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Flow of the Amery Ice Shelf and its Tributary Glaciers

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Abstract

The Amery Ice Shelf (AIS) is a major ice shelf that drains approximately 16% of the East Antarctic Ice Sheet [1]. Here we use a sequence of visible spectrum Landsat7 satellite images to track persistent surface features over the southern portion of the AIS and its three major tributary glaciers. A spatially incomplete velocity field is calculated by comparing the distances features have moved between image pairs. Key features of the flow field including the vorticity and strain rate distributions are discussed. Our velocities agree with results from recent compilation of satellite derived velocities and available Global Position System (GPS) measurements. To assess change, we compare the yearly average velocities from image pairs in 2006 and 2010 over the study region. We find the velocities show minimal changes with the exception of the Mellor Glacier which has increased.

Introduction

The contribution of Antarctica to global sea-level change over the next century, and beyond, remains poorly constrained [14]. The mass balance comprises input from precipitation and output as ice discharge across the continental margin, which ultimately ends up in the Southern Ocean through iceberg calving or direct melting of the underside of floating ice shelves [11]. There are substantial uncertainties in the present and future values of both input and output.

The majority of Antarctic ice is discharged via outlet glaciers and ice streams which flow into ice shelves. Ice shelves are floating ice that has flowed from the ice sheet into the ocean. The region where the ice begins to float is called the grounding zone. As ice flows across an ice shelf velocity usually increases from the grounding zone to the edge of the ice shelf and is locally independent of the depth of the ice. As the ice begins to float, the reduction in basal stresses allows the ice to accelerate and thin. Heat transfer from the underlying ocean can melt ice from the bottom of the ice shelf, further thinning the shelf. Where the ice comes into contact with land at the margins, or regrounds, the increase in drag can slow the ice shelf flow. These back-stresses buttress the flow of upstream glaciers [4] regulating the flow of ice from the continent. Ice shelves are sensitive to the underlying oceanic conditions, especially through latent and sensible heat processes, and are therefore an important link between oceanic changes and Antarctic ice sheet dynamics and sea-level [11].

Monitoring the velocity of the ice shelves and their tributary glaciers is important for diagnosing the response of ice to changes in forcing. Velocity data can be combined with ice thickness across the grounding zone to provide information on ice discharge. Strain rates and vorticity can be used to investigate the dynamics of the flow. The longitudinal strain rate gives insight into the way the velocity changes along the flow and may reflect influences of features beneath the ice. The shear component of the strain rate highlights the localisation of shear stresses at the margin of the flow. Vorticity displays a combination of rotation in flow direction and strong shear deformations.

The AIS is one of the largest ice shelves bordering the East Antarctic Ice Sheet. The Lambert, Mellor and Fisher Glaciers are the primary tributaries that flow into the AIS (Figure 1).

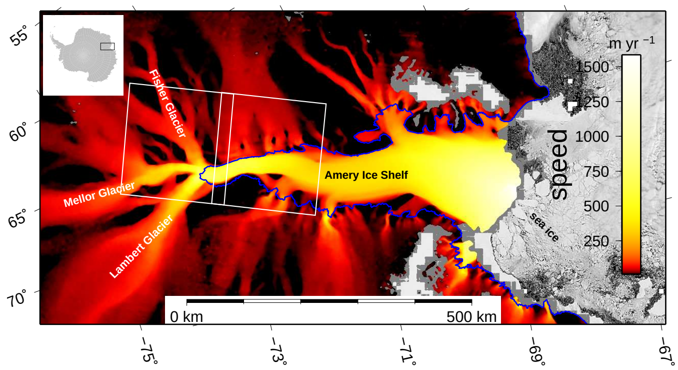

Figure 1: Ice velocities for the AIS from the MEaSUREs dataset [10]. The boxes overlain on the image are the locations of the Landsat7 images studied herein. The ASAID grounding zone [2] is shown in blue. The location of the AIS in Antarctica is given by the inset.

In this paper we calculate the velocities, strain rates and vorticity across AIS and its tributaries by tracking features between pairs of Landsat7 satellite visual imagery, with successive pairs acquired in both 2006 and 2010. The velocities are compared with those derived from an existing Interferometric Synthetic Aperture Radar (InSAR) analyses and from *in situ* GPS data. The possible changes in velocity between 2006 and 2010 are investigated over the study region.

