Development of improved Google Earth Engine (GEE) Glacier velocity estimation algorithms for long-term & large-scale monitoring of glacier velocities

Suhaib Bin Farhan[1], Ahmed Ali[2], Yinsheng Zhang[1], Haris Farhan[3], Yanhong Guo[1], Adnan Aziz[4], Jawad Nasir[5], Umair Bin Zamir[2], and Qiang Yaohui[4]

[1]Institute of Tibetan Plateau Research, Chinese Academy of Sciences
[2]University of Karachi
[3]National Centre for Remote Sensing & Geo Informatics, Institute of Space Technology, Pakistan
[4]Key Laboratory of Tibetan Environment Changes and Land Surface Processes, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing, China; University of Chinese Academy of Sciences, Beijing, China
[5]Unknown

September 30, 2023

Abstract

Feature tracking is an efficient method for estimating glacier velocity by identifying the surface displacement between image pairs through maximum normalized cross-correlation (NCC). However, this method may misidentify displacement when noise is present in one or both images or when natural causes change glacier morphology. To improve accuracy, we developed the Google Earth Engine Glacier Velocity (GEEG-Vel) estimation method, which utilizes image enhancement and multi-image pair NCC maximization. GEEG-Vel results are further filtered using PyFilter, a Python routine that improves the glacier velocity estimation by utilizing velocity pairs obtained from GEEG-Vel. The combination of GEEG-Vel and PyFilter provides an efficient and accurate approach for glacier velocity estimation across various types of datasets, including optical and SAR data. We compared the results with the ITS_LIVE glacier velocity for the same period (2013-2018), and the mean velocity difference for each year was less than 10 m/year. Our study demonstrates that the combination of GEEG-Vel and PyFilter provides a reliable and accurate approach for glacier velocity estimation, which can be useful for monitoring the dynamics of glaciers and their response to climate change.

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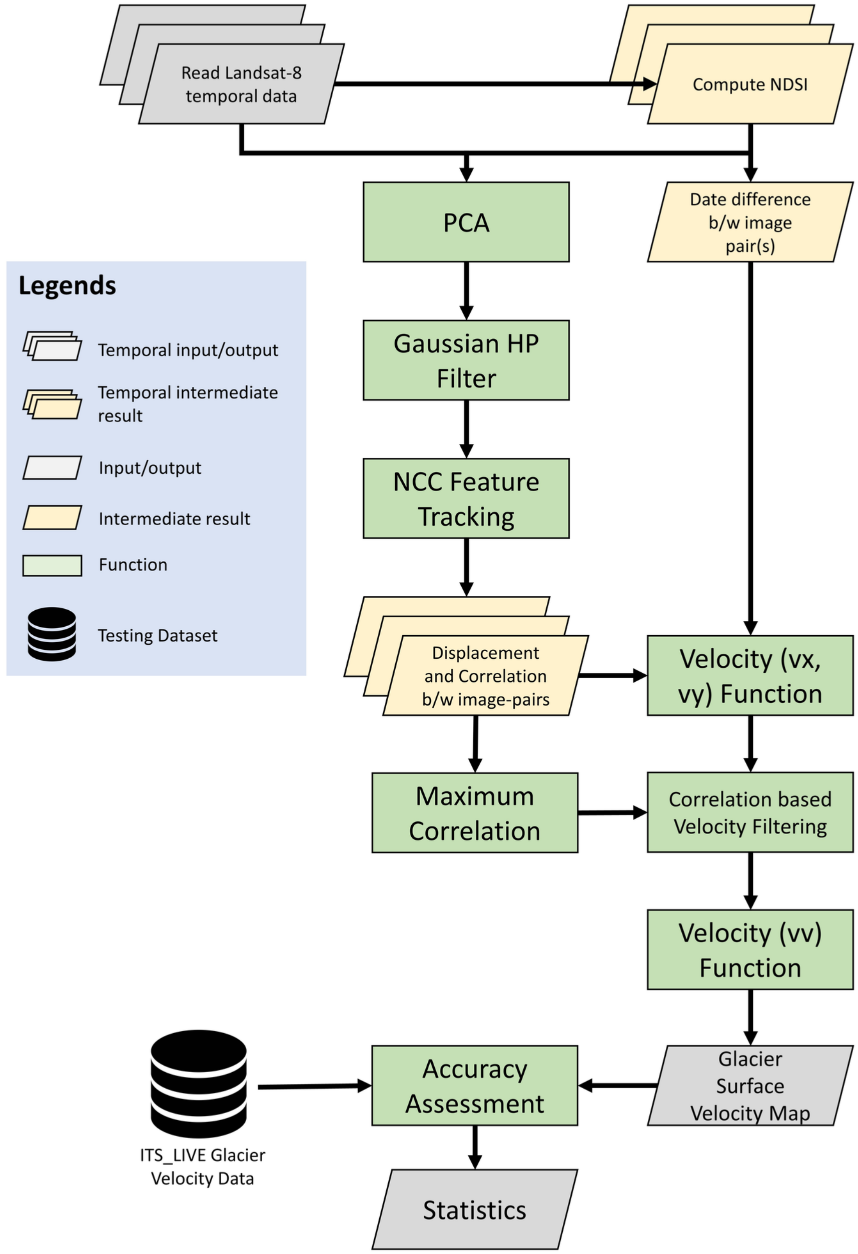
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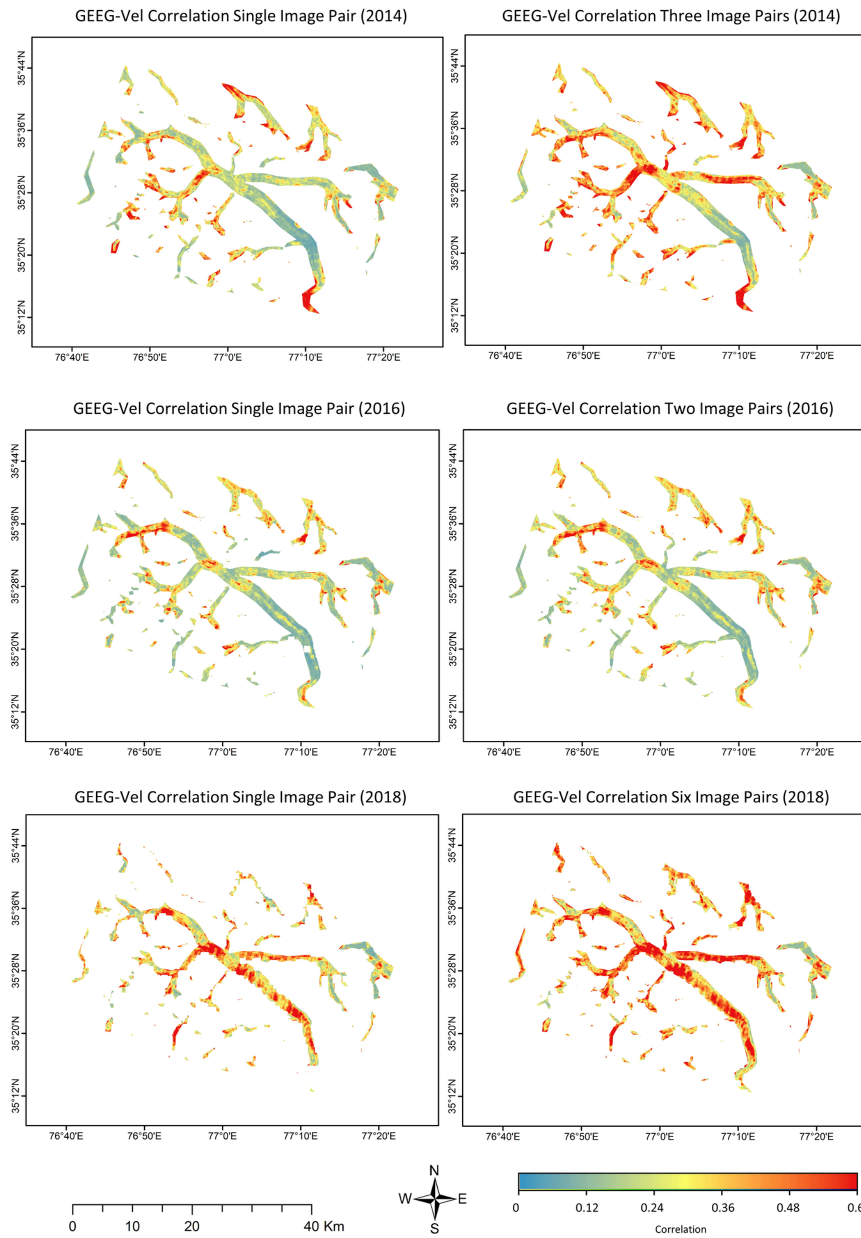
Statistics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GEEG-Vel Correlation Single Image Pair (2018)
GEEG-Vel Correlation Six Image Pairs (2018)
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35°36'N
35°28'N
35°20'N
35°12'N
76°40'E
76°50'E
77°0'E
77°10'E
77°20'E
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40 Km
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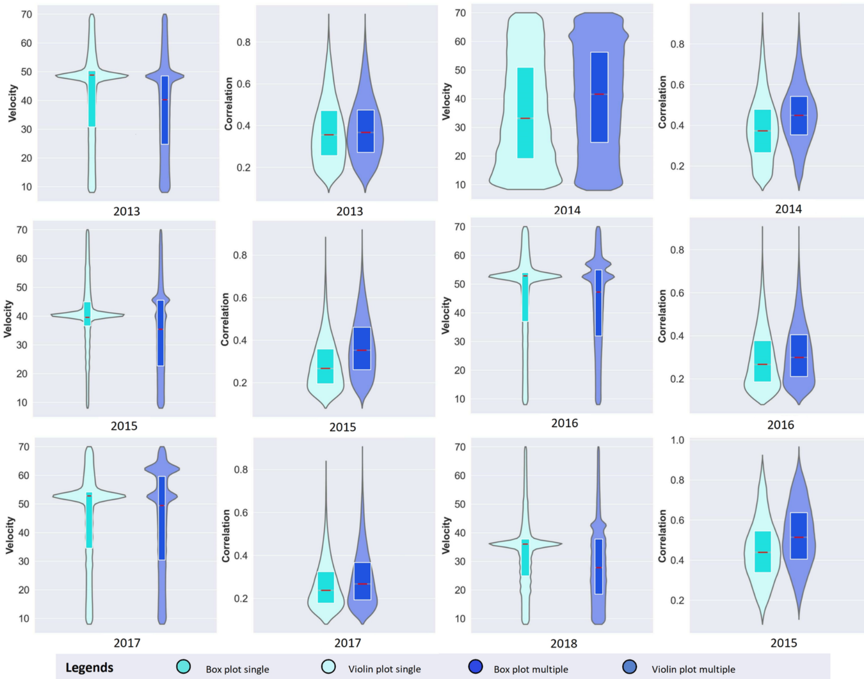
Correlation


