Department of Environmental, Land and Infrastructure Engineering

Master's Degree Course in Environmental and Land Engineering

DYNAMICS AND EVOLUTION OF FOX GLACIER IN THE SOUTERN ALPS OF NEW ZEALAND

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Abstract

Fox Glacier, in the southern alps of New Zealand, is the object of this thesis. It is located in the Westland Tai Poutini National Park., in the Western Coast of New Zealand. This glacier is the third largest glacier out of 3100 glaciers situated in the Southern Alps of New Zealand (Chinn 2001).

The surface velocity was investigated on the lower part of Fox Glacier and compared with previous literature. In this thesis, 15 pairs of satellite imagery are used to find the surface velocity of the ablation zone of the fox glacier using satellite images (Sentinel 2 and Landsat 8). Their spatial resolution is 10m (Sentinel images, visible band) and 15 m (Landsat images, panchromatic band). Glacier surface velocity fields from 2011 to 2021 are calculated with the Orientation Correlation technique, implemented in the ImGRAFT *templatematch.m* tool. This made possible to confirm the glacier retreating and to investigate the spatial and temporal variability of the velocities.

The spatial resolution is of the order of few centimeters. The velocity fields calculated on them have demonstrated the strength of the method with respect to spatial resolution and intensity of the image changes.

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PART 01

INTRODUCTION

Chapter 1

1 Introduction

Recent global warming affects the dynamics of glaciers. Glaciers across the world are growing and retreating with alarming speed. This causes negative feedback on the greenhouse effect, as it reduces the albedo effect of the earth's surface, increasing energy absorbed by the earth's surface. Furthermore, a retreat of glaciers generates drought as well as other problems. The models, knowledge and forecasts made so far on past conditions must be updated on the basis of the current climate changes.

Intra-annual variation in ablation has often been identified on valley glaciers, and this is controlled by net radiation and sensible heat contributing energy for surface melt. Surface motion is often linked to variations in water supply to the glacial drainage system, where increases water pressure in subglacial channels. New Zealand's maritime climate results in warm-based glaciers at the pressure melting point, and large quantities of meltwater, allowing basal sliding to occur throughout the year (Ruddell 1995) [1]. In addition, due to the low altitude of glaciers on the west coast (around 300 m above mean sea level), heavy rainfall events can occur throughout the year. Rainfall events have been found to significantly increase ablation as latent heat is released from the freezing of raindrops on contact with ice (Ishikawa et al., 1992; Marcus et al., 1985; Takeuchi et al., 1999) [2] [3] [4].

Fox Glacier has been the focus of little scientific research, with the majority of research being conducted on the neighboring Franz Josef Glacier (which terminates 12 km to the northeast). Fox Glacier has undergone rapid retreat since the Little Ice Age and particularly during the first three-quarters of the 20th century (Chinn, 1996) [5]. Since Sara's (1968) [6] survey, remote sensing using aerial photography has been the only method used to delineate the terminus position of Fox Glacier, and that indicated a large advance of the terminus through the 1980s and 1990s (Chinn, 1996) [5], culminating around 1999 (Coates and Chinn, 1999) [7]. Since then, the terminus position has appeared to be relatively stable.

1.1 The Importance of glaciers

Glaciers currently cover 10% of the earth's surface and, apart from 1% of them are located in remote and inaccessible areas, such as Antarctica and Greenland. However, they represent about 2/3 of all fresh water available on earth.

In mountain basins, glaciers can be an important source of water. Because mountain glaciers do not cover large regions of land, they usually act as a water supply modulator. When the seasonal snowpack melts in the summer melt season, they can deliver a significant amount of water. In addition, glacier melt increases streamflow in dry warm years. With the rise in temperatures and the consequent retreat of the glaciers, the fresh water at our disposal will tend to dramatically decrease. But there are also risks associated with glaciers: excessive volumes of glacier melt can cause river floods downstream, and large icebergs detaching from large glacial masses are dangerous for commercial and tourist ships. In addition, the fresh water released from these ice caps will increase the level of oceans and modifies the dynamics of the thermohaline circulation. This would affect the climate of the entire planet. In order to understand the climate change and glacier response, the study on the glaciers of New Zealand is significant because of the importance of interhemispheric relationships in climate change processes (e.g. Denton and others, 1999; Stocker, 2002) [8][9].

To study glaciers and their dynamics it is necessary to study the processes of accumulation, ablation and movement during all seasons. Field work is indispensable, and must be conducted with the right timing: each measure has the most suitable time to be performed.

Unfortunately not all glaciers are easy reachable throughout the year. For this reason, remote sensing techniques are increasingly being used, via satellite images. Now even free NASA images have a very high resolution: the Sentinel 2 satellite are in the orbit since 23 June 2015. They have a spatial resolution of 10 m. Field work remains fundamental, but constant and long-term monitoring term becomes much simpler and more effective if done remotely, based on the satellite images and with the appropriate processing techniques.

1.2 Objectives

The main objective of this thesis is to observe the changes in dynamics and evolution of Fox Glacier, New Zealand by the use, calibration and validation of a tool developed in Matlab environment (http://imgraft.glaciology.net/) by A. Messerli and A. Grinsted in 2014 [10]. ImGRAFT is an open source tool developed for feature tracking of glaciers starting from satellite images (Landsat and Sentinel) or directly from photographs in the field. Thanks to these techniques it is possible to monitor the dynamics of the fox glacier remotely, overcoming the difficulties of field measurements, and managing to cover a long temporal span, at regular intervals.

With the cross-correlation methods that is implemented in the *templatematch* function of ImGRAFT, the goal is to estimate the surface speeds of the fox glacier, distributed throughout the ablation zone.

The thesis is developed in two main phases: the first concerns the calibration and the validation of the method, the second concerns the calculation of the surface velocity of the Fox Glacier. Initially, in Chapter 2, the climatic characteristics of the area will be described. Almost all of the information used to write this chapter comes from previous researches and studies published in literature, which begins to be present from 1970s, and will be described in Chapter 3.This chapter concludes the first part of the thesis, the introductory one.

Chapter 4 will focus on the results and discussion part of the thesis. This chapter describes the data used and processed during the research activity. It mainly include satellite images provided by ESA (European Space Agency), in particular LANDSAT8 and SENTINEL2. Chapter 5 is the most important part of the thesis: here the ImGRAFT tool is described *templatematch*, the methods it uses, and its calibration on the Fox Glacier area and method validation. The third part (Results and Discussion) describes the results obtained regarding the field of speed and the goodness of the method.

Chapter 2

2 Territorial framework

Fox Glacier is located on the South Island's west coast at 170˚10'E and 43˚30'S (Fig.1). At 2700 m above sea level, the glacier is known to be one of the largest glacier among all glaciers in the New Zealand with the catchment area of 67.7 km^2 in 2009 by Jonathan L. Carrivick & E. Lucy Rushmer [32] (since then the glacier tends to advance for a little period and then retreat). The nearest coast line is present only 17km from the lowest point of the glacier that is located at 270 m above sea level. This difference in the top and low level of the glacier proves that the glacier descends steeply about 2000m over a distance of 12.7 km. (Anderson 2003) [11] Fox glacier receives a heavy rainfall of about 3669 mm per year because the catchment area of the glacier is dominated by the westerly airflows (Coates and Chinn, 1999) [7].

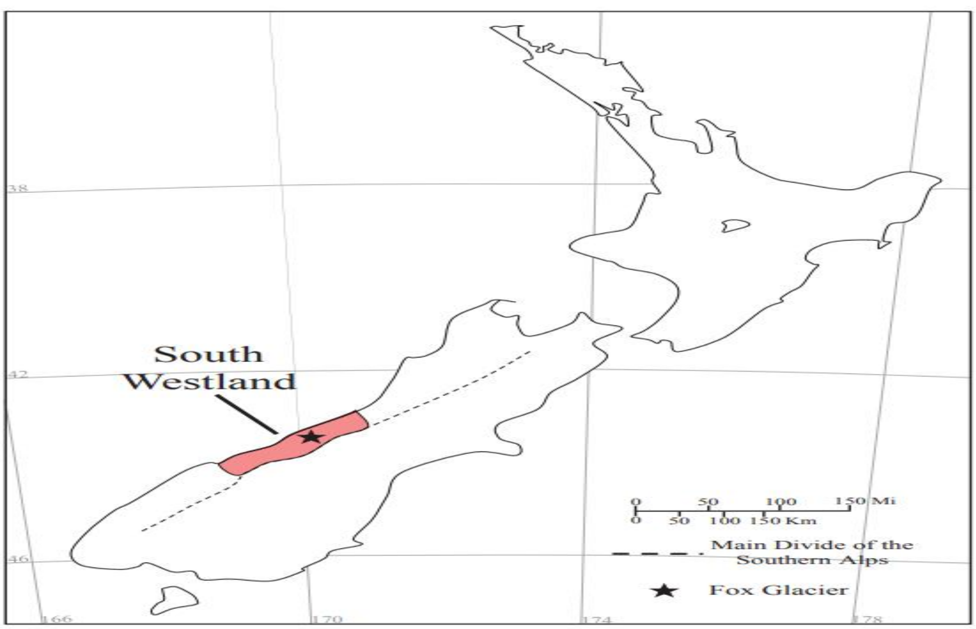

Figure 1 Location of Fox Glacier (shown by star) within Tai Poutini South Westland World Heritage Area on the West Coast of New Zealand's South Island. (John Richard, 2012) [12]

