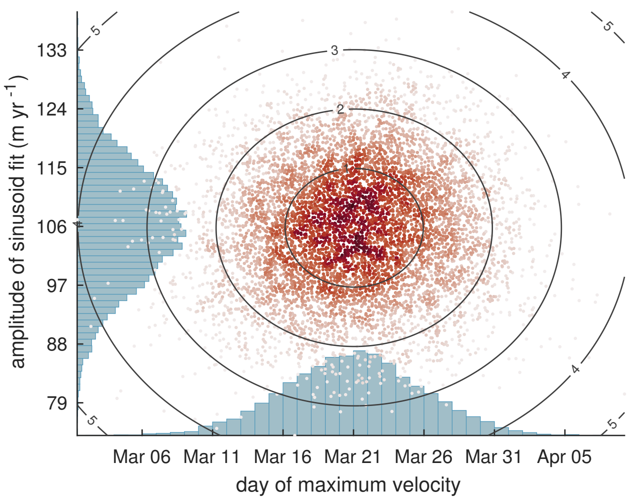
We thank Alex Gardner and our anonymous reviewer for their thoughtful reading of the manuscript and for their suggestions that have led to a number of minor to critical improvements. Both reviewers noted that original manuscript was well written, logically organized, and that our analysis was accurate, thorough, and easy to follow. As such, we have made an effort to keep the original text untouched wherever possible, but not at the expense of fully addressing the reviewers' concerns.

Both reviewers stated clearly that the largest issue of concern regarded our use of a sinusoid to describe measurements of subannual velocity variability at TIS. Reviewer 1 felt there is "no justification for assuming a nice seasonal sine wave" and that providing metrics of its amplitude and phase is "unreasonable" and has "little scientific or practical value." Dr. Gardner was also skeptical due to appreciable noise in the MODIS velocity measurements used to estimate the sinusoid, and more importantly, Dr. Gardner pointed out our failure to present uncertainty estimates for the parameters of the sinusoid fit. We appreciate this feedback, as it brought to our attention the need to clarify and add analytical support for one of the key aspects of our paper.

In particular, we have followed Dr. Gardner's suggestion and added an Appendix in which we use a bootstrapping technique to estimate uncertainty in the amplitude and phase of the sinusoid fit to noisy MODIS data. The results are shown in this new figure, which now appears in the Appendix:



The figure shows the amplitudes and phases of sinusoids fit to 10,000 random resamplings of the MODIS velocity data. The intensity of the red color indicates data density, and distributions of each parameter are shown as histograms. Contour intervals and axis labels are shown at 1σ intervals.

The remarkably narrow skews (i.e., low uncertainty) of the amplitude and phase parameters in the figure above show that the sinusoid is robust and provides a direct response to both reviewers' concern of whether or not the sinusoid is justified by the data. To this question we state conclusively that yes, the sinusoid is justified by the data. The sinusoid is not behavior we have assumed—it is behavior we have measured.

The reviewers might be reasonably concerned that while a sinusoid fits the data well, it will not describe any higher-frequency behavior that occurs in nature. That is certainly true, but just as a linear least-squares fit provides the simplest, most robust assessment of a trend over time, a sinusoid provides the simplest, most robust assessment of cyclic behavior.

We do not attempt to model higher frequency behavior, nor would our data allow it. The MODIS data represent displacements over periods of 92 to 182 days that span the entire calendar year, which together meet Nyquist's requirement for representation of a sinusoid with a 365 day period, but do not allow higher-frequency investigation. We note here, that although we cannot detect abrupt velocity events with the MODIS data, the MODIS velocity measurements do still provide a record of all accelerations and slowdowns (albeit lowpass-filtered) by providing the sum total ice displacement between image pairs.

Our overall conclusions do not hinge on the representation of the MODIS velocity data as a sinusoid, but we do find it prudent and insightful to try to characterize the amplitude and phase of the seasonal variability, to the best that the data will allow. We have responded in further detail to the reviewers' specific comments on this point below. We have also responded to all other comments and we have incorporated most of the reviewers' suggestions, as documented below. The original reviewer comments appear in *blue italics* and our response is provided in upright black text. We believe the changes we have made in response to the reviewer feedback have resulted in a stronger, clearer, and more scientifically sound paper.

RC1: Anonymous Referee #1:
General comments:
Greene et al. investigate velocity variations on the Totten Ice Shelf and examine the physical mechanisms that may cause these variations. Overall, the authors have succeeded in providing a denser velocity time series than previous studies and a thorough analysis of the top candidates for causing ice shelf flow variations. The paper is well written and figures are clear and appropriate. The title, abstract, and general organization are accurate, thorough, and logical.

Some revision is needed to provide consistent messaging across the paper regarding the temporal limitations of the data. The authors emphasize the importance of capturing seasonal variations, but do a somewhat poor job of acknowledging and discussing the seasonal limits of their own study. Figures 2 and 7 make this point nicely. The authors have captured more temporal coverage than previous studies, but the data still has large time gaps. There is, for example, no data to confirm that speedup begins in October – that is simply when the measurements begin in earnest and show a continued speedup from there. Similarly, I see no justification for assuming a nice seasonal sine wave as the "mean" seasonal behavior (page 5, line 10). The authors do not refer to other studies with data that might fill their time gaps or other evidence for this assumption of time evolution. Studies of seasonal velocity in Greenland outlet glaciers show a wide variety of annual patterns, including sudden slowdowns and speedups as well as more gradual *changes. Why couldn't more dramatic events occur during the data gaps for Totten Ice Shelf? The authors acknowledge this on page 13, paragraph 2, but this point should be raised earlier and must be clearly reflected in the whole paper. Other instances where the overall paper obscures a point made at a specific spot in the paper are highlighted below – these need to be addressed to craft a cohesive full manuscript.*

In response to our measurement of cyclic behavior, we point to the discussion at the top of this document, and we discuss the more detailed concerns below.

Detailed comments (by page/line number):
1/17. Briefly mention what the "more complex picture" is.

The sentence in question previously read,

Short-term observations have identified Totten Glacier and its ice shelf (TIS) as thinning rapidly (Pritchard et al., 2009, 2012) and losing mass (Chen et al., 2009), but longer-term observations paint a more complex picture of interannual variability (Paolo et al., 2015; Li et al., 2016; Roberts et al., 2017; Greene et al., 2017a).

Following the reviewer's suggestion we have added a brief mention of what is meant by a "more complex picture." The sentence now reads,

Short-term observations have identified Totten Glacier and its ice shelf (TIS) as thinning rapidly (Pritchard et al., 2009, 2012) and losing mass (Chen et al., 2009), but longer-term observations paint a more complex picture of interannual variability marked by multi-year periods of ice thickening, thinning, acceleration, and slowdown (Paolo et al., 2015; Li et al., 2016; Roberts et al., 2017; Greene et al., 2017a).

3/17+. It's odd to have data separated only into spring or autumn. What about summer and winter?...

The paragraph in question reads,

To understand the spatial pattern of TIS seasonality, we developed characteristic velocity maps for spring and autumn separately...The resulting difference between spring and autumn velocities is shown in Fig. 1.

There are myriad ways to look at these datasets, and indeed, our analytical process involved slicing the data in many different fashions that proved less insightful than the analyses we ultimately included in the manuscript. For our purposes the spring/autumn comparison hardly seems odd, as it provides a spatial overview of the difference in ice speeds between the fastest time of the year and the slowest time of the year.

...The authors talk about all different seasons throughout the manuscript, so it becomes unclear what season is what and how the data fit into those seasons. Clarity is needed on what spring/summer/fall/winter means and what data fits into each season.

We have stated in the text that for the GoLIVE data,

Spring velocity was taken as the mean of 76 velocity measurements whose image pairs were obtained between June 16 and December 15. Autumn velocity was taken as the mean of 67 velocity fields from images obtained during the remainder of the year.

Elsewhere in the text, we have been careful to discuss the results with an appropriate level of temporal precision, stating that for the GoLIVE data,

The terminal ~50 km of TIS accelerates each year from spring to autumn, then slows during the winter.

Given the well-constrained definition of the spring and autumn velocity data, we feel that this statement gives a physical description of the observed behavior and is unlikely to lead to any confusion. Later in the text we state that

Everywhere beneath the ice shelf, basal melt rate reaches a maximum in autumn and a minimum in the spring.

And we support this statement with a clearly marked figure showing the time series of basal melt rates, that the reader may inspect and should thus leave no room for confusion. The section on basal melt rates concludes,

Thus, it is unlikely that the seasonal cycle of basal melt could explain the observed pattern of spring-to-fall acceleration of TIS.

And again, we feel this statement is given with an appropriate level of precision.

In the Discussion section, we state that,

In the GoLIVE dataset and in MODIS-derived velocities, we find that the outer TIS accelerates each year between spring and autumn.

We feel that this statement is accurate and clear as it stands.

The process of scouring the manuscript for potentially misleading language helped us identify this sentence:

We find that the outer TIS accelerates each ***spring****, likely in response to lost buttressing upon the breakup of rigid sea ice at the ice shelf terminus.*

which we have modified into the following, more conservative statement:

We find that the outer TIS accelerates each ***year****, likely in response to lost buttressing upon the breakup of rigid sea ice at the ice shelf terminus.*

Other mentions of seasons include this statement:

The seasonal variability we observe at TIS suggests that measurements acquired in the spring likely underestimate, and autumn measurements overestimate, the mean annual velocity of the ice shelf.

which we feel is accurate and appropriate. Seasons of the year do come up a few other times in the manuscript, but only in general contexts where a higher level of precision is not warranted.

3/26. Indicate the location of the 'mid-shelf ice rumple' in Figure 1.

We have indicated the location of the mid-shelf ice rumple in Figure 1 by including the following text in the figure caption:

The black line indicates the grounding line, and includes a grounded ice rumple near the center of the ice shelf (Mouginot et al., 2017b).

5/7. Why is there no overlap in the areas used for MODIS velocities v. GoLIVE velocities?

There is overlap between GoLIVE and MODIS measurements in the sense that Figure 1 shows the presence of a seasonal cycle in the MODIS polygon. We realize there would be some advantages to carrying out the full analysis with overlapping measurements, both for continuity of the time series, and for measurement redundancy. However, given the different strengths and limitations of the MODIS and GoLIVE datasets, we found it beneficial to optimize the measurement areas separately for each sensor. In particular, the 15 m resolution of Landsat 8 allows us to measure a small, responsive area of the ice shelf, close to the ice shelf front, where the seasonal signal is the strongest. The 250 m MODIS pixels require a larger template chip for a unique fingerprint, and a longer time between images for reduced uncertainty in estimates of velocity. These two characteristics of MODIS mean the search area must be quite large, which prevents measurements close to the ice shelf front. In addition, the high noise of the MODIS displacement measurements means we must average over a large area to increase the signal-to-noise ratio. Thus the GoLIVE measurement area is more suited to capturing the large amplitude seasonal cycle close to the ice shelf front, whereas the MODIS dataset captures the larger-scale behavior of the ice shelf. Accordingly, these measurement areas provide two independent measures of the seasonal dynamics of TIS. We describe these points in the first paragraph of Section 2, which states,

...Each image dataset was processed separately, using different feature tracking programs, and the resulting time series represent two independent measures of TIS velocity. The 15 m resolution of Landsat 8 permits precise displacement measurements over short time intervals, but the relatively brief four-year Landsat 8 record and limited number of cloud-free images inhibits our ability to separate interannual velocity changes

from seasonal variability. The MODIS record contains many cloud-free images per year from 2001 to present; however, the 250 m spatial resolution of MODIS images limits measurement precision where ice displacements are small between images. Thus, the two image datasets each offer incomplete, but complementary insights into the seasonal dynamics of TIS. Processing methods for each dataset are described below.

5/9+. The authors state here that 'the timing of springtime acceleration cannot be accurately determined for any given year'. Yet, language in other parts of the manuscript suggest that it can (e.g., in Figure 7 caption – 'begins with the breakup of landfast sea ice'). The whole manuscript needs to reflect the limits of the data.

We have tried to clear up any confusion by specifying that our approach is to analyze the characteristic seasonal behavior of TIS rather than attempting to attribute particular ice shelf acceleration events to specific transient causes. To alleviate any confusion, we have clarified the section mentioned by the reviewer, which now reads,

...subannual template matching applied to 250 m resolution MODIS images produces such noisy velocity estimates that the timing of springtime acceleration cannot be accurately determined for any given year. However, by combining data from all years we can assess the characteristic cycle of ice shelf acceleration and slowdown that occurs throughout the typical year.

and we have edited the caption of Figure 7 to clarify that the

characteristic springtime acceleration begins with the breakup of landfast sea ice.

In the Discussion Section 6.2 we do discuss velocities obtained by Li et al. that were specific to the years 2009 and 2010, but we do not compare our velocity measurements to theirs for those years or any other specific years. We found no other instances in the manuscript that could imply analysis of velocities for any given year.

6/1-3. Here the authors use the seasonal sine wave approximation to give information about seasonal cycle amplitude, maximum, and minimum. The problems with assuming this seasonal cycle are mentioned in the general comments. Thus, it's unreasonable to give these metrics – they have little scientific or practical value.

We have not assumed sinusoidal behavior—we have measured it. And by fitting sinusoids to 10,000 random subsamplings of the measurements, we have confirmed that no matter how you slice it, there is periodicity at the 1 yr^{-1} frequency, and its timing and amplitude are consistent.

To ensure that readers are not misled into thinking that we have simply assumed sinusoidal behavior, we have checked the manuscript for any instances of misleading language, and we have added the following clarifying statement the section that describes the MODIS velocity data:

The sinusoid provides a measure of periodicity at the 1 yr^{-1} frequency and matches observations to a root-mean-square error of 93 m yr^{-1}.

In the General Comments section, the reviewer makes the point that "in Greenland, outlet glaciers show a wide variety of annual patterns, including sudden slowdowns and speedups as well as more gradual changes," and goes on to ask, "why couldn't more dramatic events occur during the data gaps for Totten Ice Shelf?"

There is no doubt that Totten's dynamic seasonal cycle is more complex than a simple sinusoid, but just as a linear least-squares fit can provide a first order of understanding of long-term trends (e.g., Pritchard et al., 2009, Pritchard et al., 2012 for linear trends applied to surface elevations—work that has motivated nearly a decade of Antarctic science), a sinusoidal least-squares fit provides a first-order understanding of cyclic behavior.

