Investigating flow pathways and transit times for the dispersal of hydrocarbon pollution on Rabots glacier, Kebnekaise

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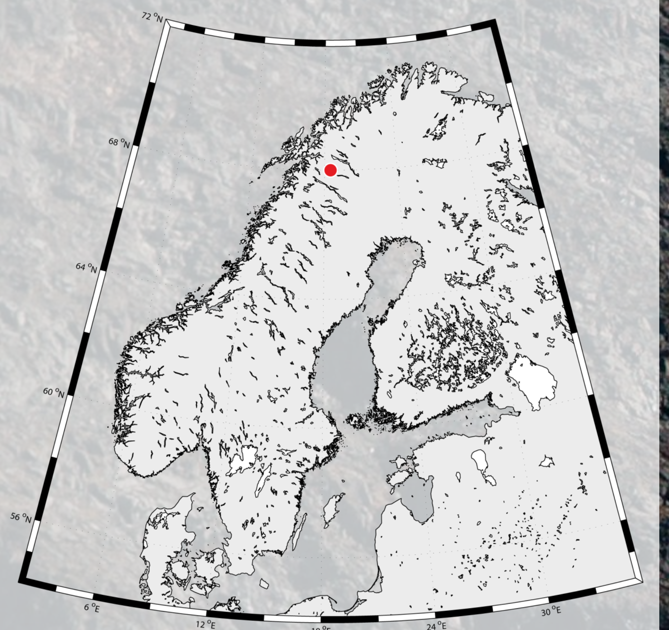
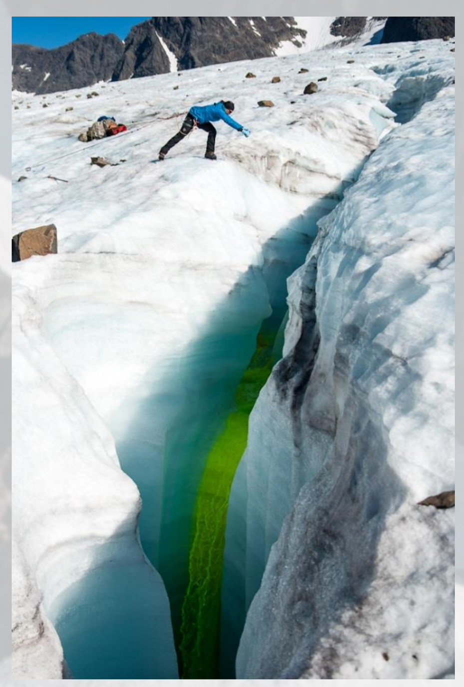
1. Motivation

Rabots glacier is a polythermal glacier of c.3.7 km^2 on the west facing slope of Kebnekaise, the highest mountain in Sweden (2099 m). On 15th March 2012 a Royal Norwegian Air Force Lockheed Martin C-130J Super Hercules aircraft crashed into the western face of Kebnekaise during a military exercise, approximately 50 m below the mountain ridge at 2014m, killing all five of the aircraft crew. **8900 kg (11100 l) Jet-A fuel, 50 l motor oil, and 170 l hydraulic oil were spilled**, together with 40 tonnes of wreckage, over the mountain. Most ended up high on Rabots glacier where snow avalanches distributed the fuel, oil and wreckage downslope. Intensive fieldwork has been conducted over two years to **investigate the storage and transport pathways of pollutants, the potential effects on the surrounding environment**. It also provides an opportunity to increase our understanding of the glaciers hydrological system.