Velocity
Correlation
2013
2013
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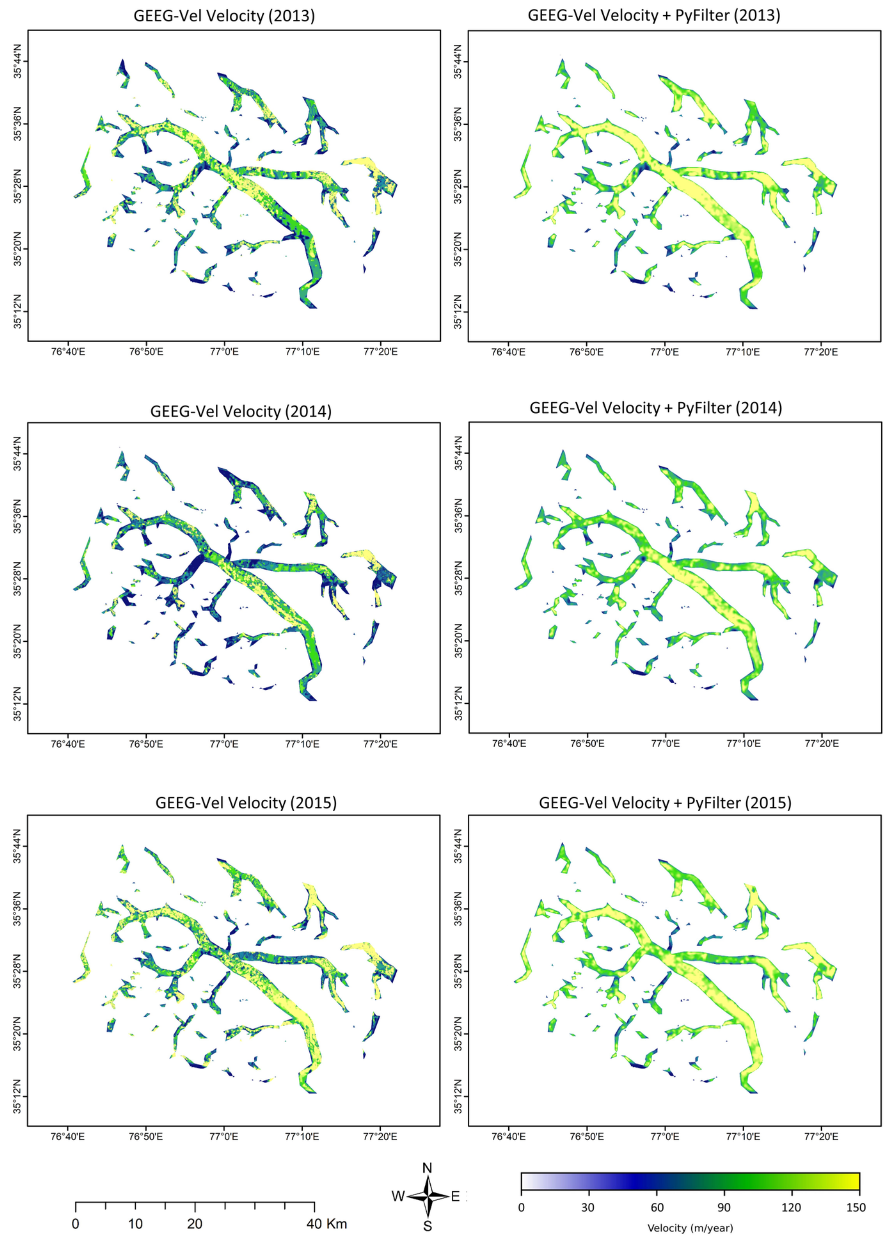
Legends
Box plot single
Violin plot single
Box plot multiple
Violin plot multiple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GEEG-Vel Velocity + PyFilter (2014)
GEEG-Vel Velocity (2015)
GEEG-Vel Velocity + PyFilter (2015)
35°44'N
35°36'N
35°28'N
35°20'N
35°12'N
76°40'E
76°50'E
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77°10'E
77°20'E
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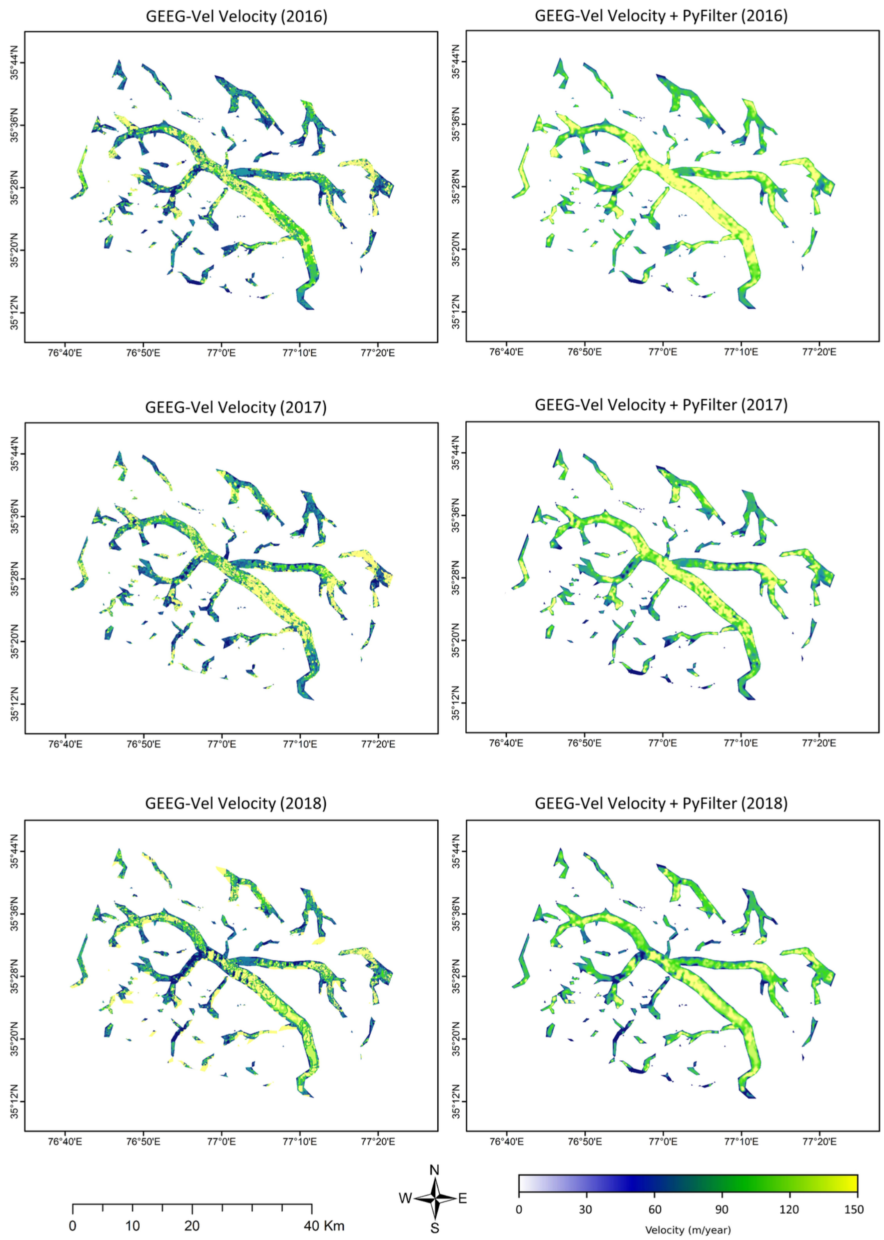
Velocity (m/year)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GEEG-Vel Velocity + PyFilter (2018)
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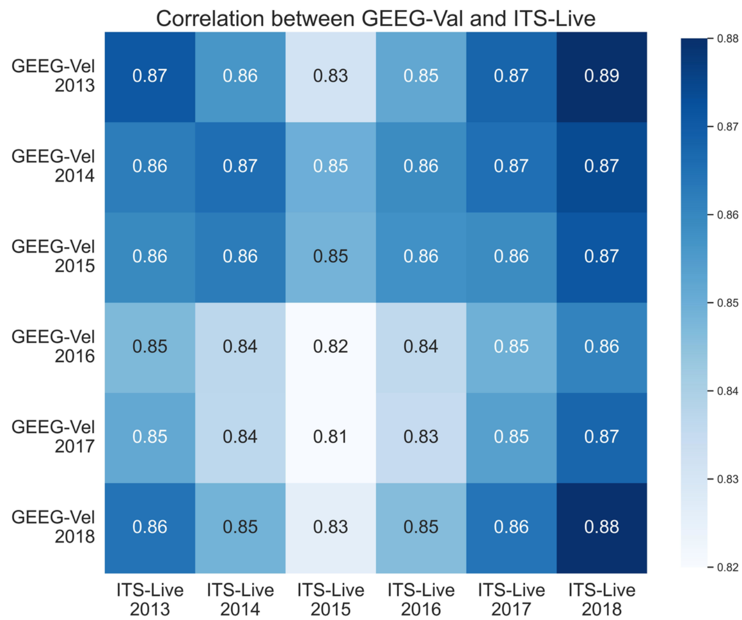
Velocity (m/year)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GEEG-Vel 2014
GEEG-Vel 2015
GEEG-Vel 2016
GEEG-Vel 2017
GEEG-Vel 2018
ITS-Live 2013
ITS-Live 2014
ITS-Live 2015
ITS-Live 2016
ITS-Live 2017
ITS-Live 2018
0.87 0.86 0.83 0.85 0.87 0.89
0.86 0.87 0.85 0.86 0.87 0.87
0.86 0.86 0.85 0.86 0.86 0.87
0.85 0.84 0.82 0.84 0.85 0.86
0.85 0.84 0.81 0.83 0.85 0.87
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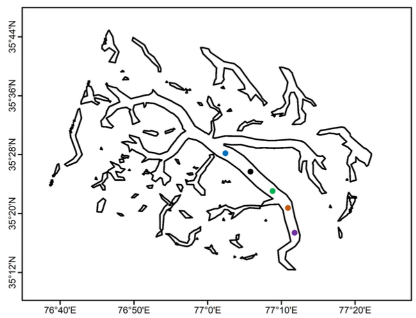
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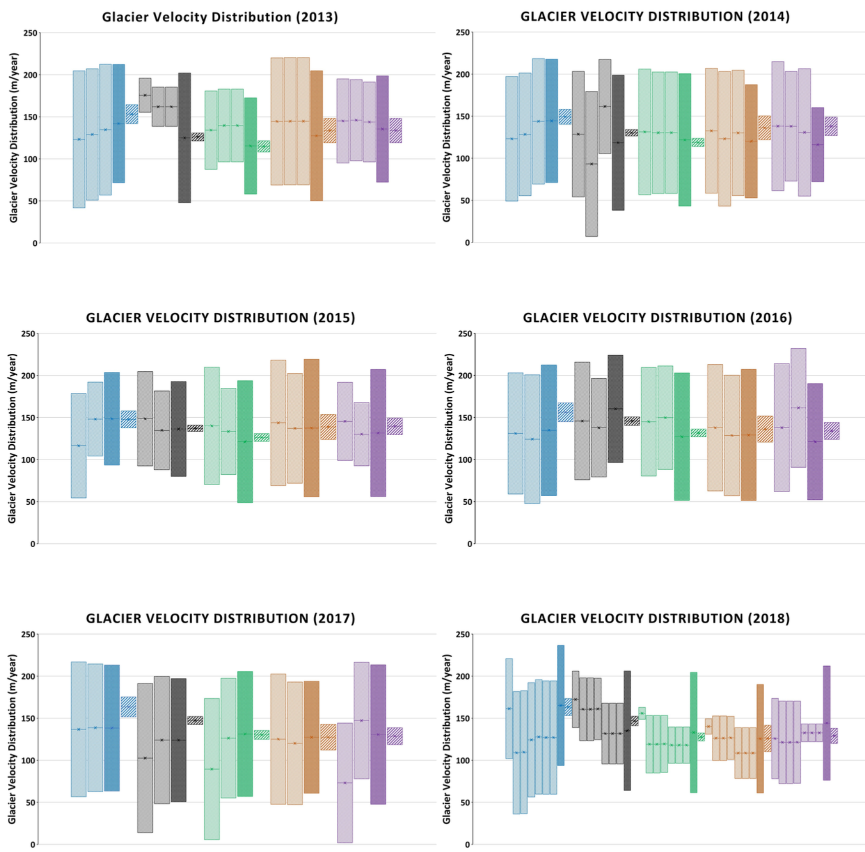
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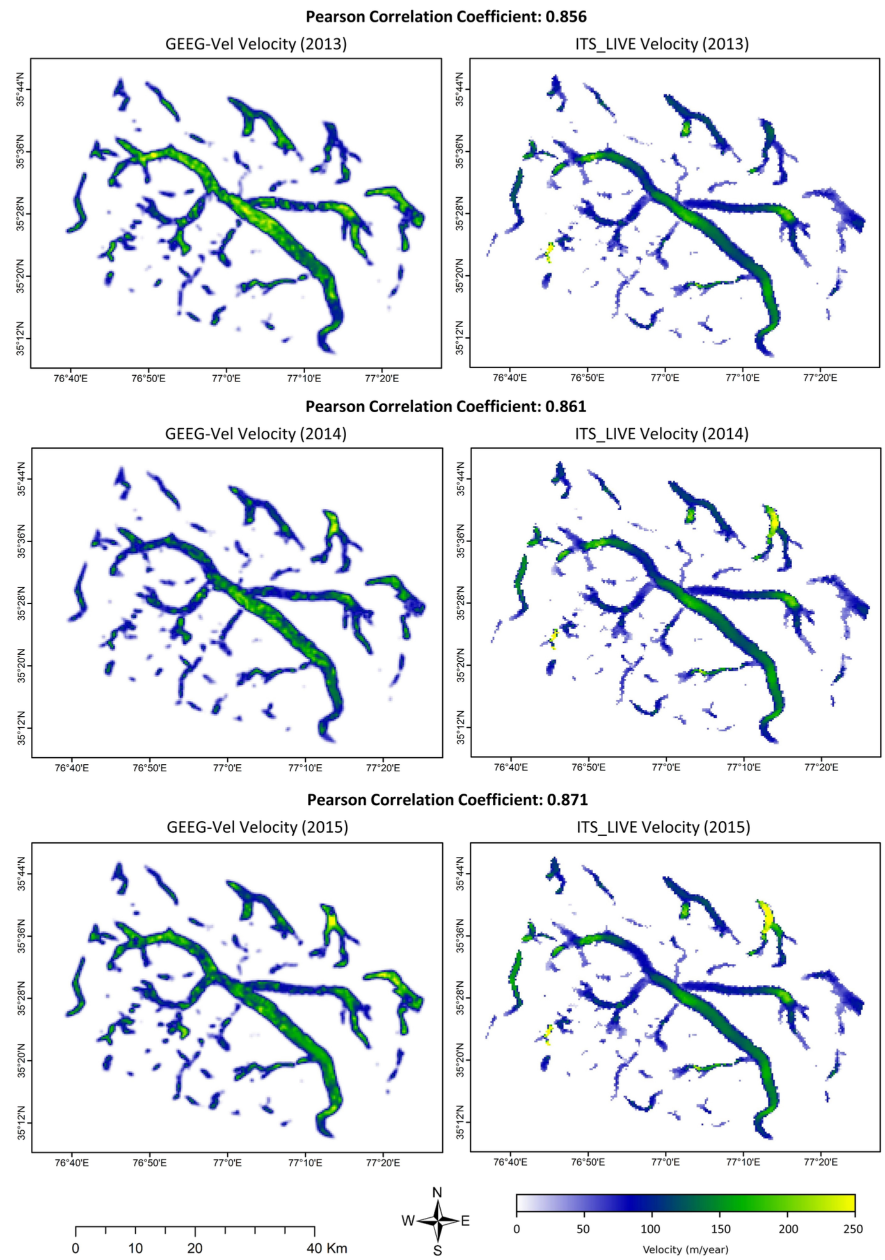
GLACIER VELOCITY DISTRIBUTION (2014)
GLACIER VELOCITY DISTRIBUTION (2015)
GLACIER VELOCITY DISTRIBUTION (2016)
GLACIER VELOCITY DISTRIBUTION (2017)
GLACIER VELOCITY DISTRIBUTION (2018)
Glacier Velocity Distribution (m/year)
0
50
100
150
200
250


Pearson Correlation Coefficient: 0.856
GEEG-Vel Velocity (2013)
ITS_LIVE Velocity (2013)
Pearson Correlation Coefficient: 0.861
GEEG-Vel Velocity (2014)
ITS_LIVE Velocity (2014)
Pearson Correlation Coefficient: 0.871
GEEG-Vel Velocity (2015)
ITS_LIVE Velocity (2015)
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35°12'N
76°40'E
76°50'E
77°0'E
77°10'E
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50
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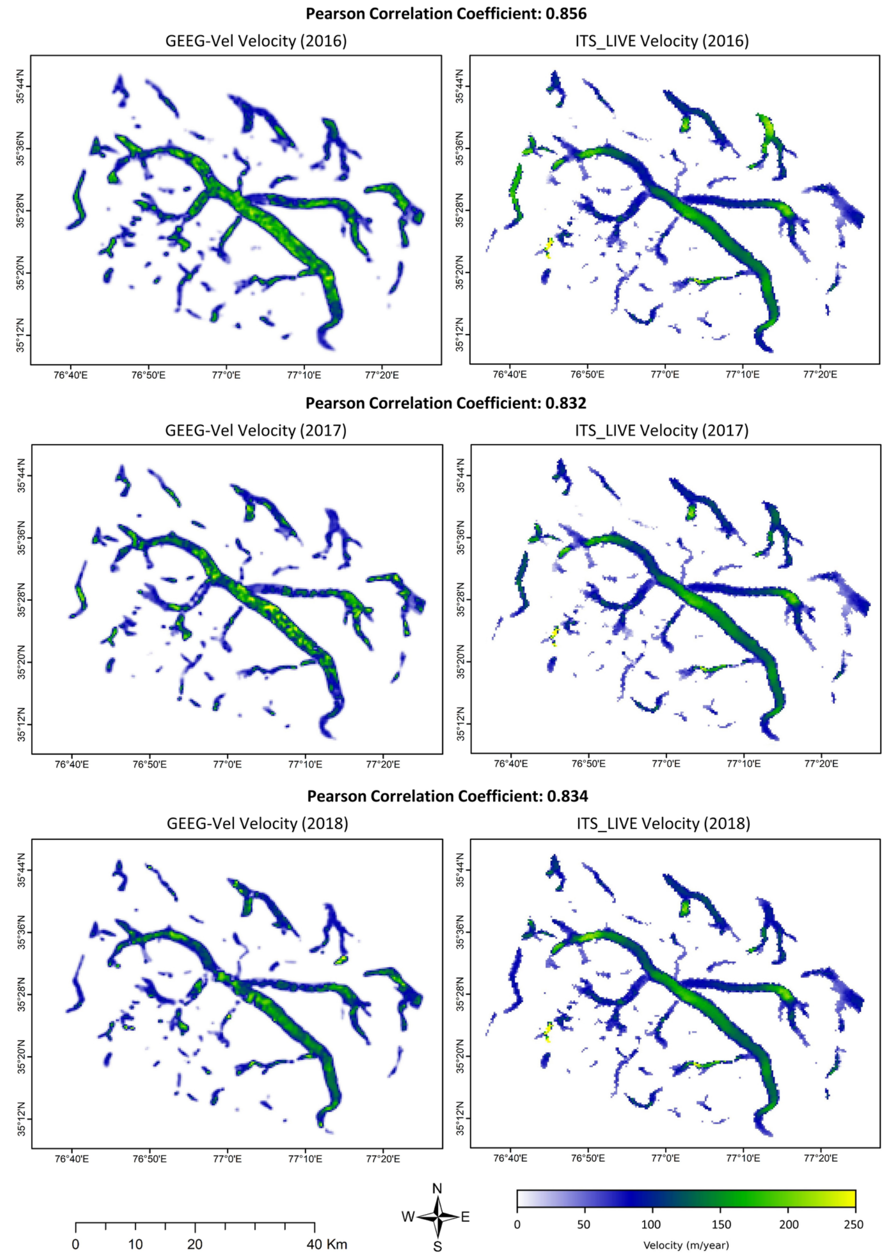
250
Velocity (m/year)



Pearson Correlation Coefficient: 0.856
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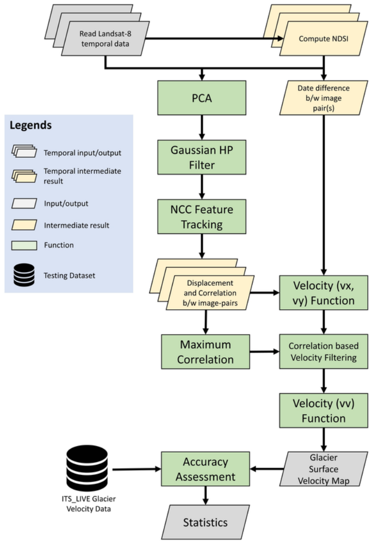
ITS_LIVE Velocity (2016)
Pearson Correlation Coefficient: 0.832
GEEG-Vel Velocity (2017)
ITS_LIVE Velocity (2017)
Pearson Correlation Coefficient: 0.834
GEEG-Vel Velocity (2018)
ITS_LIVE Velocity (2018)
35°44'N
35°36'N
35°28'N
35°20'N
35°12'N
76°40'E
76°50'E
77°0'E
77°10'E
77°20'E
0
10
20
40 Km
N
W
E
S
0
50
100
150
200
250
Velocity (m/year)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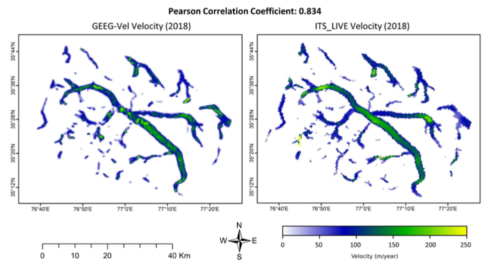
Pearson Correlation Coefficient: 0.834
GEEG-Vel Velocity (2018)
ITS_LIVE Velocity (2018)
0
10
20
40 Km
N
W
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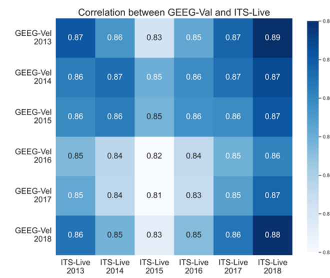
S
0
50
100
150
200
250
Velocity (m/year)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GEEG-Vel 2015
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GEEG-Vel 2016
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GEEG-Vel 2018
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ITS-Live 2013
ITS-Live 2014
ITS-Live 2015
ITS-Live 2016
ITS-Live 2017
ITS-Live 2018

Development of improved Google Earth Engine (GEE) Glacier velocity estimation algorithms for long-term & large-scale monitoring of glacier velocities

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[1]Key Laboratory of Tibetan Environment Changes and Land Surface Processes, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing, China; [2]University of Chinese Academy of Sciences, Beijing, China; [3]University of Karachi, Pakistan; [4]National Centre for Remote Sensing & Geo Informatics, Institute of Space Technology, Pakistan.