Regarding the potential for sudden slowdowns and speedups, such dramatic events may occur at Totten, and if they do, we have captured them. With MODIS we have measured total displacements over 92 to 182 days—In other words, we measured the displacements associated with every abrupt speedup and slowdown throughout the year, integrated over time.

Regarding the concern about data gaps throughout the year—there are none. We intentionally allowed up to 182 days temporal separation between image pairs so we could capture all ice movement that occurs at all times of the year. We could show this in Figures 3 and 7 as we do in Figure 2, with horizontal bars connecting the collection times of the image pairs, but with 565 MODIS image pairs, if each bar were a just a few pixels thick, they would clearly cover the entire calendar year with no gaps, but would blend together into an unintelligible mess. Thus, we represent each MODIS measurement as a single dot placed at its central time, but even still, the points cluster. To clear up any confusion, we have added this reminder to the caption of Figure 3:

Velocity measurements are shown at the mean of the acquisition times of their MODIS image pairs.

We disagree with the statement that it is unreasonable, unscientific, and impractical to fit a sinusoid to measurements of total displacement taken over periods of 92 to 182 days. The sinusoid provides a reasonable first-order understanding of the amplitude and phase of velocity variability throughout the year. Given that the large pixels of the MODIS sensor limit our temporal resolution to 92 to 182 days, Nyquist's theorem is quite clear that it would be unreasonable and unscientific to fit a higher-order model to the data. And given that we measure total displacement in each image pair, the sinusoid provides a complete assessment of velocity variability at the 1 yr^{-1} frequency. Thus, stating the amplitude and phase of the sinusoidal behavior we measure is reasonable, scientific, practical, and meaningful.

6/6. I recommend against referencing Zwally et al. 2002. While it was the initial paper *that set off the wave of research on the 'Zwally effect', it is now a poor reference for understanding the complex relationships between hydrology and glacier flow. In fact, Tedstone et al. (Tedstone, A. J., P. W. Nienow, N. Gourmelen, A. Dehecq, D. Goldberg, and E. Hanna (2015), Decadal slowdown of a land-terminating sector of the Greenland Ice Sheet despite warming, Nature, 526(7575), 692–695, doi:10.1038/nature15722.), which demonstrates a long-term slowing on land-terminating areas despite increased melt, is a better reference at this point...*

The Tedstone et al. 2015 paper is an excellent paper that found long-term glacier slowdown in the presence of increased surface melt. Their suggested mechanism for the slowdown is that more meltwater at higher elevations allows efficient drainage systems to develop farther into the ice sheet interior. Although Tedstone et al. tracked ice displacements using several hundred image pairs (and in this way is similar to our approach), they properly removed seasonal effects from their decadal trend analysis by limiting image separation times to 352 to 400 days. We seek to understand the seasonal cycle that takes place within those ~365 days, and what effects such a cycle may have on the flow of Totten. Accordingly, we describe hydrological processes that take place over the course of days to months, and we provide references accordingly. The sentence in question begins our discussion of how surface melt can affect glacier flow, and it reads,

Surface melt has been shown to affect the flow of grounded ice in Greenland when surface water drains through moulins or crevasses to the bed, where it alters basal water pressure and allows the overlying ice to accelerate (Zwally et al., 2002; Schoof, 2010; Bartholomew et al., 2010; Andrews et al., 2014).

The findings of Tedstone et al., 2015 do not in any way contradict this statement, and in fact their manuscript directly affirms the 'Zwally effect,' and includes a citation of Zwally, stating that "inputs of surface meltwater...lubricate the ice-bed interface, transiently speeding up the flow of ice (Zwally et al., 2002; Sole et al., 2013)." We feel it is appropriate to give credit to the originator of the idea, but we also reference some of the follow-on work that has brought a deeper understanding of the processes that are most directly related to our paper. Thus, we prefer to keep this sentence unchanged.

...A word of caution on the larger discussion of subglacial hydrology in the manuscript. At times (e.g., this paragraph) there is a clear distinction between the processes of subglacial hydrology that might actually influence the ice shelf v. subglacial hydrology and its influence on grounded ice (which constitute most citations in the paper). At other points, however, this point can feel muddled. Unfortunately, using the 'TIS' acronym does not help and makes it easier for the reader to forget that the study is focused on an ice shelf instead of grounded ice. As the authors go through revisions, please be conscious of keeping the fact that you are looking at ice shelf speeds forefront in the readers' mind.

This point is well taken. We have a vested interest in clarity, and we do not want to come across as careless in our language or in our treatment of the underlying physics. However, while subglacial hydrology is most closely associated with local accelerations of grounded ice, no process occurs in isolation, and when grounded ice accelerates, it most surely influences the flow of ice downstream, though the extent to which local accelerations affect large-scale flow is largely unknown. We also leave open the possibility that surface melt can lead to shear margin weakening, which would primarily affect the flow of the floating ice shelf.

In discussions of theory, it is easy to separate these different processes and we can be quite specific. For example, the paragraph in question states clearly,

Surface melt has been shown to affect the flow of grounded ice in Greenland when surface water drains through moulins or crevasses to the bed, where it alters basal water pressure and allows the overlying ice to accelerate (Zwally et al., 2002; Schoof, 2010; Bartholomew et al., 2010; Andrews et al., 2014). The seasonal velocity anomalies we observe at TIS are strongest near the floating ice front, so it is unlikely that the seasonal variability of TIS velocity is driven by subglacial hydrology on nearby grounded ice. However, the presence of englacial liquid water can weaken ice (Liu and Miller, 1979), and it is plausible that surface melt at TIS could percolate into the ice, weaken shear margins, and allow TIS to speed up as a result of reduced buttressing.

When analyzing the data, we were careful to consider surface melt on grounded ice, the inner TIS, and the outer TIS separately, and we are clear about this distinction throughout the discussion. We have also been careful to separate grounded and floating ice processes in the final Discussion Section 6.1 in which we state,

On grounded ice, seasonal velocity variability often results from surface water draining to the bed, where it can temporarily pressurize an inefficient hydrological system, allowing the overlying ice to accelerate until an efficient drainage system forms or the water otherwise evacuates (Zwally et al., 2002; Parizek and Alley, 2004; Bartholomew et al., 2010). At Totten Glacier, we detect very little seasonal velocity variability on grounded ice, and the onset of acceleration we observe on the floating ice shelf begins well before surface water is detected anywhere in the region (Fig. 7). We therefore rule out the possibility that surface melt is responsible for initiating TIS acceleration each year.

8/19-21. This sentence is confusing and the part about the constant 300 m offset does not make sense.

The section in question previously read,

Seafloor topography was based on the RTOPO dataset (Timmermann et al., 2010), while cavity geometry was inferred from ICESat-derived ice surface elevation above flotation and a constant 300 m thick offset along the central flow line. Between the central flow line and the grounding line, cavity bathymetry was linearly interpolated (see Gwyther et al., 2014, for details).

We have changed the wording to make it more clear, replacing the two sentences above with the following four sentences:

Seafloor bathymetry for the deep ocean and continental shelf was taken from the RTopo-1 dataset (Timmermann et al., 2010). As RTopo-1 does not contain the cavity of TIS, we inferred the cavity geometry. Ice basal draft for the TIS cavity was obtained from ICESat-derived surface elevations, assuming hydrostatic equilibrium and a mean ice density of 905 kg m^{-3} (following Fricker et al., 2001). Water column thickness was obtained by linearly interpolating from 0 m thick along the grounding line to 300 m thick along the central flow line of the ice shelf (see Gwyther et al., 2014, for details).

10/8. Always specify 'sea ice' if that is the subject. Check the full manuscript for this clarification.

We have corrected this ambiguity by specifying "sea ice thickness" in all 10 instances in the manuscript that previously said only "ice thickness."

13/last paragraph (onto next page). This paragraph discusses some specific details of the Li et al. (2016) paper without ever pulling back to the big picture of that paper to discuss this study's overall influence on interpretations of the Li et al. paper. Are the Li et al. conclusions still good ones or should the larger conclusions be reinterpreted? Also, while it's fine to point the reader to these references, try to craft this manuscript to cover all the major points so that reference to the other paper directly is not a necessity to get to the primary points regarding its (re)interpretation. The reader should come away with a sense of the pertinent conclusions of Li et al. and how they may be shifted (or not) – not only an understanding of how very specific details should be considered. This comment can be applied to any previous study the authors want to comment on.

The original manuscript failed to provide an overview of the findings of previous TIS papers before delving into the details that are pertinent to our reinterpretation. We also failed to convey the nuance that although some of the specific velocity measurements presented by Li et al. may have been partly aliased by subannual variability, their overall findings of interannual sensitivity to ocean forcing and their grounding line flux estimates still hold. Following the reviewer's suggestion, we now begin the discussion of previous work with the following two sentences:

Velocity variability at TIS has been investigated in three recent papers that tracked ice accelerations and slowdowns over the past few decades, and each study found that on interannual timescales, TIS dynamically responds to ocean forcing from below. We do not find any evidence that contradicts the overall findings of the previous studies, but in some cases, velocities were measured over periods of less than one year, and may have been aliased by seasonal variability...

We then discuss some of the details of how velocity measurements were obtained and interpreted in the previous studies, and we conclude our discussion of the Li et al. results with the following two sentences:

Despite the seasonal variability we observe near the TIS front, mass balance of an ice sheet is more meaningfully measured at the grounding line, where ice begins to have an impact on sea level. Our results show little subannual velocity variability at the grounding line, thus supporting the grounding line flux estimates by Li et al. (2016).

14/14. Remove 'strength' – this paper does not include a scientific assessment of sea ice strength.

We have taken the reviewer's advice and removed the word strength. The sentence in question previously read,

...TIS is sensitive to environmental forcing on subannual timescales, and its flow is primarily controlled by the presence and strength of sea ice at the TIS front.

The sentence now reads,

...TIS is sensitive to environmental forcing on subannual timescales, and its flow is primarily controlled by the presence of sea ice at the TIS front.

14/20. This final sentence is more declarative than I think the data supports.

The Discussion section previously concluded as follows:

...However, calving front processes can have far-reaching effects on glacier thickness and velocity (Nick et al., 2009), and it is possible that long-term changes in winter sea ice cover (Bracegirdle et al., 2008) could have integrated effects on TIS buttressing: The duration and thickness of sea ice cover each winter controls the total annual buttressing at the ice front, the annual flow of the ice shelf, and potentially the long-term mass balance of TIS and the Aurora Subglacial Basin.

As this wraps up the Discussion section of the paper, we feel it is warranted to stand back and consider the implications of the processes we have reported, but following the reviewer's suggestion we have softened the language and ensured it is qualified with **can**, **possible**, **could**, **if**, and **potentially**. The section now reads:

...However, calving front processes ***can*** *have far-reaching effects on glacier thickness and velocity (Nick et al., 2009), and it is* ***possible*** *that long-term changes in winter sea ice cover (Bracegirdle et al., 2008)* ***could*** *have integrated effects on TIS buttressing:* ***If*** *the duration and thickness of winter sea ice control the total annual buttressing at the ice shelf front, long-term changes in sea ice cover* ***could*** *affect the annual flow of TIS, and* ***potentially*** *the mass balance of TIS and the Aurora Subglacial Basin.*

14/25. Regarding 'may have aliased some previous measurements of interannual variability' – as mentioned earlier, discuss directly what these previous studies say and what the new outlook is after applying the data from this paper.

Following the reviewer's previous recommendation in comment 13/last paragraph above, we have added a section that directly discusses what these previous studies say and what the new outlook is after reinterpreting the previous results with subannual variability in mind.

14/29+. This paragraph mixes interannual basal melt and velocity changes and intra-annual basal melt and velocity change. I agree that the authors have done a nice job of showing how seasonal basal melt variations cannot explain seasonal speed variations, but I don't think the authors have shown that multi-year thickness changes could not play a role in multi-year speed trends.

The confusion here is due to a lack of clarity on our part. The primary culprit may have been the first of the following two sentences, which previously read:

Previous studies have investigated TIS velocity variability and have broadly concluded that interannual changes in ice velocity have been caused by sustained basal melt rate anomalies. Basal melt cannot explain the seasonal velocity variability we observe, because the seasonal amplitude of melt is too weak to produce enough thinning for an observable velocity response...

The intent of the paragraph is to put our findings into context with previous work, but the language in the first sentence above may have inadvertently implied that we don't believe basal melt affects ice flow on interannual timescales. Hopefully this rewrite is a bit more clear:

Previous studies have linked interannual velocity variability at TIS to periods of ice shelf thickening and thinning caused by sustained basal melt rate anomalies. On subannual timescales, however, the seasonal amplitude of basal melt variability is insufficient to produce enough thinning to elicit an observable velocity response...

Typos, etc. (by line number):
2/13. All instances of 'mélange' should have the correct accent added.

The accent has been added for all instances.

3/23. 'Throughout' is more correctly 'during' since there is no winter data to show the timing of speed changes.

Agreed. 'during' is a better word choice, and the change has been made accordingly.

Figures:
Figure 6. In the MODIS images it looks like the sea ice is not in contact with the glacier ice. Is there a shadow effect? Something else? Please explain/clarify.

We have edited the caption of the figure to better describe the sea ice presence the MODIS images. The caption now states, *Five example MODIS images (Scambos et al., 2001; updated 2018) show sea ice fastened to half of the TIS front in May and September, with dashed quadrangles indicating the region of ice concentration averaging and a gold marker denotes the location of the ECCO sea ice thickness time series.*

Figure 7. Specify 'sea ice thickness'.

We have edited the y axis label of Figure 7 to make the 'sea ice thickness' distinction.

RC2: Alex Gardner:
Paper Summary: In this study the authors examine intra-annual changes in the surface velocity of the Totten Ice Shelf (TIS). Velocity measurements are acquired from feature tracking of Landsat-8 (GoLIVE, 2013-2018, 12-112 day separation) and MODIS (ImGRAFT, 2003-2017, 92-182 day separation) image pairs. Fitting a sinusoid to the MODIS velocities, by means of least squares, the authors identify a 106 m/yr fluctuation in surface velocity. From the Landsat image pairs they determine an average spring to fall speedup of 0.8 m/yr. per day. Mapped differences between spring and fall velocities indicate that the summer speedup is concentrated towards the terminus of the ice shelf.

