Dear Kenny Matsuoka,

We are very appreciative for the reviews of our manuscript "Antarctic Ice Shelf Thickness Change from Multi-Mission Lidar Mapping." In response to the reviewer comments, we have revised the manuscript to clarify some essential points and add a comparative analyses with Pritchard et al. (2012) and Rignot et al. (2013) for the ice shelves in the Amundsen Sea. The modifications did not change the overall conclusions or results.

In the revision, we include:

- 1. A point-by-point response to the reviewer comments. Responses are *italicized and gray*.
- 2. An enumerated list of the modifications made to the manuscript.
- 3. A copy of the manuscript with the changes noted. (Highlighted with red struck-through text to denote subtractions and blue underlined text to denote additions)
- 4. A final copy of the manuscript with those same changes incorporated.

Regards, Tyler C. Sutterley

First Reviewer Comments:

In this second version of the manuscript, the Authors have added a substantial discussion to the text, and have also included several new references. The text has been restructured, which does improve the overall flow of the manuscript. There are, however, some pending issues that should be addressed/clarified in the final version.

Thank you for your helpful review of our revised manuscript. We address your comments point-by-point and update the manuscript accordingly.

• There is an issue that has been raised during the first round of review (Reviewer #2 pointed this out very clearly): The distinction between Eulerian vs Lagrangian melt rates. There are two (main) melt quantities when referring to ice shelf melting in the broad sense: (1) The background melt; the melting that gives the ice shelf its configuration (i.e. thicker at the GL and thinning towards the ice front). This means, there is a great deal of melting occurring in the steady state for the ice shelf to acquire its stable geometry. (2) The excess melt; which reflects the ice shelf loss or variability at the base. When equating this melt with the mass change at the surface we obtain the iceshelf net mass loss or gain. Ultimately, we are interested in estimating #2. By tracking a fixed point on the surface of a flowing ice shelf, and comparing this point at two different epochs (this is a Lagrangian observation), we are detecting both melt signals: the thickness gradient (1) and the temporal change (2). So one needs to deconvolve these two from a purely Lagrangian observation. A Eulerian observation, on the other hand, is detecting #2. This is why it is inconsistent to compare directly Lagrangian vs Eulerian observations.

These are good points and points towards the purpose of comparing multiple time periods. By looking at more than span of time, we are able to compare snapshots around the baseline melt. In the future with ICESat-2 and beyond, we can extend the time series and looking at more sub-periods to help isolate both the modern-day background melt, and determine deviations from the background due to climatic variations and possibly long-term change.

• The authors may have addressed this properly, but it is (still) not clear in the text when referring to "Lagrangian melt" what signal is being referred to: the total melt (#1 + #2) [Dh/Dt], which is inherent to the Lagrangian observation; or the Lagrangian-derived melt in excess (#2) $[dh/dt_{\text{Lagrange}}]$, which requires posterior separation. For example, in Figure 4, are all the 3 upper panels referring specifically to the temporal change of surface lowering/melt in excess (i.e. $dh/dt_{\text{Euler}} \text{ vs } dh/dt_{\text{Lagrange}} \dots$ or it is $dh/dt_{\text{Euler}} \text{ vs. } Dh/Dt$)?

We update the text accordingly to clarify that we are looking at variations in DH/Dt. We are not determining deflections from the background as we do not have a long enough (30 years) baseline of observations to adequately determine the mean.

• I think this issue still needs to be clarified in the text. It is a complex, and some times nonintuitive, matter. This is a good opportunity for a manuscript addressing both types of measurements to shed some light into it.

This is a great point. We add some context to the discussion section.

• Please increase the dots/symbols on all your plots. Since your estimates are sparse (due to the nature of OIB sampling), it is far more informative to identify the color/value and location of the plotted estimates than trying to stay true to the spatial scale of the measurements (i.e. footprint size of flight lines).

Fair point. The symbol size has been increased.

 "We find that our method is a significant improvement over Eulerian-derived estimates that require substantial smoothing or spatial averaging of the data." (Isn't "smoothing or spatial averaging" the same?) This broad statement is only true because you are dealing with very sparse along flight data. In the presence of good spatial coverage (as that provided by satellites) and high-quality velocity fields, a Eulerian approach might be preferred over a Lagrangian derivation since the latter leads to massive data loss and potentially misses the GL.

Fair point. Intent was to differentiate between smoothing (e.g. Gaussian averaging) and reducing the spatial resolution (i.e. increasing the grid step size). We modify the sentence as the impact of either technique is the same. Yes, idealistically Eulerian-derived thickness change would be preferred. We add more context to the discussion section.

Minor edits:

p1, I3: Operation IceBridge → NASA's Operation IceBridge

References have been updated

p1, I3: oceanic and surface processes, using

Changed to "oceanic processes from measurements and models, surface velocity measurements from synthetic aperture radar, and high-resolution outputs from regional climate models."

p5, I3: "The absolute precision of the RACMO2.3p2 model outputs has been estimated...", and what's the precision?

Kuipers Munneke et al. (2017) list the SMB uncertainty as 15% uncertainty of the SMB rate.

p9, I5: "to test their coherence". In the formal statistical sense, "coherence" is correlation as a function of frequency, which I don't think is what you are referring to.

Fair point. Changed to "correspondence".

Second Reviewer Comments

SUMMARY

The authors use airborne laser altimetry (from airborne topographic mappers (ATM)) over Antarctic Peninsula (AP) and Amundsen Sea (AS) ice shelves, plus models of surface mass balance and firn compaction, to measure ice shelf thinning rates and assign these rates to individual terms in the mass balance. The study is complementary to several previous studies that used satellite altimeters. The coverage of ATM is poor prior to Operation Icebridge (OIB). However, it has some advantages in terms of dedicated tracks, in particular allowing measurements to get close to grounding lines. It is therefore a valuable study, and dataset, to provide to the community.

Thank you Dr. Padman for your helpful second review of our manuscript. We have further revised the manuscript following your suggestions to clarify some essential points and to improve the overall analysis.

RESPONSES TO ANONYMOUS REFEREE #1

• "We did not compare with Pritchard et al. (2012) as the data is not provided in a compiled form. Rignot et al. (2013) do not provide publicly available data." This is true; however, data sets are available from these authors on request.

Good point. We updated the manuscript to include comparisons with Pritchard et al. (2012) and Rignot et al. (2013) for the ice shelves in the Amundsen Sea.

 "However, laser altimetry datasets have more accurate surface determination and can more accurately track over regions of abrupt topographical change. ICESat-2 should provide a valuable extension to the laser altimetry record and help separate short term oscillations with longterm change."

It is true that lasers track the true surface better (much better!) than radar. However, if your firn density model (providing the correction for firn air content) is wrong, it is possible that the radar provides a *better* estimate of basal mass balance than you get from laser.

This is an excellent point. We expand upon this in the discussion to clarify the strengths and weaknesses of each instrument.

GENERAL COMMENTS

The authors have carried out a major overhaul of their manuscript in response to the first round of reviewer comments, including much better organization. However, I still have issues that I think need to be addressed.

1. Figures are not ordered correctly. This made it hard to follow at some points.

We reworked the text to improve continuity for the figures.

2. As I think I now understand, *all* thickness change rates are cited in Lagrangian terms. Even "Eulerian TINs" have been corrected for divergence. However, the authors need to appreciate that at least some of their readers are going to default to "thickness change means Eulerian" (i.e., evidence that mass/volume of the ice shelf is changing). I still contend that the "standard" use of Lagrangian methods is to smooth out the individual estimates of height change before *removing* the divergence term to get back to thickness change in Eulerian terms, rather than reporting on

Lagrangian changes where all of it *might* be divergence with no SMB and BMB contributions. Hence, I still argue for using the Lagrangian derivative symbol (DH/Dt) rather than the words "thickness change", so readers are constantly reminded what they are looking at.

These are good points. We update the passages accordingly.

3. Related to this: One way in which Lagrangian methodology "smooths" thickness change is when changes due to divergence dominant over SMB and BMB variability. That is, even ignoring surface topographic variability that is subsequently advected to create "noise" in the method. Lagrangian processing might produce a smoother field just because the thickness change numbers are larger and more coherent. I'm not arguing against Lagrangian processing, but the manuscript should explain in more detail the effects of different processing options.

While it is true that there may be an inherent smoothing due to the dominance of the flux divergence term, the Lagrangian processing does make a major difference. The plot below is surface elevation from 2008-10-26 compared with a flight line from 2016-11-10 (not corrected for oceanic or surface processes and not corrected for strain). When using Eulerian processing, the oscillations in ice thickness advect "out of phase" and can cause large artificial anomalies when calculating elevation change (difference between Red and Green). With Lagrangian processing, the effect of these gradients is minimized as the same parcels of ice can be compared (difference between Red and Purple).



4. Minor general comment: consistent units (either m or meters, not changing), and space between values and units (200 m, not 200m)

Done.

SPECIFIC

p.1/I.8–9: See general comments. The first part of this sentence sort of makes sense in terms of Lagrangian DH/Dt, but is then violated by the second part which says that other processes also play a role. Maybe it is "dominated by flux divergence" but certain times and places show other important terms?

Fair point. We modified the sentence accordingly.

"We find that the Larsen-C Ice Shelf is close to steady state over our observation period with spatial variations in ice thickness largely due to the flux divergence of the shelf. Firn and surface processes are responsible for some short-term variability in ice thickness of the Larsen-C Ice Shelf over the time period."

p.1/I.21: I still don't think Rignot et al. (2013) is a good citation for evidence of buttressing. There are many others that focus more on the mechanics of this process rather than just asserting it. The same goes for Shepherd et al. (2003) and Fricker and Padman (2012).