Corresponding author: Ahmed Ali (ahmedali24633@outlook.com)

Key Points:

- Efficient glacier velocity estimation using GEEG-Vel and PyFilter.
- Improved accuracy by utilizing image enhancement and multi-image pair NCC maximization.
- Potential for near-real-time comprehensive glacier velocity mapping at a global scale.

Abstract

Feature tracking is an efficient method for estimating glacier velocity by identifying the surface displacement between image pairs through maximum normalized cross-correlation (NCC). However, this method may misidentify displacement when noise is present in one or both images or when natural causes change glacier morphology. To improve accuracy, we developed the Google Earth Engine Glacier Velocity (GEEG-Vel) estimation method, which utilizes image enhancement and multi-image pair NCC maximization. GEEG-Vel results are further filtered using PyFilter, a Python routine that improves the glacier velocity estimation by utilizing velocity pairs obtained from GEEG-Vel. The combination of GEEG-Vel and PyFilter provides an efficient and accurate approach for glacier velocity estimation across various types of datasets, including optical and SAR data. We compared the results with the ITS_LIVE glacier velocity for the same period (2013-2018), and the mean velocity difference for each year was less than 10 m/year. Our study demonstrates that the combination of GEEG-Vel and PyFilter provides a reliable and accurate approach for glacier velocity estimation, which can be useful for monitoring the dynamics of glaciers and their response to climate change.

Plain Language Summary

In our study, we've created a new way to measure how fast glaciers are moving on the Earth's surface. This method, called GEEG-Vel and PyFilter, uses images from satellites and special computer techniques to figure out glacier speeds quickly and accurately. We tested this method using data from a satellite called Landsat-8, and it worked really well, giving us results that matched up with another method called ITS_LIVE. This new technique is a big deal because it can help us keep a close eye on glaciers and how they change over time because of things like climate change. It also works fast, so we can get updates on glacier speeds almost in real-time. This means we can monitor glaciers all around the world and better understand how they are responding to our changing climate.

1 Introduction

Feature tracking in its early stage uses manual tracking of ice features on aerial images (Harrison, Echelmeyer, Cosgrove, & Raymond, 1992; Whillans & Bindschadler, 1988). The same methodology was adopted on satellite images for ice flow determination using moderate-resolution satellite images (Lindstrom & Tyler, 1984; Lucchitta & Ferguson, 1986). Bindschadler & Scambos in 1991 and Emery, Fowler, Hawkins, & Preller, in 1991, developed the first computerized method for image enhancement and feature tracking using the correlation of image pairs. This methodology revolutionaries satellite-based computerized feature tracking of ice sheets. Since 1991, hundreds of computerized implementations on glacier velocity are published, among which many studies are dealing with the advancement of methodology (Bindschadler, Fahnestock, Skvarca, & Scambos, 1994; Bindschadler, Vornberger, Blankenship, Scambos, & Jacobel, 1996; Scambos, Echelmeyer, Fahnestock, & Bindschadler, 1994; Berthier et al., 2005; Kääb, 2002).

A review of computerized glacier velocity estimation shows extensive use of both optical and SAR data. Although researchers usually prefer SAR data over optical data due to its all-weather imaging capability, large swath width, and enhanced texture, the advantage of optical data over SAR is its large time-span data coverage (Joughin, Smith, Howat, Scambos, & Moon, 2010; Rignot, Mouginot, & Scheuchl, 2011). In the beginning, satellite images are of low radiometric resolution, fewer repeat passes, poor geometric accuracy, and geometric distortion were present. Due to this reason, inaccurate glacier velocities were estimated with few measurements of glacier velocity per year.

With the advancement of satellite technology in the 21st century, most of the problems in glacier velocity estimation were resolved (Bindschadler, 2003; s Morfitt et al., 2015). However, the feature tracking method still realizes on NCC of features in the image pair. The main disadvantage of feature tracking is the inability of NCC to accurately identify features if noise is present in anyone image of the image pair (Huang and Li, 2011; Heid and Kääb, 2012). Noise in optical satellite images is mainly due to the presence of clouds, haze, atmospheric effects, and strong weather phenomena. In the glacial environment, weather phenomena, like rain, thunderstorms, and snowfall are nearly for a whole year period that changes the illumination of the surface. This makes glacier velocity estimation even more difficult when very few satellite images are acquired per year. In addition, NCC may also misidentify features in the image pair if the morphology of the feature is altered in the second image due to glacier melting or other natural cause (Lange et al. 2007).

To resolve these issues, we present a new Google Earth Engine Glacier Velocity (GEEG-Vel) estimation method. The proposed method has a list of characteristics: (1) GEEG-Vel is a post-processing methodology that improves glacier velocity estimation results obtained from the feature tracking approach. (2) It is independent of the type of dataset used i.e. SAR of optical data. (3) It enables glacier velocity estimation even in the presence of noisy images i.e. cloud, haze, atmospheric effects, or changes in illumination due to strong weather phenomena. (4) The GEE implementation enables rapid glacier velocity estimation of the large area. (5) The improved glacier velocity results are at the cost of multi-image pair utilization instead of signal pair.

2 Methodology

2.1 Study sites and dataset

The study was conducted in the Karakoram range of the Himalayas, known for its vast expanse of glaciers. This region is geographically significant and presents unique challenges for glacier research. The glacier, covering an area of about 700 km² and spanning approximately 75 km in length, was chosen as the site for this project.

To carry out the research, Landsat 8 satellite imagery from the years 2013 to 2018 was utilized. Specifically, the study made use of the surface reflectance bands 3, 4, 5, and 6, as well as the panchromatic band from Landsat 8 TOA data. In addition, the normalized difference snow index (NDSI), a widely used index for snow and ice detection, was calculated using bands 3 and 6, which correspond to green and shortwave infrared radiation, respectively.

2.2. Processing steps

For each year, we have selected multiple image pairs of Landsat 8 datasets working from 2013 to 2018. The velocity estimation for each image pair is performed separately. The velocity estimation process includes image enhancement through fusion, highpass filtering, displacement estimation through NCC, and post-processing of multi-image pairs for maximization of correlation. A basic flow diagram is shown in Figure 1.

2.3. Glacier surface enhancement

Glacier surface enhancement is important for velocity estimation because of the dependency of NCC-based displacement estimation on the texture of surfaces. Hence, efforts are made to improve the texture details of glacier surfaces using image fusion and high-pass filtering. Firstly, the fusion of panchromatic image with green, red, near-infrared (NIR), shortwave-1 (SWIR1), and normalized difference snow index (NDSI) is performed using principal component transform. Secondly, a high-pass Gaussian filter is applied to the resulting PC1 images having a radius of 20 pixels (i.e., 300m), and standard deviation of 3 pixels, and normalization of filter is set true. The filtered image is than used for displacement estimation.

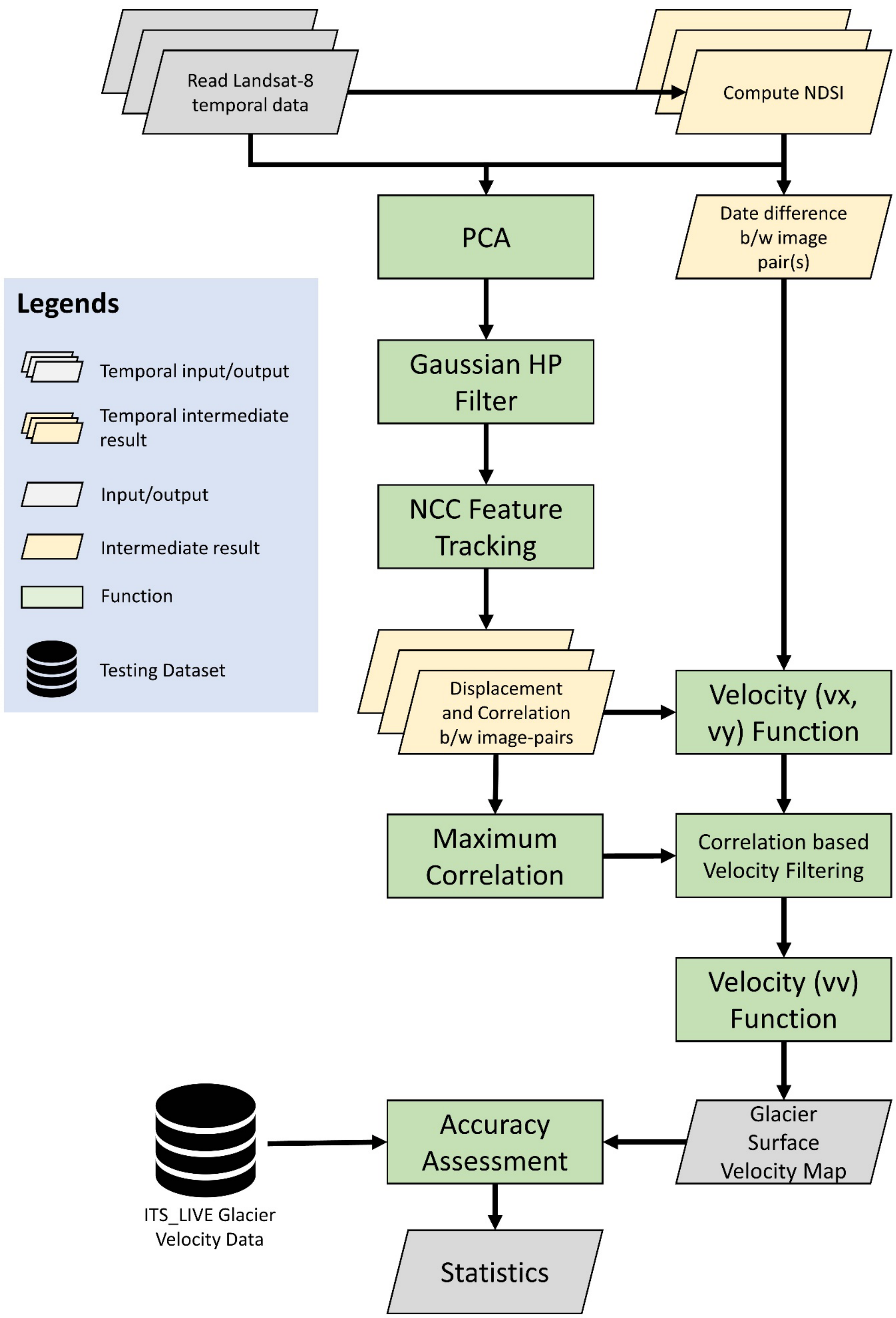


Figure 1. Processing steps of proposed GEEG-Vel algorithm.

Table 1. List of datasets used in this study.

Year	Image pairs
2013	Image pair 1: 2013-03-22 and 2013-11-03 Image pair 2: 2013-03-22 and 2013-07-30 Image pair 3: 2013-03-22 and 2013-07-14
2014	Image pair 1: 2014-04-28 and 2014-06-15 Image pair 2: 2014-04-28 and 2014-09-19 Image pair 3: 2014-04-28 and 2014-10-21
2015	Image pair 1: 2015-01-09 and 2015-10-08 Image pair 2: 2015-01-11 and 2015-10-10
2016	Image pair 1: 2016-02-29 and 2016-09-08 Image pair 2: 2016-03-02 and 2016-09-24
2017	Image pair 1: 2017-05-06 and 2017-10-29 Image pair 2: 2017-05-08 and 2017-11-30
2018	Image pair 1: 2018-02-02 and 2018-12-03 Image pair 2: 2018-03-06 and 2018-12-03 Image pair 3: 2018-04-07 and 2018-12-03 Image pair 4: 2018-02-02 and 2018-11-17 Image pair 5: 2018-03-06 and 2018-11-17 Image pair 6: 2018-04-08 and 2018-11-17

2.4. Displacement from NCC

We applied the NCC algorithm to Landsat data via the GEE platform. The dataset we chose has a multispectral spatial resolution of 30 m and a panchromatic resolution of 15 m. We calculated the maximum NCC between glacier surfaces of the image pair within a provided window. For image pairs, we compared window sizes ranging from (15 x 15) to (30 x 30), with a maximum allowable shift of 20 pixels. The selected window's surface area corresponds to 50,625 m² to 202,500 m² for Landsat 8 data. The NCC algorithm generated four images through the correlation of two glacier surfaces. The three output images of NCC represent the displacement estimations, i.e. delta-x for the displacement in the x-direction, delta-y for the displacement in the y-direction, and the Euclidean distance. The fourth image displays the maximum cross correlation between glacier surfaces of the image pair.

$$NCC_{xy} = \frac{1}{n}\sum_{x,y}\frac{(f(x,y) - \mu_f) * (g(x,y) - \mu_g)}{\sigma_f - \sigma_g} \tag{1}$$

Where n is number of pixels in image window f(x,y) and g(x,y). μf is mean of image window f and μf is standard deviation of f.

2.5. Maximization of NCC

In glacier velocity estimation, it's common to use a cloud-free, atmospherically corrected single image pair. However, such images are not always available due to various weather conditions such as cloud cover, haze, or high snowfall. To address this issue, we used a multi-image pair approach to enhance the accuracy of glacier velocity estimation.

We began by using the NCC algorithm to estimate the displacement of glacier surfaces from multiple sets of images, creating displacement and correlation image collections for each pair of images. Next, we estimated the velocity magnitude for each pair of images by considering the difference in days between them and the displacement image. Then, we identified the maximum correlation image by comparing the correlation image collection. Finally, I filtered out velocity image collection pixels with correlation equal to the maximum correlation using this maximum correlation image.