2. Methods and monitoring



Over the course of the 2013 the following was conducted in the field:

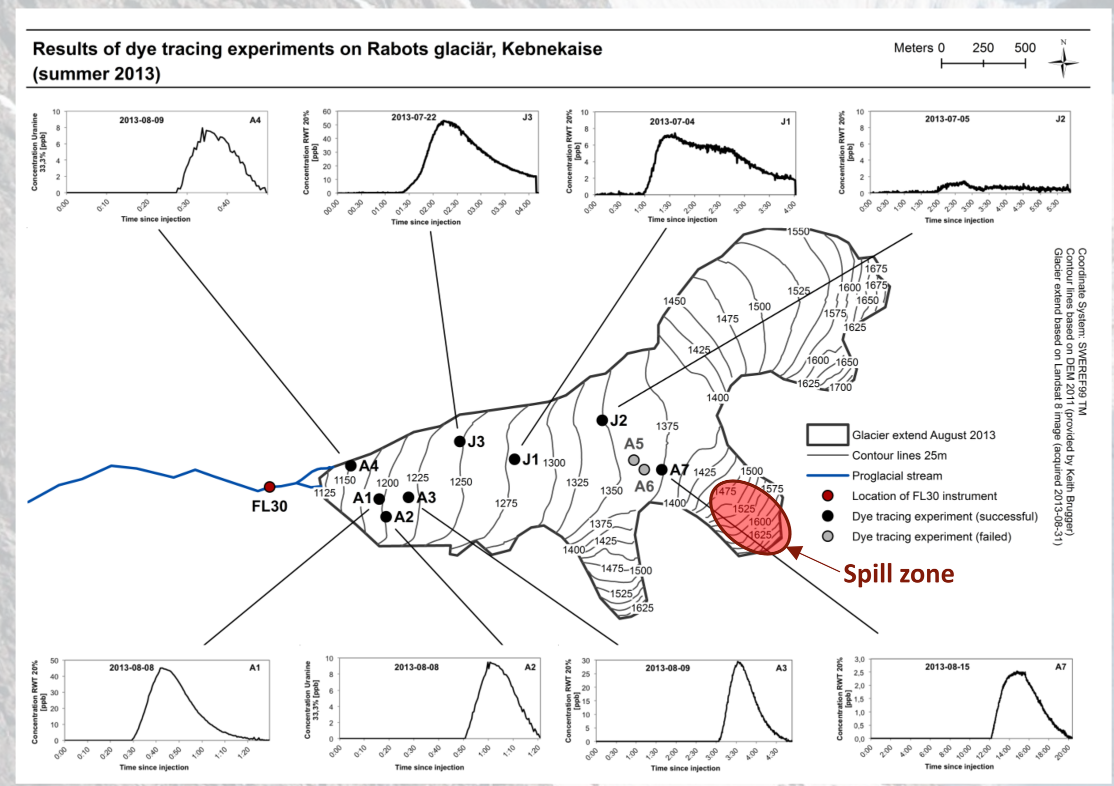
- Water sampling in Kaitum river system (2012 & 2013)
- River stage; water and air pressure; discharge from ratings curve (river dye tracing)
- Snow depth and density (2012 & 2013)
- Stratigraphic snow samping at spill site (2012 & 2013)
- Dye tracing in the snowpack
- Supraglacial meltwater sampling
- Dye tracing in the supraglacial system
- Dye tracing in crevasses and moulins
- Meteorological data from AWS on the glacier
- Ice penetrating radar

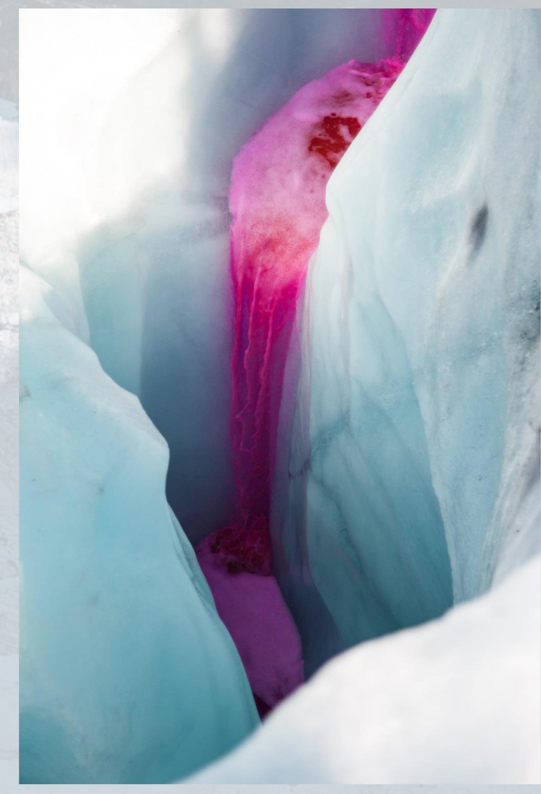
Data analysis and modelling was subsequently carried out:

