cloudy due to the onset of the monsoon (Benn and Owen, 1998) and is thus often unusable. The first choice for satellite images has therefore been images acquired during April.

The intention for the study was to use three images, one from around 2000, one from around 2005 and one from around 2010. This would allow for some variance in the data. For 2010, a cloud free image from 9 April was acquired. But it was troublesome to find cloud free images for 2005 and 2000. In the end, images from 5 January, 2002 and 3 January, 2007 were selected. These were cloud free and showed less snow cover than the images from February to April from the same years (some snowfall that is not adherent to the monsoon does occur in this area (Ageta and Higuchi, 1984)). The images were obtained from The USGS Global Visualization Viewer, GloVis (www.glovis.usgs.gov).

A color composite of band 5, 4 and 3 were made for each of the selected years. This was done with the program FW Tools (available at www.fwtools.maptools.org). Ice and snow have very low spectral reflectance in the middle-infrared (MIR) wavelength region and very high spectral reflectance in the visible-red (RED) and the near-infrared (NIR) wavelength regions. A color composite of these bands therefore denotes the glaciers very well (Albert, 2002). Color composites for all three years were imported into ArcGIS were the glacier mapping was conducted.
For topographic data a Radar Digital Elevation Map, DEM was acquired from The Shuttle Radar Topography Mission, SRTM. This radar DEM was however not possible to use due to data voids. Instead an Advanced Spaceborne Thermal Emission and Reflection Radiometer Digital Elevation Map, ASTER DEM was acquired. The data was imported into ArcGIS in the form of a TIFF-file. The spatial references were set to WGS_1984_UTM_Zone_45N in order for the ASTER DEM to be compatible with the Landsat TM images. The spatial resolution for the ASTER DEM is 30 m (ASTER User Guide, 2005).

5.2.2 Mapping

The mapping was done by manual digitization. This method has been estimated to be 99% accurate as opposed to supervised or unsupervised classification which has an accuracy of 75% to 90% (Albert, 2002).

When the mapping started, the area was first divided into three vertical and three horizontal profiles that overlapped each other. This created 9 squares with Mt Everest in the center. In each square 15 random glaciers were mapped. This gave 135 glaciers in total which is a feasible number to map as well as sufficient enough data for this type of study. The expectation was that the different squares would present difference in AAR which reflected the squares location in relation to the spatial precipitation. This was however not the case, as was obvious after the mappings was done. The “square approach” was therefore rejected. 135 diversely spread glaciers all over the area were then mapped instead with the hope to find a gradient in ARR which could be connected to glacier location and precipitation pattern.

The total area of the glaciers was mapped as polygons. The accumulation zones were also mapped as polygons and this was done by distinguishing the snowline which then the polygon emanated from. The snowlines were parts of this polygon and therefore not mapped as individual lines. This was done for all 135 glaciers in each year. First, an attempt to make the mapping in the program FW Tools and then export the result to ArcGIS was made. However, it proved to be faster and easier to conduct the mapping directly in ArcGIS and therefore this was opted for.
The intention was to not map glacier smaller than 1 km\(^2\). The margin of error due to pixel miss-mapping is too large for comfort in such small glaciers (Albert, 2002). The 135 mapped glaciers were thus reduced to 111 glaciers after a thorough revision.

Attempts to map more basic shaped glaciers were also done. In this area there is a problem with reconstructed glacier (Figure 12). In a reconstructed glacier the accumulation and ablation area is separated by un-glaciated, steep rock slopes (Benn and Lehmkuhl, 2000). Such glaciers are not suitable for AAR and AABR calculation (Furbish and Andrew, 1984; Rea, 2009) since the theoretical ELA can be located at an un-glaciated rock wall (Benn and Lehmkuhl, 2000). There is also a problem with glaciers located below steep head walls and avalanche slopes (Figure 13). Snow covered head walls and avalanche slopes can be mistaken as part of the glacier and this would influence the AAR and AABR value (Furbish and Andrew, 1984; Rea, 2009). Glaciers with to complex forms and or snowlines were therefore excluded.

![Example of a reconstituted glacier. This glacier is located in upper Chandra Valley, Lahul Himal, India (Benn and Lehmkuhl, 2000).](image-url)
Trends in mass balance indexes connected to spatial location and precipitation in the Everest region

Figure 13. Two examples from the study area. The left glacier is a reconstructed glacier. Unglaciated rock areas are visible in between the ice. The right glaciers is a glaciers situated beneath steep headwalls. Including the walls in the mapping would yield a to high AAR (Benn and Evans, 2010) and influence the AABR highly since AABR considers hypsometry (Furbish and Andrew, 1984). The images are from the color composite derived from the Landsat TM 5, 9 April, 2010, scale 1:50 069.

Google Earth (available at http://www.google.com/earth/index.html) is a helpful tool to use when mapping becomes difficult. Google Earth can be used to verify that the mapping is conducted correctly.

Only unmantled ice was mapped in this study. Debris-cover ice is complicated to map. The debris-covered part of the glacier cannot be distinguished from the surrounding terrain because both have the same spectral characteristics. Thus ice cannot be detected in a pixel if the pixel is dominated by the debris. Manual delineation can still be possible since the glacial boundary shows differences in illumination that are caused by the shape. But even in situ observation has shown inability to delineate boundaries between supra– and periglacial debris and stagnant ice. Potential buried ice may have to be detected by geophysical field investigations (Paul et al, 2004).

5.2.2.1 Visual interpretation

The hand digitization from the mapping also gave the advantage of a basic visual interpretation of the area. This lead to a understanding of the glacier types represented
in the study area, which also allowed for a better understanding of the result from the mapping.