The authors then explore 3 likely causes for the summer speedup (surface melt, basal melt, and changes in sea ice backstress). Examining melt days determined from passive microwave data, the authors conclude the speedup precedes melt onset and therefore surface melt is unlikely to be the trigger for springtime speedup but they acknowledge that it may play a role later in the season. Through a combination of ocean modeling within the ice shelf cavity and simplified ice shelf mechanics the authors demonstrate that seasonal change in basal met rates, that have seasonal amplitudes of >8m/yr. at the grounding line and 3 m/yr. near the terminus, have little impact on rates of ice flow (several orders of magnitude below the observed signal). Lastly the authors explore changes in sea ice concentration and sea ice thickness and postulate that the breakup of fast ice in spring is the most likely trigger for the summer speedup.

Overall Opinion: The paper is well written, has a logical layout, and the analysis is transparent and easy to follow. The subject matter is appropriate for TC and will be well received by its audience. Despite the overall good quality of the manuscript I was left with a few concerns on the conclusions as drawn from the data. I see no barriers to the authors addressing these concerns in a revised manuscript.

We thank Dr. Gardner for his comments and suggestions. Most of the issues he raised were also raised by the anonymous reviewer, giving strong support for our need to fully address them in this revised version of the manuscript. We have addressed these concerns in response to Reviewer #1, so for conciseness we address only the remaining issues below.

1. My most pressing concern is the characterization of the intra-annual variability of *ice shelf surface flow given the limitation in deriving surface velocities from the Landsat and MODIS images; low SNR, observations limited to polar day, and large/variable image-pair time separations. All of these conditions make it challenging to characterize intra-annual fluctuations in surface velocities. To this end I think it would be very valuable if the authors could explore the sensitivity of the least squares parameter fits to the velocity fields. For example: what is the implication of using large image-pair separations? Using bootstrapping can you better quantify the uncertainty in the fit? What does the phase and amplitude look like if you derive parameters on a pixel by pixel basis? How much do fits to the Landsat and MODIS data differ when constrained to the period of overlap? Is a sinusoidal fit justified by the data or should the authors solely focus on the spring to fall speedup?*

We have embraced this suggestion and added a sensitivity analysis section to the paper, in which we use bootstrapping to quantify the sensitivity of the least squares parameter fits to the velocity fields. The analysis is described in our general response at the top of this document, and in our responses to the detailed comments of Anonymous Reviewer #1. We appreciate the suggestion to use bootstrapping, because without it, our analysis may have been interpreted as arbitrary or incidental. By following the sinusoid fitting technique for 10,000 random subsamples of the data, we have shown that our measurements contain robust cyclic behavior of consistent amplitude and timing.

2. It would be very valuable if the authors could provide uncertainties with their estimates. What is the uncertainty of the estimated annual amplitude in velocity? What is the uncertainty in the modeled melt rate and respective response in modeled ice shelf velocity? What are the uncertainties in the estimated velocities and how do these propagate into the model fits (the authors could use bootstrapping to answer this)?

The new Appendix provides an assessment for the uncertainties in the estimates of annual amplitude in velocity. We have also included our uncertainty estimates in the main text, which now states,

The resulting best-fit sinusoid is characterized by a 1601 m yr^{-1} mean velocity, an amplitude of 106±9 myr^{-1}, a maximum velocity on March 21 (±1σ =5 days), and a minimum velocity on September 19 (±1σ =5 days). The sinusoid matches observations to a root-mean-square error of 93 m yr^{-1}. Uncertainty analysis of the sinusoid fit is explored in Appendix A.

Quantifying uncertainty in the modeled melt rates, however, is less straightforward, as the model is forced by reanalysis data and relies on poorly constrained bathymetry as well as a number of parameterized assumptions about friction at the ice shelf base, etc. A thorough description of the model and a discussion of its uncertainties is provided in the Gwyther et al., 2014 reference we have cited in the text.

3. One of the 3 environmental forcings examined as a potential trigger for spring-time speedup is surface melt. Given the very low number of days that experience any liquid water at the surface, I am suspect that there is any liquid water that does not re-freeze *within the first few meters of the firn column. Can the authors provide any support that this is not the case? If not I would suggest removing this section from the paper and simply state that the vast majority of meltwater will refreeze within the firn and therefore it will not impact ice shelf flow.*

In Greenland and in mountain glaciers around the world, surface meltwater can be sufficiently abundant to drain fully to the bed and lead to ice acceleration. Surface melt has not previously been explored at Totten, but we show that it does not play a major role in ice dynamics here, rather than simply assuming it. This finding in itself may be meaningful to anyone wanting to understand what does or does not affect the flow of Totten.

We also note that bed lubrication/pressurization is not the only process by which surface melt can affect ice speed. In Greenland, it has been shown that surface melt must only make its way into crevasses, where it can weaken shear margins without reaching the bed, and lead to ice acceleration. We show that this process is not a primary contributor to seasonal variability at Totten, and again, we feel that this brings meaningful understanding to the dynamics of Totten.

Given the major role that surface meltwater plays in the seasonal variability of glacier dynamics elsewhere in the world, we feel that it is important to report our findings about the role of surface melt for Totten.

4. There are a few places in the manuscript, including the introduction, Section 6.3 and the conclusions, where variability in discharge and its potential aliasing in mass change estimates are presented as the motivation for this work. I don't think this is an appropriate justification. Maybe the authors could simply us the justification that improving understating of glacier mechanics/response to intra-annual changes in boundary conditions is relevant to improving glacier models and thus future projections of sea level rise.

We do mention aliasing in the introduction, stating that

The current best estimates of Totten Glacier and TIS mass budgets have been calculated using a mosaic of surface velocity measurements collected at different times throughout the year (Rignot et al., 2013); however, such estimates have been built on an unconfirmed assumption that ice velocity does not vary on subannual timescales. Where glacier flow varies throughout the year, it is possible that velocity measurements collected over short time intervals may lead to inaccurate estimates of annual mass balance or incorrect interpretation of interannual changes in velocity. Furthermore, most common methods of ice velocity measurement, such as satellite image feature tracking or in-situ GPS measurements taken over the course of a field season, are strongly biased toward summer acquisition and may not accurately represent winter ice dynamics. Wherever seasonal velocity variability exists, it is important to consider how ice velocity is measured, and how the measurements can be interpreted.

Aliasing is not mentioned in Section 6.3, but we do bring it up again in the Conclusions section, stating,

We find that TIS has a characteristic seasonal velocity profile, which could lead to inaccurate estimates of the annual mass balance of TIS, and may have aliased some previous measurements of interannual variability. Annual ice velocity maps are now available covering most of Antarctica (Mouginot et al., 2017c), but interpreting such datasets at TIS and elsewhere requires understanding where ice velocity varies seasonally and by how much. Our results provide context for how and where such velocity mosaics may be used to interpret interannual change at Totten Glacier.

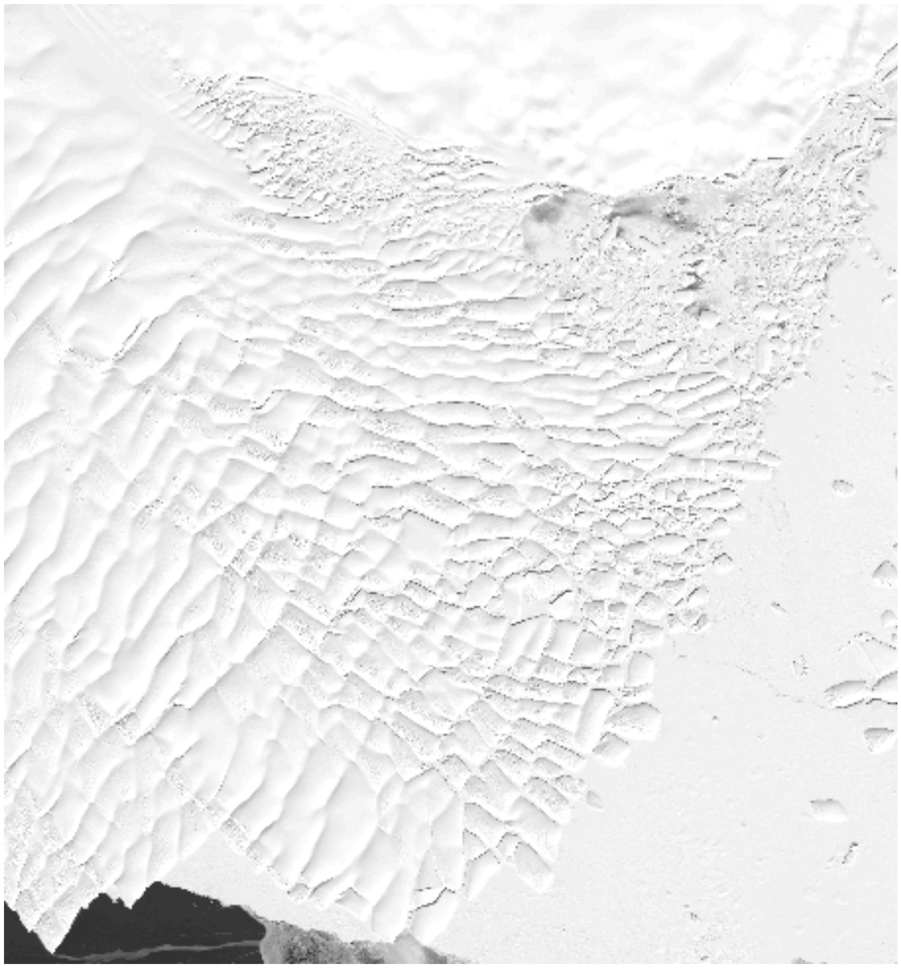
We feel that this is an important discussion because the concept of aliasing has previously been neglected or worked around in nearly every study of long-term velocity change in Antarctica. We show that the natural seasonal cycle of ice dynamics at Totten is on the same order as variability that has previously been attributed to long-term change. Identifying and separating intra-annual variability from interannual variability is of critical importance for interpreting and understanding the causes of dynamic change at Totten and elsewhere around Antarctica.

5. The authors clearly demonstrate that seasonal changes in ice shelf thickness on the order of 0.3 to 1 m are unimportant for seasonal fluctuations in ice shelf velocity. This is well proven through their combined ocean and ice shelf modeling. They go on to conclude that changes in sea ice thickness of the same magnitude (1 – 1.5 m) are the cause of seasonal ice-shelf acceleration. They come to this conclusion primarily through the coincident removal of fast ice and ice shelf speedup. While I think this is a plausible conclusion it would be helpful for the authors to discuss the mechanisms by which sea ice is able to exert such an influence. Do the authors see seasonal fluctuations in the position of the ice shelf front that could suggest a modification in the calving rate? I would think that the backstress from 1 m of sea ice would not be sufficient in itself and instead it there would need to be some mechanism by which a small force at the front of the ice shelf could disproportionately modify the fontal stress regime

The point about the influence of ~1 m of ice at the ice shelf base versus the same ice thickness at the ice shelf front is well taken. But as in architecture, the placement of structural supports is critical.

In the Introduction and in the Discussion section 6.1 we go into significant depth, describing the array of different studies that have shown how the presence of sea ice or ice melange can temporarily prevent calving, inhibit crevassing near the ice shelf front, or maintain the structural integrity of the ice shelf by preventing calved icebergs from rotating away from the ice front. Temporary reductions in calving can preserve internal stresses in the ice shelf and slow the flow of the ice. The modeling studies we describe and reference have investigated these processes in much more detail than we can consider given the limitations of our observational data.

The calving front position would indeed be an insightful time series for this analysis, but due to the large megaripples at Totten, digitizing the location of the ice front can lead to tremendous uncertainty based on visual interpretation of ice features. For example, this is a Landsat 8 image of the Totten Ice Shelf front:



The image above is 40 km wide, and when tasked with identifying the structural bounds of the ice shelf, we find that we cannot confidently distinguish between intact shelf ice, sea-ice-fastened icebergs, and "loose teeth" that may be partly connected to the ice shelf without supporting the full stress regime of the ice shelf. Uncertainties in identifying the structural bounds of the ice shelf would be on the order of kilometers or more, and would ultimately lead to an analysis of the interpretation of the ice shelf front location, rather than interpretation of a physically meaningful time series. Given the spatial and temporal limitations of all data in this region, here we can only observe the end members of the process, and use what is known from modeling studies and observations elsewhere in the world to infer the small-scale processes that are occurring in between. Accordingly, we do not attempt to directly measure the calving rate of the ice shelf in this revised manuscript.

Seasonal dynamics of Totten Ice Shelf controlled by sea ice buttressing

Chad A. Greene[1], Duncan A. Young[1], David E. Gwyther[2], Benjamin K. Galton-Fenzi[3,4], and Donald D. Blankenship[1]

[1]Institute for Geophysics, Jackson School of Geosciences, University of Texas at Austin, Austin, Texas, USA.
[2]Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Tasmania, Australia
[3]Australian Antarctic Division, Kingston, Tasmania 7050, Australia
[4]Antarctic Climate & Ecosystems Cooperative Research Centre, University of Tasmania, Hobart, Tasmania 7001, Australia

Correspondence: Chad A. Greene (chad@chadagreene.com)

Abstract. Previous studies of Totten Ice Shelf have employed surface velocity measurements to estimate its mass balance and understand its sensitivities to interannual changes in climate forcing. However, displacement measurements acquired over timescales of days to weeks may not accurately characterize long-term flow rates where ice velocity fluctuates with the seasons. Quantifying annual mass budgets or analyzing interannual changes in ice velocity requires knowing when and where observations of glacier velocity could be aliased by subannual variability. Here, we analyze 16 years of velocity data for Totten Ice Shelf, which we generate at subannual resolution by applying feature tracking algorithms to several hundred satellite image pairs. We identify a seasonal cycle characterized by a spring to autumn speedup of more than 100 m yr^{-1} close to the ice front. The amplitude of the seasonal cycle diminishes with distance from the open ocean, suggesting the presence of a resistive backstress at the ice front that is strongest in winter. Springtime acceleration precedes summer surface melt and is not attributable to thinning from basal melt. We attribute the onset of ice shelf acceleration each spring to the loss of buttressing from the breakup of seasonal landfast sea ice.