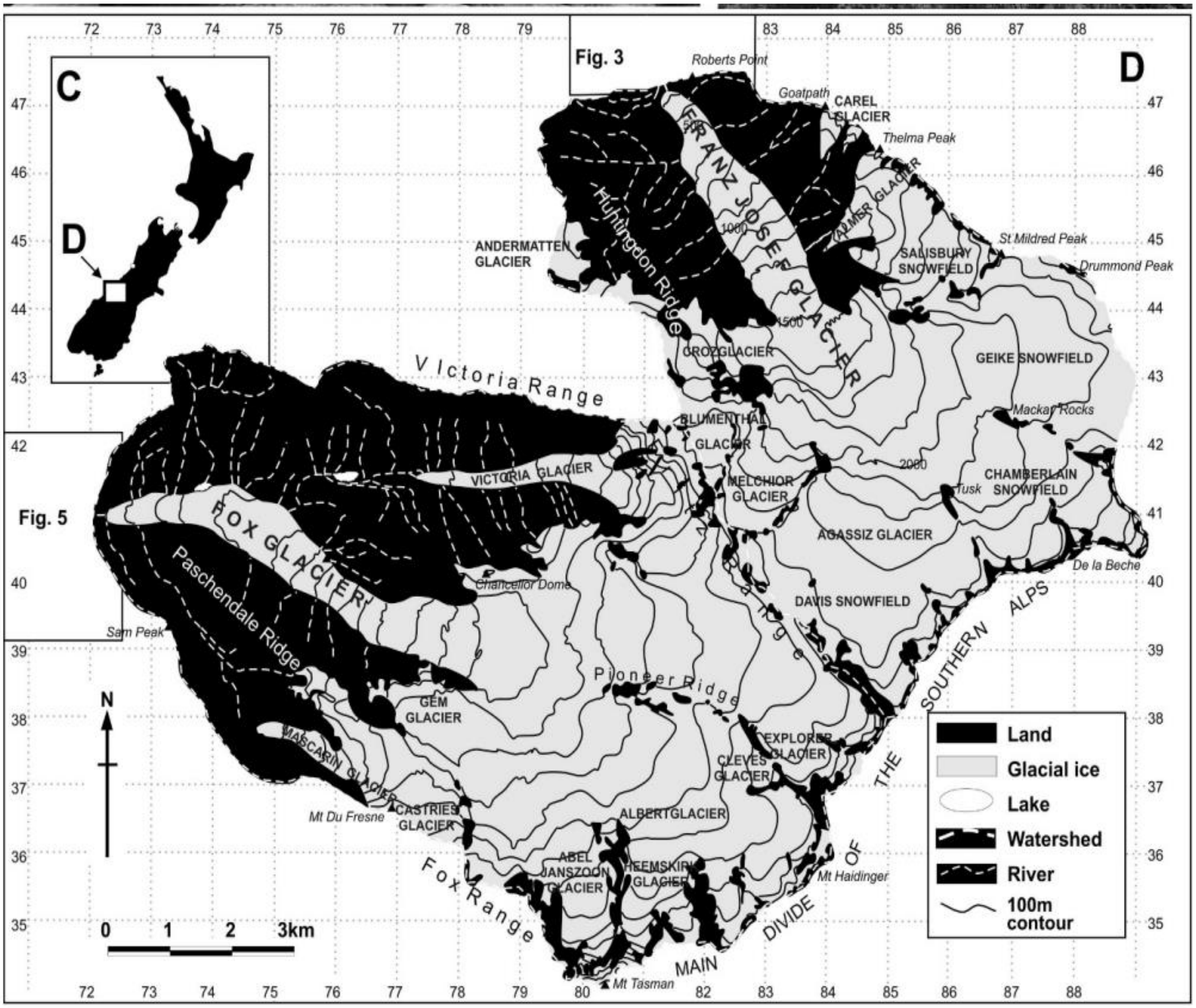

Figure 2 Location of Fox Glacier (D) located on the western side of the Southern Alps, New Zealand (C) (Jonathan L. Carrivick & E. Lucy Rushmer (2009))

The glacier makes a left (westerly) curve along its path, concluding with a westerly view. The glacier surface slope is broken by two massive icefalls in long-profile, the first as the névé is channeled into the main valley, and the second just above the left bend near to the terminal (Figure 2.3).

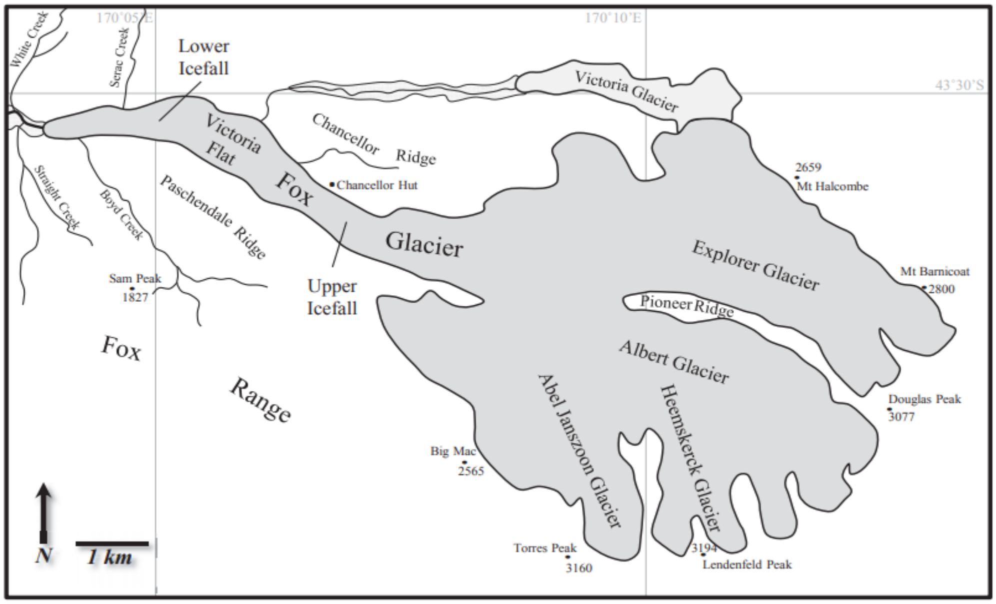

Figure 3 Map of fox Glacier and its nearby tributaries and Ice Falls (John Richard, 2012) [12]

2.1 The Climate of Fox Glacier

The Fox Glacier has a warm and mild climate. Even the driest month has a lot of rain in it. According to the Köppen-Geiger climate classification, this climate is classified as Cfb. In Fox Glacier, the average annual temperature is 6.7 degrees Celsius. Average annual precipitation is 127.35 mm. February is the driest month of the year, with only 240mm of rain, and it is also the warmest month of the year. The month of December has the most precipitation, with an average of 391 mm. In February, the average temperature is 12.0 degrees Celsius.

The lowest temperature was recorded in July, which was 0.9 degrees Celsius on average. The temperature fluctuates by 11.1 degrees Celsius throughout the year, with a 151-

millimeter variance in precipitation between the wettest and driest months. June is the month with the highest relative humidity (87.1 %). January is the month with the lowest relative humidity (80.5 %). December is the month with the largest amount of rainy days (19.37 days). July is the month with the least amount of rainy days (13.0 days). All of the climate and weather data in this section, as well as their precise values, is based on past research.

The Fox Glacier, located on New Zealand's West Coast in the Southern Alps, is part of a climate system with seasons that are reversed from those in the Northern Hemisphere. Seasons are so defined as follows:

• Summer: January, February, March;

• Autumn: April, May, June;

• Winter: July, August, September;

• Spring: October, November, December.

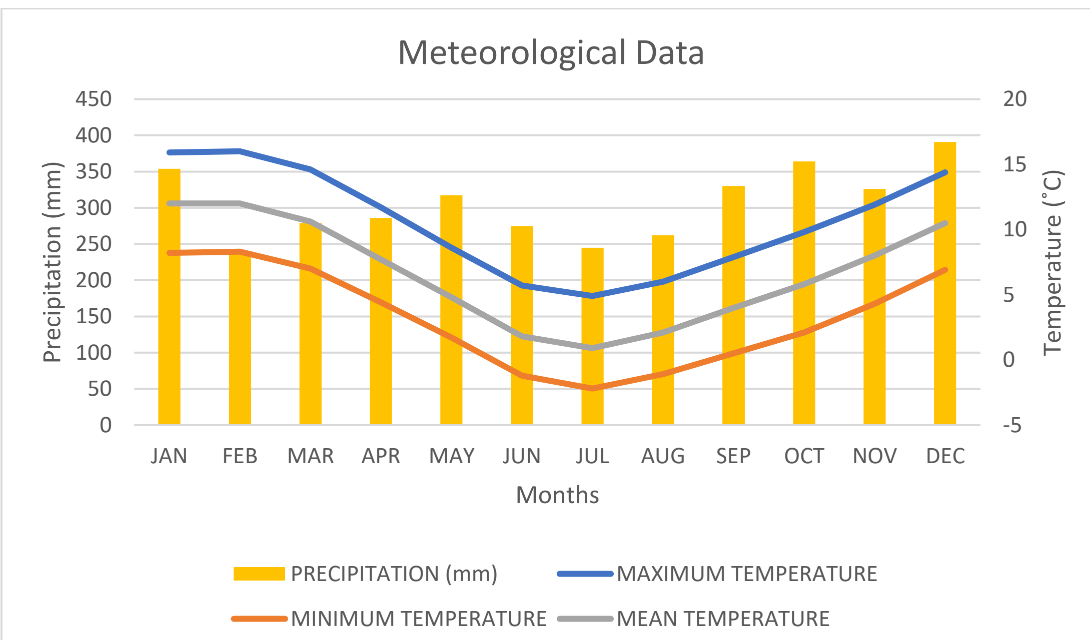

Figure 4 Variation in Precipitation and temperatures in Fox Glacier over months (NIWA) [34]

3 Literature Review

3.1 Remote sensing of the cryosphere

Remote sensing is the process of acquiring information from an object without making direct physical contact with it (Pellikka and Rees 2009) [26]. Information is gathered from above an item utilizing airborne or space borne platforms in a narrower meaning.

