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Critical slip and time dependence in sea ice friction

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ABSTRACT

Recent research into sea ice friction has focussed on ways to provide a model which maintains much of the clarity and simplicity of Amonton's law, yet also accounts for memory effects. One promising avenue of research has been to adapt the rate- and state- dependent models which are prevalent in rock friction. In such models it is assumed that there is some fixed critical slip displacement, which is effectively a measure of the displacement over which memory effects might be considered important. Here we show experimentally that a fixed critical slip displacement is not a valid assumption in ice friction, whereas a constant critical slip time appears to hold across a range of parameters and scales. As a simple rule of thumb, memory effects persist to a significant level for 10 s. We then discuss the implications of this finding for modelling sea ice friction and for our understanding of friction in general.

1. Sea ice friction and memory effects

The behaviour of sea ice ensembles is of scientific and engineering interest on a range of scales, from determining local forces on an ice-moored structure to predicting whole-Arctic behaviour in climate models. Sea ice deformation is controlled by friction, through ridging, rafting, and in-plane sliding. Dry friction, on the macroscopic scale, is well understood by Amonton's law (that the ratio of shear to normal forces on a sliding interface is a constant, μ). Ice friction, in contrast, involves processes of melting and freezing, and associated lubrication and adhesion, and is hence somewhat more complicated. One key understanding is that when melting and freezing occur, friction can only be predicted if we know the state of the sliding interface, and hence memory effects must be included in any model.

There are two different approaches to this challenge, and progress has been made in both. The first is to work towards a better understanding of the detailed thermodynamics and micromechanics of ice friction. Work on lubrication models of ice friction has built on the foundation provided by Oksanen and Keinonen (1982); the effects of freezing have been summarised by Maeno and Arakawa (2004); the micromechanics of asperity contacts are considered by e.g. Hatton et al. (2009). The second possibility is to work on empirical adaptations of Amonton's law to incorporate memory effects (see e.g. Fortt and Schulson, 2009; Lishman et al., 2009, 2011). It seems reasonable to believe that the two approaches are mutually compatible, and might combine to provide a clearer picture of ice friction.

One empirical adaptation of Amonton's law which has gained significant traction in the rock mechanics literature is a rate and state friction model. Such a model accounts for two properties of friction which are frequently empirically observed:

1) Friction depends on the rate at which surfaces slide past each other, and
2) The state of the sliding surface affects the friction coefficient, and is itself affected by frictional sliding.

Friction in such models is assumed to be composed of a constant value, a rate-dependent term, and one or more state variables (see Ruina (1983) for discussion). The simplest rate and state model has the form:

$$\mu = \mu_0 + \theta + A \ln \frac{V}{V^*} \qquad (1a)$$

$$\frac{d\theta}{dt} = -\frac{V}{L}\left(\theta + B \ln \frac{V}{V^*}\right) \qquad (1b)$$

where μ is the time-dependent effective friction coefficient, V is the slip rate, V^* is a characteristic slip rate, and θ is the state variable, which affects the overall friction coefficient (Eq. (1a)) and varies with sliding (Eq. (1b)). A, B, and μ_0 are empirically determined parameters of the model. In this work, however, we wish to focus on L, the critical slip displacement. Ruina (1983) states that one basic feature of a system which fits a rate and state model is that "the decay of stress value after [a] step change in slip rate has characteristic length that [is] independent of slip rate". Ruina notes that this feature "appears to be common to the limited recent observations" in rock mechanics. Both Lishman et al. (2009), and

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Fortt and Schulson (2009), have gone on to make the assumption that a critical slip displacement is also a characteristic of ice friction.

The critical slip displacement is best understood graphically from Fig. 1. The upper graph shows an instantaneous change in slip rate across a sliding interface, while the lower part shows the typical frictional response for such a change. Qualitatively, such a response has been shown to occur in ice (Fortt and Schulson, 2009). Under steady sliding at initial slip rate V_1, friction is steady at some constant value μ_1^{ss}. On acceleration, friction instantaneously increases to some value μ_{peak}, and then gradually decays to some new steady state value μ_2^{ss}. The critical slip displacement, L, is defined as the distance over which friction decays from μ_{peak} to $[e^{-1}(\mu_{peak} - \mu_2^{ss}) + \mu_2^{ss}]$ (hereon abbreviated to μ_{cs}), and is shown as such on Fig. 1.

In this work we wish to better understand the critical slip of sea ice, and so we are particularly interested in the scaling of the frictional decay from μ_{peak} to μ_2^{ss}, and this region of interest (R.O.I.) is marked with a dot-dashed line: the R.O.I. is what will be shown in later experimental plots. Further, since we are interested in the scaling of the decay, we normalise for μ_{peak} and μ_2^{ss}. Experimental plots will therefore be shown as normalised friction μ_n:

$$\mu_n = \frac{\mu - \mu_2^{ss}}{\mu_{peak} - \mu_2^{ss}} \tag{2}$$

to allow straightforward comparison across results with varying μ_{peak} and μ_2^{ss}.

