Title: Understanding and anticipating dynamical changes as Greenland Ice-Sheet outlet glaciers Transition from Marine- to Land-terminating (TransMariLand)

Extended synopsis

Background and motivations

Ice-Sheets are vast reservoirs of ice exerting increasingly large contributions to sea-level rise as climate continues to warm, with global implications for Earth's coastal environments and human populations. The net annual ice loss of Greenland (7 m potential equivalent sea-level rise) and Antarctica (60 m potential equivalent sea-level rise) each grew six-fold since the 1990s, from about 0.15 mm a^{-1} to about 0.9 mm a^{-1} equivalent sea level rise[1,2]. Not only these rates are increasing, but they are doing so in a non-linear fashion as feedbacks potentially enhance ice loss. Two decades ago, a study demonstrated accelerated Greenland ice flow occurs in response to surface melting[3]. Water from surface melt does not simply flow out over the Ice-Sheet surface, but penetrates via englacial vertical conduits to the Ice-Sheet bed, where it enhances basal motion through bed lubrication. This discovery attracted high attention given its potential for unforeseen Greenland vulnerability to warming as a result of a positive feedback between higher ice melt rates and faster ice flow, which enhances ice loss through discharging more icebergs to the ocean and enlarging the ablation area via dynamic thinning. Since then, however, a wealth of investigations has led to the opposite conclusion, that is the feedback between melt rates and ice velocity is negative. Increased surface melt rates turn out to enlarge subglacial channels that can more efficiently evacuate the lubricating basal melt water, thus reducing rather than enhancing basal slipperiness, and limiting the potential of melt forcing to increase mass loss as temperatures rise into the future[4]. Based on these evidences, the Intergovernmental Panel on Climate Change (IPCC) concluded in its 2022 special report on Ocean and Cryosphere in a Changing Climate[5]: "there is high confidence that for most of the Greenland Ice Sheet, increased surface melt has not led to sustained increases in glacier flux on annual timescales because subglacial drainage networks have evolved to drain away the additional water inputs[6–10]".

A new paradigm

In our recent study published in Nature[11], we revisited the impact of surface melt on ice flow from a particularly innovative perspective combining satellite observations and modelling inversions. This approach enabled quantification at temporal and spatial scales unyielded before, that is over multiple decades and the entire Western Greenland Ice-Sheet. Surprisingly, we find that the rate at which surface melt occurs does not significantly affect basal slipperiness. Instead, we demonstrate that conditions at the ice edge, whether the ice flows directly into the ocean or terminates on land, has the largest difference on how melt influences basal slipperiness including far into the interior of Greenland. We hypothesized this different response is due to morphology differences between marine terminating and land terminating glaciers. Being consistently slower and flatter than marine-terminating glaciers, land-terminating glaciers hinder the removal of lubricating basal water and have increased bed slipperiness. This suggests unforeseen dynamic changes are likely to occur as result of a MORphology-driven POsitive melt-water FEEdback (MorPoFee) generating higher than anticipated mass loss as glaciers transition from marine- to land-terminating into the future, as many are expected to do over the next century[12–14].

Current challenges

Our hypothesis to explain increased bed slipperiness as glaciers transition from marine- to land-terminating is qualitatively consistent with current knowledge. However, better assessing the impact of MorPoFee on Ice-Sheet evolution requires more quantitative understanding of its underlying physics.

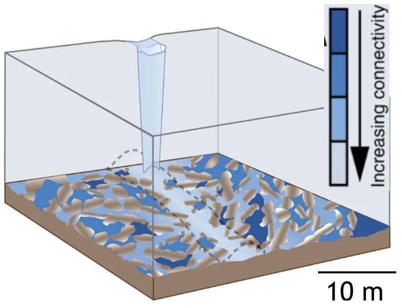

Figure 1: Expected subglacial hydrology networks and connectivity below Greenland glaciers. A central channel coexists with a population of cavity networks of various sizes and degree of connectivity (adapted from XX).

