

**UNRAVELING SHORT-TERM VARIATIONS IN TIDEWATER GLACIER FLOW:
INSIGHTS FROM TERRESTRIAL RADAR INTERFEROMETRIC STUDIES**

BY

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PREVIEW

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DEDICATION

To Megan, Logan, and Julia – Thank you! Your sacrifices helped make this a reality.

PREVIEW

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I started this journey several years ago with little more than a handful of ideas, a great deal of motivation, and a healthy dose of optimism. I was quite fortunate to gain the support and encouragement of many people along the way that helped frame this research, and to whom I owe a great debt of gratitude.

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TABLE OF CONTENTS

Dedication.....	iv
Acknowledgements.....	v
List of Tables	xi
List of Figures	xii
ABSTRACT	xv
1 Introduction.....	1
2 Nonlinear glacier response to calving events, Jakobshavn Isbræ, Greenland	6
2.1 Introduction.....	6
2.2 Methods	8
2.2.1 TRI-derived speeds	10
2.2.2 TRI-derived surface elevation changes.....	15
2.2.3 Mapping Calving Events and Terminus Locations from TRI.....	17
2.3 Results.....	18
2.3.1 Short-term Variations in Speed	18
2.3.2 Response in Speed to Calving	19
2.3.3 Dynamic Changes in Surface Elevation.....	20
2.4 Discussion.....	22
2.4.1 A Trigger for Fast Flow	22
2.4.2 Spatiotemporal variations in speed, strain rate, and elevation.....	24
2.4.3 Changes in tidal-induced flow	27

2.4.4	Dynamic processes, feedbacks, and short-period instability.....	29
2.4.5	Transient perturbations and long-term change	32
2.5	Implications for tidewater glacier stability	34
2.6	Conclusions.....	36
3	The bimodal character of granular ice mélange and the influence on calving at Jakobshavn Isbræ	37
3.1	Introduction.....	37
3.2	Methods	39
3.3	Observations.....	41
3.3.1	Two-dimensional Mélange Speeds.....	41
3.3.2	Divergence of the velocity fields	42
3.3.3	Shear strain rates.....	44
3.4	Discussion.....	45
3.4.1	Wind and subglacial discharge	46
3.4.2	Iceberg calving and terminus dynamics.....	47
3.4.3	Tidal forcing	48
3.4.4	Internal controls with granular ice mélange.....	49
3.4.5	Downfjord initiation of ice mélange variability	52
3.5	Conclusions.....	53
4	Large velocity response to precipitation and tidal forcing at Columbia Glacier, Alaska – evidence for late summer changes in subglacial hydrology	55
4.1	Introduction.....	55
4.2	Methods	59
4.3	Results	60
4.3.1	Speeds along the Main Branch	60
4.3.2	Speeds along the West Branch	62

4.4 Discussion 63

 4.4.1 Response to precipitation..... 63

 4.4.2 A change in tidal forcing 66

 4.4.3 Change in effective pressure 71

 4.4.4 Subglacial change and the Implications for seasonal variations in speed 74

4.5 Conclusions..... 76

5 Conclusions..... 78

References 81

PREVIEW

LIST OF TABLES

Table 1: MLI acquisition times used for target integer maps	11
Table 2: List of constants used in model	72