2.6. Filtering of low velocities

The methodology discussed in previous steps results in a precise glacier velocity estimate due to selection of velocity magnitude from maximum correlation among multiple image pairs. However, this method results in filtering out low velocity pixels as the morphology of glacier surface with low velocities does not generally alters. Hence, implementing this methodology to multiple image pairs will results in lower mean yearly glacier surface velocity that will not account for the actual velocity profile of the glacier in study.

To account the problem of lower glacier surface velocity pixels, we develop a python routine called the PyFilter that filters out low velocity pixels by putting higher velocities with fair correlation value. This routine first identifies the pixels with velocity less than 5% of the mean glacier velocity of the study area. It than fills these pixels with velocity for the second most largest correlation pixels. The method repeat for all pixels with velocity less than 5% and move to a lower correlation value filter. The method stops moving to lower correlation value when it reaches below 0.3 correlation value. This method sets the velocity of the highest correlation pixel velocity, for pixels with velocity less than 5% in each image pair having correlation above 0.3. These are the only piexls on which we obtain low glacier surface velocities after implementing PyFilter. The PyFilter then implements an averaging filter on the estimated glacier surface velocity and downscale to resulting velocity map to 300m spatial resolution.

3 Results and Discussion

3.1 GEEG-Vel noise removal

Glacier surface velocity estimation is an important factor in understanding the changes in glacier mass balance and dynamics, but it can be affected by various factors such as noise in satellite images and natural changes in glacier morphology. Atmospheric effects such as clouds, haze, and strong weather phenomena contribute to the noise in satellite images, which in turn can reduce the performance of normalized cross-correlation (NCC) in matching the similarity of glacier surfaces between two images. These issues highlight the need for improved methods that can account for these factors and reduce the impact of atmospheric effects on glacier surface velocity estimation.

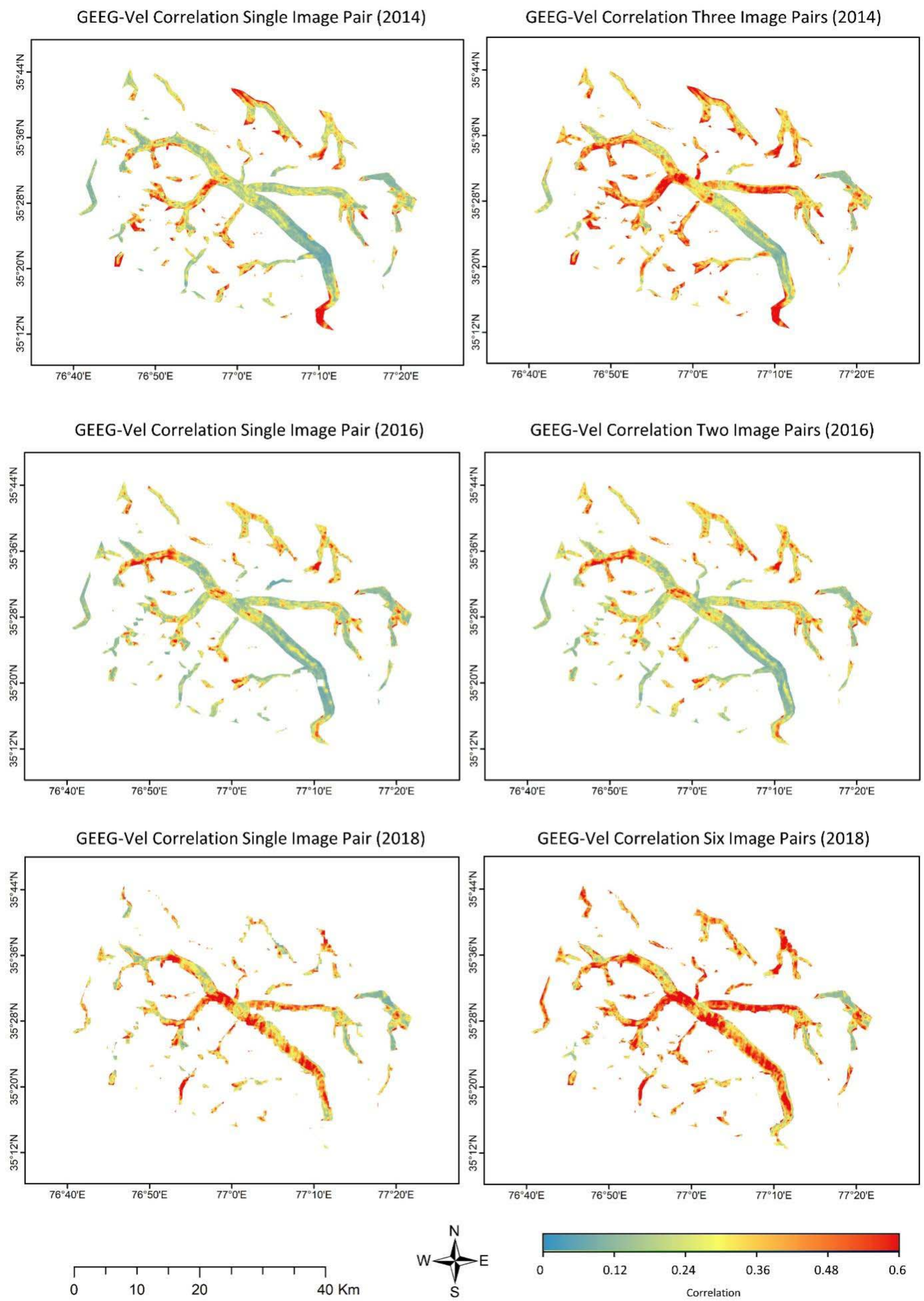


Figure 2. Correlation for single image pair and multi-image pair.

To address these issues, we have developed and tested a new method called GEEG-Vel, which uses multiple image pairs to improve the velocity estimate by maximizing the correlation. Figure 2 demonstrates the comparison of single image pair and multi-image pair correlation images. The results show that the correlation on the glacier surface is low in single image pair, while high correlation is observed in multi-image pair correlation images obtained from GEEG-Vel. The high correlation at the glacier surface is obtained by finding the maximum correlation among all the image pairs used for a single year glacier surface velocity estimation.

In Figure 3, the distribution of glacier velocity and correlation is presented for a single image pair obtained from feature tracking and multi-image pair obtained from GEEG-Vel. The findings suggest that the single image pair has lower 1st, 2nd, and 3rd quartiles of correlation values, while the multi-image pair has higher 1st, 2nd, and 3rd quartiles of correlation. Furthermore, the analysis shows that the mean velocity in the surrounding areas of the glacier is higher for the single image pair, whereas it is lower for the multi-image pair.

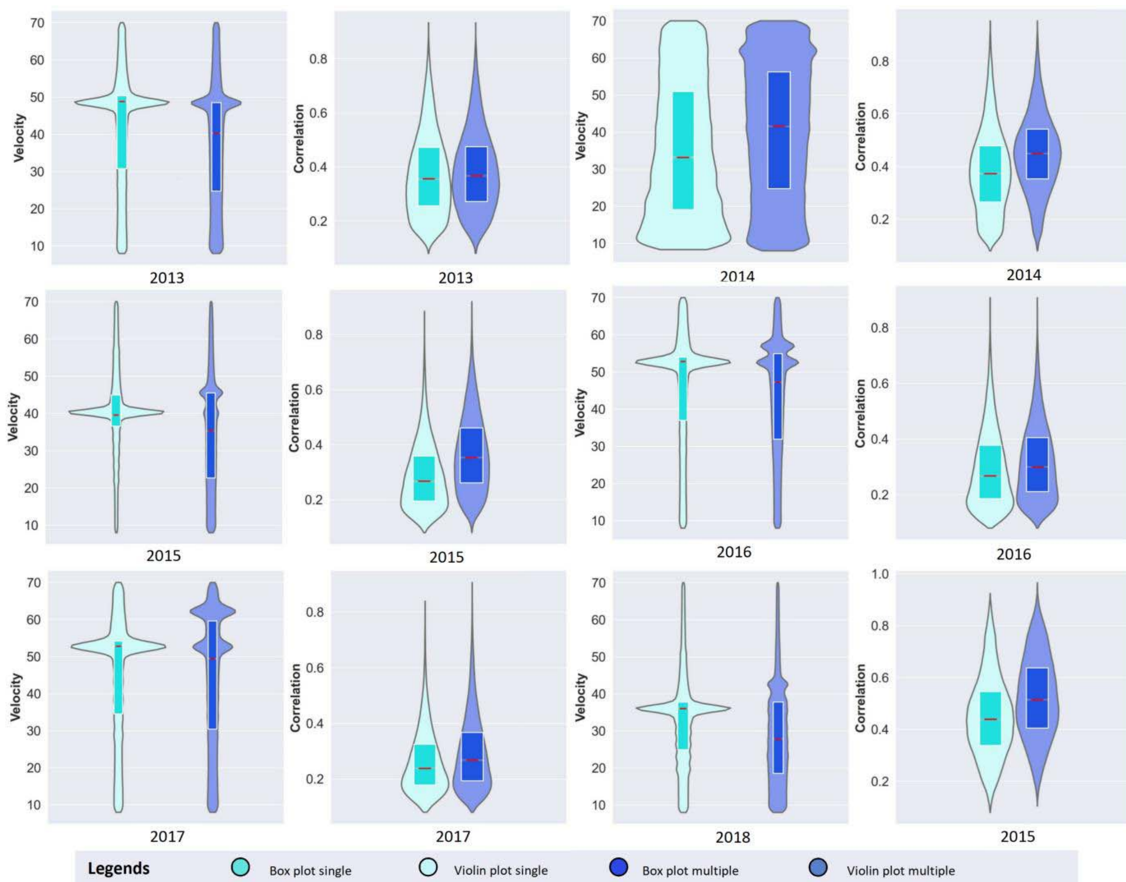


Figure 3. Comparison of distribution of correlation and velocity for single and multi-image pair.

3.2 GEEG-Vel with PyFilter

Upon conducting a comparison between GEEG-Vel and PyFilter, it was found that GEEG-Vel estimated velocities close to zero for many pixels on the glacier surface. This issue arose due to the methodology's selection of the highest correlation pixels from multiple image pairs, which could also include low-velocity pixels with minimal morphology changes over time. However, including these low-velocity pixels in the velocity estimation could significantly decrease the mean glacier velocity, even if the glacier surface moved considerably during the study period.

To address this issue, we developed PyFilter as explained in the methodology section. PyFilter significantly eliminated a large number of low-velocity pixels in the final velocity map obtained from GEEG-Vel, resulting in a more accurate estimation of glacier surface velocity as shown in Figure 4. It is important to note that using too many image pairs in GEEG-Vel may increase the correlation of glacier velocity estimation but at the cost of adding low-velocity pixels in the final velocity map.

3.3. Correlation between GEEG-Vel and ITS_LIVE

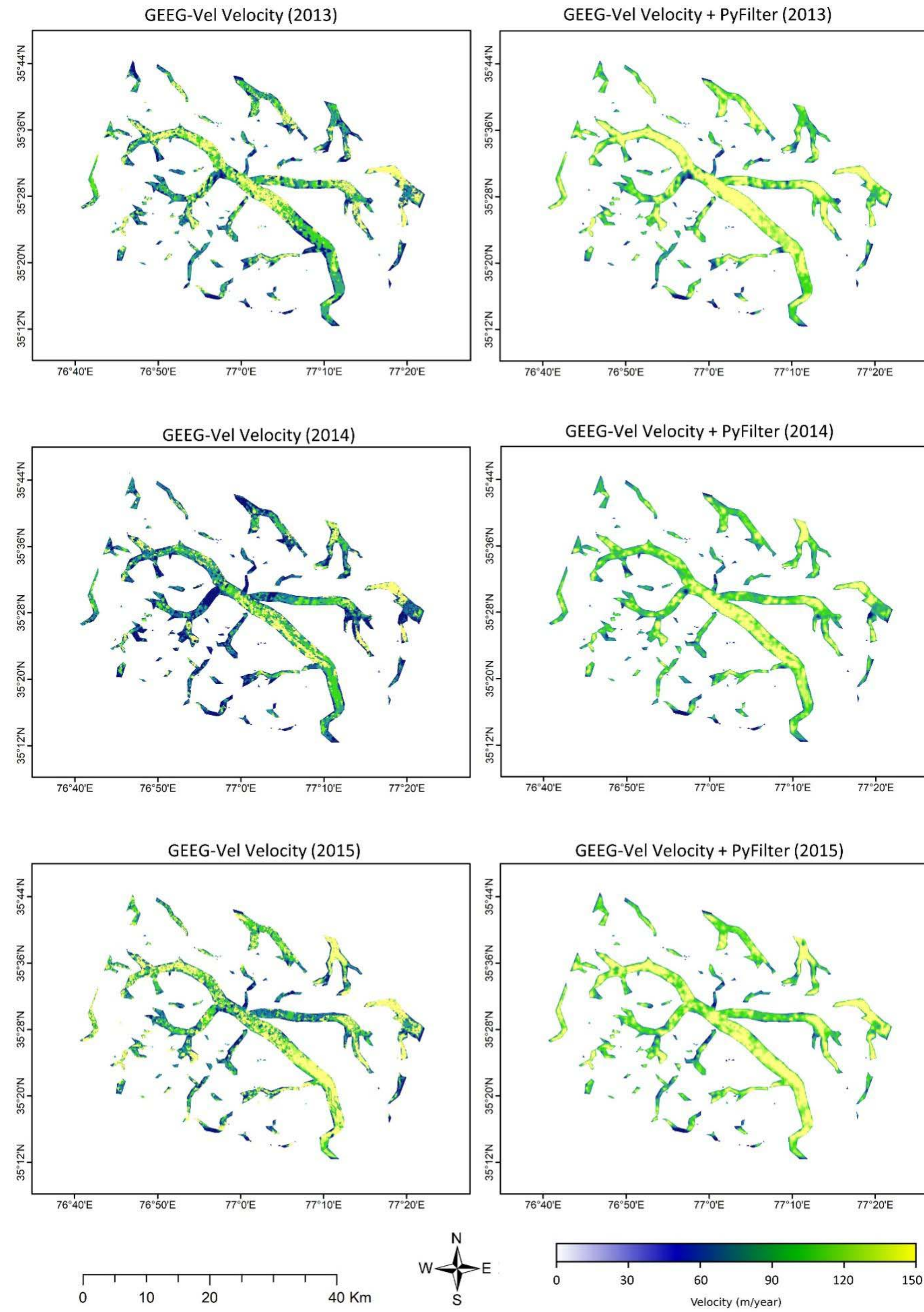
To evaluate the performance of the proposed methodology, we compared it with the widely used global glacier velocity dataset ITS_LIVE, which is based on multi-source remote sensing data including Sentinel-1 and Landsat 8. Figure 5 presents the comparison of glacier surface velocity estimated by the proposed method and ITS_LIVE for the period from 2013 to 2018. Pearson's correlation coefficient was computed to evaluate the correlation between the two methods, and the results showed a high correlation coefficient of >0.8 with a very high significance ($p\text{-value} \ll 0.05$), indicating a strong agreement between the two datasets. We observed a similar spatial distribution of glacier velocity for each year, which suggests that the proposed method can accurately capture glacier dynamics over time (Figure A1). The comparison with ITS_LIVE further highlights the potential of the proposed method for glacier surface velocity estimation from multi-temporal remote sensing data.

3.4. Statistical comparison

In this study, a circle of radius 600 meters was created with the center located on the glacier surface at five different latitude and longitude points, namely P1, P2, P3, P4, and P5. The mean and standard deviation of pixels within this circle were computed for both the proposed GEEG-Vel method and the ITS_LIVE glacier velocity estimate. Figure 6 displays the mean and standard deviation values of single and multi-pair GEEG-Vel velocity estimates, as well as the result of PyFilter and the reference ITS_LIVE statistics. While the GEEG-Vel mean may not always close to the ITS_LIVE glacier surface velocity, the mean glacier surface velocity of PyFilter is consistently within a range of ± 10 m/year from the ITS_LIVE mean velocity. This demonstrates the effectiveness of the proposed GEEG-Vel method in combination with PyFilter for accurate glacier velocity estimation.