The known unknowns. Subglacial flow drainage theories incorporate thoughtful descriptions[4,15–20], but also involve numerous poorly constrained physical parameters as well as lacking physics. In particular, the evolution of connectivity between pockets of water forming in the lee side of bedrock bumps, commonly referred to as cavities, lacks appropriate theoretical description despite recent increase observational evidences that it exerts primary control on ice dynamics[16,21,22] (Figure 1).

The unmet needs. Lacking knowledge is mostly due to lacking observations. Water at the ice-bed interface is known to organize itself in a strongly heterogenous manner, with weakly-connected cavities transitioning to well-connected cavities and to channels over distances as short as few meters to tens of meters, all of which exhibiting ramifications up to several tens of kilometers[4,18,19] (Figure 1). Resolving this complexity from traditional punctual water pressure measurements in boreholes is strongly limited and costly, especially in remote areas like Greenland. Even when manageable, these observations are difficult to interpret and compare with models. **The unknown unknowns.** Although our hypothesis of a subglacial hydrology control leading to MorPoFee is the most plausible one given present knowledge, yet we cannot firmly rule out the potentiality that other unidentified mechanisms mitigate MorPoFee, such that for example unforeseen differences in ground water flow or internal ice deformation.

Project goal

In TransMariLand I aim to quantitatively understand the physics controlling MorPoFee and predict its impact on Ice-Sheet evolution and sea-level rise from paleo-climatic timescales to coming centuries

This proposed research pushes beyond the state of the art not only because it builds up on a recent change of paradigm regarding Greenland susceptibility to surface meltwater, but also because it involves a particularly innovative monitoring strategy based on seismic and satellite observations (see insets a. and b.) to probe key differences in marine- versus land-terminating subglacial hydrology characteristics and fill long-lasting knowledge gaps on subglacial hydrology and basal sliding. Contrary to observations of basal water pressure in boreholes, seismic and geodetic observations are by nature non-local and allow to retrieve multi-scales spatial fields that can more easily be confronted to models at considerably reduced financial cost and human resources enabling systematic investigations in remote areas like Greenland. Although proofs of concepts exist, yet a multi-scale monitoring strategy combined with dedicated modelling enabling making full sense of observations has not been conducted, nor in Greenland nor elsewhere. The plan of investigation is structured through two overlying aims gathering 5 work packages that all have their own independent merit, but taken together will synergistically provide unprecedent and quantitative insights.

a. Innovative use of seismology. The field of seismology underwent a particularly large diversification over the past decade[48–50]. Recent discoveries, to which I actively contributed[51–58], suggests that dedicated array designs, signal processing schemes and theoretical frameworks allow locating both channel and cavity drainage with high spatial and temporal resolution, inferring cavity network structure and evolutions as well as channel pressure and size.

b. Innovative use of geodesy. New satellite sensors and improved processing schemes now put satellite observations at another level of increased temporal and spatial coverage and resolution. We have recently demonstrated that differential radar interferometry (DInSAR) allows investigating centimetric changes in surface motion resulting from underneath fluid migrations[66], such that flow pathways and velocities are inferred over large areas of several hundreds of kilometers.

(AIM1) Observe the specific physics associated with the recently identified dominant glacier morphology control on bed slipperiness

I plan to conduct an unprecedent multi-physics and multi-scale monitoring scheme that offers the necessary spatial and temporal coverage for experiencing changes in subglacial hydrology in response to changes in settings (bed topography, glacier morphology), which typically occur over the season and the entire Ice-Sheet scale, while ensuring sufficient spatial and temporal resolution to assess underlying mechanisms (channels, cavities) and their associated control parameters (melt water input, bed roughness, glacier sliding velocity), which may typically vary over few meters and few hours[15,16,23–25]. These investigations involve a highly ambitious field deployment plan mostly based on deploying seismic acquisitions, but also a range of other instruments providing either redundant or complementary information to cross-validate results, constrain boundary conditions for subsequent process-based modelling (AIM2) and investigate the possibility that subglacial hydrology does not solely control difference in marine- versus land-terminating response to melt.

