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Ice velocity changes in the Ross and Ronne sectors observed using satellite radar data from 1997 and 2009

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Abstract. We report changes in ice velocity of a 6.5 million km^2 region around South Pole encompassing the Filchner-Ronne 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 processed the data to assemble a comprehensive map of ice speed changes between those two years. On the Ross Ice Shelf, our results confirm a continued deceleration of Mercer and Whillans Ice Streams with a 12-yr velocity difference of $-50\,\mathrm{m\,yr^{-1}}$ ($-16.7\,\%$) and $-100\,\mathrm{m\,yr^{-1}}$ ($-25.3\,\%$) at their grounding lines. The deceleration spreads 450 km upstream of the grounding line and more than 500 km onto the shelf, beyond what was previously known. Ross and Filchner Ice Shelves exhibit signs of pre-calving events, representing the largest observed changes, with an increase in speed in excess of $+100\,\mathrm{m\,yr^{-1}}$ in 12 yr. Other changes in the Ross Ice Shelf region are less significant. The observed changes in glacier speed extend on the Ross Ice Shelf along the ice streams' flow lines. Most tributaries of the Filchner-Ronne Ice Shelf show a modest deceleration or no change between 1997 and 2009. Slessor Glacier shows a small deceleration over a large sector. No change is detected on the Bailey, Rutford, and Institute Ice Streams. On the Filchner Ice Shelf itself, ice decelerated rather uniformly with a 12-yr difference in speed of $-50\,\mathrm{m\,yr^{-1}}$, or $-5\,\%$ of its ice front speed, which we attribute to a 12 km advance in its ice front position. Our results show that dynamic changes are present in the region. They highlight the need for continued observation of the area with a primary focus on the Siple Coast. The dynamic changes in Central Antarctica between 1997 and 2009 are generally second-order effects in comparison to losses on glaciers in the Bellingshausen and Amundsen Seas region and on the Antarctic Peninsula. We therefore conclude that the dynamic changes shown here do not have a strong impact on the mass budget of the Antarctic continent.

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 (e.g. Bindschadler et al., 2003), field measurements continue to be vital in glaciology (e.g. Adalgeirsdóttir 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). The first and so far only complete InSAR mapping campaign covering

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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 manoeuvre 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 collection 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 autumn 2009 with a limited gap filler campaign to complete the mapping in 2011 (Crevier et al., 2010). During the International Polar Year (IPY 2007–2008), the IPY Space Task Group (STG) coordinated the contributions of four space agencies (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° S 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, which operates nominally in right-looking mode. Data collection in left-looking mode 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 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 available allows the extraction of ice surface velocity (1997 and 2009) and grounding line position (2009 only).

3.1 Velocity measurements

We use a speckle tracking technique (Michel and Rignot, 1999) to derive slant range and azimuth displacements from the InSAR data. The quality of the result is further improved for areas of slow flow where the unwrapped interferometric phase of tracks can be used in range instead of range offsets from speckle tracking (Rignot et al., 2011b). Assuming surface parallel flow, we use a DEM (Bamber et al., 2009) to calculate the two-dimensional displacement field. To obtain the two-dimensional ice velocity, we apply tide correction (per track) and velocity calibration (per track and using multiple tracks together) as discussed below. A detailed description of our method including an analysis of the flow directional sensitivity is provided in Mouginot et al. (2012). Three data cycles are available in 2009, we therefore combine the resulting two velocity products per track to reduce data noise.

3.1.1 Tide correction

The movement 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 (Doake et al., 2002). 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

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 collection 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)*		
Coverage (lat)			77.5° to 87°	86.5° to Pole		

* 14 tracks were aquired in 2011 to close data gaps from the 2009 AMM.

value of ice shelf velocities (or 1 km yr^{-1}), but is large when examining temporal changes in speed.

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 the 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).

Potential issues for tide correction result from the use of a MOA-based grounding line as well as inaccurate bathymetry in the Filchner Ice Shelf region in the current version of the tide model. The MOA-based grounding line differs from ICESat-based and differential InSAR-based grounding lines in some areas (Brunt et al., 2010; Rignot et al., 2011a). Among the erroneous areas is Slessor Glacier where a difference of up to 150 km was noted (Rignot et al., 2011a). We ignore tide model results upstream of the differential InSAR (DInSAR) grounding line on Slessor Glacier but expect residual effects on the shelf. In addition, recent observations from instrumented seals (Padman et al., 2010) suggest that the sub ice shelf cavity at that location is deeper than previously thought, thus also affecting the tide model. The tide model is currently being updated to reflect the new information available (L. Padman, personal communication, 2012).

