Measuring the state and temporal evolution of glaciers in Alaska and Yukon using SAR-derived 3D time series of glacier surface flow

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Abstract. Climate change has reduced global ice mass over the last two decades as enhanced warming has accelerated surface melt and runoff rates. Additionally, glaciers have undergone dynamic processes in response to a warming climate that impacts the surface geometry and mass distribution of glacial ice. However, until recently no single technique could consistently measure the evolution of surface flow for an entire glaciated region in three dimensions with high temporal and spatial resolution. We have developed such a technique and use it to map, in unprecedented detail, the temporal evolution of glaciers in southeastern Alaska during 2016-2020. We observe seasonal and interannual variations in flow velocities at Seward and Malaspina glaciers as well as culminating phases of surging at Klutlan, Walsh and Kluane glaciers. On a broader scale, this technique can be used for reconstructing the response of worldwide glaciers to the warming climate using nearly 30 years of archived SAR data and for near real-time monitoring of these glaciers using rapid revisit SAR data from satellites, such as Sentinel-1 (6 or 12 days revisit period) and the forthcoming NISAR mission (12 days revisit period).

1 Introduction

Glacier dynamics, specifically the direction and intensity of glacier flow, adjust in response to the warming climate, leading to changes in seasonal flooding and droughts, landscapes and habitats, and ultimately sea-level variations. Surface flow is a key variable for determining glacier mass balance (Shepherd et al., 2020), ice thickness (Morlighem et al., 2011; Werder et al., 2019) and surface mass balance (Bisset et al., 2020). Here we present a technique that can be used for measuring the temporal evolution of surface flow for an entire glaciated region in three dimensions (3D) with high temporal and spatial resolution.

Modern techniques and platforms used for monitoring glacier flow include Synthetic Aperture Radar (SAR) (Goldstein et al., 1993; Mohr et al., 1998; Rignot, 2002; Joughin, 2002), Global Navigation Satellite System (GNSS) (van de Wal et al., 2008; Bartholomew et al., 2010), optical imagery (Berthier et al., 2005; Herman et al., 2011; Dehecq et al., 2015; Fahnestock et al., 2016), and uncrewed aerial vehicles (Immerzeel et al., 2014). Among these, SAR is the only active side-looking sensor with global coverage at high temporal and spatial resolutions that can operate in any weather conditions, day or night. SAR techniques comprise meter-scale speckle offset tracking (SPO) (Strozzi et al., 2002), which is used in this study, and split-beam interferometry (or multi-aperture interferometry, MAI) (Bechor and Zebker, 2006; Gourmelen et al., 2011), and centimeter-

scale differential interferometry (DInSAR) (Massonnet and Feigl, 1995; Rosen et al., 2000). SPO applies image correlation algorithms to radar data to measure displacements in the satellite range and azimuth directions using two SAR images. Since its early inception SAR has been used in glacier monitoring for estimating flow velocities, surface flux, tidal variations, grounding line behaviour and subglacial lake activity (Goldstein et al., 1993; Joughin et al., 1995, 1998; Rignot, 1998; Shepherd et al., 2001; Gray et al., 2005; Palmer et al., 2010; Minchew et al., 2017).

The SAR-derived displacements for a single epoch can be transformed into 3D (north, east, vertical) displacements by either combining multiple data sets or assuming various model constraints (Mohr et al., 1998; Wright et al., 2004; Gourmelen et al., 2007; Kumar et al., 2011; Hu et al., 2014). However, the 3D displacement time series cannot be easily computed due to limitations inherent in the data acquisition strategy, i.e. SAR data on ascending and descending orbits are usually acquired at different days, often with different incidence angles, temporal and spatial resolutions and even wavelengths. The Multidimensional Small Baseline Subset (MSBAS) methodology (Samsonov and d'Oreye, 2012, 2017; Samsonov, 2019; Samsonov et al., 2020) has been developed especially for computing multidimensional displacement time series from SAR data acquired with different acquisition parameters.

Historically, three components of mean glacier velocity were computed from DInSAR and/or range offsets by introducing a surface-parallel flow (SPF) constraint. This approach was used for 3D mapping of Greenlandic (Joughin et al., 1998; Mohr et al., 1998) and Himalayan (Kumar et al., 2011) glaciers and validated by independent GPS (Kumar et al., 2011) measurements. In our previous work (Samsonov, 2019), we adopted the SPF method for computing the 3D flow displacement time series of the Barnes Ice Cap using ascending and descending DInSAR data combined using MSBAS technique. However, the SPF constraint ignores submergence and emergence velocities and other vertical motion. In some studies, ascending and descending DInSAR (Gray, 2011) or range and azimuth offsets (Wang et al., 2019) were used to compute 3D glacier velocities for a few isolated epochs. Recently, Guo et al. (2020) developed a technique based on MSBAS that computes 3D flow velocity time series from ascending and descending range and azimuth offsets and used it for studying Hispar Glacier in Central Karakoram. Here, we present our independently developed version of this algorithm. Our software provides additional functionalities, such as zeroth, first (implemented in Guo et al. (2020)) and second-order Tikhonov regularizations, and the ability to produce 1D, 2D, constrained 3D, unconstrained 3D (presented in this manuscript), and 4D (Samsonov et al., 2021) velocity and/or displacement time series. The software is also parallelized (OpenMP, MPI), making it suitable for running on personal workstations and high-performance computers. It is provided to the research community free of charge.

In contrast to MSBAS-based techniques, Minchew et al. (2017) and Milillo et al. (2017), took a different approach and inferred time-dependent 3D flow velocity by assuming a form for the temporal basis functions based on prior knowledge of the study area. The need for prior knowledge means that this method is not general and so its application is limited to areas where the assumed basis functions should be valid. But the advantage of the Minchew et al. (2017) approach is interpretability of the results, a straightforward connection of the results to the physics of the systems being observed, and robust quantification of uncertainties. A recent improvement to Minchew et al. (2017) is Riel et al. (2021) that adopts some of the methods of Riel et al. (2014, 2018) and applies them to remote sensing observations of glaciers. From a methodological perspective, this generalizes the approach of Minchew et al. (2017) and allows for a generic set of temporal basis functions, from which a

sparsity-inducing optimization is used to identify the simplest set of basis functions that describe the data. The advantage there is also in the interpretability of the results and robust uncertainty quantification, which provides the ability to decompose the observed signal into short and long-term variations, and features the ability to constrain transients, secular, and periodic signals. However, this method still requires a priori knowledge to provide confidence in the resulting basis functions. The technique we present here is complementary because it does not rely on basis functions and provides flexibility at the expense of interpretability of the results, whereas the Minchew et al. (2017) and Riel et al. (2021) techniques sacrifice flexibility in the method for enhanced interpretability of the results.

Here we focus on dynamic changes along six land-terminating glaciers in southeastern Alaska during 20 October 2016 - 21 January 2021: Agassiz, Seward, Malaspina, Klutlan, Kluane and Walsh Glaciers (Figure 3). This technique can be used to analyze 3D flow velocities of glacier surfaces over large regional scales using nearly three decades years of archived SAR data and for near real-time monitoring of these glaciers using rapid revisit SAR data.

2 Model

The inversion technique described below utilizes ascending and descending range and azimuth speckle offset products computed from SAR data using speckle offset tracking algorithm implemented in GAMMA software (Wegmuller and Werner, 1997). We chose to use speckle offsets because their computation does not require phase unwrapping, which is not possible due to large flow velocities in our study area.

The 3D displacement time series are computed by inverting a set of linear equations, first solving for the north, east and vertical flow velocities $V_{n,e,v}$ for each acquisition epoch (Fialko et al., 2001; Bechor and Zebker, 2006) and then for cumulative 3D flow displacements $D_{n,e,v}$

$$\begin{pmatrix} A \\ \lambda L \end{pmatrix} \begin{pmatrix} V_n \\ V_e \\ V_v \end{pmatrix} = \begin{pmatrix} RO^{asc} \\ AO^{asc} \\ RO^{dsc} \\ AO^{dsc} \\ 0 \end{pmatrix} \tag{1a}$$

$$D^{i+1}_{n,e,v} = D^i_{n,e,v} + V^i_{n,e,v}\Delta t_i. \tag{1b}$$

Equation (1a) has a straightforward application: time interval multiplied by velocity is equal to displacement. Here, in a matrix form, RO are the range and AO are the azimuth offsets computed from SAR data; L is the Tikhonov regularization matrix multiplied by the scalar regularization parameter, λ, and A is the transform matrix constructed from the time intervals between consecutive SAR acquisitions and the range s_r and azimuth s_a directional cosines with north, east, and vertical

components

$$s_r = \{s_{nr}, s_{er}, s_{vr}\} = \{\sin(\phi)\sin(\theta), -\cos(\phi)\sin(\theta), \cos(\theta)\}$$

$$s_a = \{s_{na}, s_{ea}, s_{va}\} = \{\cos(\phi), \sin(\phi), 0\}, \tag{2}$$

where ϕ is the azimuth and θ is the incidence angles. The azimuth angle is the compass heading of the satellite, measured from the north; it discerns ascending vs descending orbits. The incidence angle is the angle between the ground normal and the look direction from the satellite; it is one of the acquisition parameters of the side-looking SAR sensor.

The number of columns in the transform matrix A is equal to the number of available distinct SLC images minus one multiplied by three and the number of rows is equal to the total number of range and azimuth offset maps computed from those SLC images. The structure of A can be deduced from a simplified example shown in Figure 1 and described below. In this example, it is assumed that the ascending set consists of three SAR images acquired on t_0, t_2, and t_4 and the descending set consists of four SAR images acquired on t_{-1}, t_1, t_3, and t_5. Two ascending range $RO^{asc} = \{\rho_{0-2}^{asc}, \rho_{2-4}^{asc}\}$ and azimuth $AO^{asc} = \{\alpha_{0-2}^{asc}, \alpha_{2-4}^{asc}\}$ offset products are computed from three ascending SAR images, and three descending range $RO^{dsc} = \{\rho_{-1-1}^{dsc}, \rho_{1-3}^{dsc}, \rho_{3-5}^{dsc}\}$ and azimuth $AO^{dsc} = \{\alpha_{-1-1}^{dsc}, \alpha_{1-3}^{dsc}, \alpha_{3-5}^{dsc}\}$ offset products are computed from four descending SAR images. A boundary correction (shown as blue arrows in Figure 1) is applied to the first and last descending offset products ρ_{-1-1}^{dsc}, α_{-1-1}^{dsc}, ρ_{3-5}^{dsc}, and α_{3-5}^{dsc} by multiplying by $(t_1 - t_0)/(t_1 - t_{-1})$ and $(t_4 - t_3)/(t_5 - t_3)$ in order to adjust the temporal coverage to match the ascending offset products. The boundary-corrected descending offsets therefore become ρ_{0-1}^{dsc}, α_{0-1}^{dsc}, ρ_{3-4}^{dsc}, and α_{3-4}^{dsc}. Assuming that $\Delta t_i = t_{i+1} - t_i$ in this simplified example, the equation (1a) becomes:

$$
\begin{pmatrix}
s_{nr}^{asc}\Delta t_0 & s_{er}^{asc}\Delta t_0 & s_{vr}^{asc}\Delta t_0 & s_{nr}^{asc}\Delta t_1 & s_{er}^{asc}\Delta t_1 & s_{vr}^{asc}\Delta t_1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & s_{nr}^{asc}\Delta t_2 & s_{er}^{asc}\Delta t_2 & s_{vr}^{asc}\Delta t_2 & s_{nr}^{asc}\Delta t_3 & s_{er}^{asc}\Delta t_3 & s_{vr}^{asc}\Delta t_3 \\
s_{na}^{asc}\Delta t_0 & s_{ea}^{asc}\Delta t_0 & 0 & s_{na}^{asc}\Delta t_1 & s_{ea}^{asc}\Delta t_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & s_{na}^{asc}\Delta t_2 & s_{ea}^{asc}\Delta t_2 & 0 & s_{na}^{asc}\Delta t_3 & s_{ea}^{asc}\Delta t_3 & 0 \\
s_{nr}^{dsc}\Delta t_0 & s_{er}^{dsc}\Delta t_0 & s_{vr}^{dsc}\Delta t_0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & s_{nr}^{dsc}\Delta t_1 & s_{er}^{dsc}\Delta t_1 & s_{vr}^{dsc}\Delta t_1 & s_{nr}^{dsc}\Delta t_2 & s_{er}^{dsc}\Delta t_2 & s_{vr}^{dsc}\Delta t_2 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & s_{nr}^{dsc}\Delta t_3 & s_{er}^{dsc}\Delta t_3 & s_{vr}^{dsc}\Delta t_3 \\
s_{na}^{dsc}\Delta t_0 & s_{ea}^{dsc}\Delta t_0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & s_{na}^{dsc}\Delta t_1 & s_{ea}^{dsc}\Delta t_1 & 0 & s_{na}^{dsc}\Delta t_2 & s_{ea}^{dsc}\Delta t_2 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & s_{na}^{dsc}\Delta t_3 & s_{ea}^{dsc}\Delta t_3 & 0 \\
\lambda & 0 & 0 & -\lambda & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \lambda & 0 & 0 & -\lambda & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & \lambda & 0 & 0 & -\lambda & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & \lambda & 0 & 0 & -\lambda & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & \lambda & 0 & 0 & -\lambda & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & \lambda & 0 & 0 & -\lambda & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & \lambda & 0 & 0 & -\lambda & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & \lambda & 0 & 0 & -\lambda & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \lambda & 0 & 0 & -\lambda
\end{pmatrix}
\begin{pmatrix}
V_n^0 \\ V_e^0 \\ V_v^0 \\ V_n^1 \\ V_e^1 \\ V_v^1 \\ V_n^2 \\ V_e^2 \\ V_v^2 \\ V_n^3 \\ V_e^4 \\ V_v^4
\end{pmatrix}
=
\begin{pmatrix}
\rho_{0-2}^{asc} \\ \rho_{2-4}^{asc} \\ \alpha_{0-2}^{asc} \\ \alpha_{2-4}^{asc} \\ \rho_{0-1}^{dsc} \\ \rho_{1-3}^{dsc} \\ \rho_{3-4}^{dsc} \\ \alpha_{0-1}^{dsc} \\ \alpha_{1-3}^{dsc} \\ \alpha_{3-4}^{dsc} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0
\end{pmatrix}. \tag{3}
$$