4. Limitations

We performed the proposed methodology on the Landsat-8 dataset, demonstrating its applicability to other optical datasets such as Landsat-5, 7, and 9, and Sentinel-2 datasets. By utilizing multiple optical datasets, we can evaluate the proposed methodology's performance across various sensors and their spectral characteristics, providing a more robust analysis. However, it is important to note that the proposed methodology has only been tested on one study area. To validate its applicability across different glaciers and regions, further testing is required on other glaciers. Evaluating the proposed methodology on multiple glaciers will help to identify any potential limitations and improve its performance.


GEEG-Vel Velocity (2013)
GEEG-Vel Velocity + PyFilter (2013)
GEEG-Vel Velocity (2014)
GEEG-Vel Velocity + PyFilter (2014)
GEEG-Vel Velocity (2015)
GEEG-Vel Velocity + PyFilter (2015)
35°44'N
35°36'N
35°28'N
35°20'N
35°12'N
76°40'E
76°50'E
77°0'E
77°10'E
77°20'E
0
10
20
40 Km
N
W
E
S
0
30
60
90
120
150
Velocity (m/year)

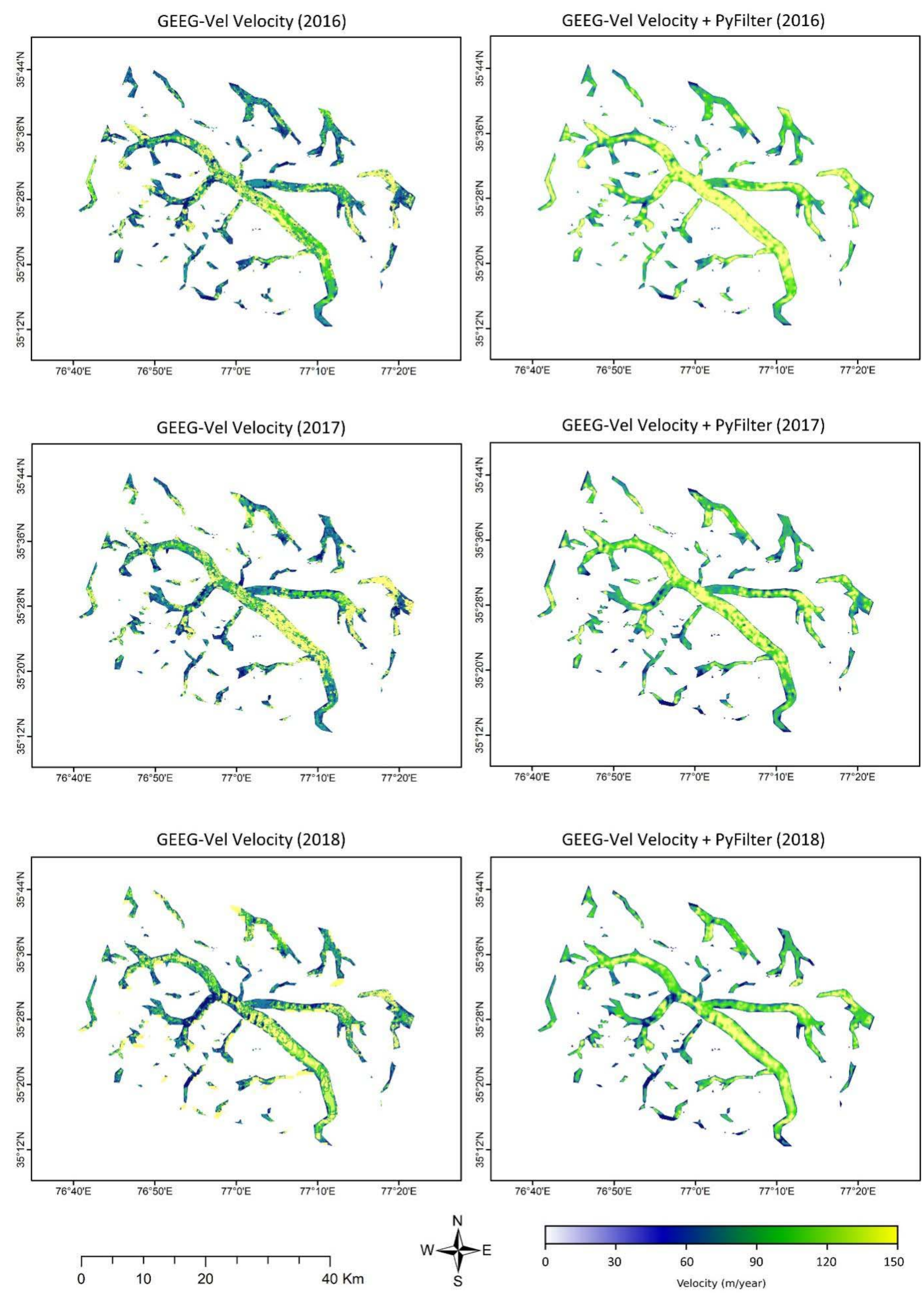


Figure 4. Comparison of GEEG-Vel and PyFilter glacier surface velocity.

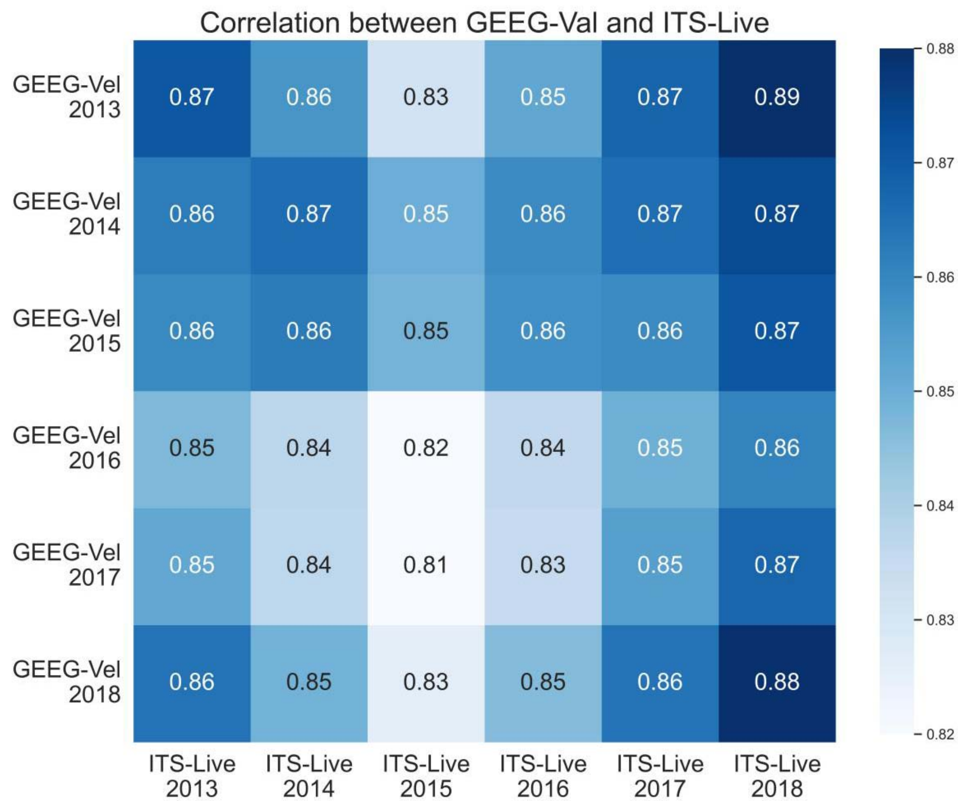


Figure 5. Pearson correlation of proposed method with ITS_LIVE glacier surface velocity with a p-value of less than 0.05.

5. Conclusion

We have developed a novel processing scheme that enables glacier surface velocity mapping with high temporal coverage. Our algorithm, named GEEG-Vel and PyFilter, offers short processing times, allowing for near-real-time velocity mapping from optical imagery. The proposed methodology was tested on Landsat-8 data and exhibited highly accurate velocity mapping when compared with ITS_LIVE velocity results. The applications of this methodology are vast, ranging from developing comprehensive glacier surface velocity mosaics to detailed velocity time series that support investigations in outlet glacier dynamics.

The rise of moderate-resolution imaging satellites and the proposed methodology that operates on Google Earth Engine (GEE) has enabled the implementation of a near-real-time processing system that offers comprehensive glacier velocity mapping at a global scale. With this capability, we are currently working towards an automated processing and distribution system that would produce glacier velocity maps from multi-sensor optical data in near real time, utilizing the same location image pairs with seasonal time separations.

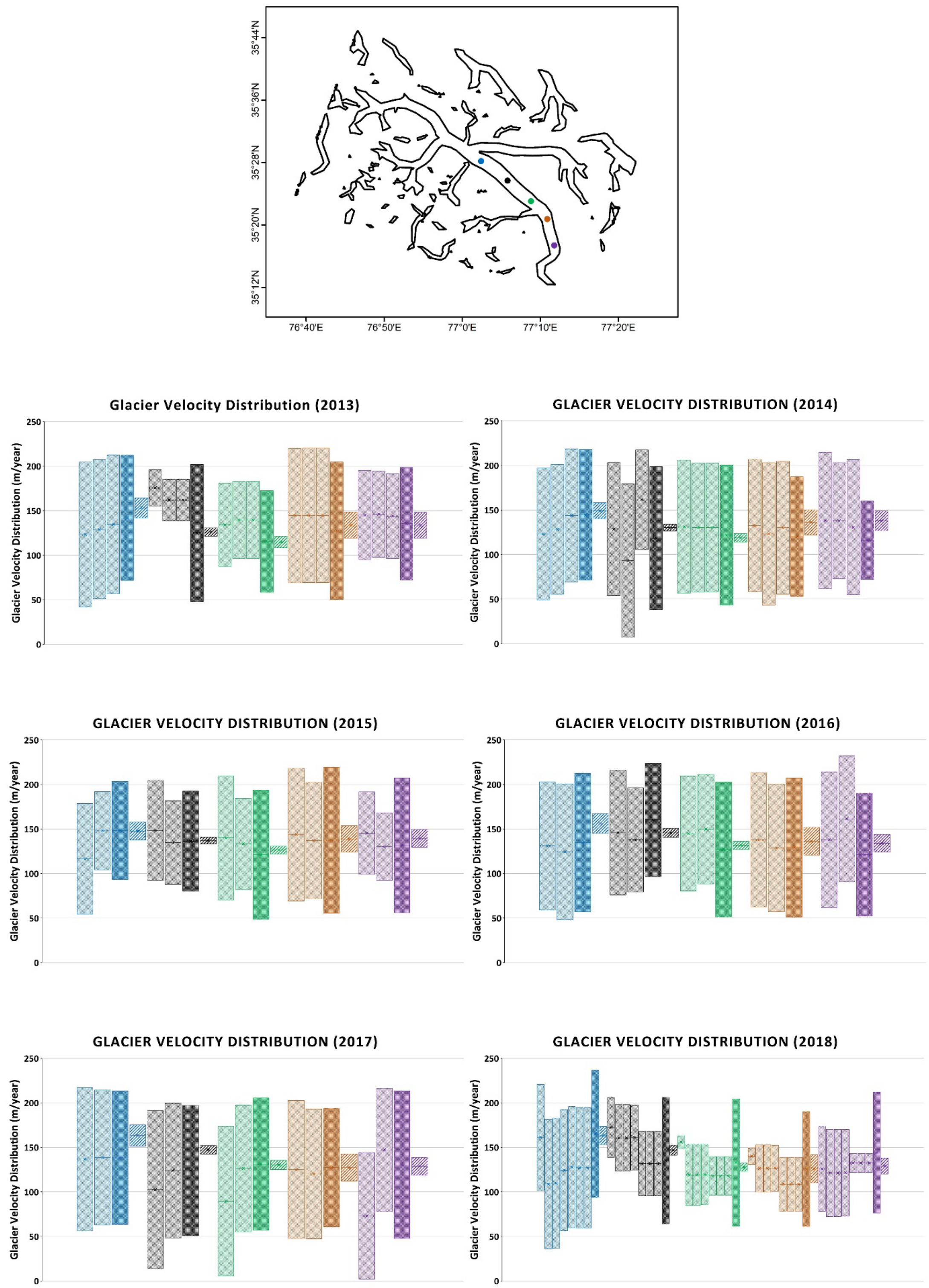


Figure 6. Mean and standard deviation values of single and multi-pair GEEG-Vel velocity estimates, as well as the result of PyFilter and the reference ITS_LIVE statistics.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT by OpenAI in order to improve language and readability. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Open Research

The Google Earth Engine implementation of this methodology is available at "https://code.earthengine.google.com/527a14c66b2da8b221bea023c86faea4" and can also be obtained by contacting the corresponding author.