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 available a priori. This is one of the reasons why only a few 1997 InSAR data could be analysed 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 mosaic 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).

We find that the tide estimates from the Padman model are of sufficient quality to implement a tide correction. When combined with our velocity calibration scheme, patch boundaries between tracks on the ice shelf as well as inconsistencies between overlapping tracks acquired at different times are eliminated.

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 minimised to increase the ability to detect subtle changes in speed. Track boundaries of difference maps are highly sensitive to calibration or mosaicking errors even if these issues are not apparent in the original velocity maps. 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 smoothens out shorter-time scale fluctuations, for instance associated with tides. In addition, the data collection extended only over 3 months, which minimises the impact of long-term changes on the data. 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 minimise 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 (88.5° S, 165.0° E), and Pecora Escarpment near Foundation Ice Stream), we find a 1-sigma variation of the difference in speed of $\pm 2.8\,\mathrm{m\,yr^{-1}}$. The corresponding 2009 speed 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). This indicates that the precision of velocity mapping is about ± 2–$3\,\mathrm{m\,yr^{-1}}$; and the precision of speed change measurements is about ± 3–$4\,\mathrm{m\,yr^{-1}}$ for the 12-yr period. This estimate is rather optimistic compared to previously published error estimates. The most significant contribution to velocity estimation uncertainty is the Ionosphere (Rignot et al., 2011b; Mouginot et al., 2012). The error for velocity estimates using RADARSAT-1 and RADARSAT-2 is estimated as $\pm 6\,\mathrm{m\,yr^{-1}}$ (Rignot et al., 2011b) (SOM). This leads to an error estimate for the difference product of $\pm 8.5\,\mathrm{m\,yr^{-1}}$ in areas where only a single coverage is available from both sensors (i.e. no track overlap, decorrelation in one of the two RADARSAT-2 pairs). 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 modelling, and the analysis of ice-ocean interactions (Rignot et al., 2011a). An ice shelf moves up and down with changes in the oceanic tide. This vertical motion is detected directly using DInSAR at a precision of millimetres, i.e. orders of magnitude better than laser altimetry (±10–20 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, DInSAR-based mapping of the grounding line south of 80° S, which is now available online (Rignot et al., 2011c). The product has a positional accuracy of ±100 m. Only points that were measured (i.e. both interferograms show correlation) are provided resulting in a coverage of consistent quality but with coverage gaps. The InSAR data from 1997 do not include repeat interferograms and therefore a DInSAR based grounding line cannot be derived for that year. The 2009 DInSAR-based grounding line has a generally good agreement with the ICESat-based grounding line (Brunt et al., 2010), which is also based on vertical motion but has a higher detection noise compared to DInSAR (Rignot et al., 2011a). Unlike methods relying on changes in surface slope, aspect, or visible features, the DInSAR approach is, similar to the ICESat-based approach, a direct measurement of the grounding line position. The ICESat-based grounding line reveals some areas of uncertainty or erroneous areas in a MOA based grounding line (Brunt et al., 2010), a detailed comparison between MOA-, ICESat-, and DInSAR-based grounding line is provided in Rignot et al. (2011a). These differences are relevant as the tide correction used is based on the MOA-based grounding line.

4 Results

Figure 1 shows the surface velocity product for 1997 (Fig. 1a) and 2009 (Fig. 1b) overlaid on the MODIS mosaic of Antarctica or MOA (Haran et al., 2005). The 1997 map is presented to its full extend and with improved calibration. Prior analyses 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).

