Flow variability and ongoing margin shifts on Bindschadler and MacAyeal Ice Streams, West Antarctica

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Abstract. Ice streams on the Ross Sea side of the West Antarctic Ice Sheet are known to experience flow variability on hourly, annual, and multi-century time scales. We report here on observations of flow variability at the decade scale on the Bindschadler and MacAyeal Ice Streams (BIS and MacIS). Our analysis makes use of archived ice velocity data and new mappings from composited Landsat 7 and Landsat 8 imagery that together span the interval from 1985 to 2014. Both ice streams speed up and slow down in a range of about $\pm$ 5 ma^{-2} over our various comparison intervals. The rates of change are variable in both time and space and there is no evidence of external forcing at work across the two streams. Widespread changes are most likely linked to instability in the subglacial till and/or subglacial water flow. Sticky spots near the confluence of the two ice streams are loci for speed changes. These relatively young and slow-flowing features appear to be forcing shifts in margin position near the outlets of both streams. The margin jumps reduce the effective outlet widths of the streams, by 20% and 30% on BIS and MacIS, respectively. Those magnitudes are similar to the outlet narrowing experienced by Kamb Ice Stream prior to its stagnation.

1. Introduction

The three large drainage basins of the West Antarctic Ice Sheet (WAIS) discharge into the Amundsen, Weddell, and Ross Seas. Outlet glaciers in the Amundsen Sea sector are now responsible for most of the negative mass balance in Antarctica [*Shepherd and others*, 2012]. In contrast, the mass balance of the Ross Sea sector of the WAIS (Ross-WAIS) is positive due to the stagnation of Kamb Ice Stream (KIS) about 160 years ago and the ongoing slow-down of Whillans Ice Stream (WIS) [*Catania et al.*, 2012b; *Joughin and Tulaczyk*, 2002; *Pritchard et al.*, 2009; *Zwally and Giovinetto*, 2011]. These trends must be interpreted in the context of known time scales for internal ice sheet variability.

The Ross-WAIS ice streams experience significant variation on century time scales, including redirection, stagnation and reactivation [*Catania et al.*, 2012b; *Hulbe and Fahnestock*, 2007]. Stagnation appears to initiate near the grounding line, where the ice transitions from grounded on the subglacial bed to floating at the ocean surface [*Catania et al.*, 2012b; *Joughin and Tulaczyk*, 2002; *Retzlaff and Bentley*, 1993]. Processes implicated in ice stream stagnation include changes in the configuration of lateral shear margins, switches from melting to freezing at the ice stream base, feedbacks between ice and the underlying till, and changes in the routing of subglacial water [*Bougamont et al.*, 2003, 2011; *Carter et al.*, 2013; *Catania et al.*, 2005; *Christoffersen et al.*, 2014; *Fried et al.*, 2014; *Gray et al.*, 2005].

Ice streams vary on shorter time scales as well. For example, changes in the subglacial water system and basal sticky spots (sites of locally slow flow and relatively large traction) together modulate the ongoing deceleration of WIS on annual to sub-decade time scales

[*Carter et al.*, 2013; *Winberry et al.*, 2014]. Recent high-resolution inversions for basal traction beneath ice streams find widespread rib-like structures oriented oblique to flow, which suggest an underlying viscous instability that would also modulate the rate of ice flow on multi-year time scales [*Sergienko and Hindmarsh*, 2013; *Sergienko et al.*, 2014]. On hourly to daily time scales, ocean tides modulate ice stream flow at their grounding lines and 10s of km upstream from that boundary [*Anandakrishnan et al.*, 2003; *Bindschadler et al.*, 2003; *Winberry et al.*, 2014]. Processes acting on longer time scales likely affect the ways in which the more rapid effects play out [*Sergienko et al.*, 2009; *Winberry et al.*, 2014].

In this contribution, the focus is on Bindschadler and MacAyeal Ice Streams (BIS and MacIS, respectively), which discharge into the easternmost part of the Ross Ice Shelf (RIS), north of Siple Dome. Together, the streams account for about 55% of the mass flux through the WAIS-Ross system [*Joughin and Tulaczyk*, 2002]. Both BIS and MacIS have experienced large-scale flow variation within the last 1000 years. While the upstream reach of BIS appears relatively steady on multi-century time scales [*Siegert et al.*, 2003], "Siple Ice Stream" (SIS), a former distributary of KIS that flowed north around Siple Dome to merge with BIS, stagnated some time within the last 500 years [*Catania et al.*, 2012b; *Nereson*, 2000]. MacIS appears to have stagnated and reactivated between about 800 and 650 years ago [*Hulbe and Fahnestock*, 2007]. The downstream reaches of BIS and MacIS experience flow variation on shorter time scales as well. BIS is observed to be strongly modulated by the tide, its speed near the grounding zone varying by a factor of three over the course of a day [*Anandakrishnan et al.*, 2003]. MacIS is observed to experience changes related to the variable flow of water through the subglacial meltwater system [*Carter et al.*, 2011].

The flow variability presented here, spanning the interval from 1985 to 2014, fills in some of the gap between century and annual to shorter time scales. This may reveal ice stream response to processes internal to the ice sheet system, such as basal water drainage events [*Carter et al.*, 2011] and viscous instability in the subglacial till [*Sergienko et al.*, 2014; *Sergienko and Hindmarsh*, 2013]. It may also clarify the processes associated with longer time scale changes such as ice stream stagnation. For example, the stoppage of Kamb Ice Stream (KIS) about 160 years ago was preceded by changes in the configuration of its lateral margins near the grounding line, which shifted 10s of km inward about 200 years before stagnation [*Catania et al.*, 2010; *Retzlaff and Bentley*, 1993]. Margin migration has been inferred from relict features and investigated theoretically but has not been observed directly.