We will investigate two different scales on both Russel Glacier as land-terminating and Store Glacier as marine-terminating (Figure 1). The small-scale of few kilometers, equivalent to mesh size in large scale models[26], and the intermediate-scale of tens to a hundred of kilometers, associated with the glacier ablation zone. The high density of observations at the small scale will enable unraveling subglacial drainage heterogeneity down to few tens of meters over the spring-summer season when melt water input strongly varies. Instrumentation at the intermediate scale will operate over an entire year, and is designed to monitor large drainage structures, to extrapolate findings at the small scale and to compare with satellite observations. Satellite observations will be conducted systematically from the intermediate scale up to the entire Greenland Ice-Sheet, over the entire ten years' time span of the Sentinel 1 satellite (2013-current).

WP1: Acquisition of a comprehensive dataset at small to intermediate spatial scales (4-year engineer and 2-year technician)

We will make full use of new opportunities offered by modern sensors and technologies to sample the seismic wavefield with a coverage and resolution never reached before on glaciers. Seismic acquisitions will be made with a total number of 400 hundred seismic sensors referred to as Nodes, with Distributed Acoustic Sensing

(DAS) with several tens of km long optic fiber placed at the surface and in borehole, and 13 broad band stations (Figure 1a). Nodes are specifically designed for such types of deployments: sensor, acquisition and battery are embedded into all-in-one robust casing enabling fast deployment. DAS is a particularly innovative technique currently revolutionizing the field of seismology through offering monitoring capabilities unreachable before (REF). Based on Rayleigh scattering of a coherent laser pulse sent and backscattered by impurities along the optic fiber that act as a distributed interferometer, strain rate can be measured at high frequencies (>1000 Hz) over the entire fiber distance with spatial sampling as small as few meters (set by the gauge length). Crucially, DAS sensing in boreholes will enable turning the classical 2D into 3D observations, which will drastically increase resolution with depth, and DAS sensing at the surface will enable extrapolating observations at the small- scale towards the intermediate-scale. These measurements will be complemented by traditional and more innovative techniques including radar, drone, GNSS positioning, surface and borehole fibers for Distributed Strain and Temperature Sensing (DSTS) and basal pressure. DSTS sensing (using Brillouin scatter to measure deformation and temperature with high accuracy and spatial resolution) has also never been conducted in this type of setting, and may provide key information on the complexity of ice-thermodynamics.