PREVIEW

LIST OF FIGURES

Figure 1: Differential interferogram superimposed on a Landsat 8 image of Jakobshavn Isbræ shows displacement during a 3-minute interval. (Inset) Photograph of the GPRI2 at the study site.	9
Figure 2: Sample unwrapped phase showing the results after each correction step at a discrete pixel.....	12
Figure 3: Topographic phase correction for vertical alignment errors. (a) Mean phase for a stack of interferograms on 30 Jul. (b) The azimuth and (c) linear range corrections applied to the mean phase maps.	16
Figure 4: Variations in speed. (a) Time series of speed along a flow line of Jakobshavn Isbræ's southern branch; the timing of calving events is indicated by black lines. (b) Speed at 0.5-km intervals along the profile. Location of the flow line is shown in Figure 6.....	18
Figure 5: Characterization of calving events. (a) Polygons highlighting calving area losses for select events; (b) the distribution and relative size of all calving events mapped by the centroid; (c) change in speed during calving events; legend indicates the time and areal size of events; (d) instantaneous change in speed versus calving area loss.	20
Figure 6: Variations in surface elevation. (a) Map of surface elevations with the location of a profile (white line) sampled in (b-d). (b) Cross-sections of surface elevations along the profile for five different epochs, dashed lines show interpolated values for missing data; note the reverse surface slope prior to calving in the early record. (c) A time-series of surface elevations along the profile. (d) Time-series of elevations 0.5 km along the profile. Diamonds in (b) and (c) indicate the location of the calving front.	21
Figure 7: Bed topographic trigger to fast flow. Longitudinal strain rates (a) before and (b) after the 2 Aug 23:10 calving event; purple indicates extension, green compression. (c) Front positions (colors) and Morlighem et al.'s [2014] bed model (yellow contours) overlain on an MLI image. The largest step change in speed resulted from a very small retreat of the calving front into a subtly wider region in the deep, narrow channel (white dashed line). "G" represents GPRI-derived front positions.	23
Figure 8: Spatiotemporal variations around 2 Aug 23:10 calving event. (a) speeds, (b) longitudinal strain rates with purple indicating extension and green compression, (c) surface elevation changes, (d) height above flotation (HAF), (e) tidal admittance amplitude, and (f) tidal admittance phase lag. Contours in (b) represent bed elevations from Morlighem et al, [2014]; polygon in (c) indicates 9-km ² sample area shown in time-series in Figure 9b; colored triangles in (f) show the location of tidal admittance sampled in time-series in Figure 9.	25
Figure 9: Variations in stability through feedbacks along the terminus. Time-series of (a) mean front position relative to 2012 maximum, (b) speed and surface elevation changes measured from beginning of the record over a 6.5-km ² patch of the ice stream (Figure 8), (c-e) the phase lag between tides and ice speeds, and (f) admittance amplitude for three locations	

along the terminus (Figure 8f); black lines in (f) indicate the tidal amplitude (see text). Gray vertical lines throughout indicate the timing of calving events.	29
Figure 10: Impact of short-term perturbations. (a) 17-year history of terminus positions with a time-series of mean front positions in (b); (c) closer look at 2012 mean front positions from satellite and GPRI; (d) time-series of satellite-derived speeds from NASA MEaSUREs....	32
Figure 11: Landsat 8 image of Jakobshavn Isbræ and the proglacial ice mélange with TRI-derived speeds (colors) sampled ~30 minutes before a calving event on 2 Aug 2012. (Inset) Photograph of the TRI at radar site 2 with ice mélange in the background.....	39
Figure 12: (a-d) Mélange speeds at different times in the record, (e) a time-series of speed sampled along the profile (white line in a), with the timing of calving events indicated by horizontal black lines. (f) the speed and location of the glacier terminus (see 2.3.1). Magenta triangle in (a) shows location of glacier speeds sampled.....	42
Figure 13: Bimodal strain rates: (a) Coherent, distributed strain fields between calving, and the (b) rapid deterioration of strain rates prior to calving. (c) Time-series of strain rates along the profile in (a), black lines indicate timing of calving events. (c) The speed and location of the glacier terminus (see 2.3.1). Magenta triangle in (a) shows location of glacier speeds sampled.	43
Figure 14: Maps of shear strain rates (a,b) show clockwise (CW) or opening of shear margins downfjord (red), where the fjord widens and the mélange is less confined. Alternating patterns of red (CW) and blue (CCW or closing of the shear margin) appear near the glacier, where the fjord narrows. (c) Time-series of shear strain rates sampled along a transverse profile (black line in a) show the dynamic character of the shear margins. Shear margins are clearly defined along the northern margin and move towards the mélange center between calving events (black lines).	45
Figure 15: Polar histogram showing the origination direction of winds in the fjord sampled from a weather station near the northern terminus of Jakobshavn Isbræ [Holland and Holland, 2016].	46
Figure 16: (a) Admittance amplitude and (b) phase lag of mélange speeds on 7 Aug. Time-series of (c) ocean tides, (d) speeds, (e) acceleration, and (f) divergence at discrete points in the mélange. The colors in (d-f) correlate to the colored triangles in (b)	49
Figure 17: Landsat 8 image from the study area with TRI-derived speeds from Oct 2014; white lines indicate the location of the profiles sampled in Figures 2 – 4. (Inset) TRI instrument deployed at a bedrock camp ~4 km from the Main Branch.....	56
Figure 18: (a) Precipitation and insolation records from a Natural Resources Conservation Service weather station in nearby Valdez. (c) Satellite record of speeds from Fahnestock et al, (2015) sampled along the profile in Figure 1. Red dashed boxes indicate the time of our field study. (b) and (d) same as (a) and (c) but for Sep – Nov 2014.....	58

