Measuring recent dynamic behaviour of Svalbard glaciers to investigate calving and surging

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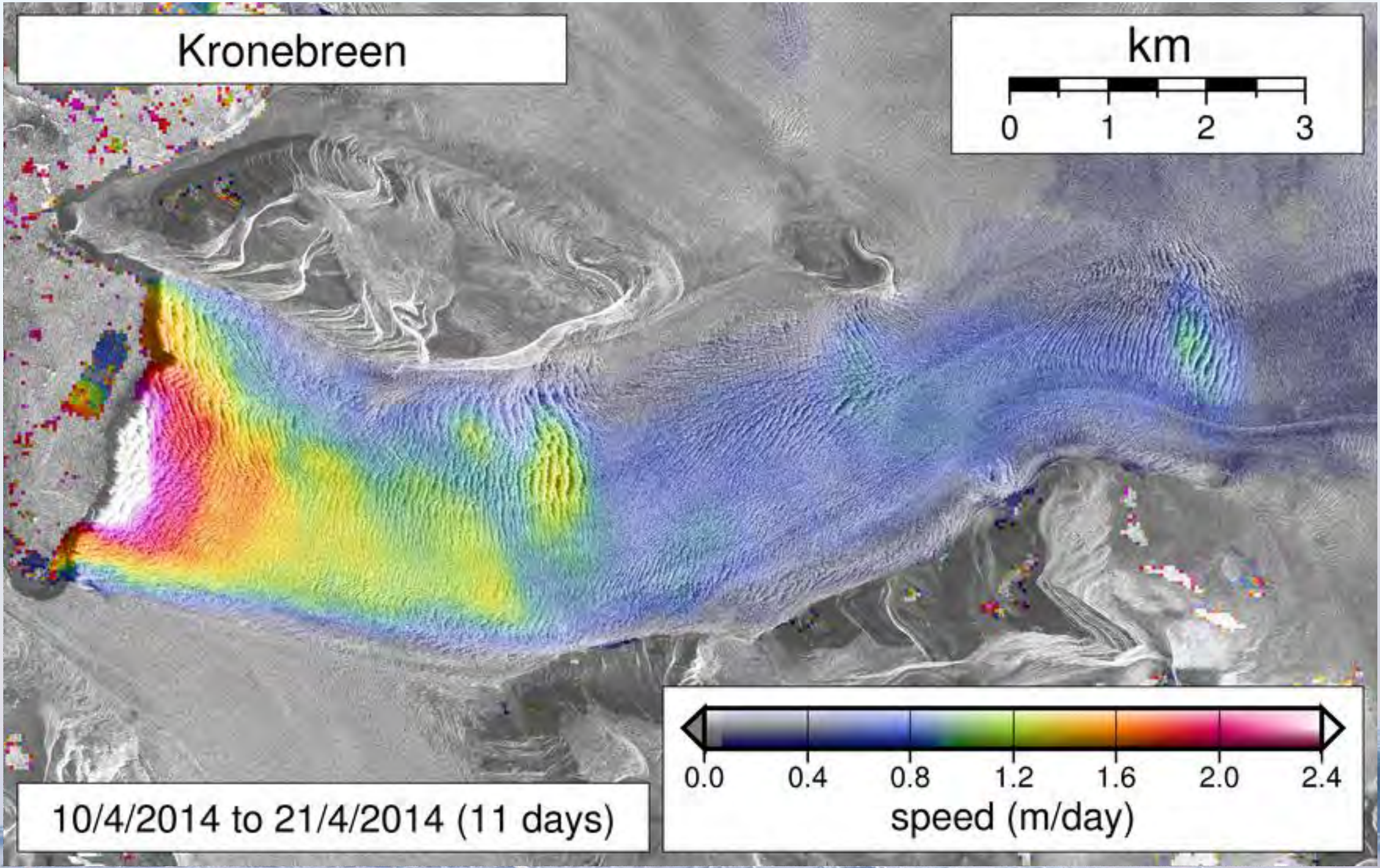
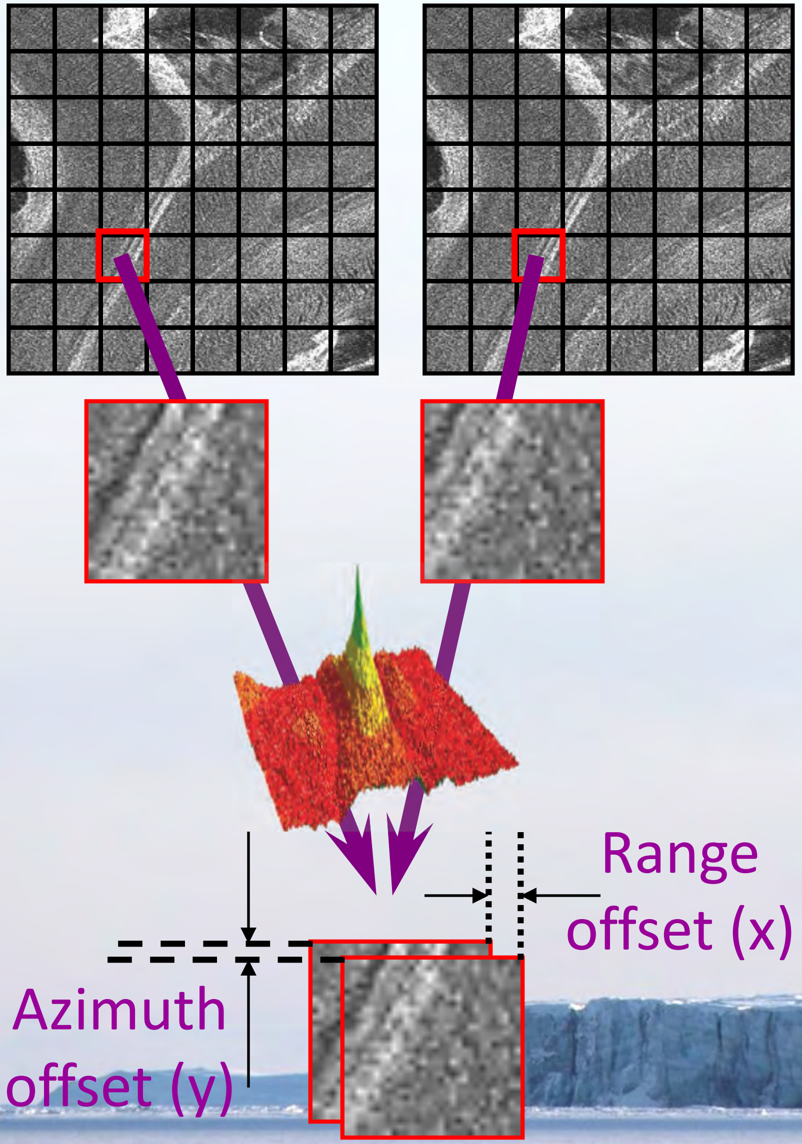
Introduction

- At tidewater-terminating glaciers, ice flow speed controls the rate of mass transfer from land to ocean
    - A component of mass balance, and contributor to sea level rise through the process of **calving**
- Flow speed responds to environmental conditions and climate change, but can also vary periodically in surge-type glaciers
    - Understanding variable flow in glacier **surges** can help us understand how normal glaciers and ice streams may behave in the future
- Ice flow speed is an '*essential climate variable*'
- Ice surface velocity can be measured using remote sensing through:
    - Satellite radar interferometry
    - Repeat image **feature tracking**
- Svalbard glaciers in particular are dynamically interesting because:
    - 60% of Svalbard is glaciated
    - Mass balance is strongly negative
    - Svalbard contains a '*cluster*' of surge-type glaciers
- This talk will focus on using remote sensing to explore the processes of **calving** and **surging** in Svalbard glaciers
    - Using techniques that you will learn later in the week

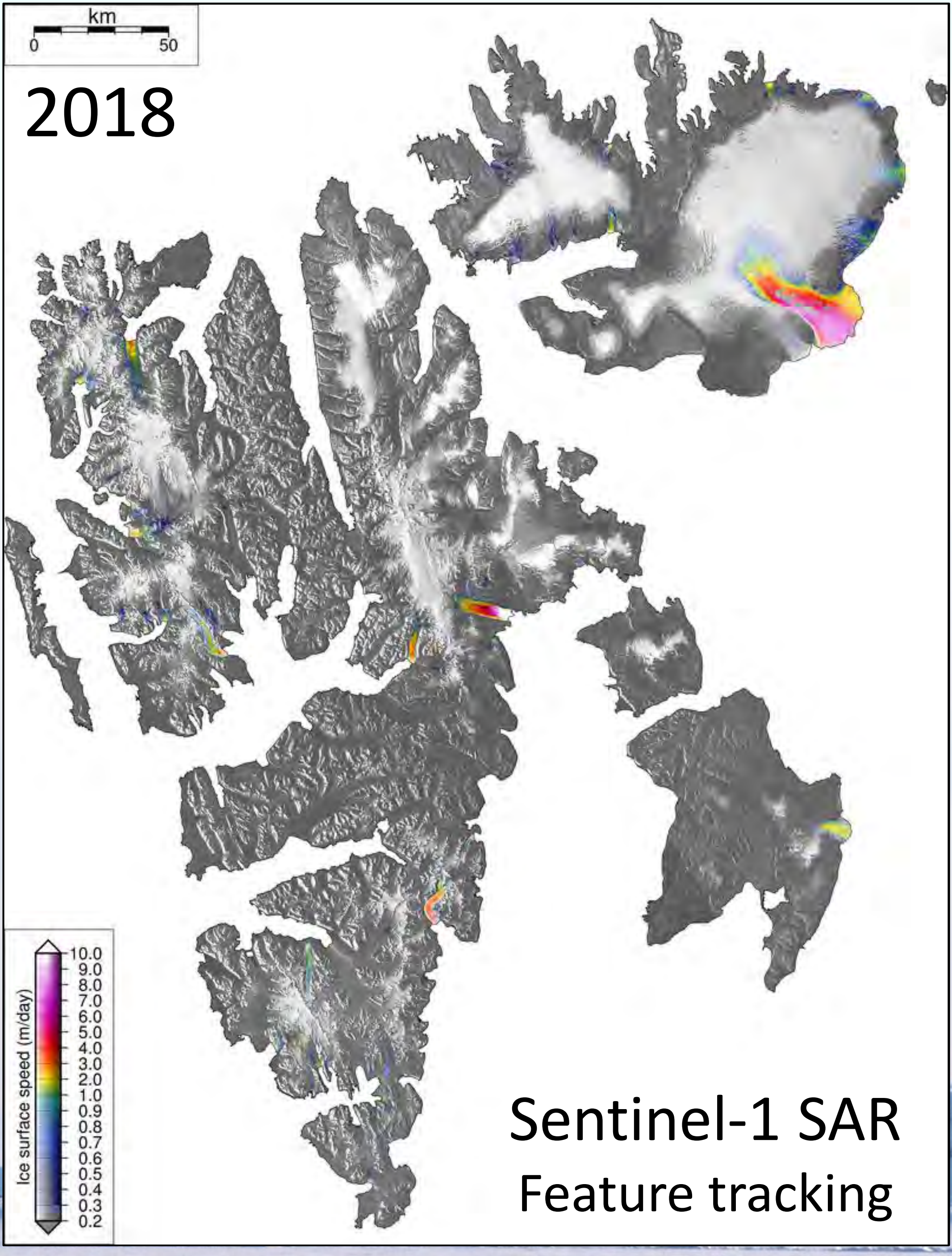
TerraSAR-X feature tracking, Kronebreen



The feature tracking method



- Take a pair of images from a single satellite sensor separated in time
- Co-register these precisely, so that stationary features occupy identical image positions
- Divide the images into a number of patches
- Find the similarity of these two patches at all possible overlap positions by performing a 2D cross-correlation
- The maximum correlation coefficient occurs where features match between image patches
- The position of this best match relative to the zero reference gives the movement of the features between image acquisition times
- Use the time delay between images and the pixel size to translate this movement into a surface ice velocity vector (2D)
  - Speed is the magnitude of this vector

