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

BY

RYAN K. CASSOTTO

B.S., University of Hartford, 1999

M.S., University of New Hampshire, 2011

DISSERTATION

Submitted to the University of New Hampshire
in Partial Fulfillment of
the Requirements for the Degree of

Doctor of Philosophy

in

Earth and Environmental Sciences

December 2017

This thesis/dissertation has been examined and approved in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Earth and Environmental Sciences by:

Dissertation Director, Margaret S. Boettcher, Associate Professor of Earth Sciences

Mark Fahnestock, Affiliate Research Professor of Earth Sciences

Joseph M Licciardi, Professor of Earth Sciences

Jason M. Amundson, Associate Professor of Geophysics
University of Alaska Southeast, Juneau, AK 99801

Martin Truffer, Professor of Physics
University of Alaska Fairbanks, Fairbanks, AK 99775

On November 2, 2017

Original approval signatures are on file with the University of New Hampshire Graduate School.

Dedication

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

ACKNOWLEDGEMENTS

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.

I am truly grateful to my committee for their expertise, commitment, and patience. Early on, I was lucky enough to convince Mark Fahnestock, my primary advisor and committee co-chair, to serve as my mentor as I started graduate school as a non-traditional student. He constantly challenged me to explore new and exciting opportunities and to approach solutions to problems by thinking far outside the box. He provided tremendous field experiences in Greenland and Alaska, and generously supported me through various research grants for several years. Mark and Judy welcomed me into their home on several occasions – in New Hampshire, Alaska, and Denmark. I am incredibly grateful to Margaret Boettcher, my UNH advisor and committee chair, who kept an open mind and ventured into glaciology despite her expertise in seismology and rock mechanics. Margaret welcomed me into her geophysics group and was a tremendous supporter and mentor to me throughout my PhD career. She helped me to develop proposal writing skills, and she and Linda provided hospitality in the final days of my defense. Jason Amundson advised me as though I was one of his own students. He tirelessly (and quickly) provided detailed comments and fresh ideas during several iterations of manuscripts. Jason also invited me to collaborate on mélange-related projects with condensed matter physicists; that experience helped frame chapter 3. Martin Truffer readily dispenses simple and yet sound advice – whether it pertains to research, coursework, field techniques, or just plain old advice to navigate the complexities of life. He possesses the most remarkable ability to guide one through the most complex of problems with ease, all while instilling valuable analytical lessons. Joe Licciardi introduced fundamental glacial principles through coursework in geomorphology, glacial geology, and paleoclimate. Joe also provided detailed and constructive comments that significantly improved my manuscripts.

A variety of organizations provided financial support throughout my PhD career. A NASA Earth and Space Science Fellowship funded the bulk of this research. I was awarded a fellowship through the New Hampshire Space Grant Consortium. Mark Fahnestock generously supported me through various research grants, including the Gordon and Betty Moore Foundation. The Department of Earth Sciences provided financial support through scholarships, teaching assistantships, and the ESCI-EOS student research fund, which helped fund attendance at the International Summer School in Glaciology. The Natural Resources and Earth System Science Program provided a tuition waiver during my last semester. Finally, I received travel support for various meetings and workshops from the National Science Foundation, the International Glaciological Society, and the US Climate Variability and Predictability Program.

I am grateful to the Department of Earth Sciences for the many years of exceptional support and encouragement. I am particularly grateful for conversations with Wally Bothner, Will Clyde, Linda Kalnejais, and Anne Lightbody. I am also grateful to the Earth Systems Research Center, especially Jack Dibb, Cameron Wake, Joe Souney, and Mark Twickler for providing guidance and residency (office space) in the glaciers group; Belinda Camire, Gary Desjardins, and Linda Tibbetts eased clerical and accounting responsibilities. I am also grateful for the many conversations, insight, and feedback from the members of the UNH Geophysics group – Pamela Moyer, Evangelos Korkolis, Monica Wolfson-Schwehr, Debra Kane, Jiawei Jiang, and Liam Kenefic; Liam digitized hundreds of calving fronts from satellite and terrestrial radar images.

Many colleagues enriched my graduate experience. Roman Motyka provided guidance and expertise in the field, and welcomed me to collaborate on several occasions. Kelly Brunt provided indispensable advice in career planning. Shad O'Neel supported and funding field work at Columbia Glacier. Justin Burton provided a condensed matter physicist's perspective on the granular flow of ice mélange. Colin Meyer suggested initial ideas for modeling of observations at Columbia Glacier. I am grateful to Louis Sass, David Podrasky, Bob McNabb, and Santiago de la Peña for their assistance in the field. The Juneau Icefield Research Program provided me with a tremendous opportunity and my first field experience in glaciology. The International Summer School in Glaciology provided guidance and expertise in addressing glaciological questions.

Finally, this research would not have been possible without the tremendous love and support of my family. My wife, Megan, encouraged me throughout my graduate career – from early, geology 100 level courses to completing this doctoral dissertation. Although she may not have been fully aware of her commitments when I started, she nonetheless provided unwavering support throughout. The sacrifices made by her and our children, Logan and Julia, enabled me to pursue a life-long goal. I am truly fortunate and incredibly grateful!

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

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

By

Ryan K. Cassotto

University of New Hampshire, December 2017

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, JAKOBSHAVN 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