1 Introduction

Totten Glacier in East Antarctica drains the Aurora Subglacial Basin, which is grounded well below sea level (Young et al., 2011; Roberts et al., 2011) and contains enough ice to raise the global sea level by at least 3.5 m (Greenbaum et al., 2015). Short-term observations have identified Totten Glacier and its ice shelf (TIS) as thinning rapidly (Pritchard et al., 2009, 2012) and losing mass (Chen et al., 2009), but longer-term observations paint a more complex picture of interannual variability marked by multi-year periods of ice thickening, thinning, acceleration, and slowdown (Paolo et al., 2015; Li et al., 2016; Roberts et al., 2017; Greene et al., 2017a). The current best estimates of Totten Glacier and TIS mass budgets have been calculated using a mosaic of surface velocity measurements collected at different times throughout the year (Rignot et al., 2013); however, such estimates have been built on an unconfirmed assumption that ice velocity does not vary on subannual timescales. Where glacier flow varies throughout the year, it is possible that velocity measurements collected over short time intervals may lead to to inaccurate estimates of annual mass balance or incorrect interpretation of interannual changes in velocity. Furthermore, most common methods of ice velocity measurement, such as satellite image feature tracking or in-situ GPS measurements taken over the course of a field season, are strongly biased toward summer acquisition and may not accurately represent winter ice dynamics. Wherever seasonal velocity variability exists, it is important to consider how ice velocity is measured, and how the measurements can be interpreted.

Seasonal variations in glacier velocity have been observed in Greenland and Antarctica (e.g., Joughin et al., 2008; Nakamura et al., 2010; Moon et al., 2014; Zhou et al., 2014; Fahnestock et al., 2016), and have been attributed to a number of different mechanisms. On grounded ice, surface meltwater can drain into crevasses or moulins, make its way to the bed, pressurize inefficient subglacial hydraulic systems, and allow the glacier to speed up until pressure is reduced (Sohn et al., 1998; Bartholomew et al., 2010; Moon et al., 2014). On floating ice, surface meltwater may also influence ice shelf velocity by percolating through and weakening the ice shelf shear margins (Liu and Miller, 1979; Vaughan and Doake, 1996)(Liu and Miller, 1979; Vaughan and Doake, 1 Observations have shown correspondence between seasonal advance and retreat of marine-terminating glaciers and the presence of ice melange mélange at the glacier terminus (Howat et al., 2010; Cassotto et al., 2015; Moon et al., 2015). The exact mechanisms by which ice melange mélange can affect glacier dynamics are poorly understood, but modeling studies have shown that the back stress provided by sea ice can prevent calved icebergs from rotating away from the ice front (Amundson et al., 2010), and in some cases can shut down calving entirely (Robel, 2017) causing an appreciable effect on glacier velocity (Todd and Christoffersen, 2014; Krug et al., 2015). For example, the buttressing strength of ice melange mélange at Store Glacier in Greenland has been estimated at 30–60 kPa, which is an order of magnitude below the driving stress of the glacier, but is sufficient to cause observable subannual changes in glacier velocity up to 16 km from the ice front (Walter et al., 2012; Todd and Christoffersen, 2014).

In Antarctica, marine ice is known to strengthen the Brunt and Stancomb-Willis ice shelf system (Hulbe et al., 2005), and an ice shelf acceleration event observed there in the 1970s has been attributed to a reduction in stiffness of the ice melange mélange that connects the two ice shelves (Khazendar et al., 2009). Similarly, multi-year landfast sea ice is strongly mechanically coupled to Mertz Glacier Tongue (Massom et al., 2010) and may have delayed a major calving event that occurred there in 2010 (Massom et al., 2015). Closer to TIS, two recent major calving events in Porpoise Bay (76°S,128°E) were attributed to the breakup of landfast sea ice at the ice shelf termini (Miles et al., 2017), and on the Antarctic Peninsula it has been shown that sea ice can protect ice shelves from fracture induced by ocean swell (Massom et al., 2018). At TIS, long-term changes in calving front position have been reported with a possible connection to local sea ice processes (Miles et al., 2016), but corresponding links to glacier dynamics have not previously been investigated. To our knowledge, there have been no reports of seasonal variability of TIS or any of the mechanisms that may drive TIS variability at subannual timescales. In this paper we find seasonal variability in two independent ice velocity datasets and we consider the potential roles of surface melt water, ice shelf basal melt, and sea ice buttressing, in influencing the flow of TIS at subannual timescales.

2 Surface velocity observations

We analyzed surface velocity time series using feature tracking algorithms applied to Landsat 8 and MODIS (MODerate-resolution Imaging Spectroradiometer) images. Each image dataset was processed separately, using different feature tracking programs, and the resulting time series represent two independent measures of TIS velocity. The 15 m resolution of Landsat 8 permits precise displacement measurements over short time intervals, but the relatively brief four-year Landsat 8 record and limited number of cloud-free images inhibits our ability to separate interannual velocity changes from seasonal variability. The MODIS record contains many cloud-free images per year from 2001 to present; however, the 250 m spatial resolution of MODIS images limits measurement precision where ice displacements are small between images. Thus, the two image datasets each offer incomplete, but complementary insights into the seasonal dynamics of TIS. Processing methods for each dataset are described below.

2.1 GoLIVE (Landsat 8) velocities

We used the Global Land Ice Velocity Extraction from Landsat 8 (GoLIVE) dataset (Scambos et al., 2016; Fahnestock et al., 2016), which is processed at 600 m resolution for most of Antarctica. We analyzed the high-confidence `vx_masked` and `vy_masked` velocity fields from late 2013 to early 2018 and limited the dataset to 143 image pairs separated by $16 \leq dt \leq 112$ days. Many of the image pairs overlap in time, providing several redundant, semi-independent velocity measurements, particularly throughout the summer months when each image may contribute to multiple image pairs.

To understand the spatial pattern of TIS seasonality, we developed characteristic velocity maps for spring and autumn separately. Spring velocity was taken as the mean of 76 velocity measurements whose image pairs were obtained between June 16 and December 15. Autumn velocity was taken as the mean of 67 velocity fields from images obtained during the remainder of the year. We discard all pixels where the mean ice speed is less than 250 $\mathrm{m\,yr^{-1}}$. We also discard all pixels containing fewer than 10 high-confidence spring or autumn velocity measurements. The resulting difference between spring and autumn velocities is shown in Fig. 1.

The terminal $\sim$50 km of TIS accelerates each year from spring to autumn, then slows ~~throughout~~ during the winter. Seasonality is strongest close to the glacier terminus and decays with distance from the open ocean. The relatively featureless nature of the inner TIS surface limits the number of high-confidence matches in that region of the ice shelf, but the available measurements indicate minimal seasonality upstream of the mid-shelf ice rumple identified by InSAR (Mouginot et al., 2017b). The grounded ice of the eastern tributary accelerates slightly throughout the summer, while some grounded ice of the western tributary exhibits a weak slowdown.

To assess the timing of the annual TIS acceleration, we generate a velocity time series for a region of TIS near the terminus shown in Fig. 1. We populate a velocity time series from the means of all GoLIVE velocity measurements within 5 km to 10 km from the ice front, considering only pixels with a mean velocity exceeding 1700 $\mathrm{m\,yr^{-1}}$. The resulting TIS velocity time series is shown in Fig. 2.

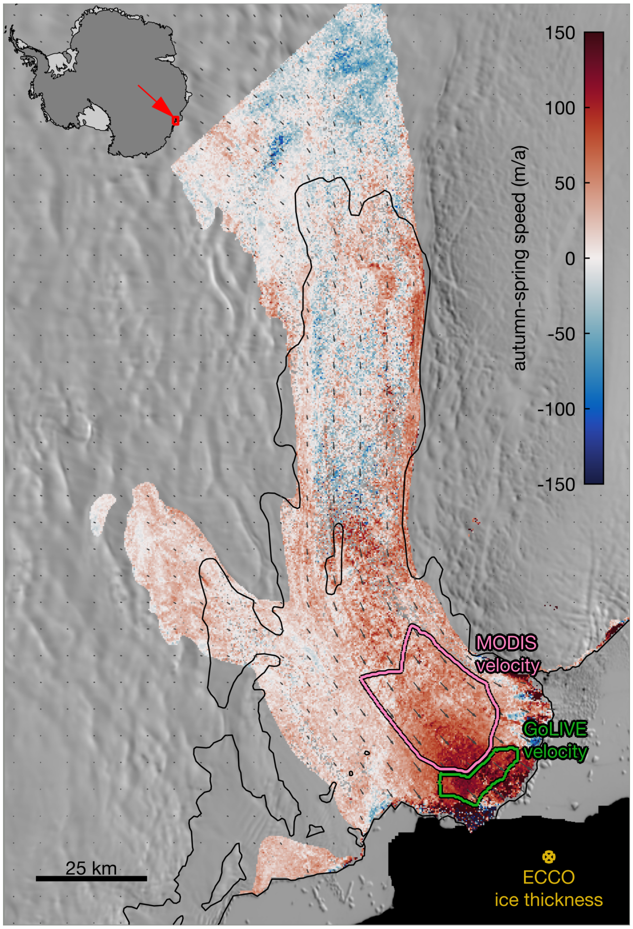


Figure 1. Summer ice shelf acceleration. Toward the ice front, autumn velocity exceeds spring velocity by more than 100 m yr^{-1}. This image shows the difference between the means of 76 spring and 67 autumn GoLIVE velocity fields. Dark green vectors indicate the mean velocity, supplemented by MEaSUREs InSAR-derived velocity (Rignot et al., 2011) outside the range of Landsat path 102, row 107. Green and pink polygons indicate the bounds of velocity averaging for the velocity time series shown in Fig. 2 and Fig. 3, respectively. A gold marker shows the location of the ECCO sea ice thickness time series described in Sec. 5. The black line indicates the grounding line, and includes a grounded ice rumple near the center of the ice shelf (Mouginot et al., 2017b).

The short record and low temporal resolution of the GoLIVE dataset make it difficult to identify the exact timing of the onset of acceleration in any given year, but a linear trend fit to all available measurements indicates a typical acceleration of 0.8 m yr^{-1} per day from late September to early April. Further investigation into the timing of accelerations each year requires a more complete time series of TIS velocity, which we generate from MODIS images.

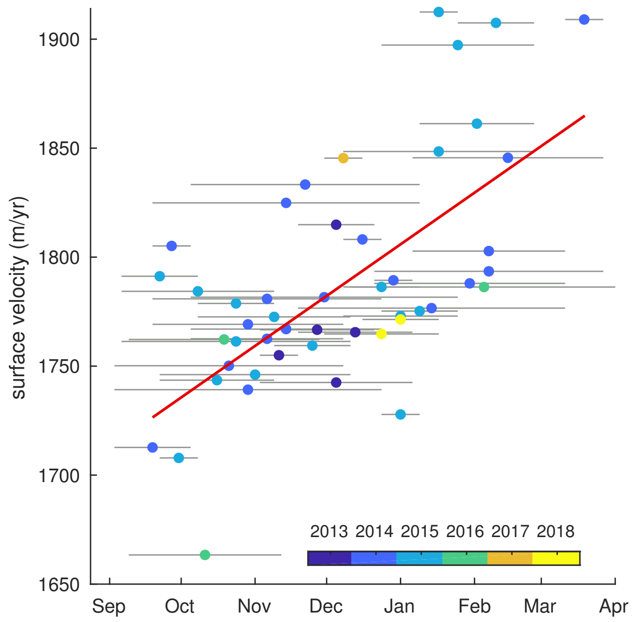


Figure 2. Ice front acceleration from GoLIVE (Landsat 8). The GoLIVE dataset contains many overlapping TIS velocity measurements captured between September and April of each year. The velocities here represent all displacements measured over $16 \leq dt \leq 112$ days (indicated by gray lines), averaged within the green polygon in Fig. 1. The red trend line is a linear least-squares fit to the observations, indicating a typical spring-to-fall acceleration of 0.8 $\mathrm{m\,yr^{-1}}$ per day.

2.2 MODIS velocities

A MODIS velocity time series was generated from 672 pairs of cloud-free MODIS band 2 images (Scambos et al., 2001, updated 2018; Greene and Blankenship, 2018) acquired between 2002 and 2018. Each image pair was separated by 92 to 182 days and was processed at 250 m resolution using the ImGRAFT template matching software (Messerli and Grinsted, 2015) with Antarctic Mapping Tools for MATLAB (Greene et al., 2017b). Similar to the method described by Greene et al. (2017a), we used 2.5 km square templates with 4.0 km search boxes centered on locations predicted by InSAR-derived velocities (Rignot et al., 2017). To generate the MODIS velocity time series we averaged velocities from all pixels within 10 km to 30 km from the ice front, bounded on each side by the glacier shear margins identified by Greene et al. (2017a). We discarded any image pairs for which fewer than 99% of the pixels within the polygon contained valid displacement measurements, resulting in 565 valid MODIS velocity measurements in the time series. The polygon used for the MODIS time series is shown in Fig. 1.