- **Degree day melt modelling** for expanding recorded discharge and calculating flow accumulation & routing.
- **Analysis and modelling of dye returns** to investigate the efficiency and form of the drainage system.
- Dye return analysis and image classification for preferential **flow pathways of dye in the snowpack.**
- **Chemical analysis of water and snow samples** for detection of hydrocarbon/pollutant components.
- **Modelling mass flux of hydrocarbons** from spill zone.

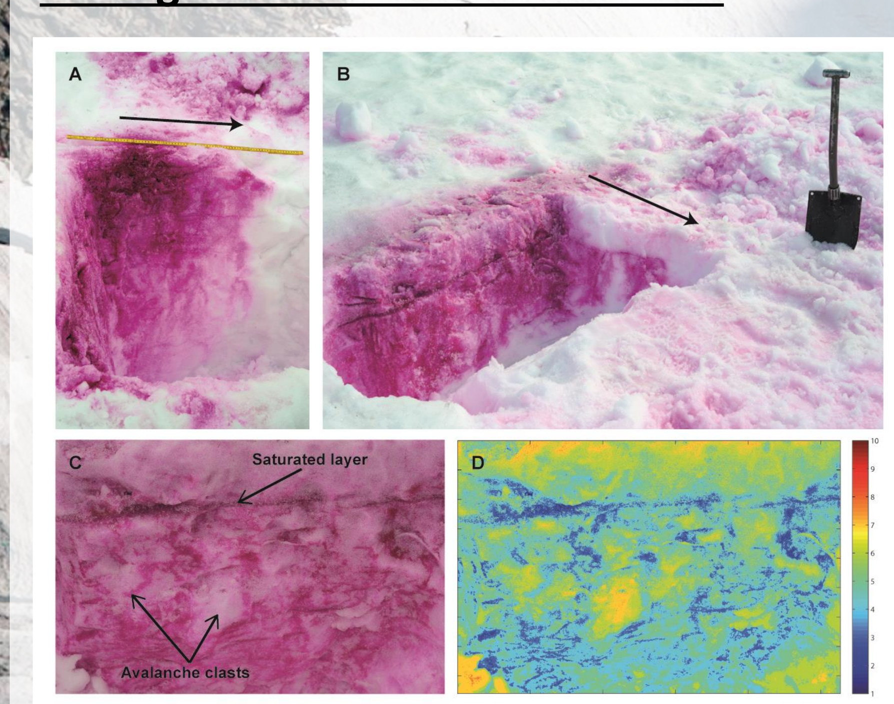
3. Results summary

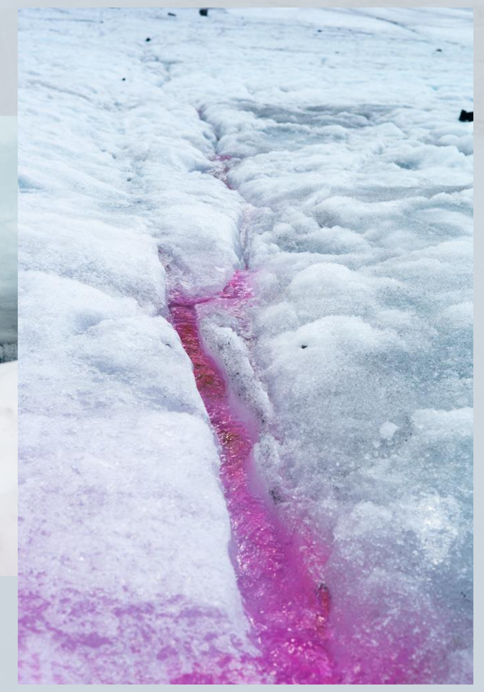
Englacial dye tracing over the 2013 ablation season allowed us to conceptualise the form of the drainage system. Due to early onset of melt, the evolution of drainage