USING OPTICAL FLOW TO ESTIMATE GLACIER DISPLACEMENTS IN THE SOUTH PATAGONIA ICEFIELD

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ABSTRACT: In this work, the feasibility of using optical flow as a possible solution to obtain accurate movement data at pixel level to derive ice velocities in a glacier was investigated. The study of glacier dynamics requires the accurate mapping of surface velocities that vary along the glacier, following complex patterns defined by stress and strain rate distributions. In order to obtain a dense and accurate grid of ice velocities by optical flow algorithm as the result of the apparent movement pattern between objects, we carried out a test of the proposed large displacement optical flow (LDOF) method in Viedma Glacier, located at the Parque Nacional Los Glaciares, South Patagonia Icefield, Argentina. We collected a monoscopic image terrestrial sequence (time lapse), acquired by a calibrated camera; images were taken every 24 hour from April 2015 until April 2016, a total of 346 days. The Correlated Image Filter (CIF) process was applied to avoid and minimize errors due to the significant changes in lighting, shadows, clouds and snow that allowed to select a sequence of correlated image pairs of comparable radiometric characteristics. The results show a strong flow field in the direction of the glacier movement with acceleration in the terminus. In addition, the errors between different images pairs were analyzed, and the matches generally appear to be adequate, although some areas show random gross errors related to the presence of substantial differences in lighting. These errors were minimized by averaging the image sequence based on seasons, which yielded better results. In summary, the LDOF method applied to terrestrial time lapse data can provide a fairly good solution to detect large daily changes in the glacier; typically, at sub-pixel level.

1. INTRODCUTION

Glaciers are important indicators of global climate changes, as they are widely distributed on many continents, and their conditions/trends provide relatively reliable information on long-term weather patterns. Changes in thickness, extension, and velocity are of prime interest, surveying glaciers goes back to the mid-nineteenth century. Unfortunately, earlier surveying methods provided very limited information, mainly related to the location of the tongue of the glaciers. The introduction of optical imagery represented a major change in observability, the changes at good spatial resolution could be detected for the first time. Shortly, airborne and terrestrial photogrammetry along with satellite based remote sensing have become the dominant technique to map glacier topography.

Sustained developments in platforms and sensors are producing increasingly better and more affordable technologies to observe and monitor the Earth. For example, the recently introduced UAS (Unmanned Airborne System) may easily map hard to access areas, such as glaciers, or airborne and terrestrial LiDAR (Light Detection and Ranging) can directly provide surface models. With respect to glaciers, deploying sensors permanently has become economic recently, as ruggedized customer and semi-professional cameras can be easily installed for long-term observations. Supported by solar panels, these systems can be collect time lapse imagery at high-resolution. Depending on models the 20-100 megapixel range generally provides high spatial resolution of the glacier surface, allowing the extraction of dense elevation models. The highly accurate observation of specific glacier areas can nicely complement the global observations (Paul et al., 2009), which generally provide low resolution and less details.

Using optical time lapse imagery, there are several photogrammetric and computer vision methods to create surface models, including monoscopic, stereo, and multiray techniques. Ideally, multiray intersection is the optimal solution, as the highly redundant imagery provides for the most robust object space reconstruction. In practice, however, due to limitations in access and affordability, it is hard to deploy a good network of cameras, and mono and stereo configurations are typically used. Furthermore, efficient extraction methods, such as optical flow can provide relatively good estimation of changes in the surfaces based on mono imagery, and may be able to provide relatively optimal solution.

The optical flow extracted from imagery is the result of the apparent movement pattern between objects, caused by either relative deformation or absolute movements. Estimating correspondence between pairs of points in two images remains one of the fundamental computational challenges in Computer Vision (Wedel et al., 2009). The objective of motion estimation is to compute an independent estimate of motion for each pixel, which is generally known as optical flow (Szeliski, 2010). The majority of today's methods strongly resemble the original formulation of Horn and Schunck (Horn and Schunck, 1981). The majority of the algorithms concern small displacements and only a few procedures have been developed to detect large displacements, such as those occurring with glaciers; note that large displacement is due to the low image acquisition rate. The Large Displacement Optical Flow (LDOF) method (Brox et al., 2004, Brox and Malik, 2011) offers an interesting alternative to estimate large displacement in image sequences, and is based on a solid numerical method that includes a coarse-to-fine strategy using the so-called warping technique, and implements the non-linear optical flow constraint for image registration. The constancy assumption of the gradient makes this method robust to changes in image radiometry. Finally, the descriptor matching and the discrete optimizations provide subpixel accuracy.

