

MID-TERM REPORT

Mass balance and ice dynamics of Antarctic Peninsula glaciers, MIT-AP

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1 EXECUTIVE SUMMARY

The report summarizes the aims and the work performed of the Living Planet Fellowship of the principal investigator (PI) Dr. Thorsten Seehaus for the first project year. The project aims at obtaining spatially detailed information on glacier mass changes and long-term information on ice dynamic variations on the Antarctic Peninsula (AP) by using multi-mission remote sensing data.

Digital elevation models (DEMs) are generated from bistatic TanDEM-X SAR imagery for different time periods since 2013. Since the AP has only a very limited amount of ice free areas, the individual DEMs are referenced by including also sea ice covered areas and ice shelf areas around the AP. Therefore, tidal corrections and ice free board estimations of the ice shelves based on tidal simulations and altimeter data are included in the processing. Finally, information on glacier volume changes are obtained by differentiating the DEMs from different time periods.

For some sections of the AP, it is assumed that up-welling of warm circum polar deep water (CDW) triggered the glacier recession. Therefore, ocean temperature data from oceanic modeling was analyzed and will be correlated with the revealed glacier change information.

Moreover, the glacier surface velocities data base for the AP at FAU was updated by processing additional TanDEM-X and TerraSAR-X imagery. Thus, a long-term data base for the analysis of glacier dynamic variations exists for the remaining project run time.

Preliminary results of the project were presented at two conferences and an joint publication with researchers from Madrid was published on the glacier mass balance on the South Shetland Island (next to the northern AP) using approaches partly developed with this project.

Overall, the project progress is with in the proposed work plan (note: the project has been interrupted twice due to the parental leave of the PI and personal issues at FAU, 8 project month were realized in total) and the preparation of two scientific publications is targeted within the remaining project run time.

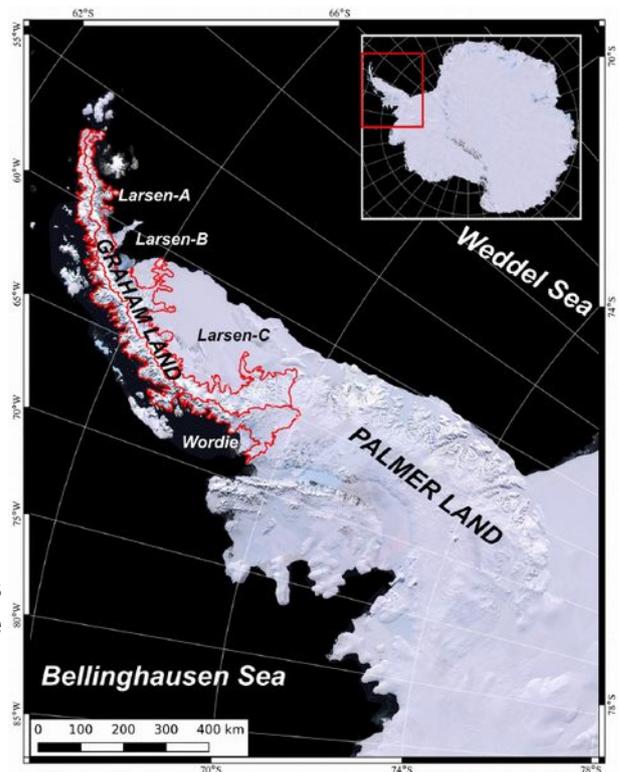


Figure 1: Overview map of the Antarctic Peninsula. Red polygons: study area and outlines of the major drainage basins north of 70°S. Background Landsat LIMA Mosaic by USGS

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2 OBJECTIVES AND WORKPLAN

This proposal aims to carry out a comprehensive analysis of spatio-temporal glacier changes along the Antarctic Peninsula (AP) north of 70°S (Figure 1). By using multi-mission remote sensing data from mainly ESA or European Missions in combination with in-situ data and modeling results, enhanced and new information on the mass budget and ice dynamics will be obtained and drivers of the revealed changes identified.

The following specific objectives are targeted:

- first area wide assessment of geodetic mass balances by means of repeated bistatic InSAR satellite acquisitions
- improved and precise estimation of ice losses on regional and glacier scales
- enhanced analysis of temporal changes of glacier flow and quantification of ice discharge throughout the study region
- analysis on spatio-temporal variations in the mass balance estimates and ice dynamics
- assessment of drivers for revealed change patterns by including oceanic and atmospheric modeling and in-situ data sets

In order reach the proposed objectives, the project is subdivide into the following two work packages (WP):

- WP1: Geodetic mass balance of the Antarctic Peninsula
- WP2: Analysis of temporal changes in ice dynamics

More details regarding the work packages are provided further down.

We defined the following initial work plan to complete the work-packages with in the 2 years of project run time. The project kick-off was in November 2020.

project year	st 1 year				nd 2 year			
	1	2	3	4	1	2	3	4
quarter work package								
WP 1	■	■	■	■	■	■		
WP 2			■	■	■	■	■	■

The initial workplan had to be changed, since the PI took two month of parental leave in June and July 2021. Moreover, the PI will took over a 100% position at the host institute due to change human resource planing for the winter term (Oct. 2021 – March 2022) and to compensate the exit of some staff. Thus, there will be a project pause of 6 month starting in October 2021. During this period, the PI will be available for any project meetings and will also continue to work on the project, but with reduced capacities.

In agreement with ESA the workplan had to be change to:

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year	2020	2021												2022												2023						
month	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	
WP1																																
WP2																																

Detailed description of work packages:

WP1: Geodetic mass balance of the Antarctic Peninsula

The automated processing routine to derived surface elevation changes from TanDEM-X data implemented at FAU will be used to obtain geodetic mass balance information of the AP. The routine allows to process large amount of TanDEM-X scenes. It includes the interferometric processing of the TanDEM-X CoSSC tiles, the 3D-coregistration to a reference DEM (enhanced approach of Nuth and Kääb, 2011), generation of regional DEM mosaics and elevation change maps, gap-filling and the computation of the geodetic glacier mass balances, including a rigorous error assessment (detailed descriptions of the routine can be found here: Braun et al., 2019; Seehaus et al., 2020, 2019). The enhanced ASTER DEM of the Antarctic Peninsula (Cook et al., 2012) or the edited TanDEM-X DEM (12m resolution) for the Antarctic Peninsula (release date currently unknown) will be used as reference for the 3D coregistration the TanDEM-X data of the AP. The other TanDEM-X coverages will be coregistered to this generated reference TanDEM-X DEM to obtain precise elevation change information. The algorithm uses off-glacier areas (stable ground) to perform the 3D-coregistration and error assessment. Due to the relatively low fraction of ice-free areas along the AP, the registration will be supported by analysing elevation differences on sea ice next to the glacier termini. Information on the sea-ice thickness will be obtained from e.g. "meereisportal.de" based on SMOS or CryoSat-2 data. A tidal correction of the measured elevation on sea ice by TanDEM-X needs to be carried out. Such an approach was already successfully applied by the applicant at two glacier systems on the northeastern AP (Seehaus et al., 2015, 2016), using the Circum-Antarctic Tidal Simulations model (CATS) (Padman et al., 2002).