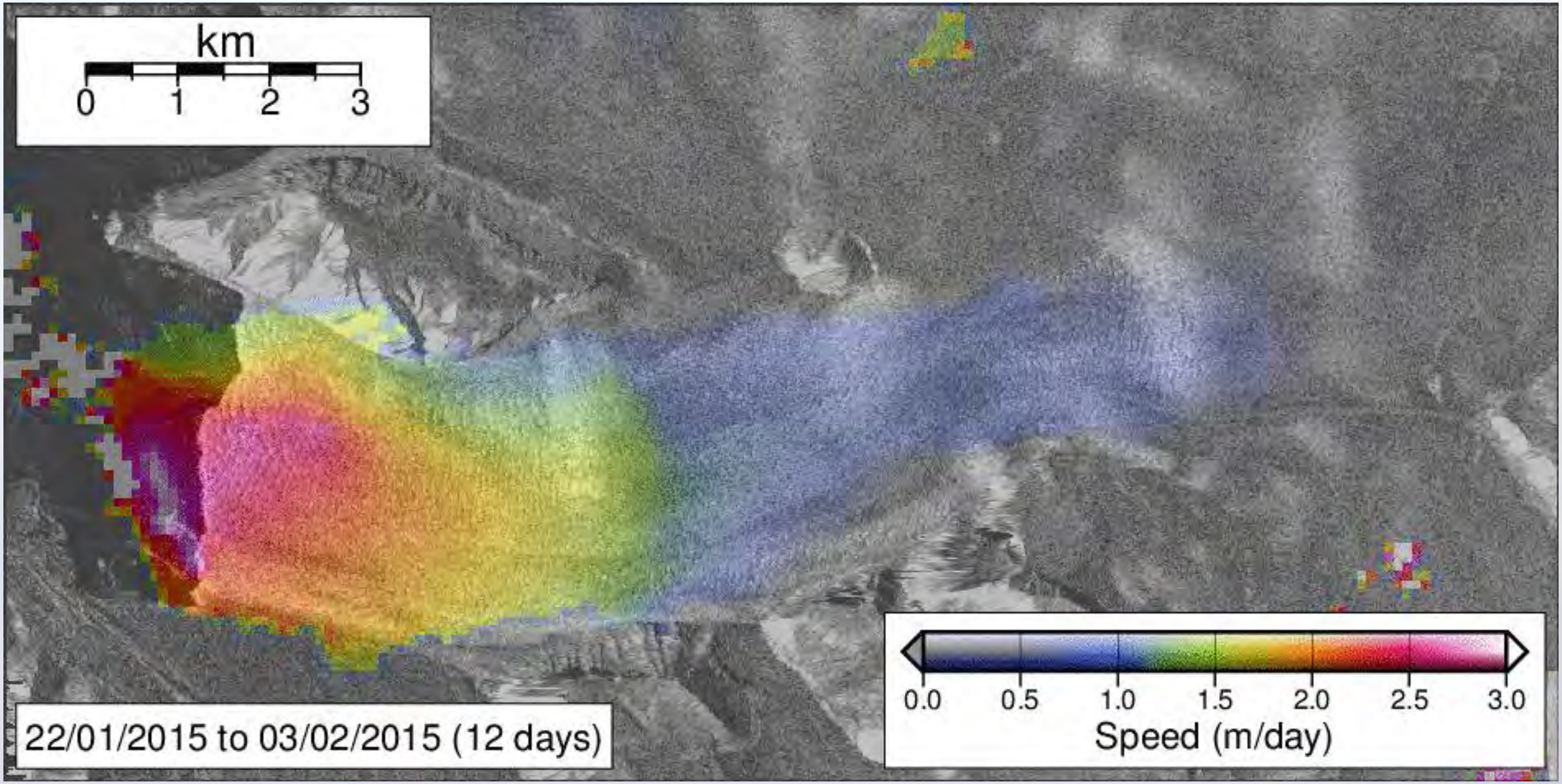


2018

Sentinel-1 SAR
Feature tracking

Sentinel-1 time-series of surface velocity

Kronebreen, NW Spitsbergen



22/01/2015 to 03/02/2015 (12 days)

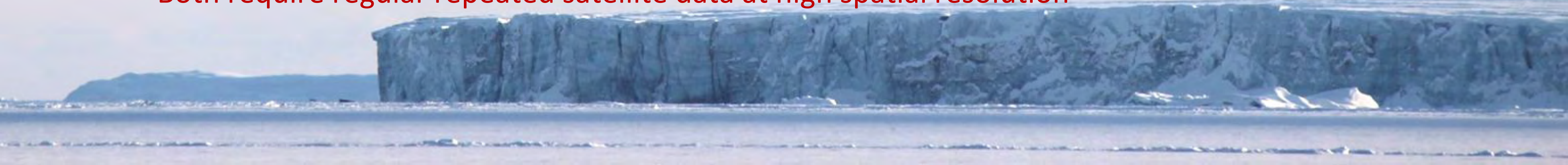
Calving of ice from tidewater glaciers


https://grist.org

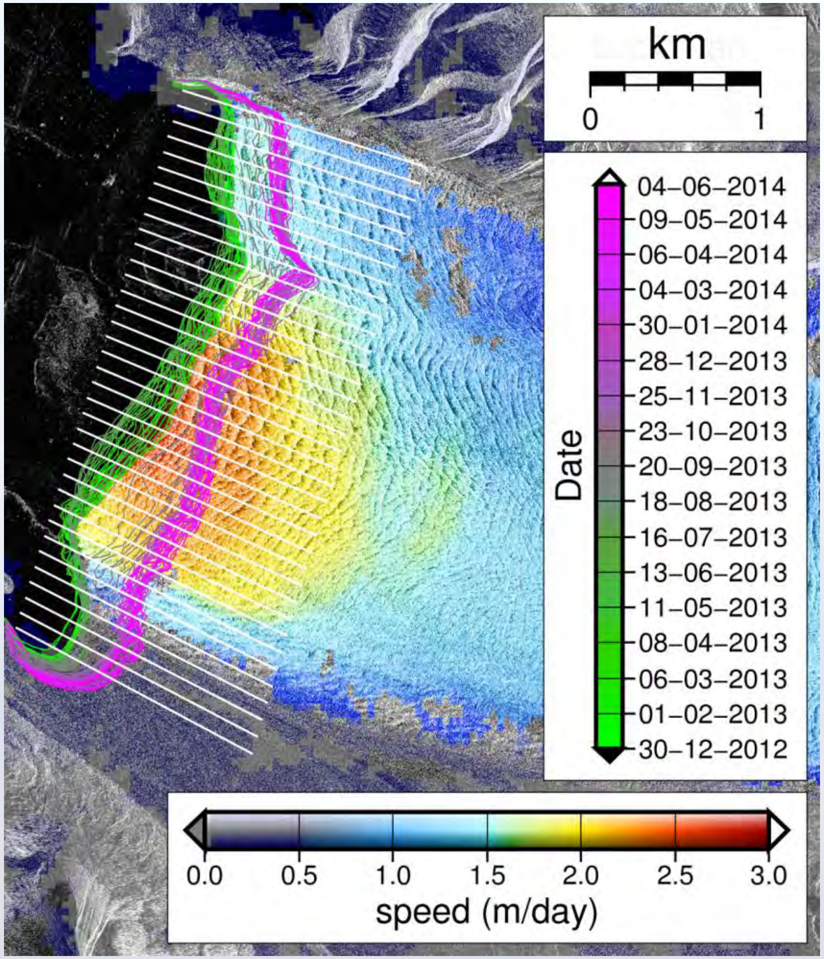
- Significance:
  - Accounts for over half of the discharge from ice sheets
  - Dynamic thinning in Greenland and Antarctica has been blamed on increased calving rates
  - Needs to be understood for prognostic ice sheet modelling
- Current understanding is poor because:
  - Calving is complex, potentially involving:
    - Large scale effects (ice shelves, stress fields, glacier/fjord geometry)
    - Small scale processes (fracture propagation, granular material behaviour)
    - Ice-ocean interactions that are poorly quantified (temperature, circulation)
  - Observations of calving rates at appropriate spatial and temporal scales are lacking

Measuring calving rates

- Calving must account for the ice flowing to the end of the glacier, plus any retreat or minus any advance
- Calving flux, Q_C:
  - Ice flux to the terminus, minus the change in volume
    - $Q_C = (U_T . W . H) – (dL/dt . W . H)$
    - U_T: depth-averaged mean terminus speed, or mean surface speed where sliding can be assumed
    - W: width, H: mean ice thickness, L: length
  - This can be usefully simplified to:
- Calving speed or *length calving rate*, U_C:
  - Terminus speed, minus length change over time
    - $U_C = U_T – dL/dt$
  - Ice thickness and glacier width can be factored in later if known
- Measuring the length calving rate requires observations of:
  - Ice front position
    - Varies seasonally and inter-annually on the order of meters to kilometers
    - Can be captured from satellite images
  - Terminus speed
    - Varies seasonally and inter-annually on the order of m/day
    - Can be measured using feature tracking between repeat-pass satellite images
  - Both require regular repeated satellite data at high spatial resolution