Background

Previous velocity measurements have been made using a range of techniques. The first precise velocity and strain rate measurements were conducted in 1968-1970 by terrestrial tellurometer surveys [3]. GPS data collection commenced in 1988, with ice movement measured for the years 1988-1991, 1995 and 1997-1999 [9]. The 1968-1970 data was re-analysed and compared to the GPS measurements and it was found that on average, the velocity of the AIS decreased by 0.6% over the 30 year period [9]. In contrast to such point observations, satellites offer broad coverage and simultaneous measurements. A number of satellite based InSAR studies cover various epochs post 1992 [16, 7, 6, 17, 10]. InSAR studies show that the velocity is approximately 800 m/year across the grounding zone, it then decreases, which is unusual for ice shelves, to a minimum of approximately 300 m/year and then increases to approximately 1300 m/year near the oceanward margin [16, 7, 6, 17, 10]. The MEaSUREs analyses and database is a recent study that presents the velocity from 2007 and 2009, that highlights the unusual flow regime [10](Figure 2).

InSAR technique is reliant on the interferometric measurement of phase change of a reflected signal as observed between a pair of SAR images. This phase change is a measure of the displacement of a ground surface reflector with respect to the orientation of the satellite acquisition geometry ('look' angle)[5].

While InSAR offers the advantage of penetration through clouds, it often requires the use of (frequently uncertain) datasets such as firn depth and topography derivatives to derive ice velocities [10]. Feature tracking using visual images only sees surface features, but is impeded by cloud cover. The advantage of this technique is it can offer longer time series and does not rely on other datasets to derive its velocity.

Methods

The Landsat7 satellite was launched in 1999 with a Enhanced Thematic Mapper Plus (ETM+) instrument including 15m spatial resolution panchromatic band imagery. The satellite has provided information continuously since its launch, however, on May 31, 2003 the Scan Line Correlator (SLC) in the ETM+ failed. This failure causes the ETM+ images to have data gaps aligned normal to the direction of satellite motion and these are more significant towards the edges of the images [15].

Data

This study uses panchromatic image pairs from the Landsat7 satellite covering the southern AIS and its tributary glaciers acquired over 2005/06 and 2010/11 (Figure 1, Table 1). Temporal change is investigated by differencing the calculated velocities between the 20005/06 and 2010/11 image pairs (Table 1).

Table 1: The Landsat7 images used in the analysis

Path	Row	Date Image 1	Date Image 2
128	111	11/12/05	30/12/06
128	112	12/01/06	30/12/06
128	111	07/01/10	10/01/11
128	112	07/01/10	11/02/11

GPS data (Table 2) used for validation were acquired in 1991 [8] and 1997-2000 (unpublished) as part of various campaigns conducted over the AIS (see Figure 2 for locations).

Analysis

The surface velocity of flowing ice can be measured by calculating the displacement of persistent surface features (such as crevasses) between pairs of images [13]. Suitable pairs of images are pre-processed to enhance surface features (herein via a local contrast enhancement filter). The displacement of surface features is then calculated using the Fast Fourier Transform (FFT) based IMCORR software package [13] (for this study using 64×64 pixel reference sub-images corresponding to 960×960 m), and the resulting displacement field is converted into a velocity field. Here we use a modified version of IMCORR [15] which permits the FFT processing of images containing data gaps by filling these regions with random data drawn from the intensity histogram of the valid data regions of each image. The IMCORR analysis includes an estimate of the correlation errors, which for this analysis had an average value of around 0.5 pixels, corresponding to a maximum error of 8.22 m yr^{-}1.

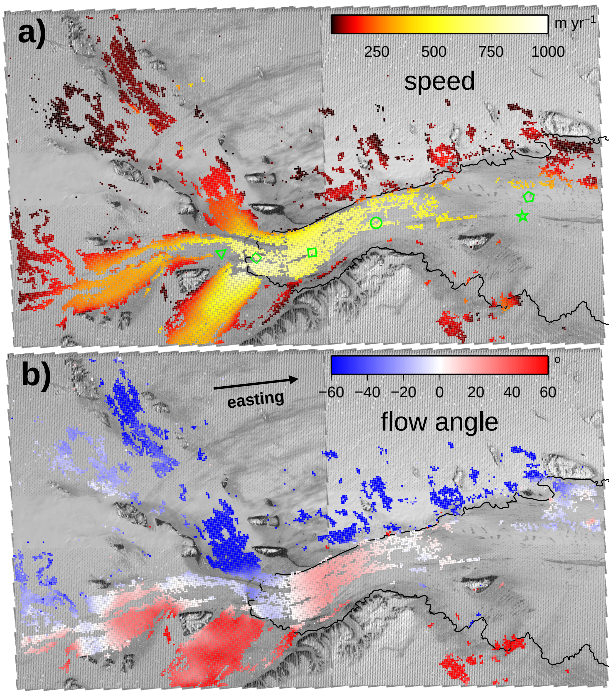

Figure 2: (a) Speed (m/year) and GPS locations (b) Flow angle relative to polar stereographic easting direction (indicated) in an anticlockwise positive sense. GPS locations (Table 2) are shown on (a): TS06 (triangle), TS05 (diamond), v5 (square), v3 (circle), GA29 (star) and GA35 (pentagon). See electronic version for colour Figures.