Using optical flow algorithm for ice motion are reported in (Vogel et al., 2012; Bown, 2015). In this work, the feasibility of using the LDOF algorithm to estimate the motion of a glacier by terrestrial monoscopic time lapse imagery is investigated. Using a non-metric professional DSLR camera systems, tests were carried out at the Viedma glacier, Southern Patagonia Icefield (SPI), Argentina. This study is the continuation of our earlier work (Lannutti et al, 2016), and aims to accuracy of the motion estimates and, ultimately, determine ice velocities in the terminal part of the glacier. The outline of this paper is as follows: Section 2 describes the proposed workflow, Section 3 provides a detailed description of the study area and data collection, Section 4 presents the results with analysis, and Section 5 provides the conclusion.

2. PROPOSED APPROACH

The workflow, shown in Fig. 1, includes the major steps from the data acquisition till the final product, the glacier motion estimates. The time lapse imagery is preprocessed before the LDOF algorithm is applied, including windowing the ROI, and radiometric analysis and filtering. The entire data process is implemented in Matlab, using existing tools as well as code developed to support the specific processing.

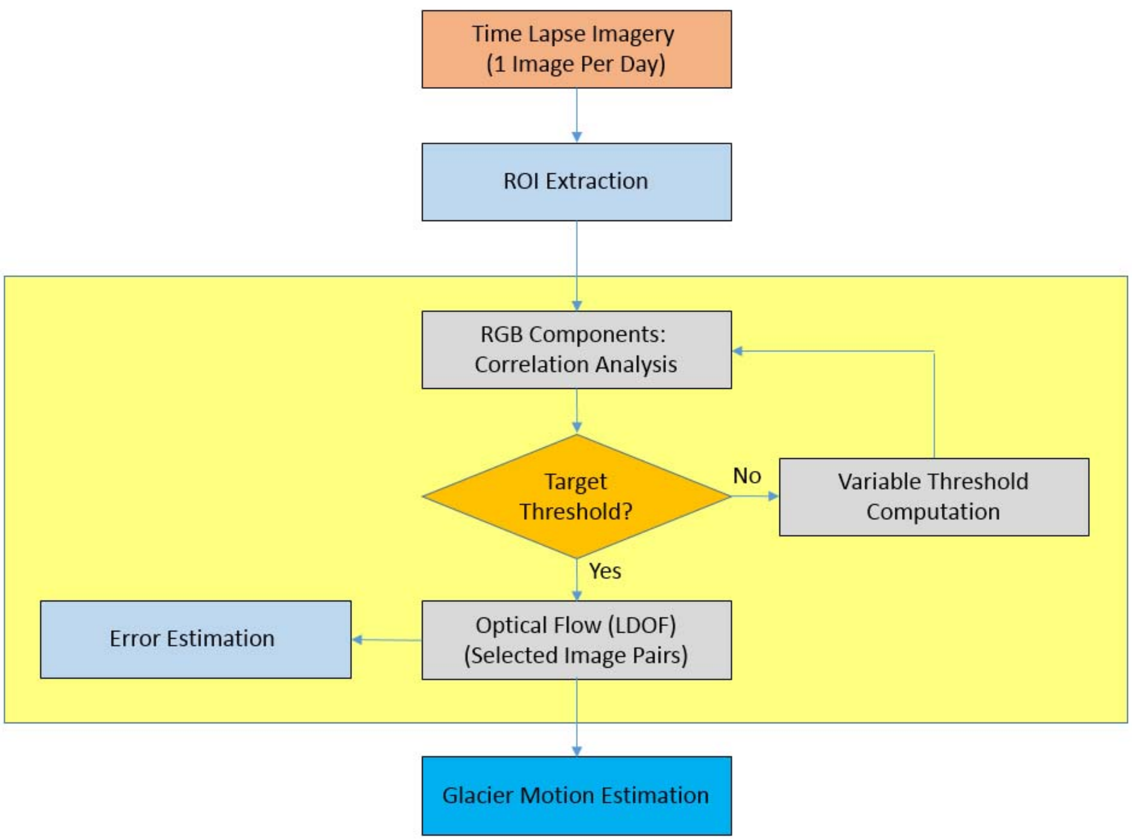

Figure 1. Workflow to estimate glacier motion from time lapse imagery.

2.1 Preprocessing of Time Lapse Imagery

Images acquired daily may have significant fluctuations due to changing weather conditions and seasons. In general, images should have fairly similar radiometric characteristics to obtain acceptable optical flow results. Big discrepancies in images due to snow, rain, etc., can easily make the LDOF fail. Therefore, Correlated Image Filtering (CIF) is applied to remove images with extreme radiometric properties. The CIF is based on the assumptions that optical flow brightness is constant over time, and nearby points in the image move in a similar way (Schalkoff, 1989). Consequently, important changes in lighting should be avoided to assume that changes of image irradiance are only caused by the image sequence (Klette, 2014). This generally involves the summation of color differences between corresponding pixels over the image. In this study, the daily changes in solar radiation and the seasonal snow cover were corrected by the CIF.

First, an image pair is selected, IM_n (Master) and IS_{n+1} (Slave), both of which are separated into the three RGB bands in order to perform a correlation for each channel separately for both images. The mean correlation value of each of the three channels is analyzed. If the mean value is equal or greater than 0.94, a value based on empirical data, then the pair remains selected. Otherwise, the initial threshold of 0.94 is iteratively reduced in 0.005 steps and a new correlation between the IM_n and the IS_{n+2} is computed until the pair of images surpasses the descending correlation threshold. The reason to apply a