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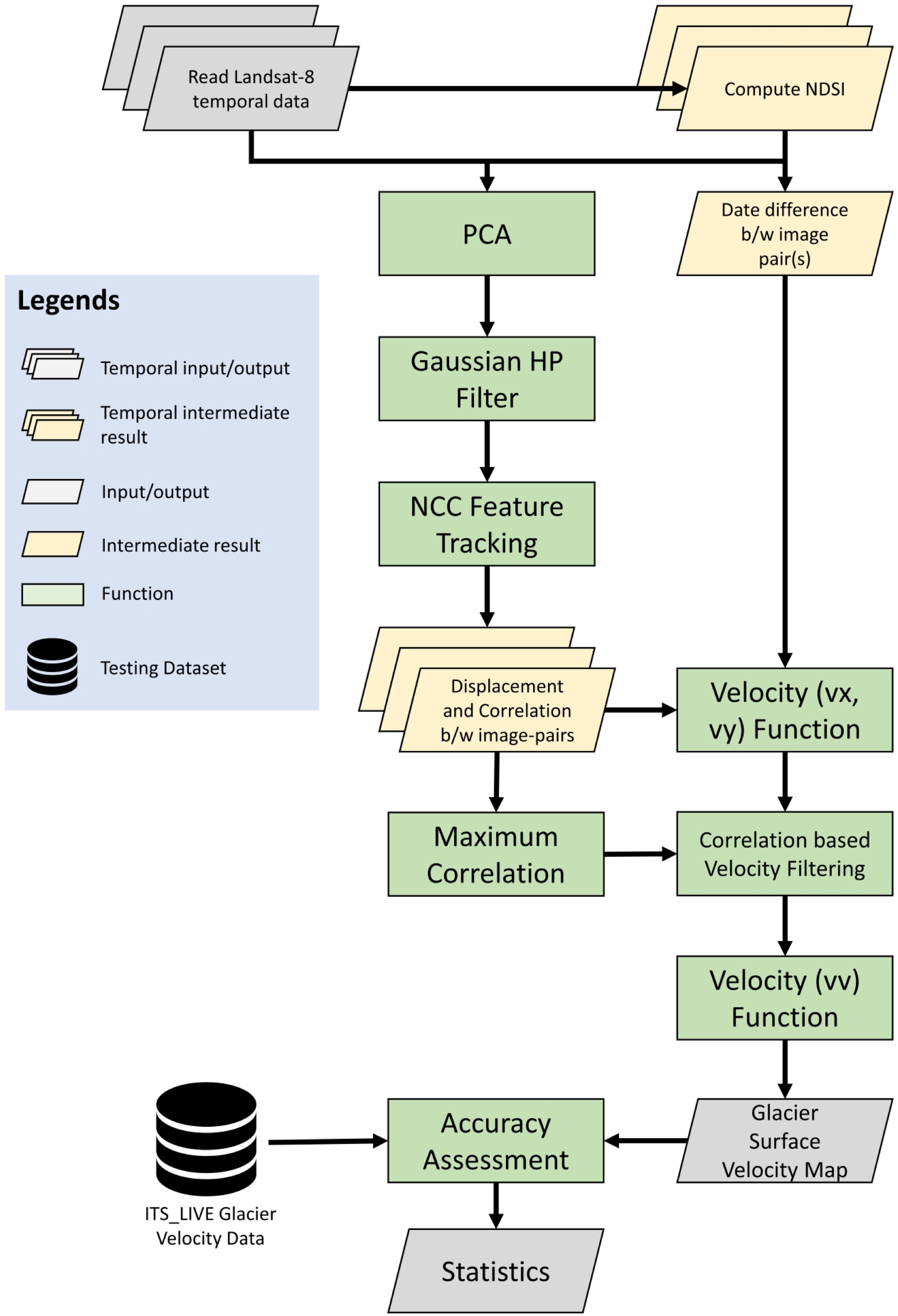
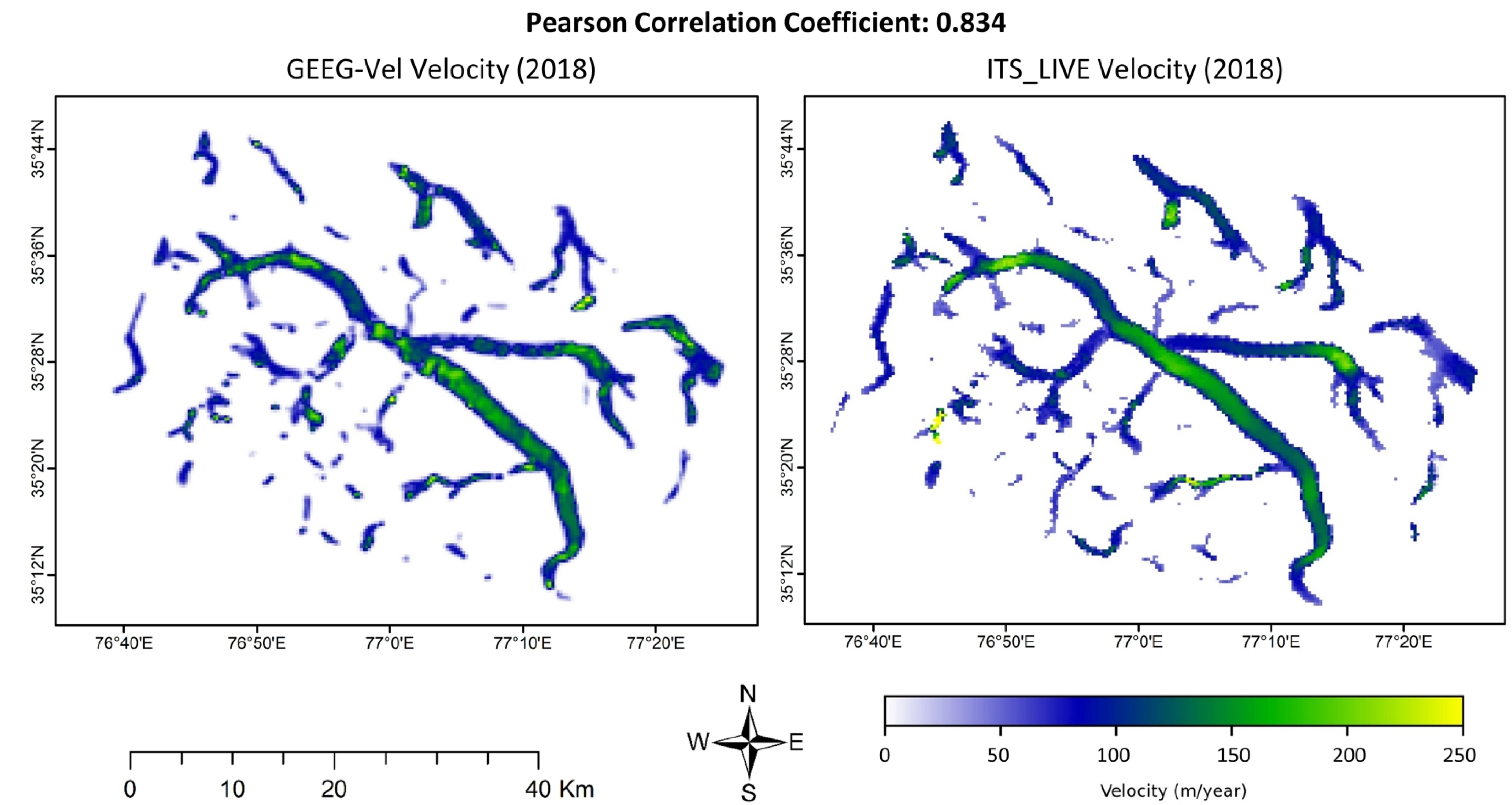
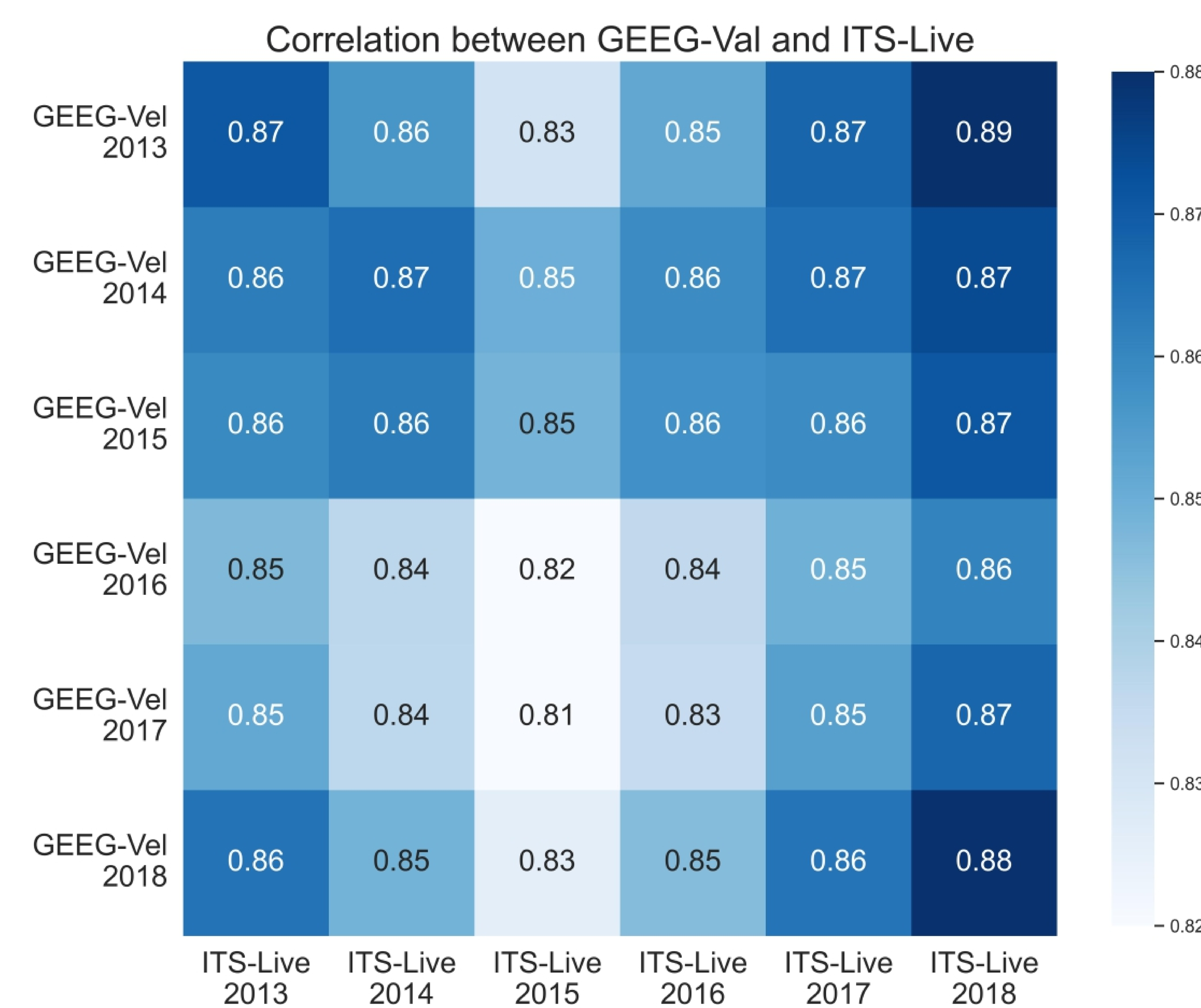
Graphical Abstract.



Read Landsat-8 temporal data
Compute NDSI
PCA
Date difference b/w image pair(s)
Gaussian HP Filter
NCC Feature Tracking
Displacement and Correlation b/w image-pairs
Velocity (vx, vy) Function
Maximum Correlation
Correlation based Velocity Filtering
Velocity (vv) Function
Glacier Surface Velocity Map
Accuracy Assessment
ITS_LIVE Glacier Velocity Data
Statistics
Legends
Temporal input/output
Temporal intermediate result
Input/output
Intermediate result
Function
Testing Dataset



Pearson Correlation Coefficient: 0.834
GEEG-Vel Velocity (2018)
ITS_LIVE Velocity (2018)
35°44'N
35°36'N
35°28'N
35°20'N
35°12'N
76°40'E
76°50'E
77°0'E
77°10'E
77°20'E
0
10
20
40 Km
N
W
E
S
0
50
100
150
200
250
Velocity (m/year)



Correlation between GEEG-Val and ITS-Live
GEEG-Vel 2013
0.87 0.86 0.83 0.85 0.87 0.89
GEEG-Vel 2014
0.86 0.87 0.85 0.86 0.87 0.87
GEEG-Vel 2015
0.86 0.86 0.85 0.86 0.86 0.87
GEEG-Vel 2016
0.85 0.84 0.82 0.84 0.85 0.86
GEEG-Vel 2017
0.85 0.84 0.81 0.83 0.85 0.87
GEEG-Vel 2018
0.86 0.85 0.83 0.85 0.86 0.88
ITS-Live 2013
ITS-Live 2014
ITS-Live 2015
ITS-Live 2016
ITS-Live 2017
ITS-Live 2018
0.88
0.87
0.86
0.85
0.84
0.83
0.82

Figure 1. Processing steps of proposed GEEG-Vel algorithm..


Read Landsat-8 temporal data
Compute NDSI
PCA
Date difference b/w image pair(s)
Legends
Temporal input/output
Temporal intermediate result
Input/output
Intermediate result
Function
Testing Dataset
Gaussian HP Filter
NCC Feature Tracking
Displacement and Correlation b/w image-pairs
Velocity (vx, vy) Function
Maximum Correlation
Correlation based Velocity Filtering
Velocity (vv) Function
ITS_LIVE Glacier Velocity Data
Accuracy Assessment
Glacier Surface Velocity Map
Statistics

Figure 2. Correlation for single image pair and multi-image pair..


GEEG-Vel Correlation Single Image Pair (2014)
GEEG-Vel Correlation Three Image Pairs (2014)
GEEG-Vel Correlation Single Image Pair (2016)
GEEG-Vel Correlation Two Image Pairs (2016)
GEEG-Vel Correlation Single Image Pair (2018)
GEEG-Vel Correlation Six Image Pairs (2018)
35°44'N
35°36'N
35°28'N
35°20'N
35°12'N
76°40'E
76°50'E
77°0'E
77°10'E
77°20'E
0
10
20
40 Km
N
W
E
S
0
0.12
0.24
0.36
0.48
0.6
Correlation

Figure 3. Comparison of distribution of correlation and velocity for single and multi-image pair..


Velocity
Correlation
2013
2013
2014
2014
2015
2015
2016
2016
2017
2017
2018
2015
Legends
Box plot single
Violin plot single
Box plot multiple
Violin plot multiple

Figure 4(a). Comparison of GEEG-Vel and PyFilter glacier surface velocity..


GEEG-Vel Velocity (2013)
GEEG-Vel Velocity + PyFilter (2013)
GEEG-Vel Velocity (2014)
GEEG-Vel Velocity + PyFilter (2014)
GEEG-Vel Velocity (2015)
GEEG-Vel Velocity + PyFilter (2015)
35°44'N
35°36'N
35°28'N
35°20'N
35°12'N
76°40'E
76°50'E
77°0'E
77°10'E
77°20'E
0
10
20
40 Km
N
W
E
S
0
30
60
90
120
150
Velocity (m/year)

Figure 4(b). Comparison of GEEG-Vel and PyFilter glacier surface velocity..


GEEG-Vel Velocity (2016)
GEEG-Vel Velocity + PyFilter (2016)
GEEG-Vel Velocity (2017)
GEEG-Vel Velocity + PyFilter (2017)
GEEG-Vel Velocity (2018)
GEEG-Vel Velocity + PyFilter (2018)
35°44'N
35°36'N
35°28'N
35°20'N
35°12'N
76°40'E
76°50'E
77°0'E
77°10'E
77°20'E
0
10
20
40 Km
N
W
E
S
0
30
60
90
120
150
Velocity (m/year)

Figure 5. Pearson correlation of proposed method with ITS_LIVE glacier surface velocity with a p-value of less than 0.05..