In the 1870s and 1880s, early photogrammetric technologies were used to do multi-temporal glacier surveys. Glaciers are mostly located in remote areas, therefore remote sensing techniques have been useful on them. Although remote sensing instrument were carried into orbit around the earth in 1960s, the age of satellite remote sensing began in 1972 with the launch of Landsat 1 satellite. In the early twentieth century, glaciological remote sensing was characterized by the use of terrestrial photogrammetry and stereographic technologies. The major application of the glacier remote sensing was to measure glacier velocities from far by comparing the displacement of different characteristics on the glacier surface (Pellikka and Rees, 2009) [26]. Documenting changes in glacier geometry or termini positions were also significant objectives.

With the launch of the first private Earth observation satellite, the Earth Resources Technology Satellite, in 1972, modern cryosphere remote sensing became widely applicable. Later, it was titled as Landsat-1. Since then, the Landsat family has been collecting intermediate resolution multispectral data on a continuous basis (USGS, 2016).

The Landsat archive is useful for a variety of glaciological applications, including glacier inventories (Paul et al., 2011; Frey et al., 2012) [27] [28], glacier length and area changes (e.g., Bayr et al., 1994; Bolch et al., 2010) [29] [30], surface velocities (Bindschadler et al., 2001) [31].

3.2 First explorations on Fox Glacier

Glaciers that are located in the Southern Hemisphere are not well represented in glaciological databases. However some unpublished data for Franz Josef and Fox Glaciers of New Zealand have a record of extensive length-change that was combined by Purdie in 2005.

Fox glacier is not rich in the literature but some early explorations on Franz Josef Glacier that took into account unpublished data was used to understand the changes on fox glacier because both the glaciers share the similar topographies features and are located close to each other. Few measurements have been used to understand the changes in the length, ablation zone and velocity etc. of the fox glacier. The early exploration on fox glacier includes the Geographic and geological surveys that were commissioned by the government in the southern Westland region in the 19th century. Explorers like Douglas and Wilson (1896) and other government survey departments carried out these surveys.

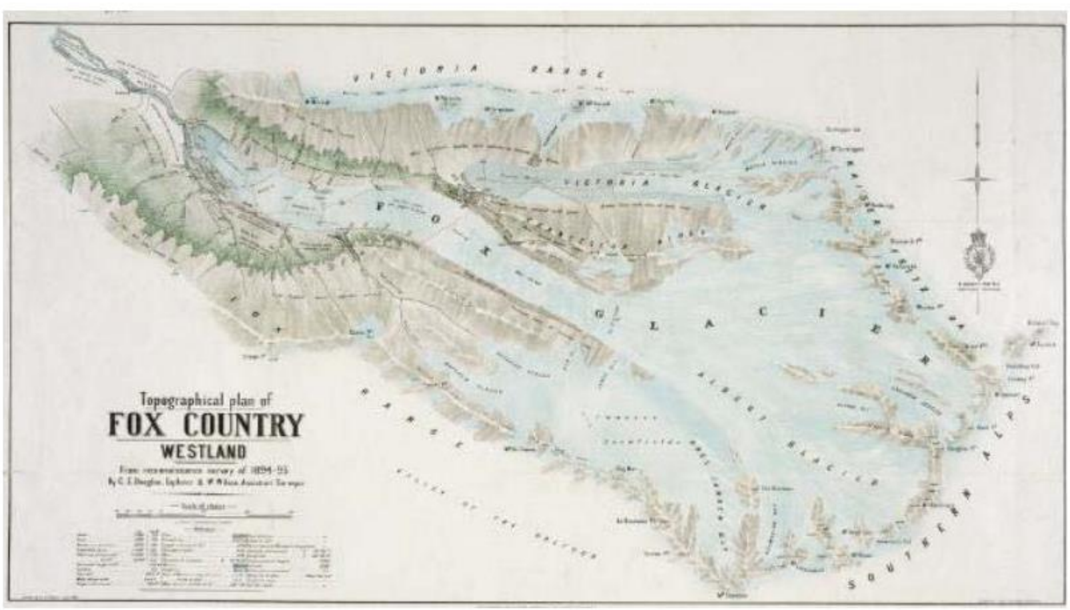

Figure 5 Topographical map of Fox Glacier showing the extent of glacier territory in the neve and the location of the glacier terminus. (Douglas and Wilson, 1896) [13]

A brief account of the explorations of length changes of the fox and its neighboring Franz Josef glacier was conducted by Wardle (1973), Sara (1979) and Chinn T.J (1979). In these articles, they provide some research and measurement that was helpful to detect the length change across glaciers situated in the southern alps of New Zealand. These early explorations were combined to obtain and understand fox glacier's fluctuation in terms of length changes with varying degrees of accuracy (Purdie, H. L., 2005) [14] as shown in figure 5.

Figure 6 Summary of length changes at Fox and Franz Josef Glaciers from 1894 to 2020 (Purdie 2005) [14]

3.3 Present Literature

During the last decade, there has been a great interest of interaction between glaciers of Southern Alps of New Zealand and climate (e.g. Chinn 1999, Ruddell 1995, Anderson & Mackintosh 2006, Batt and others 2000, Fitzsimons 1997, Vandergoes & Fitzsimons 2003), because climate fluctuations are indicated by temperate glaciers having short response times. Many previous studies have focused Franz Josef glacier (Anderson and others 2008, Anderson and others 2006, Hessel 1983, Oerlamans 1997) than Fox Glacier.

The studies of glacier mass balance (Cutler & Fitzharris 2005, Woo & Fitzharris 1992) [15] [16] presented the effect of climatic variations and fluctuations in a form of glacier retreats or advances on terminal positions of Fox Glacier. The negative climate signal affect the glaciers more rapidly with less advances and more retreats (Imhofet Al, 2011) [17]. A significant change was observed between 2002 and 2006 which results in positive mass balance.

In order to interpret climate variability from past studies of glacier extent, there is a need of improved measurements to define glacier retreat. Many mountain glaciers exhibit short-term (sub-monthly) velocity variations due to variations in sliding velocities (e.g. Iken and Bindschadler, 1986) [18]. Velocity variations in fox glacier at seasonal and sub-monthly scales were identified by previous research (Anderson, 2003) [11]. These researches included identifying changing in velocities in the lower ablation zone of fox glacier using ASTER imageries. This comparison was highlighted on the most sensitive and responsive ablation part of the fox glacier.

Using ASTER images, less changes were observed for smaller glaciers in the study period and all the classification methods failed for estimating velocity changes at debris covered parts of the glacier (Anderson 2003) [11]. The importance of combining satellite data with situ studies and climatic data to observe glacier changes was highlighted by (Khromova

2006) [19]. He also emphasized on gathering more fieldwork data for understanding the current process of rapid retreat of glacier with proglacial lakes.

Sugiyama et al. (2011) [20] instead investigate the relationships between basal water pressure and speed of the glacier. Since the base of the glaciers is notoriously difficult to reach, the boundary conditions at the base of the glacier are almost always unknown. Maxwell et al. (2008) [21] propose an iterative method to measure it. Satellite imagery has been used more and more intensely over the years to overcome the problem of difficult data acquisition in the field and their lack.

Landsat-type medium-resolution optical satellite sensors are very important for operating worldwide glacier mapping and monitoring, and are used to retrieve glacier outlines, surface ice velocities and ablation among other things (Paul 2013) [22]. In comparison to Landsat 5 and 7, Landsat 8 significantly improved the possibilities for glacier observations from space in 2013, due to improved radiometric performance (12 bit original, scaled to 16 bit for delivery, compared to 8 bit of Landsat 5 and 7; higher dynamic range; reduced noise level and significantly higher acquisition rate (i.e., higher temporal resolutions) (Roy D.P 2013) [23]. The European Copernicus Sentinel-2 satellite series, which includes two satellites, Sentinel 2A and Sentinel 2B, could improve global monitoring of glaciers and land ice masses, as well as their changes over time.

Part II

Data and methods

4 Data used

As mentioned in Chapter 4, the scientific literature is not rich in fox glacier studies as compared to other glaciers located in the Southern Alps of New Zealand. Fundamental resources in these cases, which thanks to technology recent years are becoming more and more accurate, are the images taken from satellite. For this analysis, ESA (European Space Agency - http://www.esa.int/ESA), in particular LANDSAT 8 and SENTINEL 2 downloaded free of charge at https://earthexplorer.usgs.gov/. The images that cover the area of the Fox Glacier are those with the upper corner left in position 43°30’00’’ S, 170°04’59’’ E(path: 76, row: 90).

4.1 GLIMS Database

GLIMS (Global Land Ice Measurements from Space) is an initiative designed to monitor the world's glaciers primarily using data from optical satellite instruments. At first, the GLIMS database is available on the website (https://www.glims.org/) that was download as shape file for the area and perimeter of fox glacier and its ablation zone. They were put in the ArcGIS to obtain the coordinates of the perimeter of the ablation zone of the fox glacier that were later converted into the pixel coordinates using matlab to provide as grid file to the *templatematch* tool in matlab environment.

4.2 ESA images

ESA images were used because they are open source, so there are many studies in the literature, many people who are using them and therefore a good chance to improve methods and techniques. The frequencies of the visible and panchromatic bands were used as they are those with the highest spatial resolution, and those with one more immediate viewing. By working with these frequencies, however, one is subjected to weather conditions: clouds cannot be passed and, if any, cover the ground.