2. Observations

2.1. Ice velocity

Surface motion has been measured, episodically, on BIS and MacIS via feature tracking since the 1980s [*Bindschadler et al.*, 1996]. Here, new velocities computed using images collected by Landsat 7 and Landsat 8 extend the record to the year 2014 (Table S1). The older velocities were computed using Landsat 4, Landsat 5, and SPOT 3 observations [*Bindschadler et al.*, 1996] and the IMCORR software [*Scambos et al.*, 1992] . Errors in the the older velocity measurements are a combination of a systematic 1.0 pixel and random 0.5 pixel error divided by the separation interval. This results in a 15 m a^{-1} error for a two year interval. In our case, the errors range from about 5.4 to 14 m a^{-1}. Velocity here has also been measured via InSAR [c.f., *Joughin et al.*, 2002].

New velocities (Figure 1) are computed using Landsat 7 and Landsat 8 images and a Python-based software named PyCorr [*Fahnestock et al.*, 2014]. The process matches small sub-scenes between sequential images according to similarity in their grey-scale value patterns and uses peak fitting in the region of maximum correlation for each sub-scene pair to generate sub-pixel fits for offset vectors. Editing after the correlation process seeks to eliminate spurious vectors and correct residual geo-location error. This editing requires knowledge of plausible ice strain rates and near-zero flow features (ice domes, rock outcrops). As many image pairs as possible are stacked together to reduce error in the derived velocities. For a single image pair, the error is 18.25 m a^{-1}. In cases where multiple pairs are used, the error reduces according to the inverse of the root of the number of pairs. The number of pairs ranges from 4 to 7 in the most of the study area and we use conservative values of 5 and 10 m a^{-1} for the Landsat 7 and Landsat 8 derived speeds, respectively.

Rates of change in ice speed are computed for various intervals within the compiled Landsat- and SPOT-derived data (Figure 2). We do not compare our velocities with multi-epoch composite velocity products. Because we do not have any knowledge of changing ice thickness or surface accumulation rate at our spatial and temporal scales, we do not attempt to use our observations for time-varying force budget computations.

The Landsat 7 and 8 velocities are co-registered and can be compared simply. In all other cases, we find nearest neighbours between velocity data sets, keeping only comparisons of points within 200 m of each other. The separation time between images in the older data sets is as large as 5 years. While the longer interval means a smaller error on the rate of change, it also means that the mid-point of the measured total displacement (the appropriate location for the mean velocity) may be hundreds of meters downstream from the initial sub-scene center used in the image pair. Thus, to compare various intervals accurately we translate the longer-term velocity locations to midpoints along the trajectories between images. We assume linear trajectories for this correction.

Measurement errors are propagated through the difference calculations as the root of the sum of the squares divided by the interval length for rates (Table 1). The resulting errors on the rates of change in observed ice speed range from about $\pm$ 0.5 m a^{-2} for the longest intervals to just under 5 m a^{-2} for the older Landsat 4 and 5 comparisons. Not all of the rates of change posted in Figure (2) escape the errors on the various calculations (Table 1).

Several characteristic relationships between ice speed and surface morphology are important to our analysis [*Bindschadler et al.*, 2001; *Gudmundsson*, 2003]. Interstream ridges are relatively smooth and flow at speeds between 0 and a few m a^{-1}. Ice streams are characterized by more irregular surface shape (undulations), streaklines oriented along flow, and speeds in excess of about 100 m a^{-1}. Well-developed shear margins between ridges and streams are relatively narrow, a few km, giving across-stream speed profiles a distinctive U shape (Figure 2, panels h, i, j). Sticky spots within the ice stream are characterized by irregular surfaces and streaklines, but flow at speeds slower than that of the surrounding stream.

2.2. Shear margins and crevasses

Large across-flow velocity gradients mark the boundaries between fast-flowing streams and more slowly-flowing areas in the ice sheet. To highlight these (Figure 1), we calculate the effective strain rate $\dot{\epsilon}_e$ as

$$\dot{\epsilon}_e^2 = \dot{\epsilon}_{xx}^2 + \dot{\epsilon}_{yy}^2 + \dot{\epsilon}_{zz}^2 + 2\left(\dot{\epsilon}_{xy}^2 + \dot{\epsilon}_{xz}^2 + \dot{\epsilon}_{yz}^2\right) \tag{1}$$

using gradients of the gridded Landsat 8 derived velocity field. Vertical shearing is negligible in the ice stream and the vertical normal strain rate is calculated from the horizontal divergence ($\dot{\epsilon}_{zz} = -\dot{\epsilon}_{xx} - \dot{\epsilon}_{yy}$). The strain rates are averaged in a 500 m radius around each measurement point before contouring, in order to reduce noise in the map.

In addition to their appearance in the flow field, ice stream shear margins have distinct morphological markers. The surface slope breaks from steeper on the ridge side to shallower on the stream side, and the surface changes from relatively smooth and featureless on the ridge to a more complicated, undulating pattern with crevasse fields on the stream. Within the shear margin, large (order 100 kPa) shear stresses in ice stream margins yield distinctive crevasse patterns [*Merry and Whillans*, 1993; *Raymond*, 1996]. Fractures transition from short (∼1 km), en echelon, hook-shaped crevasses at the boundary with an interstream ridge, through a chaotic zone marked by complicated cross-cutting relationships, to long (several km) transverse fractures that originate with upstream-pointing geometries and rotate as they advect downstream [*Merry and Whillans*, 1993; *Raymond et al.*, 2001].