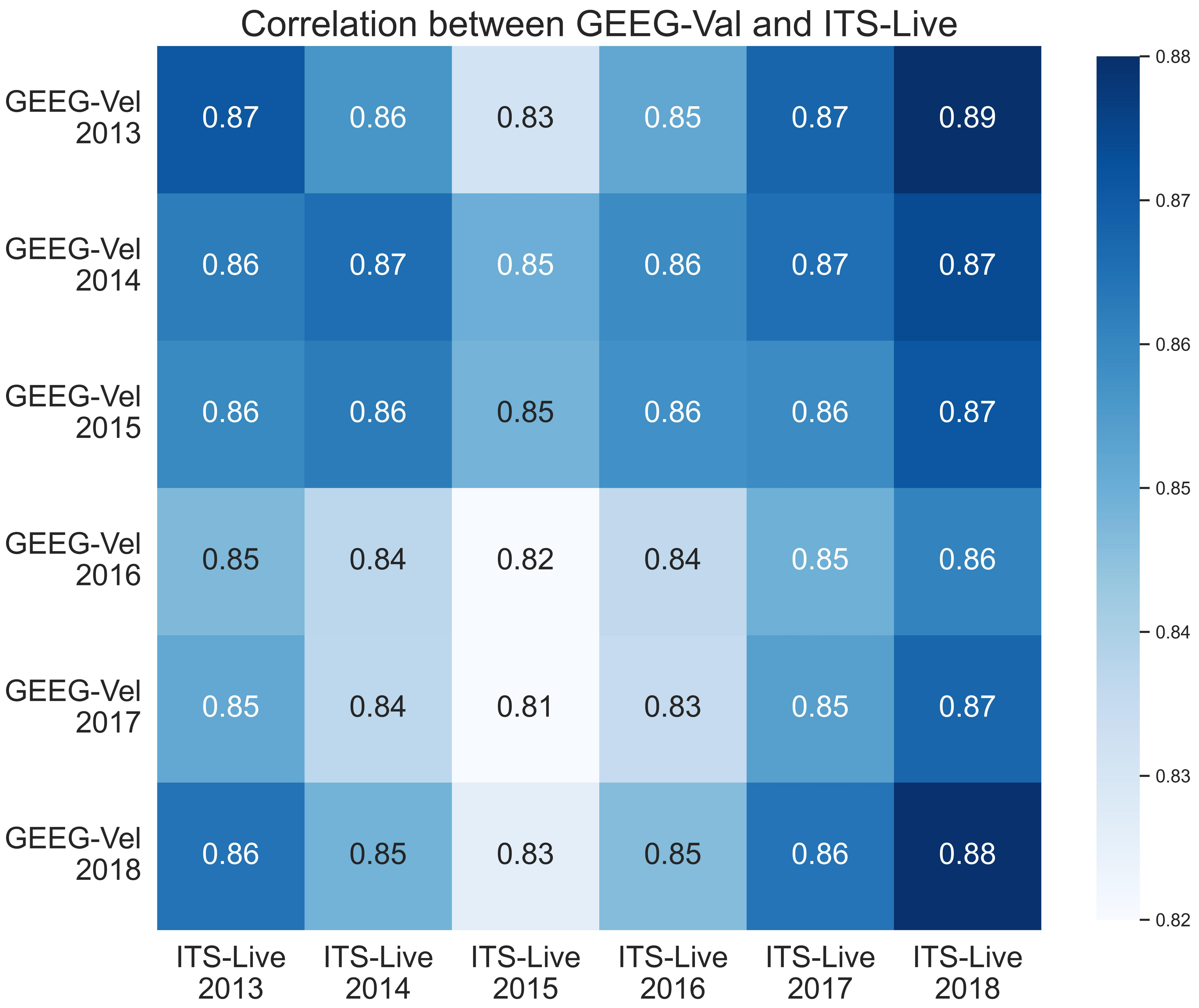
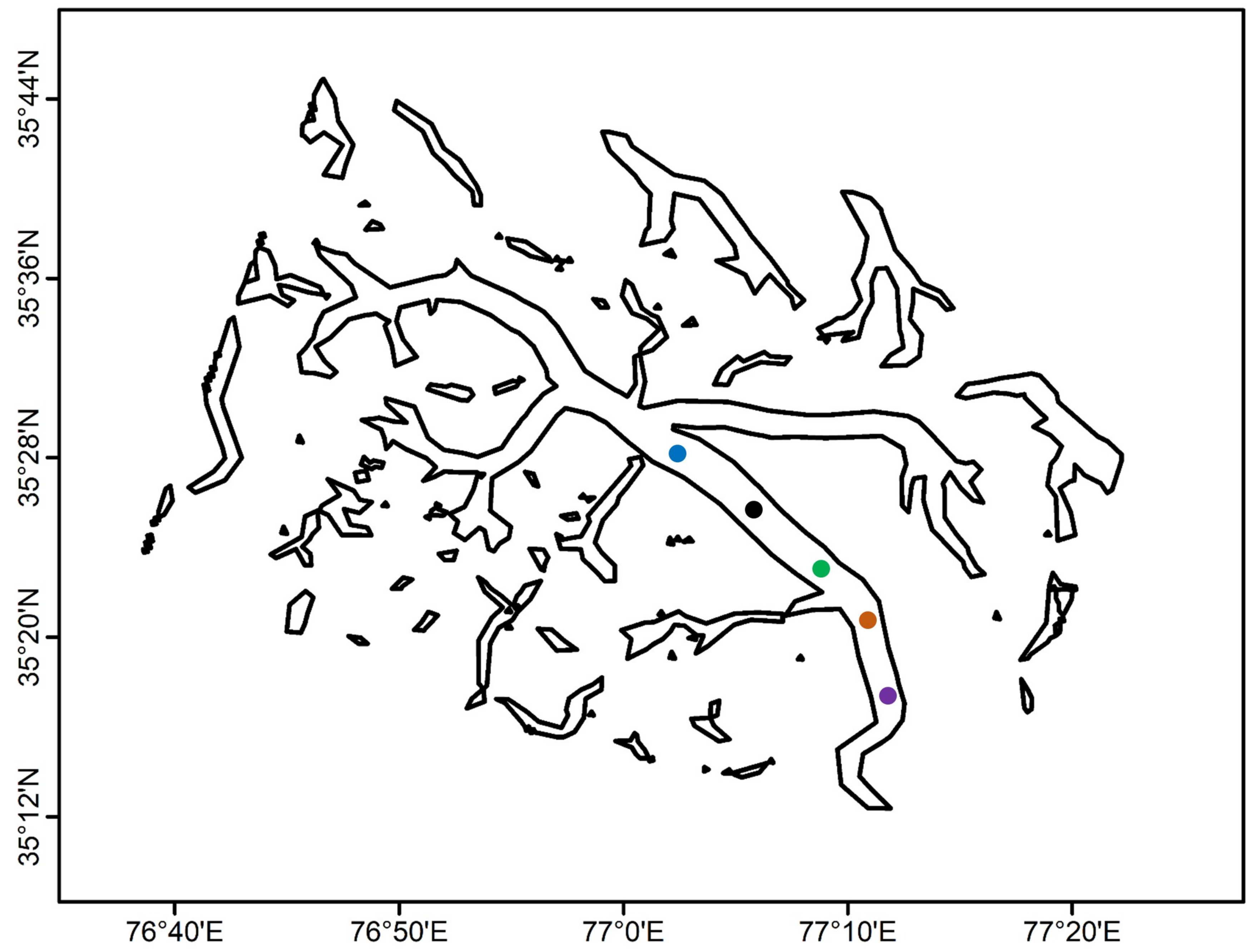
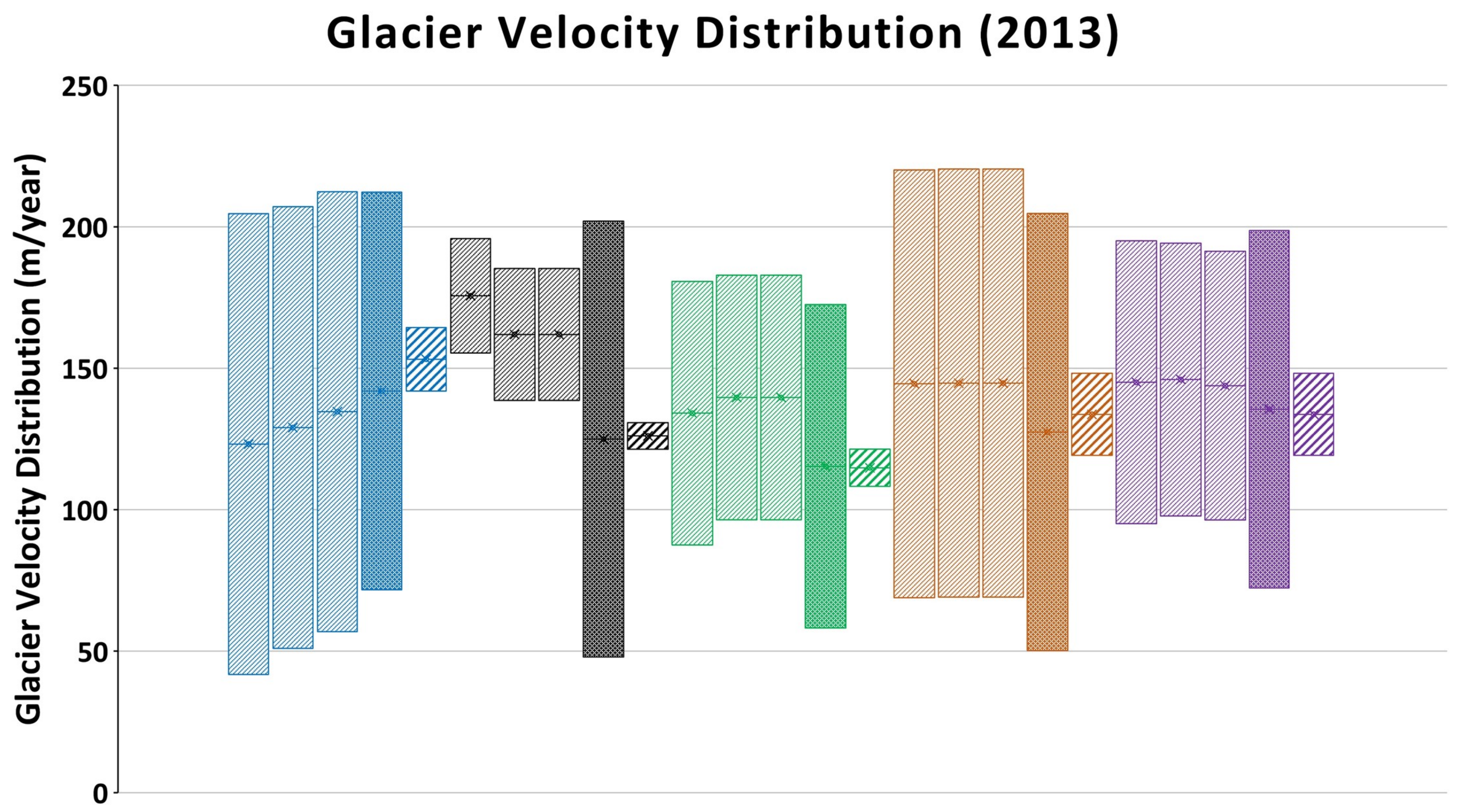
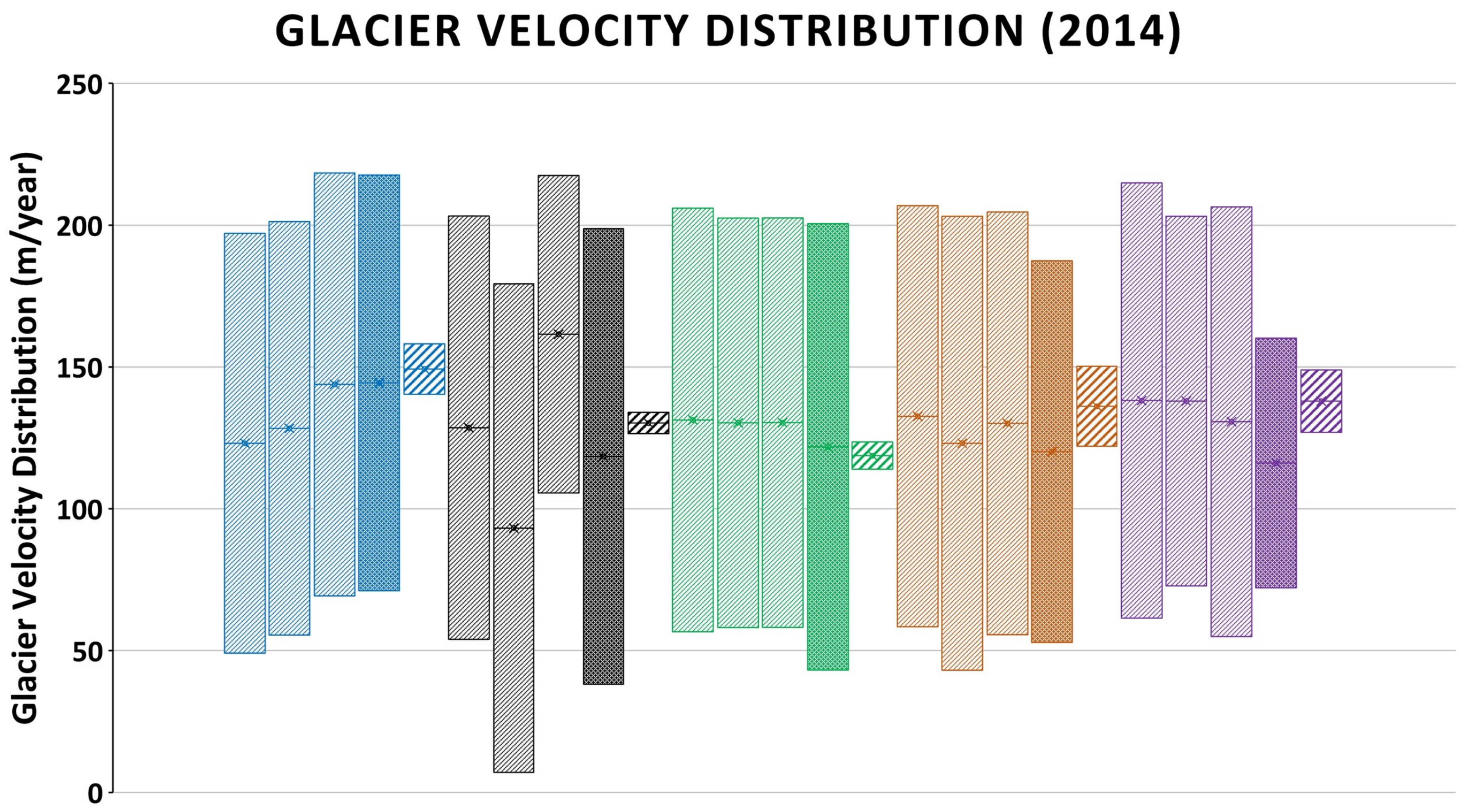
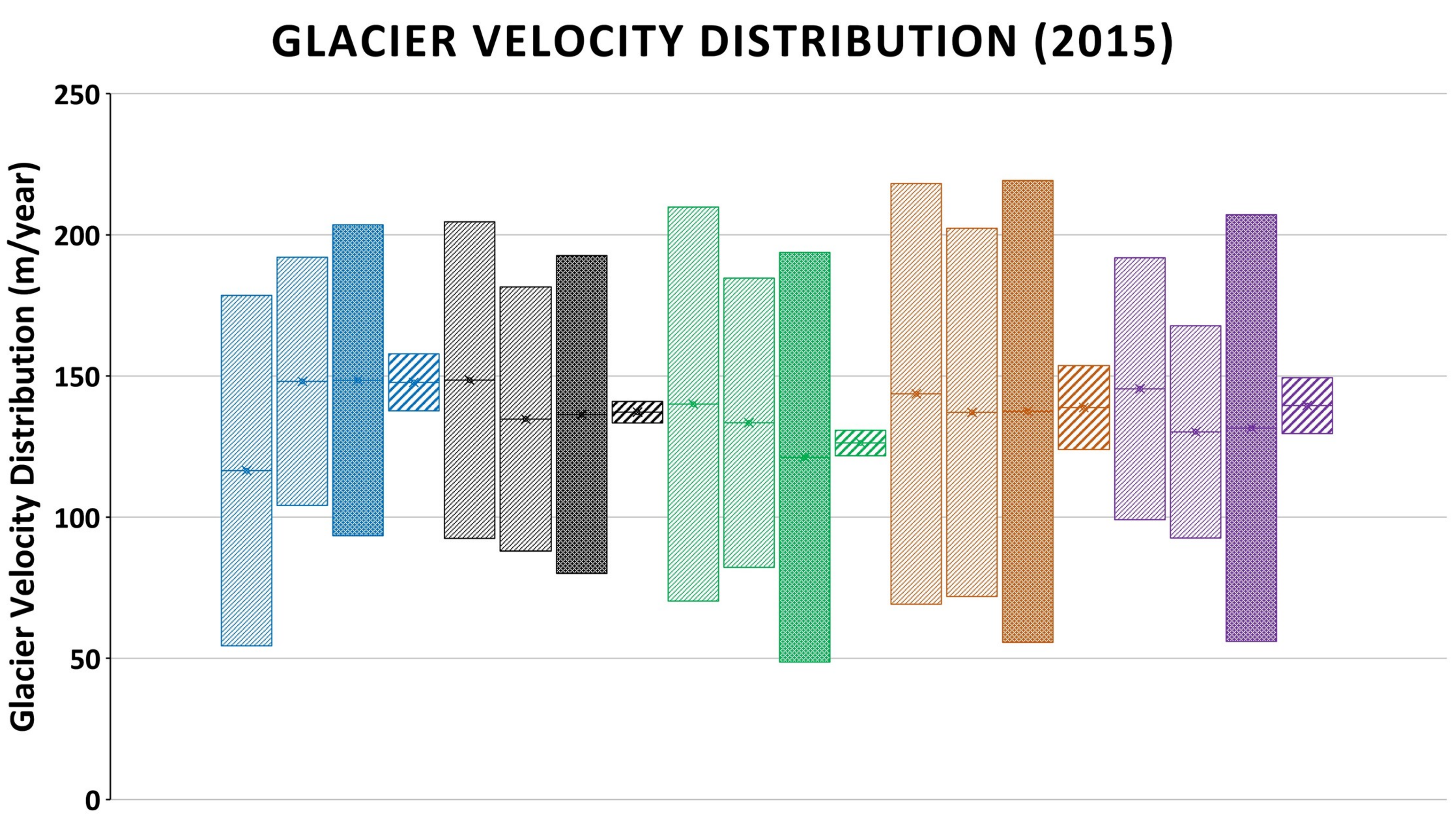