4.2.1 LANDSAT 8

In 2013, with the launch of the new satellite (LANDSAT 8), it was possible to resume and use LANDSAT images The Fox Glacier is flown over every 16 days, and with this frequency temporal images are available in all 11 spectral bands. The band 8, the panchromatic one has double spatial resolution, equal to 15 m. For these images the panchromatic band was then used. The method used to perform feature tracking on the glacier is based precisely on the pixels of the images. Among all Landsat 8 images from 2013 to 2022, 18 pairs were analyzed with valid LANDSAT 8 images but only 7 were selected. The reason of not using all of them was that at some images pairs, the ablation zone of fox glacier was covered by clouds. Then some were neglected due to large time gap with previous or following images or due to one that is too low feature tracking quality

The image pairs used are listed in Table 1.

4.2.2 SENTINEL 2

The SENTINEL 2 mission, developed by ESA, uses two twin satellites (S2A and S2B), in a latitude range from 56 ° S to 84 ° N. The first satellite was launched on 23 June 2015, the second on 7 March 2017, and are still in operation. To study the Fox Glacier the images acquired by these satellites are very useful as they have a temporal frequency of 7 and 13 days and images are available in 13 spectral bands (infrared and visible). Combining bands

4, 3 and 2 you get a natural color image at 10 m of spatial resolution, which is used to monitor the displacements of the ablation zone of the glacier. There were 11 images acquired by the SENTINEL 2 satellite not covered by clouds from 2017 to 2022 but only 8 pairs were used due to same problems mentioned for Landsat 8.

Also in this case the pairs of images used are listed in Table 1.

Table 1 Satellite Images used to measure velocity on the ablation zone of the fox Glacier

PAIR	SATALLITE	IMAGE A	IMAGE B	ΔT (days)
1	LANDSAT8	10/18/2013	12/21/2013	64
2	LANDSAT8	12/21/2013	2/7/2014	43
3	LANDSAT8	9/3/2014	11/6/2014	64
4	LANDSAT8	11/6/2014	2/26/2015	55
5	LANDSAT8	2/26/2015	4/15/2015	48
6	LANDSAT8	12/23/2015	2/1/2016	40
7	LANDSAT8	2/13/2016	4/17/2016	64
8	SENTINEL 2	1/27/2017	3/28/2017	60
9	SENTINEL 2	12/27/2017	2/25/2018	60
10	SENTINEL 2	11/13/2018	12/23/2018	40
11	SENTINEL 2	12/23/2018	2/1/2019	40
12	SENTINEL 2	2/1/2019	4/2/2019	60
13	SENTINEL 2	12/27/2020	2/25/2021	60
14	SENTINEL 2	10/18/2021	12/21/2021	64
15	SENTINEL 2	3/2/2022	4/1/2022	30

5 Methods

5.1 ImGRAFT templatematch

ImGRAFT is a toolbox developed in the environment MATLAB by Aslak Grinsted and Alexandra Messerli for image georectification and feature tracking. The first article published in this regard by Messerli in 2014 was used for feature tracking on glaciers of Greenland using LANDSAT 8 images (Messerli, A. and Grinsted, A 2014) [24]. There are numerous functions that comes with ImGRAFT toolbox but we have used *templatematch.m* function for our thesis to find the velocity of fox glacier using template matching.

The feature tracking technique consists in identifying reference points easily recognizable and monitor its movement, to understand how much they are moving and therefore what is the speed of the glacier. The limitation of this technique is that the data is punctual, do not cover the entire area.

How templatematch works

This function, through cross-correlation techniques, calculates the displacement that exists state between two images at distance ΔT, giving as output a map of displacements for each point of the grid that you set. Then the velocity range of the area is calculated by knowing the change in time between two images acquired with specific dates.

As input, templatematch needs two images (A and B), where A is the old and B is the most recent. The contour of the region to be studied is defined: in this case the perimeter of the glacier was used for the preliminary analyzes, and the perimeter of the ablation area only. On these areas, you can decide with what resolution to implement the method: a grid of points is defined, which can be regular or contain only precise points that you want to follow, and on these points the tool applies feature tracking, whose scheme is graphically described in Figure 6.1. Around each of these points, a template is defined for a region in image A to be followed in image B. Before looking for it in image B, however, you can enter some parameters that refine the search, such as the hypothesized initial displacement and the size of the search area.

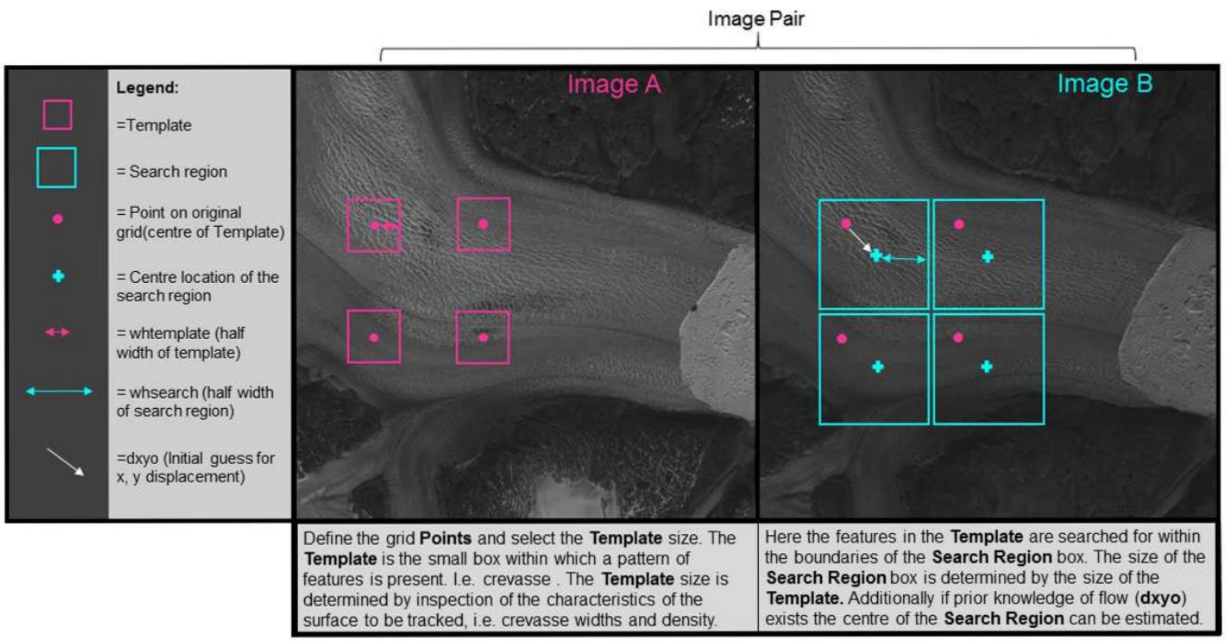

Figure 7 Operation diagram of the templatematch.m tool [10]

The parameters that can be varied to best calibrate the method are the following:

- **pu, pv:** coordinates of the points in image A to be followed in image B. Usually we define a regular grid of points at different resolutions that was obtained using image viewer window on Matlab tool by importing the satellite image as tiff file.

- **Template Height and Template Width:** width and height of the template, centered at the coordinate points (pu, pv). The default suggested by the authors is a region square with side 21 pixels and for our thesis, the results were validated using the default square size.
- **Search Width, Search Height:** width and height of the search region (default = Template Width + 40);
- **Super Sample:** super sample factor of the input images for an increased sub-pixel resolution (default = 1)
- **Initial du, Initial dv:** hypothesized initial displacement between A and B. One is required a priori knowledge of the glacier flow so in our calibration they are input as 0.
- **Method:** method used for feature tracking. In templatematch they are implemented four different methods, described in other section.

In output, templatematch returns:

- **du, dv:** matrix of the displacements of each point in pu, pv. Point A (pu, pv) when they move to B (pu + du, pv + dv);
- **C (or peakCorr):** correlation coefficient between A's templates and templates associated in B;
- **Cnoise (or meanAbsCorr):** module of the mean of the correlation coefficients across the entire research region. It is an estimate of the noise level;
- **pu, pv:** real position of the central pixel of the templates in A (they may differ slightly from the inputs due to rounding effect);
- **Objective functions:** functions defined to better evaluate the quality of the feature tracking.
- **Velocity:** by entering the time difference (days) of the two images as input, templatematch calculates speed automatically.

5.2 Calibration on the Fox Glacier

The first necessity in using templatematch on a new area is to define the grids. Due to large size of the images, Sentinel and Landsat images were cut with the Matlab geoimread function by eliminating the parts outside a rectangle surrounding the fox glacier. Subsequently, point grids (pu, pv in the inputs) have been defined which cover the fox glacier ablation area. Grids have also been created only of the ablation area of the fox glacier. In doing this, templatematch works in a reference system based on the number of pixels of the image, where the origin is the upper left corner. The image viewer in the matlab is used to define the pu pv coordinates in a form of pixel coordinates.

The Landsat and sentinel are too large in size to be processed and calibrated manually as done in the past. Therefore, the images were cut in matlab using geoimread function. The *geoimread* function limits the region of the geotiff file to the limits given in geographic coordinates of degrees latitude and longitude.