We edited these sentences and added more detail about the technical mechanics. "Floating ice shelves can exert control on the grounded ice sheet's overall stability by buttressing the flow of the glaciers upstream (Dupont and Alley, 2005). The response of inland glaciers to ice shelf variations is complicated, and is dependent on both the inland bed topography and the ice shelf geometry (Goldberg et al., 2009; Gagliardini et al., 2010; Gudmundsson, 2013)."

p.1/I.21–24: This would flow better if you started with something like "The mass budget of an ice shelf is the sum of several mass gain and loss terms (Thomas, 1979). Mass is gained by, ... Losses are associated with ... "

Done.

p.2/I.1: Isn't mass rather than volume the important term? I think Paolo et al. (2016) used volume because of concerns over firn models, but the other two papers there are attempting *mass* balance calcs.

Updated.

p.2/I.4: "at accelerated rates FOR SEVERAL years following the collapse"

Done.

p.2/I.7–9: I think I pointed this out last time: It's the *increase* of CDW heat that would drive accelerated thinning, not just the presence of CDW heat. Unless you think it wasn't there at all, the last time these glaciers were in balance, or you are referring to changes *after* the irreversible onset of MISI (in which case you need more words.)

Fair points. Jacobs et al. (2011) note that it is likely due to both an increase in CDW heat content and an increase in sub-shelf cavity circulation. We updated the passage accordingly. "The dynamical change of these glaciers likely stems from increases in sub-shelf circulation and heat content of warm Circumpolar Deep Water, which enhanced ocean-driven melt causing thinning of the buttressing peripheral ice shelves (Jacobs et al., 2011)."

p.2/I.18: What is "Icessn" after "Atm"? If it's important, it'll need to stay with the "ATM" name later on.

Icessn is the name of the Level-2 ATM product. According to Michael Studinger (GSFC) the meaning of Icessn has been lost over time.

p.2/l.28: delete "be in reference to"; okay just to say "converted to the 2014 solution ... "

Done.

p.3/I.22: Scambos et al. (2001) is a very early cite for delineation of ice shelf extent

NSIDC suggests this citation for the MODIS images of ice shelves dataset. The delineations were done in this study.

p.3/I.27: "corrected for ice strain effects following...". Clearer, and more precise, might be to say "have been corrected to Lagrangian thinning rates by adding in the effects of strain." Also, I think Moholdt et al. *removed* strain (to get to Lagrangian-processed, *Eulerian* dh/dt), rather than adding in strain.

Done.

"Measurements compiled using the Eulerian TINs scheme have been made comparable to the Lagrangian thinning rates by adding the effects of strain using the relation from Moholdt et al. (2014)."

p.5/I.14–15: "firn-column heights" is a bit vague. Something like Fig. 3 would have been a good place to outline what everything is. Is this height relative to "pore closeoff depth" (defined as some density?), or the equivalent of "firn air content", or ???

Good point. We update the text to note that we use the firn-column air content.

p.5/I.29: I'm assuming everything is Lagrangian, but saying "the change in ice thickness of" always implies, to me, a change in the volume/mass of the ice shelf. But in fact you conclude that it's fairly close to steady state, and these 'changes' are just because ice diverges.

Yes, of course. Modified to fit intent.

p.5/I.30: Cite to Figure 6 is wrong; or at least, Fig. 6 should be moved to Fig. 4, and this cite should be to Fig. 4 (it is the first figure cite after Fig. 3).

We added an initial paragraph in the results section to improve the continuity.

p.6/I.3: Again "is thinning" means something different from what you want people to be thinking in your Lagrangian FoR.

Updated.

p.6/l.10: wrong figure cite. (last one l'll point out.)

Figure 7 was the correct cite for this sentence.

p.6/I.11: "Wilkens" \rightarrow "Wilkins"

Fixed.

p.6/l.14: Not clear what other way it can "ablate" other than through basal melting. What other explanation do you have in mind, that you are discounting?

Particularly in the Peninsula, there can be surface melt but how melt is routed is pretty uncertain.

p.6/l.16: Many readers will not know whether 6000 km² is a lot or not. Maybe add ", from xx,xxx to yy,yyy km²"

Done. We also added the percent change

p.6/I.19–21: This is an interesting case where basal melt rate greatly exceeds Lagrangian thinning. But I struggled to understand how it could be, since Lagrangian thinning includes the basal melt. Since DH/Dt<BMB, flow is CONvergent, and/or SMB is quite large. But then you could tell us that it isn't large enough to prevent *Eulerian* rates from being negative (ice shelf thinning).

Fair points. Eulerian values are similar to the Lagrangian values as shown by the plot below. In this case, the basal melt rates are largely due to surface mass balance effects except near the Haydn Inlet (HI) and Schubert Inlet (SI). We expand the results section for WIlkins.



p.6/I.26–31: This discussion is convoluted. You need to tell us first about the existence of a "once grounded (when?) but not any more (after ???)" region. Then explicitly discuss the "always ungrounded" and the "sometimes ungrounded" parts separately.

Section has been reworked to improve continuity.

(same area): On I.31 you say "significantly weaker", but I don't know "than what"? Part of the trouble is that you are jumping back and forth between basal melting and "ice shelf thinning rates". Because of this, I don't know whether I'm meant to be comparing rates in regions, or rates in the same region between epochs.

Fair point. We add "weaker than in the previously grounded area". Section has also been rearranged to improve continuity following your suggestions.

p.6/I.34-p.7/I.1: I really don't think Rignot and Jacobs (2002) tell you that GL melt rates have the highest impact on glacial flow dynamics; they just base their decision to analyze near-GL melt on that assumption. They say "We focus on melt rates near the grounding lines of deep draft outlet glaciers because continental ice discharge is principally controlled by the channeled flow of these ice streams into the ocean (Fig. 1). If these regions are the locus of high basal melting, the potential exists for substantial ocean control over ice shelf, if not ice sheet, mass balance (11213). Indirect observations and computer models have suggested high basal melting in the proximity of deep grounding lines and have shown that melting efficiency will decrease as buoyant plumes lose heat and rise to shallower depths along ice ocean interfaces (14, 15)."

Fair point. They do not test this assumption using ice sheet models and thus are basing their study off of this assumption. However, for our purposes, the next line in Rignot and Jacobs (2002) says that "[...] it is not the average ice shelf melt rate but the melt rate near the grounding line that will have the greatest impact on ice flow dynamics".

p.7/I.56: I don't see how this is a "However, …" statement, since it essentially repeats the content of the previous sentence. Maybe it doesn't matter, but it seems to point to your wanting to tell us about *mean* conditions, *then* variability, but that isn't the distinction I get from these two sentences.

We modified this sentence and moved it to the end of the paragraph. "In addition, isolated crossovers can be calculated with the airborne data using Lagrangian tracking for some ice shelves using along-flow and cross-flow measurements from separate years. These singular crossovers would likely not be representative of the large-scale behavior of the ice shelf due to the spatial variability of ice thickness change, but may still provide valuable metrics for evaluating outputs from ice sheet models."

p.7/I.11–12: Rewrite sentence starting "Ice thickness …". You cannot cite figure panel IDs before the reader even knows what figure to look at. This might be because I recommended *not* starting sentences with "Fig. X shows that …", but there are other ways around it.

That was the reason. We modified the sentences accordingly.

p.7/I.19–21: "much less noise compared with ...". I get what you're saying, but it is dependent on the content of the next sentence to remind us *why* this is true. It also assumes that the benefits outweigh the "costs" of Lagrangian processing. These might include fewer data (depending on flight path choice (and orbits, for satellite application), and dependence on velocities that might not be well enough known to calculate divergence (think of a shear margin where spatial scales of velocities are smaller than what you can comfortably get out of InSAR).

Very fair points. We add in these additional caveats throughout the discussion.

"Using a Lagrangian reference frame may result in fewer co-registered data points and less spatial coverage of measurements compared with using an Eulerian reference frame (Figure 4)."

"Lagrangian-derived estimates also greatly depend on the quality of the velocity estimates used for advecting the ice parcels in time."

"In addition, for some locations, such as near shear margins, ice velocities can vary at smaller spatial scales than what is presently available from SAR measurements and visible imagery feature-tracking."

p.8/I.25: Adusumilli et al. (2018) expanded on the Paolo et al. work by adding in CryoSat-2, but they didn't expand coverage; instead, they limited themselves to just the greater AP area.

Indeed. We rearranged this sentence to clarify this point.

"Adusumilli et al. (2018) expanded on this work by including radar altimetry data from CryoSat-2 to estimate the basal melt rates in the Antarctic Peninsula over a 23 year period."

p.9/I.11: I thought the data set used here is more than IceBridge: Figure 1 shows data going back to 2002, well before OIB.

Good point. We clarify that we use both NASA/CECS Antarctic ice mapping and NASA Operation IceBridge data.

List of Changes

- 1. Added "NASA/CECS Antarctic ice mapping campaigns and NASA"
- 2. *Deleted* "and surface"
- 3. Added "from measurements and models"
- 4. Modified "We find that ice thickness variations of the Larsen-C Ice Shelf are due to the flux divergence of the shelf with firn and surface processes controlling short-term variability over our observation period." to "We find that the Larsen-C Ice Shelf is close to steady state over our observation period with spatial variations in ice thickness largely due to the flux divergence of the shelf. Firn and surface processes are responsible for some short-term variability in ice thickness of the Larsen-C Ice Shelf over the time period."
- 5. Replaced "thinning" with "thickness change"
- 6. Replaced "thinning" with "decreasing in thickness"
- 7. *Replaced* "Operation IceBridge provides a validation dataset" *with* "NASA/CECS Antarctic ice mapping and NASA Operation IceBridge campaigns provide validation datasets"
- 8. *Deleted* "Floating ice shelves exert control on the grounded ice sheet's overall stability by buttressing the flow of the glaciers upstream (Dupont and Alley, 2005; Rignot et al., 2013)."
- 9. Added "modern-day"
- 10. *Deleted* "reduces their ability to buttress the glaciers that flow into them and makes"
- 11. *Added* "may make"
- 12. *Added* "The mass budget of an ice shelf is the sum of several mass gain and loss terms (Thomas, 1979)."
- 13. *Modified* "ice shelves gain mass" to "Mass is gained"
- 14. *Modified* "They lose mass through runoff, wind scour and sublimation at the surface of the shelf, melting at the base of the shelf and through calving (Thomas, 1979)." to "Mass is lost by the runoff of surface meltwater, the erosion and sublimation of snow by wind, the sublimation of snow at the surface of the shelf, the melting of ice at the base of the shelf, and the calving of icebergs (Thomas, 1979)."
- 15. *Added* "Floating ice shelves can exert control on the grounded ice sheet's overall stability by buttressing the flow of the glaciers upstream (Dupont and Alley, 2005)."
- 16. *Added* "The response of inland glaciers to ice shelf variations is complicated, and is dependent on both the inland bed topography and the ice shelf geometry (Goldberg et al., 2009; Gagliardini et al., 2010; Gudmundsson, 2013)."
- 17. Added "Presently,"
- 18. *Modified* "volume, which has" to "mass, which may have"
- 19. *Added* "several"