The 3D flow displacement time series are then computed as in the equation (1b) as $D_{n,e,v}^{i+1} = D_{n,e,v}^{i} + V_{n,e,v}^{i}\Delta t_i$, for $i = \{0,1,2,3\}$, assuming that the initial displacements $D_{n,e,v}^0$ are equal to zero. Note, that in this notation $D_{n,e,v}^0$ are the 3D

displacements at the time t_0, while $V_{n,e,v}^0$ and Δt_0 are the 3D velocities and the time interval at the time epoch $t_0 - t_1$, thus effectively available at the time t_1. For simplicity of presentation, a linear trend is computed by applying linear regression to the derived values in such a way as to illustrate the 3D displacement time series and three linear rate maps are used for visualizing the results. Note, that in the case of non-steady-state flow the linear rates, which effectively are mean linear rates (i.e. there is more than one method of computing mean values), can significantly differ from the instantaneous flow velocities. Linear rates can potentially be computed over a time interval of any duration (for example, one month or one year).

Tikhonov regularizations of various orders can be applied during the inversion, resulting in temporal smoothing. The zeroth-order regularization effectively is the constant displacement constraint. The first-order regularization effectively is the constant velocity constraint, and the second-order regularization effectively is the constant acceleration constraint. The first and second-order regularizations both produce good, virtually indistinguishable, results. The example above, equation (3), uses first-order regularization. Zeroth- and second-order regularizations are explicitly shown in Samsonov and d'Oreye (2017) for the 2D case. The magnitude of smoothing is controlled by the regularization parameter λ that can be selected, for example, using the L-curve method (Hansen and O'Leary, 1993; Samsonov and d'Oreye, 2017). The value of λ equal to 0.1 was used in our case.

MSBAS methodology has been developed for computing multidimensional time series by combining multiple DInSAR data acquired at different times and in various observational geometries. The 2D (east and vertical) method was described in (Samsonov and d'Oreye, 2012, 2017) and the surface-parallel-flow constrained 3D (north, east, vertical) method in (Samsonov, 2019; Samsonov et al., 2020). The novel unconstrained 3D method presented here uses both range and azimuth measurements for computing 3D displacements. This work is now possible due to the improved availability over large areas of high-quality, high-resolution, temporally dense ascending and descending SAR data and the increase in computational power that allows computing a large amount of range and azimuth offset maps and inverting large matrices. Since this method does not make any assumptions about the direction of motion, it provides the optimal solution applicable to any phenomenon (e.g. glacier flow, tectonic and anthropogenic deformation, etc). The typical size of the transform matrix exceeds 100s and often 1000s of columns and rows for each pixel. It is 666×446 (or 666×1109 including regularization terms) in our case. The singular value decomposition (SVD) algorithm from the Linear Algebra PACKage (LAPACK) library called from C++ code is used for inverting this matrix for each pixel. Processing is parallelized using Open Multi-Processing (OpenMP) implementation of multi-threading. Depending on the number of cores in the processing unit and the number of pixels, this process can take from several hours to several days. Processing time in our case, on a 44-core workstation is approximately 24 hours. The Message Passing Interface (MPI) version of the software has also been developed. The processing time in an MPI version is reduced proportionally to the number of nodes.

2.1 Synthetic tests

For demonstrating the effectiveness of our technique, we performed synthetic tests using the actual transform matrix A in detail described in the next section. First, we reconstructed deformation components using the harmonic input signal in only one of the components, described in the respectful legends in Figures 2(a-c). Then we added 10% of Gaussian noise and repeated the computations (Figures 2(d-f)). Second, we reconstructed deformation components using the harmonic and linear input signals

in the horizontal components and the harmonic signal in the vertical component. Three runs were performed with 0%, 10% and 30% Gaussian noise added (Figures 2(g-i)). Note that in the second scenario, the period of a harmonic signal was different for each component (to make the scenario more complex).

140   Without added noise, the reconstructed output signal is practically identical to the input signal. The covariance terms (computed but not shown here) are equal to zero, which signifies that the ascending/descending geometry is sufficient for a full reconstruction of 3D motion. This also can be inferred theoretically by computing a rank of the transform matrix in the case of one ascending and one descending pair, acquired at the same time, which would be equal to three. With added noise, the reconstructed signal still resembles the input signal and the covariance terms are still equal to zero. Therefore, we conclude that the precision of this technique is defined by the precision of the input speckle offset products and is not limited by the acquisition geometry.

3   Study area and Data

Southeast Alaska has experienced significant ice mass loss and retreat over the last 50 years (Arendt et al., 2009; Arendt, 2011). Of the 27,000 glaciers that occupy the region, the majority (99.8%) are land terminating (RGIConsortium, 2017).

150   Consequently, monitoring the mass balance and ice dynamic variations of Alaska's land-terminating glaciers is paramount for the future of its landscape and resultant contributions to sea level rise (Larsen et al., 2015). Unlike the plethora of ice velocity data products available for Greenland and Antarctica, regional studies of Alaskan glacier surface velocities pale in comparison. The first regional map of Alaskan glacier flow velocities was released in 2013 using ALOS PALSAR data (Burgess et al., 2013). Soon after, feature tracking of Landsat optical data began to regularly map regional surface velocities (Fahnestock

155   et al., 2015; Gardner et al., 2018, 2019). Recent studies demonstrate the importance of characterizing the temporal evolution of glacier surface flow for understanding changes in ice dynamics in Alaska (Waechter et al., 2015; Altena et al., 2019). However, all regional studies of Alaskan glacier flow have so far been limited to two dimensions; thus, ignoring an important vertical component of flow, which links glacier surface elevation change and its mass balance. Here, we introduce a technique to generate a dense record of regional Alaskan glacier surface flow in three dimensions.

160   We focus on studying the dynamic changes along six land-terminating glaciers in southeastern Alaska during 20 October 2016 - 21 January 2021: Agassiz, Seward, Malaspina, Klutlan, Kluane and Walsh Glaciers (Figure 3). The Malaspina Glacier is the world's largest piedmont glacier covering approximately 2200 km^2 on the flat coastal foreland (Sharp, 1958; Muskett et al., 2003; Sauber et al., 2005) and is partially fed by Seward Glacier, a surge-type glacier that originates in the upper reaches of Mt. Logan (Sharp, 1951; Ford et al., 2003). A mass budget deficit in the Malaspina-Seward complex has long been recognized

165   (Sharp, 1951). Agassiz Glacier is another surge-type that flows in an adjacent sinuous valley northwest of the Malaspina-Seward complex (Muskett et al., 2003; Sauber et al., 2005). The Klutlan Glacier is an 82-km long surge-type valley glacier located at elevations between 1300 and 2100 m; it has surged repeatedly over the last few hundred years (Wright, 1980; Driscoll, 1980). The surge at Kluane Glacier in the eastern St. Elias Mountains during 2017-2018 was previously reported in Main et al. (2019).

Walsh Glacier is a 90-km long surge-type valley glacier located at a higher elevation of about 1500-3000. It is fed by two major branches, one from the north and one from the east and converges with the Logan Glacier downstream (Fu and Zhou, 2020).

In this study, we used 218 ascending (track 123) and 232 descending (track 116) Sentinel-1 Interferometric Wide (IW) single-look complex (SLC) images with 2.3 × 14.9 m range × azimuth spatial resolution from the NASA Distributed Active Archive Center (DAAC) operated by the Alaska Satellite Facility (ASF) (Table 1). Two ascending and two descending frames along the azimuth directions were concatenated for each, resulting in 109 and 116 swaths, respectfully. Ascending and descending sets were processed individually using GAMMA software (Wegmuller and Werner, 1997) that produced range and azimuth offsets for consecutive pairs (Figure 4). To compute offsets, we used a 64×16 pixels sampling interval (or approximately 200×200 m) and a square 128×128 pixels (or approximately 400×1600 m) correlation window. Such a large window was required to obtain a distinct, statistically significant peak of the 2D cross-correlation function; its square shape produced similar precision in range and azimuth directions in radar coordinates, and azimuth precision four times lower than range precision in geocoded products. Note, that the correlation window is not uniform, with larger weights given to the pixel in the center of the window. While the estimation of spatial resolution resulting from a non-uniform weighting of the pixel is beyond the scope of this study, the initial tests suggest that the spatial resolution is significantly better than the window size, which is also confirmed by the developers of GAMMA software. Offsets were spatially filtered using a Gaussian filter with a 1.3 km (6-sigma) filter-width, geocoded using TerraSAR-x 90 m DEM and resampled to a common grid with a ground spacing of 200 m. Using Gaussian weights for filtering proved to be particularly beneficial as the filter produced satisfactory results for small and large glaciers. Filter-width was chosen experimentally for our study but maybe sub-optimal for applying in other regions.

4   Results

A magnitude of the 3D mean linear flow velocities plotted for the entire region using a logarithmic scale is shown in Figure 5. For 5× 5-pixel regions P1-P4 at Malaspina/Seward Glaciers, P5-P6 at Klutlan Glacier, P7-P8 at Walsh Glacier and P9 and Kluane Glacier time series are provided in Figures 10 and 11. This figure contains a massive amount of data. Thus, an in-depth analysis was further performed for four small areas of interest (AOI1, AOI2, AOI3 and AOI4 in Figure 3) shown in detail in Fig 6-9. The flow lines in Figure 3 were computed using the Open Global Glacier Model (OGGM) software (Maussion et al., 2019) and the central flow lines were chosen for in-depth analysis. Note, that these flow lines are approximated to the actual glacier flow pattern. They are, however, computed in a consistent and repeatable way.

For each AOR, the SAR intensity images show the six glaciers in detail: Agassiz, Malaspina and Seward (AG, MG and SG, Figure 6(a)), Klutlan (KtG, Figure 7(a)), Walsh (WG, Figure 8(a)) and Kluane (KnG, Figure 9(a)) Glaciers. For five of these glaciers (excluding the Agassiz Glacier) flow lines with 20 km markers are shown. Mean flow velocities are shown in Figures 6(b), 7(b), 8(b) and and 9(b); horizontal flow velocities are shown as vectors and vertical flow velocities are colour-coded, with red representing downward motion. For aesthetic purposes, horizontal flow vectors are resampled to a coarser resolution. The fastest horizontal flow velocity exceeds 1000 m/year and the fastest vertical flow velocity exceeds 200 m/year. Overall, Seward Glacier experiences the fastest motion and Malaspina Glacier experiences the slowest motion (Figure 6(b)); vertical flow is

predominately downward along both glaciers. In contrast, vertical flow along the Klutlan (Figure 7(b)), Walsh (Figure 8(b)) and Kluane (Figure 9(b)) Glaciers changes direction a number of times.

The direction and magnitude of the mean linear flow velocities sampled along central flow lines from Malaspina and Seward, Klutlan, Walsh and Kluane Glaciers are shown in Figures 6(c), 7(c), 8(c) and 9(c) as vectors with tails that start at the surface elevation of each glacier. Animations of these flow velocities as time series along these profiles are also provided as supplemental materials. Note that the vertical axis (surface elevation) and horizontal axis (distance along profile) are scaled differently, producing significant but equal angular distortion in the flow velocities and topographic slopes. The mean linear flow velocities provide insight into the direction and magnitude of mean velocities calculated over a specific interval (e.g. the Sentinel-1 record); however, these values can vary over time. This is evident in the temporal evolution of the horizontal velocity magnitude and vertical velocity sampled along these profiles for the Seward and Malaspina Glaciers (Figures 6(d)-6(e)), the Klutlan Glacier (Figures 7(d)-7(e)), the Walsh Glacier (Figures 8(d)-8(e)) and the Kluane Glacier (Figures 9(d)-9(e)). Flow along the lower reaches of the Malaspina Glacier varies seasonally; although, the seasonal acceleration was delayed in 2020 and was higher in magnitude. Seasonal flow along the Klutlan, Walsh and Kluane Glaciers is far less pronounced; however, each shows an episodic shift in a flow that occurred around mid-2018, mid-2017, and mid-2018, respectively.