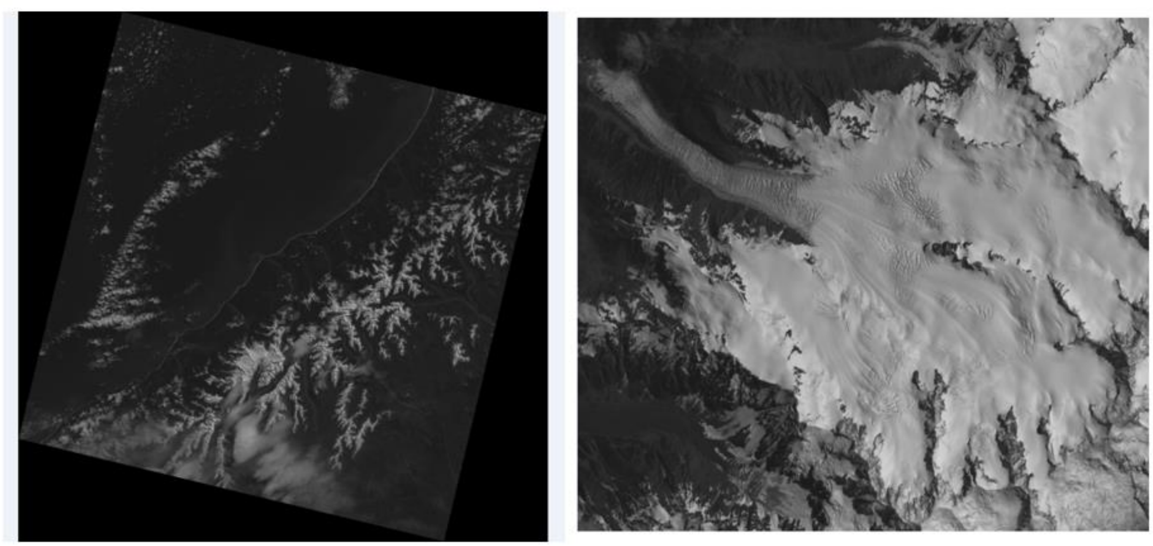

Figure 8 Full size Landsat 8 image that is being cropped to Fox Glacier using geoimread function on matlab

5.2.1 Objective functions

To perform any calibration, it is necessary to have a validation dataset or as in this case, the objectives to aim for:

• **Mean Correlation Coefficient:** The correlation coefficient is a statistical measure of how strong a relationship exists between two variables' relative movements. From a mathematical definition, the coefficient of correlation is defined in a range of -1.0 to 1.0.

By default, cells with correlation less than or equal to 0.6 are discarded.

• **Average Signal to Noise Ratio (SNR):** is a signal-to-noise ratio typical of signal analysis. It is defined as:

$$SNR = C/Cnoise$$

Where C is defined as the peakCorr that is the maximum correlation coefficient found at the location of each match and Cnoise is defined as the meanAbsCorr that is the average or typical correlation coefficient over the entire search window.

The authors suggest, in agreement with the literature, to use it as an indicator of false matches, when it is too low. In fact, by default, cells with SNR values lower than 2 are discarded.

• **Valid Cells:** percentage of valid cells out of the total number of analyzed cells;

• **Correct SNR:** Signal to Noise Ratio corrected to include information regarding the number of valid cells.

The following indicator was therefore created:

$$\text{Correct SNR} = (\text{SNR} \cdot \text{Valid Cell}) + [\text{NaN} \cdot (100 - \text{Valid Cell})]/100$$

Where NaN indicates the dummy SNR value assigned to the cells discarded by the program.

Using the Orientation Correlation method (Section 6.2.2) the correlation coefficient is calculated without normalization.

5.2.2 Methods and Parameters

Before calibrating the actual parameters, it was verified which cross-correlation method is best for the region under examination.

All of the methods takes the two images (A and B) as input and returns as output the correlation of each cell of A with all the cells present in the region of research in B. Going to look at where the maximum correlation is recorded for each cell, the pixel in which the pixel followed by image A is most likely is identified positioned in image B. From here, you can easily return to a measurement expressed in meters, and dividing by the time step to get the speed.

According to these considerations, the spatial displacements of each pixel between A and B should be multiples of the resolution of the images but the comparison does not take place in the form of the pixels, but in a form of frequency domain: all four methods implemented uses the Fast Fourier Transformation to move into continuous space and determine the correlation there. By doing so, it can identify displacements smaller than a single pixel. In fact, if you analyze the image, it is easy to see that even if a feature of it (crevasse of glacier) moves by a shorter length than the size of pixels, the pixels changes due to the change in the color of the pixel. That why working in the space defined by the pixels will lead to no identification of such displacements as it is invisible in this space. But in the domain of the frequencies using Fourier transform, this shift becomes visible.

There are four method choices that can be chosen before template matching to measure the correlation between two images.

Normalized Cross Correlation (NCC)

It is the simplest of the four methods, set as the default. It derives from the Cross-Correlation method, elaborated in turn starting from Eulerian distance squared

$$d^2_{(f,t)}(u,v) = \sum_{x,y}[f(x,y) - t(x-u,y-v)]^2$$

Where f is the image, and the sum is on x, y, in the window containing the feature t positioned in (u, v). In the case of *templatematch*, the image is image B, and the feature is the feature you want to follow within the template in the image A.

Cross Correlation Function (CCF)

In templatematch this algorithm is implemented using a slight variation of the xcorr function of MATLAB, again exploiting the Fourier transform to be able work in the frequency domain.

Using this method, the correlation is not normalized, producing a mathematically incorrect correlation coefficient. The value of SNR (Signal to Noise Ratio), given that it is calculated as a ratio between two non-normalized correlations remains correct.

Orientation Correlation (OC)

Orientation Correlation is the method used to estimate the speed on the Fox Glacier. This method is fast, comprehensive, statistically robust and invariant to brightness of image as shown in figure 8. The orientation correlation works by correlating orientation images: each pixel of these images is a complex number that represents the orientation of the gradient of intensity. The representation then becomes invariant with respect to changes in brightness. It is the angles of the orientation gradients that are associated between the two images, using a particular type of kernel function. This method is fast because it is possible to use the Fourier Transform Fast (FFT).

For the evaluation of a translation of an image there are two prevailing methodologies in the literature:

• Area-based methods (or direct methods): associate quantities linked to the image, such as brightness [33], or phase [29];

• Feature-based methods: associate features extracted from images, such as angles [31] lines [13], junctions [10].

The OC associates the characteristics of the orientation gradient for each pixel. Once the image transformation has been defined as translation and the feature-based method has been chosen, an optimization problem remains: finding the better translation parameters. The cross-correlation has the peculiarity of performing an exhaustive search in a short time [4]. Correlation also avoids the classic point's weak optimization techniques:

• Does not require an initial state;

• Does not require prior knowledge;

• Since the search is exhaustive, local minima do not create problems.

The correlation of these digital signals occurs quickly, using the Fast Fourier Transform [83].

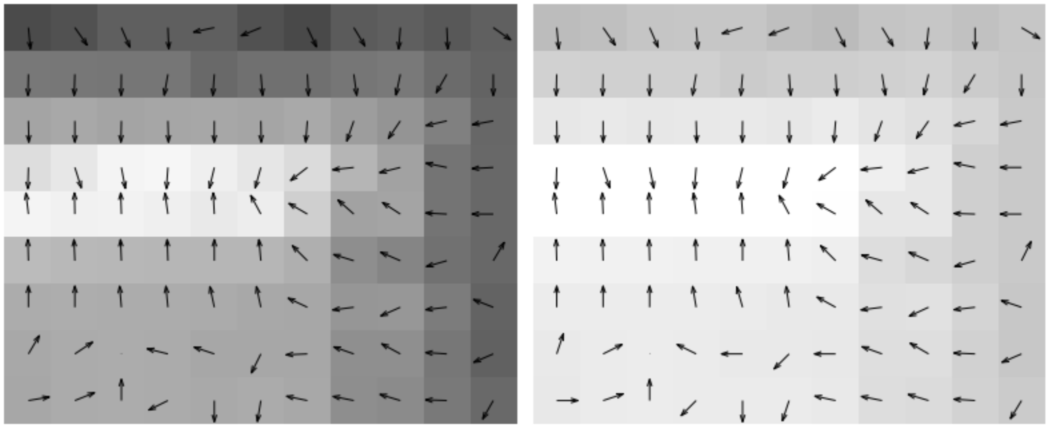

Figure 8: Sub-image and overlaid arrows representing the orientation image [33]

Figure on left shows a region of a picture frame with arrows overlaid to show the complex pixel values of the orientation image. Figure on right shows the region scaled and offset. Orientation correlation is well suited to matching images of different modalities, e.g. matching infrared images with intensity images. This is because all orientation images have the same units; each pixel is a measure of an angle.

Phase Correlation (PC)

A more robust approach is given by Phase Correlation. In this approach the transform coefficients are normalized to unity before calculating the correlation in the frequency domain. Hence, the correlation is based solely on phase information and is insensitive to variations in image intensity. While experience has shown that this approach is useful, it has the disadvantage of weighing all components of the transform equally. On the contrary, one would expect to place lower weights on less significant components. In principle, a spectral pre-filtering could be selected in order to maximize the expected signal-to-noise ratio of the correlation.

The methods in templatematch

The methods described above are implemented in ImGRAFT *templatematch*.

- Orientation Correlation works very well, but the normalization of the correlation coefficient has not yet been implemented, generating a correlation in any case consistent with the outputs produced, but mathematically incorrect.
- The Cross Correlation Function, Phase Correlation and Normalized Cross Correlation does not produce significant results (at least for the ablation zone of Fox Glacier) as shown in figure 6.

