The Cryosphere Discussions

Twelve years of ice velocity change in Antarctica observed by RADARSAT-1 and -2 satellite radar interferometry

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Abstract

We report changes in ice velocity of a 6.5 million km^2 region around South Pole encompassing the Ronne/Filchner and Ross Ice Shelves and a significant portion of the ice streams and glaciers that constitute their catchment areas. Using the first full interferometric synthetic-aperture radar (InSAR) coverage of the region completed in 2009 and partial coverage acquired in 1997, we process the data to assemble a comprehensive map of ice velocity changes with a nominal precision of detection of ± 3–$4\,myr^{-1}$. The largest observed changes, an increase in speed of $100\,myr^{-1}$ in 12 yr, are near the frontal regions of the large ice shelves and are associated with the slow detachment of large tabular blocks that will eventually form icebergs. On the Ross Ice Shelf, our data reveal a slow down of Mercer and Whillans Ice Streams with a 12 yr velocity difference of $50\,myr^{-1}$ (16.7 %) and $100\,myr^{-1}$ (25.3 %) at their grounding lines. The slow down spreads 450 km upstream of the grounding line and more than 500 km onto the shelf, i.e., far beyond what was previously known. Also slowing in the Ross Ice Shelf sector are MacAyeal Ice Stream and Byrd Glacier with a 12 yr velocity difference near their grounding lines of $30\,myr^{-1}$ (6.7 %) and $35\,myr^{-1}$ (4.1 %), respectively. Bindschadler Ice Stream is faster by $20\,myr^{-1}$ (5 %). Most of these changes in glacier speed extend on the Ross Ice Shelf along the ice streams' flow lines. At the mouth of the Filchner/Ronne Ice Shelves, the 12 yr difference in glacier speed is below the 8 % level. We detect the largest slow down with a 12 yr velocity difference of up to $30\,myr^{-1}$ on Slessor and Recovery Glaciers, equivalent to 6.7 % and 3.3 %, respectively. Foundation Ice Stream shows a modest speed up ($30\,myr^{-1}$ or 5 %). No change is detected on Bailey, Rutford, and Institute Ice Streams. On the Filchner Ice Shelf proper, ice slowed down rather uniformly with a 12 yr velocity difference of $50\,myr^{-1}$, or 5 % of its ice front speed, which we attribute to an 12 km advance in its ice front position. Overall, we conclude that the ice streams and ice shelves in this broad region, in contrast with their counterparts in the Amundsen and Bellingshausen seas, exhibit changes in ice dynamics that have almost no impact on the overall ice balance of the region.

1   Introduction

Ice velocity is crucial information for estimating the mass balance of glaciers and ice sheets and for studying ice dynamics. Satellite information has fundamentally changed the way velocity information is collected today. Firstly, Global Positioning System (GPS) has simplified the way ground measurements are made, allowing for high precision measurements of key areas at dense temporal spacing. For detailed analyses of specific motion patterns (i.e. Bindschadler et al., 2003), field measurements continue to be vital in glaciology (e.g. Aðalgeirsdóttir et al., 2008). Secondly, spaceborne remote sensing satellites are a means to measure ice velocity without the necessity of ground campaigns. They allow data collection over vast areas, thereby providing information that would be practically impossible to collect in the field. Since the launch of the European ERS satellites in the early 1990's, spaceborne Interferometric Synthetic Aperture Radar (InSAR) data have become the single most important means of measuring ice velocity. Projects and area coverage have evolved from single glaciers, over ice fields to most recently covering the vast ice sheets of Greenland and Antarctica (Rignot et al., 2011b; Joughin et al., 2011). InSAR satellite data coverage in Central Antarctica remains sparse. The first complete interferometric mapping campaign covering South Pole took place in 2009 as part of a coordinated acquisition campaign for the International Polar Year (IPY) (Jezek and Drinkwater, 2008).

In this paper, we present a new ice velocity map and a grounding line map based on RADARSAT-2 InSAR data collected in fall 2009. We revisit and re-calibrate the InSAR data collected by RADARSAT-1 in 1997. A difference map is created using the two data sets to reveal for the first time changes in speed over a vast extent of Central Antarctica in the 12 yr interim. After exposing the details of the data processing, we discuss the changes observed along Siple Coast and the Filchner/Ronne sectors and conclude on the ongoing evolution of glaciers and ice shelves in these regions.

2   Data

We use InSAR data from the 1997 RADARSAT-1 Antarctic Mapping Mission (AMM) and the 2009 RADARSAT-2 mapping campaign. Imaging of South Pole requires left looking capability, which RADARSAT-1 used in experimental mode in 1997 and RADARSAT-2 is able to use operationally since 2008. Most other SAR sensors are right looking, hence pointing away from South Pole and leaving a coverage gap that is sensor dependent but typically south of 80° S. More recently, TerraSAR-X has added capabilities in left looking mode that are being explored (Floricioiu and Jezek, 2009) but the area coverage provided by this radar is not as comprehensive as RADARSAT-1/2.