Margin morphology can be used to chart the downstream development of ice streams [*Bindschadler et al.*, 2001; *Scambos et al.*, 1994]. As a margin emerges, an initially broad zone of cross-cutting crevasses narrows, becoming more chaotic in appearance, and the shear strain rate increases. Where a shear margin has become inactive, the crevassed terrain becomes snow-covered and less visible, while surface shape characteristics remain [*Catania et al.*, 2005; *Retzlaff and Bentley*, 1993]. All of these situations are observable at the margins of MacIS and BIS.

3. Ice stream changes

3.1. Speed

Both MacIS and BIS change speed at rates above the sensitivity of the velocity mapping throughout the interval between 1987 and 2014 (Figure 2). Overall, MacIS has slowed slightly while BIS has sped up but both streams exhibit acceleration and deceleration over shorter intervals. At locations where they can be compared, the differences calculated here are consistent with the difference calculations made by *Scheuchl et al.* [2012] and *Joughin and Tulaczyk* [2002] using InSAR, over other intervals. The speed changes are non-uniform in space and time, both within and across the two ice streams. The changes are on the order of a few percent of the ice speed in the trunks of the streams and up to about ± 10 % near the margins. Relatively large changes appear to be associated with shear margins (Figure 2) and temporally variable changes are typical of the sticky spots near the confluence of the two streams (best examined in Figure 2, parts h to k). Our observations on the ice shelf are limited and in most cases do not exceed the propagated error.

Rates of change computed over longer intervals may be smaller or of opposite sign to rates computed over shorter intervals. For example, when the time span on BIS is reduced from the 14 years between 1987 and 2001 to the 7 years between 1994 and 2001, the slow-down of its left-lateral margin nearly doubles as does the speed-up in the middle of the stream (Figure 2, parts c and d). Most of the rates of change are near the detection limit set by errors in the difference calculation but the spatial coherence in the overall patterns and similarities across sensors give us confidence to interpret them.

The sequence of events on BIS appears to be this:

1. 1987 to 1994: The left-lateral side of the stream slows while the right-lateral side speeds up.

2. 1994 to 2001: Most of the stream speeds up while the left-lateral margin continues to slow. Ice over the sticky spot slows down.

3. 2001 to 2014: Widespread speedup in the downstream reach, including the sticky spot, but slow-down along the upstream part of its currently active left-lateral margin, and increased speed on its old left-lateral margin.

The sequence of events on MacIS appears to be this:

1. 1987 to 1989: The confluence-area sticky spot on the MacIS side slows down.

2. 1987 to 2001: On this longer interval, a low amplitude, mixed pattern of slow-down and speed-up over the sticky spot. Widespread slow-down elsewhere on the ice stream.

3. 2001 to 2014: Speed-up near the grounding line and in the lateral margins, with some slower speeds over the sticky spot.

These are summarized graphically in Figure 3.

3.2. Sticky spots

Mismatches between the flow field and morphological features can be used to infer both past and ongoing change [*Catania et al.*, 2012a; *Fried et al.*, 2014]. Ice stream margin "scars" may persist for hundreds to thousands of years after stream stagnation [*Nereson*, 2000] but snow cover smooths the rough chaotic zone surface within a few decades [*Retzlaff and Bentley*, 1993]. Mismatches may thus provide context for the variations we observe at certain places over shorter intervals. In particular, we are interested in bands of high effective strain rates not matched by a slope break or a narrow chaotic zone, and in chaotic zones partially obscured by recent snow.

Both the MacIS and BIS sticky spots are bounded by bands of large effective strain rates and both are associated with mismatched flow and morphological features. The pattern is simpler on the MacIS sticky spot than on the BIS sticky spot but in both cases, bands of large effective strain rates connect a well-developed, upstream lateral shear margin with complex crevasse fields on the inboard sides of the sticky spots (for example, as in Figure 4). The emerging crevasse trains trace back upstream to crevasses on the inboard side of the active margin. The width of the MacIS outlet between right-lateral shear margin and the inboard large $\dot{\epsilon}_e$ band is about 56 km, while the full width to the tip of the interstream ridge is about 80 km 1. A similar comparison of widths on BIS yields 34 km and 44 km, respectively.

3.3. Shear margins

Shear bands delineate the boundaries of both ices streams and the tributaries flowing into them. Our comparisons cover part of the upstream, "onset" area of the BIS system, a region characterized by extensive crevasse fields and margin development. The margins of the central BIS tributary speed up between the late 1980s and 2001 (Figure 2, part d) and slow down between 2001 and 2014 (Figure 2, part g). *Winberry et al.* [2007] looked for flow changes in this area using velocity stake measurements from 1996 and 2002. They found minimal changes over that interval but unfortunately, a direct comparison cannot be made with our data.

Scambos et al. [1994] examined the left-lateral margin of BIS near its former junction with SIS and concluded that the margin was migrating outward (Figure 5). Migration should generate an overall speed up, as a wider region becomes entrained in the stream flow. This area is covered in our 1980s to 2001 and 2001 to 2014 comparisons (Figure 2, parts d and g, between the j and k transects). No change is apparent over the earlier interval but the margin does speed up over the latter interval.