- 20. Modified "the advection" to "increases in sub-shelf circulation and head content"
- 21. Modified "(ATM Icessn)" to "(ATM) Icessn"
- 22. Deleted "which has flown in Antarctica since 2002 and was"
- Added "ATM instruments have flown in Antarctica since 2002 as part of both NASA/Centro de Estudios Científicos (CECS) Antarctic ice mapping and NASA Operation IceBridge campaigns."
- 24. *Added* "The Level-2 ATM Icessn data is calculated by fitting planar surfaces to the original ATM point clouds at approximately 40 m spacing along track (Studinger, 2014)."
- 25. Deleted "be in reference to"
- 26. Modified "meters" to "m"
- 27. Modified "meters" to "m"
- 28. Modified "100-200m" to "100-200 m"
- 29. Modified "Measurements compiled using the Eulerian TINs scheme have been corrected for ice strain effects following Moholdt et al. (2014)." to "Measurements compiled using the Eulerian TINs scheme have been made comparable to the Lagrangian thinning rates by adding the effects of strain using the relation from Moholdt et al. (2014)."
- **30.** Added " $\frac{Dh}{Dt} = \frac{\partial h}{\partial t} + \frac{\rho_w \rho_{ice}}{\rho_w \rho_{ice}} V \cdot \nabla M$ "
- 31. *Added* "where ρ_w and ρ_{ice} are the densities of sea water and meteoric ice, respectively, and $(V \cdot \nabla M)$ is the ice shelf thickness gradient advection."
- 32. Added "For calculating the mass divergence for comparing Eulerian and Lagrangian-derived ice thickness change rates, we use ice thickness data and uncertainties from Bedmap2, which are primarily derived from Griggs and Bamber (2011) for ice shelves (Fretwell et al., 2013)."
- 33. Added "The ice thickness data from Griggs and Bamber (2011) are calculated assuming hydrostatic equilibrium, which should be valid for most areas downstream of the 1–8 km wide grounding zones (Brunt et al., 2010, 2011)."
- 34. Modified "100m" to "100 m"
- 35. Added "NASA"
- 36. Added "air content"
- 37. Added "air content"
- 38. *Deleted* " ρ_w and ρ_{ice} are the densities of sea water and meteoric ice respectively"
- 39. Added "air content"
- 40. *Deleted* "We use ice thickness data and uncertainties from Bedmap2, which are primarily derived from Griggs and Bamber (2011) for ice shelves (Fretwell et al., 2013)."
- Deleted "The ice thickness estimates are calculated assuming hydrostatic equilibrium, which should be valid for most areas downstream of the 1–8 km wide grounding zones (Brunt et al., 2010, 2011)."

- 42. *Added* "Ice shelf masses were calculated by converting the altimetry-derived ice shelf freeboard heights to ice thickness by assuming hydrostatic equilibrium (Fricker et al., 2001; Griggs and Bamber, 2011)."
- 43. *Added* "We co-register 134 days of ATM data and 32 days of LVIS data for the years 2002–2016."
- 44. *Added* "We compare elevation change measurements between Eulerian and Lagrangian approaches derived using Triangulated Irregular Networks (TINs) (Sutterley et al., 2018, Figure 4)."
- 45. *Added* "Using a Lagrangian reference frame can produce estimates of ice shelf elevation change with much less noise compared with a Eulerian reference frame (Moholdt et al., 2014, Figure 4)."
- 46. *Added* "This is because the advection of ice thickness gradients, such as that from cracks and crevasses in the ice, can saturate the Eulerian-derived estimates (Moholdt et al., 2014; Shean et al., 2018)."
- 47. *Deleted* "Figure 6 (a-b) shows the change in ice thickness of the Larsen-B Remnant and Larsen-C Ice Shelves for two periods, 2002–2008 and 2008–2016, from Pre-IceBridge and Operation IceBridge airborne data."
- 48. *Deleted* "Figure 6 (c-d) shows the estimated basal melt rate of the ice shelves over the same periods."
- 49. *Deleted* "The average thickness change rate between 2008 and 2016 from the flight line data over the Larsen-C Ice Shelf is -1.2±0.9 m/yr."
- 50. *Deleted* "From 2008–2016, the strongest thinning occurs near the grounding zone, particularly for the flight lines starting near Cabinet and Mill Inlets."
- 51. *Added* "We estimate the impact of surface processes, ice divergence, and basal melt using data from a flight line starting near the Whirlwind Inlet of the Larsen-C Ice Shelf (Figure 5a)."
- 52. *Modified* "Scatter in the ice thickness change rate across the flight line is typically 30–50 cm/yr, or a 4–6 cm/yr error in the measured elevation change rate (Figure 5a)." *to* "Scatter in the Lagrangian-derived ice thickness change, DH/Dt, across the flight line is typically 30–50 cm/yr, or a 4–6 cm/yr error in the measured elevation change rate (Figure 5a)."
- 53. *Added* ", *DH*/*Dt*,"
- 54. Added ", indicating the shelf along this line is nearly in steady-state during this period."
- 55. Modified "observed thinning" to "estimated DH/Dt"
- 56. *Added* "The average DH/Dt rate between 2008 and 2016 from the flight line data over the Larsen-C Ice Shelf is -1.4 ± 0.9 m/yr."
- 57. *Added* "From 2008–2016, the strongest DH/Dt rates occur near the grounding zone, particularly for the flight lines starting near Cabinet and Mill Inlets."

- 58. *Added* "However, due to the sensitivity of the laser altimetry estimate to the SMB model (Figure 5a), measurements from radar altimetry may be more accurate determinations of basal melt rate for the ice shelf."
- 59. *Modified* "Wilkens" to "Wilkins"
- 60. Modified "Figure 8 shows the change in ice thickness (a-b) and estimated basal melt rates (c-d) of the Wilkins Ice Shelf for two 3-year periods from 2008–2011 and 2011–2014." to "DH/Dt (a-b) and estimated basal melt rates (c-d) of the Wilkins Ice Shelf for two 3-year periods from 2008–2011 and 2011–2014 is shown in Figure 8." Modified "by over 6000 km²" to "from 16000 to 10000 km² (38%)"
- 61. Modified "thinning" to "DH/Dt"
- 62. *Added* "The average DH/Dt rates from the flight lines were insignificantly different at -35 ± 9 m/yr over 2009–2011 and -33 ± 5 m/yr over 2011–2015."
- 63. *Added* "Basal melt rates near the grounding zone have the highest impact on the glacial flow dynamics (Rignot and Jacobs, 2002)."
- 64. Modified "thinning" to "DH/Dt"
- 65. *Modified* "Ice thickness change" to "DH/Dt"
- 66. *Added* "between the 1996 and 2011 grounding lines"
- 67. *Added* "than in the previously grounded area"
- 68. *Deleted* "The average ice thinning rates from the flight lines were insignificantly different at 36±9 m/yr over 2009–2011 and 35±5 m/yr over 2011–2015."
- 69. *Deleted* "Basal melt rates near the grounding zone have the highest impact on the glacial flow dynamics (Rignot and Jacobs, 2002)."
- 70. Modified "ice thickness change" to "DH/Dt rate"
- 71. Modified "thinning" to "melt"
- 72. *Added* "We compare our estimates of Pine Island Ice Shelf change from airborne laser altimetry with ICESat-derived surface elevation change from Pritchard et al. (2012) and basal melt rate from Rignot et al. (2013) (Figures 10 and 13a-b)."
- 73. *Added* "While there are few data points for comparison and the time periods are not contemporaneous (2002–2009 for the airborne data and 2003–2009 for the ICESat data), we find some significant differences between our airborne altimetry-derived estimates and the satellite derived estimates (Figure 10c,f)."
- 74. *Added* "The RMS difference between the airborne-derived estimate and the satellite-derived estimates are 31 m/yr in terms of basal melt rate (Rignot et al., 2013) and 8 m/yr in terms of surface elevation change (Pritchard et al., 2012)."
- 75. *Added* "For the coincident data, the airborne altimetry data showed more variability in basal melt rate and surface elevation change than the satellite-derived methods (Figure 13b)."