Figure 19: Time-series of speeds for the centerline profile along the Main Branch shown in Figure 1. (a) speeds, (b) the percent change in speed, and (c) speeds (colors) at discrete pixels along the profile with the tides (black) and tidal amplitude (gray). (d) accumulated precipitation (gray) and temperatures (red/blue) at 380 m elevation, the mean elevation of glacier surfaces within far range of TRI geometry; blue indicates temperature below freezing. 61

Figure 20: Time-series of speeds along a centerline profile along the West Branch. (a) speeds, (b) the percent change in speed, and (c) speeds (colors) at discrete pixels along the profile with the tides (black) and tidal amplitude (gray). (d) accumulated precipitation (gray) and temperatures (red/blue) at 380 m elevation; blue indicates temperature below freezing. 62

Figure 21: Response to precipitation along Main Branch. Mean speeds (a) before and (b) after precipitation event. (c) The change in speed after precipitation; white (black) contours are bed elevations below (above) sea level from McNabb et al, 2012. 64

Figure 22: Response to precipitation along the West Branch. Mean speeds (a) before and (b) after precipitation event. (c) The change in speed due to precipitation; contours are bed elevations above sea level from McNabb et al, (2012). 65

Figure 23: Change in tidal forcing along Main Branch. (a) admittance amplitude and (b) phase difference before precipitation, and the (c) admittance amplitude and (d) phase difference during precipitation. 68

Figure 24: Change in tidal forcing along West Branch. (a) admittance amplitude and (b) phase difference before precipitation, and after (c) and (d), respectively. 70

Figure 25: Speed variations due to changes in effective pressure. Predicted sliding speeds (a) before and (b) after a perturbation in effective pressure caused an influx of precipitation; (c) Observed measurements from 14 Oct (after precipitation); (d) error between (b) and (c)... 74

ABSTRACT

UNRAVELING SHORT-TERM VARIATIONS IN TIDEWATER GLACIER FLOW: INSIGHTS FROM TERRESTRIAL RADAR INTERFEROMETRIC STUDIES

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Tidewater glaciers are fast-flowing valley glaciers that advect ice from the interior of ice sheets to the ocean. Processes along the submarine boundaries of tidewater glacier termini can trigger a dynamic response in glacier ice that can impact stability along the terminus. Predictions of 21st century sea level rise require a comprehensive understanding of tidewater glacier dynamics over a variety of spatial and temporal scales. Perturbations to the calving front, such as iceberg calving, tidal modulations, changes in proglacial ice mélange strength and rigidity, and the subglacial discharge of meltwater occur on time-scales that exceed temporal resolution of satellite measurements; thus, little is known about the dynamic response of glaciers to these processes. Terrestrial radar interferometry is a relatively new technology that measures millimeter scale surface deformation with a spatial resolution comparable to satellites, but at much higher temporal resolution. Here, I use terrestrial radar interferometers to measure short-term variations in speed and surface elevation along Jakobshavn Isbræ, Greenland and Columbia Glacier, Alaska. I find