Measuring the length calving rate in practice



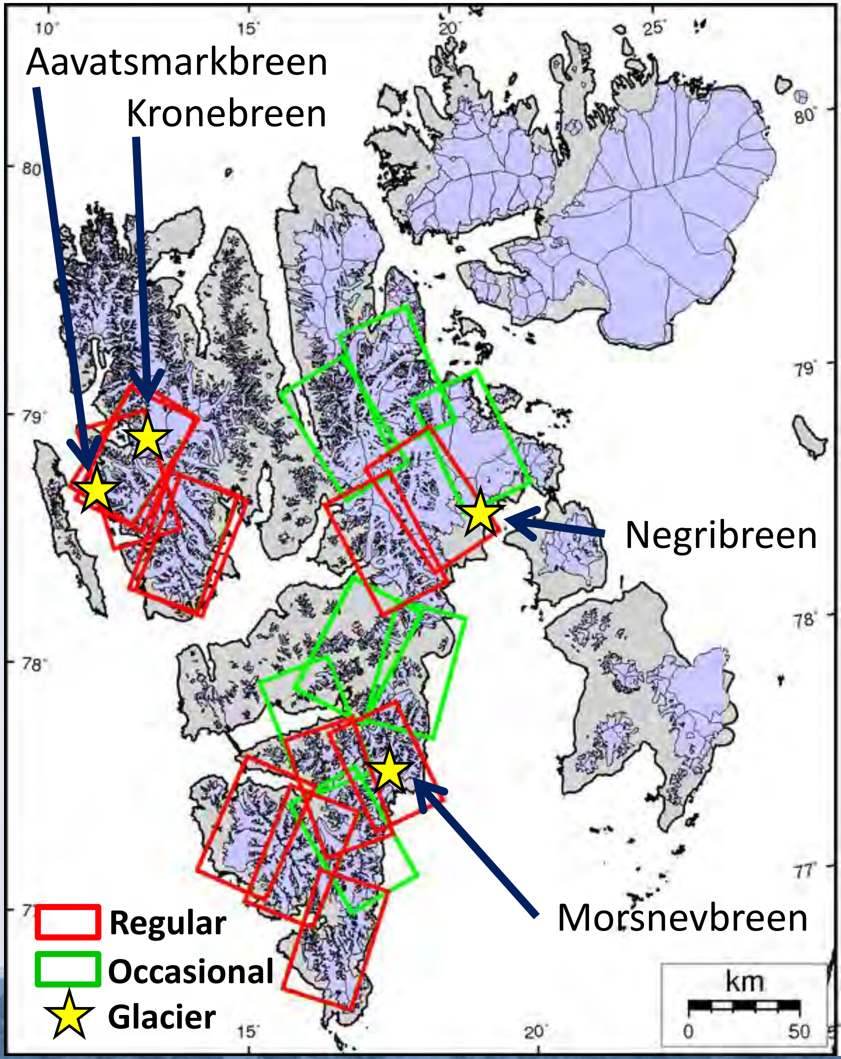
1. Co-register & geocode images
2. Digitise ice fronts at maximum resolution
   - Define a number of flowlines along which to measure
3. Find intersections between flowlines and ice fronts
4. Measure at each flowline:
   - Ice-front change between each image pair
   - Velocity from each image pair at current ice-front
5. Calculate ***mean*** ice-front change (dL) & velocity (U_T)
6. Derive mean calving rate
   - Strictly speaking, we should call this a ‘*frontal ablation rate*’ because is includes both solid ice losses and submarine melt

Data requirements for measuring surface speed and calving rate

- Required temporal resolution
  - Needs to resolve impact of change in the factors influencing calving
    - Seasonal? Diurnal? Events (rain, wind)?
    - Somewhere between daily and quarter-yearly
- Measuring ice front position
  - Calving events: on the scale of meters to km
    - High resolution is normally required
- Measuring surface velocity
  - Surface ice speeds are typically 20cm to 20m / day
  - High spatial resolution required to resolve trackable moving surface features
    - Meters to 10's of meters
  - Images from same satellite track normally required
    - To avoid differences in image geometry causing apparent displacement of features
- Conclusions
  - Many present-day high resolution satellite sensors are appropriate
  - SAR sensors have extra advantages:
    - Repeat image reliability (cloud)
    - All year round sensing (active microwaves)
    - Consistent illumination geometry
- Speed sensitivity
  - $\sim= \dfrac{\text{spatial resolution}}{\text{repeat period}}$
  - Sensitivity can be improved by feature tracking over more than one satellite cycle, but the longer the time period between images, the less similar features may appear in terms of image correlation
  - Examples:
    - Landsat: 15/16 ~= 1 m/day
    - Sentinel-2: 10/10 ~= 1 m/day
    - Sentinel-1 IW: 10/12 ~= 1 m/day
    - TerraSAR-X: 2/11 ~= 0.2 m/day

Calving Rates and Impact On Sea-level

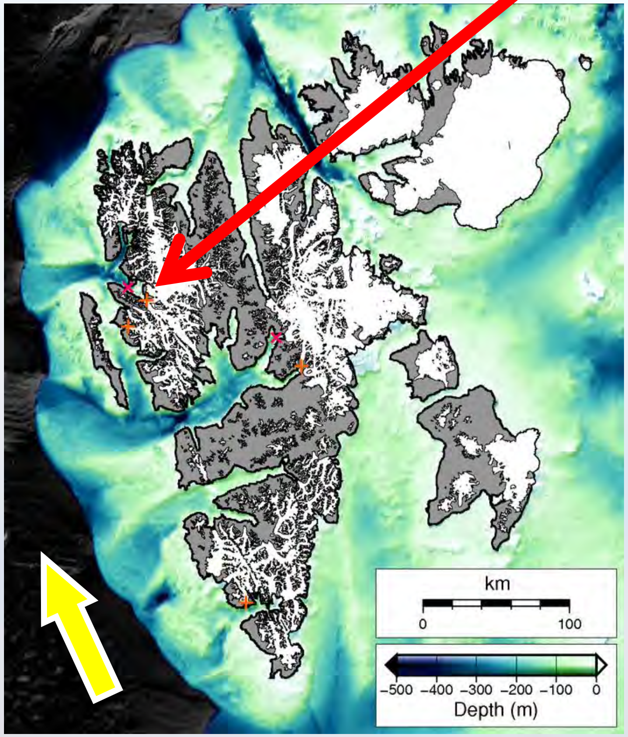
- The CRIOS project (2012 – 2015)
  - Funded by Conoco Phillips-Lundin Northern Area Program
  - Led by Doug Benn (formerly UNIS, now University of St Andrews)
- Aims:
  - To investigate controls on length calving rates at three dynamically contrasting tidewater glaciers in Svalbard
    - Kronebreen
      - Fast flowing (2.0 – 3.0 m/day)
    - Tunabreen
      - Quiescent-phase surge type (0.1 – 1.0 m/day)
    - Aavatsmarkbreen
      - Active-phase surge type (0.0 – 3.5 m/day)
- Methods
  - Fieldwork and numerical modelling
  - Remote sensing: TerraSAR-X Stripmap SAR images
    - 2m resolution, 20 x 30 km coverage
    - > 600 images (€120,000)
  - Measure ice-front positions and surface velocities at the ice front
    - $U_C = U_T - dL/dt$



Swansea University
Prifysgol Abertawe

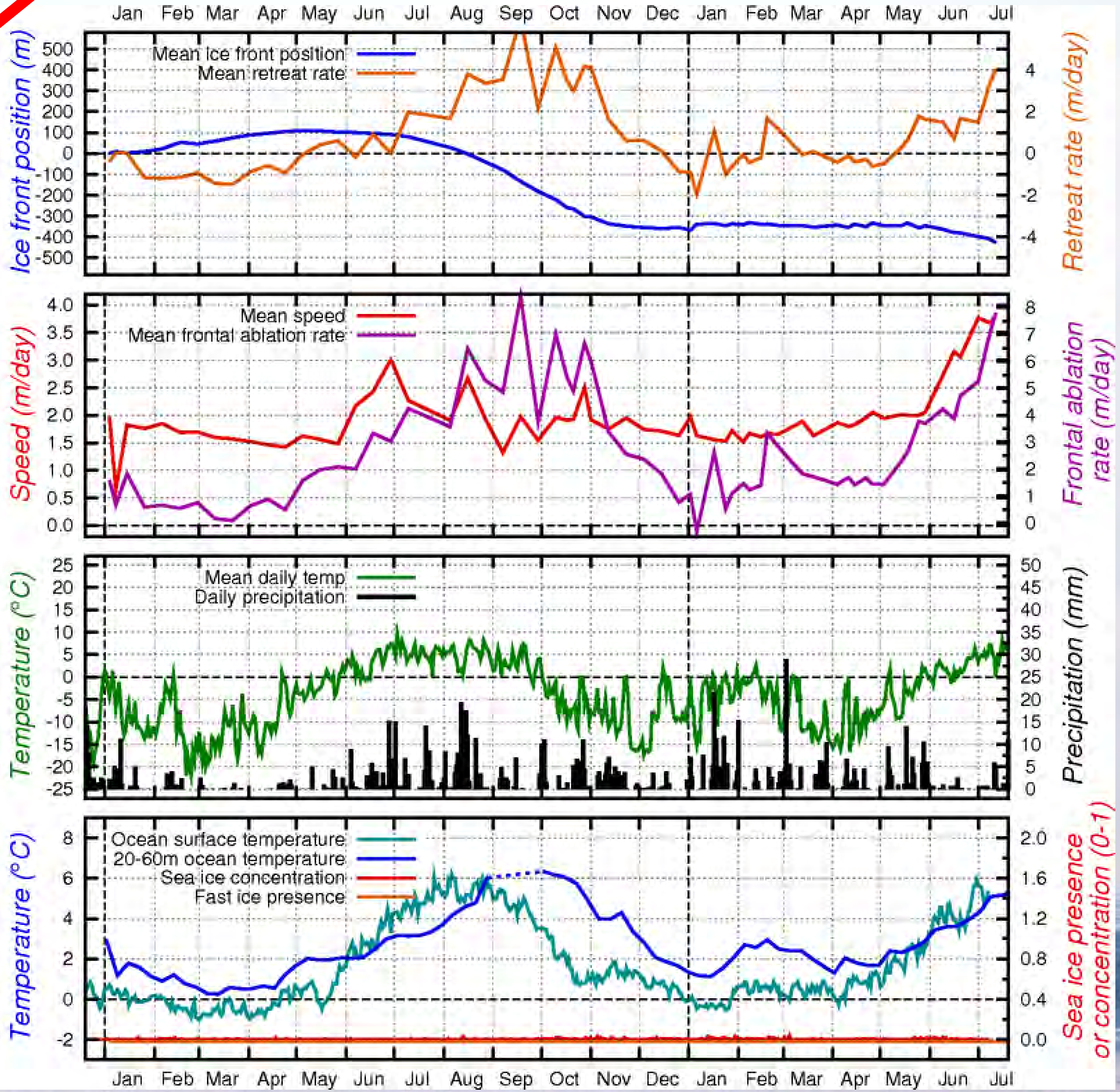
UNIS

Kronebreen (fast-flowing)