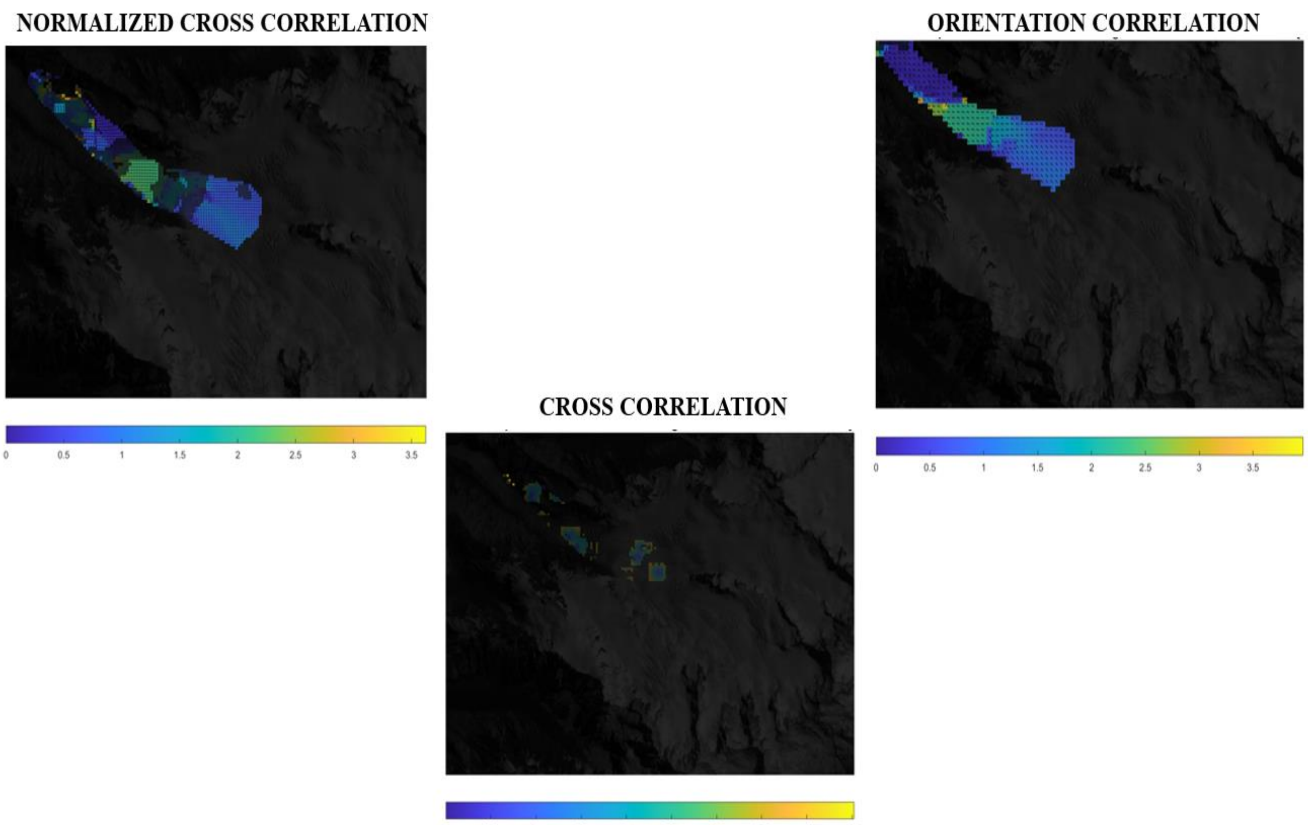

Figure 9 Result obtained using different correlation techniques in the template match tool

In light of what has been described, and of the results obtained by testing the different methods on the fox Glacier area (Figure 6), the choice fell on choosing the Orientation Correlation (OC) method.

Spectral bands

The *templatematch.m* function does not work with combined bands, such as are RGB Landsat images. Therefore the spectral bands were used individually. The best results were obtained using Landsat 8 band 8 because it has the highest resolutions of 15m. For SENTINEL images the three visible bands have the same spatial resolution. Therefore no differences were highlighted such as to be able to choose one band rather than another.

Time step

There is an absence of debris and very high speed of glacier, a long time step placed between two images will result in unrecognizable characteristics. When there's an absence of debris, crevasses can be used as reference between two images. The crevasses do change within a span of days but the area where they are formed do not change over span of years. This means that even after a year, if we analyze the same portion of the glacier, approximately the same crevasses will be found. It is due to this reason and based on results received from previous research for running *templatematch.m* function on glaciers (Chirico, 2015) why a time step less than 90 days is considered based on previous research.

Part III

Results and discussion

Chapter 6

6 Results and Discussion

6.1 Ice Velocity Measurements

We process and combine together measurements of ice velocity of Fox Glacier in New Zealand from two satellites—Sentinel-2 and Landsat-8, creating a multi-year velocity database with high temporal and spatial resolution

The spatial resolution of Landsat 8 and sentinel 2 images of up to 15m and 10m respectively can be used to measure velocity of glaciers. Climate change and it effect on worldwide glaciers can understood by observing changes in ice flow that might be responsible for glacier mass changes.

The cross correlation techniques can be used to track ice flow velocity using Landsat 8 and Sentinel 2 Images over temporal scale.

6.2 Speed range

The velocity for the fox glacier was calculated using matlab templatematch tool taking into account the ablation zone of the fox glacier.

The accumulation area is very little studied as it's always covered with snow. Therefore *templatematch.m* doesn't work on that part of glacier as no debris and crevasses can be found on the accumulation zone of fox glacier due to snow covering. For these reasons, the detailed analysis focused on the ablation area,

Using remote feature tracking techniques, such as those used by *templatematch*, it would be much easier to perform analyzes even on areas that are difficult to reach, but there are two main limitations that includes the influence of cloud cover over the interested area and the other is related to the snow covering which does not allow to identify point (debris or crevasse).

Significant speed increases of up to 1 m/d was calculated between the two pairs of satellite images with different time gaps. The majority of this increase appears to have occurred on the main, middle ice flow lower panel of the ablation zone According to ground measurements, such fluctuations in speed are very plausible, and might be caused by major rain occurrences for example (Purdie 2008) [28]. These findings show how the great accuracy of the displacements based on quality of the satellite image pixels, may be used to characterize ice velocity changes over days.

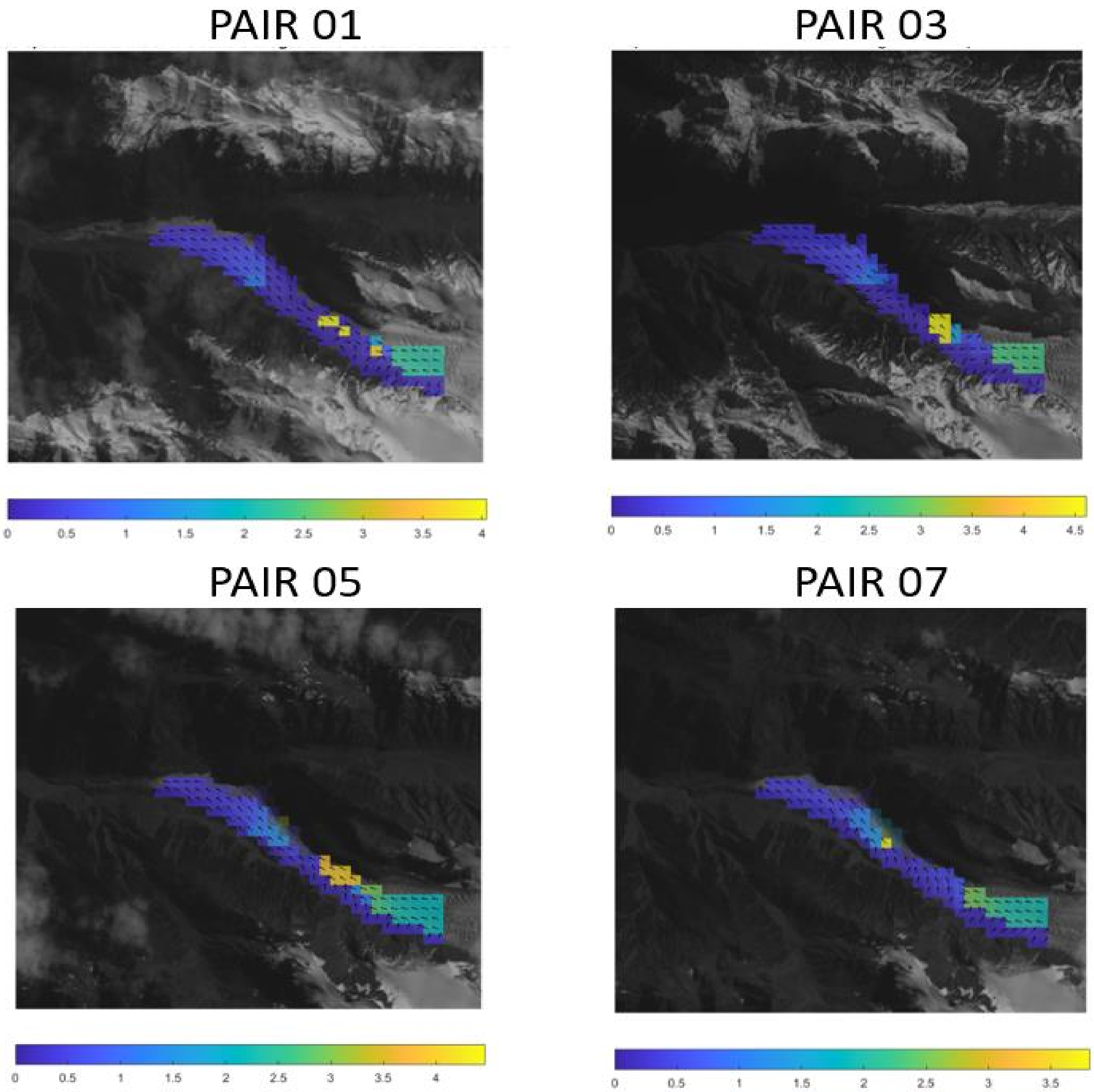

Figure 10 Ice velocity on the ablation zone of fox glacier using Landsat 8 images