that small calving events can trigger large, dynamic changes in speed and ice thickness. I present observations that show that glacier response to calving events is a consequence of two competing feedbacks: (1) an increase in strain rates leads to dynamic thinning and faster flow, thereby promoting destabilization, whereas (2) an increase in flow rates advects thick ice toward the terminus and promotes restabilization. The competition between these feedbacks depends on temporal and spatial variations in the glacier's proximity to flotation. I also present the first field evidence of a granular ice mélange influence on iceberg calving, which has implications for calving rates, the speed and thickness of the terminus, and consequently tidewater glacier stability. Finally, I present observations of a large increase in speed along Columbia Glacier in response to a precipitation event. The results demonstrate the importance that variations in basal hydrology have on sliding along the bed, and more importantly how changes in the subglacial hydrology can affect the response of a tidewater glacier to tidal fluctuations.

1 INTRODUCTION

Dynamic processes along the termini of tidewater glaciers, fast-flowing glaciers that transport ice from the interior of ice sheets to the ocean, can account for more than half of all ice mass loss in Greenland and Antarctica. In the early 2000s, changes that initiated along Greenland's ice-ocean boundary triggered feedbacks in ice dynamics that led to large calving retreats and significant ice mass loss. The changes are ongoing, but predictions for tidewater glacier evolution and the impacts to sea level are limited by a poor understanding of tidewater glacier response to perturbations at the calving front. This dearth of knowledge is due, in part, to an inability to adequately measure rapid, dynamic processes with high temporal *and* spatial resolution. As a result, several major questions remain unanswered, including: (1) How does iceberg calving affect tidewater glacier stability? (2) What effect does ice mélange have on iceberg calving, if any? (3) How do variations in subglacial hydrology and discharge affect speed? and (4) How do variations in ocean and fjord circulation impact frontal ablation? Understanding tidewater glacier response to these perturbations, including the effect of short-term velocity variations on tidewater glacier stability, is paramount for predictions of 21st century sea level rise. Recent advances in terrestrial radar interferometers, instruments that measure surface deformation using fractional changes in electromagnetic wavelengths (phase differences) between acquisitions, allow for these short-period processes to be observed with high temporal and spatial resolution, and thus has motivated the research presented here.

Historically, the study of tidewater glacier flow began in earnest in the 1970s with the conceptualization of the tidewater glacier cycle [Post, 1975]. Post hypothesized that tidewater glaciers 1) advance over millennial time scales, 2) reach an advanced position by building and mobilizing a protective moraine at the glacier terminus, 3) undergo rapid retreat on centennial time scales, and then 4) remain at the head of fjord until the cycle repeats. Seminal work by Meier and Post [1987] described the unique geophysical environment of tidewater glaciers that contributes to their fast flow. Specifically, submarine beds and high seawater pressures lead to characteristically high subglacial water pressures at the terminus, which are necessary to drive basal melt water from the system. Consequently, this enhances basal sliding and thus speeds along tidewater glacier termini. Another attribute of their work was the idea that tidewater glaciers are largely insensitive to climate variations, owing to complex fjord geometries, the distribution of mass balance, and the accumulation of eroding sediments. That view has changed in recent years to reflect a rather complex relationship between climate and tidewater glaciers [Post *et al.*, 2011], wherein tidewater glacier sensitivity to climate varies at each stage of the cycle, and is most sensitive when the terminus is in an advanced configuration [Amundson, 2016]. Furthermore, recent, concurrent changes along many of the planet's tidewater glaciers suggest a climate-induced trigger for rapid retreat.

Many recent studies have documented rapid changes throughout the cryosphere that implicate a changing climate. For example, increased surface melt [*e.g.* Nghiem *et al* [2012]] and the drainage of supraglacial lakes [Das *et al.*, 2008] have been shown to accelerate speeds along the margin of the Greenland Ice Sheet. An increase in subglacial discharge, coupled with warm ocean currents that reach the termini of tidewater glaciers [Holland *et al.*, 2008; Rignot *et al.*, 2010; Straneo *et*