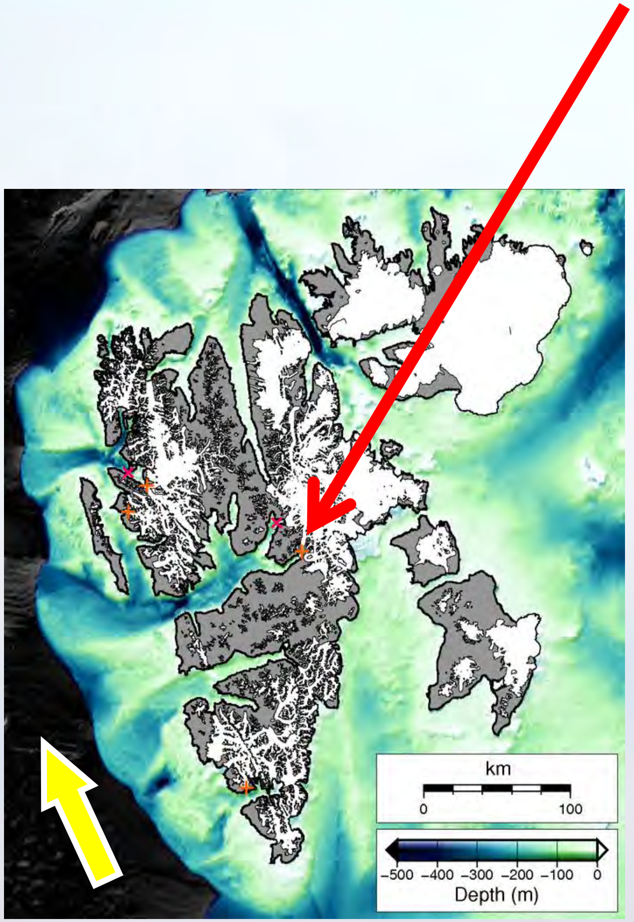


West Spitsbergen Current

http://www.ngdc.noaa.gov/mgg/bathymetry/arctic/arctic.html

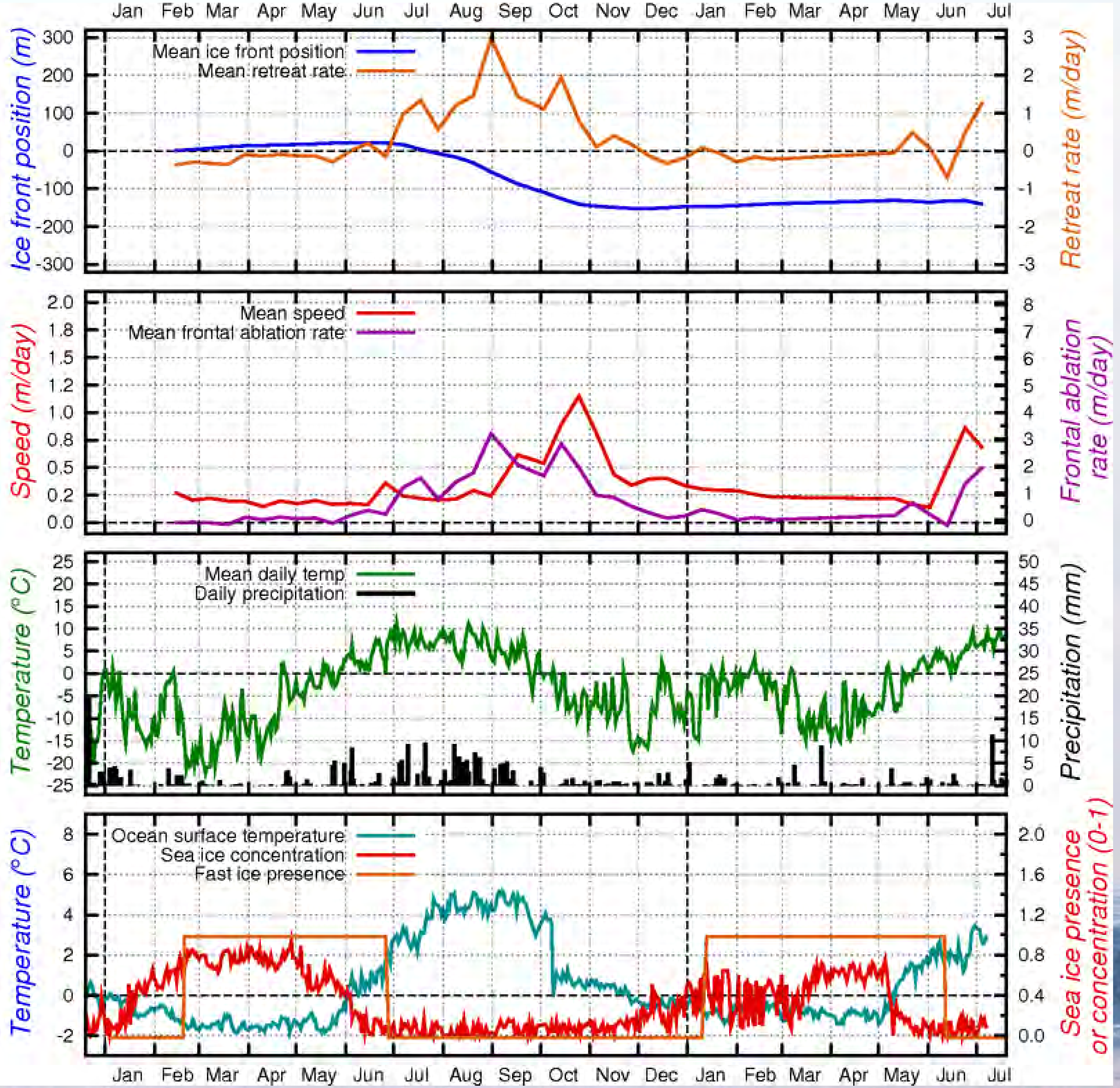


Tunabreen (quiescent surge-type)