variable correlation threshold is to avoid correlation between images that are too separated in time, as the objects may change substantially due to the glacier's movement. This sequence is repeated *n* times for all the images, where IS_{n+m} becomes IM_{n+m} , making the correlation between the latter and the IS_{n+m+1}. As a result of this process, correlated pairs of images are obtained throughout the course of the entire sequence, where the changes in luminosity are minimized, and are ready for the LDOF processing.

2.2 Large Displacement Optical Flow (LDOF)

After initial investigation with several optical flow algorithms, the LDOF Matlab implementation developed by Brox et al. (2004), Brox and Malik (2011) was selected. This algorithm implements a coarse-to-fine variational framework between two images I_1 and I_2, and computes the displacement field $w(x)= (u,v)$ by minimizing the functional energy $E(w)$ using the following model:

$$E(w) = E_{color}(w) + \gamma E_{gradient}(w) + \alpha E_{smooth}(w) + \beta E_{match}(w, w_1) + E_{desc}(w_1) \quad (1)$$

where α, β and γ are tuning parameters which can be determined according to qualitative evidence on a large variety of representative images, or can be estimated automatically from ground truth data. Note that $w= (u; v)^T$ is the optical flow field, i.e., a function w: $\Omega \rightarrow R^2$, and $w_1(x)$ denotes the correspondence vectors obtained by descriptor matching at some points x (Brox and Malik, 2011). The first and second terms in Eq. 1 represent the common assumption that corresponding image features (points) should have nearly the same gray/color value and gradient. The third term emphasizes the strength and importance of regularity constraints in optical flow estimation by a robust smoothness. The last two terms combine descriptor matching with the variational model and its coarse-to-fine optimization. The descriptor matching method is based on densely computed Histogram of Oriented Gradients (HOG). Each gradient histogram comprises 15 different orientations and is computed in a 7x7 neighborhood. The method with changing resolutions is performed by dividing the original problem into a sequence of sub-problems at different levels of resolution. The gradient constancy assumption of the grey value has some disadvantage because is susceptible to slight changes in brightness, which often appear in natural scenes in the minimization processes. Therefore, in the smoothness assumption, the model estimates the displacement of a pixel only locally without taking neighboring pixels into account. Finally, a smoothness term has to describe the model assumption of a piecewise smooth flow field. Using image pyramid, the transitions between levels is solved. Subsequently, the goal is to find a function *(u, v)* that minimizes the energy. Since the minimization is not a trivial process due to the highly nonlinear model, it is implemented by Euler-Lagrange equations to reflect boundary conditions.