Examples of 3D flow displacement and velocity time series for the $5\times$ 5-pixel regions P1-P9 are shown in Figures 10-11. Similar time series can be easily produced for any coloured pixel in Figures 5; the locations selected were chosen to demonstrate diverse ice dynamic observations possible with the MSBAS-3D method. Regions P1 and P4 are located on the lower lobes of the Malaspina Glacier, at an elevation of about 200 m above sea level. The displacement time series show that flow is predominately west-southwest at P1 and northeast at P4. An abrupt change in a flow regime occurred at P1 at the end of June 2020. Since then, the flow velocity at P1 has remained elevated in comparison to the values observed in prior years. This many-fold velocity increase can also be observed in Figures 6d-6e along the later part of the profile. Horizontal and vertical flow velocities at these regions are only a few m/year, with a seasonal signal evident at P4 in the vertical component. Such seasonal signals are observed at most low-elevation glaciers. Regions P2 and P3 are located at elevations of about 1000 and 700 m. At these locations, horizontal flow dominates flow displacement, while vertical flow displacement is minimal. The southwest direction of flow is persistent at both locations. Flow velocities along the main branch of the Agassiz Glacier, not shown, are very similar to the flow velocities along the Seward Glacier but of a lesser magnitude.

Regions P5 and P6 are located on Klutlan Glacier at elevations of about 1900 and 1500 m, respectively. The overall vertical flow is slightly downward in these regions but horizontal and vertical components both show significant variability over time. Regions P7 and P8 are located on Walsh Glacier at an elevation of about 1700 and 2000 m, respectively. At P7, northwest upward displacement is observed until July 2017 when a gradual reduction occurred. Region P9 is located on Kluane Glacier at an elevation of about 1700 m. Here, southeast and upward displacement is observed during 2018 when a gradual reduction occurred. Error bars throughout Figures 10-11 show measurement variability within the $5\times$ 5-pixel region, rather than precision, though both quantities are likely related.

5 Discussion

The technique presented in this study is a viable solution for computing 3D flow displacement time series from ascending and descending range and azimuth SAR measurements. Synthetic tests (Figure 2) suggest that the precision of the inversion largely depends on the precision of input data and is not limited by the suboptimal acquisition geometry (i.e. nonorthogonal orbits). Range offsets can be substituted or complemented with DInSAR measurements since both measures the same quantity; similarly, azimuth offsets can be substituted or complemented with Multiple Aperture Interferometry (MAI) (Bechor and Zebker, 2006) measurements. For high resolution SAR data, the precision of the SPO technique approaches that of DInSAR. In addition to glaciers, this technique can be used for studying other geophysical processes (e.g. landslides, sea/river/lake ice drift) if their motion exceeds the sensitivity of SPO and/or MAI techniques.

The precision of individual offset maps can be estimated as 1/10-1/30 of the SAR pixel size (Strozzi et al., 2002). An average precision of our speckle offset product computed over a typical interval of 12 days (i.e. Sentinel-1 repeat period) is about 1 m (or 30 m/year) in range and 4 m (or 120 m/year) in azimuth. However, for computing the mean linear velocity the length of the time series is more important than the precision of individual measurements. Standard deviations of the mean linear velocities averaged over the entire region are 0.7, 0.3, and 0.2 m/year (while the maximum values are 21, 18 and 7 m/year, these higher values would be due to seasonal variations and changes in surge activity) for northward, eastward and vertical components, respectively. This is somewhat analogous to the precision of GNSS-derived deformation rates, which largely depend on the length of time series rather than the precision of individual GNSS measurement. The best approach for estimating the absolute measurement accuracy, of course, is by comparing these remote-sensing measurements with ground-based measurements (Gudmundsson and Bauder, 1999), which unfortunately are not available for this region and this period. SAR measures glacier motion at a certain depth rather than at the surface. Previous studies for this region suggest that the C-band SAR penetrates about four meters into the glacier's firn layer in dry conditions (Rignot et al., 2001).

We compared the magnitude of mean linear horizontal flow velocities along the four profiles with the results presented in Gardner et al. (2019) (Figures S1-S4). There, surface velocities are derived from Landsat 4, 5, 7, and 8 imagery over the period from 1985 to 2018 using the auto-RIFT feature tacking processing chain described in Gardner et al. (2018). Both data sets show some agreement. Statistical parameters, such as correlation coefficients and RMSEs are provided in the figure captions. We observe that in areas experiencing nearly constant flow velocity, for example at Seward and Malaspina Glaciers, both datasets show close results with a correlation of 0.93 and RMSE of 269 m/year. At Klutlan, Walsh and Kluane Glaciers, SAR-derived velocities are affected by the surges, which are not reflected in Gardner et al. (2019) resulting in a lower correlation (0.43-0.80) and a larger RMSE (80-266 m/year) in comparison to the average velocity at those glaciers. Furthermore, the Landsat record will be temporally biased towards cloud-free images and periods when sufficient sunlight is available to obtain optical imagery; thus eliminating a significant portion of late fall and early winter scenes. One final discrepancy can be attributed to the differences in processing parameters, such as correlation window and filter shape and strength. Significant filtering is required in our processing because, for time series analysis, every single range and azimuth offset map must be defined at every pixel, which can be only achieved by using a large correlation window followed by strong filtering. Preservation of spatial coverage

in every single range and azimuth offset map forces us to select pixels with a moderate signal-to-noise ratio (SNR), which would not have been selected if we wanted to compute only the mean velocity. Our software can potentially handle missing values in data by interpolating in the time domain (using first- and second-order regularizations), but here we have chosen not to introduce interpolation bias and instead lowered SNR. Overall, in addition to providing the three components of flow velocity at a higher and more consistent temporal resolution, our study demonstrates that deviations from the mean flow velocity can be very significant.

SAR-derived time series is often compared with the GNSS-derived time series and both techniques are considered conceptually similar; however, there is an important difference between the two, particularly when applied to glacier flow. SAR measures displacement within fixed geophysical locations (Eulerian representation), while GNSS measurements track receivers that are mounted to non-stationary geophysical surfaces (Lagrangian representation). Lagrangian displacement time series describes a trajectory of an object in space as a function of time, whereas the Eulerian displacement time series describes the cumulative length (of ice, rock, etc.) that flows through a fixed geophysical location. While the distinction between these reference frames is well established in the glaciological community, it is less commonly known in the solid-earth geophysical community (Samsonov and Tiampo, 2006; Samsonov et al., 2007; Gourmelen et al., 2010; Shen and Liu, 2020). For the latter, GNSS and SAR measurements can be considered nearly identical only when flow velocity at a fixed geophysical location (i.e. SAR pixel) is equal to the flow velocity at the GNSS site; that is when GNSS-derived displacements are contained within a single SAR pixel. This occurs when the flow velocity is very small and the material is rigid, as in tectonic deformation studies. For rapidly deforming glacier surfaces, differentiation is far more critical. Although the time-series in Figure 10 resemble GNSS-derived displacements, it is important to remember that these Eulerian measurements represent the cumulative displacement at any one pixel over time. Hence to emphasize this difference, we use the *flow displacement* terminology.

The overall direction of vertical flow is down along almost the entire length of the Seward and Malaspina Glaciers (Figure 6). The downward flow is expected in the upper reaches of accumulation zones because of firn compaction, and in areas with steeply dipping surfaces due to sloping bed topography; however, downward flow in the lower ablation zone is more concerning. In general, the accumulation of snow and ice in high elevations produces a net mass gain that replenishes ice lost through ablation processes along the lower glacier. In a steady-state, these processes balance each other and lead to submergent flow in the accumulation zone and emergent flow in the ablation zone; thus, ice mass lost through melt in the ablation zone is replenished by ice that emerges from the depths of ice columns to the glacier surface to maintain a consistent surface elevation (Hooke, 2019). The predominately downward flow of ice observed throughout the Malaspina Glacier's massive lobe (Figure 6b,c,e, 11d) indicates that ablation rates have exceeded emergence velocities during our four year study period, implying that the glacier is still adjusting to climatic warming. Indeed, the Seward, Malaspina, and Agassiz Glaciers are not in a steady-state (Muskett et al., 2003; Larsen et al., 2015). Seasonal variability is observed along the Seward and Malaspina Glaciers (Figures 6d,e, 11b,c,d). The fastest horizontal motion occurs during late spring-early summer and the slowest in late summer-early fall, consistent with other glaciers in the region (Abe and Furuya, 2015; Vijay and Braun, 2017; Enderlin et al., 2018). The fastest vertical motion is observed in the middle of summer. An animation provided with the supplementary data clearly shows seasonality in flow rates over the entire complex. Seasonal variability at P1 is obstructed by a many-fold increase in velocity

observed in the second half of 2020 that lasts until the end of this study. Note that the vertical component at P1 shows upward flow, suggesting that the regime change is likely caused by the arrival of ice from the uphill.

Velocities along Klutlan Glacier vary in more complex ways with multiple zones of upward and downward flow observed (Figure 7). This surge-type glacier (RGIConsortium, 2017) has a 30 (Meier and Post, 1969) to 60-year surge cycle (Wright, 1980; Driscoll, 1980). Altena et al. (2019) used optical satellite data to show its most recent surge initiated in 2014 and continued through 2017. The surge started mid-glacier and had two propagating fronts: a dominant surge front that propagated downglacier and a secondary subdued front that propagated upglacier. Our SAR-based record shows that surge activity terminated in mid-2018. The time series at P5 and P6 (Figures 10e,f, 11e,f) show complex flow dynamics in both the horizontal and vertical components.

The Walsh Glacier is another surge-type glacier with recent surge activity. Using optical Landsat data, Fu and Zhou (2020) showed the latest surge initiated before 2015 (Figure 8). Our SAR-based observations show residual surge activity continued into 2017 and abruptly ended in mid-2017 (Figure 8(d)). The time series at P8 (Figures 10h, 11h) show regular increases in flow velocity during summer, while at P7 these seasonal increases are less pronounced (Figures 10g, 11g). The surge at P7 during 2017 is a dominant signal.

A surge of the Kluane Glacier has previously been detected using RADARSAT-2 SAR measurements (Main et al., 2019). It occurred during 2018 in a secondary valley of the glacier (Figure 9). The entire surge cycle is captured by our time series (Figures 10i, 11i). Such a complex flow pattern can only be derived from side-looking SAR measurements that capture horizontal and vertical components of motion.

These six, in-depth analyzed glaciers were selected from the regional results shown in Figure 5. Other glaciers in this region may have also experienced surges or other interesting behaviours. The entire data set, which includes instantaneous velocities and cumulative displacements for each pixel, and the processing software are provided with this manuscript.

6 Conclusions

We presented a novel flow displacement technique to observe variations in glacier surface flow in 3D using ascending and descending SAR scenes. The 3D flow displacement (and/or velocity) time series computed allowed us to map in unprecedented detail the state and the temporal evolution of six glaciers in Southeast Alaska during 20 October 2016 - 21 January 2021. On a broader scale, this technique can be used for reconstructing the historic response of the worldwide glaciers to the warming climate using over 30 years of available satellite SAR records. The horizontal components can be resolved to study flow variations over time, and if integrated along a profile that is perpendicular to flow, ice flux. The vertical component can be used to assess changes in vertical ice flux or changes in surface slope over time, which is useful for studying glacier surge dynamics or variations in driving stress as a glacier dynamically adjusts to a changing climate. The software is freely available to the research community.

335 *Code and data availability.* The data and processing software used in this study can be downloaded from Mendeley Data http://dx.doi.org/... (will be added after the paper is accepted)

Video supplement. The animations of flow velocities for studied glaciers (files movie_malaspina.gif, movie_klutlan.gif, movie_walsh.gif, movie_kluane.gif) are provided. Comparisons between a magnitude of mean linear horizontal flow velocities along the four profiles with the results presented in Gardner et al. (2019) are also provided.

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References

350   Abe, T. and Furuya, M.: Winter speed-up of quiescent surge-type glaciers in Yukon, Canada, The Cryosphere, 9, 1183–1190, https://doi.org/10.5194/tc-9-1183-2015, 2015.

Abrams, M., Crippen, R., and Fujisada, H.: ASTER Global Digital Elevation Model (GDEM) and ASTER Global Water Body Dataset (ASTWBD)., Remote Sensing, 12, https://doi.org/10.3390/rs12071156, 2020.