In 1997, RADARSAT-1 underwent a special orbit maneuver to switch to left looking mode. Most of the campaign was devoted to radar amplitude mapping of Antarctica, with a number of interferometric pairs acquired after that in a test mode, with only one interferometric pair along each track. The limited data collect in combination with short data strips made data processing and mosaicking difficult, but a map of Siple Coast ice streams was successfully generated using these data, complemented with other ice velocity measurements (Joughin et al., 2002).

The first, and so far only, complete interferometric data coverage of Central Antarctica with interferometric SAR data was achieved using RADARSAT-2 in left looking mode in fall 2009 with a limited gap filler campaign to complete the mapping in spring 2011 (Crevier et al., 2010). During the International Polar Year (IPY 2007–2008), the contributions of four space agencies were coordinated by the IPY Space Task Group (STG) (Jezek and Drinkwater, 2008). One goal of STG was to achieve pole-to-pole InSAR coverage of the ice sheets. For Antarctica, standard right looking data covering the coast to about 80° South were acquired by the Japanese ALOS PALSAR and the European Envisat ASAR. The Canadian Space Agency committed to fill the region south of 80° S using RADARSAT-2. RADARSAT-2 operates nominally in right looking mode. Planning and executing left looking mode acquisitions limits data acquisition because the SAR needs to switch back and forth between the two modes along its orbit.

Careful planning was required to avoid conflicts and maintain sensor health (Morena et al., 2004). To cover the entire area, two different modes were combined: (1) 85 tracks in Standard 5 mode for the region between 78° to 87° S; and (2) 43 tracks in Extended High 4 mode for South Pole and vicinity. Three consecutive orbits were acquired along each track to enable the generation of two 24 day interferograms per track. Acquisitions were planned with a small overlap region between the ground coverage of the two modes. Residual coverage gaps caused by acquisition conflicts during the 2009 campaign were closed with a gap filler campaign that took place in Spring 2011. Table 1 summarizes the RADARSAT-1 and -2 data collected and used in this study.

3   Methods

The RADARSAT-1 and -2 interferometric data allows the extraction of ice surface velocity (1997 and 2009) and grounding line position (2009 only).

3.1   Velocity measurements

Two dimensional ice velocity is extracted assuming surface parallel flow from a combination of speckle tracking and interferometric analysis (Michel and Rignot, 1999; Rignot et al., 2011b). In areas where phase unwrapping is successful, the unwrapped interferometric phase is used in range instead of range offsets from speckle tracking. Since three data cycles are available in 2009, we generate two velocity products per track and combine them to reduce data noise.

3.1.1   Tide correction

The rise and fall of ice shelves with changes in oceanic tide results in a tidal modulation of the velocity signal over the floating extension of ice sheets. One modulation is a vertical motion of the ice shelf caused by maintenance of hydrostatic equilibrium. Changes in air pressure are also important and operate on the same time scale as

oceanic tides, i.e. hours to days (Rignot et al., 2000). A second tidal modulation is a potential variation of the horizontal rate of motion with tides due to small changes in buttressing and driving stress forces on the ice shelves (Bamber et al., 2007). For the vertical component, the error amounts to $37\,\mathrm{m\,yr^{-1}}$ in speed (at 28° incidence angle of the radar illumination away from the vertical direction) per 1 m tide change between interferometric data acquisitions. Such an error is small compared to the absolute value of ice shelf velocities (or $1\,\mathrm{km\,yr^{-1}}$), but is large when examining temporal changes in ice velocity.

Here, we use the CATS2008a_opt tide model (Padman et al., 2008) and the TPXO6.2 load model (Egbert and Erofeeva, 2002) to estimate vertical position above the ellipsoid for each data point on ice shelves at the different acquisition times of RADARSAT-1 and 2. The corresponding elevation difference between epochs is converted into a range displacement which is subtracted from the range offsets obtained from speckle tracking – or the interferometric phase – before converting these displacements into ice velocity (Mouginot et al., 2012). The precision of the tidal model is estimated at ±5.4 cm vertical displacement based on a comparison with 16 independent tide records at or near Ross Ice Shelf (Padman et al., 2008), the root-mean-square residual magnitudes for the four main tidal constituents for the load model are between ±2.2 and ±3.8 cm (Egbert and Erofeeva, 2002).