The results of LDOF can be evaluated qualitatively by visualization, such as by the color-coded flow field of the movement of the glacier. Using the technique by Streinbruecker et al. (2009), the consistency of the flow-field by reconstructing can be quantitatively checked by the first of the two frames using the second frame and the estimated motion field *w*:

$$I_1^r(x) = I_2(x + w(x)) \quad (2)$$

If the resultant flow is adequate, then the reconstruction of I_1^r has to be identical to theI_1. In order to estimate the error, the absolute difference between the pair of images is calculated by computing the mean value of each pixel, considering all images selected.

3. TEST DATA

The South Patagonia Ice field (SPI) is located in South America, Argentina and Chile, covering an area of 13,000 km^2 with an average length of approximately 30-40 km at a mean altitude of 1,191 m ASL (Aniya and others, 1996). Presently, after Antarctica and Greenland, it is the third largest reservoir of fresh water on continental shelves. The Viedma glacier is located at 49° 31' S, 72° 59' W, Parque Nacional Los Glaciares, SPI, Santa Cruz, Argentina, see Fig. 2. This is an important calving glacier in the region covering an area of 945 km^2 (Aniya et al., 1996). The glacier was selected for this study due to the availability of several studies on the surface changes, carried out over the last 30 years (Skvarca et al., 1995, Aniya et al., 1996; Lopez et al., 2010; Rivero et al., 2013).

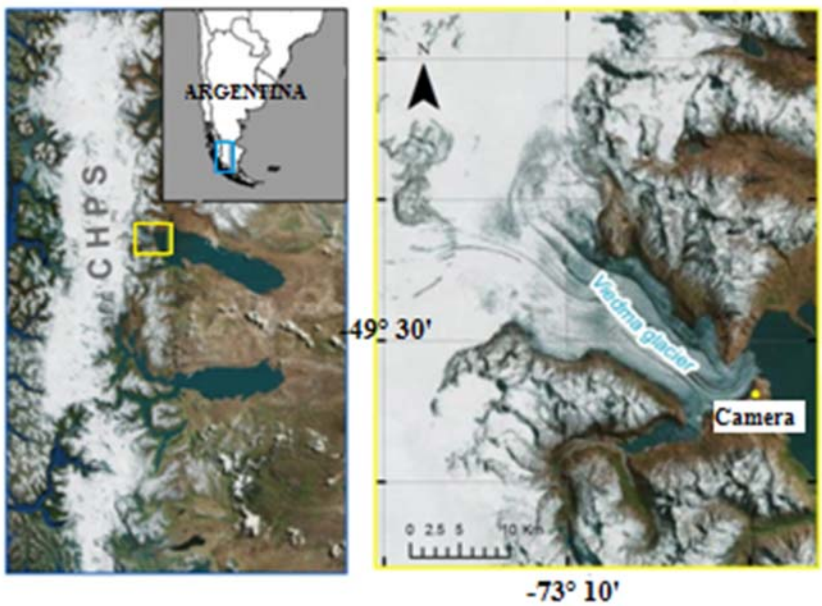

Figure 2. Study area with camera location.

The time lapse image acquisition system was based on CANON EOS Mark II DSLR camera, which was placed in a weatherproof enclosure with viewing port and visor as well as rear monitoring port to visually access the camera status. The case also included the timer unit and battery; note that the images were stored on the camera built-in CF card. The system is powered by one 12V/7Ah lead acid battery, charged by two 38W solar panels. The camera cage was installed on a rigid metal structure, fixed to outcrops of the South margin of Viedma Glacier, from where a fairly good view of the curve of glacier can be viewed, see Fig. 3.

Figure 3. Camera cage installation at the South margin of Viedma Glacier.