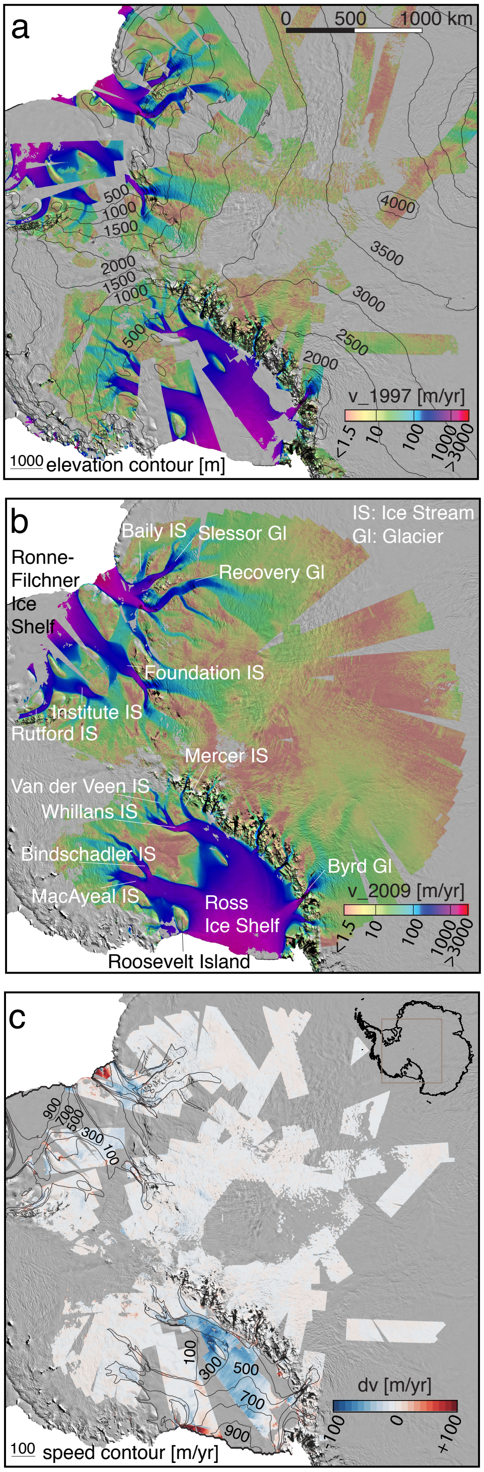

Fig. 1. Ice surface velocity maps for Central Antarctica for 1997 **(a)** and 2009 **(b)** overlaid on MOA. **(c)** shows the difference in speed dv (2009–1997) for the entire region. Blue tones indicate a deceleration, red tones an acceleration. The two dark red regions on the ice shelf edges (Ross Ice Shelf near Roosevelt Island and Filchner Ice Shelf) indicate pre-calving events.

The difference map of the entire study area shown in Fig. 1c reveals many interesting features. Most notable is a widespread deceleration on Ross Ice Shelf and Mercer and Whillans Ice Streams (formerly known as Ice Streams A and B). This deceleration – 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 deceleration through its extensive and continuous coverage. We note in particular that the deceleration 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. Prior studies reported on limited discrete points up to 400 km upstream for Whillans Ice Stream and 150 km upstream for Mercer Ice Stream (Joughin et al., 2002, 2005). Our result also shows the extent of the deceleration 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 acceleration 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 m yr^{-1}, though the main difference most likely results from the pre-calving event that happened after 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 m yr^{-1}. Locally, velocity differences between stable shelf portions and fast blocks reach +150 m yr^{-1}. Wide cracks are observable in the respective radar amplitude imagery at the transition boundary between acceleration and no acceleration for both areas, which justifies our labelling 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 acceleration and the widespread deceleration of the Mercer and Whillans Ice Streams, most of the other observed changes are small in magnitude. Values at the ±10–20 m yr^{-1} level over 12 yr are at the percent level of absolute speeds in the range of several hundred meters per year (Fig. 1). This means that we observe little change in speed of the glaciers and ice shelves between the two dates.

Figures 2 and 3 show a more detailed analysis for the Ross Ice Shelf region. The map (Fig. 2) shows the 12-yr difference in speed 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 centre of major outlets (Fig. 3). Plots and map contain markers every 100 km. The 2009 grounding line is indicated for reference. In addition to the 12-yr difference in speed, dv, we provide the difference in % of the glacier speed at the grounding line in the text below to provide some context