- 76. *Added* "The differences in variability are likely due to the different spatial resolutions of the datasets, the different geophysical corrections applied for each estimate, and the spatial smoothing applied to the Pritchard et al. (2012) and Rignot et al. (2013) estimates."
- 77. Modified "Ice thickness change" to "DH/Dt"
- 78. Modified "thinning" to "decreasing in thickness"
- 79. Modified "thinning" to "DH/Dt"
- 80. *Added* "We compare our airborne laser altimetry data of the Dotson and Crosson Ice Shelves with satellite laser altimetry estimates of surface elevation change from Pritchard et al. (2012) and basal melt rate from Rignot et al. (2013) (Figures 12 and 13c-d)."
- 81. *Added* "The RMS difference between the airborne-derived estimate and the satellite-derived estimates are 5 m/yr in terms of basal melt rate (Rignot et al., 2013) and 4 m/yr in terms of surface elevation change (Pritchard et al., 2012)."
- 82. *Added* "For the coincident data, the airborne altimetry data aligns well with the satellite-derived estimate of basal melt rate from Rignot et al. (2013) (Figure 13c)."
- 83. *Added* "However, the surface elevation estimates from Pritchard et al. (2012) do not align well with our the airborne altimetry-derived estimate (Figure 13d)."
- 84. *Added* "The difference is likely due to the lack of spatial coverage with the airborne estimate, which may not be representative at the 10 km horizontal spatial scale of the Pritchard et al. (2012) estimate, particularly closer to the grounding line (Figure 12f)."
- 85. *Deleted* "Using a Lagrangian reference frame produces estimates of ice shelf elevation change with much less noise compared with a Eulerian reference frame (Moholdt et al., 2014, Figure 4)."
- 86. Added "Using a Lagrangian reference frame may result in fewer co-registered data points and less spatial coverage of measurements compared with using an Eulerian reference frame (Figure 4)."
- 87. Modified "Operation IceBridge" to "airborne"
- 88. Added "NASA"
- 89. *Deleted* "Isolated crossovers can be calculated using Lagrangian tracking for some ice shelves using along-flow and cross-flow measurements from separate years."
- 90. Modified "ICESat-2" to "the NASA ICESat-2 mission"
- 91. *Added* "In addition, isolated crossovers can be calculated with the airborne data using Lagrangian tracking for some ice shelves using along-flow and cross-flow measurements from separate years."
- 92. *Added* "These singular crossovers would likely not be representative of the large-scale behavior of the ice shelf due to the spatial variability of ice thickness change, but may still provide valuable metrics for evaluating outputs from ice sheet models (Figures 10 and 12)."
- 93. *Added* "Lagrangian-derived estimates also greatly depend on the quality of the velocity estimates used for advecting the ice parcels in time."

- 94. *Added* "For some locations, such as near shear margins, ice velocities can vary at smaller spatial scales than what is presently available from SAR measurements and visible imagery feature-tracking."
- 95. *Modified* "Adusumilli et al. (2018) expanded on this work to estimate the basal melt rates over 23 years and including radar altimetry data from CryoSat-2." to "Adusumilli et al. (2018) expanded on this work by including radar altimetry data from CryoSat-2 to estimate the basal melt rates in the Antarctic Peninsula over a 23 year period."
- 96. *Deleted* "Our study provides a validation dataset for floating ice shelves using high-resolution airborne laser altimetry data (Figure 7)."
- 97. *Added* "In addition, in regions of uncertain surface mass balance and firn change, intercomparisons with radar altimetry estimates may help provide important metrics for improving SMB and firn models."
- 98. *Added* "In these regions, radar altimetry estimates of ice thickness change may be more accurate than from laser altimetry due to the SMB uncertainty."
- 99. Added "NASA/CECS Antarctic ice mapping and NASA"
- 100. Modified "is" to "can be"
- 101. *Modified* "require substantial smoothing or" to "may require substantial"
- 102. Added "to reduce the impact of noise"
- 103. Added "Figure 10"
- 104. Replaced "Figure 11" with "Figure 10 (previous)"
- 105. Added "Figure 12"
- 106. Added "Figure 13"

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Antarctic Ice Shelf Thickness Change from Multi-Mission Lidar Mapping

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Abstract.

We calculate rates of ice thickness change and bottom melt for ice shelves in West Antarctica and the Antarctic Peninsula from a combination of elevation measurements from <u>NASA/CECS</u> Antarctic ice mapping campaigns and <u>NASA</u> Operation IceBridge corrected for oceanic and surface processes processes from measurements and models, surface velocity measure-

- 5 ments from synthetic aperture radar, and high-resolution outputs from regional climate models. The ice thickness change rates are calculated in a Lagrangian reference frame to reduce the effects from advection of sharp vertical features, such as cracks and crevasses, that can saturate Eulerian-derived estimates. We use our method over different ice shelves in Antarctica, which vary in terms of size, repeat coverage from airborne altimetry and dominant processes governing their recent changes. We find that ice thickness variations of the Larsen-C Ice Shelf are is close to steady state over our observation period with spatial
- 10 variations in ice thickness largely due to the flux divergence of the shelfwith firm. Firn and surface processes controlling are responsible for some short-term variability over our observation in ice thickness of the Larsen-C Ice Shelf over the time period. The Wilkins Ice Shelf is sensitive to short time-scale coastal and upper-ocean processes, and basal melt is the dominate contributor to the ice thickness change over the period. At the Pine Island Ice Shelf in the critical region near in the grounding zone, we find that ice shelf thinning-thickness change rates exceed 40 m/yr with the change dominated by strong submarine
- 15 melting. Regions near the grounding zones of the Dotson and Crosson Ice Shelves are thinning decreasing in thickness at rates greater than 40 m/yr, also due to intense basal melt. Operation IceBridge provides a validation dataset NASA/CECS Antarctic ice mapping and NASA Operation IceBridge campaigns provide validation datasets for floating ice shelves at moderately high resolution when co-registered using Lagrangian methods.

1 Introduction

20 Most of the drainage from the Antarctic ice sheet is through its peripheral ice shelves, floating extensions of the land ice that cover 75% of the Antarctic coastline and represent 10% of the total ice covered area (Cuffey and Paterson, 2010; Rignot et al., 2013). Floating ice shelves exert control on the grounded ice sheet's overall stability by buttressing the flow of the glaciers upstream (Dupont and Alley, 2005; Rignot et al., 2013). The The modern-day thinning of Antarctic ice shelves reduces their

ability to buttress the glaciers that flow into them and makes may make the shelves more susceptible to fracture and overall collapse (Shepherd et al., 2003; Fricker and Padman, 2012). Ice shelves gain mass The mass budget of an ice shelf is the sum of several mass gain and loss terms (Thomas, 1979). Mass is gained by the advection of ice from the land, the accumulation of snow at the surface, and the freezing of seawater at the ice shelf base (Thomas, 1979). They lose mass through runoff,

5 wind scour and sublimation Mass is lost by the runoff of surface meltwater, the erosion and sublimation of snow by wind, the sublimation of snow at the surface of the shelf, melting the melting of ice at the base of the shelfand through calving, and the calving of icebergs (Thomas, 1979).

Floating ice shelves can exert control on the grounded ice sheet's overall stability by buttressing the flow of the glaciers upstream (Dupont and Alley, 2005). The response of inland glaciers to ice shelf variations is complicated, and is dependent on

- 10 both the inland bed topography and the ice shelf geometry (Goldberg et al., 2009; Gagliardini et al., 2010; Gudmundsson, 2013) . Currently Presently, several ice shelves across Antarctica are losing volume, which has mass, which may have led to the acceleration and intensified discharge of inland ice (Pritchard et al., 2012; Depoorter et al., 2013; Paolo et al., 2016). In 2003, a year after the collapse of the Larsen-B Ice Shelf, some tributary glaciers draining into the Weddell Sea from the Antarctic Peninsula flowed at rates 2–8 times their 1996 flow rates (Rignot et al., 2004). These glaciers continued flowing at the accelerated rates
- 15 several years after the collapse (Rignot et al., 2008; Berthier et al., 2012). Glaciers of the Amundsen Sea Embayment (ASE) in West Antarctica have experienced significant increases in surface velocity, dynamic thinning, and grounding line retreat since the 1990's (Rignot et al., 2002, 2014; Pritchard et al., 2009; Flament and Rémy, 2012). The dynamical change of these glaciers likely stems from the advection increases in sub-shelf circulation and heat content of warm Circumpolar Deep Water, which enhanced ocean-driven melt causing thinning of the buttressing peripheral ice shelves (Jacobs et al., 2011).
- 20 Here, we compile ice shelf thickness change rates calculated using a suite of airborne altimetry datasets, which have been consistently processed and co-registered. We provide a set of co-registered laser altimetry datasets for evaluating estimates from satellite altimetry, photogrammetry and model outputs. The main objectives of this study are to (i) calculate ice shelf thickness change rates, (ii) investigate processes driving the changes in the shelf, (iii) investigate the sensitivity of spatial and temporal sampling to overall estimates and (iv) evaluate different methods of calculating elevation change rates over ice shelves. In the
- 25 following sections, we discuss the co-registration method, the geophysical corrections applied, the results for a sample set of ice shelves and the overall implications of the results for ice shelf studies.

2 Materials and Methods

Our airborne lidar measurements are Level-2 Airborne Topographic Mapper (ATMleessn)) <u>Icessn</u> and Land, Vegetation and Ice Sensor (LVIS) datasets provided by the National Snow and Ice Data Center (NSIDC) (Thomas and Studinger, 2010; Studinger,

30 2014; Blair and Hofton, 2010). ATM is a conically scanning lidar which has flown in Antarctica since 2002 and was developed at the NASA Wallops Flight Facility (Thomas and Studinger, 2010). ATM instruments have flown in Antarctica since 2002 as part of both NASA/Centro de Estudios Científicos (CECS) Antarctic ice mapping and NASA Operation IceBridge campaigns. The Level-2 ATM Icessn data is calculated by fitting planar surfaces to the original ATM point clouds at approximately 40 m spacing along track (Studinger, 2014). LVIS is a large-swath scanning lidar which flew in Antarctica in 2009, 2010, 2011 and 2015 and was developed at NASA Goddard Space Flight Center (Blair et al., 1999; Hofton et al., 2008). For the data release available for Antarctica (LDSv1), the Level-2 LVIS data provides 3 different elevation surfaces computed from the Level-1B waveforms: the highest and lowest returning surfaces from Gaussian decomposition, and the centroidal surface (Blair and

- 5 Hofton, 2010). Here, we use the lowest returning surface when the waveform resembles a single-peak gaussian and the centroid surface when the waveform is multi-peak. The spatial coverages of each instrument in Antarctica for the campaigns prior to and during NASA Operation IceBridge are shown in Figure 1. The elevation datasets from each instrument are converted to be in reference to the 2014 solution of the International Terrestrial Reference Frame (ITRF) (Altamimi et al., 2016). In order to track changes in ice shelf freeboard, the ellipsoid heights for each instrument were converted to be in reference to the GGM05 geoid
- 10 using gravity model coefficients provided by the Center for Space Research (Ries et al., 2016). Changes in ice shelf freeboard are converted into changes in ice thickness by assuming hydrostatic equilibrium following Fricker et al. (2001). Uncertainties for each instrument were calculated following Sutterley et al. (2018).