system efficiency was not fully captured. **Dye trace A7 immediately downstream of the spill zone suggests long storage followed by efficient release of meltwater, and perhaps also pollution**. From manual sampling we know **it emerged in the less turbid southern proglacial stream**, likely with minimal contact with the bed.



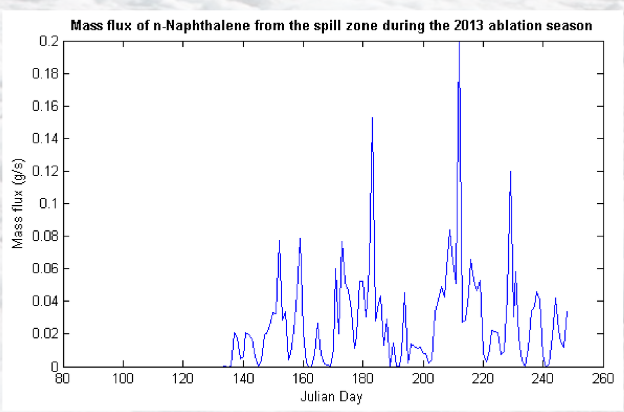


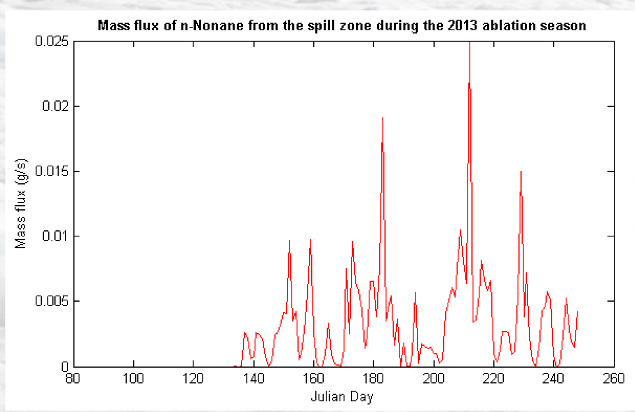
Dye tracing through snow produced **largely uninhibited percolation** through the mature snowpack (0.3 m/hour), with preferenial flow around avalanche clasts. Basal saturated flow speed was measured at 4.4 m/hour, with **rapid transfer of dye to the englacial system through closed surface crevasses** on emergence from the snowpack.