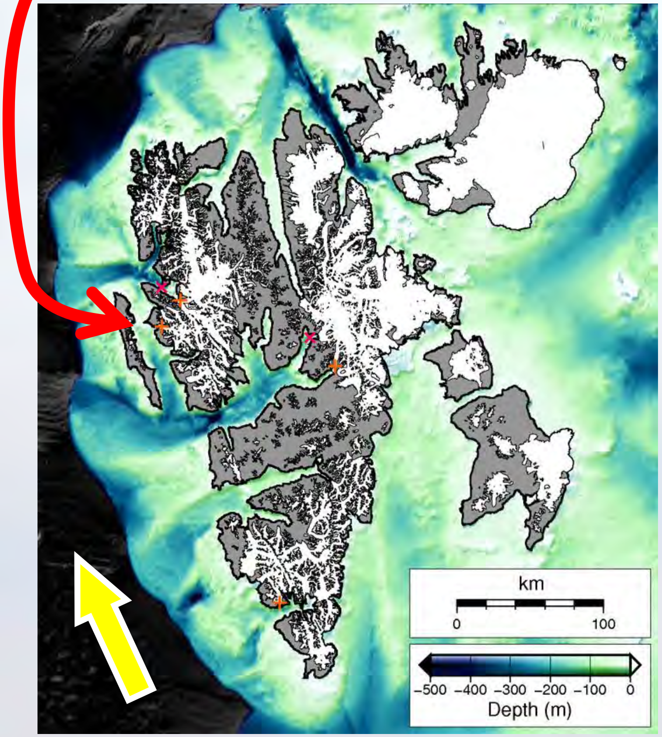


West Spitsbergen Current

http://www.ngdc.noaa.gov/mgg/bathymetry/arctic/arctic.html

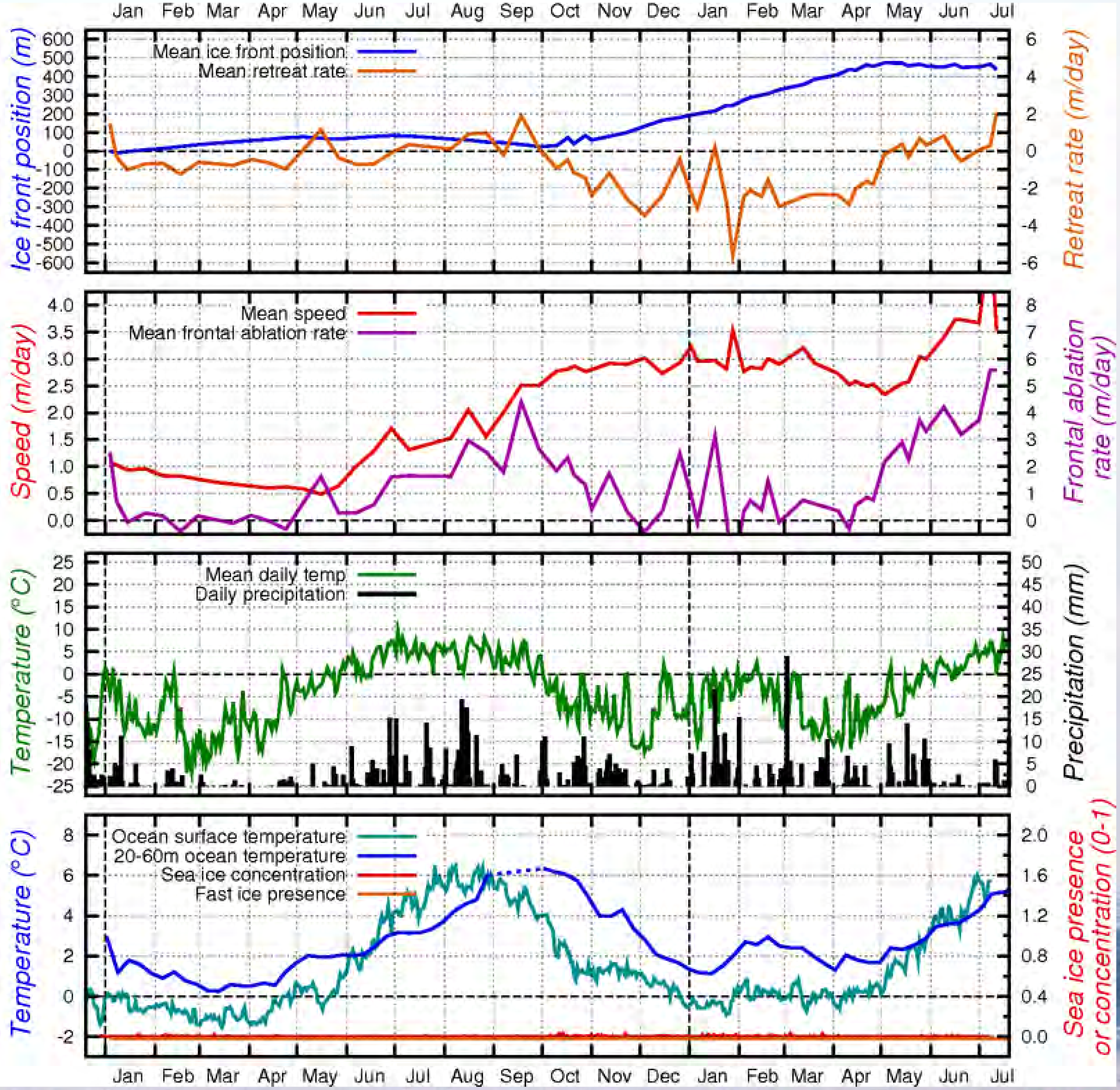


Aavatsmarkbreen (active phase surge-type)

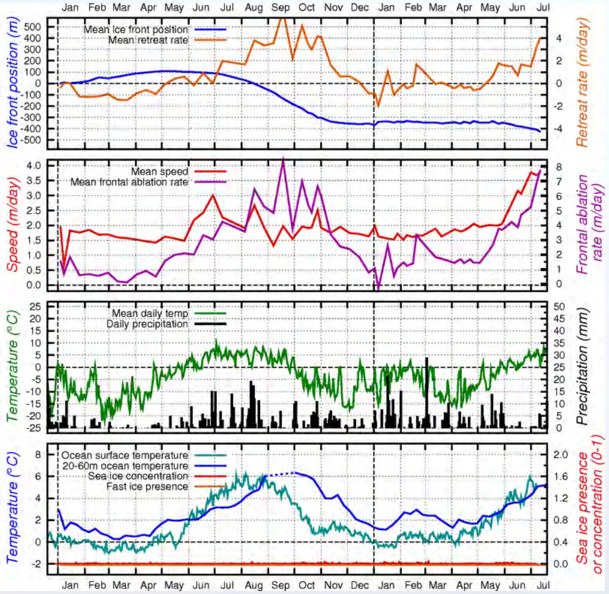


West Spitsbergen Current

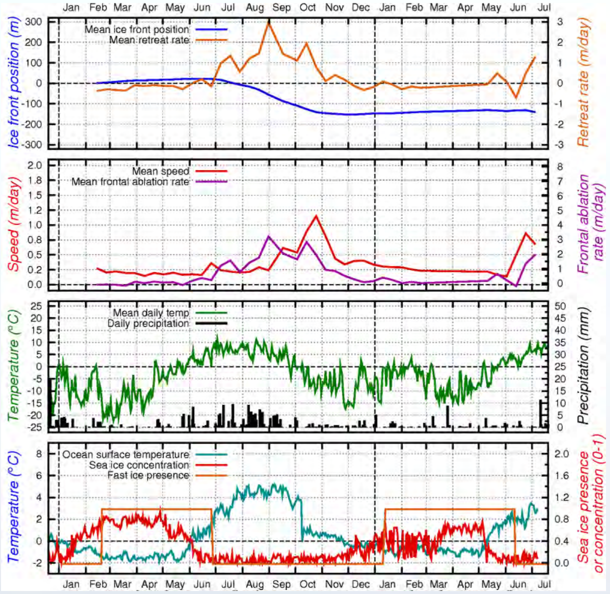
http://www.ngdc.noaa.gov/mgg/bathymetry/arctic/arctic.html



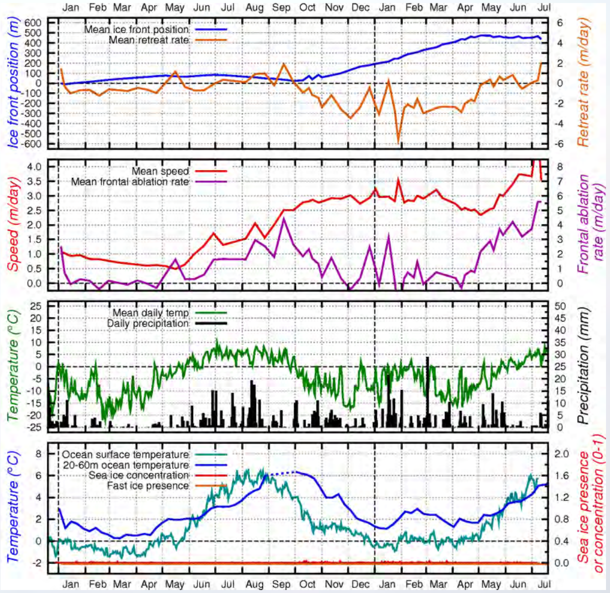
Comparison



Kronebreen



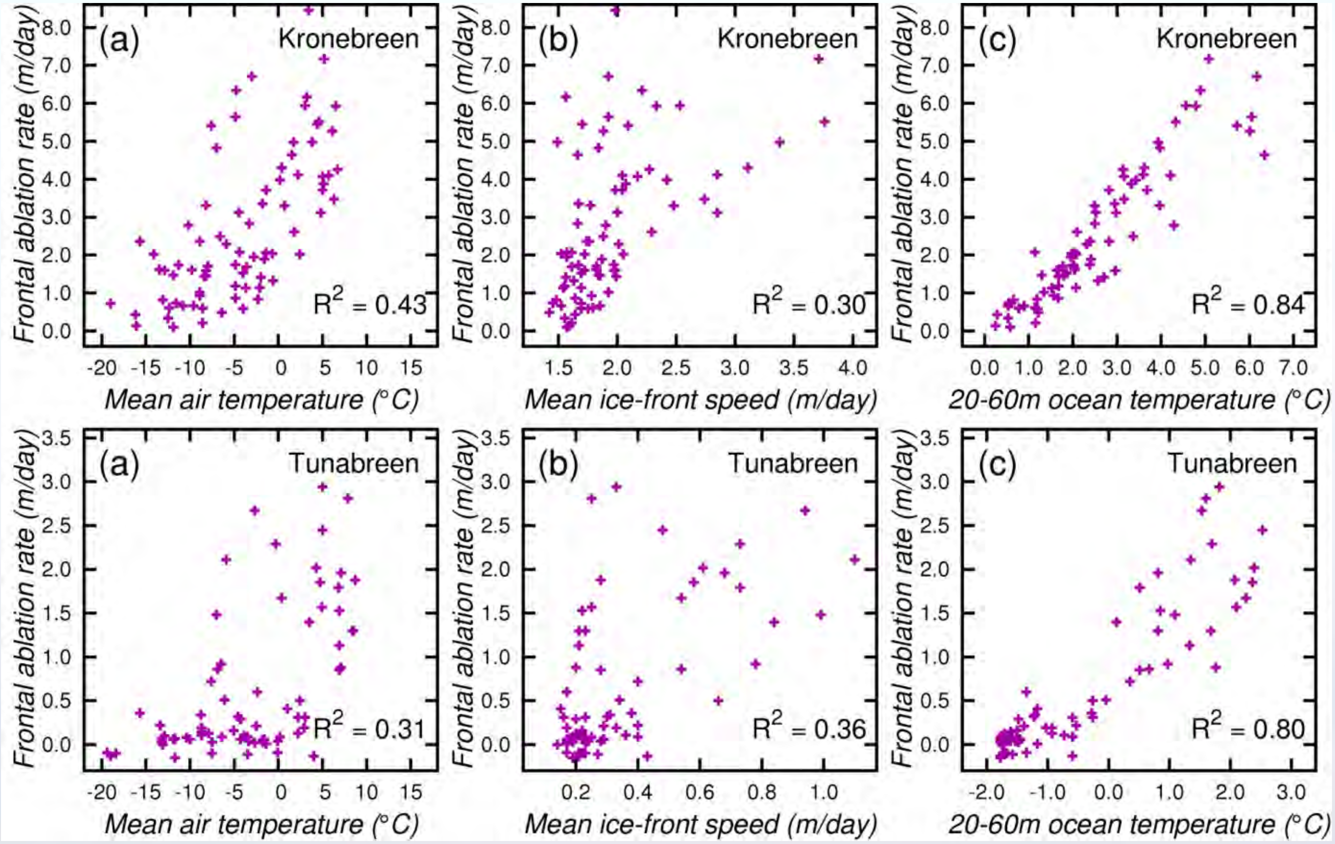
Tunabreen



Aavatsmarkbreen

- Comparable magnitude of calving rate (frontal ablation rate) despite major differences in ice dynamics
- Sept-Oct-Nov peak in calving rate
  - In sync with water temperature at depth

Drivers of frontal ablation



- Air temperature (a): No
- Ice speed (b): Only during fastest periods
- Ocean temperature (c): Good correlation