4. Discussion

Changes in ice stream flow on the time scales we observe may be driven externally, by changes in the ice shelf, or may arise internally, by variations in the coupled ice/water/till system. The spatially and temporally complicated patterns on BIS and MacIS seem unlikely to arise solely from external forcing. Nevertheless, we note that the ice shelf experienced a major change within our observation window. Iceberg B-15 calved from the RIS front, downstream of the BIS and MacIS grounding line, in March of 2000 [*Lazzara et al.*, 1999; *Scheuchl et al.*, 2012]. The new boundary condition would have influenced ice shelf velocity instantaneously, by allowing the floating ice to speed up. That signal would have been largest near the front and could have been transmitted upstream into the grounded ice, though the intervening island, ice rises, and ice-shelf rifts between the front and the grounding line would have damped the signal.

The most straightforward changes we observe are around the confluence of the two ice streams. Anomalously slow sticky spots are emerging there on both ice streams. In both cases, ice flows over the sticky spot at less than half the speed of the adjacent stream and we find episodes of both slow-down and speed-up. The sticky spots are shadowing segments of an older shear margin, while new margins form inboard of the spots. If the sticky spots persist, the most active crevassed zones will continue to develop and over time will become the new margins of the stream. Although we detect no long-term trend in the flow of the two ice streams, margin jumps may be the early signs of ice stream stagnation, as was the case on KIS [*Catania et al.*, 2006].

We do not know when the two large sticky spots began to develop but the morphological clues indicate that the margin shadowing is relatively recent. One clear effect is a reduction of the outlet width, by about 30% on MacIS and about about 20% on BIS. Maintaining a constant driving stress under such circumstances would require a significant reduction in basal drag on both streams. Alternatively, the mass flux may decrease, as was apparently the response to outlet narrowing on KIS [*Catania et al.*, 2006]. It is interesting to note in their analysis of past variability inferred from streaklines in the RIS, *Hulbe and Fahnestock* [2007] preferred a staged reactivation for MacIS after its stagnation, an effect that was necessary to limit ice thickness in the embayment between Siple Dome and the Shirase Coast. Ongoing accommodation of a large sticky spot near the grounding line is an alternative interpretation of that requirement.

Changes in the stiffness of subglacial till can also affect stream-wide flow. Theoretical treatments of ice-till feedbacks produce decade and longer time scale variations [*Bougamont et al.*, 2011; *Tulaczyk et al.*, 2000]. Recent high-resolution analyses of driving stress and basal drag on ice streams in Antarctica and Greenland reveal ubiquitous, organized patterns linked to a viscous instability in the till [*Sergienko et al.*, 2014; *Sergienko and*

Hindmarsh, 2013] that could yield decade-scale variability in ice flow. Such changes could explain much of the observed variability.

As ice sheet flow transitions into the network of tributaries that lead to ice streams, lateral margins develop. Following a margin downstream, shear strain rates increase and the zone of large deformation focuses into a relatively narrow band. Viscous deformation and local water production by viscous heating of the margin ice promotes that process [*Raymond*, 1996; *Raymond et al.*, 2001; *Scambos et al.*, 1994; *Suckale et al.*, 2014]. The velocity comparisons show both increases and decreases in speed along many stretches of the BIS margins, a pattern also observed by *Joughin et al.* [2002] and *Scheuchl et al.* [2012] over different intervals. Changes in the margin are not always of the same sign as changes in the main part of the stream, which suggests that the underlying cause is not the stiffness of the margin ice (in that case, margin and stream should always change in the same direction).

Transients arising from pulses of basal water transmitted downstream could yield low-amplitude, alternating increases and decreases in ice speed [*Carter et al.*, 2011; *Gray et al.*, 2005; *Sergienko and Hulbe*, 2011]. Shear margins produce hydropotential lows [*Carter et al.*, 2011] and variable water flow could explain the change in sign we observe, from slowing to speeding on the left-lateral margin of BIS between 2001 and 2014. It would not, however, account for the the fact that a much wider region of BIS, not just the margin, was slowing between 1987 and 1994. A two-way coupled ice-stream/basal-water model used to simulate flow over undulating bed morphologies [*Hiester*, 2013] produces channel-like features oriented obliquely to the flow direction, with variability on multi-year time scales. The channel-like features, sometimes accompanied by ponds, produced in those models are associated with widespread changes in ice speed and intensification of effective stress in the ice that mimic the basal water distribution. Such effects could explain the intense surface crevassing at some sites where we observe flow variability (Figures 4 and 5).

Ongoing adjustments to past ice stream events are another source of internal flow variability [*Fried et al.*, 2014]. Those authors used a numerical model to examine thickness and flow transients in the outlet regions of WIS and KIS. They found that changes to basal traction associated with ice rise and sticky spot formation led to widespread adjustments in the low-slope, lightly grounded ice stream outlet environment. The "Duckfoot" and "Goosefoot" low-slope areas at the corners of the KIS outlet are similar to the present sticky spots. Those wedge-shaped areas, bounded by highly fractured ice, developed over a few hundred years, just prior to ice stream stagnation. The sticky spots at the confluence of BIS and MacIS have similar morphology to the features on KIS and may have similar effects.

One recent event near the confluence of BIS and MacIS is the stagnation of Siple Ice Stream within the last 500 years [*Nereson*, 2000]. The left-lateral margin of BIS has only existed in its current configuration since that event. Before then, there must have been an interstream ridge and confluence near where the main trunk of BIS widens today (Figures 1 and 5). When SIS stagnated, the suture zone between the two streams became the left-lateral margin of BIS. By comparison with the current BIS/MacIS suture zone, we can see that stagnation of the one stream would yield an initially complicated shape, an apparent outward deflection, for the margin of the still-active stream. There would have been an outward kink near the downstream end of the former BIS/SIS interstream ridge. The margin changes now underway on BIS would then be an ongoing correction to the overall margin shape for the stream. It may be possible to distinguish ongoing mechanical adjustments of this type from water transients using surface elevation. For example, water pulses should be accompanied by upward and downward transients in surface height [*Carter et al.*, 2011], while a margin migration would yield a shifting slope break feature.