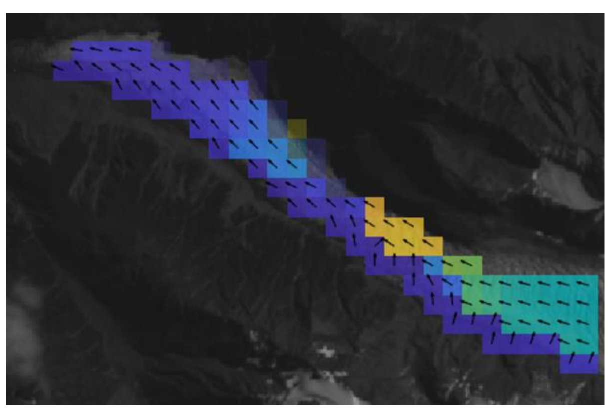

Figure 11 Results Quality of Landsat satellite image (PAIR 04) based on their resolution (15m)

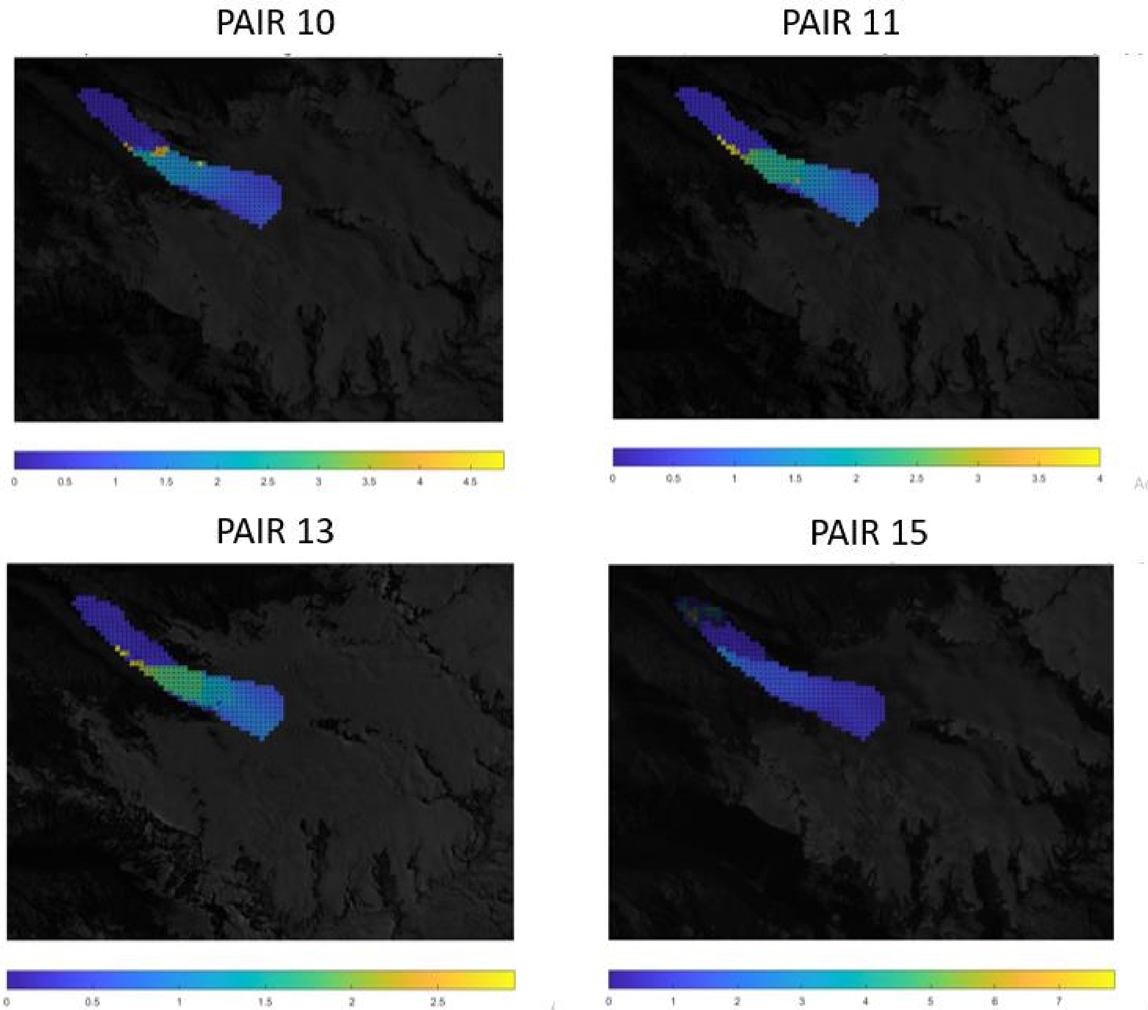

Figure 12 Ice velocity on the ablation zone of fox glacier using Sentinel 2 images

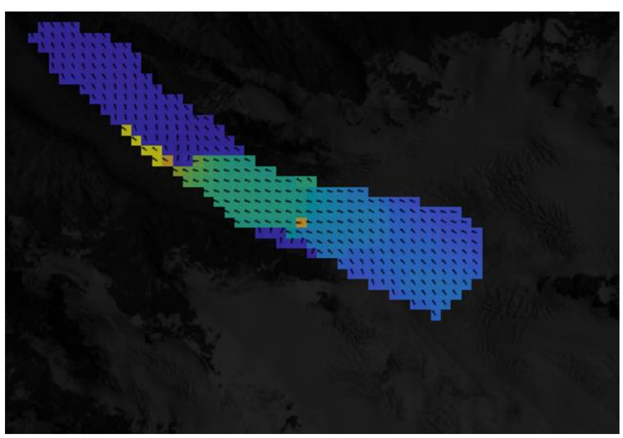

Figure 13 Result Quality of Sentinel 2 Satellite Image (PAIR 11) based on their resolution (10m)

6.3 Comparison between images at different resolution

Working with different satellites, images of different spatial resolution were used. Since *templatematch* works precisely on the characteristics of images and individual pixels, the spatial resolution affects the result. The best images are the SENTINEL 2 at 10m resolution, but the LANDSAT 8 in panchromatic band (15m resolution) have very similar performance. The probability of finding two pairs of images of the two satellites covering the same time window, both cloud-free, is very low, also because it is only starting from October 2015 that the SENTINEL 2 images are available.

6.4 Validation of Result

This particular method of feature tracking via cross-correlation does not allow to estimate the error in terms of meters or m / day. You can only get a measure of the goodness of the feature tracking, in terms of correlation or SNR (Signal to Noise Ratio).

The table 2 below shows the SNR value and mean correlation for the different pairs of satellite images.

Table 2 Validation of the results using Signal to Noise Ratio, Mean Correlation and mean corrected SNR

PAIR	SATALLITE	IMAGE A	IMAGE B	Mean correlation	mean SNR	valid cells	mean corrected SNR
1	LANDSAT8	10/18/2013	12/21/2013	595.2	6.5	82.1	5.55
2	LANDSAT8	12/21/2013	2/7/2014	724.2	8.5	82.1	7.22
3	LANDSAT8	9/3/2014	11/6/2014	559.5	6.2	82.1	5.28
4	LANDSAT8	11/6/2014	2/26/2015	543.4	6.3	82.1	5.38
5	LANDSAT8	2/26/2015	4/15/2015	594.3	6.5	82.1	5.56
6	LANDSAT8	12/23/2015	2/1/2016	601.4	6.6	82.1	5.61
7	LANDSAT8	2/13/2016	4/17/2016	563.6	5.8	82.1	4.95
8	Sentinel 2	1/27/2017	3/28/2017	564.0	7.4	99.7	7.44
9	Sentinel 2	12/27/2017	2/25/2018	651.4	8.5	99.7	8.50
10	Sentinel 2	11/13/2018	12/23/2018	769.8	10.9	99.7	10.94
11	Sentinel 2	12/23/2018	2/1/2019	708.5	10.1	100.0	10.19
12	Sentinel 2	2/1/2019	4/2/2019	568.8	7.7	99.4	7.68
13	Sentinel 2	12/27/2020	2/25/2021	611.2	8.6	100.0	8.63
14	Sentinel 2	10/18/2021	12/21/2021	651.3	8.2	99.4	8.18
15	Sentinel 2	3/2/2022	4/1/2022	864.8	10.6	100.0	10.61

Few research have been conducted on the fox glacier that was helpful to validate results of our study made on the ablation zone of the fox glacier by comparing the results of images we obtained with other studies from the past. Kääb and other (2016) accessed the ice flow of certain glacier using sentinel images and identified ice velocity over temporal scale of 10 and 20 days. Figure 5 shows us the comparison made to validate our ice velocity calculated on fox glacier ablation zone using ImGRAFT template match tool for one sentinel images data set from the result obtained by Kääb and other using other methods to calculate ice velocity on the fox glacier. Both the results showed higher ice velocity on the center part of ablation zone.