3.1.2   Velocity calibration

A critical step in data processing is the absolute calibration of the velocity data. This task is rendered difficult if coast-to-coast acquisitions are absent or control points of known (or zero) velocity are not known a priori. This is one of the reasons why only a few 1997 InSAR data could be analyzed in prior studies. The recent assembling of a map of Antarctica that employs coast to coast tracks and provides a comprehensive calibrated coverage of the entire continent enables the application of a new, improved calibration method for the 1997 data. Namely, we identify areas of zero velocity (domes, nunataks, divides with zero surface slope) in the year 2009 ice velocity map to obtain

control points for the 1997 mosaic. A few tracks are calibrated using these control points. To continue the process, new tracks are added in the calibration and mosaicking by using ice velocity from overlapping calibrated tracks (hence non-zero velocity), effectively increasing the number of control points and propagating the calibration process across the entire surveyed domain to obtain a consistent calibration scheme. With this approach, we calibrate and mosaic together 102 pairs of RADARSAT-1 data from 1997, leaving out only a few pairs with poor correlation levels. Great care is applied in the calibration and mosaicking processes to yield high quality change detection products. A high quality 1997 map for change detection cannot be assembled using the RADARSAT-1 1997 data alone. Similarly, the calibration and mosaicking of the complex ensemble of Extended High 4 and Standard 5 mode RADARSAT-2 data around South Pole in 2009 cannot be done at a comparable level of precision without the help of overlapping, coast-to-coast tracks from Envisat ASAR and ALOS PALSAR (Mouginot et al., 2012).

3.2 Velocity difference estimate

The generation of velocity difference maps requires special care during processing of individual velocity maps because data noise must be minimized to increase the ability to detect subtle changes in speed. Track boundaries are critical areas where calibration or mosaicking errors become visible in difference maps but not necessarily in the original velocity maps if the calibration and mosaicking was not effected in the best manner. Here, we expect identical measurements between overlapping adjacent tracks because the measurements are collected with a time separation of 24 days, hence effectively calculating an average velocity over that time period that smoothes out shorter-time scale fluctuations, for instance associated with tides. In addition, the data collection extended only over 3 months, which minimizes the impact of long-term changes on the data. In the process of generating the 1997 map, we found small residual imperfections in the 2009 map that could not be seen before but needed to be fixed to yield a quality change map. The implementation of a tidal correction was an important step for the

analysis of velocity differences on ice shelves. The 1997 and 2009 velocity maps were progressively revised together, in an iterative fashion, to minimize track boundaries. The resulting 1997 map covers more area compared to prior mappings as additional tracks were included in the mapping.

Looking at stagnant areas throughout our study area (more than 77 000 data points were used in Siple Dome, Raymond Ice Ridge, Central Antarctica North of Titan Dome, and Pecora Escarpment near Foundation Ice Stream), we find a 1-sigma variation of the velocity difference of $\pm 2.8\,\mathrm{m\,yr^{-1}}$. The corresponding 2009 velocity variation over the area is $\pm 1.8\,\mathrm{m\,yr^{-1}}$; the 1997 velocity variation is $\pm 2.3\,\mathrm{m\,yr^{-1}}$ (higher because fewer overlapping tracks are available for the 1997 data). We conclude that the precision of velocity mapping is about ± 2–$3\,\mathrm{m\,yr^{-1}}$; and the precision of detection of changes in speed is about ± 3–$4\,\mathrm{m\,yr^{-1}}$ for the 12 yr period. These are nominal errors. Locally, errors may exceed these values.

3.3 Grounding line detection

The grounding line (GL) is the transition boundary where ice detaches from the bed to become afloat in the ocean. Knowledge of the exact location of the grounding line is crucial for ice sheet mass balance calculations, ice sheet modeling, and the analysis of ice-ocean interactions (Rignot et al., 2011a). An ice shelf flaps up and down with changes in the oceanic tide. This vertical motion is detected directly using differential InSAR – DInSAR – at a precision of millimeters, i.e. orders of magnitude better than laser altimetry (± 10–$20\,\mathrm{cm}$) or even kinematic GPS (a few cm) (Rignot, 1998).

The 2009 RADARSAT-2 AMM includes three consecutive cycles per track. This acquisition strategy makes it possible to generate two interferograms per track spanning the same time difference (24 days or one cycle), which we then difference to detect tidal motion and map grounding line position. The RADARSAT-2 DInSAR data set represents the first comprehensive high-resolution, InSAR-based mapping of the grounding line south of 80° South, which is now available online (Rignot et al., 2011c). The product has a positional accuracy of $\pm 100\,\mathrm{m}$. Unlike methods relying on changes in

surface slope, aspect, or visible features, the DInSAR approach is a direct measurement of the grounding line position. Grounding line mapping cannot be done using InSAR data from 1997 because these data do not include repeat pairs. Methods using phase coherence to map grounding lines do not detect the grounding line per se but the outer limit of tidal flexing instead, which is typically several km seaward of the actual grounding line. This was demonstrated in the case of Evans Ice Stream in (Rignot et al., 2011a). The offset between these two positions is equivalent to the width of the flexure zone, which is not a constant. The width of the flexure zone varies with ice thickness and also with the tidal cycle because of the visco-elastic nature of the deformation. It is therefore not possible to compare the 1997 and 2009 mappings at this time with high confidence. The 2009 grounding line will however serve as a reference for measuring future changes.