5. Conclusion

BIS and MacIS experience unforced flow variability on the order of $\pm$ 5 ma^{-2} on decade time scales. Those magnitudes are up to 10% of the ice speed. The changes have complicated spatial and temporal patterns, including positive and negative trends. In some cases, the change is widespread while in others, change is locally focused, for example, over a sticky spot or along a shear margin. In some cases, shorter comparison intervals produce larger trends, indicating some aliasing due to the sampling interval.

Some of the observed speed changes are consistent with instability in the subglacial till and/or water flow. In particular, the widespread speed-up (1987 to 2001) followed by downstream speed-up and upstream slow-down (2001 to 2014) on BIS and the slow-down (1987 to 2001) followed by speed-up (2001 to 2014) on MacIS call for broadly distributed, internal forcing with some spatial structure.

Other observations call for more local, circumstantial, explanations. For example, the left margin of BIS appears to still be adjusting to the stagnation of SIS. The suture zone at the former confluence of the two streams became the left-lateral shear margin of BIS, and structural features at that site indicate that the reorganization is not yet complete. Episodic subglacial water drainage events along that margin may also explain ice speed changes along that boundary. Local effects are identified in studies over other multi-year intervals as well [*Siegfried et al.*, 2014; *Stearns et al.*, 2005].

Both BIS and MacIS are adjusting to the emergence of sticky spots at their confluence. Relatively inactive shear margins now in the stress shadows of the spots are still visible beneath a snow cover, indicating that the spots are relatively young (Figure 4). We do not know what caused the sticky spots to develop but they appear to be driving shear margin jumps at both locations. The configuration of the spots and sense of change is similar to features associated with the stagnation of KIS about 160 years ago [*Catania et al.*, 2006]. MacIS is understood to have stagnated in the past, between about 800 and 650 years ago [*Hulbe and Fahnestock*, 2007]. Together, BIS and MacIS account for more than half of the mass flux through the WAIS-Ross system [*Joughin and Tulaczyk*, 2002], making change here relevant to the entire region.

Our observations may simply reflect internal variability on a previously unsampled time scale and as such, do not necessarily imply an accompanying change in grounding line position [*Horgan and Anandakrishnan*, 2006]. Alternatively, they may signal future change on one or both of the streams. If so, the transition from fast-flowing to stagnant is not smooth, but includes both negative and positive trends. Observations made on too short time scales may be misguiding with regard to longer term trends.

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Table 1. Details of ice speed rate of change calculations shown in Figure 2.

comparison	range	error (m a^{-2})	# of comparisons (> error)
DD EE	1987 to 1989	4.8	225 (2)
DD SP	1987 to 1994	4.8	1948 (63)
DD L7	1987 to 2001	1.8	21553 (4542)
EE L7	1989 to 2001	1.1	22599 (10344)
SP L7	1994 to 2001	1.9	14659 (6719)
DD L8	1987 to 2014	1.0	21514 (6345)
EE L8	1989 to 2014	0.5	22571 (12410)
SPD to L8	1994 to 2014	0.6	14695 (9002)
L7 to L8	2001 to 2014	1.2	892380 (264332)