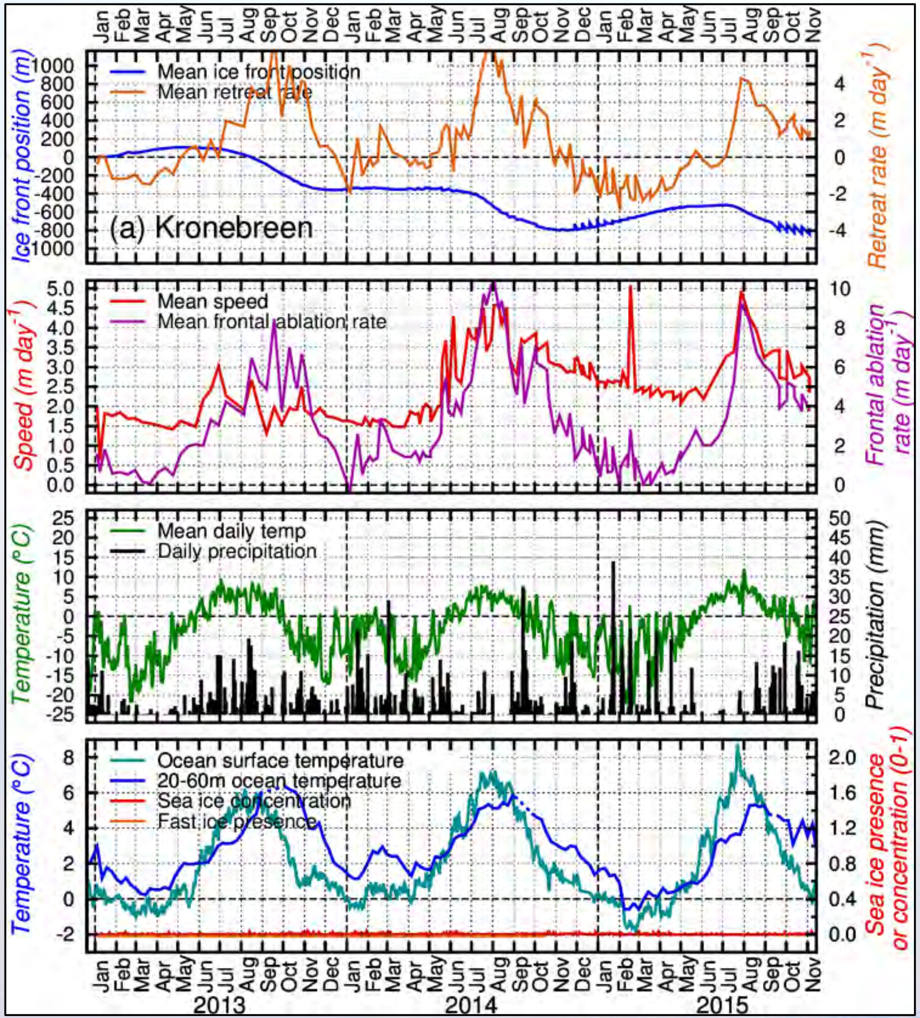
Luckman, A., Benn, D. I., Cottier, F., Bevan, S., Nilsen, F., Inall, M., Oct. 2015. Calving rates at tidewater glaciers vary strongly with ocean temperature. *Nature Communications* 6, 8566+.

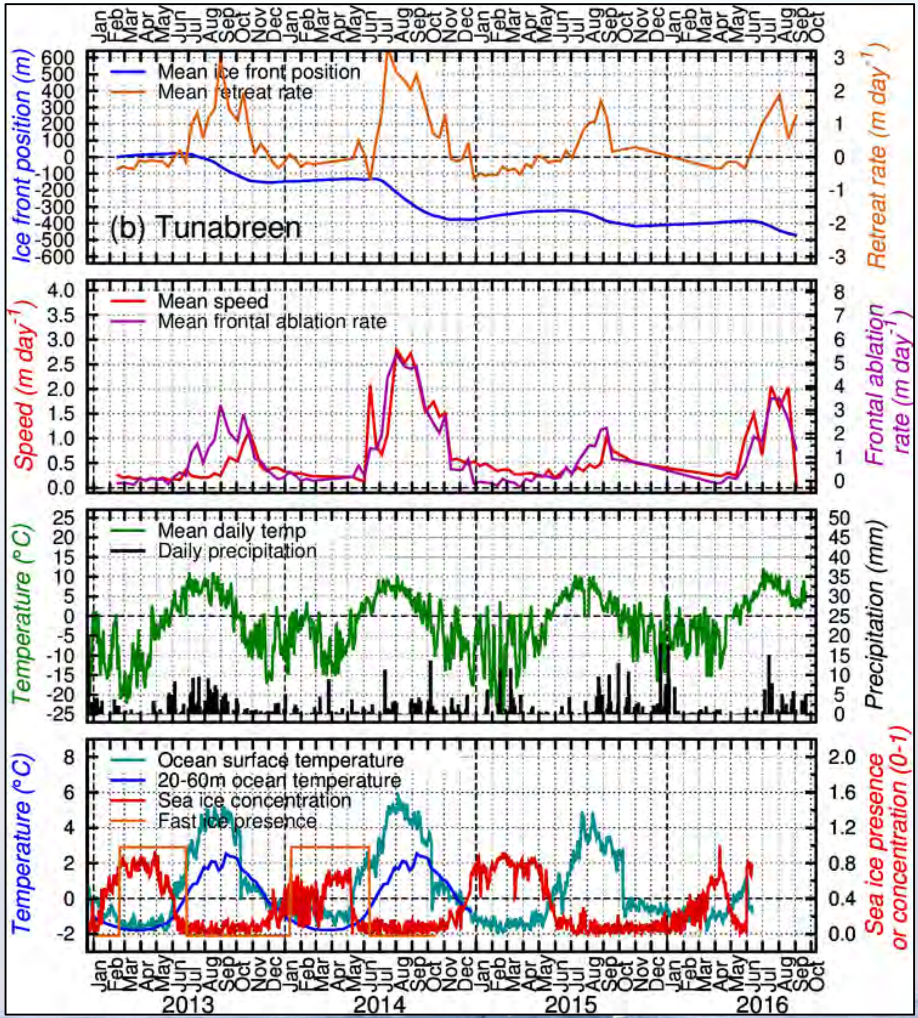
Calving conclusion

- We conclude that
  - Calving (frontal ablation) at Svalbard glaciers proceeds by the process of melt-undercutting
    - Warm ocean waters erode the ice-front at depth
      - Preferentially in late summer
    - Solid ice above is no longer supported and collapses into the water
  - This process dominates mass loss
    - In relatively small glaciers
    - Where glaciers are generally in retreat