4 Results

Figure 1 shows the impact of our tide correction on data quality and track to track boundary. Without tide correction, it would not be possible to detect changes in ice shelf velocity in our study area, because the actual signal is comparable in magnitude to the tidal modulation. We find that the tide estimates from the Padman model are of sufficient quality to implement a tide correction that eliminates patch boundary between tracks on the ice shelf as well as inconsistencies between overlapping tracks acquired at different times. This demonstrates that the tidal signal is removed effectively, consistently and accurately in our data. A few notable exceptions exist where the tidal correction is questionable. For instance near the grounding line of Slessor Glacier and Bailey Ice Stream (see Figs. 2c and 4), we detect a residual signal which is not spatially consistent with the signal recorded in the surrounding areas, including on grounded ice, which suggests that the tidal correction is in error. Looking at this problem, we find that the Padman model uses a grounding line position based on optical data for Ronne/Filchner region, that is less precise than the interferometric grounding

line (Rignot et al., 2011a). The MOA-based grounding line is about the same as the DInSAR grounding line for Bailey Ice Stream, but some ice rises in the mouth of Bailey Ice Stream are not accounted for in the MOA-based product. A large difference between MOA-based and DInSAR based grounding lines occurs on Slessor Glacier. There, the MOA-based grounding line is 150 km too far inland from its actual location detected with DInSAR (see Fig. 4). We may ignore tide model results upstream of the DInSAR groundling line for Slessor Glacier but this is not sufficient to explain residual errors (see Fig. 4). In addition, recent observations from instrumented mammals suggest that the sub-ice-shelf cavity at that location is deeper than previously thought, which is another source of error in the tidal predictions (Padman, pers. comm.). This example illustrates that a precise knowledge of the grounding line position and depth of the sea floor are critical for estimating tidal motion beneath ice shelves and for detecting long-term, subtle changes in ice shelf velocity with InSAR.

Figure 2 shows the surface velocity product for 1997 (Fig. 2a) and 2009 (Fig. 2b) overlaid on the MODIS mosaic of Antarctica or MOA (Haran et al., 2005). The 1997 coverage is the first interferometric coverage of the region that is presented to its full extent, with improved calibration. Prior analysis of the 1997 data were focused on the Ross Ice Shelf sector, with a mix of InSAR and non-InSAR data (Joughin et al., 2002, 2005). Our map includes a partial coverage of the Filchner-Ronne sector. The 2009 map is nearly complete, with residual gaps in West Antarctica caused by the systematically poor levels of temporal coherence of the InSAR signal (Rignot et al., 2011b).

The difference map (Fig. 2c) reveals many interesting features, which we will now discuss. Most notable is a widespread slow down on Ross Ice Shelf and Mercer and Whillans Ice Streams (formerly known as Ice Streams A and B). This slow down – early reports date back to Thomas (1976) – was studied in more detail at discrete locations (Joughin et al., 2002, 2005). In contrast to these earlier studies, our change detection map reveals the full extent of the area of slow down through its extensive and continuous coverage. We note in particular that the slow down extends about 450 km upstream of the grounding line of Whillans Ice Stream (and about 300 km for Mercer

Ice Stream), and affects all the tributaries of these ice streams up to their presumed source, i.e. where the ice motion signal meets our noise floor. Prior studies reported on limited discrete points up to 400 km upstream for Whillans Ice Stream and 150 km upstream for Mercer Ice Stream. Our result also shows the extent of the slow down reaching more than 500 km onto Ross Ice Shelf, an indication that the signatures of the ice stream changes determine the regional velocity changes on the shelf.

At the northwestern edge of the Ross Ice Shelf, we observe a zone of speed up that coincides with a portion of the ice shelf that is about to detach and form a tabular iceberg. The velocity difference between the two epochs exceeds $100\,\mathrm{myr^{-1}}$, though the main difference most likely results from the pre-calving event that happened past 1997. A similar pre-calving event is detected along the northeastern front of the Filchner Ice Shelf, where the velocity difference between 1997 and 2009 also exceeds $100\,\mathrm{myr^{-1}}$. Locally, velocity differences between stable shelf portions and fast blocks reach $150\,\mathrm{myr^{-1}}$. Wide cracks are observable in the respective radar amplitude imagery at the transition boundary between speed up and no speed up for both areas, which justifies our labeling of these areas as pre-detached. These two pre-calving events represent the largest changes in speed in our map. Outside of these areas of speed up and the widespread slow down of the Mercer an Whillans Ice Streams, most of the other observed changes are small in magnitude, i.e. at the 10–$20\,\mathrm{myr^{-1}}$ level over 12 yr versus absolute speeds in the range of several hundred meters per year (Fig. 2), i.e. at the percent level. This means that we observe little change in speed of the glaciers and ice shelves between the two dates.