2.1 Integrated analysis of altimetry

We calculate rates of elevation change by comparing a set of measured elevation values with a set of interpolated elevation values from a different time period after allowing for the advection of the ice (Sutterley et al., 2018; Moholdt et al., 2014; Shean et al., 2018). Each point in a flight line is advected from its original location by integrating the Rignot et al. (2017) MEaSUREs static velocity data derived from synthetic aperture radar (SAR) using a fourth-order Runge-Kutta algorithm. For each data point in a flight line, a set of Delaunay triangles is constructed from a separate flight line using all data points within 300 meters-m from the final location of the advected point (Pritchard et al., 2009, 2012; Rignot et al., 2013). If the advected point

20 lies within the confines of the Delaunay triangulation convex hull, the triangular facet housing the advected point is determined using a winding number algorithm (Sutterley et al., 2018). The new elevation value is calculated using barycentric interpolation with the elevation measurements at the three triangle vertices (Figure 2). The elevation at each vertex point is weighted in the interpolation by the area of the triangle created by the enclosed point and the two opposing vertices (Sutterley et al., 2018).

Assuming that the ice shelf surfaces are not curved over the scale of the individual triangular facet ($\sim 10-100 \text{ metersm}$),

- 25 interpolating to the advected coordinates will compensate for minor slopes in the ice shelf surface so that the elevations of equivalent parcels of ice can be compared in time (Pritchard et al., 2009). At this scale (below 100-200m100-200 m), the topographic relief of uncrevassed ice is primarily due to slopes in the ice surface and a planar assumption should be largely valid (Markus et al., 2017). Rough terrain, snow drifts and low-lying clouds will contaminate the lidar elevation values for the interpolation. In order to limit the effect of contaminated points, the elevation measurements are filtered using the Robust
- 30 Dispersion Estimator (RDE) algorithm described in Smith et al. (2017). In order to minimize the possibility of co-registering measurements over ice shelves with measurements over grounded ice near the grounding zone or measurements over the ocean, sea ice floes and icebergs, we only include points that are on the ice shelf for the compared time periods using grounded ice delineations from Rignot et al. (2016) and Mouginot et al. (2017b) and ice shelf extent delineations manually digitized from Landsat imagery courtesy of the U.S. Geological Survey and MODIS imagery from Scambos et al. (2001).

For comparison, we compile elevation change measurements using an Eulerian approach with the Triangulated Irregular Networks (TINs) technique outlined in Sutterley et al. (2018) and a Lagrangian overlapping footprint approach following Slobbe et al. (2008) and Moholdt et al. (2014). The Eulerian TINs scheme follows the methods of Pritchard et al. (2012) and Rignot et al. (2013) that used data from the NASA ICESat mission. Measurements compiled using the Eulerian TINs scheme

5 have been corrected for ice strain effects following Moholdt et al. (2014). made comparable to the Lagrangian thinning rates by adding the effects of strain using the relation from Moholdt et al. (2014).

$$\frac{Dh}{Dt} = \frac{\partial h}{\partial t} + \frac{\rho_w - \rho_{ice}}{\rho_w \rho_{ice}} V \cdot \nabla M \tag{1}$$

where ρ_w and ρ_{ice} are the densities of sea water and meteoric ice, respectively, and $(V \cdot \nabla M)$ is the ice shelf thickness gradient advection. For calculating the mass divergence for comparing Eulerian and Lagrangian-derived ice thickness change rates,

- 10 we use ice thickness data and uncertainties from Bedmap2, which are primarily derived from Griggs and Bamber (2011) for ice shelves (Fretwell et al., 2013). The ice thickness data from Griggs and Bamber (2011) are calculated assuming hydrostatic equilibrium, which should be valid for most areas downstream of the 1–8 km wide grounding zones (Brunt et al., 2010, 2011) . The Lagrangian overlapping footprint approach uses the same fourth-order Runge-Kutta algorithm to advect the coordinates of the original elevation measurement to a predicted parcel location at a separate time. If any measurements from the separate
- 15 flight line lie within 100m 100 m of the advected point, the elevation measurement closest in Euclidean distance to the advected point is compared against the original measurement.

2.2 Geophysical Corrections

We correct the elevation measurements for geophysical processes following most of the procedures that will be used with the initial release of ICESat-2 data (Markus et al., 2017; Neumann et al., 2018). The processes are described in the following sections and represented as a schematic in Figure 3.

2.2.1 Tidal and Non-Tidal Ocean Variation

Surface elevation changes due to variations in ocean and load tides are calculated using outputs from the Circum-Antarctic Tidal Simulation (CATS2008) model (Padman et al., 2008), a high-resolution inverse model updated from Padman et al. (2002). Surface heights were predicted for the M_2 , S_2 , N_2 , K_2 , K_1 , O_1 , P_1 , Q_1 , M_f and M_m harmonic constituents and then inferred

- 25 for 16 minor constituents following the *PERTH3* algorithm developed by Richard Ray at NASA Goddard Space Flight Center (Ray, 1999). Uncertainties in tidal oscillations were estimated using constituent uncertainties from King et al. (2011). We correct for changes in load and ocean pole tides due to changes in the Earth's rotation vector following Desai (2002) and IERS conventions (Petit and Luzum, 2010). We correct for changes in sea surface height due to changes in atmospheric pressure and wind stress using a dynamic atmosphere correction (DAC) provided by AVISO. The 6-hour DAC product combines outputs
- 30 of the MOD2D-g ocean model, a 2-D ocean model forced by pressure and wind fields from ECMWF based on Lynch and Gray (1979), with an inverse barometer (IB) response (Carrère and Lyard, 2003). Regional sea levels fluctuate due to changes

in ocean dynamics, ocean mass, and ocean heat content (Church et al., 2011; Armitage et al., 2018). Non-tidal sea surface anomalies are removed from the ice shelf data using multi-mission altimetry products computed by AVISO and provided by Copernicus (Le Traon et al., 1998). The non-tidal sea surface anomalies are added to estimates of mean dynamic topography, which is the mean deviation of the sea surface from the Earth's geoid due to ocean circulation. The sea surface anomalies are

5 extrapolated from the valid ice-free ocean values to the ice shelf points following Paolo et al. (2016).

2.2.2 Surface Mass Balance and Firn Compaction

After correcting for the effects of oceanic variation and advection, changes in surface height are due to a combination of accumulation, ablation and firn densification processes. To account for variations in surface elevation due to changes in surface processes, we use monthly mean surface mass balance (SMB) outputs calculated from climate simulations of the Regional Atmospheric Climate Model (RACMO2.3p2) computed by the Ice and Climate group at the Institute for Marine and Atmospheric Research of Utrecht University (Ligtenberg et al., 2013; van Wessem et al., 2014, 2018). We use 5.5km horizontal resolution outputs from a 1979–2016 climate simulation of the Antarctic Peninsula (XPEN055, van Wessem et al., 2016) and a 1979–2015 climate simulation of West Antarctica (ASE055, Lenaerts et al., 2018). The high-resolution outputs better represent

the surface mass balance state than outputs from the 27km ice sheet wide model, particularly in the highly complex topography

- 15 of mountains and glacial valleys in the Antarctic peninsula (van Wessem et al., 2016). The higher spatial resolution topography improves the modeling of wind-driven downstream effects over ice shelves (Datta et al., 2018). SMB is the quantified difference between mass inputs from the precipitation of snow and rain, and mass losses by sublimation, runoff, and wind scour (Lenaerts et al., 2012; van den Broeke et al., 2009). Runoff is the portion of total snowmelt not retained or refrozen within the ice sheet. Wind scour is the erosion and sublimation of wind-blown snow from the ice sheet surface (Das et al., 2013).
- 20 The absolute precision of the RACMO2.3p2 model outputs has been estimated using <u>NASA</u> Operation IceBridge snow radar observations, satellite observations of surface melt, and and in-situ observations, such as ice cores and surface stake measurements, following Kuipers Munneke et al. (2017) and Lenaerts et al. (2018). To correct for variations in the firn layer thickness, we use <u>air content</u> outputs from a semi-empirical firn densification model that simulates the steady-state firn density profile (Ligtenberg et al., 2011, 2012). The firn densification model is forced with surface mass balance outputs, surface temperatures
- 25 fields and near-surface wind speed fields computed by RACMO2.3p2 (Ligtenberg et al., 2011). We assume a 15% uncertainty in surface mass balance and firm <u>air content</u> height change following estimates from Kuipers Munneke et al. (2017).

2.3 Ice Shelf Bottom Melt

10

Changes in ice shelf mass in a Lagrangian reference frame are due to changes in surface mass balance (SMB) processes (M_s) , basal melt (M_b) and the divergence of the ice shelf flow field $(M\nabla \cdot V)$ (Moholdt et al., 2014).

$$30 \quad \frac{dM_s}{dt} + \frac{dM_b}{dt} - M\nabla \cdot V = \frac{\rho_w \rho_{ice}}{\rho_w - \rho_{ice}} \left(\frac{Dh}{Dt} - \frac{\partial h_{oc}}{\partial t} - \frac{\partial h_{fc}}{\partial t}\right) \tag{2}$$

where p_w and p_{ice} are the densities of sea water and meteoric ice respectively, h_{oc} are ocean heights, and h_{fc} are firn-column air content heights. We estimate ice shelf bottom melt rates along flight lines by using mass conservation and estimates of

the mass flux divergence (Rignot and Jacobs, 2002; Moholdt et al., 2014; Rignot et al., 2013). Ice flow divergence fields are calculated from ice velocities from Rignot et al. (2017) differentiated using a Savitzky-Golay filter with an 11 km half-width window (Savitzky and Golay, 1964). The Savitzky-Golay algorithm smooths the velocity field, and reduces the impact of ionospheric noise and other sources of uncertainty on the differentials. Deviations from mean ice flow were calculated

5 using annually resolved ice velocity maps derived from synthetic aperture radar and optical imagery (Mouginot et al., 2017a). We use ice thickness data and uncertainties from Bedmap2, which are primarily derived from Griggs and Bamber (2011) for ice shelves (Fretwell et al., 2013). The ice thickness estimates are calculated assuming hydrostatic equilibrium, which should be valid for most areas downstream of the 1–8 km wide grounding zones (Brunt et al., 2010, 2011). Ice shelf masses were calculated by converting the altimetry-derived ice shelf freeboard heights to ice thickness by assuming hydrostatic equilibrium

10 (Fricker et al., 2001; Griggs and Bamber, 2011).