Altena, B., Scambos, T., Fahnestock, M., and Kääb, A.: Extracting recent short-term glacier velocity evolution over southern Alaska and the
355   Yukon from a large collection of Landsat data, The Cryosphere, 13, 795–814, https://doi.org/10.5194/tc-13-795-2019, 2019.

Arendt, A.: Assessing the Status of Alaska's Glaciers, Science, 332, 1044–1045, https://doi.org/10.1126/science.1204400, 2011.

Arendt, A., Walsh, J., and Harrison, W.: Changes of glaciers and climate in northwestern North America during the late twentieth century, Journal of Climate, 22, 4117–4134, https://doi.org/10.1175/2009JCLI2784.1, 2009.

Bartholomew, I., Nienow, P., Mair, D., Hubbard, A., King, M., and Sole, A.: Seasonal evolution of subglacial drainage and acceleration in a
360   Greenland outlet glacier., Nature Geoscience, 3, 408–411, https://doi.org/10.1038/ngeo863, 2010.

Bechor, N. and Zebker, H.: Measuring two-dimensional movements using a single InSAR pair, Geophysical Research Letters, 33, https://doi.org/10.1029/2006GL026883, 2006.

Berthier, E., Vadon, H., Baratoux, D., Arnaud, Y., Vincent, C., Feigl, K., Remy, F., and Legresy, B.: Surface motion of mountain glaciers derived from satellite optical imagery, Remote Sensing of Environment, 95, 14 – 28, https://doi.org/10.1016/j.rse.2004.11.005, 2005.

365   Bisset, R., Dehecq, A., Goldberg, D., Huss, M., Bingham, R., and Gourmelen, N.: Reversed Surface-Mass-Balance Gradients on Himalayan Debris-Covered Glaciers Inferred from Remote Sensing., Remote Sensing, 12, 1563, https://doi.org/10.3390/rs12101563, 2020.

Burgess, E., Forster, R., and Larsen, C.: Flow velocities of Alaskan glaciers, Nature Communications, 4, https://doi.org/10.1038/ncomms3146, 2013.

Dehecq, A., Gourmelen, N., and Trouve, E.: Deriving large-scale glacier velocities from a complete satellite archive: Application to the
370   Pamir–Karakoram–Himalaya, Remote Sensing of Environment, 162, 55 – 66, https://doi.org/10.1016/j.rse.2015.01.031, 2015.

Driscoll, F. J.: Formation of the neoglacial surge moraines of the Klutlan glacier, Yukon Territory, Canada., Quaternary Research, pp. 19–30, https://doi.org/10.1016/0033-5894(80)90004-6, 1980.

Enderlin, E. M., O'Neel, S., Bartholomaus, T. C., and Joughin, I.: Evolving Environmental and Geometric Controls on Columbia Glacier's Continued Retreat, Journal of Geophysical Research: Earth Surface, 123, 1528–1545, https://doi.org/10.1029/2017JF004541, 2018.

375   Fahnestock, M., Scambos, T., Moon, T., Gardner, A., Haran, T., and Klinger, M.: Rapid large-area mapping of ice flow using Landsat 8, Remote Sensing of Environment, Remote Sensing of Environment, 185, 84–94, https://doi.org/10.1016/j.rse.2015.11.023, 2015.

Fahnestock, M., Scambos, T., Moon, T., Gardner, A., Haran, T., and Klinger, M.: Rapid large-area mapping of ice flow using Landsat 8, Remote Sensing of Environment, 185, 84–94, https://doi.org/10.1016/j.rse.2015.11.023, 2016.

Fialko, Y., Simons, M., and Agnew, D.: The complete (3-D) surface displacement field in the epicentral area of the 1999
380   MW7.1 Hector Mine Earthquake, California, from space geodetic observations, Geophysical Research Letters, 28, 3063–3066, https://doi.org/10.1029/2001GL013174, 2001.

Ford, A. L., Forster, R. R., and Bruhn, R. L.: Ice surface velocity patterns on Seward Glacier, Alaska/Yukon, and their implications for regional tectonics in the Saint Elias Mountains, Annals of Glaciology, 36, 21–28, https://doi.org/10.3189/172756403781816086, 2003.

Fu, X. and Zhou, J.: Recent surge behavior of Walsh glacier revealed by remote sensing data, Sensors, 20, 716,
385   https://doi.org/10.3390/s20030716, 2020.

Gardner, A., Moholdt, G., Scambos, T., Fahnstock, M., Ligtenberg, S., van den Broeke, M., and Nilsson, J.: Increased West Antarctic and unchanged East Antarctic ice discharge over the last 7 years, The Cryosphere, 12, 521–54, https://doi.org/10.5194/tc-12-521-2018, 2018.

Gardner, A., Fahnestock, M., and Scambos, T.: ITS_LIVE Regional Glacier and Ice Sheet Surface Velocities. Data archived at National Snow and Ice Data Center, https://doi.org/10.5067/6II6VW8LLWJ7, 2019.

390 Goldstein, R. M., Engelhardt, H., Kamb, B., and Frolich, R. M.: Satellite Radar Interferometry for Monitoring Ice Sheet Motion: Application to an Antarctic Ice Stream, Science, 262, 1525–1530, https://doi.org/10.1126/science.262.5139.1525, 1993.

Gourmelen, N., Amelung, F., Casu, F., Manzo, M., and Lanari, R.: Mining-related ground deformation in Crescent Valley, Nevada: Implications for sparse GPS networks, Geophysical Research Letters, 34, https://doi.org/10.1029/2007GL029427, 2007.

Gourmelen, N., Amelung, F., and Lanari, R.: Interferometric synthetic aperture radar–GPS integration: Interseismic strain accumula-
395 tion across the Hunter Mountain fault in the eastern California shear zone, Journal of Geophysical Research: Solid Earth, 115, https://doi.org/10.1029/2009JB007064, 2010.

Gourmelen, N., Kim, S., Shepherd, A., Park, J., Sundal, A., Björnsson, H., and Pálsson, F.: Ice velocity determined using conventional and multiple-aperture InSAR, Earth and Planetary Science Letters, 307, 156–160, https://doi.org/10.1016/j.epsl.2011.04.026, 2011.

Gray, L.: Using multiple RADARSAT InSAR pairs to estimate a full three-dimensional solution for glacial ice movement., Geophysical
400 Research Letters, 38, https://doi.org/1029/2010GL046484, 2011.

Gray, L., Joughin, I., Tulaczyk, S., Spikes, V., Bindschadler, R., and Jezek, K.: Evidence for subglacial water transport in the West Antarctic Ice Sheet through three-dimensional satellite radar interferometry, Geophysical Research Letters, 32, https://doi.org/10.1029/2004GL021387, 2005.

Gudmundsson, G. and Bauder, A.: Towards an Indirect Determination of the Mass-Balance Distribution of Glaciers Using the Kinematic
405 Boundary Condition., Geografiska Annaler. Series A, Physical Geography, 81, 575–583, 1999.

Guo, L., Li, J., Li, Z.-w., Wu, L.-x., Li, X., Hu, J., Li, H.-l., Li, H.-y., Miao, Z.-l., and Li, Z.-q.: The Surge of the Hispar Glacier, Central Karakoram: SAR 3-D Flow Velocity Time Series and Thickness Changes, Journal of Geophysical Research: Solid Earth, 125, https://doi.org/10.1029/2019JB018945, 2020.

Hansen, P. and O'Leary, D.: The use of the L-curve in the regularization of discrete ill-posed problems, SIAM Journal on Scientific Comput-
410 ing, 14, 1487–1503, 1993.

Herman, F., Anderson, B., and Leprince, S.: Mountain glacier velocity variation during a retreat/advance cycle quantified using sub-pixel analysis of ASTER images, Journal of Glaciology, 57, 197–207, https://doi.org/10.3189/002214311796405942, 2011.

Hooke, R. L.: Principles of Glacier Mechanics, Cambridge University Press, 3 edn., https://doi.org/10.1017/9781108698207, 2019.

Hu, J., Li, Z., Ding, X., Zhu, J., Zhang, L., and Sun, Q.: Resolving three-dimensional surface displacements from InSAR measurements: A
415 review, Earth-Science Reviews, 133, 1 – 17, https://doi.org/10.1016/j.earscirev.2014.02.005, 2014.

Immerzeel, W., Kraaijenbrink, P., Shea, J., Shrestha, A., Pellicciotti, F., Bierkens, M., and de Jong, S.: High-resolution monitoring of Himalayan glacier dynamics using unmanned aerial vehicles, Remote Sensing of Environment, 150, 93 – 103, https://doi.org/10.1016/j.rse.2014.04.025, 2014.

Joughin, I.: Ice-sheet velocity mapping: A combined interferometric and speckle-tracking approach., Annals of Glaciology, 34, 195–201,
420 https://doi.org/10.3189/1727564027818179, 2002.

Joughin, I., Winebrenner, D., and Fahnestock, M.: Observations of ice-sheet motion in Greenland using satellite radar interferometry, Geophysical Research Letters, 22, 571–574, https://doi.org/10.1029/95GL00264, 1995.

Joughin, I., Kwok, R., and Fahnestock, M.: Interferometric estimation of three-dimensional ice-flow using ascending and descending passes., IEEE Transactions on Geoscience and Remote Sensing, 36, 25–37, https://doi.org/10.1109/36.655315, 1998.

425 Kumar, V., Venkataramana, G., and Høgda, K.: Glacier surface velocity estimation using SAR interferometry technique applying ascending and descending passes in Himalayas, International Journal of Applied Earth Observation and Geoinformation, 13, 545–551, https://doi.org/10.1016/j.jag.2011.02.004, 2011.

Larsen, C., Burgess, E., Arendt, A. A., O'Neel, S., Johnson, A. J., and Kienholz, C.: Surface melt dominates Alaska glacier mass balance, Geophysical Research Letters, 42, 5902–5908, https://doi.org/10.1002/2015GL064349, 2015.

430 Main, B., Copland, L., Samsonov, S., Dow, C., Flowers, G., Young, E., and Kochtitzky, W.: Surge of Little Kluane Glacier in the St. Elias Mountains, Yukon, Canada, from 2017-2018., in: American Geophysical Union, Fall Meeting, abstract C31B-1517, 2019.

Massonnet, D. and Feigl, K.: Discrimination of geophysical phenomena in satellite radar interferograms, Geophysical Research Letters, 22, 1995.

Maussion, F., Butenko, A., Champollion, N., Dusch, M., Eis, J., Fourteau, K., Gregor, P., Jarosch, A. H., Landmann, J., Oesterle, F., Recinos,

435 B., Rothenpieler, T., Vlug, A., Wild, C. T., and Marzeion, B.: The Open Global Glacier Model (OGGM) v1.1, Geoscientific Model Development, 2019, 909–931, https://doi.org/10.5194/gmd-12-909-2019, https://www.geosci-model-dev.net/12/909/2019/, 2019.

Meier, M. and Post, A.: What are glacier surges?, Canadian Journal of Earth Sciences, 6, 807–817, https://doi.org/10.1139/e69-081, 1969.

Milillo, P., Minchew, B., Simons, M., Agram, P., and Riel, B.: Geodetic imaging of time-dependent three-component surface deformation: Application to tidal-timescale ice flow of Rutford Ice Stream, West Antarctica., IEEE Transactions on Geoscience and Remote Sensing,

440 55, 5515–5524, https://doi.org/10.1109/TGRS.2017.2709783, 2017.

Minchew, B. M., Simons, M., Riel, B., and Milillo, P.: Tidally induced variations in vertical and horizontal motion on Rutford Ice Stream, West Antarctica, inferred from remotely sensed observations, Journal of Geophysical Research: Earth Surface, 122, 167–190, https://doi.org/10.1002/2016JF003971, 2017.

Mohr, J., Reeh, N., and Madsen, S.: Three-dimensional glacial flow and surface elevation measured with radar interferometry., Nature, 391,

445 273–276, https://doi.org/10.1038/34635, 1998.

Morlighem, M., Rignot, E., Seroussi, H., Larour, E., Ben Dhia, H., and Aubry, D.: A mass conservation approach for mapping glacier ice thickness, Geophysical Research Letters, 38, https://doi.org/10.1029/2011GL048659, 2011.

Muskett, R. R., Lingle, C. S., Tangborn, W. V., and Rabus, B. T.: Multi-decadal elevation changes on Bagley Ice Valley and Malaspina Glacier, Alaska, Geophysical Research Letters, 30, https://doi.org/10.1029/2003GL017707, 2003.

450 Palmer, S. J., Shepherd, A., Sundal, A., Rinne, E., and Nienow, P.: InSAR observations of ice elevation and velocity fluctuations at the Flade Isblink ice cap, eastern North Greenland, Journal of Geophysical Research: Earth Surface, 115, https://doi.org/10.1029/2010JF001686, 2010.