Figure 3 shows a more detailed analysis for the Ross Ice Shelf region. The map shows the 12 yr velocity difference overlaid on the MOA, the 2009 grounding line, as well as the 1997 and 2009 ice fronts. In addition, MOA provides information on the 2004 ice front position. We generate flow lines using the 2009 velocity vector map (Rignot et al., 2011d) and plot changes in speed along these flow lines at the center of major outlets. Markers are set every 100 km on the map and plots to ease interpretation. The 2009 grounding line is indicated for reference. In addition to the 12 yr

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velocity difference, dv, we provide the velocity difference in % of the glacier speed at the grounding line in the text below to provide some context for each glacier. Our results show that Byrd Glacier slowed down slightly with a 12 yr velocity difference of less than $35\,\mathrm{myr^{-1}}$ or $4.1\,\%$ at the grounding line. The slow down extends roughly 100 km upstream of the grounding line and decreases with distance. For comparison, Mercer and Whillans Ice Streams experience a more significant slow down. Their 12 yr velocity difference near the grounding line is up to $50\,\mathrm{myr^{-1}}$ ($16.7\,\%$) and $100\,\mathrm{myr^{-1}}$ ($25.3\,\%$), respectively. Most likely, as a result of slow down and thickening, their grounding line must have migrated downstream between 1997 and 2009. The decrease in speed increases from the interior toward the grounding zone, to peak at the grounding line and subsequently remains fairly constant on the ice shelf (with dv at about $50\,\mathrm{myr^{-1}}$). Bindschadler Ice Stream displays a modest speed up near the grounding line region, which is only partially covered in our data (dv up to $20\,\mathrm{myr^{-1}}$ or $5\,\%$). A speed up can be traced up to about 200 km upstream of the grounding line. I contrast, MacAyeal Ice Stream slowed down slightly between 1997 and 2009 with a 12 yr velocity difference of up to $30\,\mathrm{myr^{-1}}$ or $6.7\,\%$). Here, the slow down (dv between $10\,\mathrm{myr^{-1}}$ and $30\,\mathrm{myr^{-1}}$) can be traced to about 300 km upstream of the grounding line. The respective velocity difference pattern on the western portion of Ross Ice Shelf is determined by these two ice streams and is different from the pattern on the eastern half which is determined by Whillans and Mercer Ice Stream change signatures.

Figure 4 shows detail for the Ronne-Filchner Ice Shelf. The 1997 coverage is less extensive compared to Ross Ice Shelf. A more complete map by Joughin and Padman (2003) mixes data from 1997 and 2000 and is not used here. The DInSAR grounding line is shown in green. For Slessor Glacier, we also indicate the erroneous MOA-based grounding line (yellow/black dashed line) discussed earlier. In the region indicated by a yellow arrow in Fig. 4 we noted the presence of residual errors in tidal error correction, i.e., the real change in ice velocity is masked by these residual errors. On Bailey Ice Stream, we detect a small slow down in speed with a 12 yr velocity difference of about $10\,\mathrm{myr^{-1}}$ or $5\,\%$. On nearby Slessor and Recovery Glaciers, the decrease in

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speed is larger. The 12 yr velocity difference is up to 30 m yr^{-1}, equivalent to 6.7 % and 3.3 % for Slessor and Recovery Glaciers, respectively. This slow down is confined to within 100 km upstream of the grounding line region in the case of Recovery but more pervasive over a vast area for Slessor. The flow line for Foundation Ice Stream shows a spike in speed change near the grounding line, which may indicate residual errors in tide correction. Even with this uncertainty present, the data reveal velocity increase at the grounding line (dv less than 30 m yr^{-1} or 5 %). We detect only a small slow down on Institute Ice Stream, i.e., dv of less than 10 m yr^{-1} or 5 %. Coverage of Rutford Ice Stream is spotty, particularly around the grounding line. The velocity difference over 12 yr upstream of the grounding line indicates a higher speed in 2009 (dv up to about 15 m yr^{-1}, or 3.8 %).

On the Filchner/Ronne Ice Shelves proper, we detect a widespread and spatially relatively uniform slow down. The 12 yr velocity difference reaches 50 m yr^{-1} for Filchner Ice Shelf, or 5 % of its ice front speed. The observed region on Ronne Ice Shelf is small and mainly covers the area around Korff and Henry Ice Rise. The 12 yr velocity difference is about 30 m yr^{-1} or 7.5 % of the Ice Shelf velocity in the area. We note here that because our InSAR data combine data acquired 24-day apart, we are not sensitive to transitory signals occurring at much lower temporal frequencies. Furthermore, because our mosaic combines many tracks acquired at different times and for different tidal modulation, we are quite sure that the changes in speed detected on the ice shelves are not tidal related. If they were, it would be impossible to mosaic the data together correctly, especially at patch boundaries. The signal observed on the ice shelf therefore represents a true change in overall speed between the two epochs.