5.2.3 Calculations

All the numbers received from the mapping in ArcGIS were exported to Microsoft Excel were the calculations were conducted. The export of the snowline polygons were at first done manually from ArcGIS to Microsoft Excel, but since there was a large quantity of numbers to export this proved tedious and prone to human errors. A computer program for this were therefore used instead (Appendix, Computer Program A). This was needed since the calculation of the total area over snowline required the data to be sorted under glacier ID instead of Field Identifier which ArcGIS does automatically. The data from the total area polygons were imported directly from ArcGIS to excel without the use of the computer program.

5.2.3.1 Snowline and snowline altitude

The lowest elevation of the accumulation area polygon was estimated by using the ASTER DEM. The result was regarded as the snowline altitude. The results were then compared to glacier longitude, latitude, aspect and mean elevation in order to search for patterns.

5.2.3.2 AAR

In this study all area above the snowline was regarded as the accumulation area and hence all area below the snowline was considered to be ablation area. The AAR values were calculated according to the equation described in section 4.2. The AAR values were compared to glacier longitude, latitude, mean elevation and aspect in order to see if there were any connections. To review if AAR were connected to the aspect the total AAR in each year and aspect were area weighted and the results were then plotted against glacier aspect.

5.2.3.3 AABR and ELA

For the AABR calculation, an ELA is needed. Since the ELA of these glaciers are not known the snowline altitude, SLA (see section 5.2.3.1) was used as an approximation for the ELA. At first the same approach as above were used; the lowest elevation of the
accumulation polygon were set as the SLA. This approach however proved unusable due to the distinct variations in the snowline altitude which could differ hundreds of meters in elevation. A mean SLA was therefore needed. This was derived through a computer program that excluded the polygon lines that overlapped each other in the glacier total area and in the glacier accumulation area (Appendix, Computer Program B). This exclusion left one line, which corresponded to the snowline. A mean altitude of this line was then calculated with the help of the ASTER DEM. This approach was faster than re-mapping all snowlines as polylines in ArcGIS. The AABR was then calculated using the mean SLA as an approximation for ELA. The mean SLA will from now be referred to as ELA.

In order to calculate AABR, area-weighted mean altitudes of the accumulation and the ablation areas were calculated by tabulating the altitudes within the mapped glacier boundaries. ArcGIS has the ability of summing the total area with a specific altitude within a polygon. As the total number of different altitudes can be quite large, the vertical altitudes within a 20 m range were counted in one bucket. This means that the number of columns in the table shrinks 20 times compared to if a resolution of 1 m was used.

The tabulated values were imported into Microsoft Excel where several formulas were applied to the data. Firstly, by adding all area values corresponding to altitudes below ELA, the area below ELA \( (A_{ab}) \) was calculated. Using the same method, the area above ELA was calculated \( (A_{ac}) \). The area weighted mean altitudes referenced from ELA were calculated as follows: for all altitudes below ELA, the distance from ELA was multiplied by the total area for this altitude. The products were then added together and the sum was divided by the total area below ELA. This equals \( z_{ab} \). The same was applied to all altitudes above ELA which results in \( z_{ac} \). This allowed calculation of AABR for all the mapped glaciers with a snowline. The equation used to calculate AABR is expressed in section 4.3.

The AABR and ELA were compared to glacier longitude, latitude, mean elevation and aspect in order to search for patterns.
5.2.3.4 Aspect

The aspects of all glaciers were noted. Average glacial area, mean ELA as well as area weighted AAR and median AABR for each aspect was calculated.

5.3 Review of the chosen methods

5.3.1 Expedition

It could be better to conduct the expedition in late April instead of early April. This would allow for more snow melt to occur which would give a more accurate estimation of the accurate SLE. However, the risk of precipitation increases as the monsoon approaches (Ageta and Higuchi, 1984) and hence this calls for consideration as well.

Extensive ice climbing experience is needed to take snow density samples at the glacier in the expedition area. If sampling is the goal for the expedition, one should opt for trekking to one or two glaciers to take samples and exclude other trekking. Trekking a larger area allows for a visual interpretation but is rather draining coupled with ice climbing for sample collection.

5.3.2 Remote sensing

5.3.2.1 Data

5.3.2.1.1 Landsat Thematic Mapper and Landsat Enhanced Thematic Mapper Plus

The used satellite image from 2007 is from Landsat 7 ETM+ which suffered loss of its scan line corrector in May 2003. The satellite still acquires approximately 75% of the data (National Aeronautics and Space Administration) and hence was regarded as usable for this study.

The problem with obtaining good quality satellite images resulted in the use of images from different months. This is not optimal. The images from 2002 and 2007 are from January and show more snow. The snow quantity will render lower snowlines and larger accumulation areas. The January images also contain more shadows due to that the solstice is different in January than in April (Ageta and Higuchi, 1984). Ice that is
shaded can get a depressed spectral curve which would appear as water (Albert, 2002). This was however not the problem for this study, the issue was rather that the mountain walls shaded the glaciers which made the glacier outlines and snowlines harder to detect. Hence the image from 2010 shows a clearer view of the glacier.

5.3.2.1.2 ASTER DEM

The ASTER DEM is composed by triangulation from several images taken from various angels over time. This is produced by using bands 3N (nadir-viewing) and 3B (backward-viewing) of an ASTER Level-1A image, the image is acquired by the Visible Near Infrared sensor. No ground control points are used for the ASTER DEM (Earth Remote Sensing Data Analysis Center, 2005). This means that the elevation from the ASTER DEM will not be completely accurate and that the information is complied in different periods. The ASTER DEM is therefore not optimal to use. A DEM derived from a radar satellite, like SRTM, would give a more correct estimation of the elevation at a specific time since this type of DEM is composed by a snapshot of the area. However, radar signal in mountain areas has problem with reflections of the signal due to the extreme topography (Farr et al, 2007; Jacob et al, 2012). The SRTM DEM for the study area was therefore incomplete and hence impossible to use.