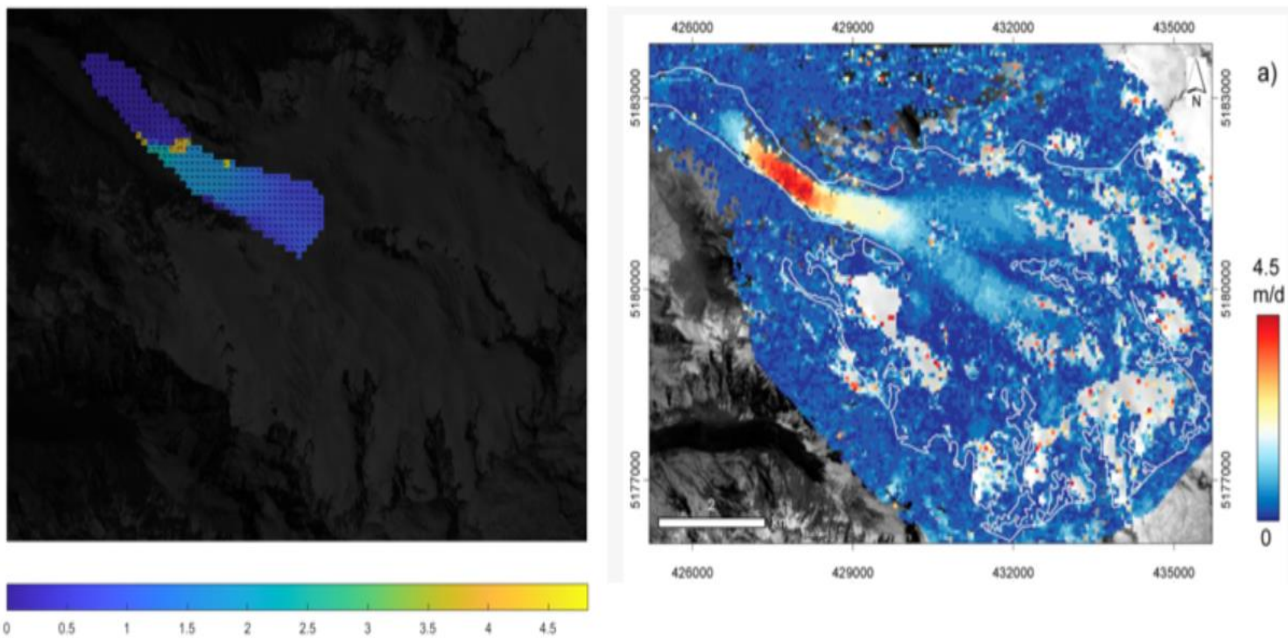

Figure 14 Comparison of Ice velocity using sentinel images calculated using template match tool (on left) and ice velocity calculated by Kääb and others (on right)

Short time-scale surface velocity measurements that were studied in the past on fox glacier was combined as shown in the table 5.1 by Purdie (2006) and majority of the values of the ice velocity lies between 0.5 m/day to 1.0 m/day on average. These ice velocity measured over small time scale were calculated using different methodologies, hence they gives us the estimate about the evolution of ice velocity for fox glacier over previous years. The mean velocities calculated for the last decade starting from 2012 till 2022 that are calculated using ImGRAFT in the matlab environment on the ablation zone of the fox glacier is shown in table 3.

Table 3 Ice Velocity on Fox Glacier from Past Research (Purdie. 2016)

Study	Survey period	Mean velocity (m/day)	Location
Wilson (1896)	6 July–3 August 1894	0.24	Transect 2 km up-valley from terminus at time of survey (~600 m down-valley from present terminus).
Speight (1935)	9 September–30 October 1932	0.76	Transect ~1200 m up-glacier from terminus (~1 km down-valley from present terminus)
Gunn (1964)	January–February 1955	0.38	Appears close to transect of present study
Gunn (1964)	April 1956	0.17	Appears close to transect of present study
Ruddell (1995)	February–March 1991	0.28–0.70	Névé and Albert Glacier
		4.93–9.30	Seracs in upper Ice fall
Lawson (pers. comm., 2005)	February 1992	0.70	Similar location to this study
Purdie (2005)	January/February 2005	0.87	Measured at ~450 m a.s.l.
This study	June/July	0.64	
Massey Students (2006)	12–16 January 2006	1.75	100 m below transect of present study

Looking at the values in table 3, it can be validated that the results obtained from the template match tool in the matlab environment for the ice velocity on the ablation zone of fox glacier are precise.

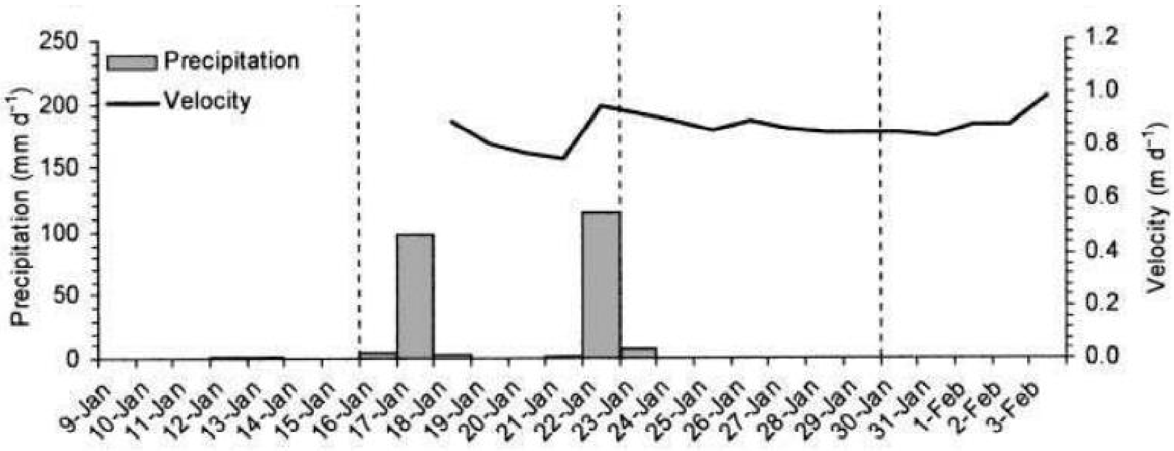

Figure 15 Relationship between surface velocity and precipitation on the lower Fox (Purdie 2006)

Moreover, Purdie (2006) also calculated the average velocity on the lower part of fox glacier that is estimated around 0.87 m/day during summers as shown in figure 8. From the table 5.2, we can further validate the results by comparing it with the values of ice velocity obtained during summer months by Purdie (2006) because majority of satellite images data sets that were used to calculate ice velocity on template match tool, were acquired during summers and the velocity calculated on them lies between 0.7 m/day to 0.9 m/day.

Table 4 Mean Ice Velocity Calculated by template match tool on Fox Glacier ablation zone using satellite images

PAIR	SATALLITE	IMAGE A	IMAGE B	ΔT (days)	V mean(m/day)
1	LANDSAT8	10/18/2013	12/21/2013	64	0.63
2	LANDSAT8	12/21/2013	2/7/2014	43	0.53
3	LANDSAT8	9/3/2014	11/6/2014	64	0.81
4	LANDSAT8	11/6/2014	2/26/2015	55	0.60
5	LANDSAT8	2/26/2015	4/15/2015	48	1.0
6	LANDSAT8	12/23/2015	2/1/2016	40	0.95
7	LANDSAT8	2/13/2016	4/17/2016	64	0.75
8	Sentinel 2	1/27/2017	3/28/2017	60	1.02
9	Sentinel 2	12/27/2017	2/25/2018	60	0.96
10	Sentinel 2	11/13/2018	12/23/2018	40	0.88
11	Sentinel 2	12/23/2018	2/1/2019	40	1.06
12	Sentinel 2	2/1/2019	4/2/2019	60	0.74
13	Sentinel 2	12/27/2020	2/25/2021	60	0.79
14	Sentinel 2	10/18/2021	12/21/2021	64	0.75
15	Sentinel 2	3/2/2022	4/1/2022	30	0.94

6.5 Future Improvements

The method used in this thesis revealed great potential for glacier monitoring. The use of templatematch is very significant for studying and monitoring of glaciers using remote sensing techniques.

To improve it on the Fox Glacier, a network of meteorological stations would be needed, both on the ablation and accumulation zone. The method, with SENTINEL 2 images, revealed good reliability, and could be used for continuous monitoring in the future.

The methods used in template match function in the ImGRAFT software should be improved to better calibrate the results. Continuous monitoring of this kind would be useful not only for purely glaciological studies, but also for everything that uses data and hydrological forecasts of water bodies of glacial origin.

One possible development would be discrete automation of template match method using automatic controls and iterative methods so that it could better calibrate the parameters independently without using the need of supervision.

7 Conclusion

Ice motion observations are essential for constraining ice sheet mass balance and contributing to sea level rise, as well as forecasting future changes. For measuring ice motion from orbit, there is now a variety of imagery. The amount of available satellite observations has expanded dramatically over the previous decade, allowing for substantially more frequent monitoring of glacier speed. To effectively cope with the massive volumes of data generated and relatively substantial intrinsic errors connected with the measurements, appropriate post-processing procedures must be created.

The Fox Glacier is very famous, but the scientific data on it are not abundant. In this thesis the images acquired by the LANDSAT 8 and SENTINEL 2 satellites were used, with spatial resolution respectively equal to 15 m and 10 m. Thanks to ImGRAFT *templatematch*, an open source tool developed in MATLAB environment, it was possible to calculate the velocity field on the ablation area, in the long term (the first images used in this thesis were acquired in 2012).

The accumulation area, on the other hand, is very often covered by clouds and snow, and the surface of the glacier is very uniform, being almost always covered with snow. It was therefore impossible to study the long-term velocity field for the accumulation area.

The best results were obtained with the SENTINEL 2 images. Working with satellite images allows long-term results to be obtained, overcoming the difficulties of fieldwork on a glacier so large and difficult to navigate due to its very deep crevasses.

The pool of remote sensing products that has resulted is a huge step forward in terms of observing changes in ice dynamics across entire ice sheets and their contribution to sea level rise.

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