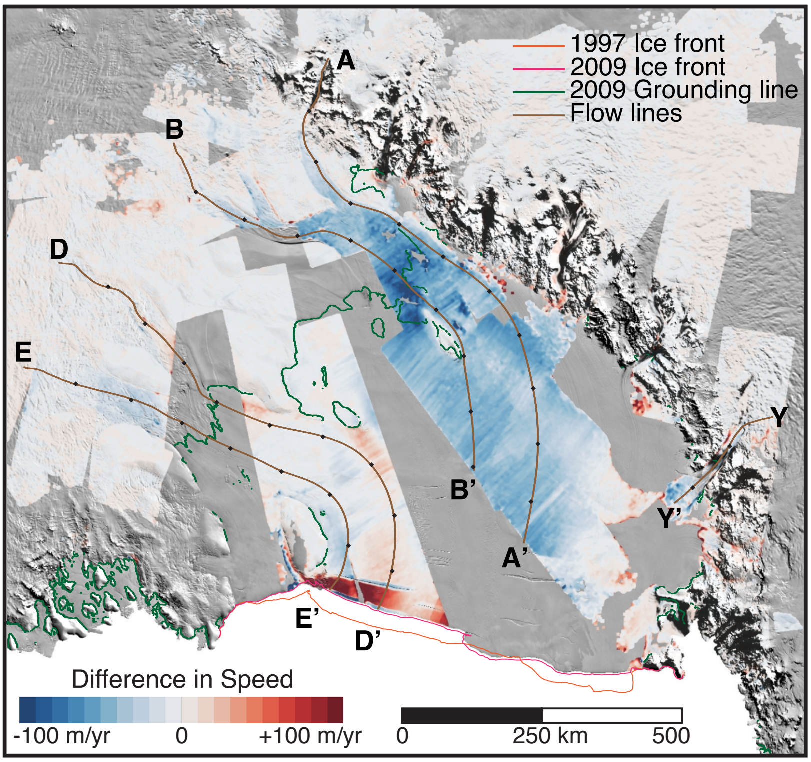

Fig. 2. Map of the difference in speed (2009–1997) detail, 1997 and 2009 ice front, and flow line plots for Ross Ice Shelf overlaid on MOA. Each flow line includes markers every 100 km. Corresponding flow line plots are shown in Fig. 3. The dark red region on the ice shelf edge near Roosevelt Island indicates a pre-calving event.

for each glacier. Our results show that the Byrd Glacier decelerated slightly with a 12-yr difference in speed of less than $-35\,\mathrm{m\,yr^{-1}}$ or $-4.1\,\%$ at the grounding line. The deceleration extends roughly 100 km upstream of the grounding line and decreases with distance. For comparison, Mercer and Whillans Ice Streams experience a more significant deceleration. Their 12-yr velocity difference near the grounding line is up to $-50\,\mathrm{m\,yr^{-1}}$ ($-16.7\,\%$) and $-100\,\mathrm{m\,yr^{-1}}$ ($-25.3\,\%$), respectively. Most likely, as a result of deceleration and thickening, the latter is reported between 2003 and 2008 in the grounding line section (Pritchard et al., 2012), 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 $-50\,\mathrm{m\,yr^{-1}}$). The Van der Veen arm of Whillans Ice Stream shows thin lines along the edges of the ice stream. These lines are most likely artefacts related to a slight misregistration. A possible slight migration of the ice stream margins cannot be confirmed with the data at hand. One of the reasons is that the quality of the orbit information for RADARSAT-2 is better than that of RADARSAT-1 due to improvements in the satellite design (Luscombe, 2009). Bindschadler Ice Stream displays a modest acceleration near the grounding line region, which is only partially covered in our data (dv up to $+20\,\mathrm{m\,yr^{-1}}$ or $+5\,\%$). An acceleration can be traced up to about 200 km upstream of the grounding line. In contrast, the MacAyeal Ice Stream decelerated slightly between 1997 and 2009 with a 12-yr difference in speed of up to $-30\,\mathrm{m\,yr^{-1}}$ or $-6.7\,\%$. Here, the deceleration (dv between $-10\,\mathrm{m\,yr^{-1}}$ and $-30\,\mathrm{m\,yr^{-1}}$) can be traced to about 300 km upstream of the grounding line. The respective velocity difference pattern on the western portion of the 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. Our results generally correspond with results derived using ICESat data (Lee et al., 2012). Their 2006–1997 velocity differences for specific coordinates near Crary Ice Rise appear to be about $20\,\mathrm{m\,yr^{-1}}$ lower than our 2009–1997 velocity differences (i.e. ICESat estimates higher velocities compared to InSAR, a fact that the study authors state as well, Lee et al., 2012). Assuming continued deceleration between 2006 and 2009, both results are comparable within the error bars of the methods.