The elevation change measurements can be influence by the radar signal penetration in snow and ice (e.g. Seehaus et al., 2015 reported 2-3 m seasonal fluctuations at a glacier system on the northeastern AP). By comparing elevation measurements from the same season (assuming similar glacier surface conditions), the bias due to SAR signal penetration can be minimized (Malz et al., 2018; Seehaus et al., 2020a). Rott et al. (2018) showed at the Larsen-A and B embayments (eastern AP), that the SAR signal penetration can be neglected when comparing DEMs derived from TanDEM-X acquisitions from austral winter season. Consequently, surface elevation changes will be only derived from TanDEM-X coverages from the same season, in order to minimize biases due to SAR signal penetration.

Laser altimeter data from the ICESat-2 mission in combination with co-incident TanDEM-X acquisitions will be employed to evaluate the hypothesis, that the SAR

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signal penetration can be neglected when comparing TanDEM-X data from the same season. If the hypothesis fails, the ICESat-2 data will be used to empirically quantify a potential penetration bias, which will be included in the analysis of the elevation change data.

Finally, glacier mass balance will be derived from the elevation change maps considering different volume to mass conversion factors. An average density of 850 kg/m^3 is considered, as suggested by Huss (2013). Kääb et al. (2012) reported that such a constant density scenario is suitable for glaciers where the volume changes are mainly forced by glacier dynamics, as suggested by various studies at the AP. A correction for GIA will not be applied, since we reference the DEMs to each other on stable ground. Moreover, the GIA rate of a few mm per year at the study site (Ivins et al., 2013) is negligible considering the study period and previously reported glacier change rates.

The glacier mass balances will be computed on regional scales by using “standard major drainage basin definitions” like the “ICESat basins” (Zwally et al., 2012) and the delineations by Rignot et al. (2013) in order to facilitate the comparison with other studies and techniques, but also to provide “standardized” information for initiatives like IPCC, WGMS and IMBIE and for improving the computations of the glacial-isostatic adjustments (GIA) of the solid Earth caused by ice mass depletion. Mass balances will be also computed on sub-basin and glacier catchment scales in order to analyse spatial and/or temporal variations and to infer potential driver. Therefore, climatic observations and modelling output as well as oceanic information will be included in a comprehensive analysis (see work package 2 for more information). Such a fusion of various data sets to study the changes of the AP ice sheet will be novel and provide an unprecedented insight into the ongoing processes.

WP2: Analysis of temporal changes in ice dynamics

The dynamics and thus the ice discharge in the ocean, of the glaciers along the AP have shown considerable changes in the past decades. In particular, the disintegration of several ice shelves led to dramatic speed up and ice wastage of the tributary glaciers (Eineder et al., 2011; Rott et al., 2014; Scambos et al., 2014; Seehaus et al., 2015). However, also non-ice-shelf tributaries showed considerable changes in the ice flow, as shown by the PI for several glaciers along the northern tip of the AP (Seehaus et al., 2018). Therefore, a comprehensive analysis of the temporal evolution of the glaciers dynamics throughout the AP and to infer correlations with other parameters (climate and oceanic data, geodetic mass balance, see also WP1) is targeted.

Since the AP is affected by frequent cloud cover, SAR data is preferable to obtain information on the changes of glacier flow by using offset tracking techniques. This work package can rely on the huge amount of SAR data in the archive at FAU, data access via granted data proposals and an automated routine (developed by the PI and extended by other group members) to derive glacier surface velocity maps. This algorithm can be applied to data from various SAR sensors (e.g. ERS, TerraSAR-X, ALOS-Palsar, Sentinel-1) and automatically selects the consecutive SAR image pairs, runs an iterative coregistration, multi-parameter intensity offset tracking, iterative outlier filtering and geocoding of the results. Various regions and periods of the available data along the AP are already processed. Within this work-package, the database will be temporally and spatially completed in order to facilitate a comprehensive analysis of the ice flow throughout the study region.

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Besides information on the glacier velocities, ice thickness information at the grounding line or slightly upstream is crucial to compute the ice discharge to the ocean. Grounding line positions will be taken from NASA MEaSUREs-2 products available at NSIDC. In contrast to the ice discharge estimates by Rignot et al. (2019), which assumed balanced glacier conditions in the early 1970s for a huge fraction of the analyzed glaciers to estimate the ice thickness (see “State of the art”), it is targeted to use modeled or measured ice thickness information for all analyzed glacier catchments. Ice thickness measurements using airborne ground penetrating radar are only available for a limited amount of the glaciers. However, various ice thickness reconstructions using different approaches are available for the AP. Many glaciers on the AP showed pronounced thinning in the last decades (e.g. Rott et al., 2014; Scambos et al., 2014; Seehaus et al., 2015). Thus, temporal changes in the ice thickness due to glacier thinning throughout the study period will be accounted for (similar to Seehaus et al., 2015). A correction of the ice thickness will be employed using information on the glacier surface lowering obtained in work package 1 and from literature. Finally, the obtained information on the ice discharge will be analyzed in combination with the geodetic mass balance data from work package 1 and atmospheric and oceanic parameters in order to identify causes for the revealed spatial and temporal pattern in ice discharge. Data from oceanic modeling and from the World Ocean Database will be employed to obtain information on the oceanic setting affecting the glaciers of the study region. Atmospheric parameters are taken from region climate modeling (RACMO and MAR) and in-situ measurements (from the REference Antarctic Data for Environmental Research Project “READER” by the Scientific Committee on Antarctic Research). In addition to work package 1, glacier mass balance will be computed using the input-output method by differentiating the CMB (obtained from regional climate modeling RACMO or MAR and the ice discharge. This method allows an independent estimation of the glacier mass balances in addition to the geodetic measurements and provide substantial information for initiatives like IMBIE, WGMS and IPCC.