Despite having measurements from dozens of MODIS image pairs most years, subannual template matching applied to 250 m resolution MODIS images produces such noisy velocity estimates that the timing of springtime acceleration cannot be accurately determined for any given year. However, by combining data from all years we can assess the characteristic cycle of ice shelf acceleration and slowdown that occurs throughout the typical year. Figure 3 shows the MODIS velocity time series overlaid on the mean seasonal cycle. Because no visible-band MODIS images are available during the dark winter months, no

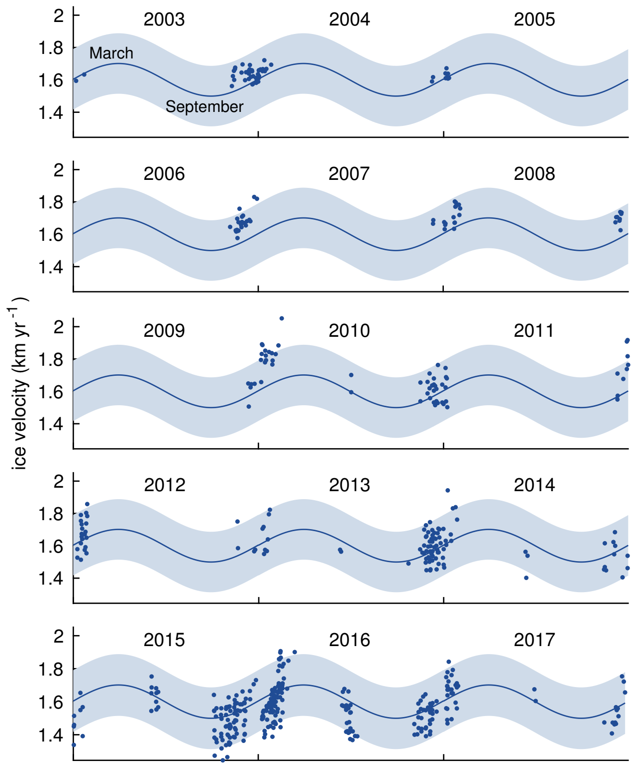


Figure 3. Seasonal cycle of ice shelf velocity from MODIS. TIS velocity measurements from 565 MODIS image pairs separated by 92 to 182 days, averaged within the pink polygon shown in Fig. 1. Velocity measurements are shown at the mean of the acquisition times of their MODIS image pairs. The average seasonal cycle is shown approximated as a sinusoid, with 95% confidence intervals shaded.

image pairs separated by 92 to ~~192~~ 182 days are centered on any days in April, May, August, or September. However, 46 image pairs span the winter, providing velocity measurements centered on June and July.

We approximate the seasonal cycle of the TIS velocity as a sinusoid obtained by least squares fit to the 565 MODIS velocity measurements. To minimize the influence of interannual variability, the one-year moving average was removed before analyzing the seasonal cycle. The resulting best-fit sinusoid is characterized by a 1601 $\mathrm{m\,yr^{-1}}$ mean velocity, an amplitude of 106$\pm$9 $\mathrm{m\,yr^{-1}}$, a maximum velocity on March 21 ($\pm 1\sigma = 5$ days), and a minimum velocity on September ~~19. The sinusoid~~ 19 ($\pm 1\sigma = 5$ days). The sinusoid provides a measure of periodicity at the 1 $\mathrm{yr^{-1}}$ frequency and matches observations to a root-mean-square error of 93 $\mathrm{m\,yr^{-1}}$. Uncertainty analysis of the sinusoid fit is explored in Appendix A.

3 Surface melt observations

Surface melt has been shown to affect the flow of grounded ice in Greenland when surface water drains through moulins or crevasses to the bed, where it alters basal water pressure and allows the overlying ice to accelerate (Zwally et al., 2002; Schoof,

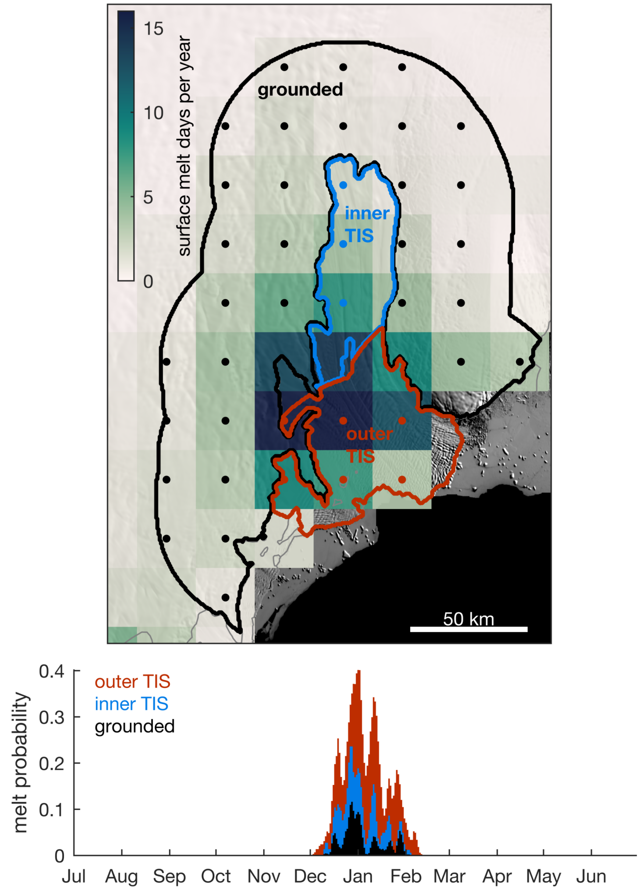


Figure 4. Surface melt observations, 2000–2017. Spatial distribution of mean annual surface melt and daily probability of surface melt in each subdomain. Low-elevation areas near the coast experience more days of surface melt than high-elevation grounded ice, but the timing of surface melt is similar throughout the domain. Data are from Picard and Fily (2006).

2010; Bartholomew et al., 2010; Andrews et al., 2014). The seasonal velocity anomalies we observe at TIS are strongest near the floating ice front, so it is unlikely that the seasonal variability of TIS velocity is driven by subglacial hydrology on nearby grounded ice. However, the presence of englacial liquid water can weaken ice (Liu and Miller, 1979), and it is plausible that surface melt at TIS could percolate into the ice, weaken shear margins, and allow TIS to speed up as a result of reduced buttressing.

To assess the possible link between surface melt and TIS velocity anomalies, we used daily observations of surface melt from passive microwave radiometers (SMMR and SSM/I) gridded to 25 km resolution (Picard and Fily, 2006). We limited the period of analysis to 2000 through 2017 to roughly coincide with available MODIS image data. Figure 4 shows the spatial distribution of mean annual surface melt during this period. Using the masks developed by Mouginot et al. (2017b) with the

Antarctic Mapping Tools for MATLAB `dist2mask` function (Greene et al., 2017b), we define three subdomains for surface melt analysis as

1. *outer TIS:* the floating portion of the ice shelf up to 50 km from the ice shelf front,

2. *inner TIS:* the floating portion of the ice shelf more than 50 km from the ice shelf front, and

3. *grounded:* all grounded ice within 50 km of the TIS grounding line.

Surface melt is most prevalent in the outer TIS, where in some locations surface melt is detected up to 16 days per year. Fewer surface melt days occur far from the ice front on the inner TIS, and surface melt is least common on the high-elevation grounded ice surrounding TIS. Figure 4 shows that although the number of annual surface melt days varies throughout the region, the timing of surface melt is roughly the same in all three subdomains, with the typical melt season lasting from December to February. For the outer TIS, the onset of surface melt typically occurs on December 23 ($\pm 1\sigma = 12$ days), with the earliest summer melt recorded on December 6, 2006. The mean final day of surface melt occurs on January 23 ($\pm 1\sigma = 9$ days), but has been observed as late as February 11 in 2005.

4 Modelled ice shelf basal melt

On interannual timescales, TIS is known to accelerate in response to prolonged periods of elevated basal melt rates (Roberts et al., 2017; Greene et al., 2017a), and a similar process has been observed at Pine Island Ice Shelf in West Antarctica (Christianson et al., 2016). For these laterally-bounded ice shelves restrained largely by shear stress at their margins, thinning reduces resistance to glacier flow and allows ice shelf acceleration.

To assess whether TIS may dynamically respond to basal melt anomalies at subannual timescales, we used the Regional Ocean Modeling System (ROMS; Shchepetkin and McWilliams, 2005) to simulate TIS-ocean interactions, then considered the effects that subannual basal melt anomalies could have on TIS velocity. The model domain extended from 104.5°E–130°E in longitude and 60°S–68°S in latitude with a horizontal resolution of approximately 2 to 3 km. A terrain-following vertical coordinate provided enhanced resolution close to the seafloor and ice shelf interface. Modifications to the code allowed thermodynamic interaction between ocean and steady-state ice shelves, following Dinniman et al. (2003) and Galton-Fenzi et al. (2012). Seafloor ~~topography was based on the RTOPO dataset (Timmermann et al., 2010), while cavity geometrywas inferred~~ bathymetry for the deep ocean and continental shelf was taken from the RTopo-1 dataset (Timmermann et al., 2010). As RTopo-1 does not contain the cavity of TIS, we inferred the cavity geometry. Ice basal draft for the TIS cavity was obtained from ICESat-derived ~~ice surface elevation above flotation and a constant 300 m thick offset along the central flow line . Between~~ surface elevations, assuming hydrostatic equilibrium and a mean ice density of 905 kg m^{-3} (following Fricker et al., 2001). Water column thickness was obtained by linearly interpolating from 0 m thick along the grounding line to 300 m thick along the central flow line ~~and the grounding line, cavity bathymetry was linearly interpolated~~ of the ice shelf (see Gwyther et al., 2014, for details). The model lateral and surface boundaries were forced over the hindcast period 1992–2012. Lateral forcing was derived from the ECCO2 cube92 reanalysis solution (Menemenlis et al., 2008); surface forcing was ERA-interim wind

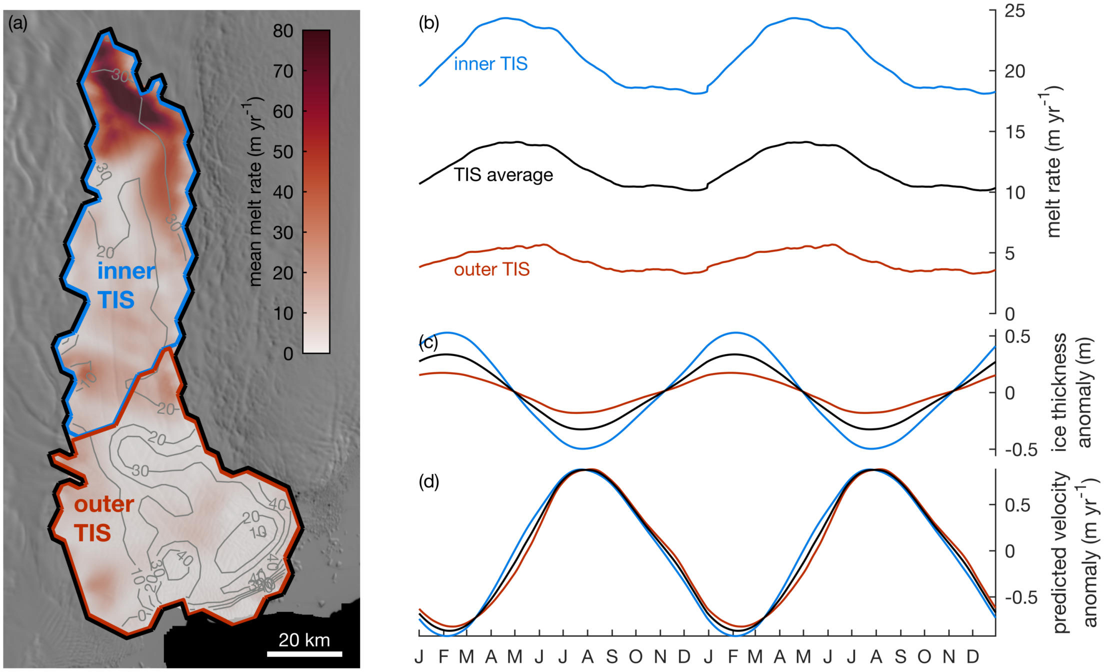


Figure 5. Modeled basal melt. (a) Mean melt rate distribution shows melt focused where the ice shelf base is deepest, exceeding 80 m yr^{-1} near the grounding line of the inner TIS. Gray contours show melt rate lag times in days relative to anomalies at the ice front, indicating melt anomalies propagate in a clockwise fashion around the cavity. **(b)** Two years of 1992–2012 climatological melt rates averaged within the subdomains in **(a)**. **(c)** Ice thickness anomalies corresponding to the time integral of melt rate anomalies. **(d)** Ice velocity anomalies expected to result from seasonal variations in ice shelf thickness.

stress (Dee et al., 2011), and heat and salt fluxes were derived from Special Sensor Microwave/Imager (SSM/I) algorithms for sea-ice production (Tamura et al., 2016). The model was spun-up for 21 model years using 1992–2012 forcing. After spin-up, the 1992–2012 forcing was repeated and we analyzed the mean seasonal cycle of melt from the second run. The mean spatial distribution and temporal variability of basal melt are shown in Fig. 5.

The distribution of basal melt at TIS mimics observations of other ice shelves, with the highest melt rates focused near the deep grounding line (e.g., Dutrieux et al., 2013). Seasonal variability is most significant in the inner TIS, where mean melt rates are highest, whereas the shallow ice base of the outer TIS experiences only a weak seasonal cycle superimposed on a low mean melt rate. Everywhere beneath the ice shelf, basal melt rate reaches a maximum in autumn and a minimum in the spring.

Ice shelf thinning tends to reduce buttressing and allow ice shelf acceleration. Using a simple model developed by Greene et al. (2017a) (adapted from Joughin et al., 2004) to estimate velocity anomalies resulting from seasonal changes in ice thickness, we find that on subannual timescales, basal melt anomalies should only affect TIS velocity on the order of 1 m yr^{-1} (Fig. 5). Note that velocity predictions are negatively correlated with ice thickness, which is calculated from the time integral of basal melt rate anomalies. Accordingly, velocity maxima related to basal melt do not correspond directly to basal melt rate maxima, but should occur at the end of the high-melt season in July, when ice thickness reaches a minimum.

Small perturbations in ice shelf thickness have the greatest influence on ice shelf buttressing where the ice shelf is thin. However, the thick ice of the inner TIS experiences much more seasonal melt variability than the thin ice of the outer TIS, so it is somewhat by coincidence that the large (> 8 m yr^{-1}) increase in melt rate from spring to autumn beneath the thick (> 2000 m) ice of the inner TIS, affects local ice velocity to approximately the same degree as the much smaller (~ 3 m yr^{-1}) seasonal melt rate variability in the outer TIS, where ice is much thinner (Fig. 5).