5.3.2.2 Mapping

Manual digitization is based on subjective decision. Especially the pixels along the ice margin are prone to misclassification. The terminal moraines in front of the glaciers are often light colored and therefore hard to distinguish from older ice (Albert, 2002). In this case the mapping only included debris free ice and the problem with terminal moraines was hence avoided. Instead the difficulty of debris free ice mapping was a fact. The debris-cover is continuous up to a certain elevation, then it becomes patchy and after that it vanishes (Paul et al, 2003). It is not always easy to determine when it becomes continuous and hence the mapping could be slightly off at this location. There is also a problem with pixels located at the very fringe of the glaciers sides and at the upper part. These pixels are likely to be mixtures of ice and other material - or as in this particular case; an adherent glacier. This may have a slight effect on the results of glacier size in the mapped area, especially since some of the mapped glacier in this
study are rather small, although not smaller than >1 km$^2$. These errors are however random and should not affect the end result noticeably.

5.3.2.3 Visual interpretation

The visual interpretation is an arbitrary assessment and thus possibly bias. The intention was however not to conduct a comprehensive glacial shape and dynamic study but merely to establish a notion of the represented glaciers.

5.3.2.4 Calculations

This study includes a large amount of data and the management of the large quantities of data is subject to human error. All data were however automatically exported to Microsoft Excel where all calculations were conducted. The margin of errors is therefore regarded as extremely low. The use of a computer program for exporting and sorting data from ArcGIS (see section 5.2.3) is highly recommended.

5.3.3 Glacier index

5.3.3.1 AAR

AAR is an index term that indicates glacier mass balance. This indication can be off if there have been resent snowfall in the satellite image or if there is complications like internal accumulation in the reviewed glacier. AAR works well if coupled to fieldwork such as glacier surface measuring, probing and snow sampling etc since the fieldwork will serve as ground data which is used for comparison (Østrem and Brugman, 1991). If ground data is not possible to incorporate, the result from the remote sensing cannot be regarded to be equally reliable.

5.3.3.2 AABR

It is noteworthy that the assumption for calculating AABR is that ablation and accumulation gradients are assumed to be linear (Furbish and Andrew, 1984; Rea, 2009). A straight curve will give a constant gradient, but a linear gradient does not give a straight curve. Hence the mass balance is the factor that should be linear and not the gradient; the calculation for AABR divides two gradients with each other which would be impossible to do unless they were constant. However, this problem could be
explained by a simple typing error and is not further explored here. The basic assumption made for AABR calculation in this study is therefore that glacier altitudinal mass-balance is linear.

The glaciers in this study are subjected to severe topographical effects on the mass balance which are responsible for creating distinctly non-linear mass-balance gradients. Benn and Lehmkuhl conclude that AABR cannot be applied to this type of glacier due to the non linear ablation gradient (Benn and Lehmkuhl, 2000). However, if the debris covered part of the glacier is excluded one can somewhat elude this problem. Since debris covered glacier parts are not included in this study an attempt to calculate AABR therefore seems possible.

But these glaciers also have a non-linear accumulation which further limits the use of AABR. The Khumbu glacier for example is prone to accumulation by avalanches just like a number of other glaciers in this area. Mass balance curves for the Khumbu glacier has been calculated by Inoue (Figure 14) and shows a strictly nonlinear ablation gradient due to the debris covered snout. The gradient however seem to revert to a linear behavior at about 5400 m a.s.l.. The debris cover is rather continuous up to 5200 m a.s.l. and then becomes scattered up to approximately 5300 m a.s.l. The ice is clean and uncovered above this elevation (Inoue, 1997).
Figure 14. Mass balance curve for Khumbu glacier (Inoue, 1997). It is noteworthy that this mass balance curve is likely to be highly idealized. Yet it does give an understanding of the mass balance situation of the glacier.

In the Khumbu glacier the accumulation is linear, but only presents gradients up to about 5750 m.a.s.l.. Above this the mass balance contribution is constant (Figure 14; Inoue, 1977). Since AABR calculation relies on the mass balance being linear in the entire accumulation area (Furbish and Andrew 1984) the approximation for this glacier will be misleading. It would yield a too high AABR. This problem could be addressed by deriving an equation that considers the declining slope of the mass balance gradient and thus such an equation has been derived. Remember the equation for AABR

\[ AABR = \frac{\sum_{i=0}^{n} z_{ac_i} * A_{ac_i}}{\sum_{i=0}^{n} z_{ab_i} * A_{ab_i}} \]

where \( z_{ac_i} \) is the elevation measure positive above the ELA and \( A_{ac_i} \) is the area corresponding to the same elevation. \( z_{ab_i} \) and \( A_{ab_i} \) are the equivalent below ELA.
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Assuming a constant (instead of linear) contribution above a certain altitude, the above formula can be expressed as

$$AABR = \frac{\sum_{i=0}^{k} Z_{ac,i} \cdot A_{ac,i} + \sum_{i=k+1}^{n} Z_{ac,k} \cdot A_{ac,i}}{\sum_{i=0}^{l} Z_{ab,i} \cdot A_{ab,i}}$$

where $i = 0 \ldots k$ corresponds to elevations from ELA and up to 150 m above ELA. $i = k+1 \ldots n$ corresponds to all elevations 150 m and higher than ELA.