3 WORK PERFORMED

3.1 Scientific context

During the last decades, glacial systems of the Antarctic Peninsula (AP) have undergone fast and strong changes (Cook and Vaughan, 2010; Rott et al., 2018; Scambos et al., 2014). Due to widespread increased thinning and retreat, as well as rapid disintegration events, ice shelves on both sides of the Antarctic Peninsula have partly or completely disappeared (Cook & Vaughan 2010). On the east side of the Antarctic Peninsula, Prince Gustav (1995), Larsen A (1995) and the northern Larsen B (2002) already disintegrated. At Larsen C a huge iceberg (A-68) broke up in 2017 (Voosen et al., 2017). On the western Antarctic Peninsula, Jones Ice Shelf disappeared in 2003 and Müller as well as Wordie Ice Shelf considerably retreated (Cook and Vaughan, 2010). It is proposed that considerable atmospheric warming on the Antarctic Peninsula during the second half of the 20th century (Scambos et al., 2003; Turner et al., 2016; Vaughan et al., 2003) has triggered these events. Additionally, increased basal melt due to warming ocean water, as suggested for Larsen C Ice Shelf (Hogg and Gudmundsson, 2017; Holland et al., 2015), may have thinned and weakened the ice shelves prior to their collapses.

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Moreover, on the western Antarctic Peninsula the adjacent ocean experienced a warming of up to ~ 1 K (Cook et al., 2016; Meredith and King, 2005). An important process besides general global ocean warming is the periodic up-welling of warm Circum Polar Deepwater (CDW) (Holland et al., 2010) associated with climate change induced shifts of the Southern Annular Mode (SAM) (Walker and Gardner, 2017). Such processes have been linked e.g. with frontal retreat of western Antarctic Peninsula tidewater glaciers south of 64°S (Cook et al., 2016).

Thinning, retreat and disintegration of ice shelves reduces buttressing (Fürst et al., 2016), which leads to acceleration and dynamic thinning of their tributary glaciers (Friedl et al., 2018; Rott et al., 2014, p. 2; Seehaus et al., 2015). These processes are the main causes of the observed increase in mass loss at the Antarctic Peninsula from 7 ± 13 Gt/a (1992 – 1997) to 33 ± 16 Gt/a (2012 – 2017) (IMBIE Team, 2018).

The estimates by the Ice Sheet Mass Balance Inter-comparison Exercise (IMBIE) team are based on mass budget computations from different studies and observation periods, using altimetric, gravimetric and input-output methods. At the AP, the reported mass balances have considerable uncertainties. Within the “overlap period” (2003-2010), the average mass balance values of the individual approaches have uncertainties of up to 90% and vary by up to 500%. Altimetric assessments of elevation changes along the AP is hampered by the pronounced topography (especially due to the large footprints of radar altimeter) and the frequent cloud cover (laser altimeter) (Schröder et al., 2019), in particular for the region north of 70°S (Shepherd et al., 2019). The narrow West to East span of the AP and difficulties in accurately assessing the regional glacial-isostatic adjustments (GIA) of the earth crust (Horwath and Dietrich, 2009), explain the wide span (-39 to -9 Gt/a) and error range (1 - 24 Gt/a) of the gravimetric mass balance estimates. Only two data sets based on the input-output method are collated in the IMBIE study. During the overlap period (2002-2010) differences of up to 30 Gt/a (the range of the average mass loss rate for the period 2012-2017) are found at the AP. As stated by the IMBIE Team, the uncertainty of the input-output method depends on the error budget of the modeled climatic mass balance (CMB, often also called surface mass balance SMB) and the computed ice flux. The latter is strongly affected by the accuracy of the ice thickness data. Measured ice thickness along the AP is only available for a few glaciers (mainly by NASA Operation IceBridge), so the authors relied on the low-resolution (1km) Bedmap2 data-set, which has certain limitations at the AP (Seehaus et al. 2015). No information is provided on the achieved coverage of the ice thickness information and discharge estimates. In the previous analysis (IMBIE-1; Shepherd et al., 2012) ice thickness of huge fractions along AP were unknown. Meanwhile a high-resolution (100 m) ice thickness reconstruction from Huss and Farinotti (2014) is available for the AP north of 70°S and a continent-wide ice thickness map (450 m spatial resolution) derived by using the state of the art approach of BedMachine was released in 2019 (Morlighem et al., 2019).

In early 2019, a study by Rignot et al. (2019) dealing with antarctic-wide ice discharge to the ocean was released. The authors reported an increase in the ice mass loss along the AP from -16.0 ± 2 Gt/a in the period 1979-1989 to -41.8 ± 5 Gt/a in the period 2009-2017. However, the ice discharge estimation do not have a full coverage (78%) and ice thickness information at only 39% of the glacier catchment along the AP were considered in the analysis. At the other catchments, ice discharge changes are obtained by assuming balanced glacier conditions in 1979 (using average modeled CMB 1979-2008 scaled by the ice flow speeds, e.g. for

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Western Graham Land). For several glaciers along the AP, this assumption is certainly reasonable. However, the changes in the climatic conditions in the previous century led already to cryospheric changes before 1979. Cook et al. (2005) and Cook and Vaughan (2010) reported significant glacier and ice shelf recession for the period before 1979. Thus, it is quite likely that several glaciers were not in balanced condition in 1979. Information on the ice flow before 1979 is not available to proof this hypothesis, but Rignot et al. (2019) reported for example for Western Graham Land increasing ice discharge in the years past 1979 indicating unbalanced glacier conditions. Therefore, an ice discharge analysis based on ice thickness information will be favorable.

Besides the analysis of Rignot et al. (2019), which contributed to the IMBIE analysis in 2018, and the previous IMBIE estimates (Shepherd et al., 2012), information on the temporal changes of the ice discharge are available for some glacier basins along the north eastern AP (mainly Larsen-A/B region) for previous decades (e.g. Rott et al., 2018, 2011; Seehaus et al., 2015). However, for the other large sections along the east coast and nearly all glaciers along the west coast (<70°S, except e.g. the Wordie embayment Friedl et al., 2018; Rignot et al., 2005) no additional ice flux studies using ice thickness measurements or reconstructions exist. Significant glacier retreat (since the 1950s) and increasing glacier surface velocities (1992-2005) were measured along the west coast (Cook et al., 2005; Pritchard and Vaughan, 2007), whereas, for the north eastern tip of the AP a general decrease of the glacier surface velocities (1992-2014) was found (Seehaus et al., 2018).