3 Results

We co-register 134 days of ATM data and 32 days of LVIS data for the years 2002–2016. We compare elevation change measurements between Eulerian and Lagrangian approaches derived using Triangulated Irregular Networks (TINs) (Sutterley et al., 2018, Figure 4). Using a Lagrangian reference frame can produce estimates of ice shelf elevation change with

15 much less noise compared with a Eulerian reference frame (Moholdt et al., 2014, Figure 4). This is because the advection of ice thickness gradients, such as that from cracks and crevasses in the ice, can saturate the Eulerian-derived estimates (Moholdt et al., 2014; Shean et al., 2018).

3.1 Larsen Ice Shelves

- The ice shelves draining from the Antarctic Peninsula into the Weddell Sea have undergone some significant changes over the past three decades. The Larsen-A Ice Shelf collapsed in 1995, and the Larsen-B Ice Shelf partially collapsed in 2002 (Rott et al., 2002, 2011)(Rott et al., 2002, 2011). The tributary glaciers once flowing into these shelves accelerated with the loss of the ice shelf abutment (Rignot et al., 2008). shows the change in ice thickness of the Larsen-B Remnant and Larsen-C Ice Shelves for two periods, 2002–2008 We estimate the impact of surface processes, ice divergence, and 2008–2016, basal melt using data from Pre-IceBridge and Operation IceBridge airborne data. shows the estimated basal melt rate of the ice
- 25 shelves over the same periods. The average thickness change rate between 2008 and 2016 from the flight line data over the Larsen-C Ice Shelf is -1.4±0.9 m/yr. From 2008-2016, the strongest thinning occurs near the grounding zone, particularly for the flight lines starting near Cabinet and Mill Inlets. For a flight line starting near the Whirlwind Inlet, the ice shelf is thinning near the grounding zone at 2 m/yr of the Larsen-C Ice Shelf (Figure 5a). Scatter in the Lagrangian-derived ice thickness changerate, DH/Dt, across the flight line is typically 30–50 cm/yr, or a 4–6 cm/yr error in the measured elevation change
- 30 rate (Figure 5a). Most of the thickness change, DH/Dt, along this line is due to the flux divergence of the shelf, indicating the shelf along this line is nearly in steady-state during this period. As the basal melt rate is calculated via mass conservation and the observed thinning estimated DH/Dt rate largely matches the flux divergence, estimates of the basal melt rate of the

Larsen-C Ice Shelf are highly dependent on the SMB flux estimate. Any uncertainties in reconstructing the regional SMB will significantly impact the resultant basal melt rate estimate. The DH/Dt rate of the Larsen-B Remnant and Larsen-C Ice Shelves for two periods, 2002–2008 and 2008–2016, from NASA/CECS Pre-IceBridge and NASA Operation IceBridge airborne data is shown in Figure 6 (a-b). The estimated basal melt rate of the ice shelves over the same periods is shown in Figure 6 (c-d).

- 5 The average DH/Dt rate between 2008 and 2016 from the flight line data over the Larsen-C Ice Shelf is -1.2 ± 0.9 m/yr. From 2008–2016, the strongest DH/Dt rates occur near the grounding zone, particularly for the flight lines starting near Cabinet and Mill Inlets. We compare our airborne laser altimetry estimate of basal melt rates with a long-term record derived from radar altimetry (Adusumilli et al., 2018). We find that the radar-derived estimate is comparable with the laser-derived estimate within uncertainties for most points outside of the grounding zone (Figure 7). However, due to the sensitivity of the laser altimetry
- 10 estimate to the SMB model (Figure 5a), measurements from radar altimetry may be more accurate determinations of basal melt rate for the ice shelf.

3.2 Wilkens-Wilkins Ice Shelf

The Wilkins Ice Shelf is fed by glaciers on Alexander Island, which is located near the west coast of the Antarctic Peninsula and is the largest of the Antarctic islands. Wilkins Ice Shelf is sensitive to short time-scale coastal and upper-ocean processes

- 15 (Padman et al., 2012) and ablates largely through basal melting (Rignot et al., 2013). shows the change in ice thickness <u>DH/Dt</u> (a-b) and estimated basal melt rates (c-d) of the Wilkins Ice Shelf for two 3-year periods from 2008–2011 and 2011–2014 is shown in Figure 8. The extent of the ice shelf reduced by over 6000 from 16000 to 10000 km² (38%) between 1990 and 2017 (Scambos et al., 2009). The partial collapse occurred once the shelf started decoupling from Charcot Island (Vaughan et al., 1993) and likely occurred due to hydro-fracturing (Scambos et al., 2009). Meltwater ponds covered areas of 300–600 km²
- in Landsat imagery in 1986 and 1990 (Vaughan et al., 1993). The ponds existed largely in the now-collapsed portions of the shelf near Rothschild Island. Average thinning_DH/Dt rates of the Wilkins Ice Shelf from the flight lines were 1.2–1.3±0.7 m/yr from 2008–2011 and 0.7–0.7±0.5 m/yr from 2011–2014. Average estimated basal melt rates from the flight lines were 2.82.5±1.3 m/yr in the earlier period and 2.01.8±0.9 m/yr in the latter period. Basal accretion could have occurred in some regions during the 2011–2014 period.

25 3.3 Pine Island Ice Shelf

The Pine Island Ice Shelf abuts one of the most rapidly changing glaciers in Antarctica (Pritchard et al., 2009; Flament and Rémy, 2012). Figure 9 shows the change in ice thickness (a-b) and estimated basal melt rates (c-d) of the Pine Island Ice Shelf for two periods from 2009–2011 and 2011–2015. These periods were chosen to include repeat measurements from LVIS of the ice shelf near the grounding zone and to use the high-resolution outputs of RACMO2.3p2 ASE055. In the previously grounded

30 region The average DH/Dt rates from the flight lines were insignificantly different at -35 ± 9 m/yr over 2009–2011 and -33 ± 5 m/yr over 2011–2015. Because basal melt rates near the grounding zone have the highest impact on the glacial flow dynamics, we estimate the basal melt rate between the 1996 and 2011 grounding lines (Rignot and Jacobs, 2002). In this previously grounded region, the ice shelf thinning rates were 97DH/Dt rates were -96 ± 15 m/yr during 2009–2011 and $81-79\pm7$ m/yr

during 2011–2015. In this area that was previously grounded, the average estimated basal melt rates from the flight lines were $7077\pm20-18$ m/yr over 2009–2011 and $5461\pm15-12$ m/yr over 2011–2015. Lee thickness change DH/Dt rates outside of the previously grounded area between the 1996 and 2011 grounding lines are significantly weaker , averaging -21 than in the previously grounded area, averaging -20 ± 7 m/yr for 2009–2011 and -15 ± 3 m/yr for 2011–2015. The average ice thinning

- 5 rates from the flight lines were insignificantly different at 36 ± 9 m/yr over 2009–2011 and 35 ± 5 m/yr over 2011–2015. Basal melt rates near the grounding zone have the highest impact on the glacial flow dynamics (Rignot and Jacobs, 2002). The difference in melt rates near the grounding zone between 2009–2011 and 2011–2015 could possibly explain some of the moderation in thinning of the grounded ice and stability in ice discharge from Pine Island Glacier after 2010 (McMillan et al., 2014; Medley et al., 2014). As shown in Figure 9c-d, the ice thickness change DH/Dt rate is dominated by strong submarine thinningmelt,
- 10 which is further evidence of the dominant oceanic controls on the ice shelf mass balance in this region (Rignot, 2002; Shean et al., 2018). However, some of the changes in basal melt rate over the period could be due to large regional interannual-to-decadal variability (Dutrieux et al., 2014; Paolo et al., 2015; Jenkins et al., 2018). We compare our estimates of Pine Island Ice Shelf change from airborne laser altimetry with ICESat-derived surface elevation change from Pritchard et al. (2012) and basal melt rate from Rignot et al. (2013) (Figures 10 and 13a-b). While there are few data points for comparison and the
- 15 time periods are not contemporaneous (2002–2009 for the airborne data and 2003–2009 for the ICESat data), we find some significant differences between our airborne altimetry-derived estimates and the satellite derived estimates (Figure 10c,f). The RMS difference between the airborne-derived estimate and the satellite-derived estimates are 31 m/yr in terms of basal melt rate (Rignot et al., 2013) and 8 m/yr in terms of surface elevation change (Pritchard et al., 2012). For the coincident data, the airborne altimetry data showed more variability in basal melt rate and surface elevation change than the satellite-derived
- 20 methods (Figure 13a-b). The differences in variability are likely due to the different spatial resolutions of the datasets, the different geophysical corrections applied for each estimate, and the spatial smoothing applied to the Pritchard et al. (2012) and Rignot et al. (2013) estimates.

3.4 Dotson and Crosson Ice Shelves

The glaciers flowing into the Dotson and Crosson Ice Shelves have rapidly thinned, increased in speed and experienced significant retreats of grounding line positions over the past 20 years (Mouginot et al., 2014; Scheuchl et al., 2016). Flow speeds of the Crosson Ice Shelf have doubled in some regions over 1996 to 2014, while the flow speed of Dotson has remained largely steady (Lilien et al., 2018). Ice thickness change <u>DH/Dt</u> rates (a-b) and estimated basal melt rates (c-d) of the Dotson and Crosson Ice Shelves are shown in Figure 11 for two periods, 2002–2010 and 2010–2015. Regions near the grounding lines of the input glaciers are thinning decreasing in thickness rapidly for both shelves driven by strong basal melt. Basal melt rates av-

30 eraged 45-71-47-81 m/yr near the grounding zone of Smith glacier over the two periods. Khazendar et al. (2016) documented rapid submarine ice melt and the loss of 300-490 m of floating ice between 2002 and 2009. Our work here provides independent evidence of this large-scale melt using a separate method and more years of data. We find that the ice mass wastage continued unabated between 2010 and 2015 with thinning-DH/Dt rates over the flight lines averaging 22-21±1 m/yr. We compare our airborne laser altimetry data of the Dotson and Crosson Ice Shelves with satellite laser altimetry estimates of

surface elevation change from Pritchard et al. (2012) and basal melt rate from Rignot et al. (2013) (Figures 12 and 13c-d). The RMS difference between the airborne-derived estimate and the satellite-derived estimates are 5 m/yr in terms of basal melt rate (Rignot et al., 2013) and 4 m/yr in terms of surface elevation change (Pritchard et al., 2012). For the coincident data, the airborne altimetry data aligns well with the satellite-derived estimate of basal melt rate from Rignot et al. (2013) (Figure 13c).