The ELA of the Khumbu glacier was estimated to be at 5600 m.a.s.l. in 1977 (Inoue, 1977), but it has risen since then. The result from the mapping in this study shows an ELA at 5826 m a.s.l. in 2010. In the study from 1977, the accumulation gradient is linear from ELA at 5600 m a.s.l. and up to 5750 m a.s.l., or 150 m above the ELA, after this it turns constant. The ELA apparently has risen since 1977, therefore the assumption that the linearity of the accumulation and the elevation were the gradient becomes constant would still be at the same elevations is not feasible. The ELA had risen 226 m in 2010. We therefore assume that the accumulation gradient has followed the same pattern and place the constant gradient at 5976 m a.s.l., 150 m above the current ELA.

The equation above relies on accurate measurements of the elevation that show where the mass balance becomes constant. Such information is obtained by field measurements and thus requires extensive field work (Østreng and Brugman, 1991). One of the AABRs main purposes is to approximate glacier mass without the help of field work (Furbish and Andrew, 1984; Rea, 2009) and thus the above equation seems senseless. But it could be useful for cases were such data already exist. The calculated AABR for such a glacier could be used as a proxy for similar glacier in glacier reconstructing or for present day glaciers in the Himalaya that are subjected to similar conditions.

The Inoue study of the Khumbu glacier mass balance show that from approximately 5750 m a.s.l there are no more gradients in the accumulation, meaning that there is no ablation occurring at this elevation and that the precipitation is constant. This is probably due to that the temperature is low enough to allow all accumulation to remain
and that there are no more precipitation gradients at this elevation and above (Inoue, 1977). It is not unlikely that this occurs at other similar glaciers at this elevation in this area, since it is implausible for a distinct temperature gradient to exist at the same elevation within the same area. Hence it is conceivable to assume similar accumulation, which resembles the Khumbu glacier gradients, in glaciers located at similar high elevation. This is supported by a study by Bolch et al which show comparatively little scatter of the mass balance amongst twelve avalanche fed glacier situated in this area (Bolch et al, 2011). However, for avalanch fed glacier the mass balance gradient can vary significantly. This is apparent when for example viewing the mass balance curve of the Ama Dablam glacier, located at 86° 35´ E; 27° 35´ N (Figure 15; Benn and Lehmkuhl, 2000). In the Ama Dablam case, the above presented equation would of course not be applicable

![Schematic mass-balance curve of the Ama Dablam Glacier, Khumbu Himal, Nepal](from Benn and Lehmkuhl, 2000). This mass balance curve is likely to be highly idealized just like the one in Figure 14, but it still gives a notion of the mass balance distribution of this glacier.

Thus the linear approximation is not well meet by the Himalayan glaciers and when the linear assumption is not meet, the AABR equation will not work as intended (Furbish and Andrews, 1984; Benn and Lehmkuhl, 2000; Rea, 2009). AABR could however be used to indicate how much these glaciers deviate from the assumed linearity. If the mass balance gradient is not known and the result from the AABR calculation, using the standard AABR equation, is higher than expected, this could indicate overestimation of
the accumulation gradient. Hence AABR would still give an indication of the mass balance although this is in no way an absolute estimation. It would merely signal that there is non-linearity in the accumulation gradient and/or that the gradient is overestimated. It could also indicate that the ablation gradient is underestimated. This relationship is also possible to use the other way around; if the calculated AABR for a glacier is suspiciously low, the accumulation gradient could be underestimated or the ablation gradient could be overestimated.

The linear assumption is assumed to be the normal state for a majority of glaciers. But mass balance curves from other areas in the world also show non-linear mass balance (Mayo, 1984). This is not unique for the Himalayan glaciers. AABR is a more elaborative index then the AAR and is therefore a more interesting index to use. The disadvantage with AABR, that it assumes linearity in the mass balance curves, could be used reversed. In this study AABR is used as an indicator of how much these glacier deviate from the assumed linearity.
6 Results

6.1 Expedition

During the expedition hundreds of photographs of the area, the glaciers and their stratigraphy were taken (Figure 3; Figure 5; Figure 6; Figure 7; Figure 8; Figure 16; Figure 17). Photographs of snow accumulation layers were foremost taken on the glacier located at the Imja Tse, 27° 55’ 21” N, 86° 56’ 10” E, also referred to as Island Peak (Figure 16). This is a small glacier, only about 0.16 km², and thus not included in the mapped glaciers in this study.

Figure 16. Snow accumulation layers at the small south facing glacier located at the Imja Tse. Picture taken at 27° 54” N, 86° 55” E, elevation 5909.5 m a.s.l, 20 April, 2011, by A. Burström during the expedition.
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Snow stratigraphy in this part of the Himalaya has been analyzed by Steinegger et al. They concluded that two snow strata are formed annually; one dark, shallow winter layer and one clean, thick summer layer (Steinegger et al, 1993). These layers are clearly distinguished in Figure 16. The layers indicate a rather healthy glacier with reasonable accumulation, although this is not reflected in the size of the glacier. Steinegger et al estimated that the annual accumulation is in the range of 600 to 1300 mm of water equivalent in the Langtang region, Nepal. The Khumbu region shows slightly lower numbers (Steinegger et al, 1993).

Observations of glacier accumulation by avalanches were foremost made at the Khumbu Icefall. Two nights were spend at Everest Base Camp which is situated at the debris covered part of the Khumbu glacier. Avalanches were noticed in the evenings and nights, at least two avalanches were heard both nights. Avalanches were also seen in the midmornings, these avalanches were presumably powder snow avalanches judging by their appearance. One small avalanche was also photographed from the top of Lobuche East (Figure 17). This avalanche is feeding a small glacier surrounded by high and steep mountain walls.