Correlation between GEEG-Val and ITS-Live
GEEG-Vel 2013
GEEG-Vel 2014
GEEG-Vel 2015
GEEG-Vel 2016
GEEG-Vel 2017
GEEG-Vel 2018
ITS-Live 2013
ITS-Live 2014
ITS-Live 2015
ITS-Live 2016
ITS-Live 2017
ITS-Live 2018
0.87 0.86 0.83 0.85 0.87 0.89
0.86 0.87 0.85 0.86 0.87 0.87
0.86 0.86 0.85 0.86 0.86 0.87
0.85 0.84 0.82 0.84 0.85 0.86
0.85 0.84 0.81 0.83 0.85 0.87
0.86 0.85 0.83 0.85 0.86 0.88
0.88
0.87
0.86
0.85
0.84
0.83
0.82

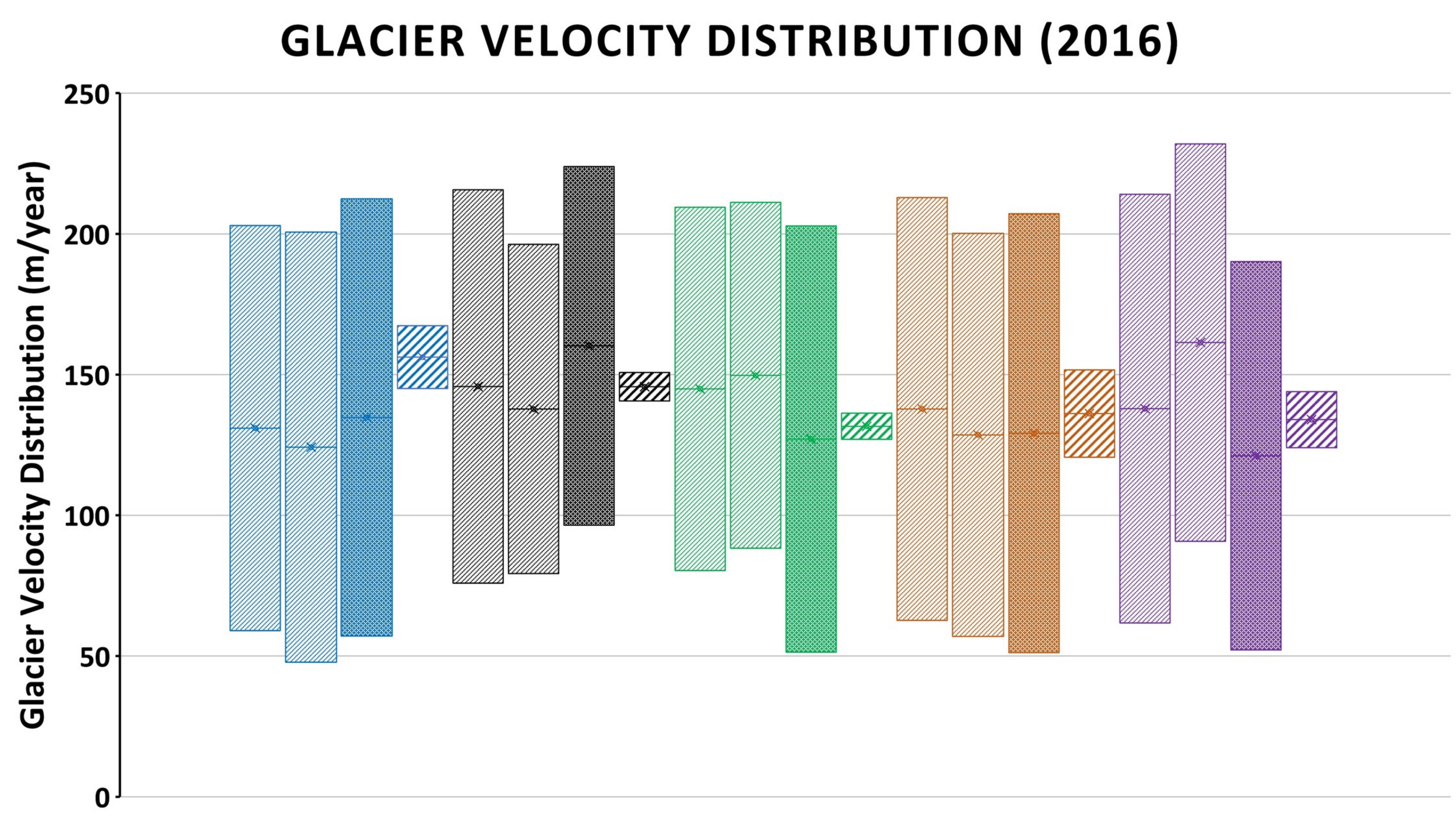
Figure 6. Mean and standard deviation values of single and multi-pair GEEG-Vel velocity estimates, as well as the result of PyFilter and the reference ITS_LIVE statistics..

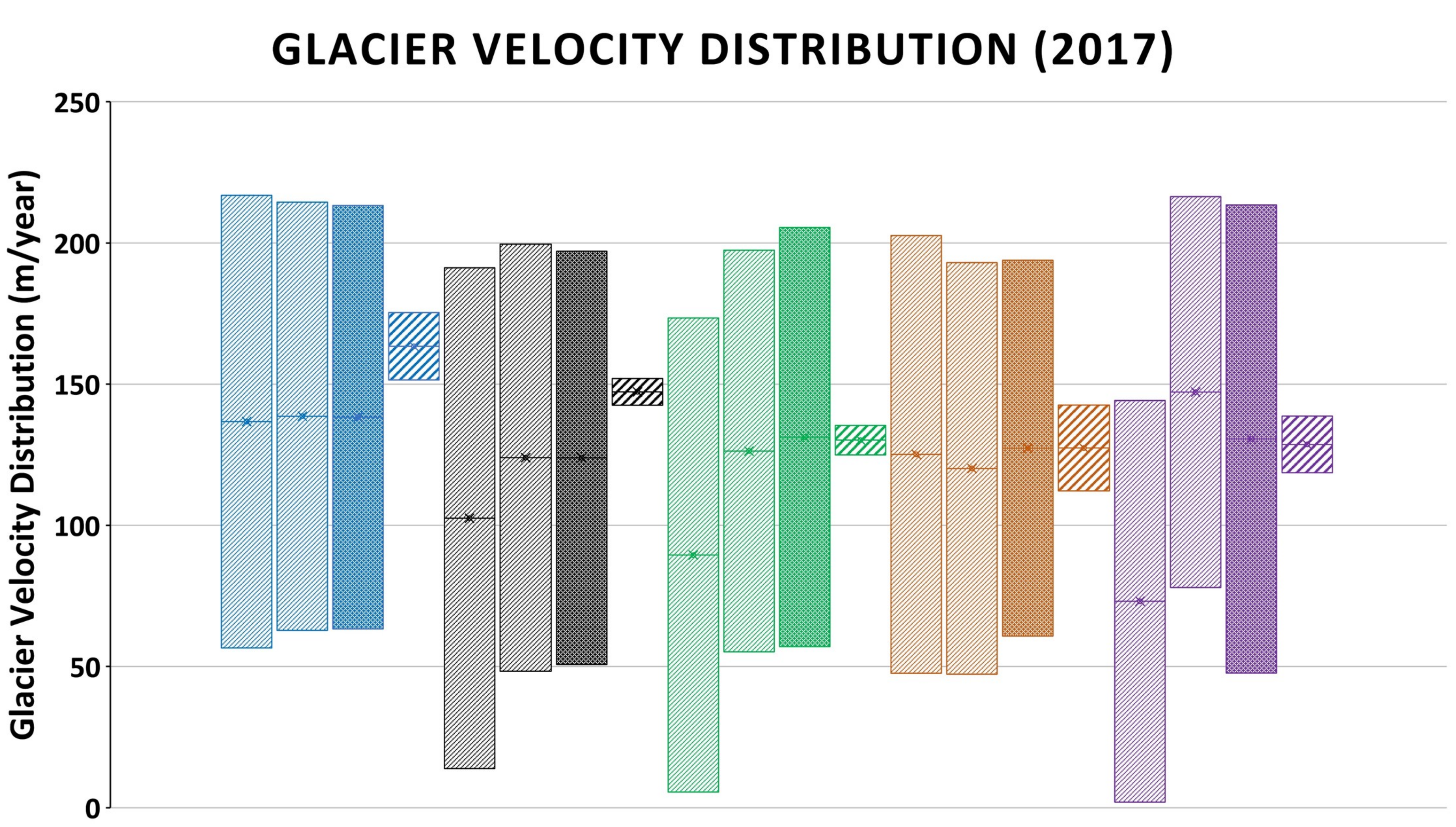

35°44'N
35°36'N
35°28'N
35°20'N
35°12'N
76°40'E
76°50'E
77°0'E
77°10'E
77°20'E


Glacier Velocity Distribution (2013)
Glacier Velocity Distribution (m/year)
0
50
100
150
200
250


GLACIER VELOCITY DISTRIBUTION (2014)
Glacier Velocity Distribution (m/year)
0
50
100
150
200
250


GLACIER VELOCITY DISTRIBUTION (2015)
Glacier Velocity Distribution (m/year)
0
50
100
150
200
250


GLACIER VELOCITY DISTRIBUTION (2016)
Glacier Velocity Distribution (m/year)
0
50
100
150
200
250


GLACIER VELOCITY DISTRIBUTION (2017)
Glacier Velocity Distribution (m/year)
0
50
100
150
200
250

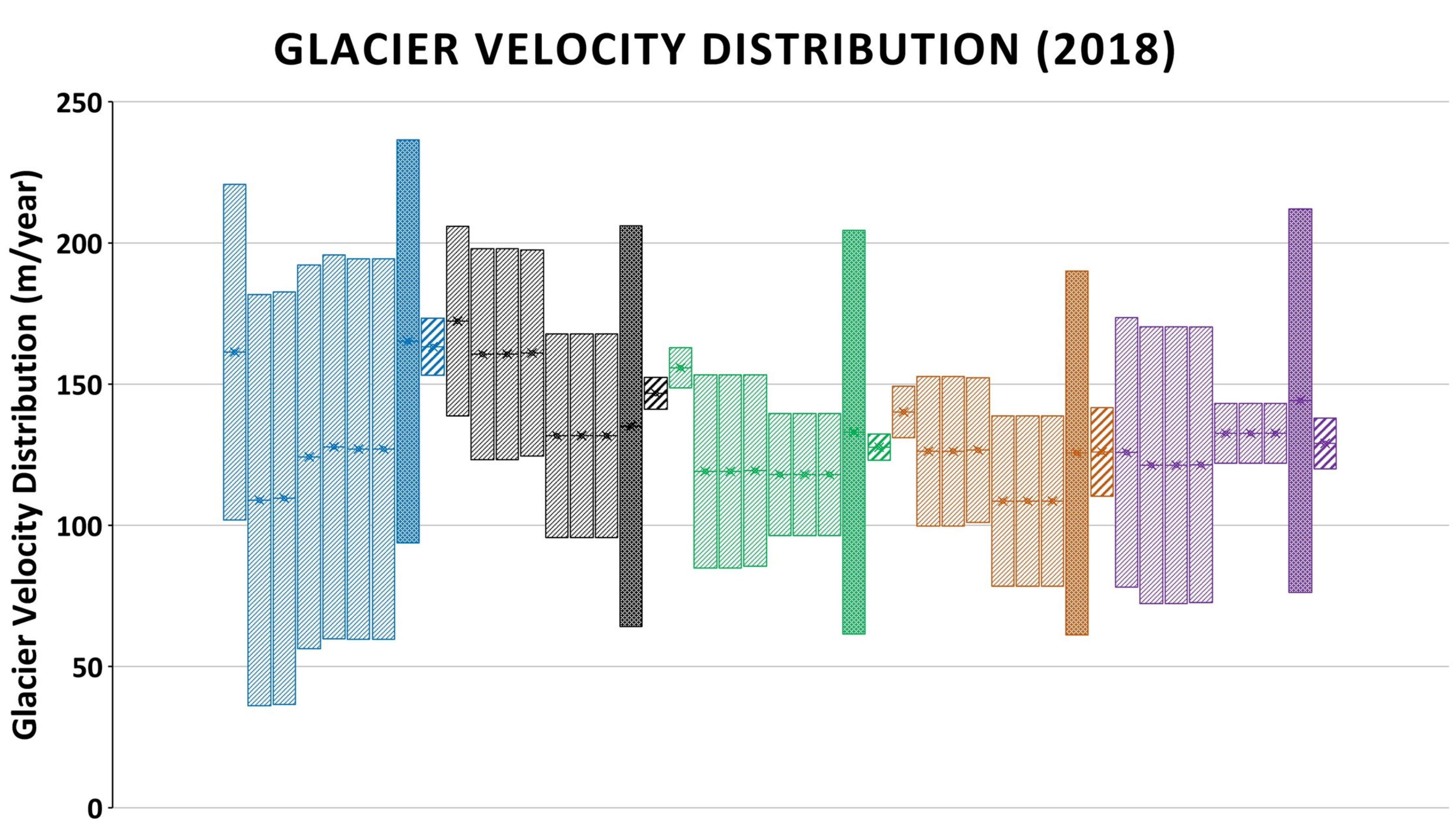

GLACIER VELOCITY DISTRIBUTION (2018)
Glacier Velocity Distribution (m/year)
0
50
100
150
200
250

Figure A1(a). Testing of proposed method with ITS_LIVE glacier surface velocity..


Pearson Correlation Coefficient: 0.856
GEEG-Vel Velocity (2013)
ITS_LIVE Velocity (2013)
Pearson Correlation Coefficient: 0.861
GEEG-Vel Velocity (2014)
ITS_LIVE Velocity (2014)
Pearson Correlation Coefficient: 0.871
GEEG-Vel Velocity (2015)
ITS_LIVE Velocity (2015)
35°44'N
35°36'N
35°28'N
35°20'N
35°12'N
76°40'E
76°50'E
77°0'E
77°10'E
77°20'E
0
10
20
40 Km
N
W
E
S
0
50
100
150
200
250
Velocity (m/year)

Figure A1(b). Testing of proposed method with ITS_LIVE glacier surface velocity..


Pearson Correlation Coefficient: 0.856
GEEG-Vel Velocity (2016)
ITS_LIVE Velocity (2016)
Pearson Correlation Coefficient: 0.832
GEEG-Vel Velocity (2017)
ITS_LIVE Velocity (2017)
Pearson Correlation Coefficient: 0.834
GEEG-Vel Velocity (2018)
ITS_LIVE Velocity (2018)
35°44'N
35°36'N
35°28'N
35°20'N
35°12'N
76°40'E
76°50'E
77°0'E
77°10'E
77°20'E
0
10
20
40 Km
N
W
E
S
0
50
100
150
200
250
Velocity (m/year)

Table 1. List of datasets used in this study.

Year	Image pairs
2013	Image pair 1: 2013-03-22 and 2013-11-03 Image pair 2: 2013-03-22 and 2013-07-30 Image pair 3: 2013-03-22 and 2013-07-14
2014	Image pair 1: 2014-04-28 and 2014-06-15 Image pair 2: 2014-04-28 and 2014-09-19 Image pair 3: 2014-04-28 and 2014-10-21
2015	Image pair 1: 2015-01-09 and 2015-10-08 Image pair 2: 2015-01-11 and 2015-10-10
2016	Image pair 1: 2016-02-29 and 2016-09-08 Image pair 2: 2016-03-02 and 2016-09-24
2017	Image pair 1: 2017-05-06 and 2017-10-29 Image pair 2: 2017-05-08 and 2017-11-30
2018	Image pair 1: 2018-02-02 and 2018-12-03 Image pair 2: 2018-03-06 and 2018-12-03 Image pair 3: 2018-04-07 and 2018-12-03 Image pair 4: 2018-02-02 and 2018-11-17 Image pair 5: 2018-03-06 and 2018-11-17 Image pair 6: 2018-04-08 and 2018-11-17