Hogg et al. (2017) have identified a correlation between the intrusion of warm circum-polar deep water (CDW) on the continental shelf of the western AP and increased ice discharge in western Palmer Land (south of 70° S, Figure 1). For the glacier north of 70°S, links between up welling of warm CDW, in particular between 64-70°S, and glacier retreat was observed by Cook et al. (2016). The impact of the intrusion of warm CDW on glacier dynamics and ice discharge has not been analyzed so far on regional scales for glaciers north of 70°S. Existing analyses focused on Fleming Glacier and suggest that grounding line retreat and subsequent glacier speed-up was triggered by up welling of CDW (Friedl et al., 2018; Walker and Gardner, 2017).

Thus, a profound analysis of the spatial and temporal analysis of the ice discharge of the AP glaciers north of 70°S and correlation with oceanic and atmospheric parameter will provide enhance information on the glaciological processes and ice mass changes.

No geodetic mass balance estimate, using differentiating of digital elevation models (DEM), exist so far that cover large regions, like the antarctic drainage basins defined by Rignot et al. (2011) or Zwally et al. (2012). The most extended geodetic mass balance analysis at the AP is based on DEMs obtained from ASTER and SPOT5 optical data, supported ICESat-1 altimeter measurements, partially covering areas north of 66°S primarily in the period 2003-2008 (Scambos et al., 2014). Various analysis of the large Patagonian ice fields (Abdel Jaber et al., 2019; Malz et al., 2018) and mountain range to continental scale studies of mountain glaciers (Braun et al., 2019; Brun et al., 2017; Dussaillant et al., 2019; Seehaus et al., 2019) demonstrated the potential and accuracy of this method. However, geodetic approaches based on optical satellite data, like ASTER, are less suitable at the AP due to limited coverage caused by the frequent cloud cover (see Dussaillant et al., 2019). Thus, geodetic measurements using interferometric SAR data, like TanDEM-X (e.g. Malz et al., 2018; Seehaus et al., 2019) are more suitable. Along the AP, the

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bistatic SAR satellite mission TanDEM-X has been acquiring data since 2011. Several “Super Test Sites” (Figure 2), where data is acquired nearly monthly, are defined along the AP. Additionally; several complete coverages of the AP were acquired for the “global DEM” and “change DEM” missions of TanDEM-X. The feasibility of obtaining geodetic mass balances at the AP were shown on glacier catchment scales by the PI (Seehaus et al., 2019, 2015) and on multi-glacier scales by Rott et al. (2018, 2014)

Such a large-scale analysis of area-wide geodetic mass balance measurements using TanDEM-X data would allow an unprecedented detailed and precise analysis of the spatial and temporal changes of the AP glacier mass balances. It would be highly complementary to the altimetry studies using ICESat-1/2 or CryoSat-2 and gravimetric measurements using GRACE or GRACE-FO, which have certain limitations in this region

3.2 Methods

WP1: First of all, the TanDEM-X archive of DLR was scanned, in order to obtain full coverage of the AP by bistatic CoSSC TanDEM-X stripmap data for certain periods. For austral winters 2013, 2014 and 2017, nearly complete coverages of the study area exists and all the needed data sets were ordered from DLR. Therefore, the PI could rely on existing data proposals to obtain the data free of charge. Subsequently, the ordered data sets were unzipped, renamed and converted to GAMMA format.

To carry out the proposed differential interferometric processing of the TanDEM-X imagery a reference elevation model is needed. The enhanced ASTER DEM of the AP (Cook et al. 2012) serves as a reference elevation model for the differential InSAR processing and for geocoding of the SAR datasets on the AP. The ASTER DEM has an initial spatial resolution of 100 m. Previous studies (e.g. Braun et al. 2019, Seehaus et al. 2020) revealed that processing the TanDEM-X to DEMs with spatial resolution of 30m (10 m is the maximum meaningful resolution) is a good trade off between spatial resolution, noise reduction and data handling. Thus, the ASTER DEM was resampled to 30 m spatial resolution and converted to GAMMA format. Note: Quite recently, a publication regarding a more recent reference elevation model of the AP was released (Dong et al., 2021), but the data set itself is still not available due to licence issues (personal communication with authors). Once the data set is available it will be evaluated regarding its performance in comparison to the enhanced ASTER DEM.

The TanDEM-X DEM processor at FAU was used to generate DEMs from the ordered TanDEM-X imagery. The processor is highly automated and its processing steps are briefly described in the following

1. The individual TanDEM-X scene are sorted based on the orbit and strip numbers as well as acquisition dates.
2. Along track images sequences from the same satellite overpass (same orbit and date) are getting concentrated to obtain continuous raw SAR imagery strips. This step strongly reduces the mosaicing effort of the final DEMs
3. Based on the orbit information of the satellites a SAR intensity imagery is simulated by means of the reference DEM. Using the simulated SAR intensity imagery and the original TanDEM-X intensity information a horizontal coregistration of the TanDEM-X data to the reference DEM is carried out. This information will be used to tune the final geocoding of the results (step 8).

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4. A differential interferogram is generated using the TanDEM-X SAR imagery and the reference DEM. Subsequently the differential interferogram is filtered using adaptive spectral filtering.
5. The filtered differential interferogram is unwrapped using both, the “minimum cost flow” and “branch-cut” algorithm. Note: The best results will be manually selected later in the post-processing (see further down).
6. In order to convert the unwrapped differential interferogram to differential heights the phase-to-height sensitivity information is needed. It is estimated by subtracting a simulated interferogram of the reference DEM and another simulated interferogram of the reference DEM elevated by 100 m.
7. The differential heights are combined with the height information from the reference DEM to obtain total height information.
8. The SAR processing was carried out in slant-range geometry. Thus, the total height information is finally orthorectified and geocoded using the reference DEM and the coregistration information (see step 3) to obtain DEMs in ground-range geometry.