RGIConsortium: Randolph Glacier Inventory - A Dataset of Global Glacier Outlines: Version 6.0: Technical Report, Global Land Ice Measurements from Space, Tech. rep., Colorado, USA. Digital Media., https://doi.org/10.7265/N5-RGI-60, 2017.

455 Riel, B., Simons, M., Agram, P., and Zhan, Z.: Detecting transient signals in geodetic time series using sparse estimation techniques., J. Geophys. Res.-Solid, 119, 5140–5160, https://doi.org/10.1002/2014JB011077, 2014.

Riel, B., Simons, M., Ponti, D., and Agram, P.and Jolivet, R.: Quantifying ground deformation in the Los Angeles and Santa Ana Coastal Basins due to groundwater withdrawal., Water Resour. Res., 54, 3557–3582, https://doi.org/10.1029/2017WR021978, 2018.

Riel, b., Minchew, b., and Joughin, I.: Observing traveling waves in glaciers with remote sensing: new flexible time series methods and application to Sermeq Kujalleq (Jakobshavn Isbræ), Greenland, The Cryosphere, 15, 407–429, https://doi.org/10.5194/tc-15-407-2021, 2021.

Rignot, E.: Fast Recession of a West Antarctic Glacier, Science, 281, 549–551, https://doi.org/10.1126/science.281.5376.549, 1998.

Rignot, E.: Mass balance of East Antarctic glaciers and ice shelves from satellite data., Annals of Glaciology, 34, 217–227, https://doi.org/10.3189/172756402781817419, 2002.

Rignot, E., Echelmeyer, K., and Krabill, W.: Penetration depth of interferometric synthetic-aperture radar signals in snow and ice, Geophysical Research Letters, 28, 3501–3504, https://doi.org/10.1029/2000GL012484, 2001.

Rosen, P., Hensley, P., Joughin, I., Li, F., Madsen, S., Rodriguez, E., and Goldstein, R.: Synthetic aperture radar interferometry, Proceedings of the IEEE, 88, 333–382, 2000.

Samsonov, S.: Three-dimensional deformation time series of glacier motion from multiple-aperture DInSAR observation., Journal of Geodesy, 93, 2651–2660, https://doi.org/10.1007/s00190-019-01325-y, 2019.

Samsonov, S. and d'Oreye, N.: Multidimensional time series analysis of ground deformation from multiple InSAR data sets applied to Virunga Volcanic Province, Geophysical Journal International, 191, 1095–1108, https://doi.org/10.1111/j.1365-246X.2012.05669.x, 2012.

Samsonov, S. and d'Oreye, N.: Multidimensional Small Baseline Subset (MSBAS) for Two-Dimensional Deformation Analysis: Case Study Mexico City, Canadian Journal of Remote Sensing, 43, https://doi.org/10.1080/07038992.2017.1344926, 2017.

Samsonov, S. and Tiampo, K.: Analytical optimization of DInSAR and GPS dataset for derivation of three-dimensional surface motion, Geoscience and remote sensing letters, 3, 107–111, 2006.

Samsonov, S., Tiampo, K., Rundle, J., and Li, Z.: Application of DInSAR-GPS optimization for derivation of fine scale surface motion maps of southern California, IEEE Transactions on Geoscience and Remote Sensing, 45, 512–521, 2007.

Samsonov, S., Dille, A., Dewitte, O., Kervyn, F., and d'Oreye, N.: Satellite interferometry for mapping surface deformation time series in one, two and three dimensions: A new method illustrated on a slow-moving landslide., Engineering Geology, 266, 105 471, https://doi.org/10.1016/j.enggeo.2019.105471, 2020.

Samsonov, S., Tiampo, K., and Cassotto, R.: SAR-derived flow velocity and its link to glacier surface elevation change and mass balance, Remote Sensing of Environment, 258, 112 343, https://doi.org/10.1016/j.rse.2021.112343, 2021.

Sauber, J., Molnia, B., Carabajal, C., Luthcke, S., and Muskett, R.: Ice elevations and surface change on the Malaspina Glacier, Alaska, Geophysical Research Letters, 32, https://doi.org/10.1029/2005GL023943, 2005.

Sharp, R. P.: Accumulation and ablation on the Seward-Malaspina glacier system, Canada-Alaska, GSA Bulletin, 62, 725–744, https://doi.org/10.1130/0016-7606(1951)62[725:AAAOTS]2.0.CO;2, 1951.

Sharp, R. P.: Malaspina Glacier, Alaska, Geological Society of America Bulletin, 69, 617–646, https://doi.org/10.1130/0016-7606(1958)69[617:MGA]2.0.CO;2, 1958.

Shen, Z.-K. and Liu, Z.: Integration of GPS and InSAR data for resolving 3-dimensional crustal deformation, Earth and Space Science, 7, https://doi.org/10.1029/2019EA001036, 2020.

Shepherd, A., Wingham, D. J., Mansley, J. A. D., and Corr, H. F. J.: Inland Thinning of Pine Island Glacier, West Antarctica, Science, 291, 862–864, https://doi.org/10.1126/science.291.5505.862, 2001.

Shepherd, A., Ivins, E., and Rignot, E. e. a.: Mass balance of the Greenland Ice Sheet from 1992 to 2018., Nature, 579, 233–239, https://doi.org/10.1038/s41586-019-1855-2, 2020.

Strozzi, T., Luckman, A., Murray, T., and Wegmuller, U.and Werner, C. L.: Glacier motion estimation using SAR offset-tracking procedures, IEEE Transactions on Geoscience and Remote Sensing, 40, 2384–2391, https://doi.org/10.1109/TGRS.2002.805079, 2002.

van de Wal, R. S. W., Boot, W., van den Broeke, M. R., Smeets, C. J. P. P., Reijmer, C. H., Donker, J. J. A., and Oerlemans, J.: Large and Rapid Melt-Induced Velocity Changes in the Ablation Zone of the Greenland Ice Sheet, Science, 321, 111–113, https://doi.org/10.1126/science.1158540, 2008.

Vijay, S. and Braun, M.: Seasonal and interannual variability of Columbia Glacier, Alaska (2011-2016): ice velocity, mass flux, surface elevation and front position., Remote Sensing, 9, 635, https://doi.org/doi.org/10.3390/rs9060635, 2017.

Waechter, A., Copland, L., and Herdes, E.: Modern glacier velocities across the Icefield Ranges, St Elias Mountains, and variability at selected glaciers from 1959 to 2012, Journal of Glaciology, 61, 624–634, https://doi.org/10.3189/2015JoG14J147, 2015.

Wang, Q., Fan, J., Zhou, W., Tong, L., Guo, Z., Liu, G., Yuan, W., Sousa, J. J., and Perski, Z.: 3D Surface velocity retrieval of mountain glacier using an offset tracking technique applied to ascending and descending SAR constellation data: a case study of the Yiga Glacier, International Journal of Digital Earth, 12, 614–624, https://doi.org/10.1080/17538947.2018.1470690, 2019.

Wegmuller, U. and Werner, C.: GAMMA SAR processor and interferometry software, in: The 3rd ERS symposium on space at the service of our environment, Florence, Italy, 1997.

Werder, M. A., Huss, M., Paul, F., Dehecq, A., and Farinotti, D.: A Bayesian ice thickness estimation model for large-scale applications, Journal of Glaciology, 66, 137–152, https://doi.org/10.1017/jog.2019.93, 2019.

Wright, H.: Surge Moraines of the Klutlan Glacier, Yukon Territory, Canada: Origin, Wastage, Vegetation Succession, Lake Development, and Application to the Late-Glacial of Minnesota, Quaternary Research, 14, 2–18, https://doi.org/10.1016/0033-5894(80)90003-4, 1980.

Wright, T., Parsons, B., and Lu, Z.: Toward mapping surface deformation in three dimensions using InSAR., Geophysical Research Letters, 31, 2004.

Table 1. Sentinel-1 SAR data used in this study, where θ is incidence and ϕ is azimuth angles.