5 Discussion

The velocity of Rutford Ice Stream is influenced by oceanic tides (Gudmundsson, 2006; Aðalgeirsdóttir et al., 2008). The relationship is complex, with diurnal and fortnightly periodicity and variations oscillating between 20 % and 12 %. While our observation

period of 24 days is larger than one periodicity, there is potential for residual tidal influence on the change map. The measured changes in speed over 12 yr are less than 5 % of the absolute velocity, with slight speed up upstream of the grounding line and slight slow down downstream. This pattern is suggestive of residual uncertainties in tidal correction rather than a real change in ice dynamics. Tidal errors could be due to inaccurate estimates of the depth of the sea floor in the sub-ice-shelf cavity. The residual signal is small however, it does not extend into the grounded part of the ice stream, which suggests that Rutford Ice Stream did not change speed between the 1997 and 2009 surveys at a detectable level. This is consistent with earlier studies that revealed stable grounding line positions (Rignot, 1998), no change in ice surface elevation (Pritchard et al., 2009) and a mass budget close to zero (Rignot et al., 2008).

Recovery and Slessor Glaciers are exhibiting the largest slow down (when expressed in velocity difference) in the Filchner/Ronne sector. The impact of this slow down on grounding line fluxes is at the percent level, or less than 1 Gt yr^{-1}, which is negligible compared to the mass budget of the entire region. In a recent study, Pritchard et al. (2009) detect a slight thickening of Slessor Ice Stream, which is consistent with our report of a more extensive area of slight slow down. No thickening is apparent in the altimetry data from Recovery Ice Stream, which is consistent with slight changes in speed being confined closer to the grounding line region in our data.

On the Filchner Ice Shelf, the magnitude of the slow down is real, but small with a 12 yr velocity difference at the 50 m yr^{-1} level versus ice shelf speeds of up to 1000 m yr^{-1}. Between 1997 and 2009, the ice front advanced by about 12 km (see Fig. 4), which increased side shear and would explain the slow down. This aspect needs to be confirmed with model simulations.

On Ronne, multiple iceberg calving events caused a retreat of the ice front between 1997 and 2004 (compare Fig. 4: 1997 and MOA ice front) (Lazzara et al., 1999). Since 2004, the ice front has been advancing. The situation is similar on Ross Ice Shelf, where large icebergs calving after 1997 resulted in a net retreat of the ice front.

On Ross Ice Shelf sector, Pritchard et al. (2009) report thickening of stagnant Kamb Ice Stream at 60 cm yr^{-1}, but thinning of Whillans and Mercer Ice Streams at 20 cm yr^{-1}. The latter is opposite to what we expect for ice stream slow down. The observed thinning must therefore be related to changes in surface mass balance. Indeed, an analysis for the time period 1995–2003 revealed a decrease in snowfall during that time period that may have caused an average decrease in surface elevation of 6 cm yr^{-1} (Helsen et al., 2008). A similar analysis should be pursued for the 1997–2009 time period.

Byrd Glacier velocities are affected by tides and the drainage of sub-glacial lakes. A 10 % speed up was observed between 2005 and 2007 as a result of sub-glacier drainage (Stearns et al., 2008). The authors show a 48 yr record of ice velocity that reveals no changes in speed along the main trunk of Byrd between 1960 and 2005. The velocity record prior to 2000 is sparse, so a surge cycle may be possible but has not been observed. The 2009 velocities of Byrd Glacier (See Fig. 3, Byrd flow line) are consistent with the pre-surge values (Stearns et al., 2008). We conclude that despite the existence of a mini surge between 2005 and 2007, Byrd Glacier continues to maintain a rather steady flow regime over the last few decades.

The slow down of Whillans and Mercer Ice Streams was analyzed using an earlier, partial version of the 1997 map, combined with ground measurements from different years (Joughin et al., 2002, 2005). Our analysis shows a general agreement of the mean annual deceleration for the trunk of Whillans Ice Stream but an increased rate of slow down at the grounding line near Crary Ice Rise for our observation period compared to pre-1990 ground measurements. A more detailed shelf-wide comparison of the 2009 velocity map with pre-1990 ground measurements will be discussed elsewhere (Thomas et al., 2012).