The resulting TanDEM-X DEMs are still subjected by vertical and horizontal shifts as well as tilts. Therefore, the multistep TanDEM-X coregistration routine of FAU was applied to refine the alignment of the DEMs (“post-processing”). Besides a reference DEM, information on stable and unstable areas is needed. In order to define stable areas on the AP, the rock outcrop masks from the Antarctic Digital Database (ADD 6.0) were applied. Moreover, glacier areas were masked out using the glacier catchment informations from ADD. Base on these auxiliary data the relevant raster masks were generated for the post-processing routine which is briefly described in the following:

1. Stable areas of the TanDEM-X DEMs are selected an elevation difference to the reference DEM are computed.
2. Based on the elevation residuals on stable areas a 2-dimensional linear fit model is computed and applied to the TanDEM-X DEMs
3. The horizontal shifts of the TanDEM-X DEMs are further reduced by using the 3-dimensional coregistration approach from Nuth and Kääb (2011). The approached is iteratively applied to increase the quality of the coregistration step by step.
4. Still remaining tilts and vertical offsets of the TanDEM-X DEMs are removed by repeating the 2-dimensional linear fitting based on remaining elevation residual on stable areas.
5. Finally, the individual DEMs are mosaicked and a data layer containing the precise date information of each pixel of the final DEM mosaic is generated.

This post-processing routine was initially designed for studies of mountain glaciers and ice caps. Regions where sufficient stable areas (ice free areas) are available for the coregistration relative to the reference DEMs. However, at the AP the amount of ice free areas is very limited (as already stated in the description of WP1). As expected, the quality of the results obtained using the initial post-processing approach was not satisfying. In order to increase the mount of areas useable for the tilt removal (steps 2 and 4), sea ice covered areas were included in the analysis. Since only austral winter imagery was used, the ocean surrounding the AP was mostly covered by sea ice. To identify ocean areas without sea ice coverage, the

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SAR coherence information of the TanDEM-X imagery was applied, since the coherence on water surfaces is generally quite low. An threshold of 0.9 was applied to define sea ice covered areas. Additionally, open water section between sea ice areas along the coastline and sea ice further away caused problems during the phase unwrapping of the differential interferograms, leading to elevation offsets on the disconnected sea ice areas. These areas were manually masked out. In order to compensated for elevation differences on the sea ice covered areas caused by different ocean tide levels, the CATS2008 tidal model (Padman et al., 2002) was applied to obtain information on the tide level during the TanDEM-X acquisition. Therefore, the python-based tidal prediction (pyTMD) software that reads OTIS, GOT and FES formatted tidal solutions for calculating ocean and load tides was applied to the CATS2008 tidal simulations database and included in the post-processing routine to obtain tidal information on sea ice areas of the respective TDX DEMs. Information on the sea-ice thickness was checked using meereisportal.de. However, the data availability, in particular next to the west coast of the AP, was strongly limited since no data was available for many sections. Considering also that the free board of the sea ice is just a small fraction of the actual sea ice thickness, a correction for variations in the sea ice thickness was neglected on the sea ice areas used for the DEM coregistration.

Along wide sections of the east coast of the AP, the coastline is seamed by the Larsen-C and SCAR inlet ice shelves. Consequently, no vertical referencing on sea ice areas is possible and the ice shelf areas were used as vertical reference. In contrast to sea ice, ice shelves can have considerable free board of 10th of meters. To account for this issues, surface elevation measurements on the ice shelves from the Radar altimeter Cryosat-2 and the Laser altimeter ICESat-2 were applied. The measurements from both instruments were processed and provided by Dr. Veit Helm, Alfred-Wegener-Institut Bremerhaven Germany. Point clouds of the altimeter measurements from the respective observation periods were used for the respective TanDEM-X coverages to obtain information on the ice shelf free board height. Similar to the corrections on sea ice areas, a tidal correction was applied to account for the different tide levels during the TanDEM-X acquisitions. By including both, the sea ice covered areas and ice shelf areas, the amount of area used for the vertical bias correction was strongly increased in order obtain good quality results.

The correction of horizontal shifts (step 3) was also strongly subjected by the limited amount of ice free areas on the AP. Consequently, the areas used for the correction of the horizontal shifts were extended by also including ice covered areas. The applied algorithm from Nuth and Kääb (2011) correlates elevation residuals with the respective aspect of the slopes to estimate the horizontal displacement between two DEMs. The PI is a ware, that ice covered areas are subjected by elevation changes due to ice losses, however along the AP mainly the glacier tongues of the outlet glaciers are affected by significant surface lowering. Thus, these strongly changing areas were masked out to define the areas used for the correction of the horizontal shifts. The algorithm by Nuth and Kääb (2011) corrects also for horizontal offsets. However, horizontal biases introduced by including also ice covered areas, which are subjected by small or moderate surface elevation change rates, are removed by the subsequent processing step 4, which uses sea ice areas and stable ground for vertical displacement corrections (see above).

The existing post-processing routine from FAU was upgraded by implementing the additional corrections needed for the processing of TanDEM-X DEMs on the AP. Therefore, several test runs were performed in order to fine tune the different

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parameters and masking options. Additionally, significant elevation offsets in the resulting TanDEM-X DEMs caused by phase unwrapping errors, were manually identified by subtracting the TanDEM-X DEMs from the reference DEM in an iterative process. Finally, the TanDEM-X DEMs were mosaicked to obtain nearly full coverages of the study site for the respective observation periods.

The resulting DEM mosaics are differentiated to generate surface elevation change maps. By integrating the surface elevation changes throughout the glacier surfaces ice volume changes are computed for the AP. In the next project steps the volume changes will be converted to mass changes using different volume-to-mass conversion scenarios and estimates of the volume and mass changes will be computed on different scales (glacier basins, major basins) to analyse the spatial variability.

In order to prepare data for the proposed correlation of glacier change information with oceanic parameters, information of available data sets on ocean temperatures were gathered and compared. Based on the spatial resolution and the data periods the EN4 subsurface temperature and salinity for the global oceans data set (Good et al., 2013) and Southern Ocean State Estimation (SOSE) database (Mazloff et al., 2010) were selected. The EN4 data set provides monthly information on 1° spatial resolution for the period 1900-2019. The SOSE database has a much higher spatial resolution of $1/6^\circ$ but provides only data for the period 2008-2019. The data of both data sets was downloaded and cropped to the spatial extend of the study region. The ocean temperature values for the different depth layers were extracted and yearly mean values were computed for each cell. Subsequently, anomalies of the yearly mean values to the long-term average temperature are generated for each cell. Maps of the yearly mean values and anomalies are plotted for the different depth layers. To better illustrate the temporal evolution of the ocean temperature throughout the different depth layers, the temperature anomalies are plotted against the date and depth for each x-y model location along the coast line of the AP (see Results Section). Such an illustration is more intuitive and will be beneficial for the interpretation and correlation of the ocean data with the glacier change information at a later stage of the project.