2. The scaling of slip in sea ice

We investigate the critical slip of sea ice in a series of laboratory experiments. Sea ice is grown in the UCL Rock and Ice Physics cold room facilities using carefully insulated cylinders to ensure a vertically oriented columnar ice structure comparable to that found in nature, with typical grain dimensions 10 mm in the horizontal (x–y) plane and 50 mm in the vertical (z) direction (see Lishman et al., 2011 for further details and thin sections). The ice is then cut to approximate shape using a bandsaw and milled to 100 μm precision. Fig. 2 shows the experimental setup, with three ice blocks (300 × 100 × 100 mm) in a double shear configuration. The sliding faces are in the x-z plane, analogous to the sliding of floating ice floes in nature. One key distinction between experiment and nature is that the experiment occurs out of the saline water, and so to minimise brine drainage we conduct all experiments within 4 hours of removing the ice from water. Table 1 gives further details of the ice properties. Normal load is provided by a hydraulic load frame, while shear load is provided by a hydraulic actuator. The entire experiment occurs within an environmental chamber in which temperature can be controlled. All loads and displacements are monitored at sub-100 ms intervals using externally calibrated load cells and displacement transducers.

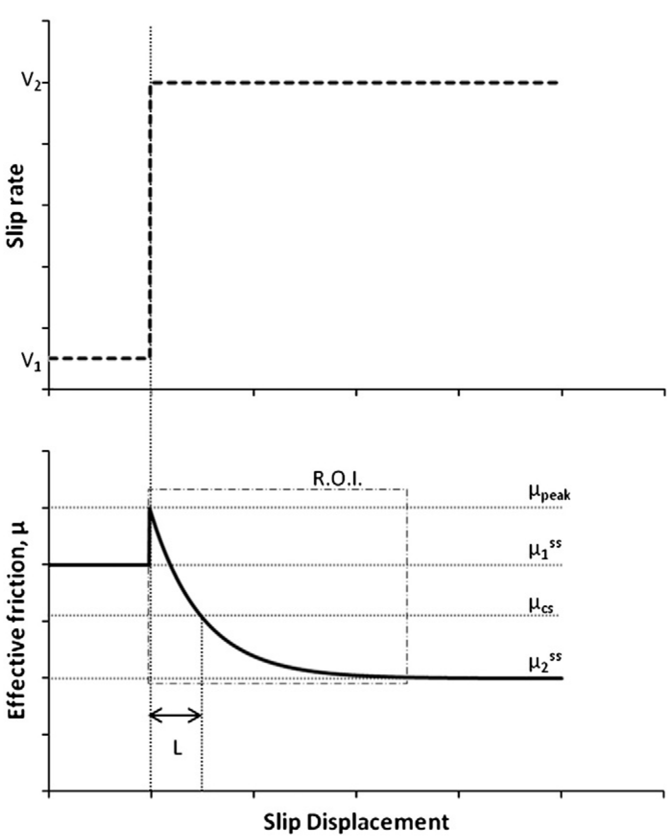

Fig. 1. Idealised evolution of friction μ as a function of slip displacement, for constant normal load, under an instantaneous increase in slip rate (after Ruina, 1983.) The dash-dotted box shows the region in which our later experiments are plotted.

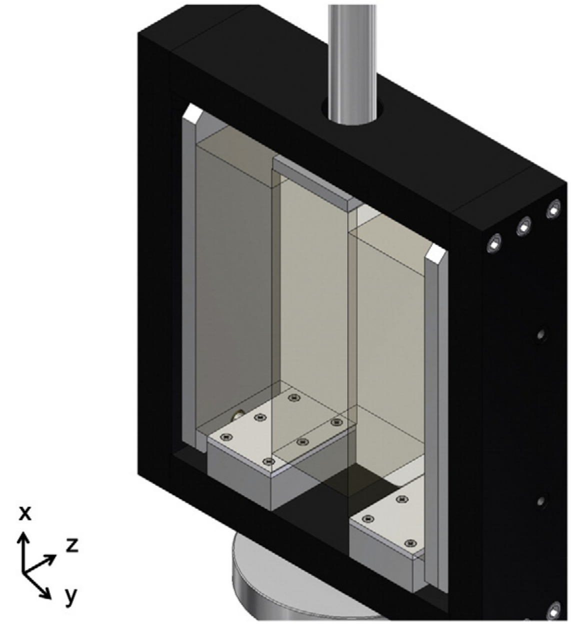

Fig. 2. Schematic of experimental apparatus. The ice blocks are milled to dimensions 300 × 100 × 100 mm. The entire apparatus shown is housed in a temperature-controlled environmental chamber. The actuator is controlled hydraulically. The x–y plane facing us is the upper surface of the ice.

Twelve experiments were run with this experimental setup and various environmental conditions, and the relevant conditions for each experiment are given in Table 2. The same ice blocks were used throughout. In each experiment the central block is moved 30 mm, under normal load, to ensure a repeatable sliding surface. Motion is then stopped for a given hold time (listed for each experiment in Table 2): this gives $V_1 = 0$. Motion is then instantaneously resumed at some slip rate V_2, again given for each experiment in Table 2. This leads to a frictional decay profile similar to that shown in Fig. 1. Fig. 3a shows a typical actuator velocity profile for an experiment with $V_2 = 1$ mms^{-1}, and we note that the laboratory actuator acceleration

Table 1
Experimental ice details.

Location	Laboratory	Ice tank
Ice thickness (m)	0.1	0.25
Water salinity (ppt)	33	33
Bulk ice salinity (ppt)	10.8	7.3
Ice density (kg m^{-3})	930	931