Figures 4 and 5 show detail for the Filchner-Ronne Ice Shelf. The 1997 coverage is less extensive compared to the 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

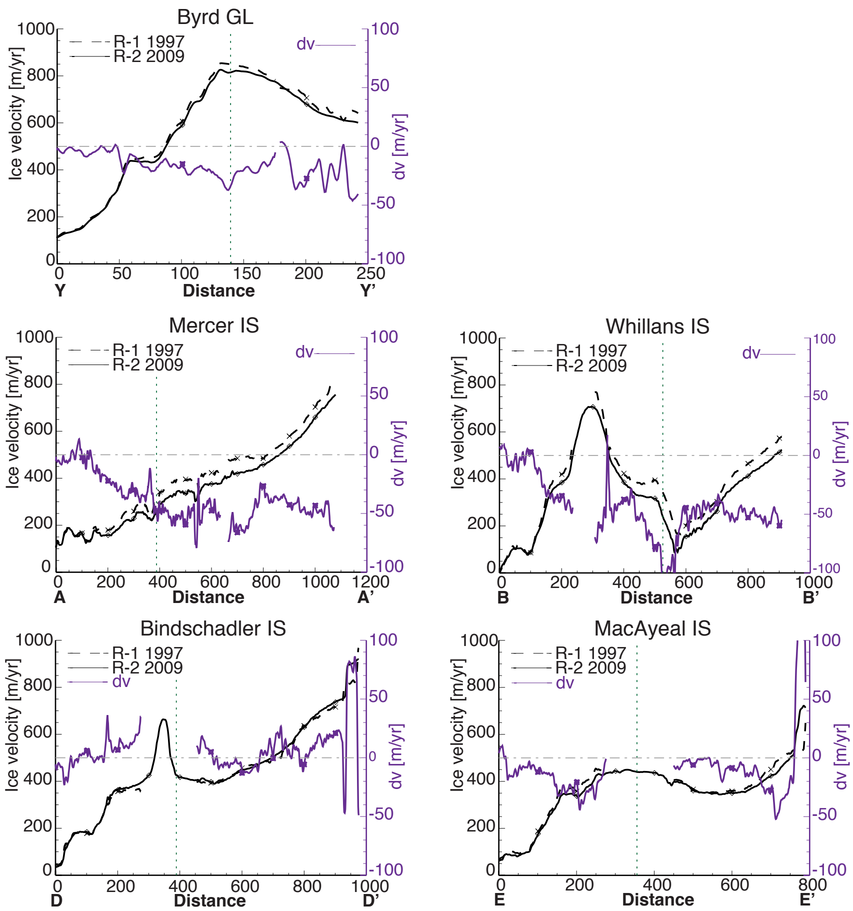

Fig. 3. Flow line plots for the Ross Ice Shelf tributaries showing the absolute velocities for 1997 and 2009 and the 12-yr difference in speed dv. Markers set every 100 km correspond to the markers shown in Fig. 2. The vertical dashed line is the 2009 grounding line.

Slessor Glacier, we also indicate the erroneous MOA-based grounding line portion (purple line) discussed earlier. In the region indicated by a black dashed circle in Fig. 4, we suspect the presence of residual errors in tidal correction. On Bailey Ice Stream, we detect a small deceleration in speed with a 12-yr difference in speed of about $-10\,\mathrm{m\,yr^{-1}}$ or $-5\,\%$. On nearby Slessor and Recovery Glaciers, the reduction in speed is larger. The 12-yr difference in speed is up to $-30\,\mathrm{m\,yr^{-1}}$, equivalent to $-6.7\,\%$ and $-3.3\,\%$ for Slessor and Recovery Glaciers, respectively. This deceleration is confined to within 100 km upstream of the grounding line region in the case of Recovery Glacier, but more pervasive over a vast area for Slessor Glacier. On Recovery Glacier, a thin blue line can be observed running parallel to the flow line. This line represents the northern edge of the fast flowing portion ($> 100\,\mathrm{m\,yr^{-1}}$) of the trunk. Similar to the trunk edge effect on the van der Veen arm of Whillans Ice Stream, it is possible that this is the result of a geolocation error. 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 acceleration at the grounding line (dv less than $+30\,\mathrm{m\,yr^{-1}}$ or $+5\,\%$). We detect only a small deceleration on Institute Ice Stream, i.e. dv of less than $-10\,\mathrm{m\,yr^{-1}}$ or $-5\,\%$. Coverage of Rutford Ice Stream is spotty, particularly around the grounding line. The difference in speed over 12 yr upstream of the grounding line indicates a higher speed in 2009 (dv up to about $+15\,\mathrm{m\,yr^{-1}}$, or $+3.8\,\%$).

On the Filchner-Ronne Ice Shelf itself, we detect a widespread and spatially relatively uniform deceleration. The 12-yr difference in speed reaches $-50\,\mathrm{m\,yr^{-1}}$ 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 difference in speed is about $-30\,\mathrm{m\,yr^{-1}}$ or $-7.5\,\%$ of the ice shelf speed in the area (or $-2.3\,\%$ of the ice front speed).