6 Conclusions

We present a 12 yr change record in ice motion in Central Antarctica, covering the two largest ice shelves and many major ice streams and glaciers. Data quality is excellent

and provides ice motion results with a precision of ±2–3 m yr^{-1} on average and detection of changes in speed with a precision of about ±3–4 m yr^{-1}. Our change map provides new, important information about the evolution of this sector of Antarctica, or lack thereof. Filchner and Ross Ice Shelves exhibit signs of pre-calving events.

Other than those, the Filchner/Ronne sector shows few changes, with most ice streams slowing down slightly. The 12 yr velocity difference for all glaciers and ice streams in the region is below 8 %, which is of little consequence for the overall mass budget of the region. The most distinct signal, however, is a slight slow down of the Filchner Ice Shelf, consistent with an ice shelf advance, and a small slow down of Slessor Glacier over a large sector that warrants further study. On the Ross Ice Shelf, we confirm the slow down of Mercer and Whillans Ice Stream, with a 12 yr velocity difference of 16.7 % and 25.3 %, respectively. Our change map shows, for the first time, the entire spatial extent of the change. The slow down, extends hundreds of km upstream and onto the shelf. Regional variations in velocity changes on Ross Ice Shelf proper are defined by the ice streams and glaciers that constitute its catchment area. Overall, however, the observed changes have little impact on the mass balance of the region. We therefore conclude that in contrast with their counterparts in the Amundsen and Bellingshausen Seas (Rignot et al., 2008) the ice streams and ice shelves in the broad region under investigation herein have not been changed in a significant way in the past 12 yr, which suggests that the ice dynamics of the entire region does not have a strong impact on the mass budget of the Antarctic continent.

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Table 1. Left looking RADARSAT-1 (September–October 1997) and RADARSAT-2 (February–April 2009 + limited gap filler in 2011) modes used for interferometric data collects in Antarctica.

RADARSAT-1	1997					
	ST2	ST3	ST4	ST5	ST6	ST7
Range Spacing	8.1 m	11.6 m	11.6 m	11.6 m	11.6 m	11.6 m
Azimuth Spacing	5.3 m	5.0 m	5.1 m	5.2 m	5.0 m	5.2 m
Incidence Angle	28.0°	34.1°	36.7°	39.5°	44.3°	47.2°
No. of Tracks	46	10	12	12	9	13
RADARSAT-2	2009					
			S5	EH4		
Range Spacing			11.8 m	11.8 m		
Azimuth Spacing			5.1 m	5.1 m		
Incidence Angle			41.3°	57°		
No. of Tracks			43	85 (+14)[a]		
Coverage (lat)			77.5° to 87°	86.5° to Pole		

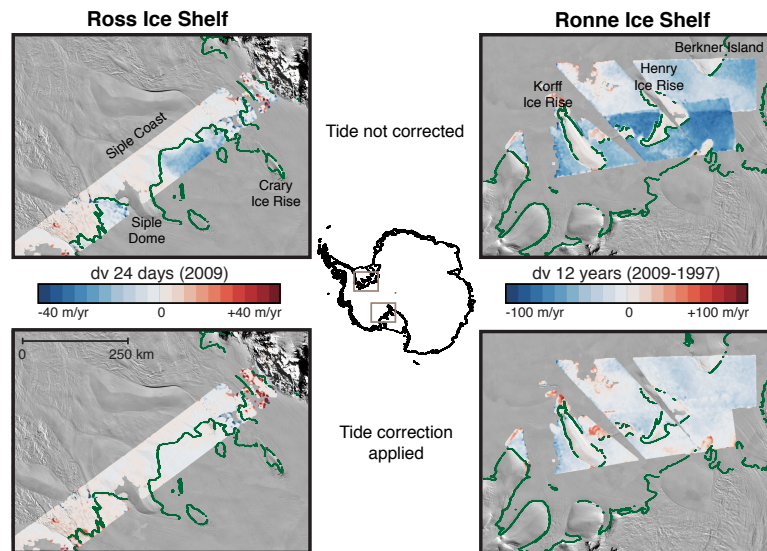[a] 14 tracks were aquired in 2011 to close data gaps from the 2009 AMM.

Fig. 1. Impact of tide correction to InSAR based ice velocity estimates. The example on the left shows a velocity difference calculated using two consecutive RADARSAT-2 pairs acquired in 2009 without (top) and with (bottom) tide correction applied. The right example shows a difference map spanning 12 yr (tide correction was applied to the 2009 RADARSAT-2 data). The impact of tide correction for the 1997 data (top: not corrected; bottom: tide corrected) shows the importance of this step for absolute velocity calibration and to generate a seamless mosaic.
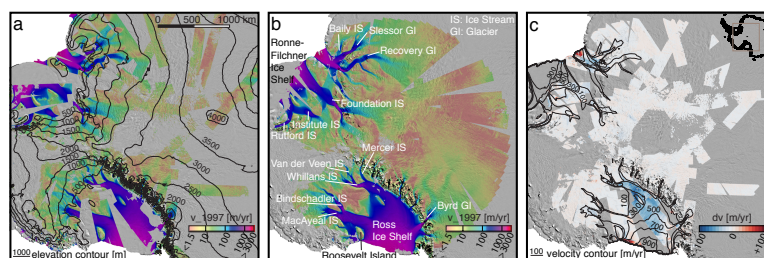
1735