![Avalanche feeding a small glacier. Picture taken at 27° 57’ 21” N, 86° 47’ 38” E, elevation 5974 m a.s.l., 16 April, 2011, by Ang Tsering Lama during the expedition.](image)

The debris covers of the glaciers were also observed (Figure 6; Figure 7; Figure 8). The debris is non-continuous and variable. The transition from clear ice to debrised ice can
be rather extended. A clear distinguishing between the two is difficult to make. The debrised glacial area varies in size and can be extremely vast and continuous, as seen at the Khumbu glacier and the Lothse Shar glacier. It can also be smaller and more disconnected as seen at the Imja glacier. There are also un-debrised glaciers, like the Chukhung glacier situated close to the Imja glacier, although they are rare.

6.2 Remote sensing

The 111 mapped glaciers are similar in total mass from year to year. The total mapped glacier area was 454.9 km² in 2002, 467.8 km² in 2007 and 440.7 km² in 2010. The highest mapped glacier elevation was 8200 m a.s.l. (2002, 2007, and 2010), the lowest elevation was 4100 m a.s.l. (2007). Mean elevation was 5836.7 m a.s.l. for 2002, 5827.3 m a.s.l. for 2007 and 5836.6 m a.s.l. for 2010.

Snowlines were not detected in all glaciers. In 2007 five glaciers had total snow cover. In 2010 the problem were reversed. Six glaciers had zero snow cover also resulting in no snowline. These glaciers have been excluded in the results that needed a snowline for the calculation (see section 5.2.3).

6.2.1 SLA and ELA

Both SLA and ELA were calculated but only ELA is presented below since ELA gives more accurate information (see section 5.2.3.3).

There is a connection between ELA and glacier mean elevation, they are therefore presented together below. ELA differs from year to year. ELA for 2002 and 2007 are similar but ELA rises in 2010. Mean ELA is 117.9 m lower than glacier mean elevation in 2002, 101.5 m lower in 2007 and 12.8 m lower in 2010. Glacier location is also connected to ELA. Higher ELA is seen towards higher longitudes and latitudes; this connection is more distinct in latitude (Figure 18).

ELA is connected to glacier size as well. The largest glaciers have ELA values in the middle range of the results (Figure 19).
Trends in mass balance indexes connected to spatial location and precipitation in the Everest region

Figure 18. ELA and glacial mean elevation plotted against latitude for 2002, 2007 and 2010.
6.2.2 AAR

AAR shows a tendency to become more widely distributed from 0 to 100% for every mapped year; the standard deviation becomes higher for each year (Table 1). There is no obvious pattern variation in AAR connected to glacier location in any of the mapped years; hence AAR does not seem to follow any longitude or latitude pattern (Figure 20; Figure 21; Figure 22).

AAR was plotted against glacier mean elevation - there is a tendency for glacier with high mean altitude to have higher AAR although there are some deviations (Figure 23). AAR is also connected to glacial total size; larger glacier has higher AAR (Figure 24).
Trends in mass balance indexes connected to spatial location and precipitation in the Everest region

Table 1. Table showing min, max, average, standard deviation from and median for AAR for each year.

<table>
<thead>
<tr>
<th>Year</th>
<th>2002</th>
<th>2007</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min</td>
<td>16.8</td>
<td>11.1</td>
<td>0</td>
</tr>
<tr>
<td>Max</td>
<td>95.2</td>
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<tr>
<td>Average</td>
<td>75.0</td>
<td>71.7</td>
<td>51.0</td>
</tr>
<tr>
<td>Std deviation</td>
<td>14.8</td>
<td>19.2</td>
<td>23.4</td>
</tr>
<tr>
<td>Median</td>
<td>78.2</td>
<td>77.5</td>
<td>52.4</td>
</tr>
</tbody>
</table>

Figure 20. AAR plotted in location for 2002.
Figure 21. AAR plotted in location for 2007.
Figure 22. AAR plotted in location for 2010.
Figure 23. AAR plotted against mean glacial elevation for each year.
6.2.3 AABR

2002 had 2 glacier showing AABR over 90 and 2007 had 2 glaciers showing AABR over 200. These four glaciers have been excluded since these values are unreasonable and affect the overall values. The highest AABR represented here is therefore 73.5; also an extremely high value which reflect high deviation from standard AABR.

AABR differ greatly from year to year. AABR in 2002 and 2007 deviate highly from standard values, 2010 shows lower AABR and hence lower deviations, but the values are still rather high (Table 2).

In 2002 and 2007 there is an indication that AABR deviation follows longitude and latitude. AABR is highest at 28° 1’ N and 87° 0’ E. 2010 does not show any such correlation (Figure 25; Figure 26; Figure 27).

High AABR show tendencies to follow ELA and glacier mean altitude, highest deviation is seen at a glacier located at a mean elevation at around 6100 m a.s.l. (Figure 28). Glacier size and AABR deviation is also connected, smaller glacier shows higher AABR (Figure 29).

Figure 24. AAR plotted against total glacier area for each year.
Table 2. Table showing min, max, average, standard deviation from and median for AABR for each year. The most representative results is likely shown by median.

<table>
<thead>
<tr>
<th>Year</th>
<th>2002</th>
<th>2007</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min</td>
<td>0.02</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>Max</td>
<td>73.50</td>
<td>73.50</td>
<td>19.03</td>
</tr>
<tr>
<td>Average</td>
<td>10.30</td>
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<tr>
<td>Std deviation</td>
<td>15.00</td>
<td>14.32</td>
<td>3.81</td>
</tr>
<tr>
<td>Median</td>
<td>5.00</td>
<td>3.50</td>
<td>1.14</td>
</tr>
</tbody>
</table>

Figure 25. AABR plotted in location for 2002.
Figure 26. AABR plotted in location for 2007.
Figure 27. AABR plotted in location for 2010.
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Figure 28. AABR plotted against glacier mean elevation for each year. Highest AABR is found at glaciers located at mean elevation of 6000 m a.s.l.