5 Discussion

The observed differences in speed between 1997 and 2009 can be divided in three groups of results: (1) continued

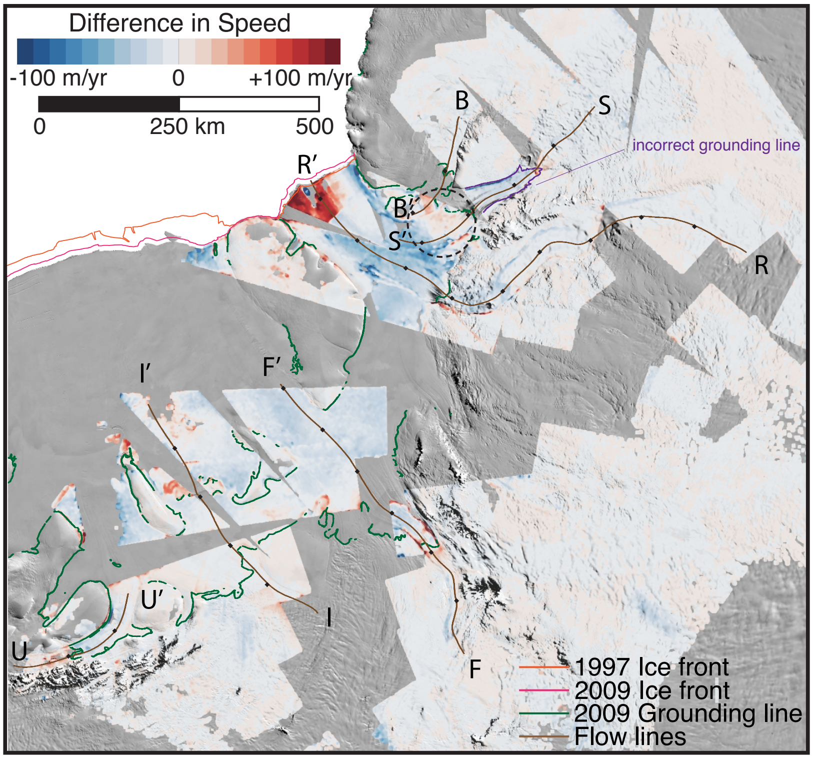

Fig. 4. Map of the difference in speed (2009–1997) detail, 1997 and 2009 ice front, and flow line plots for Filchner-Ronne Ice Shelf overlaid on MOA. Each flow line contains markers every 100 km. Corresponding flow line plots are shown in Fig. 5. The purple line is an incorrect grounding line leading to potential residual tide correction errors (marked by a black dashed circle). The dark red region on the edge of the Filchner Ice Shelf indicates a pre-calving event.

deceleration of Mercer and Whillans Ice Streams with potential impact on the entire Ross sector, (2) relative stability of several tributaries in both sectors, and (3) a small but notable deceleration of the Filchner-Ronne Ice Shelf.

The evolution of the Siple Coast Ice Streams over approximately the last 1000 yr is known based on the analysis of satellite imagery and ground penetrating radar. A detailed summary of the current knowledge is provided in Catania et al. (2012). The aspects most relevant for this study are a shutdown of Whillans Ice Stream about 850 yr ago (Catania et al., 2010) and the subsequent restart about 450 yr ago (Hulbe and Fahnestock, 2007). Our results and earlier studies in the region (Joughin et al., 2002, 2005) show that dynamic changes in the region are ongoing. Stearns et al. (2005) suggest a change of basal conditions as the cause of velocity changes in upper Whillans Ice Stream. The authors speculate that the depletion of meltwater at the base of the ice stream is most likely responsible for the observed changes. This is the same scenario described by Retzlaff and Bentley (1993) for the Kamb Ice Stream. This ice stream started to decline output about 440 yr ago (Catania et al., 2010) and shut down about 140 yr ago (Fahnestock et al., 2000). The shutdown scenario is described as a wave of stagnation that started near the grounding zone and propagated upstream (Retzlaff and Bentley, 1993). One of the conclusions of an analysis of streaklines is that interactions between the downstream reaches of adjacent ice streams are important to ice stream discharge variability (Hulbe and Fahnestock, 2007). Dynamic changes on the Kamb, Whillans, and Mercer Ice Streams are therefore likely linked.