5 However, the surface elevation estimates from Pritchard et al. (2012) do not align well with our the airborne altimetry-derived estimate (Figure 13d). The difference is likely due to the lack of spatial coverage with the airborne estimate, which may not be representative at the 10 km horizontal spatial scale of the Pritchard et al. (2012) estimate, particularly closer to the grounding line (Figure 12f).

4 Discussion

- 10 Using a Lagrangian reference frame produces estimates of ice shelf elevation change with much less noise compared with a Eulerian reference frame (Moholdt et al., 2014, Figure 4). The advection of ice thickness gradients, such as that from cracks and crevasses in the ice, can saturate the Eulerian-derived estimates (Moholdt et al., 2014; Shean et al., 2018). Moholdt et al. (2014) showed similar improvements in estimating basal melt rates between Eulerian and Lagrangian processing methods for the Ross and Filchner-Ronne Ice Shelves. In their study, Moholdt et al. (2014) used data from the ICES at mission that were integrated
- 15 using an overlapping footprints scheme.

Using a Lagrangian reference frame may result in fewer co-registered data points and less spatial coverage of measurements compared with using an Eulerian reference frame (Figure 4). Lagrangian tracking of airborne data requires 1) accurate flow-line flight planning, 2) a sufficiently wide scanning swath, or 3) dense grid measurements. Flight lines along-flow need to be accurately planned to ensure upstream measurements can be paired with future downstream measurements. With the current

- 20 Operation IceBridge airborne data at most locations, cross-flow flight lines advected outside of the swath width over multi-year repeat times. This limited our dataset to regions with flow-line measurements, such as the Larsen-C Ice Shelf (Figure 6), or frequent measurements, such as the Dotson and Crosson Ice Shelves (Figure 11). For most ice shelves, repeated airborne data is too sparse to extract large-scale spatial trends, particularly in the era before NASA Operation IceBridge. Isolated crossovers can be calculated using Lagrangian tracking for some ice shelves using along-flow and cross-flow measurements from separate
- 25 years. However, these singular crossovers would likely not be representative of the large-scale behavior of the ice shelf due to the spatial variability of ice thickness change. Satellite altimetry measurements from the NASA ICESat-2 mission (Markus et al., 2017) should help rectify the data limitation problem by providing dense and repeated point clouds. ICESat-2 data could be combined with photogrammetric digital elevation models (DEMs) to create high-resolution ice shelf-wide thickness change maps (Berger et al., 2017; Shean et al., 2018). Combining ICESat-2 with DEMs would help improve the use of the laser
- 30 altimetry data in a Lagrangian reference frame as ice parcels could be accurately tracked between separate satellite tracks. In addition, isolated crossovers can be calculated with the airborne data using Lagrangian tracking for some ice shelves using along-flow and cross-flow measurements from separate years. These singular crossovers would likely not be representative of

the large-scale behavior of the ice shelf due to the spatial variability of ice thickness change, but may still provide valuable metrics for evaluating outputs from ice sheet models (Figures 10 and 12).

Lagrangian-derived estimates also greatly depend on the quality of the velocity estimates used for advecting the ice parcels in time. Here, the airborne data are co-registered in a Lagrangian reference frame using a static velocity map provided by

- 5 NSIDC through the MEaSUREs program (Rignot et al., 2017). However, there are cases that do not fit the assumption of temporally-invariant velocities. Prior to the calving event of the 40,000 km² A-68 iceberg from the Larsen-C Ice Shelf on July 11, 2017, the ice was rifting from the south and the regions downstream of the crack were rotating outward (Hogg and Gudmundsson, 2017, Figure 6). In the Amundsen Sea Embayment, the ice velocity structure has changed year-to-year since the 1990's (Rignot et al., 2008; Mouginot et al., 2014). The floating ice shelves in the Amundsen Sea are also rifting concurrently
- 10 with the acceleration of the instreaming glaciers (Macgregor et al., 2012). For both of these cases, it would be more appropriate to predict the advected parcel location using time-variable velocity maps. However, the spatial coverage of annual velocity maps is lacking for some time periods, which will complicate the advection calculation. For some locations, such as near shear margins, ice velocities can vary at smaller spatial scales than what is presently available from SAR measurements and visible imagery feature-tracking. With the high-temporal resolution data from the ESA Sentinel mission, the Landsat-based
- 15 goLIVE project and the future NASA-ISRO SAR mission (NISAR), the advected parcel locations could be predicted with much greater accuracy for recent NASA Operation IceBridge campaigns and future altimetry missions (Fahnestock et al., 2016; Gardner et al., 2018; Mouginot et al., 2017a). Improvements in ice thickness and ice velocity estimates will also greatly improve estimates of flux divergence and as a consequence estimates of basal melt rates calculated using mass conservation (Berger et al., 2017; Adusumilli et al., 2018).
- This work builds off of the work of Paolo et al. (2015) and Adusumilli et al. (2018) that used radar altimetry data to analyze the recent thinning and basal melt rates of ice shelves. Paolo et al. (2015) calculated changes in the ice thickness time series over an 18-year time period using a suite of satellite radar altimetry data compiled in an Eulerian frame of reference. They found that the overall volume loss of ice shelves accelerated over the period 1994–2012, particularly for the ice shelves of West Antarctica. Adusumilli et al. (2018) expanded on this work by including radar altimetry data from CryoSat-2 to estimate the
- 25 basal melt rates over in the Antarctic Peninsula over a 23 years and including radar altimetry data from CryoSat-2year period. Laser altimeters and radar altimeters can measure different surfaces over snow-covered ice surfaces (Rémy and Parouty, 2009). Idealistically, the laser altimeter will detect the snow surface and the radar altimeter will detect the snow-ice interface. Because laser altimeters ideally detect the snow surface, an estimate of the total column snow/firn height change is needed to calculate the ice shelf freeboard change (Pritchard et al., 2012). For radar altimeters, the radar penetration depth is affected by variations
- 30 in the dielectric properties of the surface layer due to variations in temperature, snow grain size, snow density and moisture content (Partington et al., 1989; Rémy and Parouty, 2009). Due to the variations in penetration depth, estimates of the firm height change below the detected surface are necessary in order to calculate the freeboard change. Determining the sensitivity of radar estimates to surface penetration over different surface types could help reconcile differences between the various estimates . Our study provides a validation dataset for floating ice shelves using high-resolution airborne laser altimetry data
- 35 ((Figure 7). In addition, in regions of uncertain surface mass balance and firn change, inter-comparisons with radar altimetry

estimates may help provide important metrics for improving SMB and firn models. In these regions, radar altimetry estimates of ice thickness change may be more accurate than from laser altimetry due to the SMB uncertainty.

Compiling estimates of elevation change from laser altimetry is non-trivial and different processing methods can produce differing results. Felikson et al. (2017) compared four different processing schemes (crossover differencing, along-track surface

- 5 fits, overlapping footprints and triangulated irregular networks) using ICESat data in an Eulerian sense over grounded ice in Greenland. They found discernible and irreconcilable differences between methods when deriving elevation change over the grounded ice sheet. We compare results from overlapping footprints and triangulated irregular networks to test their coherence correspondence over ice shelf surfaces. As the surface slopes on ice shelves are small, we find that overlapping footprints and TINs approaches produce similar estimates of elevation change with scanning lidars in Lagrangian frames of reference (Figure
- 10 4). The overlapping footprints approach produces a slightly noisier but statistically similar estimate compared with the TINs approach, and is a significantly simpler algorithm to implement.

5 Conclusions

We present a method for measuring ice shelf thickness change through the co-registration of <u>NASA/CECS</u> <u>Antarctic ice</u> mapping and <u>NASA</u> Operation IceBridge laser altimetry data in a Lagrangian reference frame. We use our method to detect

- 15 changes in ice shelves in West Antarctica and the Antarctic Peninsula where the airborne data are available. We find that our method is can be a significant improvement over Eulerian-derived estimates that require substantial smoothing or may require substantial spatial averaging of the data to reduce the impact of noise. However, there are significant limitations when using airborne data for detecting ice shelf thickness change with Lagrangian tracking, particularly the lower spatial coverage and typical lack of repeat tracks over ice shelves. Data from the recently launched NASA ICESat-2 mission will help rectify these
- 20 problems, particularly if combined with high-resolution photogrammetric digital elevation models.