Figure 29. AABR plotted against total glacier size for each year. Small glaciers shows higher AABR.
6.2.3.1 Adjusted AABR equation

The adjusted AABR equation (see section 5.3.3.2) gives the Khumbu glacier lower AABR (Table 3).

<table>
<thead>
<tr>
<th>Year</th>
<th>AABR with conventional equation</th>
<th>AABR with adjusted equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>5.19</td>
<td>1.35</td>
</tr>
<tr>
<td>2007</td>
<td>4.70</td>
<td>1.24</td>
</tr>
<tr>
<td>2010</td>
<td>4.90</td>
<td>1.29</td>
</tr>
</tbody>
</table>

6.2.4 Aspect

Southeast is the dominant aspect, west, northwest and north is least favorable (Figure 30). Average glacier area is slightly higher in the north and in the northeast. Mean ELA is highest in the north and lowest in the northeast and in the southeast. Mean ELA is similar, although higher in 2010, for each mapped year (Figure 31). The difference between ELA and glacial mean altitude varies from year to year and is higher in 2002 and 2007 than in 2010. The difference is highest in the north (Table 4).

Area weighted AAR for 2002 and 2007 is slightly higher in the east to the south than in the other aspects.

AABR is diverse both from year to year but also within years (see section 6.2.3). The large standard deviation in AABR indicates that an average AABR in each aspect is not a good parameter to visualize, therefore the median AABR was used instead. The results show that the median AABR is highest in the north for 2002 and 2007. 2010 does not follow the results from 2002 and 2007.
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**Figure 30.** Total number of glacier in each aspect.

**Figure 31.** Mean ELA plotted against aspect for each year.
Table 4. Table showing the difference between ELA and mean glacier elevation. Negative value means that ELA is located below mean elevation.

<table>
<thead>
<tr>
<th>Aspect</th>
<th>Diff between mean elevation and ELA 2002</th>
<th>Diff between mean elevation and ELA 2007</th>
<th>Diff between mean elevation and ELA 2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>North</td>
<td>178.7</td>
<td>141.9</td>
<td>70.3</td>
</tr>
<tr>
<td>North east</td>
<td>113.7</td>
<td>116.3</td>
<td>50.2</td>
</tr>
<tr>
<td>East</td>
<td>149.8</td>
<td>79.0</td>
<td>-31.7</td>
</tr>
<tr>
<td>South east</td>
<td>98.7</td>
<td>105.2</td>
<td>-8.3</td>
</tr>
<tr>
<td>South</td>
<td>117.6</td>
<td>102.3</td>
<td>-28.3</td>
</tr>
<tr>
<td>South west</td>
<td>120.6</td>
<td>132.9</td>
<td>34.6</td>
</tr>
<tr>
<td>West</td>
<td>113.9</td>
<td>139.6</td>
<td>65.1</td>
</tr>
<tr>
<td>North west</td>
<td>54.8</td>
<td>-4.7</td>
<td>8.0</td>
</tr>
</tbody>
</table>

6.2.5 Differences in glacier shape, size and dynamic

The visual interpretation from the mapping indicates that the glaciers differ in shape, size and possibly dynamics depending on their location. Three different glacier types seem to be possible to distinguish; glaciers located at the higher, at the middle and at lower latitudes. Glaciers located at the highest latitudes, 28° 15’ N to 28° 4’ N are rather small and displays tendencies to be cold glaciers since they seem to have less glacier movement (Figure 32). The largest glaciers tend to be located at the middle latitudes, 28° 4’ N to 27° 5’ N. These glaciers also tend to have lager debris cover then the smaller glacier (Figure 33). Glaciers located at the lowest latitudes, 27° 5’ E to 27° 38’ E, appears to be rather stagnant and in a more ablated state then the glaciers further north (Figure 34).

Glacier size seems to follow longitude and altitude as well; the largest glacier are found at longitudes 86° 52’ to 87° 09’ and at elevation around 6000 m a.s.l. with two exception (Figure 35; Figure 36).
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Figure 32. Glaciers located at 28° 16’ N-28° 13’ N, 86° 45’ E-86° 39’ E. Color composite derived from Landsat TM, image acquired 9 April, 2010. Scale 1:58 560.

Figure 33. Glaciers located at 28° 4’ N-28° 0’ N, 86° 54’ E-86° 45’ E. Color composite derived from Landsat TM, image acquired 9 April, 2010. Scale 1:58 560.

Figure 34. Glaciers located at 27° 47’ N-27° 42’ N, 86° 57’ E-87° 5’ E. Color composite derived from Landsat TM, image acquired 9 April, 2010. Scale 1:58 560.
Figure 35. Glacier size in 2002 plotted in location for each year. Glacial size is similar in 2002, 2007 and 2010.

Figure 36. Glacier size plotted against glacier mean elevation.
Discussion

The three images used in this study yielded diverse results. The differences could be explained by the different timing in the data compiling. Note however that the snowlines vary substantially for some, but not for all, glaciers. This suggests that the differences are not solely due to the date variation. A likely explanation is the difference in time coupled with windblown and avalanche fueled snow distribution. 2002 and 2007 probably also display rather high quantities of snow which suggest positive mass balance years. 2010 on the other hand appears to be a poor glacial year displaying very little snow cover left from the previous year. The average annual snow accumulation is likely to be somewhere in the middle of these three estimations. Anders et al concluded that the precipitation pattern was notably stable from year to year during these years, see section 3.2.1