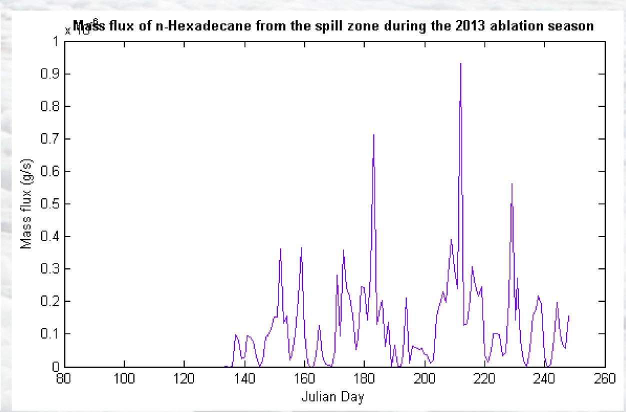


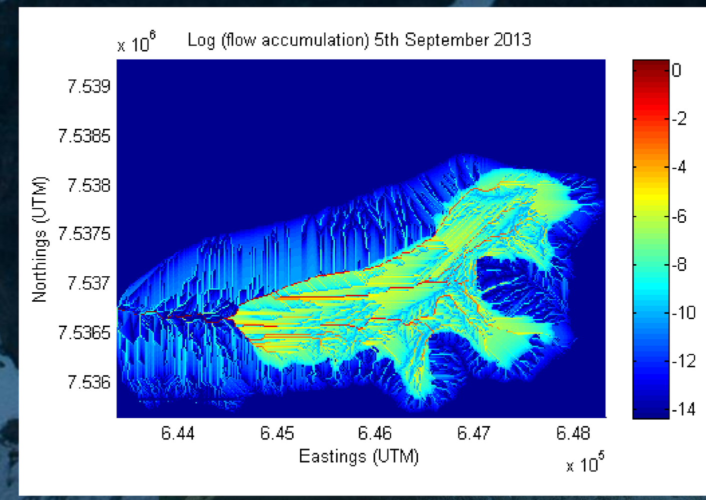


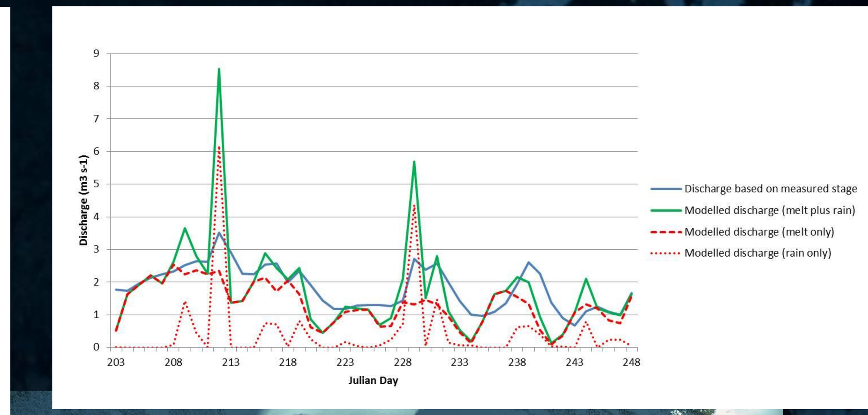
From modelling the mass flux of fuel compunds from the spill zone (where mass flux = efficient solubility x discharge) , we calculate a **2013 ablation season average flux of 1.7 kg/day of n-Naphthalene, 225 g/day of n-Nonane, and 3 g/year of n-Hexadecane**. It should be noted this assumes mass flux through solubility alone, and is an upper estimate.