The main parameters of the CANON EOS Mark II DSLR camera are: pixel size: 7.2 μ, focal length: 50 mm, and FOV: 46°. The camera was calibrated several times, initially by the United States Geological Survey (USGS), and prior to field deployment. The system has been in operation for several years, the imagery used is this study are from the data acquisition session between April 17, 2014 and April, 8 2015, when one image was captured at 12 pm local time every day, totaling in 356 images.

Figure 4. Camera cage.

4. RESULTS

The time lapse imagery was initially reduced to the ROI, by removing the sky and mountain range and thus resulting in computational cost in the subsequent processing. Fig. 5 shows an example for resizing. In addition, images with low radiometric characteristics are also removed.

Figure 5. Original (left) and ROI reduced image (right).

4.1 Pre-processing

The Correlated Image Filter (CIF) process, described in Section 2.1, eliminated about half the images, as only 107 image passed the test; Fig. 6 shows the correlation numbers and the time distribution of the filtered images.

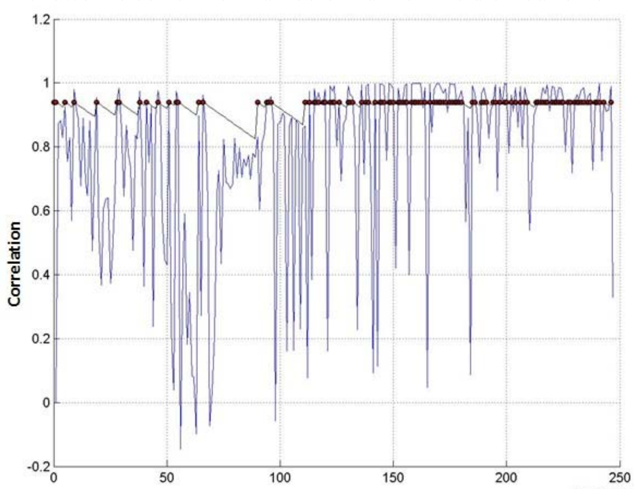

Figure 6. Results of the CIF filtering.

4.2 Flow computation

The optical flow computation (LDOF) was executed on the filtered lapse imagery. The flows obtained were averaged to obtain the typical flow vector for the entire observation period, Fig. 7 shows the flow vectors with color coded magnitude.

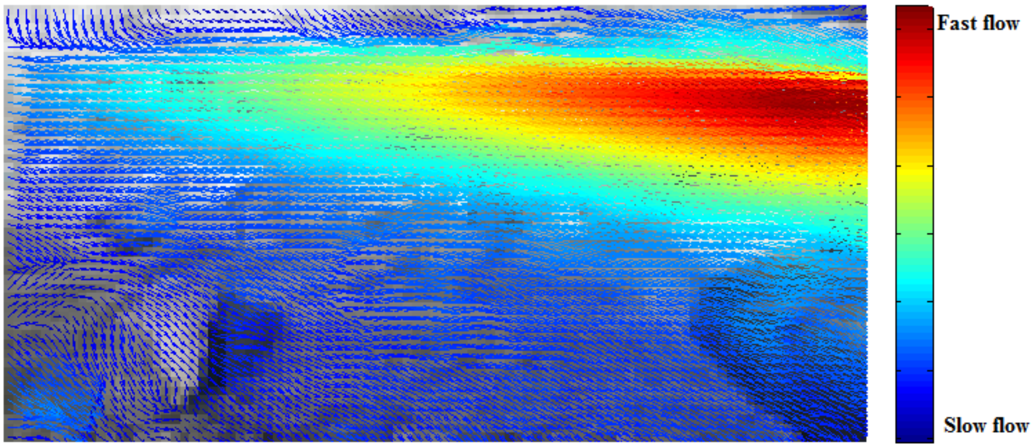

Figure 7. Flow vectors.

The results nicely match expectations, as ice flow velocities on a valley glacier cross section have maximum values at the center of the valley and then decrease to a minimum at the margins. Along the valley, ice velocity magnitude varies longitudinally depending on several factors, such as surface slope, mass balance distribution and front conditions. On calving glaciers, the velocities can reach a maximum at the glacier front, due to the pulling effect of high calving rates, where glaciers calve into deep waters (Rivera et al, 2012).