	Span	$\theta°$	$\phi°$	Number of SLC swaths
Sentinel-1 track 123 (asc)	20160816-20210128	39	342	109
Sentinel-1 track 116 (dsc)	20161020-20210121	39	198	116
Total (after boundary correction)	20161020-20210121			223
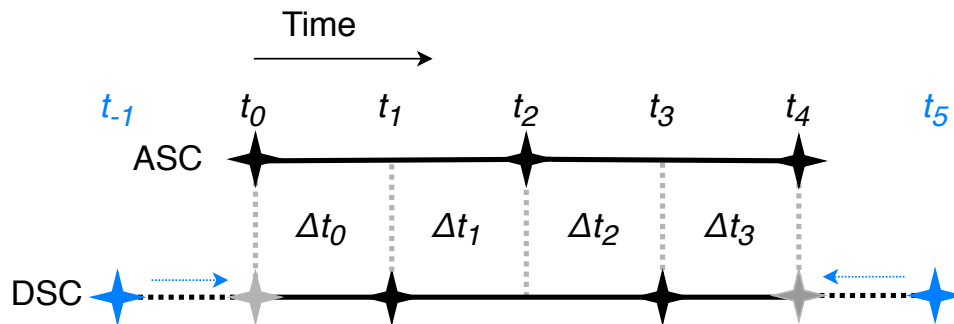
Figure 1. Schematics of simplified case described by (3). Ascending and descending SAR acquisitions at time t_i are marked with black stars. Horizontal solid lines represent range and azimuth offset maps. Vertical dashed lines divide temporal scale in time intervals $\Delta t_i = t_{i+1} - t_i$ between consecutive acquisitions. Time of first and last descending acquisitions (marked with blue stars) are adjusted to match first and last time of ascending acquisitions (marked with gray stars).
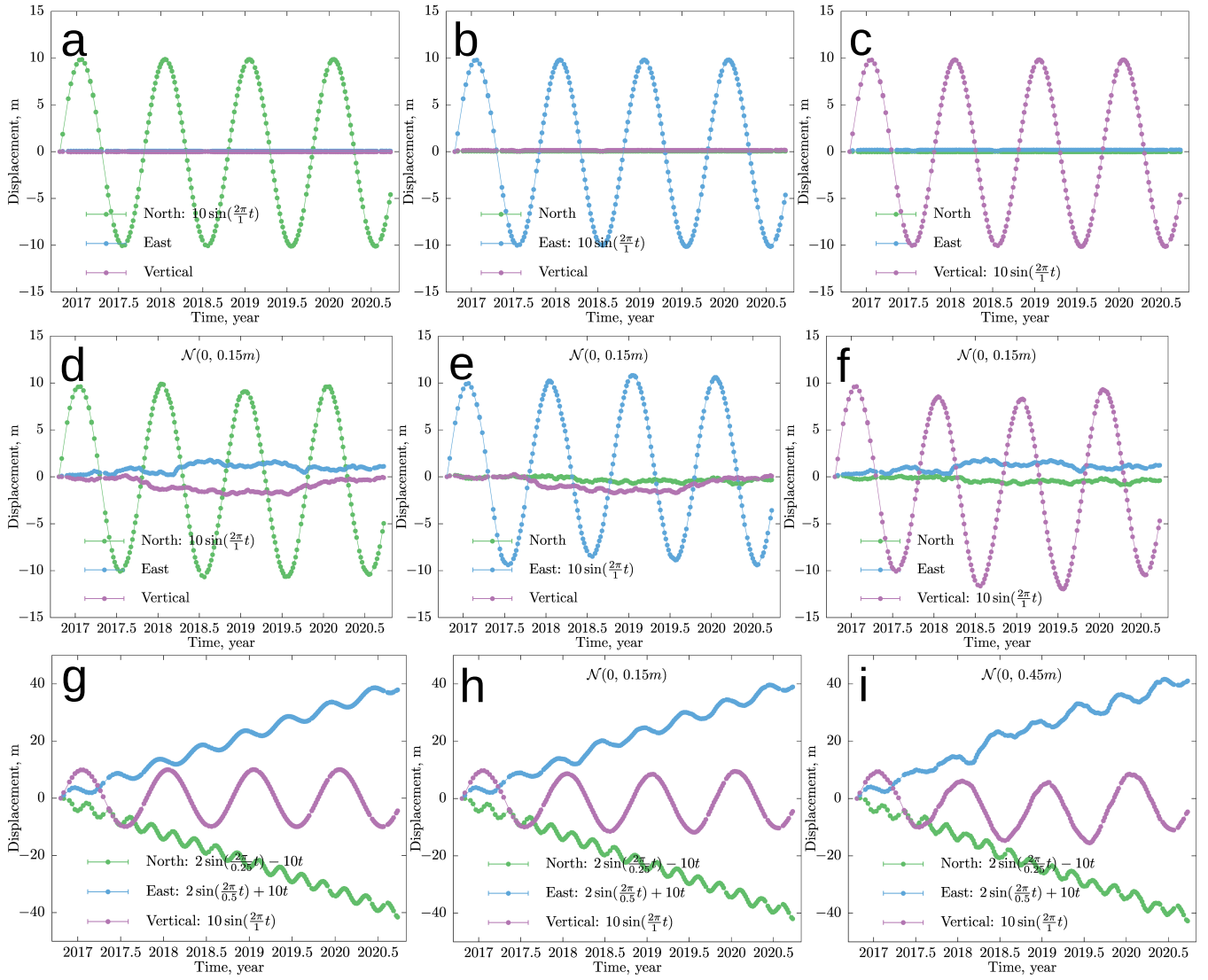
Figure 2. Results of numerical simulations. Equations of input signals are shown in corresponding subfigure legends where t is time. Harmonic and linear input signals are assumed. Gaussian noise with mean value of zero and standard deviations in range 0.15-0.45 m (which is approximately 10-30% of signal) is added to subfigures in second and third columns.
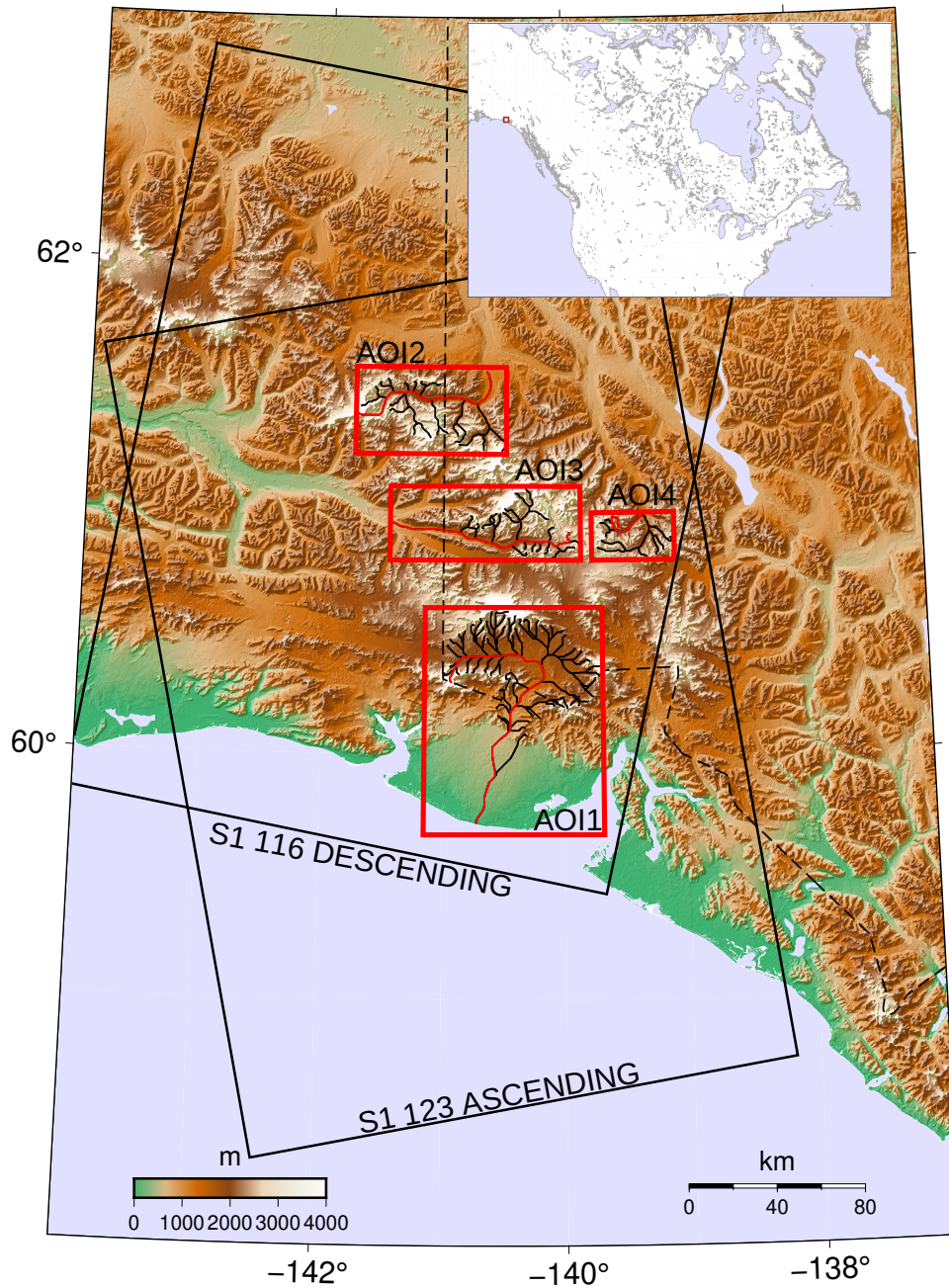
Figure 3. Outlines of four areas of interest (AOIs) in southeastern Alaska are shown in red. AOI1 covers Agassiz (AG), Malaspina (MG) and Seward (SG) Glaciers. AOI2 covers Klutlan Glacier (KG). AOI3 covers Walsh Glacier (WG). AOI4 covers Kluane Glacier. Flow lines in black and red were computed using Open Global Glacier Model (OGGM) software (Maussion et al., 2019). Outlines of ascending (track 123) and descending (track 116) Sentinel-1 swaths are shown in black. Background is 30 m Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) digital elevation model (Abrams et al., 2020). Canada-USA border is shown as dashed black line.
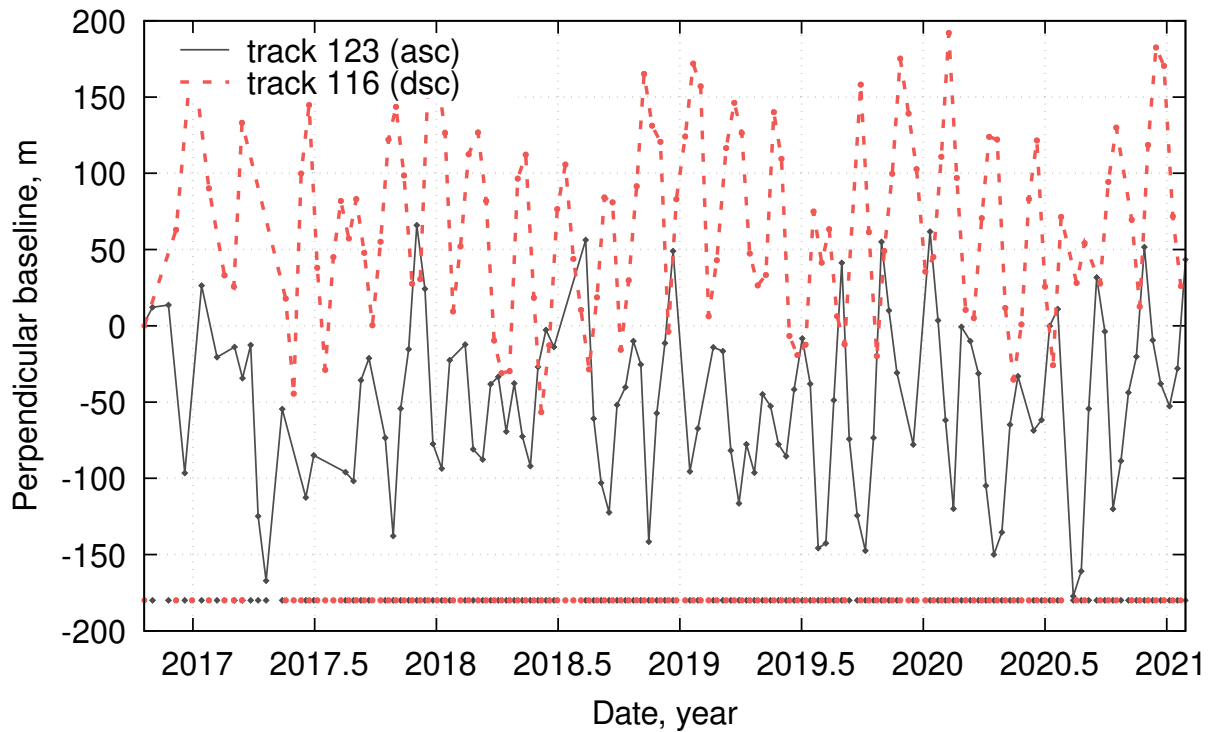