al., 2010; *Rignot et al.*, 2013b], can create convective freshwater plumes that ablate the submarine fronts of tidewater glaciers [*Motyka et al.*, 2003], which in some cases surpass the calving flux [*Bartholomaus et al.*, 2013]. These climate-induced changes can initiate positive feedbacks within ice dynamics that lead to tidewater glacier thinning [*Pritchard et al.*, 2009], faster flow [*Joughin et al.*, 2010], and rapid retreat [*Moon and Joughin*, 2008] that continue regardless of climate variations [*Amundson*, 2016; *Brinkerhoff et al.*, 2017]. The ability to predict the evolution of tidewater glacier retreat is contingent upon the ability to study and analyze dynamic processes along the terminus. However, these processes - subglacial discharge, iceberg calving, and variations in speed, all occur on spatial and temporal scales that exceed the sampling capabilities of traditional survey techniques.

Early traditional glaciological studies used theodolite and photogrammetric surveys to measure speed. Active seismic campaigns were used to measure ice thickness and the depths of submarine beds (e.g. *Clarke and Echelmeyer* [1996]). Drilling expeditions measured ice thickness as well as subglacial [*Meier et al.*, 1994] and englacial conditions [*Luthi et al.*, 2002]. These and numerous other studies that characterize glacier flow provided the framework for modern glaciology.

Technological advances have revolutionized glaciological observations and understanding. For example, GPS technology has increased temporal sampling rates. Airborne radar sensors sample bed depths and derive ice thicknesses that are combined with fundamental conservation principles to derive topographic maps of glacier beds (e.g. [*Bamber et al.*, 2000a; 2000b; *Morlighem et al.*, 2014]). The launch of multiple Earth observing satellites has significantly enhanced the spatial resolution of observations. The application of spaceborne radar interferometry allows for fine scale

surface deformation measurements over relatively moderate time scales (weekly to monthly). However, the challenge for tidewater glaciers is to monitor changes with high spatial *and* temporal (sub-daily) resolution – a technological barrier that, until recently, was not possible to cross.

Terrestrial-based radar interferometry was developed more than a decade ago but was limited to the mining and landslide communities. Terrestrial radar interferometers (TRIs) have distinct advantages over spaceborne counterparts, including the ability to deploy and observe areas not viewable by satellites. Their stationary observation position also simplifies post-processing calculations by reducing the number of measured phase displacement components. Perhaps most significant is the high sampling rate (minutes), creating an instrument capable of satellite spatial resolution but with the temporal resolution close to GPS systems. As a result, rapidly deforming surfaces that temporally decorrelate between satellite acquisitions can be observed with TRI (e.g. iceberg calving, ice mélange, rapid dynamic thinning). Recently, TRIs have been deployed to characterize flow along tidewater glacier termini [Dixon *et al.*, 2012; Voytenko *et al.*, 2015a; 2015b; 2015c; Xie *et al.*, 2016]. Here, I use dense TRI observations to create high-resolution time-series of short-term variations in speed and surface elevation along tidewater glaciers in Greenland and Alaska. In particular, I present a novel approach to DEM differencing whereby I use stationary targets in TRI-derived digital elevation models (DEMs) to reduce elevation errors and produce a record of rapid, dynamic thinning (Chapter 2, methods). The results presented herein demonstrate how TRI studies can enhance our understanding of short-term tidewater glacier dynamics, and when coupled with longer records from satellites, can be used to make predictions about the evolution of tidewater glaciers.

The focus of this thesis is to apply TRI technology to investigate the response of short-term perturbations along the termini of two glaciologically significant tidewater glaciers. Since 2000, Jakobshavn Isbræ in West Greenland has retreated ~20km, thinned by more than 100 m [*Motyka et al.*, 2011], and discharged more ice than any other Greenland glacier [*Enderlin et al.*, 2014], which has contributed to a dense proglacial ice mélange. Columbia Glacier in South-Central Alaska has also endured a nearly 40-year, 22 km retreat [*McNabb and Hock*, 2014], experienced a >50% reduction in ice volume [*McNabb et al.*, 2012], and is currently exhibiting very low speeds in late fall. Both glaciers occupy submarine beds, which suggests additional retreat is possible. In the following chapters, we investigate short-term variations in glacier flow in response to: iceberg calving (chapter 2) and precipitation (chapter 4), and short-term variations in ice mélange flow between calving events (chapter 3).