The model we use to estimate melt-induced velocity anomalies assumes TIS velocity is limited only by lateral shear stress at the ice shelf margins and velocity anomalies are purely a function of local ice thickness. These assumptions vastly oversimplify the complex stress regime of the TIS, but are used to obtain an order-of-magnitude approximation of how the TIS should respond to seasonal variability of ice thickness driven by basal melt. From this simple model it is clear that the <1 m yr^{-1} variability expected to result from seasonal basal melt anomalies cannot explain the observed >100 m yr^{-1} seasonal variability of TIS velocity. Moreover, holding other factors are constant, the seasonal cycle of basal melt produces an ice shelf that grows throughout the summer and reaches a maximum thickness in February. Accordingly, basal melt anomalies should result in a summer slowdown and a velocity minimum in February, when observations show TIS nearing its velocity maximum. Thus, it is unlikely that the seasonal cycle of basal melt could explain the observed pattern of spring-to-fall acceleration of TIS.

5 Sea ice concentration and thickness

To assess whether the presence of sea ice may influence the flow of TIS, we analyzed observational data from microwave, thermal, and visual band satellite sensors, along with model data of sea ice thickness near the TIS front. We used daily observations of sea ice concentration (Cavalieri et al., 1996) and generated a time series given by the mean of three 25 km grid cells located close to the TIS front (shown in Fig. 6). In addition to ice concentration observations, we also analyzed daily effective sea ice thickness from ECCO v4-r3 for the period 2000–2015 (Fukumori et al., 2017). We focused on the time series of sea ice thickness for the grid cell centered on (66.47°S,116.50°E), indicated by gold markers in Figs. 1 and 6. To fully understand the spatial and temporal variability of sea ice, we also inspected 315 cloud-free MODIS visual (band 2) and 164 thermal (band 32) images acquired throughout the year by the Aqua and Terra platforms between 2000 and 2017 (Scambos et al., 2001, updated 2018; Greene and Blankenship, 2018).

Figure 6 shows the seasonal cycle of sea ice growth and decay. The minimum ice concentration typically occurs at the TIS front in mid March, followed by increasing ice concentration throughout autumn as air temperatures decline (Dee et al., 2011). Inspection of visual and thermal band images reveals that sea ice consolidates and fastens to the western TIS in early to mid May. The rigid connection of landfast ice to the TIS front holds throughout the winter, with the exception of a small polynya abutting Law Dome that briefly opened in July 2016 (see Alley et al., 2016). Regardless of polynya activity, the majority of landfast ice remains connected to the TIS front, and each year the landfast connection breaks in October or early November, followed by a visible reduction in sea ice cover that occurs throughout November. In some years, sea ice concentration continues

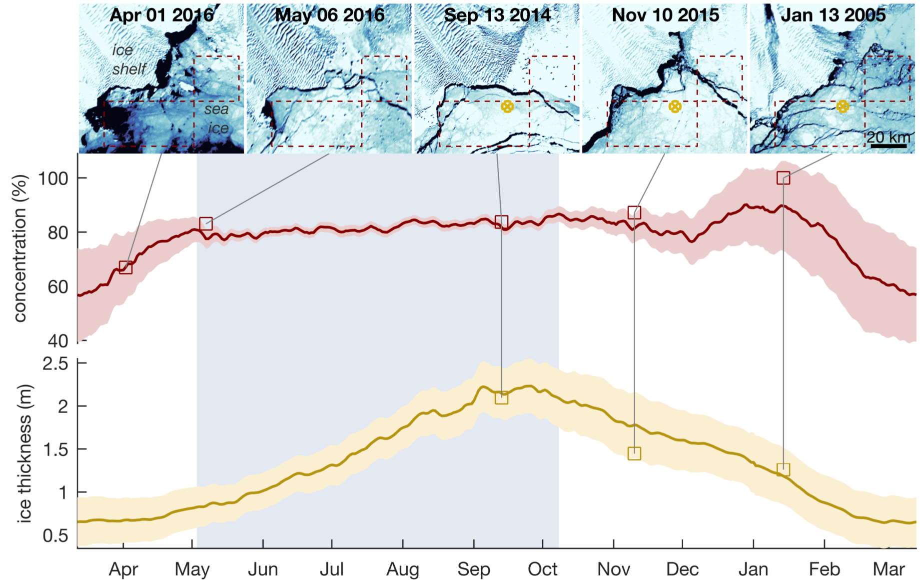


Figure 6. Seasonal cycle of sea ice at the TIS front. MODIS visual band imagery (Scambos et al., 2001, updated 2018), remotely sensed ice concentration (Cavalieri et al., 1996), and ECCO v4-r3 effective sea ice thickness (Fukumori et al., 2017) reveal a seasonal cycle of sea ice growth and decay beginning around March 12 each year, when sea ice concentration is at a minimum. Ice concentration and thickness time series are shown with corresponding shading indicating daily values of $\pm 1\sigma$. Light blue background shading indicates the presence of fast ice at the TIS front, from about May 3 to October 8. During this winter period, remotely sensed ice concentration values remain relatively constant despite continued growth of sea ice. Average sea ice thickness steadily declines throughout the summer, while thin, unconsolidated sea ice often temporarily fills the area and is detected by remote sensors. Five example MODIS images (Scambos et al., 2001, updated 2018) ~~are shown for context~~show sea ice fastened to half of the TIS front in May and September, with dashed quadrangles indicating the region of ice concentration averaging and a gold marker denotes the location of the ECCO sea ice thickness time series.

to decline throughout the summer, but more commonly, the region temporarily fills with unconsolidated ice, causing sea ice concentration to peak in January (Greene, 2017). From January to March, sea ice melts or is exported away from the TIS front until concentration reaches a minimum in mid March, then the cycle repeats. ~~Ice~~ Sea ice thickness data are more well behaved, generally waxing and waning monotonically between a minimum in late March and maximum in late September. In this way, sea ice thickness follows the broader climatology reported by Fraser et al. (2012), who found that landfast ice between 90°E and 160°E grows from a minimum extent in March to a maximum in late September or early October.

We suspect that sea ice concentration is a poor measure of ice strength, because the simple fraction of a grid cell's surface area covered by ice offers no indication of ice thickness or level of consolidation. This is seen not only in the summer melt season during which sea ice concentration often increases, but also in winter, when ice concentration observations remain constant while the ice grows steadily thicker. We posit that sea ice thickness is a better proxy for sea ice strength because the ECCO v4-r3 model was indirectly constrained by observations of sea ice concentration, but also accounts for winter sea ice growth.

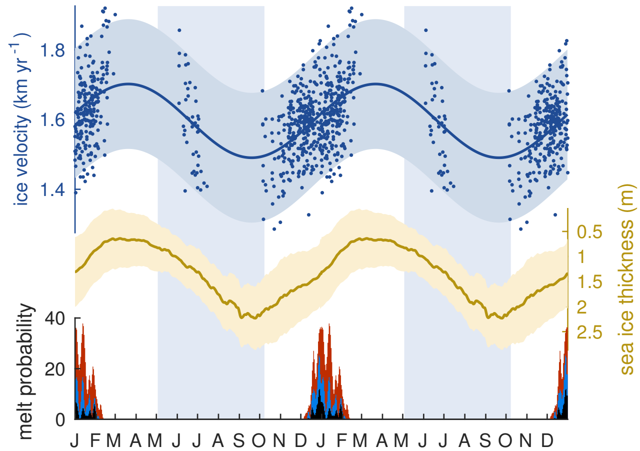


Figure 7. Causes of springtime acceleration. Time series of MODIS-derived ice velocity $\pm 2\sigma$ shaded, ECCO v4-r3 sea ice thickness$\pm 2\sigma$ shaded, and melt probability repeated from Figs. 3, 4, and 6. Note the inverted axis of the sea ice thickness time series. ~~Springtime~~ Characteristic springtime acceleration near the TIS front begins with the breakup of landfast sea ice, and is possibly enhanced later in the year by shear margin weakening resulting from surface melt. Vertical shaded blue areas indicate typical times of landfast ice connection with TIS. Two years of the mean cycle are shown for visual continuitiy. Velocity anomalies predicted from basal melt are not shown here becuase the $\pm 1\ \mathrm{m\,yr^{-1}}$ amplitude would visually indiscernible at the observed scale of interannual velocity variability.

6 Discussion

6.1 Causes of seasonal variability

Studies of floating and marine-terminating glaciers around the world have found a diverse set of causes of seasonal velocity variability, suggesting that local phenomena control glacier flow on subannual timescales, and there is no single dominating global cause of seasonal variability. In some regions of Greenland, neighboring glaciers behave differently based on the mechanisms that control them, and those mechanisms can change for a given glacier throughout the year (Howat et al., 2010; Moon et al., 2014).

On grounded ice, seasonal velocity variability often results from surface water draining to the bed, where it can temporarily pressurize an inefficient hydrological system, allowing the overlying ice to accelerate until an efficient drainage system forms or the water otherwise evacuates (Zwally et al., 2002; Parizek and Alley, 2004; Bartholomew et al., 2010). At Totten Glacier, we detect very little seasonal velocity variability on grounded ice, and the onset of acceleration we observe on the floating ice shelf begins well before surface water is detected anywhere in the region (Fig. 7). We therefore rule out the possibility that surface melt is responsible for initiating TIS acceleration each year.

On multi-year timescales, basal melt can lead to ice shelf acceleration as thinning reduces the internal buttressing strength of ice (Christianson et al., 2016; Greene et al., 2017a). However, neither the timing nor the amplitude of melt-induced thinning can account for the seasonal velocity variability we observe at TIS. We find a small seasonal cycle of ice shelf thickness due to variable basal melt throughout the year, but the corresponding velocity anomalies should be two orders of magnitude smaller than the observed velocity anomalies. Roberts et al. (2017) pointed out that at TIS, a mechanism exists that can amplify the effects of basal melt on ice velocity: Ice rumples in the middle of TIS may provide decreasing resistance to flow as the ice shelf thins, so it is possible that the simple model of ice shelf buttressing we employ in Sec. 4 underestimates the effects of basal melt on TIS velocity. Nonetheless, we find that basal melt is still incapable of causing the observed seasonal velocity cycle because ice shelf thickness maxima occur each year nearly coincident in time with observed velocity maxima.

In the GoLIVE dataset and in MODIS-derived velocities, we find that the outer TIS accelerates each year between spring and autumn. The spatial pattern of the annual acceleration suggests that the flow of ice is governed by processes at the ice front (Fig. 1), and timing of the acceleration implicates the annual breakup of landfast ice at the TIS front as an influencing factor. Figure 7 shows the relationship between sea ice thickness, surface melt, and TIS velocity. The temporal and spatial resolution of data available at TIS limit our ability to investigate the specific processes by which the presence of sea ice may slow the flow of TIS, but similar studies elsewhere have found that backstress from ice ~~melange~~ mélange (Walter et al., 2012; Todd and Christoffersen, 2014; Otero et al., 2017) can stabilize the ice front and reduce or entirely shut down calving over winter (Sohn et al., 1998; Reeh et al., 2001; Amundson et al., 2010; Moon et al., 2015; Robel, 2017), thus preserving internal stresses in the glacier and slowing its flow (Krug et al., 2015). The pattern of TIS acceleration we observe is similar to seasonal velocity anomalies observed at other marine-terminating glaciers and ice shelves, where the annual breakup of sea ice causes velocity anomalies that are seen up to tens of kilometers from the glacier terminus (Nakamura et al., 2010; Walter et al., 2012; Zhou et al., 2014).

We find that the outer TIS accelerates each ~~spring~~year, likely in response to lost buttressing upon the breakup of rigid sea ice at the ice shelf terminus. The response we observe is consistent with other studies that have shown a seasonal pattern of ice front calving and glacier acceleration in response to the disintegration of rigid sea ice caused by warm sea surface temperatures (Howat et al., 2010; Cassotto et al., 2015; Luckman et al., 2015). Ice front processes are likely responsible for the onset of TIS acceleration each spring, but we cannot rule out the possibility that other factors may influence the flow of TIS in other parts of the year. It is possible that onset of acceleration begins with the breakup of sea ice at the TIS front, but surface melt could play a role later in the summer or autumn, if water percolates into the ice and weakens the shear margins.

In Figs. 3 and 7 we approximate the seasonal velocity variability of TIS as a sinusoid. The seasonal flow of TIS is likely more complex, and the timing and magnitude of spring-to-autumn speedup presumably vary from year to year. Nonetheless, we have shown that TIS responds to local forcing on subannual timescales, the response is observable, and it correlates with the breakup of sea ice at the glacier terminus each spring.

6.2 Impacts of seasonal variability on measurements of long-term change

We find that TIS accelerates each year from spring to autumn, and this seasonal variability has the potential to contaminate estimates of annual mass flux and interannual variability. Most common methods of measuring ice velocity rely upon subannual displacement measurements to characterize annual ice flux (e.g. Mouginot et al., 2017a), but where ice velocity varies throughout the year, short-term measurements can be aliased by the natural seasonal cycle and provide an inaccurate measure of annual ice flux. The seasonal variability we observe at TIS suggests that measurements acquired in the spring likely underestimate, and autumn measurements overestimate, the mean annual velocity of the ice shelf.

The most significant seasonal variability at TIS is found near the ice front, where spring and autumn velocities can differ by up to 10% percent. Although this represents a small modulation of the mean flow, it is on the order of interannual variability that has previously been attributed to interannual changes in ocean forcing, and the pattern of summer acceleration we show in Fig. 1 bears a notable resemblance to accelerations that have previously been reported as evidence of long-term change (Li et al., 2016). Although direct investigations of interannual change are beyond the scope of this study, we can consider how seasonal variability may have influenced previous studies of TIS velocity.

Roberts et al. (2017) and Greene et al. (2017a) each found interannual changes in velocity by analyzing Velocity variability at TIS has been investigated in three recent papers that tracked ice accelerations and slowdowns over the past few decades, and each study found that on interannual timescales, TIS dynamically responds to ocean forcing from below. We do not find any evidence that contradicts the overall findings of the previous studies, but in some cases, velocities were measured over periods of less than one year, and may have been aliased by seasonal variability. Roberts et al. (2017) and Greene et al. (2017a) each measured displacements between images separated by near-integer multiples of years. By this method, it is unlikely that they inadvertently captured subannual variability, unless the timing of acceleration events occurred out of sync with the calendar year. Such is likely the case for the 2009 to 2010 acceleration observed by Li et al. (2016), who compared velocity measurements obtained between September and January of both years. Although the periods of observation were roughly the same in both years, the spring breakup of fast ice did not occur until after the start of observations in 2009, whereas the spring breakup was already underway when observations began in 2010, and the TIS had already begun to respond. The velocity difference between the 2009 and 2010 measurements shows acceleration focused at the ice shelf terminus, and this likely reflects a difference in timing of the seasonal cycle that may not be associated with any difference in mean annual velocities. The inconsistent timing of fast ice breakup each year suggests that assessments of interannual change made from short-term displacement measurements can be contaminated by seasonal effects, even if observations are taken at the same time each year.