Figure 4. Spatial and temporal baselines of Sentinel-1 pairs used in this study. Mean temporal resolution, i.e. mean temporal spacing between consecutive SAR acquisition regardless of orbit direction, computed as duration divided by number of SAR images (4.25 years*365/223) is about 7 days. Note that offset between ascending and descending sets depends on selection of reference images, which is arbitrary.
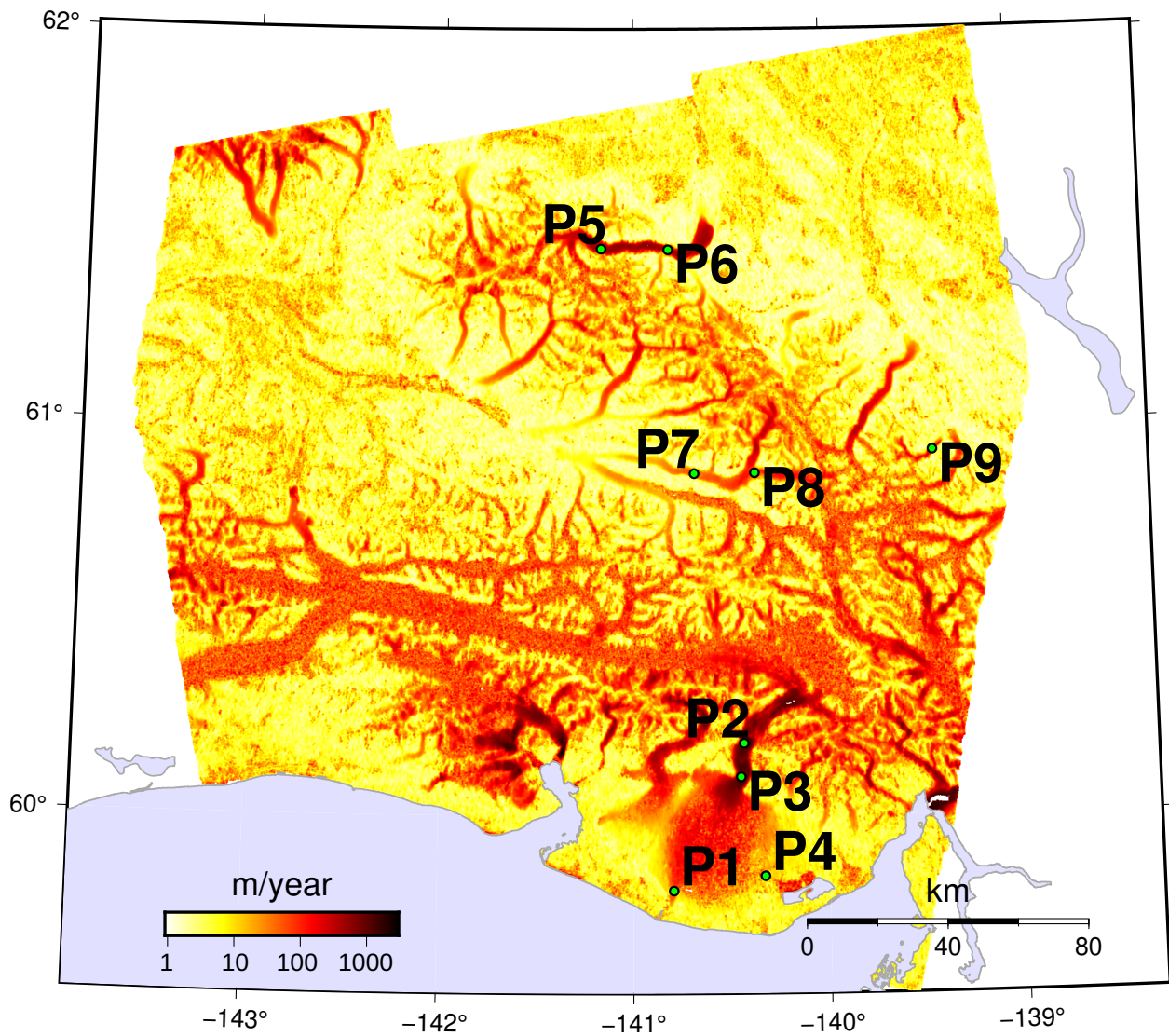
Figure 5. Magnitude of mean 3D flow velocities plotted using logarithmic scale. For regions P1-P4 at Malaspina/Seward Glaciers, P5-P6 at Klutlan Glacier, P7-P8 at Walsh Glacier and P9 and Kluane Glacier time series are provided in Figures 10-11.
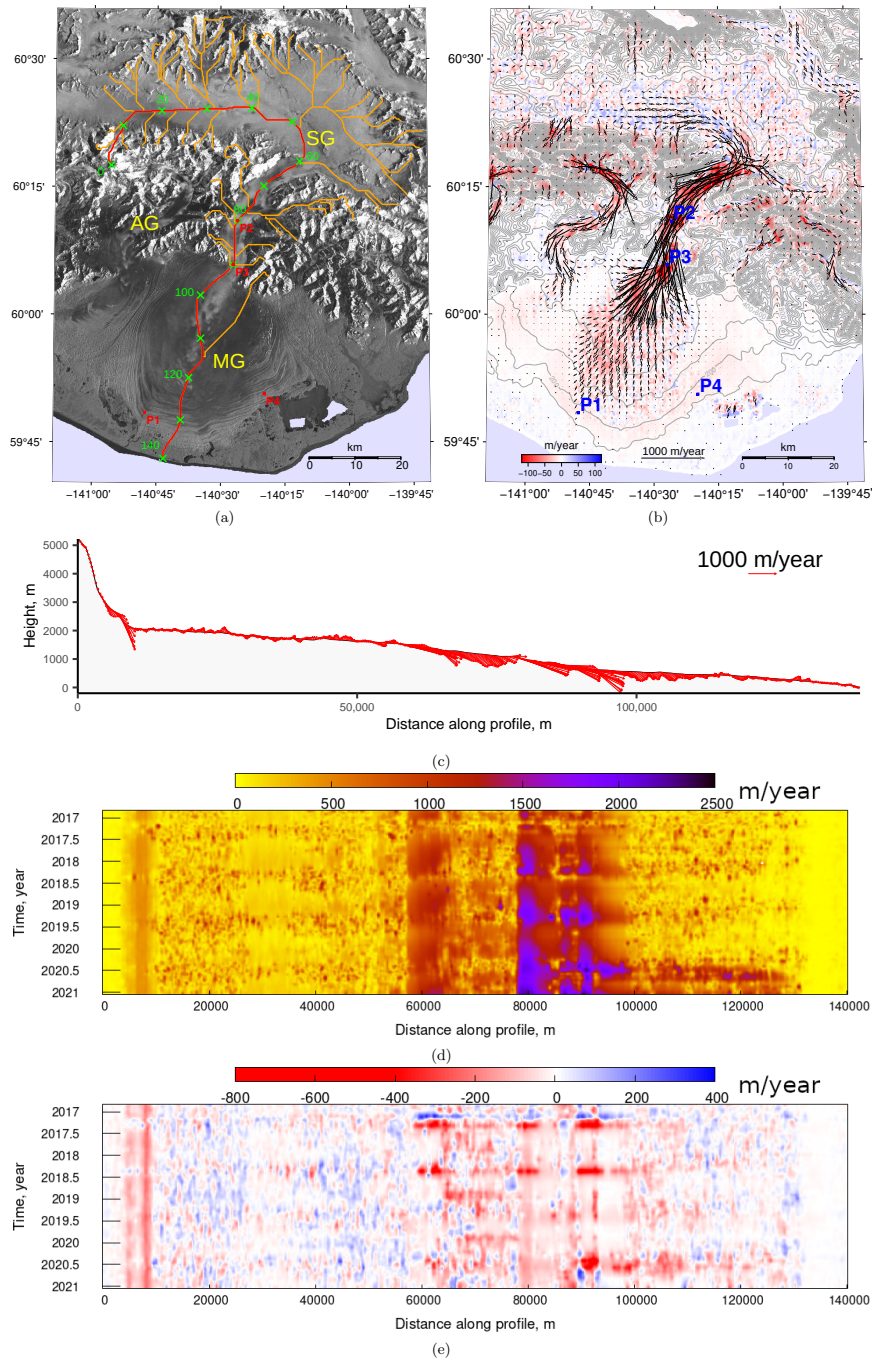
Figure 6. (a) Sentinel-1 SAR intensity image acquired on 20191222 (in YYYYMMDD format) over AOI1 that covers Agassiz (AG), Malaspina (MG) and Seward (SG) Glaciers. Flowlines are in orange and red. Markers in green show distance in kilometres along selected in red flowline. (b) Time-averaged 3D flow velocities: horizontal velocity is shown as (coarse-resolution) vector map and vertical velocity is colour-coded. Surface topographic contour lines derived from TerraSAR-x 90 m DEM with intervals of 100 m are shown in grey. Flow displacement time series for regions P1-P4 are plotted in Figure 10. (c) Time-averaged 3D flow velocities and glacier height along red flowline. (d) Temporal evolution of horizontal flow velocity magnitude along red flowline. (e) Temporal evolution of vertical flow velocity along red flowline.
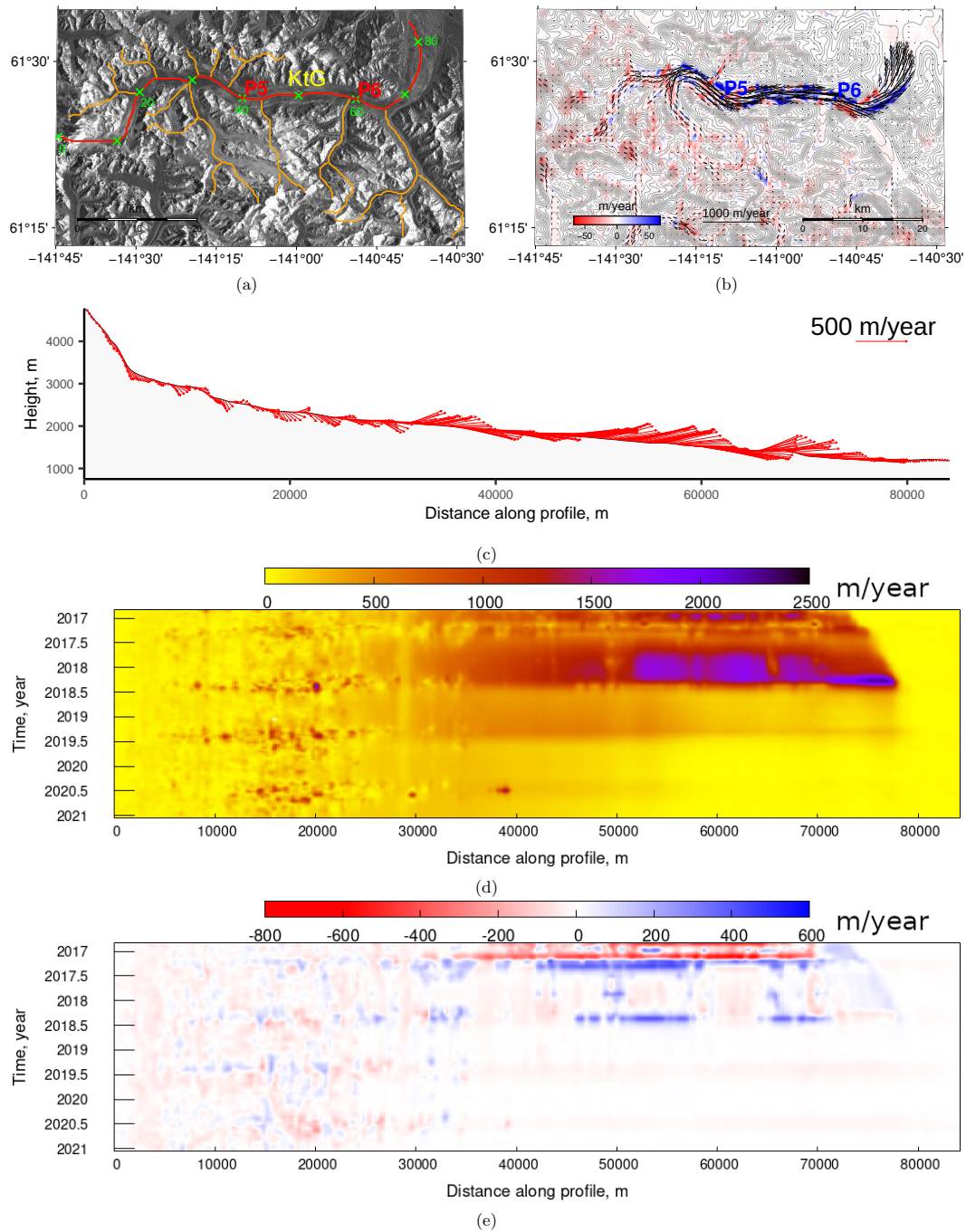
Figure 7. (a) Sentinel-1 SAR intensity image acquired on 20191222 over AOI2 that covers Klutlan Glacier (KtG). Flowlines are in orange and red. Markers in green show distance in kilometres along selected in red flowline. (b) Time-averaged 3D flow velocities: horizontal velocity is shown as (coarse-resolution) vector map and vertical velocity is colour-coded. Surface topographic contour lines derived from TerraSAR-x 90 m DEM with intervals of 100 m are shown in grey. Flow displacement time series for regions P5-P6 are plotted in Figure 10. (c) Time-averaged 3D flow velocities and glacier height along red flowline. (d) Temporal evolution of horizontal flow velocity magnitude along red flowline. (e) Temporal evolution of vertical flow velocity along red flowline.