6.3 ELA

ELA rises towards higher latitude, ELA also rises slightly towards higher longitudes. ELA is closely connected to precipitation patterns, temperature and often also aspect (Benn and Owen, 1998). A similar connection should be seen in AAR and possibly AABR for these locations if this was the cause of the rise in ELA. No such correlation was however found. The rise in ELA is therefore probably best explained by the higher mean altitudes at these locations. Glacier mean elevation was closely connected to ELA and the mean elevation rises to the north and slightly to the west. The largest glacier has ELA between 5500 m.a.s.l. and 6000 m.a.s.l., also a likely reflection of their mean elevation.
6.4 Glacier shape, size, dynamic and AAR

The glaciers at different latitudes show difference in their shape and size. The visual interpretation indicates that the northern glacier are leaning towards polar glacier were else the southern glaciers are clearly temperate. The appearance of the southern glaciers indicates more glacier movement and thus also higher mass balance turnover. This is also reflected in the larger glacial deposits and in the glacier shapes. These differences ought to render different AAR, but no clear gradient in AAR have been detected. This can be due to many reasons. For example, the precipitations pattern has not been extensively analyzed in this study. The area is complex and the precipitation pattern may not be possibly to simplify in the way that has been suggested here. The topography also plays another major role in addition to precipitation agent; it fuels avalanches and windblown snow. The results from this study indicate that these glaciers are not as precipitation sensitive as regular glaciers which could be due to that they in many cases are avalanches fed to a high degree (Benn and Lehmkuhl, 2000).

It should however exist some correlation between precipitation, glacier location and mass balances since precipitation distribute snow which compose the avalanches. But the relationship between precipitation, snow catchment, wind and avalanche distribution is complex to unravel and no such attempt has been done here. Further studies could explore the differences in ELA between 2002, 2007 and 2010 for estimation and evaluation of the snow distribution. The data could be used for observation of how the snow is spread by windblow and by avalanches since the ELA varies substantially for many both not all the glaciers.

Other factors in the area can also affect the lack of connection between precipitation pattern and AAR. The lower precipitation in the north could be compensated by lower temperature, which would allow the glacier to better keep the sparse snow fall. The glaciers in the middle latitudes are the largest in the area which indicates favorable glacier climate and catchment areas. But this area also has steep slopes which lead to problems with keeping the accumulation. The AAR could therefore be lower than if the glacier would not have been so steep. The extreme topography also limits further glacial expansion. The flatter area further north should be more favorable for bigger glaciers, but large glacier development is constrained since the area is less prone to precipitation.
The glaciers furthers south are likely subjected to the largest amount of precipitation, but these glacier are not the largest. The glacier volume is possibly balanced by slightly warmer temperatures.

This study did reveal some correlations between glacier size, glacier mean elevation and AAR. Glacier with a high mean elevation generally had higher AAR than the lower located glacier. The largest glaciers were located at around 6000 m.a.s.l. Glaciers located at high elevation thus seem to be in a healthier state. Higher elevations allow for low temperatures and are also good for creating glacier catchments areas. Note that the largest glaciers are not located at the highest elevations; the elevations where they are located suggest that they could be fed by avalanches from higher surrounding mountains.

Thus AAR reflects glacier circumstances such as elevation and size to some degree in this study. AAR does however have several shortcomings and this study suggest that AAR is not a good index for the study of glacier climatic regime and its influence over glacier mass balance. This is interesting due to that AAR is a common parameter to use for glacier comparison. However, following the reasoning above, there may not be a problem with AAR; the problem may lay with that the accumulation and precipitation pattern is not constituted as anticipated in this area. There may also be a problem with the study area being too small in order to reveal clear precipitation pattern. Had the glaciers located northwest to the study area been included this might have been avoided.

Noteworthy is also that AAR in this study is higher than normal AAR given for Himalaya glaciers. This is due to that glacier mapping in this study only included unmantled ice, the glaciers could therefore be regarded as debris free glaciers and hence the AAR becomes higher.

6.5 AABR

The intention with the AABR calculation was to use the results as an indication of how much the glaciers deviates from the normal assumed linearity in mass balance. The expectation was that the anticipated connection between precipitation and mass balance, that was undetected in AAR, could be noticed in AABR deviation since AABR is a
more elaborative index. No clear connection between the assumed precipitation pattern and AABR deviation were however found, but a connection between glaciers located at a high mean elevation and high AABR was detected. 2002 and 2007 also shows a handful of glaciers with high AABR deviation located in the northeast part of the study area. High AABR is also connected to smaller glaciers. The highest deviation is seen in glacier smaller than 3 km$^2$, but glaciers smaller than 10 km$^2$ also have high deviations (AABR up to 10). This is due to that small errors on smaller glaciers can affect the AABR heavily.

The results from the adjusted AABR equation for the Khumbu glacier show that the conventional equation overestimates the AABR for this particular glacier about four or five times. This is a low overestimation compared to other AABR values in this study which were calculated to be as high as 73.5. AABR normally range from 0.23-4.40 and the global AABR has been estimated to be 1.75 ± 0.71 (Rea, 2009). Thus the AABR represented in this study is extremely high. Such high AABR denotes high ablation per unit area which is often associated with calving glaciers (Rea, 2009). Calving glacier are not common in this area (Benn and Lehmkuhl, 2000); the high AABR are due to other causes.

The highest AABR were seen in 2002 and 2007 which were snow rich years. Excessive snow quantities will render a false ELA that is too low and this will yield a falsely large accumulation area. The overestimated accumulation area will imply high ablation rates per unit area since the ablation area is very small compared to the accumulation area. The ablation rate then has to be extremely high in order to compensate for the lack of ablation area. The Khumbu glacier does not have an excessive snow layer in 2002 and 2007, which many other glaciers had, and therefore the AABR did not reach excessively high values.