In order to analyse the temporal changes in ice dynamics along the AP (WP2), the project can rely on a huge data base of already existing ice velocity fields derived from various SAR sensors by the PI at FAU. Since new SAR imagery is steadily acquired, the existing data base needed to be updated. Therefore, the archive of DLR was scanned for additional TerraSAR-X and TanDEM-X imagery which has a suitable orbit configuration and temporal base line for the generation of glacier flow fields. The existing automated routine at FAU is applied to derive glacier surface velocities by means of SAR feature tracking from the ordered imagery. The processing routine is briefly described in the following:

1. Unzipping, renaming and conversion of the data to GAMMA formation
2. Sorting of the imagery by acquisition orbits and date
3. Concatenation of scenes from the same orbit and date in along-track directions
4. Automated selection of suitable image pairs base on temporal base line thresholds

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5. Iterative coregistration process of the selected image pairs using different parameter sets and automated selection of the best result. Unstable areas like fast flowing glacier tongues and ocean areas are masked out during the coregistration.
6. Intensity feature tracking using different search window sizes, in order to obtain best results for different velocity zones and temporal base lines, and computation of flow velocities by means of the temporal base line information.
7. Geocoding and orthorectification of the results and correction of displacement measurements in range direction by means of the local incidence angle using the enhance ASTER DEM as reference.
8. Filtering of the velocity fields by means of an iterative approach considering the velocity magnitude and direction of surrounding pixels (Burgess et al., 2012)
9. Stacking of velocity field derived by using different search window sizes in order to obtain high spatial coverage throughout the different velocity zones (see Seehaus et al., 2018).

The processing of most of the TanDEM-X and TerraSAR-X imagery is already finished, and the rest will be ready soon. Moreover, a test dataset of Sentinel 1 imagery was processed using the automated surface velocity processor for Sentinel-1 imagery at FAU.

Additionally, flux gates for the computation of ice discharge and temporal changes of glacier dynamics were defined for the outlet glaciers along the coastline of the study area.

3.3 Data

- ~600 TDX CoSSC acquisitions provided by DLR based on granted data proposals
- The enhanced ASTER digital elevation model of the AP (from <https://nsidc.org/data/nsidc-0516>)
- Glacier catchment delineations and rock outcrop masks were gathered from the Antarctic Digital Database (<https://www.add.scar.org/>)
- Regional drainage basin definitions (www.imbie.org/)
- The Circum-Antarctic Tidal Simulation CATS2008 (<ftp://ftp.esr.org/pub/datasets/tmd/CATS2008.zip>)
- ICESat-2 monthly point clouds of surface elevations (provided by Dr. V. Helm, AWI Bremerhaven)
- CryoSat-2 monthly point clouds of surface elevations (provided by Dr. V. Helm, AWI Bremerhaven)
- EN4 subsurface temperature and salinity for the global oceans data set (Good et al., 2013, available at: <https://www.metoffice.gov.uk/hadobs/en4/>)
- Southern Ocean State Estimation (SOSE) database (Mazloff et al., 2010, available at: http://sose.ucsd.edu/sose_stateestimation_data.html)

3.4 Results

Nearly complete coverages of the study area by elevation information from TanDEM-X data is obtained for austral winters 2013, 2014 and 2017. A partial coverage is currently generated for 2020, however more imagery from this period is currently

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released step by step from DLR and will be implemented to enhance the coverage. Additionally the coverage in 2021 will be integrated in the analysis (see Conclusions Section). For the years 2013 and 2017, the post-processing of the TanDEM-X DEMs is nearly finished, and preliminary DEM mosaics and elevation change maps are generated (see Figure 2). Some areas of the DEM mosaics are still affected by phase jumps and inaccurate referencing of individual DEM tiles, as indicated by the green polygons in Figure 2. Consequently, further refinement and adaptation of the different mask layers and tile selection is needed in order to remove those issues.