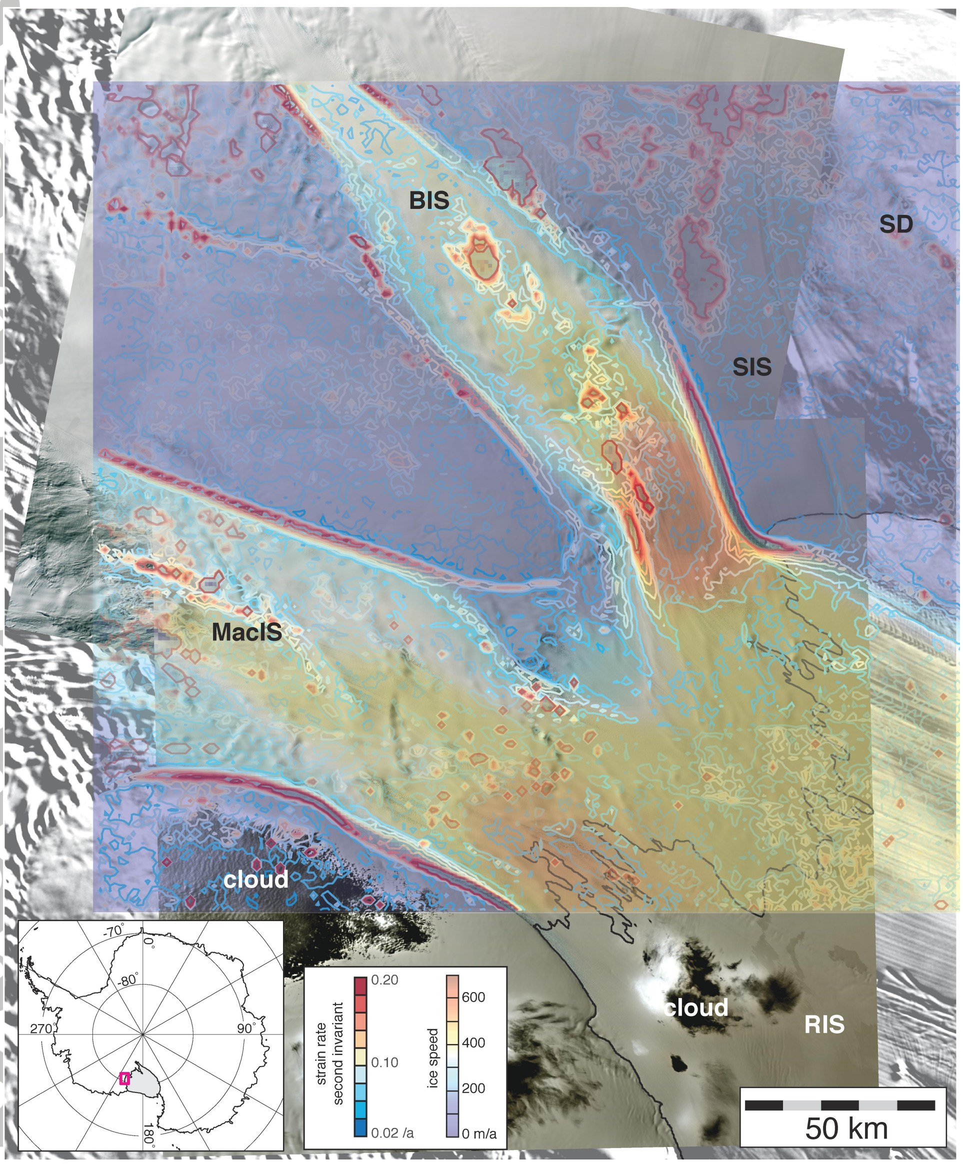

Figure 1. MacAyeal and Bindschadler Ice Streams (MacIS and BIS, respectively). The colormap is speed from Landsat 8 and the colored contours are effective strain rates calculated from that field. The now-stagnant Siple Ice Stream (SIS), Siple Dome (SD) and loating Ross Ice Shelf (RIS) are labelled. Two of the Landsat 8 scenes used in the velocity mapping and the MODIS Mosaic of Antarctica (MOA) are used as a base map. Different surface roughnesses and slope changes associated with ice flow regimes are visible. The location of the grounding line (black line) is interpreted from the MOA. Bands of relatively large effective strain rate mark shear margins and outline two relatively slow-flowing 11sticky spots” near the confluence of BIS and MacIS.