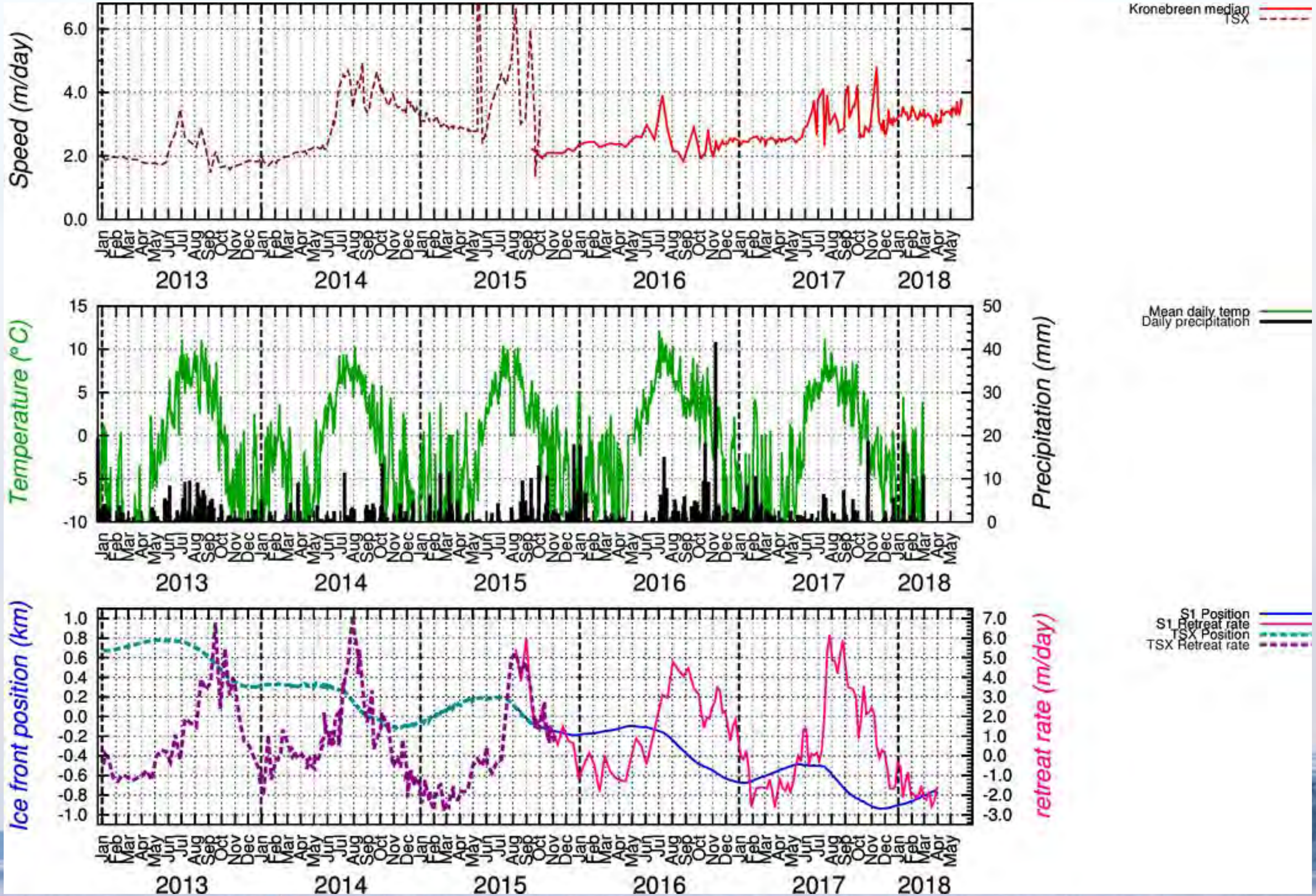
Lee Petersen

TerraSAR-X Update

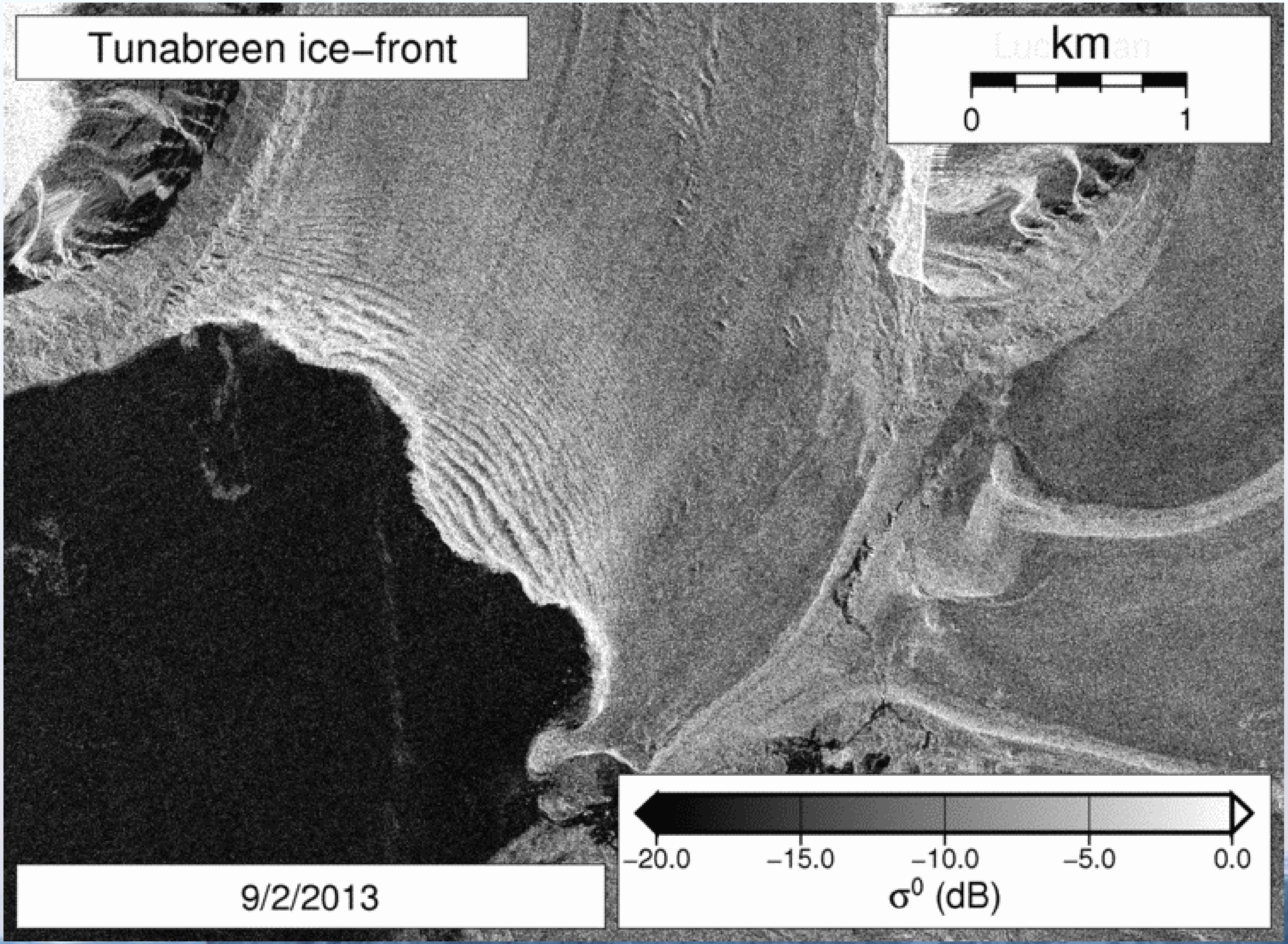


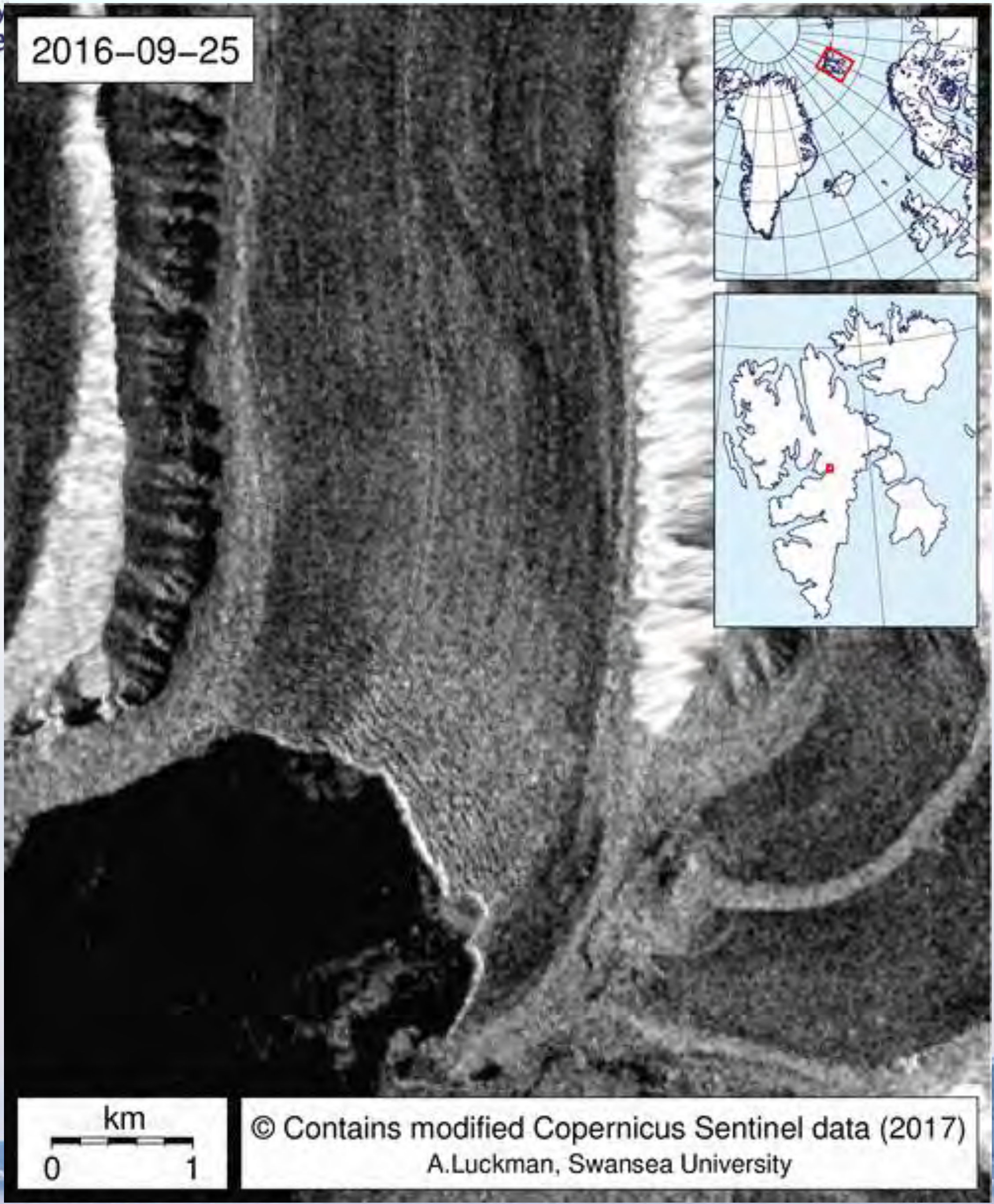


Kronebreen five-year time-series
TerraSAR-X plus Sentinel-1



Melt undercut calving




2016-09-25

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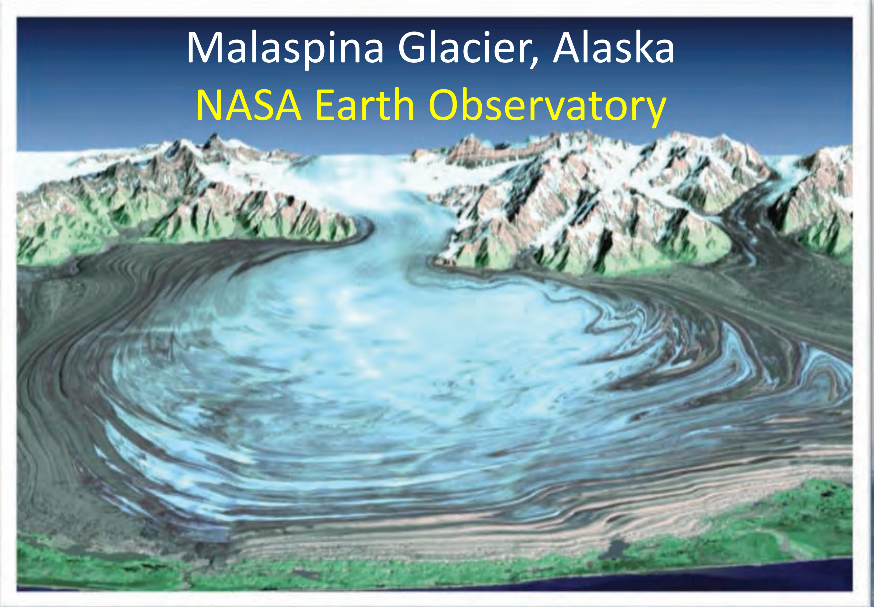
A.Luckman, Swansea University