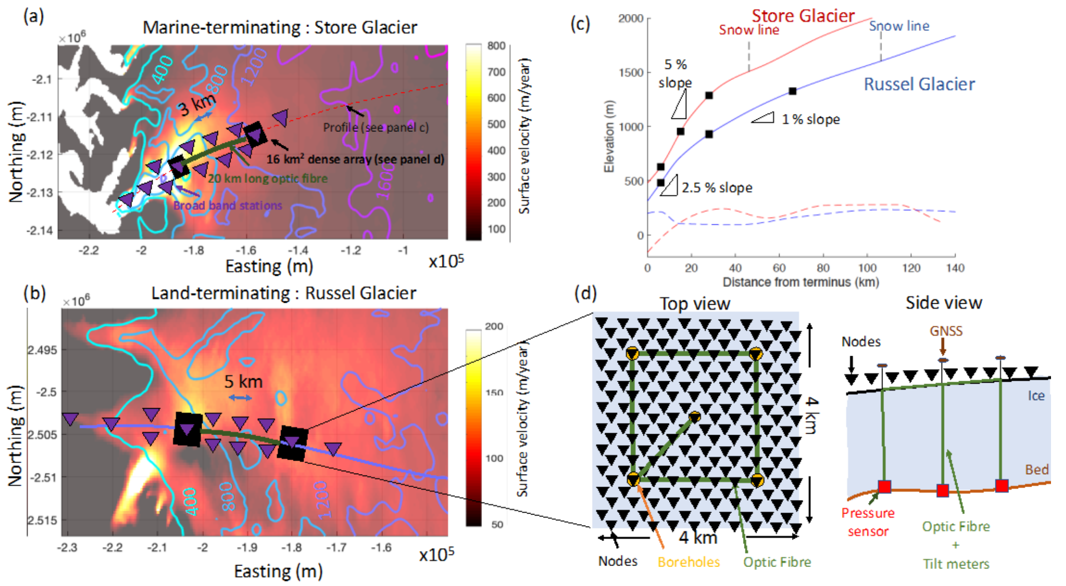

Figure 2: Schematics of the seismic deployments planned on (a) Store and (b) Russel glaciers. On (a) and (b) the colormap shows surface velocities and the line contours show ice thickness. Green triangles indicate seismic stations of the extended network and black rectangles show the spatial extensions of three dense seismic arrays (see panel (d)) located along a flow line. (c) Along flow profile of Store (red) and Russel (blue) glaciers together with dense seismic array locations (black squares). Continuous lines show surface elevations and dashed lines show bed elevations.

WP2: Analysis of seismic and complementary data to unravel subglacial hydrology characteristics and its links with ice dynamics (PhD 1 and 3 yr postdoc 1)

We will apply a wide range of signal processing techniques and theoretical frameworks to detect, locate and infer physical properties associated with all components of the subglacial hydrology configurations, including channels, well-connected and weakly-connected cavities[16,21]. The matched-field-processing technique[27] applied to both Nodes and optic fiber measurements will allow to locate channels and well-connected cavities with high spatial and temporal resolution on the order of few seconds and few tens of meters[28], and with coverage ranging from four to few tens of kilometers. Inter-station cross correlation techniques will be used to identify dominant channel and potentially cavity flow sources at the scale of the ablation zone. A theoretical framework[30,31] will be used to evaluate changes in water pressure and conduit size in both space and time based on seismic amplitude. High-resolution 2D surface-wave tomography[32–34] will be conducted using both local icequakes (at the small scale) and background noise (at the intermediate scale) and combined with inverse seismic modelling to infer geometrical properties of mainly weakly-connected cavities, which are expected to occupy the largest fraction of the bed. Finally, all seismic findings will be thoroughly compared with complementary observations in order to cross-validate results and assess other dynamical mechanisms that may differ between land- and marine-terminating glaciers, as well as with model inversions yielded in WP4 in order to investigate links between subglacial hydrology and bed slipperiness.

WP3: Analysis of satellite data to unravel subglacial hydrology characteristics and its links with ice dynamics (3 yrs postdoc 2)

Although widely used in other contexts such as for studying the Earth's crust, differential radar interferometry DInSAR has traditionally little been applied to the study of glacier dynamics, mostly as a result of signal analysis being highly challenging for such application. Improved monitoring capabilities and processing schemes have allowed strongly increasing our capability to retrieve the signal, at least in situations with non-significant changes in surface properties, such as in winter. We will use winter lake drainages as tracers probing subglacial hydrology flow in a range of land- and marine-terminating glaciers. Analysis will be based on systematically retrieving transient surface speed-up and uplift events generated from water flow migrating underneath ice. Based on these observations we will be able to quantify average flow drainage velocity, average connected cavity area and height, as well as average multi-scale cavity spatial heterogeneity. We will also compare these observations with model inversions yielded in WP4 to investigate links between subglacial hydrology and bed slipperiness. We will also test capabilities to apply DInSAR to situations with no lake drainage event in order to increase data completeness across Greenland but also in the Russel and Store glaciers where field instrumentation is planned.

AIM1 Key outcomes

-Highly-resolved maps of channels, well-connected and weakly-connected cavities covering the entire glacier ablation zone and melting season, with spatial and temporal resolutions as low as few tens of meters and few hours, respectively.