Fig. 2. Ice surface velocity maps for Central Antarctica for 1997 **(a)** and 2009 **(b)** overlaid on MOA. **(c)** shows the velocity difference d*v* (2009–1997) for the entire region. Superimposed on **(c)** are velocity contour lines taken from the IPY ice velocity map (Rignot et al., 2011b). Blue tones indicate a slow down. The two dark red regions on the ice shelf edges (Ross Ice Shelf near Roosevelt Island and Filchner Ice Shelf) indicate pre-calving events.
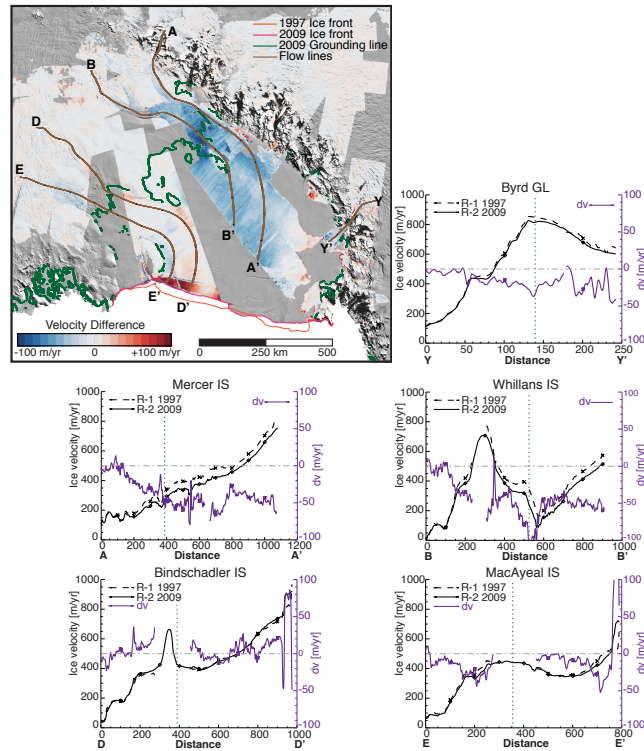
Fig. 3. Velocity Difference map (2009–1997) detail, 1997 and 2009 ice front, and flow line plots for Ross Ice Shelf overlaid on MOA. Each flow line includes markers every 100 km for easier orientation. The flow line graphs show the absolute velocities for 1997 and 2009 and the velocity difference. The vertical dashed line is the 2009 grounding line.
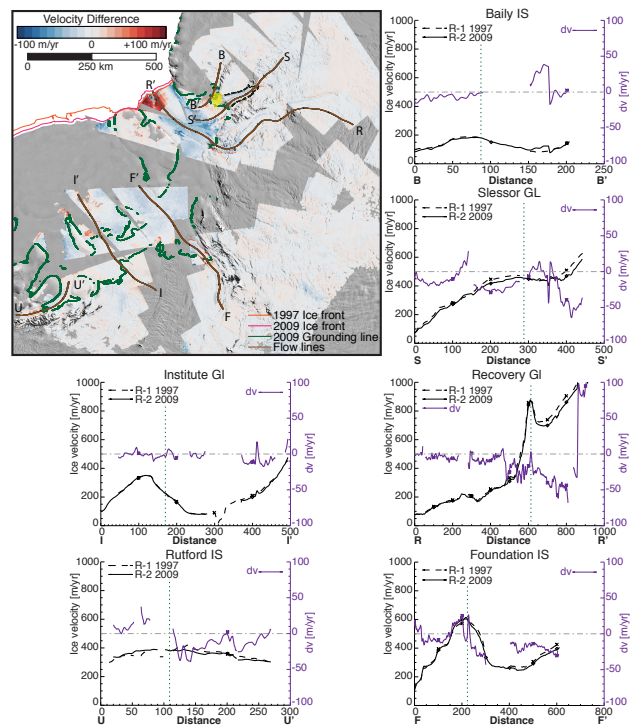
Fig. 4. Velocity Difference map (2009–1997) detail, 1997 and 2009 ice front, and flow line plots for Ronne Filchner Ice Shelf overlaid on MOA. Each flow line contains markers every 100 km. The yellow-black dashed line is an incorrect grounding line leading to residual tide correction errors (marked by a yellow arrow). The flow line graphs show the absolute velocities for 1997 and 2009 and the velocity difference. The vertical dashed line is the 2009 grounding line.