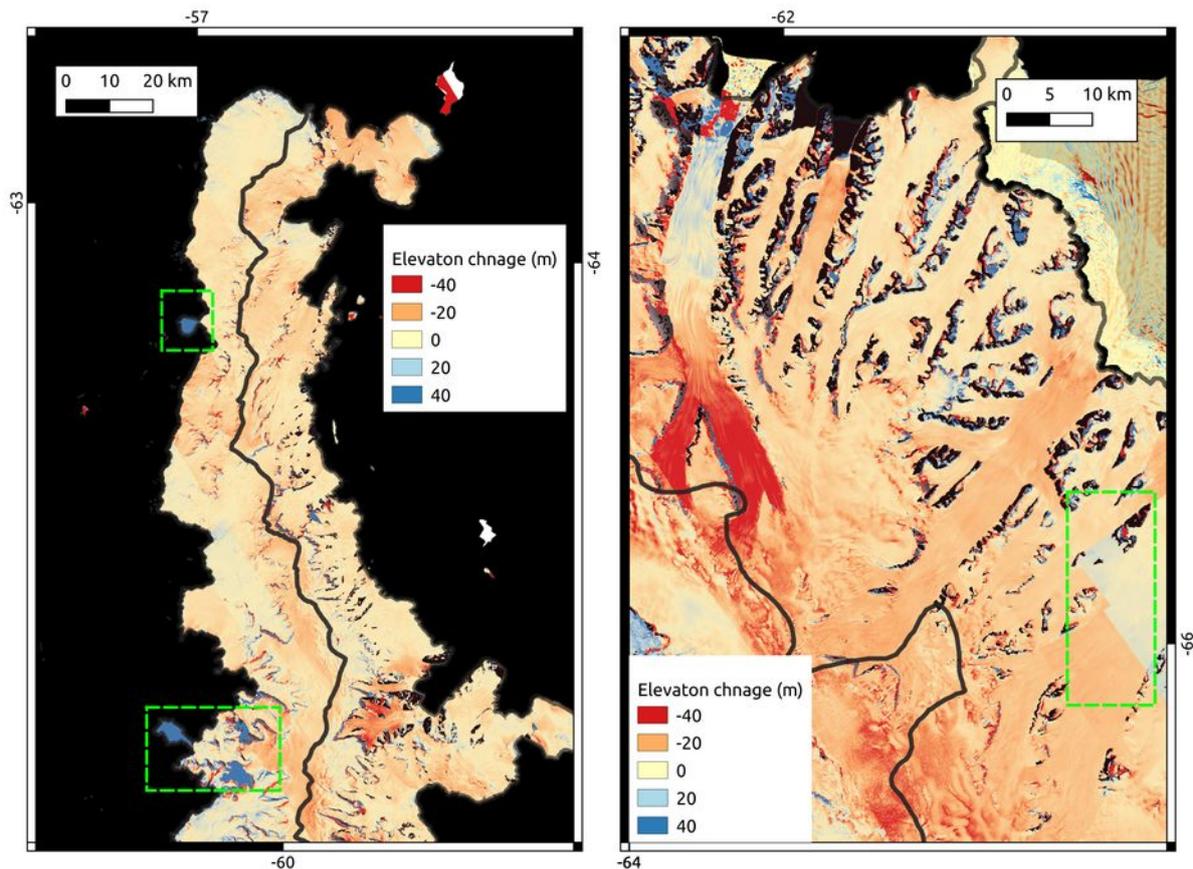


Figure 2: Elevation changes between 2013 and 2017. Left panel: Northern tip of the AP; Right panel: Larsen-B embayments Green polygons: Areas affected by phase jumps or imprecise DEM referencing

The analysis of the ocean temperature database indicates positive temperature anomalies for the deeper sections of the water column in particular next to the Southwestern coast of the AP. These findings are in line with previous analysis and suggestions (Cook et al., 2016; Friedl et al., 2018; Walker and Gardner, 2017) and support the thesis that the upwelling of CDW increases frontal and basal ablation rates and thus leads to increased glacier mass losses. Figure 3 illustrates exemplarily the temporal evolution of the water column temperature for one pixel of the EN4 data set on the south-western coast of the AP. Within the further project runtime the revealed glacier change information will be correlated with the oceanic information in order to facilitate the identification of driving factors of the glacier changes.

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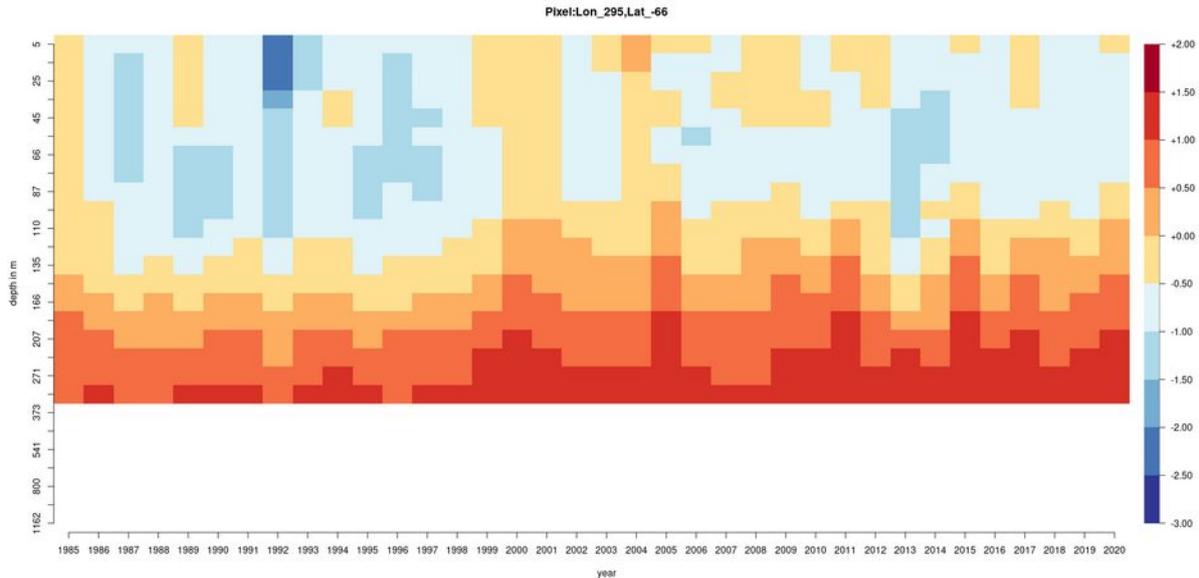


Figure 3: Temperature anomalies through out the water column at 295° Longitude and -66° Latitude obtained from the EN4 data set for the period 1985-2020.

The updating of the glacier surface velocity fields data base at FAU is nearly finished. A huge amount of additional TanDEM-X and TerraSAR-X imagery was processed. Additionally, the first processing test using Sentinel-1 data were carried out. Figure 4 illustrates a surface velocity mosaic of the southern Section of the study area derived from Sentinel-1 imagery from 2017.

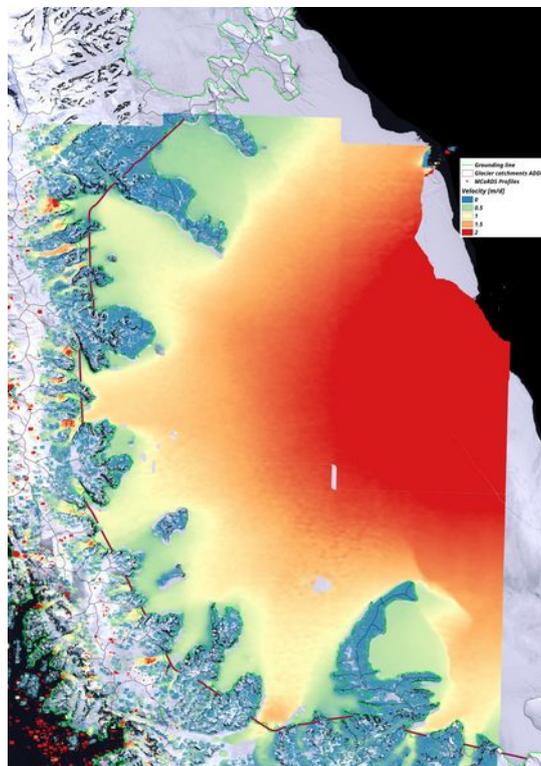


Figure 4: Mosaic of surface velocities for the southern section of the study area (Larsen-C embayment) derived from Sentinel-1 imagery in 2017.