Another complete shutdown of Whillans Ice Stream in the near future is possible given the observed trends over the last 40 yr. An analysis of the mass budget for the Ross Ice Shelf region, which includes our data, shows a change from near balance in 1975 to growth in 2009 (Thomas et al., 2012). The authors predict stagnation by around 2070. Our results also suggest an upward moving wave of stagnation similar to the pattern reported for the Kamb Ice Stream (Retzlaff and Bentley, 1993).

Analysing ICESat data between 2003 and 2007, Pritchard et al. (2009) report thickening of stagnant Kamb Ice Stream at 60 cm yr^{-1}, but thinning of the upper sections of Whillans and Mercer Ice Streams at 20 cm yr^{-1}. The grounding line sections of Whillans and Mercer Ice Streams are thickening as would be expected for a decelerating ice stream. The observed thinning in the upper reaches of Whillans and Mercer Ice Streams on the other hand must be related to changes in surface mass balance. Indeed, an analysis for the time

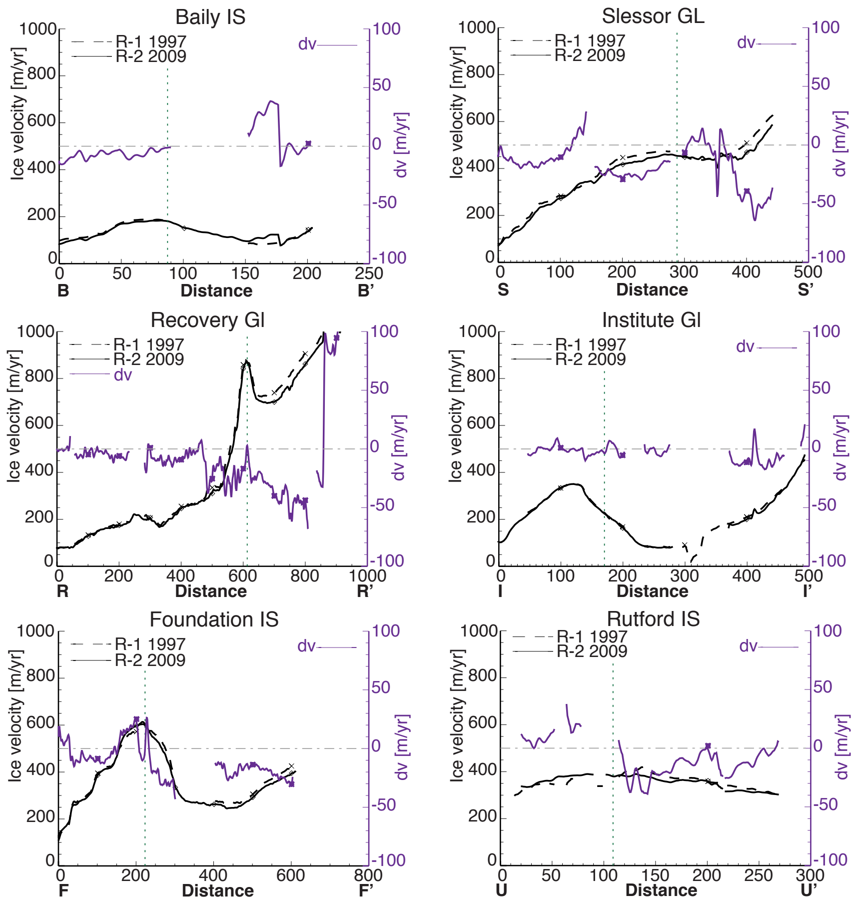

Fig. 5. Flow line plots for Filchner-Ronne Ice Shelf tributaries showing the absolute velocities for 1997 and 2009 and the 12-yr difference in speed dv. Markers set every 100 km correspond to the markers shown in Fig. 4. The vertical dashed line is the 2009 grounding line.

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. Pritchard et al. (2012) conclude that ice shelves along the Amundsen and Bellingshausen Sea coasts are strongly affected by basal melting. Both Ross and Filchner-Ronne ice shelf remain relatively stable in comparison.

Areas where we observe relative stability include the Byrd Glacier in the Ross sector and the Rutford Glacier in the Ronne sector.

The Byrd Glacier velocities are affected by tides and the drainage of subglacial lakes. A 10 % acceleration 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 cycle in the glacier dynamics may be possible but has not been observed. The 2009 velocities of the Byrd Glacier (see Fig. 3, Byrd flow line) are consistent with the values measured before the subglacial flood (Stearns et al., 2008). We conclude that despite the existence of a temporal increase in speed between 2005 and 2007, the Byrd Glacier has continued to maintain a rather steady flow regime over the last few decades.