To account for mis-registration of the image pairs, the trimmed least squares [12] displacement of nunataks (exposed rock outcrops) is first subtracted from the displacement field, before dividing by the time difference between the two images to obtain the velocity field. Finally to reduce noise in the calculated velocity field, the velocity field is binned onto a 1×1km grid via trimmed least squares.

Results and Discussion

Velocity

We show the speed and flow angle across the study region in Figure 2. The coverage of data obtained is quite comprehensive upstream, but sparser downstream on the ice shelf. This is due to surface melt features on the ice that can change between years. The melt features that evolve over time and therefore have relatively weak correlations between images. Additionally as they refreeze and get covered with snow, the change in albedo washes out smaller nearby features that may otherwise have been able to be tracked. Further pre-processing may be able to expand the spatial coverage into these regions. The striping seen on the images is due to the SLC failure.

Our image based velocities overlap with GPS locations (Figure 2(a), Table 2) and the nearest valid data was compared to the GPS velocities. The GPS velocities agree closely with our calculated velocities when you consider that our data and the points are not co-incident and the GPS are from a different epoch.

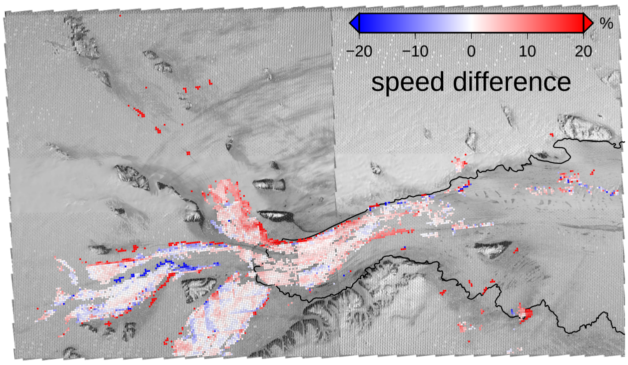

Figure 3: Difference in velocity between MEaSUREs [10] and calculated velocities.

The velocities calculated are compared to MEaSUREs [10] (Figure 3). A 900m offset in the northing coordinates was estimated between our measurements and MEaSUREs. The velocities between the two studies are good agreement for large portions of study region, however our results show a faster ice flow for the Fisher Glacier than the InSAR data. There is disagreement in the Mellor Glacier, particularly where our technique appears to overestimate on the eastern margin, and underestimate on the western margin, with respect to MEaSUREs. The symmetry of the changes either side of the glacier indicates a systematic error. This could be due a registration offset issue, or errors due to spatial gradients over both of the velocity fields. At this stage we are also unable to exclude error in MEaSUREs.

Strain Rates and Vorticity

The strain rates and vorticity of the AIS have been calculated from our 2006 velocities. We present the longitudinal and shear strain rate components in reference frames aligned with the local flow direction (i.e.$\hat{V} \cdot \dot{\varepsilon} \cdot \hat{V}$ and $\hat{V} \cdot \dot{\varepsilon} \cdot \hat{T}$, where $\dot{\varepsilon}$ is the strain rate tensor, $\hat{V}$ is the unit vector in the flow direction and $\hat{T}$ is unit vector normal to the flow).

The longitudinal strain rates shown (Figure 4(a)) illustrate the increasing speed of flow down the tributary glaciers and highlight zones where this occurs. The transition near the grounding zone to a compressive regime in the southern part of the AIS is also visible. For example, the peak velocity of the Lambert as it crosses the grounding zone is approximately 800 m/year, and begins to decrease as it flows down the ice shelf.

The local shear strain rates (Figure 4(b)) show the strong simple shear deformation at the margins of the glaciers and the ice shelf. There is a clear transition to more plug-like flow in the ice shelf due to the absence of basal drag. These zones of simple shear are also evident in the vorticity field (Figure 4(c)) but vorticity also contains the rigid body rotation of the flowing ice. Where the flow angle (Figure 2(b)) changes rapidly along the stream lines, rotation can reinforce or decrease the shear deformation contribution to vorticity as can be seen by comparing Figure 4(b) and Figure 4(c) with reference to Figure 2(b). In particular the vorticity is high where the central flow of the Lambert Glacier turns rapidly after it crosses the grounding zone while the general westward turning of the southern section of the AIS leads to a contrast with the narrow band of shear adjacent to the western margin.