Code and data availability. NASA Operation IceBridge data are freely available from the National Snow and Ice Data Center (NSIDC) at http://nsidc.org/data/ILATM2/ for the Level-2 ATM data and http://nsidc.org/data/ILVIS2/ for the Level-2 LVIS data. NASA MEaSUREs INSAR-derived velocity maps are provided by NSIDC at https://nsidc.org/data/nsidc-0484. Bedmap2 ice thicknesses are provided by the British Antarctic Survey at https://www.bas.ac.uk/project/bedmap-2/. CATS2008 tidal constituents are available from the Earth & Space Re-

- 25 search institute at https://www.esr.org/research/polar-tide-models/. Dynamic atmospheric Corrections are produced by CLS Space Oceanography Division using the Mog2D model from Legos distributed by Aviso, with support from CNES. Ssalto/Duacs non-tidal sea surface products were produced and distributed by the Copernicus Marine and Environment Monitoring Service (CMEMS). Landsat imagery is provided courtesy of the U.S. Geological Survey EarthExplorer service. MODIS images of ice shelves are freely available from NSIDC. Altimetry data from this project are available on Figshare under a CC BY 4.0 license (doi:10.6084/m9.figshare.8159852). The following pro-
- 30 grams are provided by this project for processing the NASA Operation IceBridge data: *nsidc-earthdata* retrieves NASA data from NSIDC (doi:10.6084/m9.figshare.7355063), *read-ATM1b-QFIT-binary* reads Level-1b Airborne Topographic Mapper (ATM) QFIT binary data prod-

ucts (doi:10.6084/m9.figshare.7355060), *read-ATM2-icessn* reads Level-2 ATM Icessn data products (doi:10.6084/m9.figshare.7355066), and *read-LVIS2-elevation* reads Level-2 Land Vegetation and Ice Sensor (LVIS) data products (doi:10.6084/m9.figshare.7355057).

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5 *Competing interests.* The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Figure 1. <u>NASA/CECS</u> Pre-IceBridge and <u>NASA</u> Operation IceBridge campaign flight lines over a) Antarctica b) the Antarctic Peninsula and c) the Amundsen Sea Embayment from 2002 to 2016 colored by year of acquisition and laser ranging instrument. Antarctic grounded ice delineation provided by Mouginot et al. (2017b). Flight lines overlaid on a 2008–2009 MODIS mosaic of Antarctica (Haran et al., 2014).



Figure 2. Triangulated mesh formulated around an advected 2008 ATM flight line point using points from a 2009 ATM flight line (orange dots). The red star denotes the location of the original point, the green star denotes the parcel location after advection, and the dashed green line is the path of advection. P1, P2 and P3 represent the three vertices of the triangle housing the advected ATM point. Elevation values at each vertex point are weighted in the interpolation by their respective areas, A1, A2 and A3. Inset map shows the location of the main figure.



Figure 3. Representation of processes contributing to surface elevation changes for a) ice shelves and b) grounded ice. Modified from Ligtenberg et al. (2011) and Zwally and Li (2002). Processes represented in schematic: accumulation (v_{acc}), dynamic atmosphere (v_{dac}), snowmelt (v_{me}), sublimation (v_{su}), wind scour (v_{ws}), firn compaction (v_{fc}), ice dynamics (v_{dyn}), meltwater refreeze and retainment (v_{rfz}), solid Earth uplift (v_{se}), sea level (v_{sl}), ocean tides (v_{ot}), load tides (v_{lt}), load pole tides (v_{pt}), ocean pole tides (v_{opt}), and basal melt (v_b).



Figure 4. Surface elevation change of the Larsen-B remnant and Larsen-C Ice Shelf derived using a) Eulerian TINs corrected for strain, b) Lagrangian TINs and c) Lagrangian overlapping footprint schemes for the period 2009–2016. RMS differences in elevation change from a measurement point for all points within 1 km for the d) Eulerian TINs corrected for strain, e) Lagrangian TINs and f) Lagrangian overlapping footprint methods. The elevation change rates shown here are not RDE filtered (Smith et al., 2017). Antarctic grounded ice boundaries are provided by Mouginot et al. (2017b). Plots are overlaid on a 2008–2009 MODIS mosaic of Antarctica (Haran et al., 2014). Inset map denotes the location of the maps.



Figure 5. Measured and estimated ice thickness change rates from 2008 to 2016 for a flight line over the Larsen-C Ice Shelf (a) starting near the Whirlwind inlet-Inlet with the total measured ice thickness change rate denoted in black, the surface mass balance (SMB) fluxes from RACMO2.3p2 (XPEN055) denoted in red (van Wessem et al., 2016), the flux divergence terms combining ice thicknesses from Bedmap2 (Fretwell et al., 2013) and ice-velocities from MEaSUREs (Rignot et al., 2017) and ice thicknesses denoted in green, and the residual basal thickness change rates denoted in purple. Index denotes the ATM Icessn record number for October 10, 2008. Locations of co-registered records from the flight line are shown in b). MEaSUREs INSAR-derived Antarctic grounded ice boundaries are denoted in gray (Mouginot et al., 2017b). 2016 and 2017 ice shelf extents delineated from MODIS imagery are denoted in green and light gray, respectively (Scambos et al., 2001). Map is overlaid on a 2008–2009 MODIS mosaic of Antarctica (Haran et al., 2014). Inset map denotes the location of the map.



Figure 6. Ice thickness change (a-b) and estimated basal melt rates (c-d) of the Larsen-B remnant and Larsen-C Ice Shelf for two periods, 2002–2008 and 2008–2016. AI, CI, MI, WI and MOI denote the Adie, Cabinet, Mill, Whirlwind and Mobiloil inlets-Inlets, respectively. MEaSUREs InSAR-derived Antarctic grounded ice boundaries are denoted in gray (Mouginot et al., 2017b). 2016 and 2017 ice shelf extents delineated from MODIS imagery are denoted in green and light gray, respectively (Scambos et al., 2001). Plots are overlaid on a 2008–2009 MODIS mosaic of Antarctica (Haran et al., 2014). Inset map denotes the location of the maps.



Figure 7. Estimated basal melt rates (a-b) from Adusumilli et al. (2018) and differences from melt rates derived from <u>NASA/CECS</u> <u>Pre-IceBridge and NASA</u> Operation IceBridge (c-d) of the Larsen-C Ice Shelf for two periods, 2002–2008 and 2008–2016. Stipples indicate locations with valid radar altimetry data (a-b) and coincident airborne laser altimetry data (c-d). MEaSUREs InSAR-derived Antarctic grounded ice boundaries are denoted in gray (Mouginot et al., 2017b). 2016 and 2017 ice shelf extents delineated from MODIS imagery are denoted in green and light gray, respectively (Scambos et al., 2001). Plots are overlaid on a 2008–2009 MODIS mosaic of Antarctica (Haran et al., 2014). Inset map denotes the location of the maps.



Figure 8. Ice thickness change (a-b) and estimated basal melt rates (c-d) of the Wilkins Ice Shelf for two periods, 2008–2011 and 2011–2014. HI and SI denote the Haydn and Schubert Inlets, respectively. MEaSUREs InSAR-derived Antarctic grounded ice boundaries are denoted in gray (Mouginot et al., 2017b). Historical ice shelf extents delineated from Landsat and MODIS imagery are denoted with colored lines. Plots are overlaid on MODIS images of Antarctic ice shelves provided by NSIDC (Scambos et al., 2001). Inset map denotes the location of the maps.



Figure 9. Ice thickness change (a-b) and estimated basal melt rates (c-d) of the Pine Island Ice Shelf for two periods, 2009–2011 and 2011–2015. MEaSUREs InSAR-derived Antarctic grounded ice boundaries are denoted in gray (Mouginot et al., 2017b). 1996 InSAR-derived grounding line locations from Rignot et al. (2016) are delineated in green. Plots are overlaid on MODIS images of Antarctic ice shelves provided by NSIDC (Scambos et al., 2001). Inset map denotes the location of the maps.



Figure 10. Lee thickness change Estimated basal melt rates (a-ba-c) and estimated basal differences in melt rates (e-dc) of the Dotson and Crosson Pine Island Ice Shelves for two periods, 2002–2010 Shelf from (a) NASA/CECS Pre-IceBridge and 2010–2015NASA Operation IceBridge over 2002–2009 and (b) from ICESat over 2003–2009 (Rignot et al., 2013). Estimated elevation change rates (d-e) and differences in elevation change rates (f) of the Pine Island Ice Shelf from (d) NASA/CECS Pre-IceBridge and NASA Operation IceBridge over 2002–2009 and (e) from ICESat over 2003–2009 after correcting for strain (Pritchard et al., 2012) MEaSUREs InSAR-derived Antarctic grounded ice boundaries are denoted in gray (Mouginot et al., 2017b). 1996 InSAR-derived grounding line locations from Rignot et al. (2016) are delineated in green. Plots are overlaid on a 2008–2009 MODIS mosaie-images of Antarctica (Haran et al., 2014)Antarctic ice shelves provided by NSIDC (Scambos et al., 2001). Inset map denotes the location of the maps.



Figure 11. Ice thickness change (a-b) and estimated basal melt rates (c-d) of the Dotson and Crosson Ice Shelves for two periods, 2002–2010 and 2010–2015. MEaSUREs InSAR-derived Antarctic grounded ice boundaries are denoted in gray (Mouginot et al., 2017b). 1996 InSAR-derived grounding line locations from Rignot et al. (2016) are delineated in green. Plots are overlaid on a 2008–2009 MODIS mosaic of Antarctica (Haran et al., 2014). Inset map denotes the location of the maps.



Figure 12. Estimated basal melt rates (a-b) and differences in melt rates (c) of the Dotson and Crosson Ice Shelves from (a) NASA/CECS Pre-IceBridge and NASA Operation IceBridge over 2002–2009 and (b) from ICESat over 2003–2009 (Rignot et al., 2013) . Estimated elevation change rates (d-e) and differences in elevation change rates (f) of the Dotson and Crosson Ice Shelves from (d) NASA/CECS Pre-IceBridge and NASA Operation IceBridge over 2002–2009 and (e) from ICESat over 2003–2009 after correcting for strain (Pritchard et al., 2012). MEaSUREs InSAR-derived Antarctic grounded ice boundaries are denoted in gray (Mouginot et al., 2017b). 1996 InSAR-derived grounding line locations from Rignot et al. (2016) are delineated in green. Plots are overlaid on a 2008–2009 MODIS mosaic of Antarctica (Haran et al., 2014). Inset map denotes the location of the maps.



Figure 13. Histograms of basal melt rates (a,c) and surface elevation change (b,d) of the Pine Island Ice Shelf (a,b) and Dotson and Crosson Ice Shelves (c,d) from NASA/CECS Pre-IceBridge and NASA Operation IceBridge over 2002–2009 (purple) and from ICESat over 2003–2009 (green) using data from Rignot et al. (2013) and Pritchard et al. (2012).