The Byrd Glacier is a well-documented example of temporary acceleration due to a subglacial flood. The presence of subglacial lakes has been proven in other areas of the study area (Smith et al., 2009). Specifically, lakes have been studied for some Ross Ice Shelf tributaries (Fricker et al., 2007, 2011) and for Recovery Glacier (Bell et al., 2007). The data set used in this study is not sufficient to provide a detailed evaluation of subglacial lakes. Drainage or in-fill of subglacial lakes results in a change of surface elevation. Depending on the fill level difference between the two campaigns, this would cause a signature in the velocity difference map. A detailed evaluation of a specific lake would require a more extensive data set (i.e. a time series) than is available here.

The velocity of Rutford Ice Stream is influenced by oceanic tides. The relationship is complex, with diurnal and fortnightly periodicity and variations oscillating between

20 % and 12 % (Gudmundsson, 2006; Adalgeirsdóttir et al., 2008). The RADARSAT-1 and -2 data sets used here were acquired 24 days apart, which means that we measure the mean surface displacement over that period. Averaging over 24 days greatly reduces sensitivity to variations with a cycle smaller than this period. A residual effect could be present due to annual variation (Murray et al., 2007), however, looking at Fig. 2 of Murray et al. (2007) and assuming similar cycles for 1997 and 2009, both acquisition periods fall in similar phases of the annual cycle and the effect should be small. The measured changes in speed over 12 yr are less than +5 % of the absolute velocity, with slight acceleration upstream of the grounding line and slight deceleration 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. A comparison of all available stake-velocity measurements from Rutford Ice Stream between 1979 and 2004 also shows no changes in multi-annual surface speed (Gudmundsson and Jenkins, 2009). These results are also 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).

The apparent deceleration of the Filchner-Ronne Ice Shelf is small, yet noticeable. The magnitude and extent and the uniformity of the change in speed is unlikely to be an artefact of tide, noise, or errors in processing, and so is most likely explained by a real change in flow speed. If they were artefacts, the resulting mosaic combining several tracks acquired at different times would show a mismatch between the frames. For the Filchner Ice Shelf a likely explanation for the ice sheet wide deceleration is an increase in side stress for the ice shelf during the observation interval. Between 1997 and 2009, the ice front advanced by about 12 km (see Fig. 4), which increased side shear and would explain the deceleration of the shelf. This aspect needs to be confirmed with model simulations.

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 in the region. Data quality is excellent and provides ice motion results with an estimated error of $\pm 6\,\mathrm{m\,yr^{-1}}$ on average and detection of changes in speed with an estimated error of about $\pm 8.5\,\mathrm{m\,yr^{-1}}$. Our change map provides new, important information about the evolution of this sector of Antarctica, or lack thereof.

On the Ross Ice Shelf, we confirm the deceleration of Mercer and Whillans Ice Stream, with a 12-yr difference in speed of −16.7 % and −25.3 %, respectively. Our change map shows, for the first time, the entire spatial extent of the change. The reduction in speed extends hundreds of km upstream and onto the shelf. Both Ice Streams could shut down completely within approximately the next 60 yr if they continue the current trend. The deceleration pattern appears to be similar to the shutdown pattern reported for the Kamb Ice Stream. The ice streams and glaciers that constitute the catchment area of Ross Ice Shelf define regional variations in speed changes on the ice shelf itself.

Both Ross and Filchner Ice Shelves exhibit signs of pre-calving events. These represent the largest observed changes, an increase in speed in excess of $+100\,\mathrm{m\,yr^{-1}}$ in 12 yr.

The Filchner-Ronne sector shows few changes, with most ice streams slightly decelerating. The 12-yr difference in speed for all glaciers and ice streams in the region is below 8 %. The most distinct signals in the region are a slight deceleration of the Filchner Ice Shelf, consistent with an ice shelf advance, and a small deceleration of the Slessor Glacier over a large sector.

Our results show that dynamic changes are present in our region of interest. Central Antarctica is therefore a region that deserves continued observation, with primary focus on Siple Coast. Mass balance changes of the West Antarctic Ice Sheet are driven by losses on glaciers in the Bellingshausen and Amundsen Seas region and on the Antarctic Peninsula (Rignot et al., 2008; Pritchard et al., 2012). The dynamic changes in Central Antarctica between 1997 and 2009 are generally second-order effects in comparison. We therefore conclude that the dynamic changes shown here do not have a strong impact on the mass budget of the Antarctic continent.

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