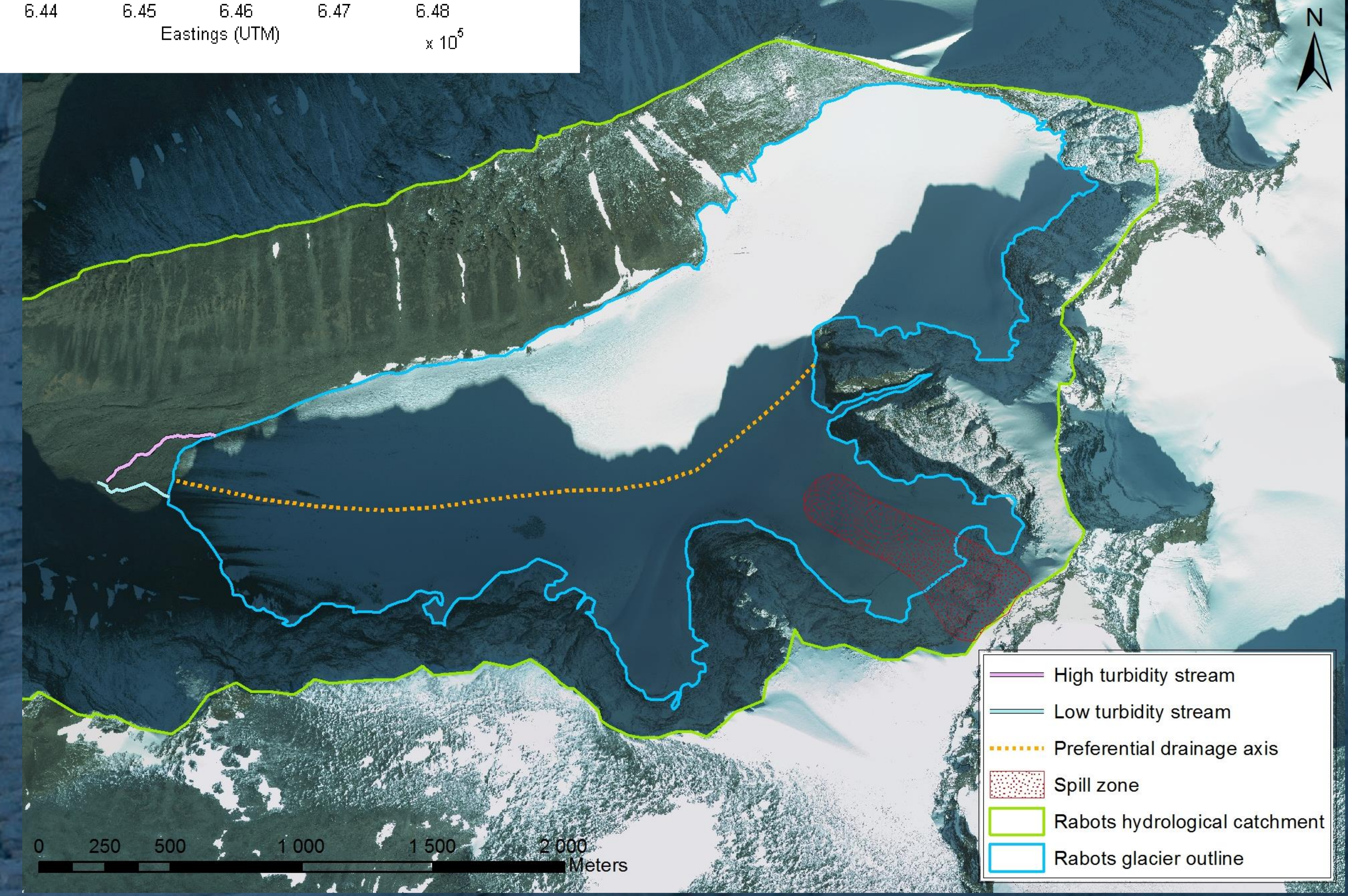












4. Implications and future work

- **This study adds to our limited knowledge of the transport, storage and effects of hydrocarbon pollution in glaciated environments** – very few studies have investigated this directly on ice, particularly in a valley glacier system.
- From simple modelling which provides an **upper estimate of mass flux**, some compounds would have left the glacier within one year (e.g. n-Naphthalene), while **others remain for centuries** (e.g. n-Hexadecane), if every day was equivalent to the 2013 ablation season average.
- Due to the relative clarity of the stream through which our longest yet “single-peaked” dye trace emerged, **storage and release of meltwater/pollution** from the crash cirque may be a factor influencing the surprisingly few times pollution has been detected in the proglacial system, in addition to the detection limits of chemical analysis.
- We plan to investigate the possible storage of pollution in the englacial system through additonal modelling.
- The storage and impact of the pollution may be explored further through the application of additional methods:
  - Comparing kerosene percolation and water percolation (tinted with dye) through a prepared snowpack
  - Ice core chemical analysis
  - Microbial impact and dark snow

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