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Land-terminating Ice Cliffs in North Greenland – (Why) Are they advancing?

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1) Introduction

- Land-terminating (dry calving) ice cliffs are intriguing features that occur in polar and tropical regions. Over flat terrain land-terminating ice cliffs can only persist under a complex interplay between certain climatic and ice dynamic conditions with *"cold"* and *"dry"* being the common pillars for their occurrence. The ice cliff position is controlled by the cliff's frontal mass balance and the ice flux.
- Wide parts of the ice sheet in North Greenland terminate as vertical cliffs on land. Their fraction of the total ice margin is unknown.
- Detailed investigations are limited to studies between 1955 and 1965 in the Thule area (Goldthwait 1971) and reveal **counterintuitive results**:

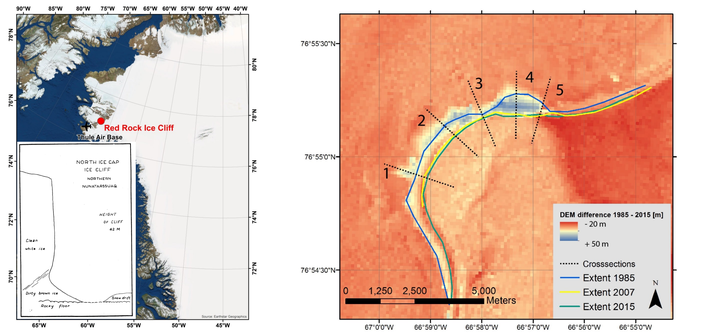
  ice surface lowering (~0.5 m/year) and
  net cliff advance (~0.5 m/year)

2) Objectives

- What is the fraction of land-terminating ice cliffs of the total glacier margin in Greenland?
- Is the counterintuitive cliff advance persisting?
- Why are the ice cliffs advancing although their surface mass balance is negative?

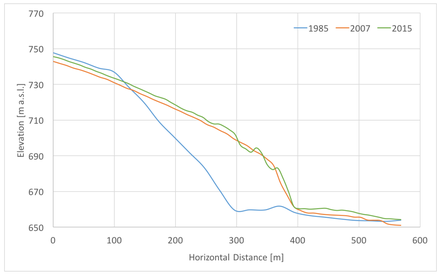
3) Methods

- DEM evaluations from 1985, 2007, 2015 (Korsgaard et al. 2016; Noh and Howatt 2015). DEM resolution studies: detectable cliff height as function of DEM resolution and slope: $tan(\theta) = \frac{dz}{dx}$
- Flow line modelling (Roe 2011)
- Radiation geometry analysis as proxy for frontal energy balance (Winkler et al. 2010)

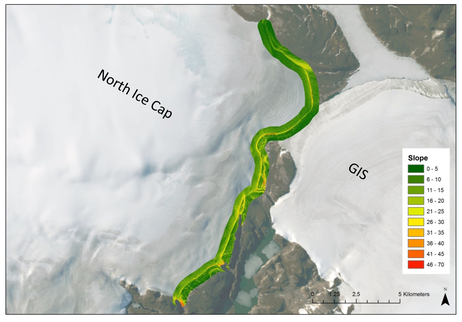


***Left**: Overview of the Red Rock ice cliff location at in northwest Greenland at ~77°N/67°W. A sketch of the cliff notes the most attracting features: clean ice, dirty ice toe, wind blown snow skirt at the base (White 1958).*

***Right**: Elevation difference and cliff advance between 1985 and 2015.*



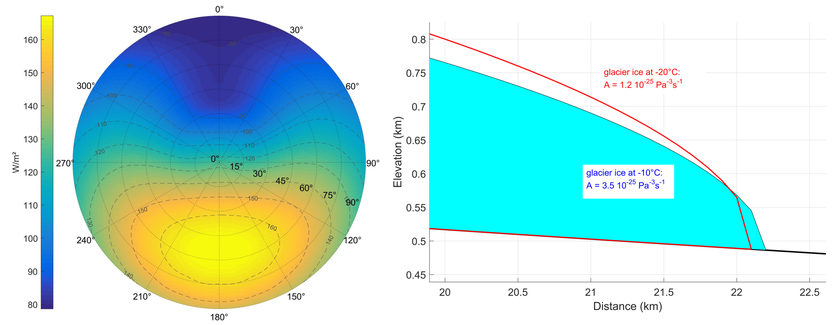
Example of profile 4 of the figure above comparing DEMs from three different acquisition times. At this location the ice cliff advanced ~3 m/year with a concurrent surface lowering of ~0.3 m/year.



Slope analysis along the ice margin of the North Ice Cap. The central steep section forms the Red Rock ice cliff. ~10% along the ice margin are >40° at this example.

4) Results & Outlook

- Between 1985 and 2015 the Red Rock ice cliff (and other cliffs not shown here) continued its advance at similar rates as observed in the 1960s with concurrent surface lowering.
- The land-terminating ice cliff fraction of the total ice margin is not fully analysed yet. Preliminary results suggest that ~10% of the ice margin is >40°. A DEM resolution <5 m is required to detect minimal cliff heights of 8 m and >60° (http://pgc.umn.edu/arcticdem).
- The solar irradiance as function of slope and aspect shows that shortwave radiation geometry has little impact on cliff morphology.
- Conceptual flow line modelling suggests that a warmer ice temperature and thus a higher creep parameter could explain the surface lowering and simultaneous cliff advance, without other parameter perturbations required.
- Further research is demanded combining in-situ observations (appointed in August 2017) with physically based models to better understand the sensitivity of land-terminating ice cliffs to mass balance and ice flux components and to evaluate their significance as climate change indicators in the Arctic.



***Left:** Mean annual solar irradiance as function of aspect and slope at 77°N including atmospheric optical thickness, ignoring clouds. The min-max range is small (80 W/m² vs 300 W/m² at tropical Mt. Kilimanjaro, Winkler 2010) thus, preferable cliff orientations as energetic optimum to solar radiation do not occur.*

***Right**: Detail of the terminus of the North Ice Cap towards the Red Rock ice cliff from a conceptual analysis using a flow line model (Roe 2011) with all available parameter estimates from this location. Two simulations were performed retaining all parameters unchanged, except applying two different creep parameters (the "A" in Glen's flow law) corresponding to ice temperatures of -20°C and -10°C, respectively.*

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Acknowledgements

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