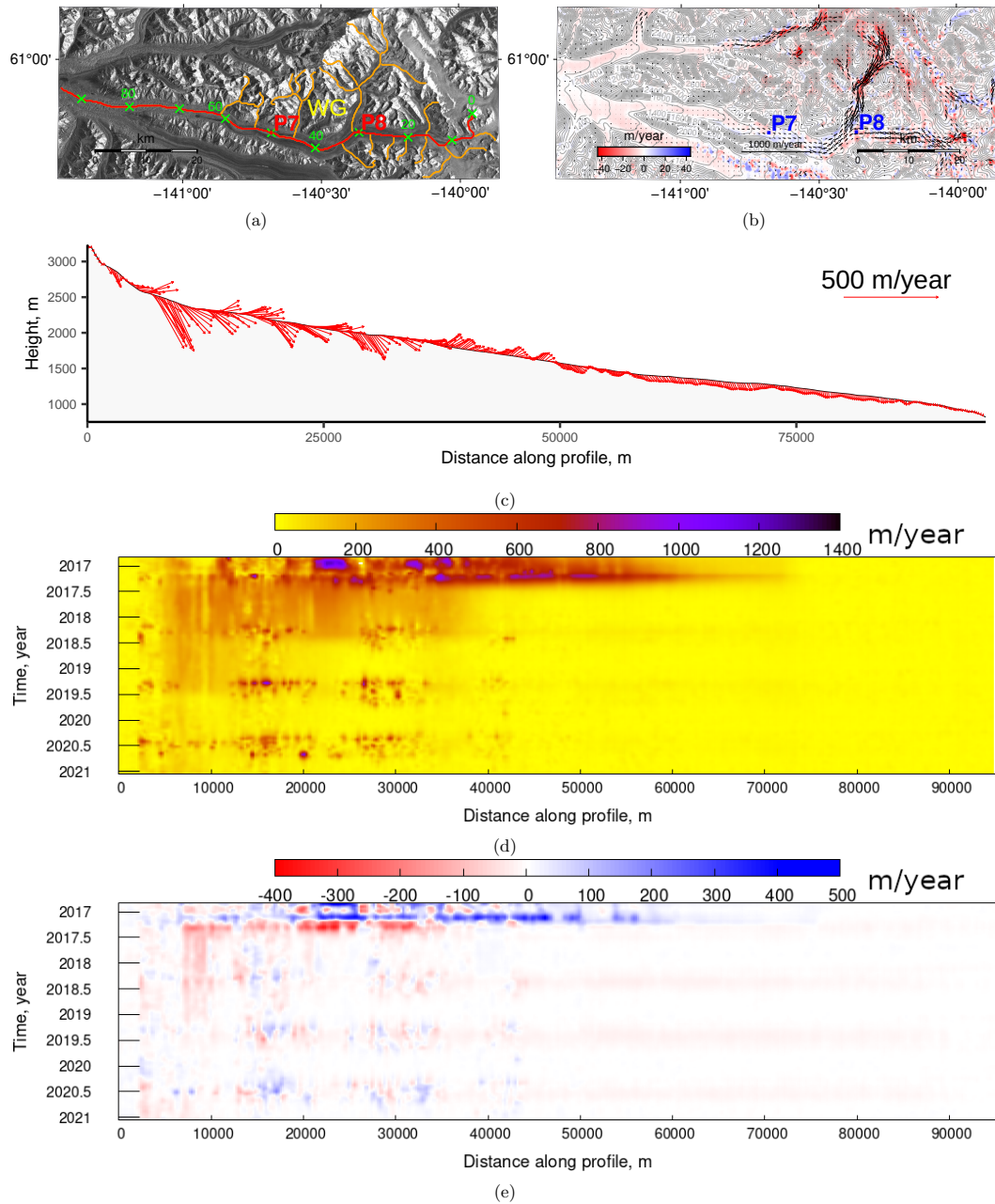
Figure 8. (a) Sentinel-1 SAR intensity image acquired on 20191222 over AOI3 that covers Walsh Glacier (WG). Flowlines are in orange and red. Markers in green show distance in kilometres along selected in red flowline. (b) Time-averaged 3D flow velocities: horizontal velocity is shown as (coarse-resolution) vector map and vertical velocity is colour-coded. Surface topographic contour lines derived from TerraSAR-x 90 m DEM with intervals of 100 m are shown in grey. Flow displacement time series for regions P7-P8 are plotted in Figure 10. (c) Time-averaged 3D flow velocities and glacier height along red flowline. (d) Temporal evolution of horizontal flow velocity magnitude along red flowline. (e) Temporal evolution of vertical flow velocity along red flowline.
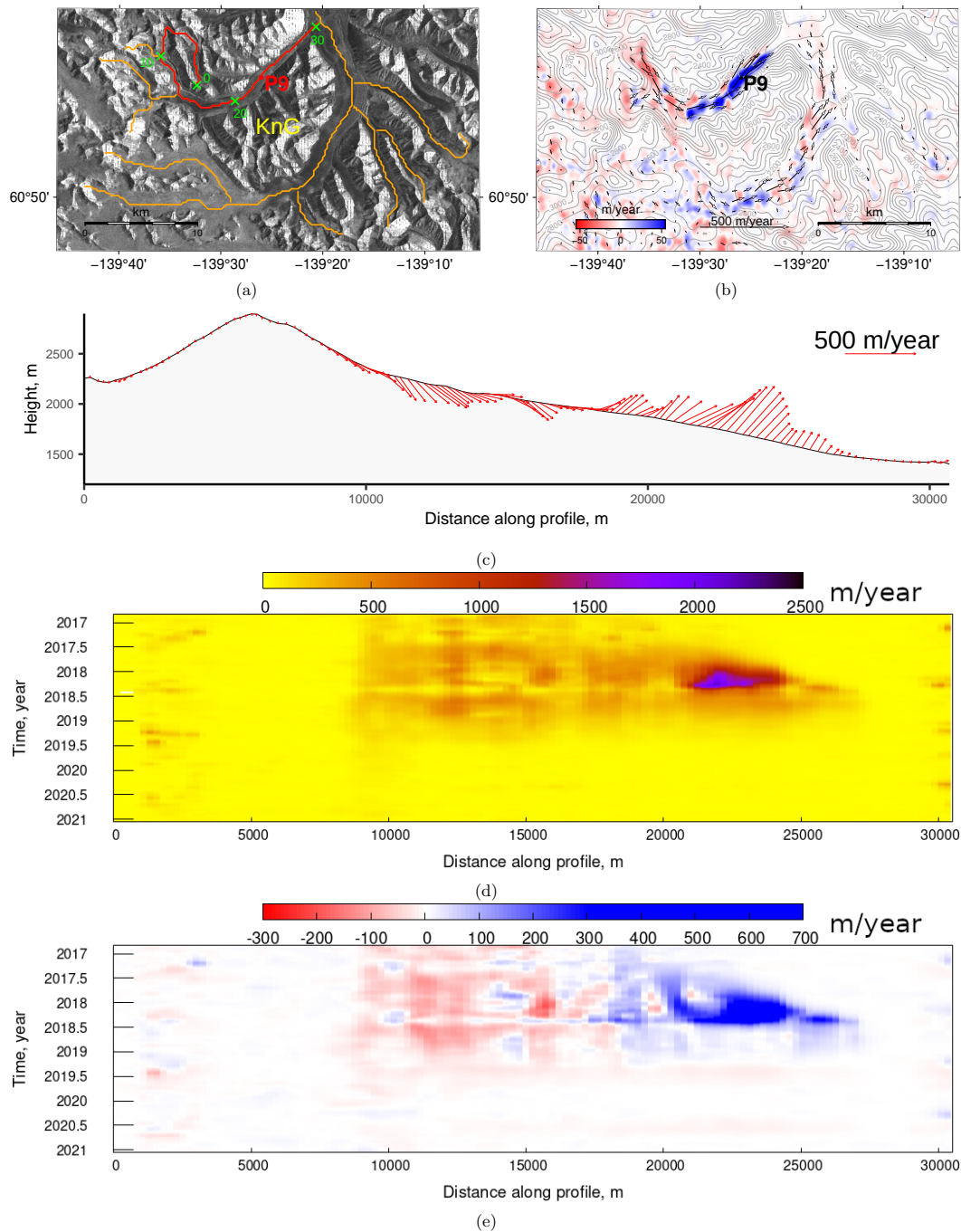
Figure 9. (a) Sentinel-1 SAR intensity image acquired on 20191222 over AOI4 that covers Kluane Glacier (KnG). Flowlines are in orange and red. Markers in green show distance in kilometres along selected in red flowline. (b) Time-averaged 3D flow velocities: horizontal velocity is shown as (coarse-resolution) vector map and vertical velocity is colour-coded. Surface topographic contour lines derived from TerraSAR-x 90 m DEM with intervals of 100 m are shown in grey. Flow displacement time series for region P9 are plotted in Figure 10. (c) Time-averaged 3D flow velocities and glacier height along red flowline. (d) Temporal evolution of horizontal flow velocity magnitude along red flowline. (e) Temporal evolution of vertical flow velocity along red flowline.
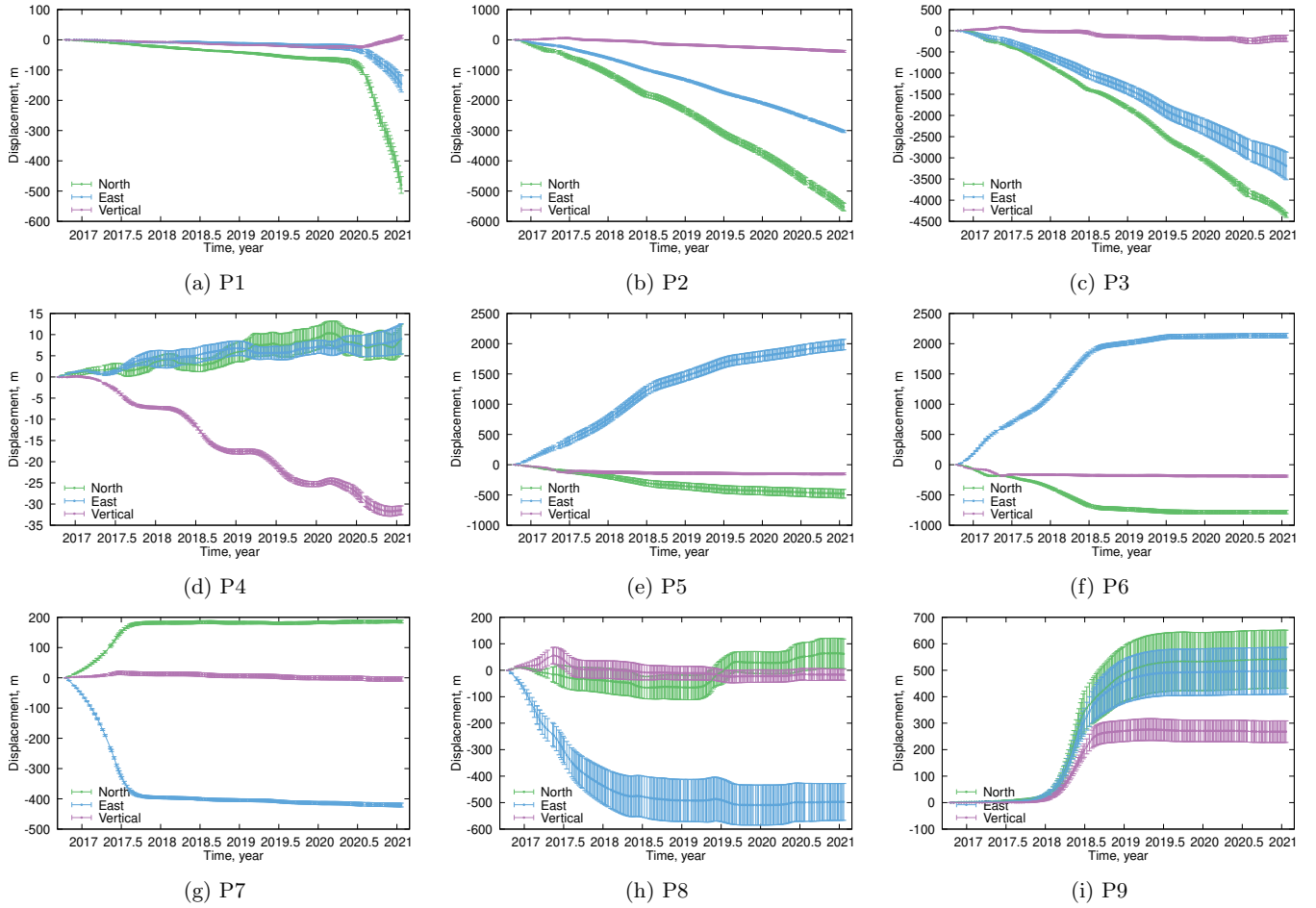
Figure 10. 3D flow displacement time series for regions P1-P9, which locations are shown in Figures 5-9.
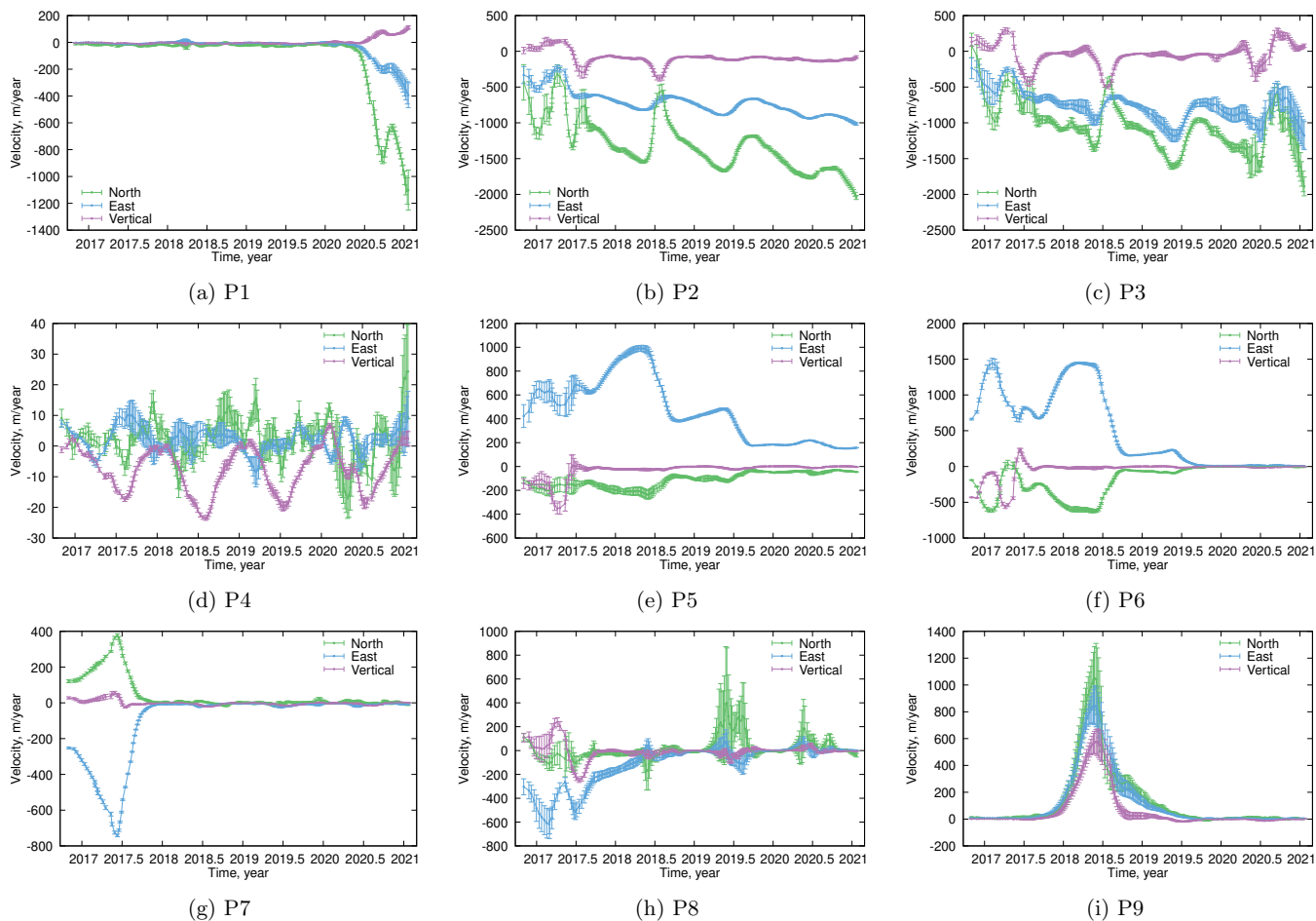
Figure 11. 3D flow velocity time series for regions P1-P9, which locations are shown in Figures 5-9.