Despite the seasonal variability we observe near the TIS front, mass balance of an ice sheet is more meaningfully measured at the grounding line, where ice begins to have an impact on sea level. Our results show little subannual velocity variability at the grounding line, thus supporting the grounding line flux estimates by Li et al. (2016).

6.3 Sea ice influence on ice sheet mass balance

The GoLIVE and MODIS velocity measurements show that TIS is sensitive to environmental forcing on subannual timescales, and its flow is primarily controlled by the presence and strength of sea ice at the TIS front. This finding warrants consideration of how changes in sea ice could affect the stability of the TIS and the long-term mass balance of the Aurora Subglacial Basin. Elsewhere in Antarctica, loss of multiyear landfast ice has led to major calving events and glacier acceleration (Khazendar et al., 2009; Miles et al., 2017; Aoki, 2017). The landfast ice we observe is not multiyear ice, and is thus unlikely to be associated with any catastrophic events at TIS in the near future. However, calving front processes can have far-reaching effects on glacier thickness and velocity (Nick et al., 2009), and it is possible that long-term changes in winter sea ice cover (Bracegirdle et al.,

2008) could have integrated effects on TIS buttressing: ~~The~~ If the duration and thickness of ~~sea ice cover each winter controls~~ winter sea ice control the total annual buttressing at the ice ~~front,~~ shelf front, long-term changes in sea ice cover could affect the annual flow of ~~the ice shelf~~TIS, and potentially the ~~long-term~~ mass balance of TIS and the Aurora Subglacial Basin.

7 Conclusions

We find that TIS has a characteristic seasonal velocity profile, which could lead to inaccurate estimates of the annual mass balance of TIS, and may have aliased some previous measurements of interannual variability. Annual ice velocity maps are now available covering most of Antarctica (Mouginot et al., 2017c), but interpreting such datasets at TIS and elsewhere requires understanding where ice velocity varies seasonally and by how much. Our results provide context for how and where such velocity mosaics may be used to interpret interannual change at Totten Glacier.

Previous studies have ~~investigated TIS velocity variability and have broadly concluded that interannual changes in ice velocity have been~~ linked interannual velocity variability at TIS to periods of ice shelf thickening and thinning caused by sustained basal melt rate anomalies. ~~Basal melt cannot explain the seasonal velocity variability we observe, because~~ On subannual timescales, however, the seasonal amplitude of ~~melt is too weak~~ basal melt variability is insufficient to produce enough thinning ~~for~~ to elicit an observable velocity response. Furthermore, seasonal basal melt anomalies result in an ice shelf that is thinnest, weakest, and should flow the fastest in winter, when our observations show the TIS reaches its minimum velocity.

In accord with other studies of ice shelves and glaciers around Antarctica and Greenland, we find that the seasonal variability of TIS velocity is most closely linked to the presence of sea ice at the ice shelf front. Each spring when surface waters warm, rigid landfast ice breaks its connection to the TIS front, the calving rate increases, and the TIS responds by accelerating by nearly 10% close the ice shelf terminus. Velocity anomalies are most significant over floating ice, and spring acceleration precedes surface melt each year, together suggesting that subglacial hydrology does not cause the seasonal cycle of TIS velocity we observe.

We find that winter sea ice is a primary contributor to the seasonal variability of the outer TIS velocity. If the future brings long-term changes in the thickness or extent of winter sea ice, the integrated effects of changes in buttressing could manifest as long-term changes in the mass balance of TIS and the Aurora Subglacial Basin.

Code and data availability. GoLIVE data (Scambos et al., 2016; Fahnestock et al., 2016) is available at https://nsidc.org/data/NSIDC-0710. MODIS images (Scambos et al., 2001, updated 2018) used in this study were obtained from ftp://sidads.colorado.edu/pub/DATASETS/ICESHELVES. The ImGRAFT template matching software (Messerli and Grinsted, 2015) is available at http://imgraft.glaciology.net. The `melting-1979-2017-v2.nc` surface melt data from Picard and Fily (2006) are available at http://pp.ige-grenoble.fr/pageperso/picardgh/melting/. ECCO v4-r3 sea ice effective thickness data can be found at ftp://ecco.jpl.nasa.gov/Version4/Release3/nctiles_daily/SIheff. Analysis was performed with Antarctic Mapping Tools for MATLAB (Greene et al., 2017b). The background image in Figs. 1, 4, and 5 is the MODIS Mosaic of Antarctica (Haran et al., 2014). Figs. 1, 4, 5, and 6 use `cmocean` colormaps (Thyng et al., 2016).

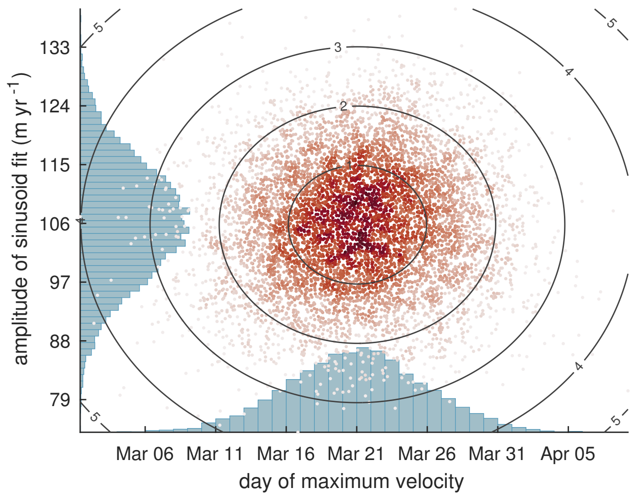


Figure A1. Bootstrap distributions of sinusoid parameters. Scattered data show the phase and amplitudes of sinusoids fit by least squares to 10,000 random samples of MODIS velocity measurements. Red color indicates local density of the scattered data. Histograms show the distributions of each parameter. Contour lines and axis tick marks indicate one-standard-deviation intervals for each parameter.

Appendix A: Uncertainty quantification

We used a bootstrapping technique to estimate uncertainty in the characteristic sinusoid fit to the MODIS velocity data. Figure A1 shows the phases and amplitudes of sinusoids fit by least squares to 10,000 random resamplings of the MODIS velocity dataset. The mean amplitude of the sinusoid is 106 $\mathrm{m\,yr^{-1}}$ with a 1-sigma uncertainty of 9.1 $\mathrm{m\,yr^{-1}}$. The phase of the sinusoid is characterized by a maximum velocity on March 21 (and corresponding minimum September 19) with a 1-sigma uncertainty of 4.9 days. The root-mean-square of the measurement residuals is 92.6±2.9 $\mathrm{m\,yr^{-1}}$, and reflects a combination of measurement error, interannual variability in amplitude and timing of acceleration or slowdown, and the difference between true seasonal variability and the sinusoid approximation.

Author contributions. CAG conceived of this study, generated the figures, and wrote the manuscript. Analysis was conducted by CAG under the direction of DDB, with guidance from DAY. DEG and BKGF developed the ice/ocean model described in Section 4 and assisted in interpreting its results.

Competing interests. The authors declare that they have no conflicts of interest.

Acknowledgements. We thank Mason J. Fried and Denis Felikson for many helpful discussions throughout the development of this work. We also thank Alex S. Gardner and the anonymous reviewer for providing feedback and suggestions that significantly improved the paper. This work was supported by the G. Unger Vetlesen Foundation and NSF grant PLR-1543452. Ocean modeling research was supported by the Australian Government's Cooperative Research Centre Programme through the Antarctic Climate & Ecosystems Cooperative Research Centre, the Australian Research Council's Special Research Initiative for Antarctic Gateway Partnership (Project ID SR140300001) and computing resource grants *m68*, *gh9* and *nk1* from the Australian Government National Computing Infrastructure.

References

Alley, K. E., Scambos, T. A., Siegfried, M. R., and Fricker, H. A.: Impacts of warm water on Antarctic ice shelf stability through basal channel formation, Nature Geoscience, 9, 290–293, https://doi.org/10.1038/ngeo2675, 2016.

Amundson, J. M., Fahnestock, M., Truffer, M., Brown, J., Lüthi, M. P., and Motyka, R. J.: Ice mélange dynamics and implications for terminus stability, Jakobshavn Isbræ, Greenland, Journal of Geophysical Research: Earth Surface, 115, https://doi.org/10.1029/2009JF001405, 2010.

Andrews, L. C., Catania, G. A., Hoffman, M. J., Gulley, J. D., Lüthi, M. P., Ryser, C., Hawley, R. L., and Neumann, T. A.: Direct observations of evolving subglacial drainage beneath the Greenland Ice Sheet, Nature, 514, 80, https://doi.org/10.1038/nature13796, 2014.

Aoki, S.: Breakup of land-fast sea ice in Lützow-Holm Bay, East Antarctica, and its teleconnection to tropical Pacific sea surface temperatures, Geophysical Research Letters, 44, 3219–3227, https://doi.org/10.1002/2017GL072835, 2017.

Bartholomew, I., Nienow, P., Mair, D., Hubbard, A., King, M. A., and Sole, A.: Seasonal evolution of subglacial drainage and acceleration in a Greenland outlet glacier, Nature Geoscience, 3, 408, 2010.

Bracegirdle, T. J., Connolley, W. M., and Turner, J.: Antarctic climate change over the twenty first century, Journal of Geophysical Research: Atmospheres, 113, https://doi.org/10.1029/2007JD008933, 2008.

Cassotto, R., Fahnestock, M., Amundson, J. M., Truffer, M., and Joughin, I.: Seasonal and interannual variations in ice melange and its impact on terminus stability, Jakobshavn Isbræ, Greenland, Journal of Glaciology, 61, 76–88, https://doi.org/10.3189/2015JoG13J235, 2015.

Cavalieri, D., Parkinson, C., Gloersen, P., and Zwally, H. J.: Sea Ice Concentrations from Nimbus-7 SMMR and DMSP SSM/I-SSMIS Passive Microwave Data, Version 1, https://doi.org/10.5067/8GQ8LZQVL0VL, http://dx.doi.org/10.5067/8GQ8LZQVL0VL, 1996.

Cavanagh, J., Lampkin, D., and Moon, T.: Seasonal variability in regional ice flow due to meltwater injection into the shear margins of Jakobshavn Isbræ, Journal of Geophysical Research: Earth Surface, 122, 2488–2505, https://doi.org/10.1002/2016JF004187, 2017.

Chen, J., Wilson, C., Blankenship, D., and Tapley, B.: Accelerated Antarctic ice loss from satellite gravity measurements, Nature Geoscience, 2, 859, 2009.

Christianson, K., Bushuk, M., Dutrieux, P., Parizek, B. R., Joughin, I. R., Alley, R. B., Shean, D. E., Abrahamsen, E. P., Anandakrishnan, S., Heywood, K. J., et al.: Sensitivity of Pine Island Glacier to observed ocean forcing, Geophysical Research Letters, https://doi.org/10.1002/2016GL070500, 2016.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A. C. M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., Haimberger, L., Healy, S. B., Hersbach, H., Hólm, E. V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., McNally, A. P., Monge-Sanz, B. M., Morcrette, J.-J., Park, B.-K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J.-N., and Vitart, F.: The ERA-Interim reanalysis: configuration and performance of the data assimilation system, Quarterly Journal of the Royal Meteorological Society, 137, 553–597, https://doi.org/10.1002/qj.828, http://dx.doi.org/10.1002/qj.828, 2011.

Dinniman, M. S., Klinck, J. M., and Smith, W. O.: Cross-shelf exchange in a model of the Ross Sea circulation and biogeochemistry, Deep Sea Research Part II: Topical Studies in Oceanography, 50, 3103–3120, 2003.

Dutrieux, P., Vaughan, D. G., Corr, H. F., Jenkins, A., Holland, P. R., Joughin, I., and Fleming, A.: Pine Island Glacier ice shelf melt distributed at kilometre scales, The Cryosphere, 7, 1543–1555, https://doi.org/10.5194/tc-7-1543-2013, 2013.

Fahnestock, M., Scambos, T., Moon, T., Gardner, A., Haran, T., and Klinger, M.: Rapid large-area mapping of ice flow using Landsat 8, Remote Sensing of Environment, 185, 84–94, https://doi.org/10.1016/j.rse.2015.11.023, 2016.

Fraser, A. D., Massom, R. A., Michael, K. J., Galton-Fenzi, B. K., and Lieser, J. L.: East Antarctic landfast sea ice distribution and variability, 2000–08, Journal of Climate, 25, 1137–1156, https://doi.org/10.1175/JCLI-D-10-05032.1, 2012.

Fricker, H. A., Popov, S., Allison, I., and Young, N.: Distribution of marine ice beneath the Amery Ice Shelf, Geophysical Research Letters, 28, 2241–2244, https://doi.org/10.1029/2000GL012461, 2001.

Fukumori, I., Wang, O., Fenty, I., Forget, G., Heimbach, P., and Ponte, R. M.: ECCO Version 4 Release 3, 2017.

Galton-Fenzi, B., Hunter, J., Coleman, R., Marsland, S., and Warner, R.: Modeling the basal melting and marine ice accretion of the Amery Ice Shelf, Journal of Geophysical Research: Oceans, 117, 2012.

Greenbaum, J., Blankenship, D., Young, D., Richter, T., Roberts, J., Aitken, A., Legresy, B., Schroeder, D., Warner, R., Van Ommen, T., et al.: Ocean access to a cavity beneath Totten Glacier in East Antarctica, Nature Geoscience, 8, 294–298, https://doi.org/10.1038/ngeo2388, 2015.

Greene, C. A.: Drivers of change in East Antarctic ice shelves, Ph.D. thesis, The University of Texas at Austin, 2017.