-Links between the dynamics of subglacial hydrology systems and physical parameters. Documentation of pressure gradient, hydraulic radius, flow speed and ice-bed separation associated with active drainage, and volume and geometry associated with weakly-connected cavities.

-Control of the various flow drainage systems on glacier bed friction

-Differences in bed slipperiness and control of subglacial hydrology and/or other physics between marine- and land-terminating glaciers.

AIM1 Risk Mitigation

- Highest risk is associated with the field plan in WP1, which involves the deployment and maintenance of numerous sensors including particularly innovative fiber optic monitoring under spatially and temporally changing glacier surface conditions. Risk is mitigated by the strong expertise the team of collaborators and I have developed in the past in Alpine environments during the RESOLVE (2018, https://resolve.osug.fr/) and SAUSSURE (2018-2023, https://saussure.osug.fr/) projects, in which we pioneered the deployment of dense seismic arrays on glaciers[57], and successfully conducted all the presently foreseen experimentation, both at the surface and in boreholes. The technical department of IGE also has strong experience in the development and operation of ice drilling devices on Ice-Sheets, and the technical department at ISTerre has strong expertise in surface geophysics. Risk is also mitigated through instrumenting Russel Glacier first, which is more accessible, less crevassed and thinner (requiring less drilling), such that experience will be gained before going to Store Glacier.
- High risk is also associated with the very unlikely but not impossible scenario that our increased observational capabilities lead to the identification of a yet unforeseen process other than subglacial hydrology controlling marine- to land-terminating increase in bed slipperiness. Such a discovery would potentially make MorPoFee and thus our AIM2 obsolete. However, I believe that even if such scenario was to occur, this result would nevertheless be crucial to share with the entire scientific community. It is also possible that this other yet unidentified mechanism may exert feedback as glacier transition from marine- to land-terminating, in which case it will crucial to know, and I will readjust AIM2 accordingly.
- Risk is also associated with the portability of seismic proofs of concepts established on mountain glaciers to Greenland, as well as our capabilities to fully incorporate the novel optic fiber observations into the foreseen data analysis schemes. Although all pre-requisites are full-filled in the proposed plan, no previous investigation exists at these scales. This risk will be mitigated through closely collaborating with experts of deployed methods, namely Philippe Roux, Nikolai Shapiro, Aurélien Mordret, Olivier Coutant and Stephane Garambois from the ISTerre laboratory.

(AIM2) Evaluate the impact of MorPoFee on the Greenland Ice-Sheet evolution and contribution to sea-level, from paleo-climatic timescales to decades to come

To test the impact of MorPoFee on Ice-Sheet evolution, I first plan to evaluate physically-based models against the unprecedent observational constraints yielded with our data newly acquired in AIM1. This step will enable us to ascertain the physics behind MorPoFee, and establish a calibrated friction law applicable in large scale numerical models. Then, in a second stage, we will use a hierarchy of large-scale models, from idealized two-dimensional to realistic three-dimensional, to quantify how much MorPoFee affects sea level under a deglaciation scenario, from paleo-climatic (120 kyr) up to centuries to come (yr 2300).

WP4: Refine physically-based hydro-dynamics models and test their ability to reproduce MorPoFee (PhD)