4 CONCLUSIONS

Conclusions of experiments and lessons learned:

As expected, the very limited amount of ice free areas on the AP hampered a good quality coregistration of the TanDEM-X DEMs using the initial referencing algorithm existing at FAU. Consequently, the proposed extension of the areas used for the referencing was needed. The inclusion of sea ice covered areas strongly enhance the quality of the results. However, the ice shelves along the east coast limited the amount of usable sea ice covered areas. Therefore, the ice shelf covered areas of the TanDEM-X DEMs needed to be included. A novel referencing approach using altimeter measurements and tidal model output was developed. Finally, a good quality vertical referencing was obtained by means of the enhance approach. Overall, the generation and referencing of DEMs on the AP is a challenging task, which needs a lot of manual refinement (e.g. definition of masks to remove unreliable areas at different processing steps) and repetition of certain processing step to obtain good quality results.

However, the obtained preliminary results for the observation period 2013-2017 provide a spatially detailed information on the glacier surface elevation changes. Besides from the usages for glacier mass balance analysis, such information will be highly beneficial for further analysis e.g. enhanced ice thickness reconstructions on the AP.

Workplan:

According to the proposed work schedule and tasks (see Section Objective and Workplan), it is aimed to continue the work on the respective work packages. In the following a brief summary of the proposed tasks is provided.

WP1: The existing DEM mosaics from 2013 and 2017 will be further refined in order to remove still remaining issues due to phase jumps and inaccurate referenced DEM tiles. Similar to the TanDEM-X coverage from 2013 and 2017, the data from 2014 and 2020 will be further processed to obtain mosaics of DEMs on the AP for the respective periods.

Using the obtained DEMs the glacier volume and mass changes will be computed for the different periods. Since, the coverages have certain voids, in particular for 2020, a suitable void filling approach will be applied considering the findings revealed by Seehaus et al. (2020b).

Additionally a rigorous error assessment will be carried out to estimate the uncertainties of the glacier volume and mass changes. Therefore, the error caused by offsets between the different DEMs will be evaluated by measuring the residual between the DEMs on stable ice free areas. Since, the precision of DEMs is slope dependent (Toutin, 2002), averages of the residuals will be computed for different surface slope bins of the stable areas and the uncertainty on glacier areas will be computed by weighting these values by the surface slopes on the glacier areas (e.g. Braun et al., 2019; Seehaus et al., 2020a). No correction of difference in the SAR signal penetration is needed when comparing TanDEM-X data from the same seasons on the AP, as suggested by Rott et al. (2018). In order to prove the hypothesis by Rott et al. 2018, the glacier elevation information obtained from TanDEM-X data will be compared with measurements from ICESat-2. Depending on

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the results a certain error contribution will be included in the error assessment of the glacier volume and mass changes.

The obtained information on glacier mass changes will be correlated with oceanic and CMB data sets to infer drivers of the revealed changes. The preprocessing of the oceanic data is mostly finished. CMB data will be used from the MAR model (data already provided by Dr. Christian Kittel). Similar to the oceanic data, long-term trends and anomalies of the CMB data will be generated. Finally all findings will be summarized in manuscript and submitted to a peer-reviewed scientific journal.

Within the last 2 years record breaking positive air temperature were measured at stations on the AP. Moreover, a recent study suggests that the hiatus of the warming trend on the AP since the early 2000s ended around 2015 (Carrasco et al., 2021). Consequently, higher ice loss rates are expected for the most recent years.

A complete coverage by TanDEM-X data of the AP was targeted by DLR for austral winter 2021. The data should be soon available via the archive. It is aimed to apply the similar processing as for the other TanDEM-X data in order to temporally expand the study period, even though it was not initially proposed in the project proposal. By including the coverage 2021 a multi-temporal analysis will be facilitated in order to analyse temporal changes of glacier mass balances. Such information will provide valuable insights on the ongoing glacier change processes, in particular in the light of the currently increasing air temperatures on the AP.

WP2: The processing of velocity fields based on the TerraSAR-X and TanDEM-X will be finished soon. Additionally, all available Sentinel-1 data on the AP will be also exploited. Therefore, the PI will use the automated processing pipeline which was developed within the RETREAT project at FAU to generate glacier velocity fields by means of Sentinel-1 data for all major glacier regions outside the polar ice sheets (Friedl et al., 2021, <http://retreat.geographie.uni-erlangen.de>). The final database will comprise glacier surface velocity fields throughout the AP back to the 1990s allowing a long-term analysis of the glacier flow and discharge analysis. The glacier velocities will be extracted along defined flux gate positions close to the calving front (grounding line for ice shelf tributaries). In combination with information on the ice thickness from reconstructions, the ice discharge will be computed throughout the study period. A correction of the ice thickness using the obtained information on glacier surface elevation changes will be included in the analysis. The revealed temporal evolution patterns of the ice flow will be characterized (see Seehaus et al. 2018) and a multivariate statistical analysis (similar to Seehaus et al. 2018) will be applied including information on frontal changes, glacier geometries and oceanic and CMB data.

Additionally, the glacier mass balance will be computed by combining the ice discharge information with CMB data (input-output method) and compared to findings revealed by using the geodetic method (WP1). Major sources of uncertainty for the input-output-method are the ice thickness and CMB information. Such a comparison will allow to identify limitations in the ice thickness and CMB or help to define correction or scaling values as e.g. applied by Huss and Farinotti (2014).

Finally, the obtained results on ice dynamics and ice discharge will be summarized in a manuscript and submitted to a peer-reviewed scientific journal.

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6 PUBLICATIONS

Publications:

- Shahateet, K., **Seehaus, T.**, Navarro, F., Sommer, C., Braun, M., 2021. *Geodetic Mass Balance of the South Shetland Islands Ice Caps, Antarctica, from Differencing TanDEM-X DEMs*. *Remote Sensing* 13, 3408. <https://doi.org/10.3390/rs13173408>

Conferences and workshops:

- Living Planet Fellowship – Annual Workshop (online) on 2020-12-03. Due to problems with the internet connection during the workshop, only the slides were shared with the participants.
- virtual EGU2021 within the contribution of the workgroup: *The potential of TanDEM-X repeat acquisitions to monitor elevation and mass changes of Arctic and Antarctic glaciers* (No. EGU21-12383); Sommer, C., **Seehaus, T.**, Sochor, L., Malz, P., Braun, M., 2021. T Presented at the EGU21, Copernicus Meetings. <https://doi.org/10.5194/egusphere-egu21-12383>
- Arbeitskreis Fernerkundung 2021 meeting within the framework of GeoWoche2021, Deutsche Gesellschaft für Geographie DGfG: *Determination of mass changes of Arctic and Antarctic glaciers*; **Seehaus, T.**, Sommer, C., Sochor, L., Malz, P., Braun, M.