Chapter 6

Synopsis and Implications

This final chapter provides a brief recapitulation of the findings detailed in chapters 2 through 5. While the conclusions of each chapter largely stand alone, we then close with a prospective on viscoelasticity in the context of the short-timescale behavior of ice.

6.1 Synopsis

In chapter 2, we used two-dimensional and three-dimensional models of elastic ice streams to quantify the spatial extent of an ice stream's response to a tidal load. Our results demonstrated that the geometry of the ice stream—specifically the dimension constrained by the choice of the boundary conditions—imposes a fundamental limit on inland transmission of tidal stresses. For models approximating real ice streams, only in the singular case of Whillans Ice Plain does traction applied at the grounding line maintain sufficient amplitude over an inland distance large enough to match observations of tidal influence. In all our models of more channelized ice streams, lateral margins limit the distance of stress transmission. Thus, the inland propagation of a tidal signal is controlled primarily by the ice stream width. In such cases, the modeled extent of the response to tidal forcing fails to match observations of tidal perturbations in ice motion.

In chapter 3, we explored two potential phenomena for decoupling an ice stream from its lateral margins: damage-related compliance of the shear margins, and a nonlinear viscoelastic constitutive law for glacier ice. Using linear continuum damage mechanics to parameterize the influence of cracks, fractures, and crevasses on the effective ice elasticity, our modeling results demonstrated that spatially variable elasticity can increase the length-scale for the transmission of a tidal load relative to a homogeneous elastic model. We used our results to map the possible parameter space in terms of damage magnitude and margin size for a model with discrete "weakened" shear margins. We found that the amount of damage necessary to increase the transmission length-scale in channelized ice streams to an extent large enough to match observations would effectively pulverize the ice margins completely. Our nonlinear viscoelastic models showed a sizable decrease in the effective viscosity along the margins of the modeled ice stream relative to the central portions of the ice controlled by the gravitational stress acting on the ice. However, the timescales and magnitudes of the tidal forcing were such that the ocean tide neither perturbs the ice's viscosity profile substantially nor does the material shift into a viscously-dominated deformation regime. A large discrepancy remains between the Antarctic observations and our model results even when the ice is modeled with a nonlinear, temperature-dependent viscoelastic rheology.

In chapter 4, we outlined a methodology to use the observed phase delay between the tidal forcing of an outlet glacier and that glacier's displacement response to infer *in situ* viscoelastic material properties for ice. Using the general *arctangent* form of the phase shift for a Maxwell viscoelastic material, we demonstrated the bounds that such simple two-dimensional models can provide using the GPS data of de Juan-Verger (2011) for Helheim glacier in Greenland as a sample dataset. Additionally, we discussed the best ice streams and the potential survey requirements to collect ideal data for constraining rheological parameters for *in situ* glacial ice.

In chapter 5, we explored the importance of viscoelasticity during the rapid drainage of supraglacial lakes. Our modeling demonstrated that there is a nontrivial, yet second-order, effect of viscoelasticity during the opening of a subglacial drainage crack. Our model solutions allowed us to reinterpret some of the details of an earlier set of field observations for a supraglacial lake drainage event on Jakobshavn Isbrae. However, we suggest that viscoelasticity is less important to understanding the physics of supraglacial lake drainage than the accurate observation of the surface lake bathymetry and a better understanding of the evolution of the vertical drainage conduit.

6.2 The Importance of Ice Viscoelasticity

A recurring theme throughout this thesis is the extent to which it is important to consider viscoelastic effects during ice deformation to correctly model short-timescale glacier processes. A consideration of viscoelastic effects is relevant because the material properties of ice are such that the stress relaxation timescale of ice is similar to the timescale of the glacial phenomena explored here. While our work is not the first to model the viscoelastic deformation of ice streams, our models do provide a test for determining the relative importance of ice viscoelasticity over hourly to weekly timescales.