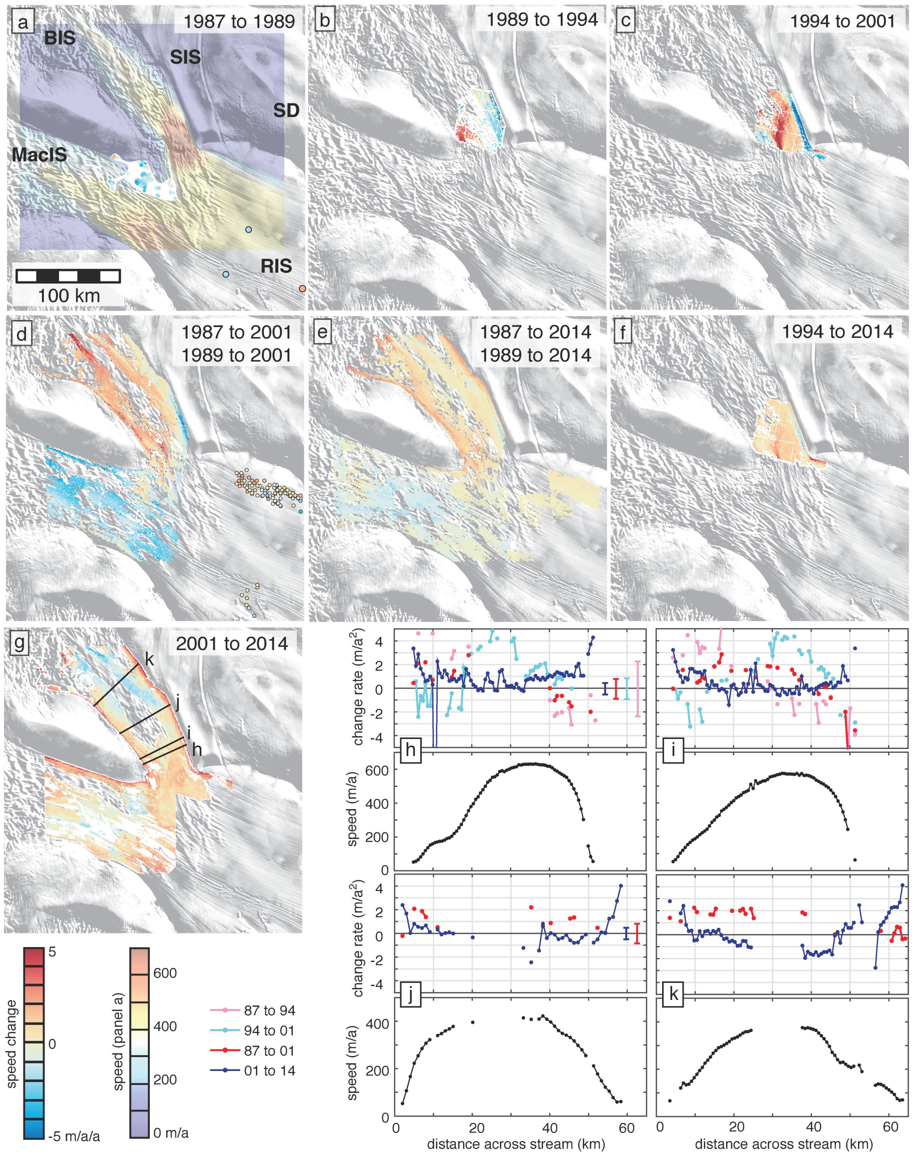

Figure 2. Speed changes over the intervals in Table 1. The 1987 to 1989 comparison on the ice shelf uses data from the Ross Ice Shelf Geophysical and Glaciological Survey [*Thomas et al.*, 1984]. Speed from Landsat 8 is rendered as a color map in panel a. High shear bands are show as grey contours in panel b. Color map scales are shown at the lower left. Rates of change and ice surface speed along cross-sections through BIS are shown in panels h to k. The black lines across BIS in panel g show the locations of the sections, from the downstream-most in panel h to the upstream-most in panel k. Errors on the rates of change are shown as bars at the right of panels h and j. Each map is underlain by an extract from the MODIS Mosaic of Antarctica.

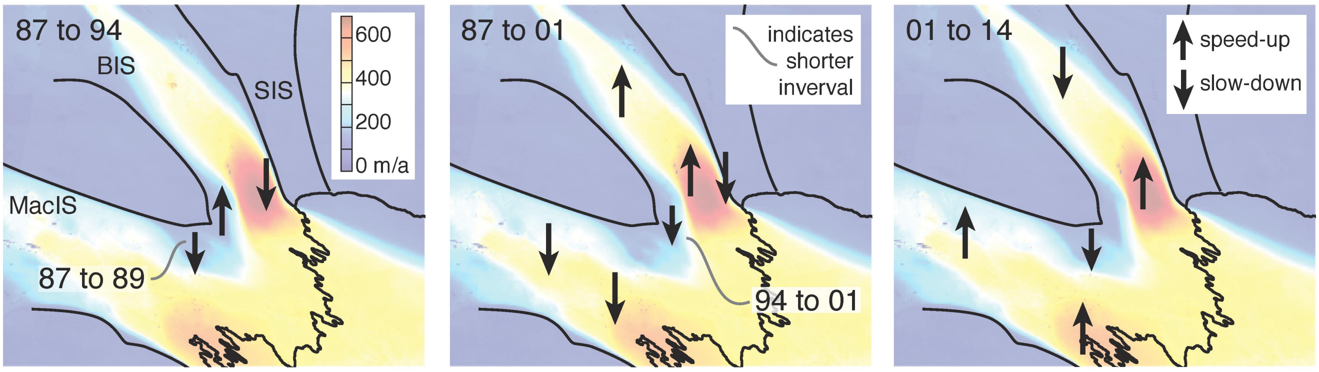

Figure 3. Summary of flow change events over the comparison intervals. An upward arrow indicates increased speed and a downward arrow indicates decreased speed.