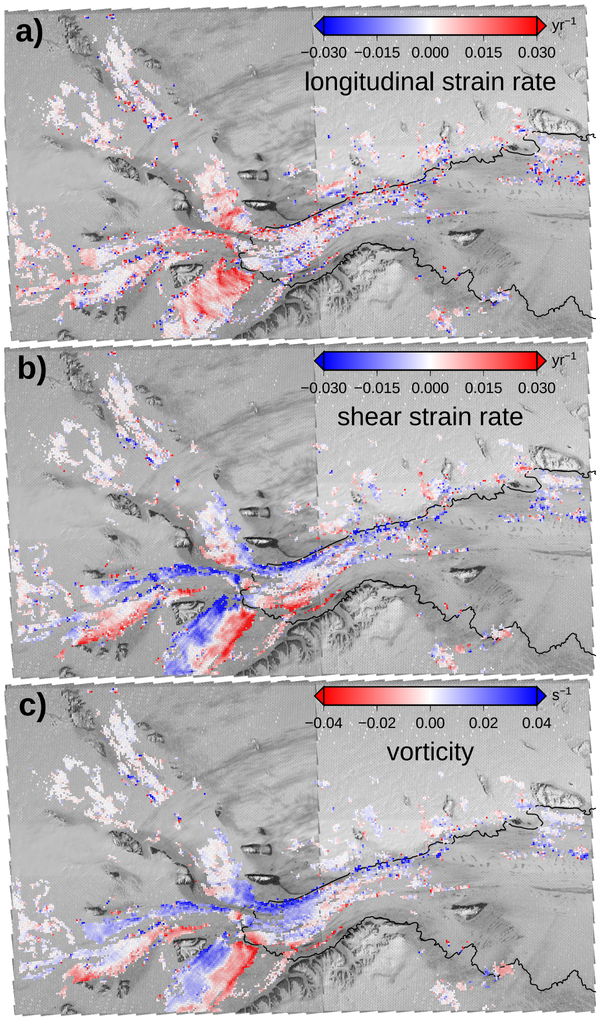

Figure 4: (a) The longitudinal strain rates shown are aligned along the flow direction (b) Shear strain rate (c) Vorticity.

Temporal Change

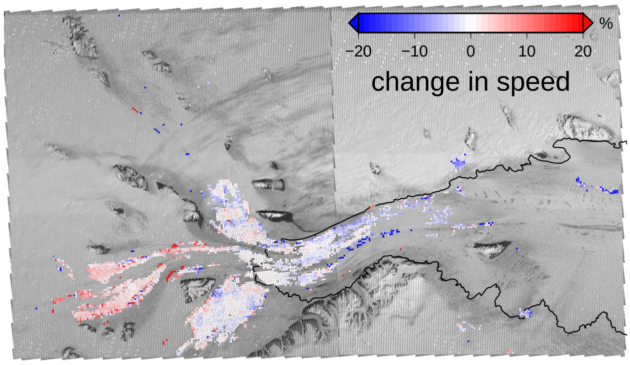

Figure 5: The change in average speed between images pairs for both 2006 and 2010.

Possible temporal change was investigated for the Fisher, Mellor and Lambert Glacier, the flow over the grounding line and

Table 2: Comparison of Velocities (m/year) for GPS locations

Station	Lat	Lon	GPS Velocity	Nearest point Velocity	Distance (m) Velocity	MEaSUREs [10]
TS06 (2000/01)	-73.40	66.68	496	362	5562	477
TS05 (2000/01)	-73.25	67.07	768	757	485	745
v5 (1997/98)	-72.98	67.48	715	681	523	657
v3 (1997/98)	-72.61	67.57	623	667	591	609
GA29 (1991)	-71.92	68.67	382	408	16552	365
GA35 (1991)	-71.84	68.43	395	399	5795	376

directly downstream on the ice shelf.

The preliminary results show that the Fisher and Lambert Glaciers are close to steady state, while the Mellor Glacier shows a widespread accelerations of about 2–4%. The velocity along the AIS shows a possible decrease, but the sparseness of the downstream velocities limits this assessment. Additional work will be required to validate these changes, with analysis of nearby satellite paths and rows available to investigate a larger spatial extent of the glaciers and ice shelf, as well as provide a greater temporal span. Assessing temporal change further north will be difficult with this technique as an increase in melt features, cloud cover and decrease traceable features limit the effectiveness of this technique.

Conclusions

We have computed a new partial velocity field for the AIS and its tributaries. Our results generally show close agreement with those of other satellite techniques and the limited GPS sites available. Further investigations will increase the spatial and temporal resolution across the Amery Ice Shelf and its tributaries, and attempt to confirm changes seen across the system, in particular possible accelerations in the Mellor Glacier.

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