Until now, very little was known about the ice flow velocities near the front of Viedma glacier, and about the ice-lake interactions taking place in this place. The near front acceleration has been previously described for other calving glaciers in Patagonia (Sakakibara et al., 2014), where calving is driven by water depths near the front. In the Viedma glacier, this is confirmed by the recently surveyed bathymetry of the lake, where up to 571 m water depths were detected. Note that, since April 2014 to March 2016 the central part of the glacier front retreated near 800 m as detected by comparing satellite images.

4.3 Error Analysis

To obtain numerical values for the flow, ice velocity, estimation errors, the typical statistical parameters are computed for the all the successfully processed image pairs. Fig. 8 shows the mean and standard deviation, which represent an internal estimation measure; in pixels the mean is about 3.7 while the standard deviation is about 5.7.

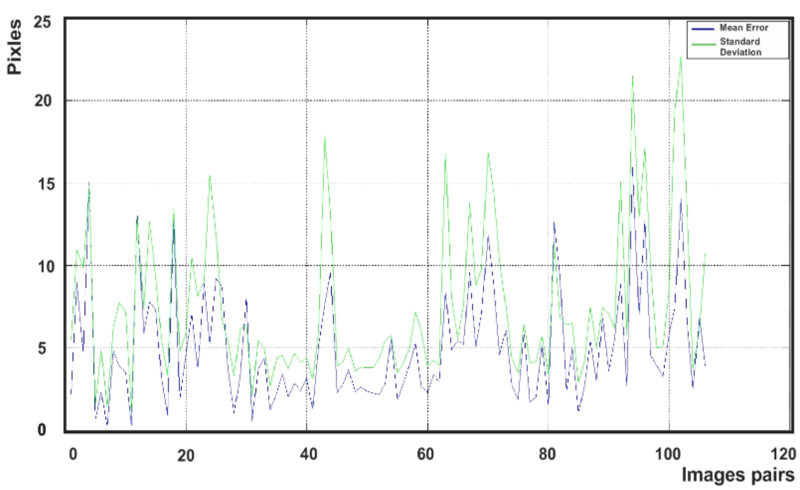

Figure 8. Mean and standard deviation for all the processed image pairs.

The variations clearly indicate the impact of the varying light conditions. Two examples in Fig. 9 show cases with significant changes in illumination (sample A) and then another good lighting conditions (sample B). In both cases, the image below the left mage is flow map while the right one shows the error estimation; both are color coded. In the case of sample A, the biggest errors are generally due to the presence of clouds, such as in the lower area that can be associated to shadows in the crevasses of the glacier, and the presence of changes in snow cover. In contrast, sample B the errors are low over the entire area. Note the interesting situation in the middle of the image, where the presence of people is observed, clearly indicating the ability of the LDOF to detect small changes with high precision.