We will evaluate the ability of hydro-dynamical models to reproduce MorPoFee using the state-of-the-art hydro-dynamics model we recently developed in the software Elmer/Ice[35] for application to an Alpine glacier[20]. We will first conduct model inversions of bed sliding and bed velocity for both Russel and Store glaciers, with mesh refinement in places of small-scale instrumentations. These inversions will be used for model initialization, but also for inferring basal slipperiness as used in AIM1 to diagnose its links with the various subglacial hydrology systems. We will run forward hydro-dynamical model predictions in all glacier and scale configurations investigated in AIM1 in order to constrain underlying physical parameters through best matching observations yielded therein. We will constrain cavity drainage connectivity based on water flow speed, resolved in WP3, and water flow spatial heterogeneity, resolved in both WP2 and WP3. We will constrain parameters setting channel drainage evolution based on seismic inference of channel inception as surface melt rate increases, of channel localization with respect to hydropotential and of channel size and pressure in response to changes in melt-water input. We will also aim to overcome the current inconsistency between observations and theory of weakly-connected cavities following previous attempts considering cavities can only connect when exceeding a critical size[19], but with the added complexity that such critical size is spatially heterogeneous, such that a certain population of large and high-water pressure cavities may not necessarily be connected, consistent with observations. We will test this model update by conducting predictions using a range of distributions for critical cavity sizes, and compare these with our observations of cavity drainage patterns inferred from seismic source localization as well as with our observations of cavity volume and geometry from seismic wave tomography. Finally, we will test the ability of MorPoFee to spontaneously arise in our hydro-dynamics model by performing simplified modelling scenarios using an analogous slab of few square kilometers corresponding to grid size in large scale models with geometry prescribed to iteratively vary from a steep, thick and fast glacier corresponding to a marine-terminating glacier to a shallow, thin and slow glacier corresponding to a land-terminating glacier. This will enable us to parametrize bed slipperiness against sliding velocity and surface slope for use in WP5.

WP5: Disentangling the impact of the morphology control on bed strength on Ice-Sheet evolution from paleo-climatic timescales to upcoming decades (2 yrs postdoc 3)

The following conceptual model is expected given MorPoFee. As air and ocean temperatures rise and glaciers transition from marine- to land-terminating, upgradient regions are expected to slow and flatten, increasing bed slipperiness through the above quantified hydrological mechanism. The associated acceleration impacts the surface geometry, resulting in upgradient thinning and thus increased surface melt. It also implies an increase in mass flux towards the margin, possibly forcing outlet glaciers to re-advance to the marine margin resulting in another period of ice discharge. On one hand, we will aim at verifying this conceptual model and quantifying amplitudes and timescales associated with changes in ice flux and glacier geometry by considering a two-dimensional idealized model in which glacier bed slipperiness is set as a function of glacier velocity and surface slope using the parametrized relationship established in WP4. As a second step, we will implement MorPoFee in state-of-the-art large-scale three-dimensional models in order to evaluate its impact on sea-level predictions over the past deglaciation and the coming centuries (REFS).

AIM2 Key outcomes
-Establishment of a parametrization relating bed slipperiness with glacier morphology.
-Quantification of timescales associated with MorPoFee.
-Evaluation of the control of MorPoFee on sea-level over the last deglaciation and centuries to come.

AIM2 Risk mitigation

Highest risk is associated with our ability to establish a reliable parametrization of bed slipperiness with glacier morphology. This relies on being able to properly calibrate our physical model based on observations from AIM1, and on including a consistent representation of weakly-connected cavities, which is currently missing in existing theory. An alternative will be to parametrize bed slipperiness using a simpler physically-based model than presently considered (REF), which involves fewer physical parameters, which will easier calibration. The drawback will be that the calibration will not be as accurate, which may not be much of a problem for paleo-climatic applications since the switch from marine- to land-terminating may operates rapidly given involved timescales, but may render the evaluation of MorPoFee in future predictions more uncertain, as changes in morphology will be tiny in this case.

Project impact

To do so we will first verify whether the range of model initial states reproduce basic features given MorPoFee, that is, mainly, whether they predict steeper surface slopes for marine- compared to land-terminating glaciers and potentially reduced bed-slipperiness. As many models are initialized from paleo spin up realizations without assimilation of present-day configurations, this step may enable us understand ingredients in current parametrizations that are more favorable at reproducing MorPoFee than others. Finally, we will consider the best candidate models to conduct paleo-climatic and modern predictions using the parametrized law established in WP4 for describing bed slipperiness dependency on glacier morphology.