High AABR can also originate from overestimation of the accumulation gradient. The gradient is assumed to increase linear to the highest point at the glacier. But this assumption does not necessarily apply to theses glaciers, which for example is shown in the mass balance curve for the Khumbu glacier and the Ama Dablam glacier. The gradient can be non-linear due to snow distribution by wind blow and avalanches which will give inaccurate, often overestimated, AABR. The gradient can also be piecewise
linear and from a certain elevation become constant (as in the Khumbu case), decreasing or even neither decreasing nor increasing. The later state will occur when the steepness of the mountain walls does not allow the snow to remain at the site. Gravitation, wind and avalanches will transfer the snow from these locations. The highest glacier mapped here is for example the Lothse Shar glacier at 8200 m.a.s.l. This elevation is not likely reflecting the highest glacier elevation; it probably rather reflects the mountain headwall. This miss-mapping is hard to avoid. It is difficult to denote the glacier from the mountain wall or peak since they are all snow covered.

High AABR can also be due to underestimated ablation. The debris-covered snouts have not been mapped in this study and this could affect the estimated ablation. The dynamics in debris covered glacier are poorly understood, this part of the glaciers may not be as stagnate as previously though. If this is the case, these areas should be included in the ablation area. The ablation rate and the AABR would then be reduced. But linearly ablation is unlikely since the debris cover is scattered and un-continuous, which gives different conditions. This means that ablation is likely to be overestimated if linear ablation from ELA is assumed. However, overestimated ablation and accumulation could possibly counter-balance each other to some degree. Including the debris glacier parts in the AABR calculation could therefore be an interesting future study.

Exaggerated AABR was observed in the results from 2002 and 2007 due to that there was more snow accumulation these years. This is likely to have been a more common state in former years when the glaciers were in a healthier state (Bolch et al, 2012). Lesser snow gives lower AABR, as is shown in the results from 2010. High mean elevation, large snow accumulation and smaller size hence suggest that the glacier will have a high deviation from the assumed linearity. This indicates that a Himalayan glacier with a high deviating AABR could be a healthy Himalayan glacier, although small in size.

One could argue that since AABR for 2002 and 2007 are so high, the results are unreasonable and therefore does not reflect any valuable insight. But AABR for 2010, does not rise over 20 and the mean AABR is the rather normal 2.68 with a standard
deviation of 3.81. Higher AABR (5-20) are more widely scatter in longitude and latitude then in 2002 and 2007, but these higher AABR are still restricted to higher elevation; around 5600-6300 m a.s.l. And again AABR is reduced at the highest elevations, from 6300 m a.s.l. and higher. Thus AABR still seem to be connected to elevation.

High AABR at these elevations could also be due to that there is a group of smaller size glaciers situated at these elevations. The high AABR could thus be rendered by glacier size. There is however small glaciers situated at all elevations, hence this particular elevation does seem to matter. The glaciers at this elevation likely possess a low ELA in relation to their mean elevation due to avalanches. This is not uncommon in the area. The avalanche fed Ama Dablam glacier for example, has an ELA 200 m below the neighboring Chhukung Glacier snout (Benn and Lehmkuhl, 2000).

6.6 Aspect

Southeast seemed to be the preferred aspect since the highest amount of glacier and the lowest ELA is represent here. Glaciers are likely easier established in this aspect since the precipitation arrives from this direction. Glaciers that have managed to establish within another aspect probably has other favorable situation, for example, shadow, leeside and snow distribution from avalanches. ELA is highest in the north suggesting that this is a dry aspect. But this result could be biased due to that it is a rather small amount of glaciers in each aspect. High (or low) ELA at one glacier could therefore influence the results quite a lot. Average glacier area is slightly larger in the north and in the northeast, which is probably connected to that these glaciers enjoys more shadow.

AAR indicates that southeast is a moist aspect since AAR tend to be slightly higher in this aspect the in the others. Median AABR shows high AABR for the north, although only in 2002 and 2007. ELA is higher in the north compared to the other aspect. This should give a low AABR, but the mean glacial elevation is also higher which compensate for this.
6.7 Conclusion

The normal standards of precipitation being closely connected to glacier accumulation and mass balance gradients being linear are not well meet in this area. It proved hard to connect glacial accumulation to local precipitation. AAR was a weak indicator of local precipitation pattern. AAR did however seem to be connected to higher elevation and to glacier size. Aspect was the parameter that best indicated the climate regime and its influence over the glaciers.

The AABR results foremost indicate high deviation at smaller, high elevated glacier. This gives a hint of these glaciers characteristic, their shape and their non-linear mass balance gradient. The high AABR imply that that they have large, wide and steep accumulation area, small ablation area and a high non-linearity in foremost the accumulation area (probably due to accumulation by avalanches).

Previous studies show that there is a connection between glaciers in this area and precipitation. This study does not show a clear difference in accumulation area or in mass balance indexes connected to local precipitation. The results here indicate that it is elevation that is connected to mass balance. Higher elevation allows for lower temperatures and good catchments area and this seems to be more important for the mass balance in this area.
7 Reference list


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Jacob, T., Wahr, J., Pfeffer, W.T and Swenson, S. 2012: Recent contributions of glaciers and ice caps to sea level rise. DOI: 10.1038/nature 10847.


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8 Appendix

8.1 Landsat images


8.2 ASTER DTM


8.3 Shape-files


8.4 Microsoft Excel Spreadsheets

Attached to the digital version of this paper as AABR-2002.xlsm, AABR-2007.xlsm, AABR-2010.xlsm, Calculations.xlsm and ExportedNumbers.xlsm
8.5 Computer program A

Computer program for importing and sorting glacier data from ArcGIS into Microsoft Excel, written by Stefan Burström. Contained in the attached file ExportedNumbers.xlsm in the digital version of this paper.

8.6 Computer program B

Program for deriving ELA lines in ArcGIS, written by Stefan Burström. Attached to the digital version of this paper as generate_elas.py