2 NONLINEAR GLACIER RESPONSE TO CALVING EVENTS, JAKOBHAVN ISBRÆ, GREENLAND

2.1 Introduction

After decades of relative stability [Sohn *et al.*, 1998; Podlech and Weidick, 2004], Jakobshavn Isbræ began to destabilize at the turn of the 21st century. Submarine melting of the floating tongue [Motyka *et al.*, 2011], enhanced by the influx of warm ocean currents in the late 1990s [Holland *et al.*, 2008], initiated changes along the glacier terminus. The glacier thinned by more than 100 m [Krabill *et al.*, 2004; Motyka *et al.*, 2010], velocities doubled [Joughin *et al.*, 2004; Luckman and Murray, 2005], and the terminus rapidly retreated [Podlech and Weidick, 2004; Moon and Joughin, 2008]. The rate of retreat peaked in 2003 with the collapse of the glacier's floating tongue [Thomas, 2004; Joughin *et al.*, 2012], and the retreat continues to this day. The pattern of accelerating flow and kilometer-scale retreat slowed in 2010 and 2011, but speeds reached record high values in 2012 as the glacier retreated to a new minimum position [Joughin *et al.*, 2014].

Retreat down a reverse bed slope is believed to have triggered the large increase in speed that occurred in 2012 [Joughin *et al.*, 2014]. Measurements and numerous bed models show a submarine channel extends far into the interior of the ice sheet [Clarke and Echelmeyer, 1996; Bamber *et al.*, 2013; Morlighem *et al.*, 2014]; however, the depth of the channel varies by model. Understanding Jakobshavn Isbræ's response to perturbations along the calving front, including bathymetric influence, is paramount for accurate predictions of tidewater glacier evolution and the resultant impact on sea level.

Variations in ice thickness affect tidewater glacier stability through changes in effective pressure (ice overburden minus subglacial water pressure). A reduction in ice overburden decreases basal friction and enhances flow, creating a positive feedback that propagates upglacier and leads to rapid retreat [Pfeffer, 2007]. The recent 15 m yr^{-1} thinning rate [Joughin *et al.*, 2012], 20 year period of fast flow [Joughin *et al.*, 2012; 2014] and ongoing retreat [Moon and Joughin, 2008; Cassotto *et al.*, 2015] indicate that positive feedbacks are driving Jakobshavn Isbræ's instability. If sustained, the glacier could retreat far into the ice sheet interior within a few decades [Joughin *et al.*, 2014]. Furthermore, proglacial studies show that the ice sheet margin around Jakobshavn Isbræ has previously responded to terminus variations on centennial time scales [Briner *et al.*, 2011; Young *et al.*, 2011]. Therefore, the continued destabilization of Jakobshavn Isbræ could have profound effects on the drawdown of interior ice, and by direct consequence, sea level rise over the next century.

On shorter time-scales, brief periods of acceleration can influence the seasonal and interannual behavior of Jakobshavn Isbræ [Podrasky *et al.*, 2012]. Here, we use terrestrial radar interferometry (TRI) to assess the influence that short-term perturbations in speed have on long-term glacier dynamics. TRI is a relatively new tool, wherein phase differences between multiple radar passes are used to derive surface deformation and digital elevation models. The portability and high sampling rates of TRI provide tremendous opportunities for geophysical surface studies (e.g. Caduff *et al.*, [2014] and references therein), including tidewater glaciers [Dixon *et al.*, 2012; Voytenko *et al.*, 2015b; Xie *et al.*, 2016]. TRI data collected at Jakobshavn Isbræ in 2012 has already been used to characterize ice mélange motion during calving events [Peters *et al.*, 2015] and towards the development of a 2D velocity field [Voytenko *et al.*, 2017]. The objective of this study is to use the full, high-resolution record of TRI observations to evaluate how short-term