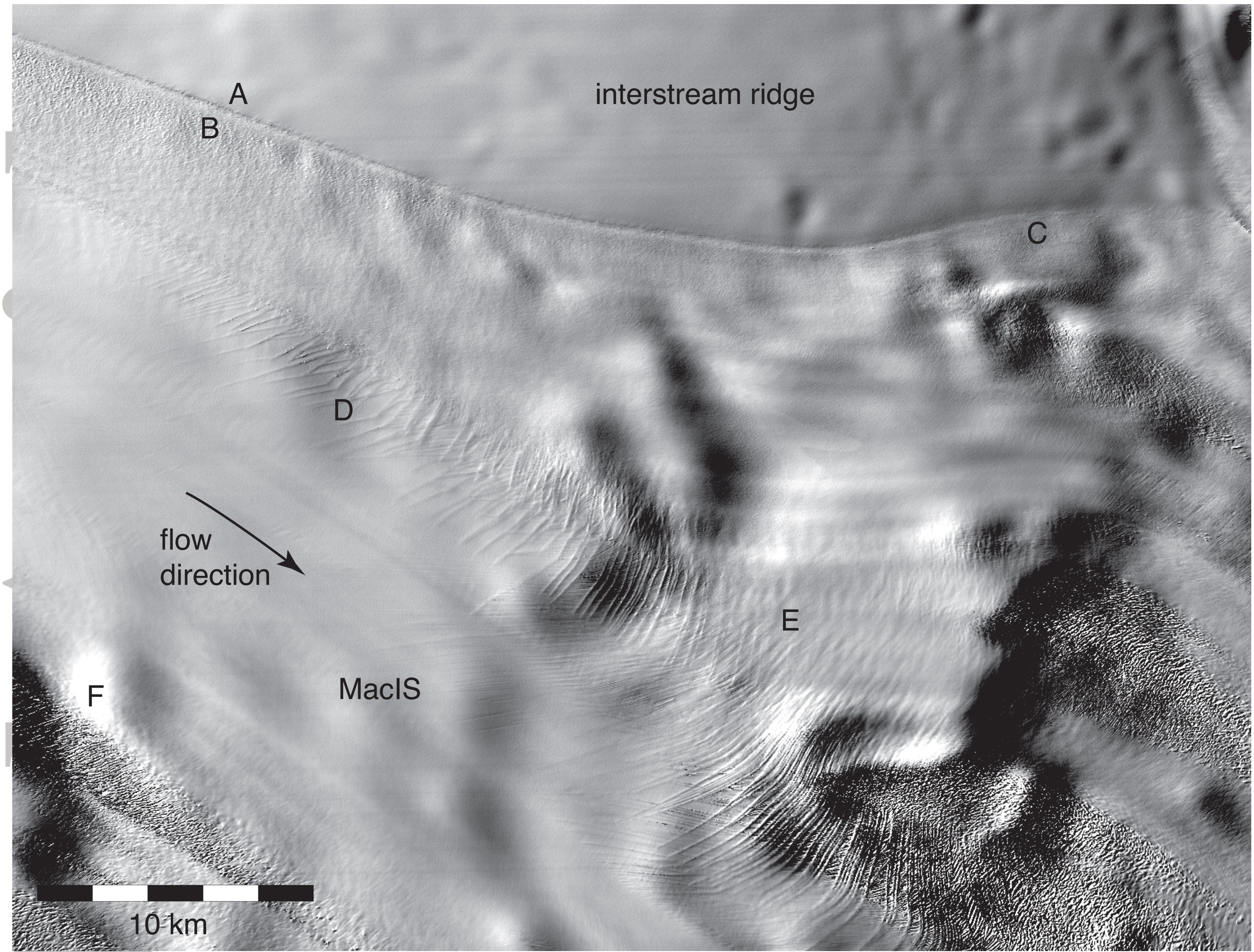

Figure 4. Crevasse features on the southern margin of MacAyeal Ice Stream include A: en echelon hook-shaped fractures at the stream/ridge boundary, B: chaotic zone, C: partially snow-covered abandoned chaotic zone, D: transverse fractures, and E: changing cross-cutting relationships. The mottled region between C and E is recently fast flowing, now slow flowing ice. F: mid-stream crevasses due basal relief or increased traction at that location. Greyscale detail from Landsat 8, path 007, row 119, 29/01/2015.

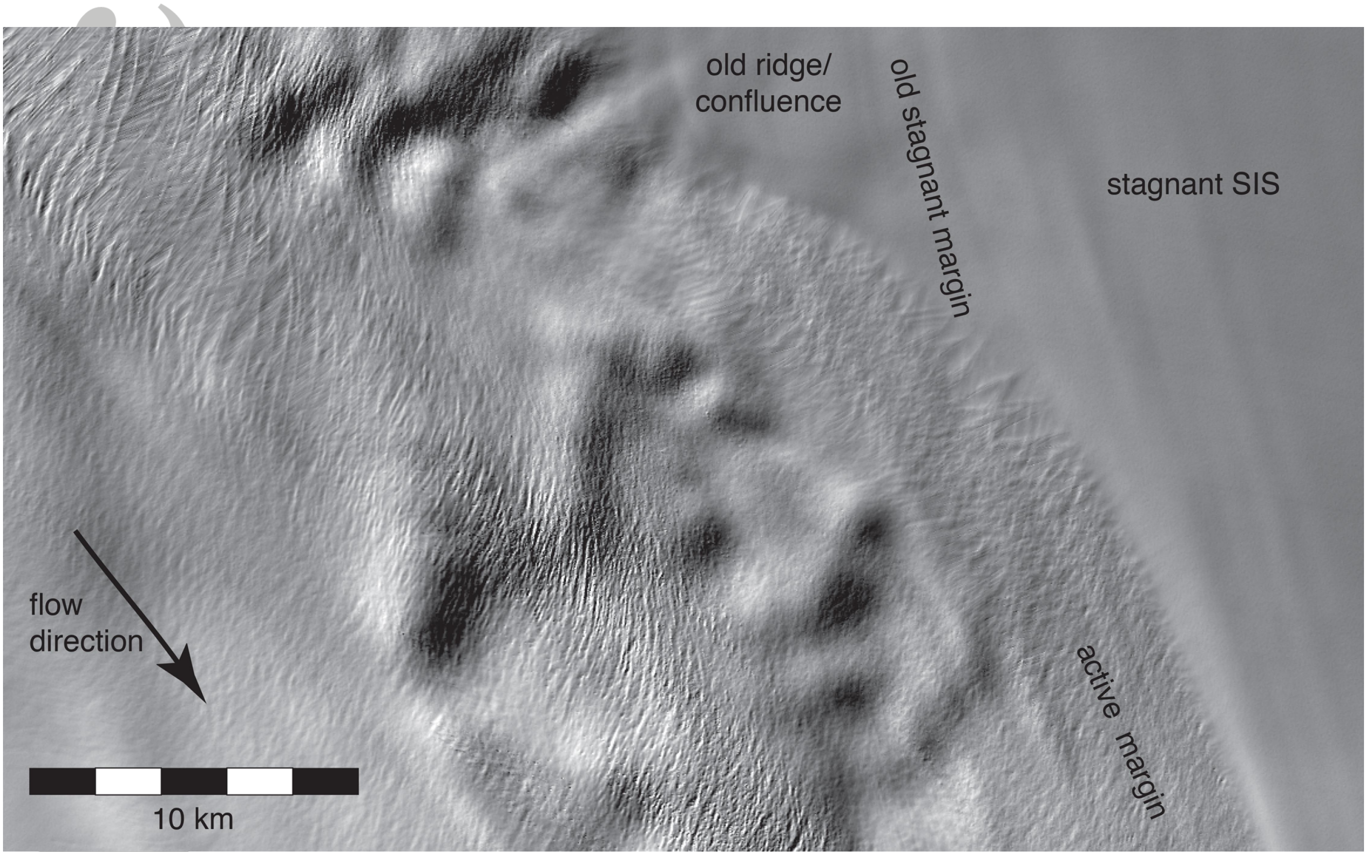

Figure 5. Changing shear margin near the former confluence of SIS and BIS. The heavily crevassed region inboard of the ice stream margin was slowing prior to our 2001 observations and sped up between 2001 and 2014. Greyscale detail from Landsat 8, path 007, row 119, 29/01/2015.