In our tidally-loaded models, viscoelasticity has a negligible effect on the stress state, perturbing the transmission length-scale by about 1% and 2% for the semidiurnal and diurnal tidal frequencies, respectively. For the fortnightly tide, incorporating viscoelasticity does increase the stress-transmission length-scale by about 45%, but even this increase is about an order of magnitude smaller than is necessary to match our model results to observations. In all cases, however, viscoelastic models exhibit a noticeable time delay between the ocean tide and the ice stream’s response. This delay grows with increasing distance inland of the grounding line. For the lake drainage problem, viscoelasticity increases the total crack opening value by about 10% late in the crack evolution, resulting in a difference in the total drainage time of about an hour (though the observable drainage duration is not strongly affected by using a viscoelastic model). Thus, at least for the problems investigated here, viscoelasticity expresses itself primarily as a change in the timing of the various forcing processes on our model glaciers relative to elastic models, rather than as a large change in the amplitude of the ice's response to these external forces.

A practical concern is that the computational modeling of a nonlinear viscoelastic material is inherently difficult, especially when compared to an equivalent linear elastic version of the same problem. Conceptually, external and internal forces and stresses due to processes other than the one of interest must be considered due to the nonlinearity, and can only be neglected after careful study. Furthermore, there is practical concern that viscous problems take more computational time than elastic problems due to the time-dependence of the solution. When combined with the "convergence loop within a convergence loop" style of iterative solver standard in many nonlinear finite element solvers, the large computation demand for a nonlinear viscoelastic problem will necessarily limit the total number of models that can be run in given span of time. For perspective, every elastic model from chapters 2 and 3 could have been run in the same period of time as a single nonlinear viscoelastic model forced at a fortnightly tidal period. Clearly, if viscoelasticity is not critical to the problem being investigated, using a linear elastic model is a powerful approximation to significantly reduce the computational time necessary to model a system.

We have demonstrated that understanding both the stress transmission of a tidal load and of the drainage process of supraglacial lakes is incomplete. While our modeling demonstrates that effects of viscoelasticity are not negligible for either phenomenon, more important questions remain to be answered before the second-order nature of viscoelasticity becomes a necessary addition to improving the accuracy of glacier models. The lack of a general mechanism for explaining the long-distance transmission of a tidal load severely hampers the believability of the current published models investigating the interactions between an ocean tide and ice stream motion.

In the lake drainage problem, the evolution of the input pressure at the base of the drainage conduit is the most critical factor determining the growth size and duration of the basal drainage crack. Modeling the formation and growth of the drainage conduit, as well as the inflow rates into such a conduit, are more important to determining the inlet pressure, and thus the overall crack evolution, than is viscoelasticity. Thus, implementing viscoelasticity at the current stage of understanding in each of the glacial processes studied here is essentially fine-tuning an inherently oversimplified model missing physics essential to the problem.

Lastly, our introduction to this thesis framed this work in the larger context of using glaciological constraints on ice stream motion as input into climate models. While the work presented here is clearly far removed from any sort of global climate model, the general conclusion from chapters 2 and 3 that the ice stream margins are critical to determining the spatial extent of tidal forcing on an ice stream is relevant. That the shear margins impose a fixed length-scale on the transmission of a tidal load demonstrates that including the shear margins in a model is at least as important as correctly modeling the basal sliding relationship. Such a requirement implies the need to use three-dimensional models of ice streams. However, our work demonstrates that, for short-timescale perturbations of ice stream motion, the magnitude of the tidal response is primarily elastic, though the timing of the ice response is controlled by viscoelasticity.

6.3 Closing Thoughts

This thesis represents an effort to quantify the short-timescale behavior of glacial ice in the context of tidal forcing and supraglacial lake drainage. More generally, this work helps elucidate the important processes—both those constrained by geophysical modeling and those still conceptual—acting during the short-timescale deformation of ice. Much of the work presented here involves determining if ice viscoelasticity is important to correctly modeling the physics of these processes. Viscoelasticity is commonly cited as the “next step” in ice modeling; however the work here suggests that viscoelastic effects are of second order, and that there are still fundamental physical processes that are missing from the collective understanding of ice stream motion before viscoelasticity become truly necessary in glaciological models.