Greene, C. A. and Blankenship, D. D.: A Method of Repeat Photoclinometry for Detecting Kilometer-Scale Ice Sheet Surface Evolution, IEEE Transactions on Geoscience and Remote Sensing, 56, 2074–2082, https://doi.org/10.1109/TGRS.2017.2773364, 2018.

Greene, C. A., Blankenship, D. D., Gwyther, D. E., Silvano, A., and van Wijk, E.: Wind causes Totten Ice Shelf melt and acceleration, Science Advances, 3, e1701 681, https://doi.org/10.1126/sciadv.1701681, 2017a.

Greene, C. A., Gwyther, D. E., and Blankenship, D. D.: Antarctic Mapping Tools for MATLAB, Computers & Geosciences, 104, 151–157, https://doi.org/10.1016/j.cageo.2016.08.003, 2017b.

Gwyther, D., Galton-Fenzi, B., Hunter, J., and Roberts, J.: Simulated melt rates for the Totten and Dalton ice shelves, Ocean Science, 10, 267–279, https://doi.org/10.5194/os-10-267-2014, http://dx.doi.org/10.1016/10.5194/os-10-267-2014, 2014.

Haran, T., Bohlander, J., Scambos, T., Painter, T., and Fahnestock, M.: MODIS Mosaic of Antarctica 2008-2009 (MOA2009) Image Map, Version 1, NSIDC National Snow and Ice Data Center, https://doi.org/10.7265/N5KP8037, 2014.

Howat, I. M., Box, J. E., Ahn, Y., Herrington, A., and McFadden, E. M.: Seasonal variability in the dynamics of marine-terminating outlet glaciers in Greenland, Journal of Glaciology, 56, 601–613, 2010.

Hulbe, C. L., Johnston, R., Joughin, I., and Scambos, T.: Marine ice modification of fringing ice shelf flow, Arctic, Antarctic, and Alpine Research, 37, 323–330, 2005.

Joughin, I., MacAyeal, D. R., and Tulaczyk, S.: Basal shear stress of the Ross ice streams from control method inversions, Journal of Geophysical Research: Solid Earth, 109, https://doi.org/10.1029/2003JB002960, http://dx.doi.org/10.1029/2003JB002960, 2004.

Joughin, I., Das, S. B., King, M. A., Smith, B. E., Howat, I. M., and Moon, T.: Seasonal speedup along the western flank of the Greenland Ice Sheet, Science, 320, 781–783, 2008.

Khazendar, A., Rignot, E., and Larour, E.: Roles of marine ice, rheology, and fracture in the flow and stability of the Brunt/Stancomb-Wills Ice Shelf, Journal of Geophysical Research: Earth Surface, 114, https://doi.org/10.1029/2008JF001124, 2009.

Krug, J., Durand, G., Gagliardini, O., and Weiss, J.: Modelling the impact of submarine frontal melting and ice mélange on glacier dynamics, The Cryosphere, 9, 989–1003, 2015.

Li, X., Rignot, E., Mouginot, J., and Scheuchl, B.: Ice flow dynamics and mass loss of Totten Glacier, East Antarctica, from 1989 to 2015, Geophysical Research Letters, 43, 6366–6373, https://doi.org/10.1002/2016GL069173, 2016.

Liu, H. and Miller, K.: Fracture toughness of fresh-water ice, Journal of Glaciology, 22, 135–143, 1979.

Luckman, A., Benn, D. I., Cottier, F., Bevan, S., Nilsen, F., and Inall, M.: Calving rates at tidewater glaciers vary strongly with ocean temperature, Nature Communications, 6, 8566, https://doi.org/10.1038/ncomms9566, 2015.

Massom, R. A., Giles, A. B., Fricker, H. A., Warner, R. C., Legrésy, B., Hyland, G., Young, N., and Fraser, A. D.: Examining the interaction between multi-year landfast sea ice and the Mertz Glacier Tongue, East Antarctica: Another factor in ice sheet stability?, Journal of Geophysical Research: Oceans, 115, 2010.

Massom, R. A., Giles, A. B., Warner, R. C., Fricker, H. A., Legrésy, B., Hyland, G., Lescarmontier, L., and Young, N.: External influences on the Mertz Glacier Tongue (East Antarctica) in the decade leading up to its calving in 2010, Journal of Geophysical Research: Earth Surface, 120, 490–506, 2015.

Massom, R. A., Scambos, T. A., Bennetts, L. G., Reid, P., Squire, V. A., and Stammerjohn, S. E.: Antarctic ice shelf disintegration triggered by sea ice loss and ocean swell, Nature, p. 1, 2018.

Menemenlis, D., Campin, J.-M., Heimbach, P., Hill, C., Lee, T., Nguyen, A., Schodlok, M., and Zhang, H.: ECCO2: High resolution global ocean and sea ice data synthesis, Mercator Ocean Quarterly Newsletter, 31, 13–21, 2008.

Messerli, A. and Grinsted, A.: Image georectification and feature tracking toolbox: ImGRAFT, Geoscientific Instrumentation, Methods and Data Systems, 4, 23, https://doi.org/10.5194/gi-4-23-2015, http://dx.doi.org/10.5194/gi-4-23-2015, 2015.

Miles, B. W., Stokes, C. R., and Jamieson, S. S.: Pan-ice-sheet glacier terminus change in East Antarctica reveals sensitivity of Wilkes Land to sea-ice changes, Science Advances, 2, e1501 350, https://doi.org/10.1126/sciadv.1501350, 2016.

Miles, B. W., Stokes, C. R., and Jamieson, S. S.: Simultaneous disintegration of outlet glaciers in Porpoise Bay (Wilkes Land), East Antarctica, driven by sea ice break-up., The Cryosphere., 11, 427–442, 2017.

Moon, T., Joughin, I., Smith, B., Broeke, M. R., Berg, W. J., Noël, B., and Usher, M.: Distinct patterns of seasonal Greenland glacier velocity, Geophysical Research Letters, 41, 7209–7216, https://doi.org/10.1002/2014GL061836, 2014.

Moon, T., Joughin, I., and Smith, B.: Seasonal to multiyear variability of glacier surface velocity, terminus position, and sea ice/ice mélange in northwest Greenland, Journal of Geophysical Research: Earth Surface, 120, 818–833, https://doi.org/10.1002/2015JF003494, 2015.

Mouginot, J., Rignot, E., Scheuchl, B., and Millan, R.: Comprehensive Annual Ice Sheet Velocity Mapping Using Landsat-8, Sentinel-1, and RADARSAT-2 Data, Remote Sensing, 9, 364, 2017a.

Mouginot, J., Scheuchl, B., and Rignot, E.: MEaSUREs Antarctic Boundaries for IPY 2007-2009 from Satellite Radar, Version 2, NASA National Snow and Ice Data Center Distributed Active Archive Center, https://doi.org/10.5067/AXE4121732AD, 2017b.

Mouginot, J., Scheuchl, B., and Rignot, E.: MEaSUREs Annual Antarctic Ice Velocity Maps 2005-2016, Version 1, https://doi.org/10.5067/9T4EPQXTJYW9, 2017c.

Nakamura, K., Doi, K., and Shibuya, K.: Fluctuations in the flow velocity of the Antarctic Shirase Glacier over an 11-year period, Polar Science, 4, 443–455, https://doi.org/10.1016/j.polar.2010.04.010, 2010.

Nick, F. M., Vieli, A., Howat, I. M., and Joughin, I.: Large-scale changes in Greenland outlet glacier dynamics triggered at the terminus, Nature Geoscience, 2, 110, https://doi.org/10.1038/ngeo394, 2009.

Otero, J., Navarro, F. J., Lapazaran, J. J., Welty, E., Puczko, D., and Finkelnburg, R.: Modeling the Controls on the Front Position of a Tidewater Glacier in Svalbard, Frontiers in Earth Science, 5, 29, https://doi.org/10.3389/feart.2017.00029, 2017.

Paolo, F. S., Fricker, H. A., and Padman, L.: Volume loss from Antarctic ice shelves is accelerating, Science, 348, 327–331, https://doi.org/10.1126/science.aaa0940, 2015.

Parizek, B. R. and Alley, R. B.: Implications of increased Greenland surface melt under global-warming scenarios: ice-sheet simulations, Quaternary Science Reviews, 23, 1013–1027, https://doi.org/10.1016/j.quascirev.2003.12.024, 2004.

Picard, G. and Fily, M.: Surface melting observations in Antarctica by microwave radiometers: Correcting 26-year time series from changes in acquisition hours, Remote Sensing of Environment, 104, 325–336, 2006.

Pritchard, H., Ligtenberg, S., Fricker, H., Vaughan, D., Van den Broeke, M., and Padman, L.: Antarctic ice-sheet loss driven by basal melting of ice shelves, Nature, 484, 502–505, https://doi.org/10.1038/nature10968, 2012.

Pritchard, H. D., Arthern, R. J., Vaughan, D. G., and Edwards, L. A.: Extensive dynamic thinning on the margins of the Greenland and Antarctic ice sheets, Nature, 461, 971, 2009.

Reeh, N., Thomsen, H. H., Higgins, A. K., and Weidick, A.: Sea ice and the stability of north and northeast Greenland floating glaciers, Annals of Glaciology, 33, 474–480, https://doi.org/10.3189/172756401781818554, 2001.

Rignot, E., Mouginot, J., and Scheuchl, B.: MEaSUREs InSAR-Based Antarctica Ice Velocity Map, https://doi.org/10.5067/MEASURES/CRYOSPHERE/nsidc-0484.001, http://dx.doi.org/10.5067/MEASURES/CRYOSPHERE/nsidc-0484.001, 2011.

Rignot, E., Jacobs, S., Mouginot, J., and Scheuchl, B.: Ice-shelf melting around Antarctica, Science, 341, 266–270, https://doi.org/10.1126/science.1235798, 2013.

Rignot, E., Mouginot, J., and Scheuchl, B.: MEaSUREs InSAR-Based Antarctica Ice Velocity Map, Version 2, https://doi.org/10.5067/D7GK8F5J8M8R, 2017.

Robel, A. A.: Thinning sea ice weakens buttressing force of iceberg mélange and promotes calving, Nature Communications, 8, 2017.

Roberts, J., Warner, R., Young, D., Wright, A., van Ommen, T., Blankenship, D., Siegert, M., Young, N., Tabacco, I., Forieri, A., et al.: Refined broad-scale sub-glacial morphology of Aurora Subglacial Basin, East Antarctica derived by an ice-dynamics-based interpolation scheme, The Cryosphere, 5, 551, https://doi.org/10.5194/tc-5-551-2011, 2011.

Roberts, J., Galton-Fenzi, B. K., Paolo, F. S., Donnelly, C., Gwyther, D. E., Padman, L., Young, D., Warner, R., Greenbaum, J., Fricker, H. A., et al.: Ocean forced variability of Totten Glacier mass loss, Geological Society, London, Special Publications, 461, SP461–6, 2017.

Scambos, T., Bohlander, J., and Raup, B.: Images of Antarctic Ice Shelves, MODIS channel 2. National Snow and Ice Data Center, https://doi.org/10.7265/N5NC5Z4N, 2001, updated 2018.

Scambos, T., Fahnestock, M., Gardner, A., and Klinger, M.: Global Land Ice Velocity Extraction from Landsat 8 (GoLIVE), Version 1.1, https://doi.org/10.7265/N5ZP442B, 2016.

Schoof, C.: Ice-sheet acceleration driven by melt supply variability, Nature, 468, 803, 2010.

Shchepetkin, A. F. and McWilliams, J. C.: The regional oceanic modeling system (ROMS): a split-explicit, free-surface, topography-following-coordinate oceanic model, Ocean Modelling, 9, 347–404, 2005.

Sohn, H.-G., Jezek, K. C., and van der Veen, C. J.: Jakobshavn Glacier, West Greenland: 30 years of spaceborne observations, Geophysical Research Letters, 25, 2699–2702, 1998.

Tamura, T., Ohshima, K. I., Fraser, A. D., and Williams, G. D.: Sea ice production variability in Antarctic coastal polynyas, Journal of Geophysical Research: Oceans, 121, 2967–2979, 2016.

Thyng, K. M., Greene, C. A., Hetland, R. D., Zimmerle, H. M., and DiMarco, S. F.: True colors of oceanography: Guidelines for effective and accurate colormap selection, Oceanography, 29, https://doi.org/10.5670/oceanog.2016.66, 2016.

Timmermann, R., Le Brocq, A., Deen, T., Domack, E., Dutrieux, P., Galton-Fenzi, B., Hellmer, H., Humbert, A., Jansen, D., Jenkins, A., et al.: A consistent data set of Antarctic ice sheet topography, cavity geometry, and global bathymetry, Earth System Science Data, 2, 261, 2010.

Todd, J. and Christoffersen, P.: Are seasonal calving dynamics forced by buttressing from ice mélange or undercutting by melting? Outcomes from full-Stokes simulations of Store Glacier, West Greenland, The Cryosphere, 8, 2353–2365, 2014.

Vaughan, D. and Doake, C.: Recent atmospheric warming and retreat of ice shelves on the Antarctic Peninsula, Nature, 379, 328, 1996.

Walter, J. I., Box, J. E., Tulaczyk, S., Brodsky, E. E., Howat, I. M., Ahn, Y., and Brown, A.: Oceanic mechanical forcing of a marine-terminating Greenland glacier, Annals of Glaciology, 53, 181–192, 2012.

Young, D. A., Wright, A. P., Roberts, J. L., Warner, R. C., Young, N. W., Greenbaum, J. S., Schroeder, D. M., Holt, J. W., Sugden, D. E., Blankenship, D. D., et al.: A dynamic early East Antarctic Ice Sheet suggested by ice-covered fjord landscapes, Nature, 474, 72–75, https://doi.org/10.1038/nature10114, 2011.

Zhou, C., Zhou, Y., Deng, F., Songtao, A., Wang, Z., and Dongchen, E.: Seasonal and interannual ice velocity changes of Polar Record Glacier, East Antarctica, Annals of Glaciology, 55, 45–51, https://doi.org/10.3189/2014AoG66A185, 2014.

Zwally, H. J., Abdalati, W., Herring, T., Larson, K., Saba, J., and Steffen, K.: Surface melt-induced acceleration of Greenland ice-sheet flow, Science, 297, 218–222, https://doi.org/10.1126/science.1072708, 2002.