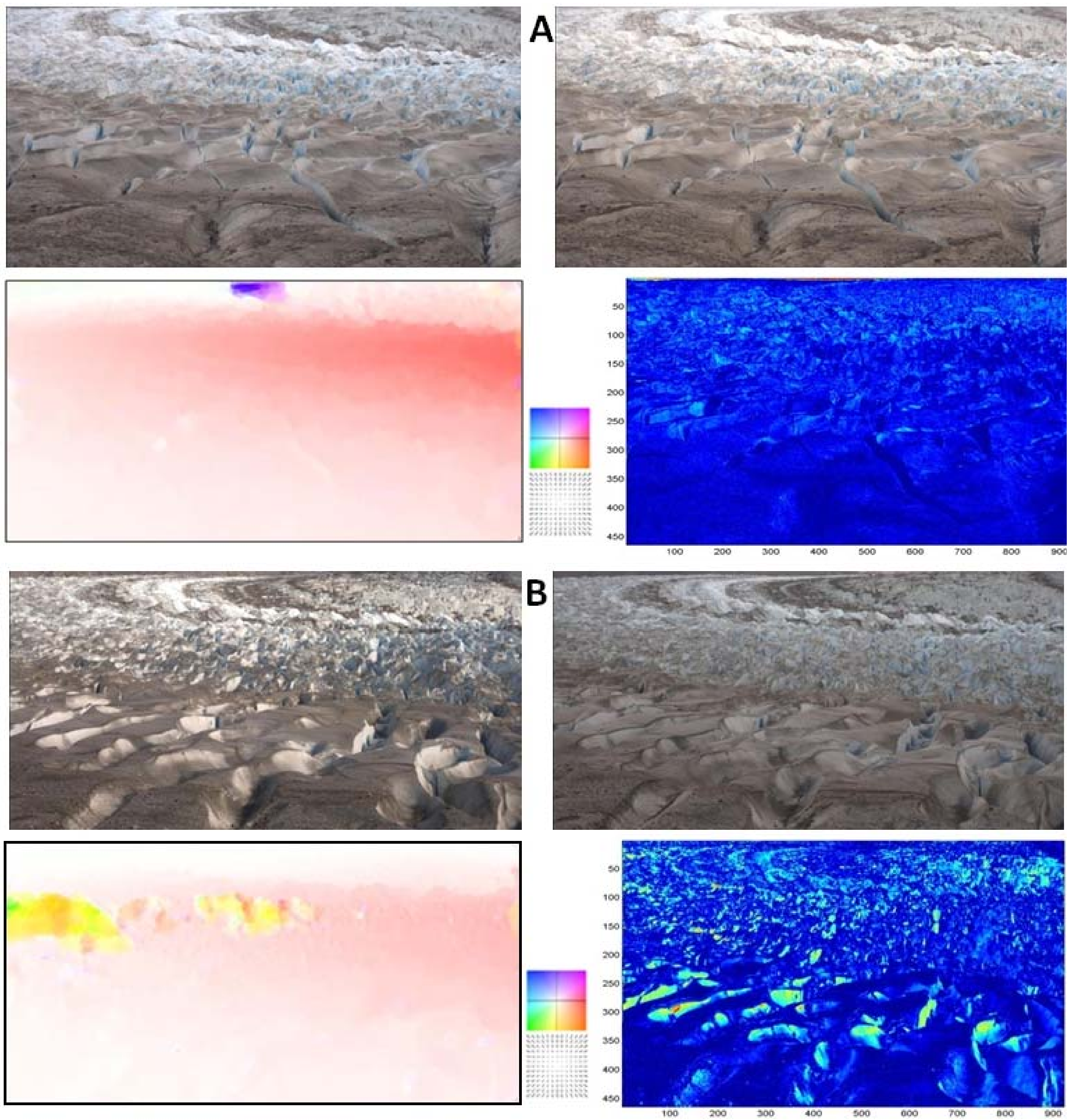

Figure 9. Image pairs with result for good and bad radiometric differences; top image pair, left below derived flow, and right below error estimates for both samples, A and B, respectively.

5. CONCLUSIONS

In this work, dense optical flow field methods were used to estimate glacier movement with high precision. The proposed method integrates the CIF and LDOF algorithms, and showed good results to detect the movement of Viedma glacier. In natural environments, such as glaciers, there are a continuously changing lighting conditions due to the presence of clouds, snow cover, and objects that appear or disappear, resulting in noticeable variations in radiometric conditions (brightness) of the images, strongly impacting all the subsequent processes. Therefore, the developed CIF proved to be essential for the LDOF algorithm; the optimization and improvement of the brightness changes resulted in a better performance. Though only 36% of the images passed the applied test, they were enough for fairly well estimating the motion of Viedma glacier.

Under good radiometric conditions, the efficient LDOF solution was able to provide solutions to detect the large daily changes at sub-pixel level accuracy. The estimation error was evaluated qualitatively and quantitatively, where the error reconstruction was computed and yielded a mean and STD value of 3.7 ±5.7 pixels, respectively. Although there are few examples of optical flow algorithms applied for detecting ice velocities, this study clearly demonstrated the capabilities of LDOF for this purpose. The resulting velocities are consistent with the expected ice flow in a calving glacier with high velocities near the ice front.

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