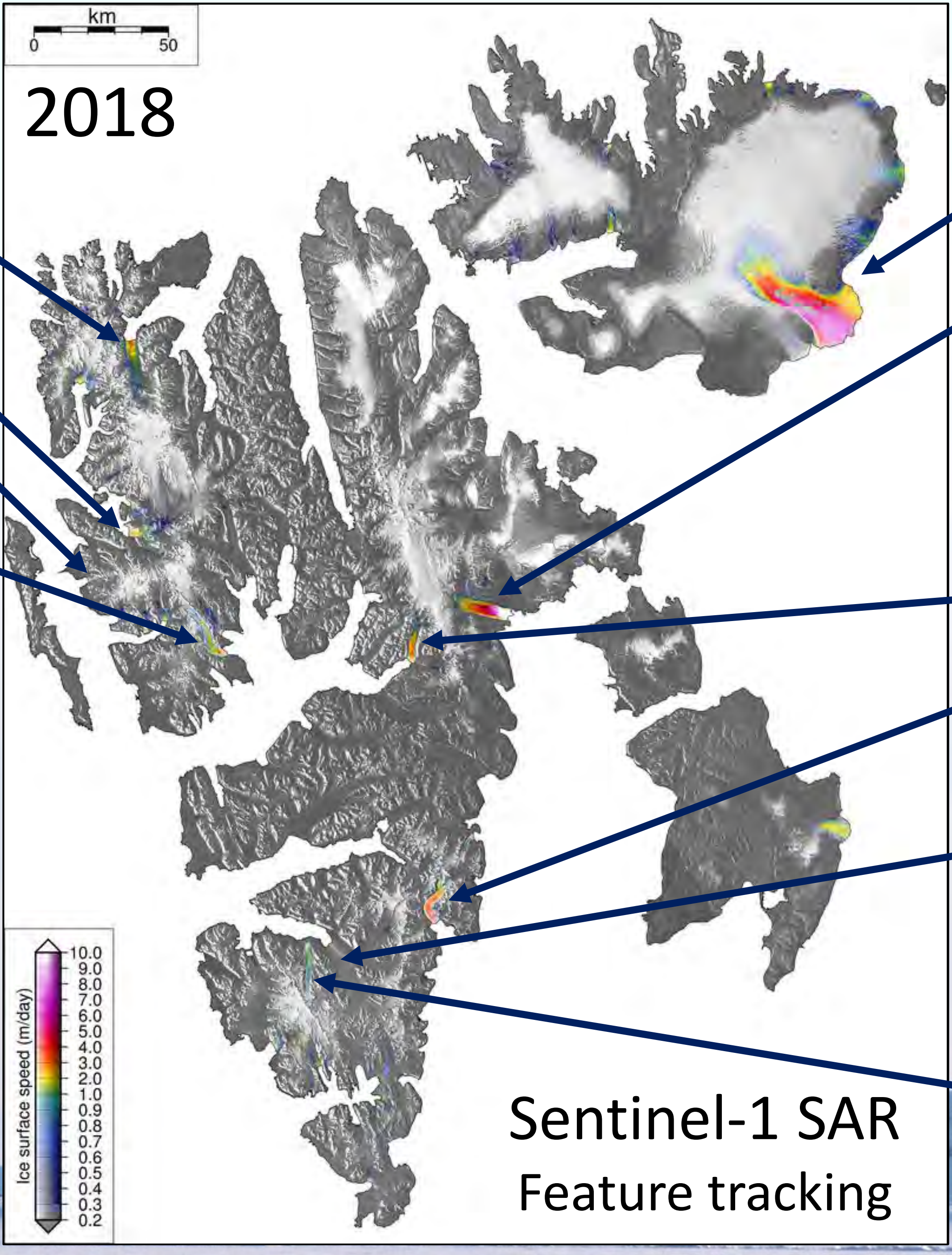
Glacier surges

- A small percentage of glaciers worldwide are '*surge type*'
  - Characterized by short periods of fast flow (surges) punctuating longer periods of slow flow (quiescence)
    - Surge periods vary from a few years to many tens of years
    - Surge velocities are 10's to 100's of times faster than quiescen
- Surge-type glaciers are '*out of balance*' with the climate in which they exist
  - They build up mass to a critical threshold whereupon some internal instability triggers a faster mode of flow
- Surge-type glaciers occur in '*clusters*'
  - **Svalbard**, Karakoram, parts of Greenland, parts of Alaska

- Understanding glacier surges:
  - What makes a glacier surge-type?
  - How a surge gets triggered?
  - What changes occur (e.g. at the glacier bed) between surge and quiescence?
- Can help us to understand fast glacier flow and changes in dynamics elsewhere
  - E.g. Antarctic Ice Streams


Malaspina Glacier, Alaska
NASA Earth Observatory

Svalbard surges



Sentinel-1 SAR

Feature tracking

Monacobreen

(Kronebreen)

Aavatsmarkbreen

Wahlenbergbreen

Basin 3, Austfonna

Negribreen

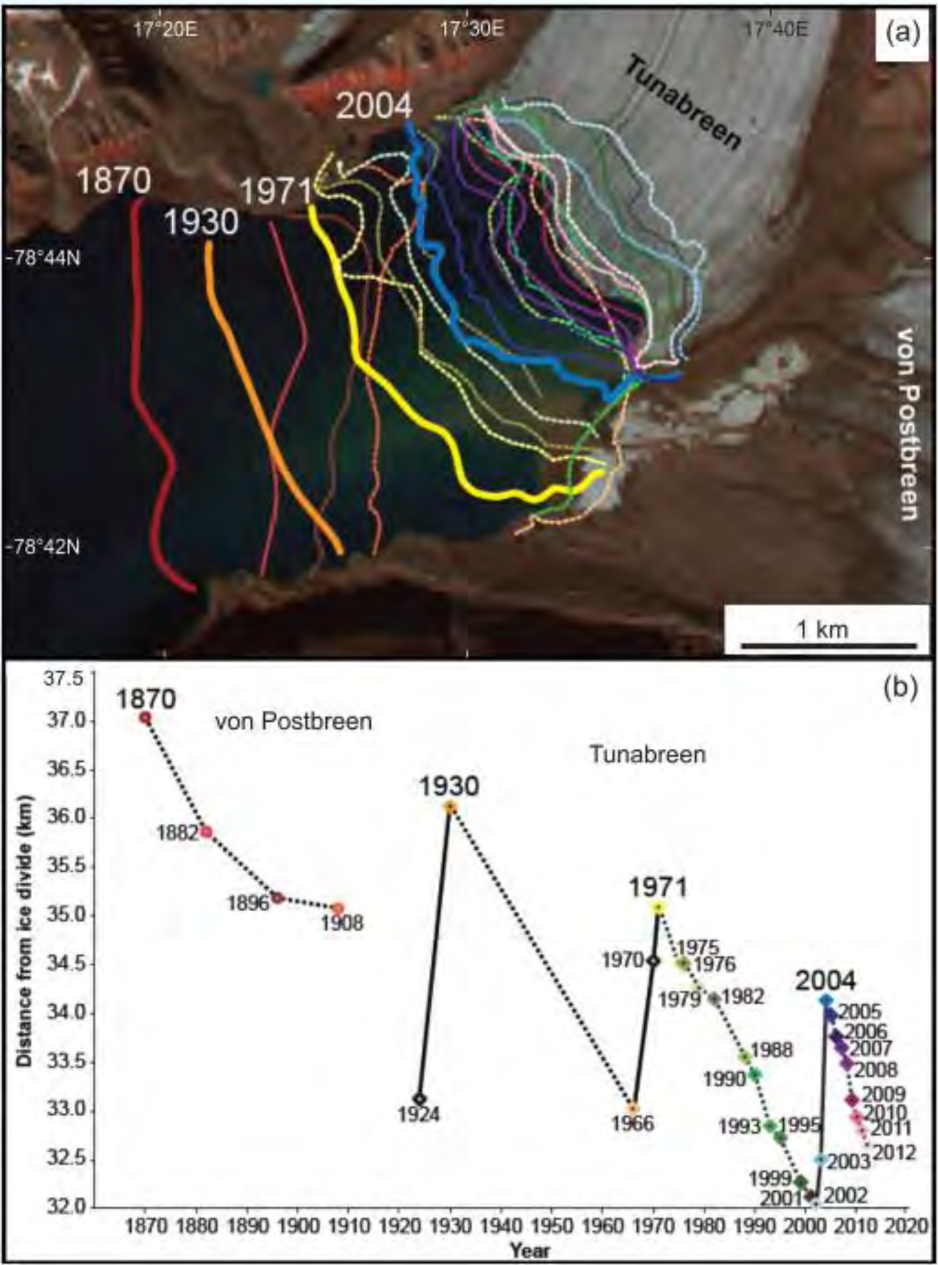
Tunabreen

Morsnevbreen

Nathorstbreen

Penckbreen

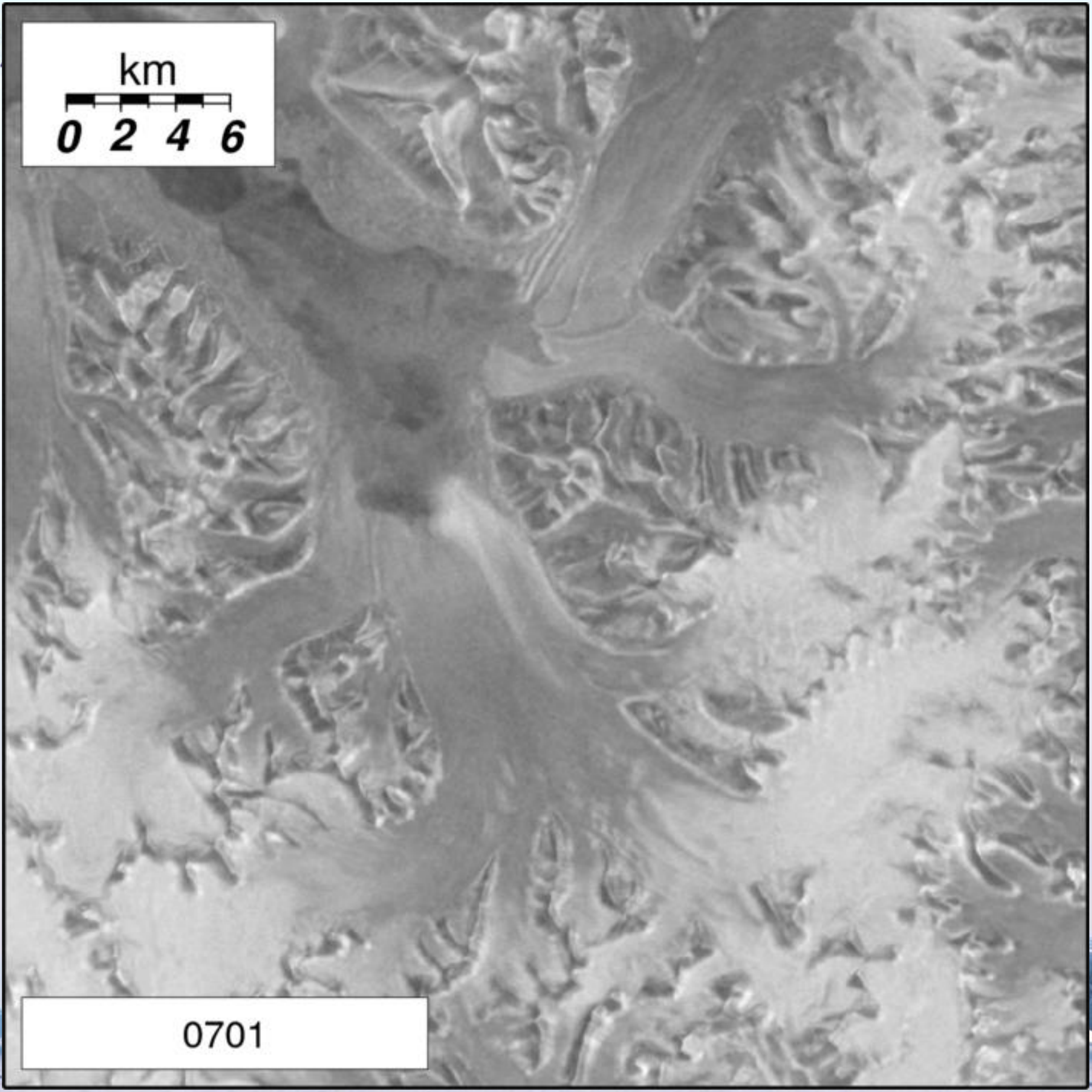
Tunabreen history



- Tunabreen is unique
  - No other glaciers with 4 previous known surges
- Surge cycle is established
  - Around 40 years
- So the recent surge appears to be ‘early’

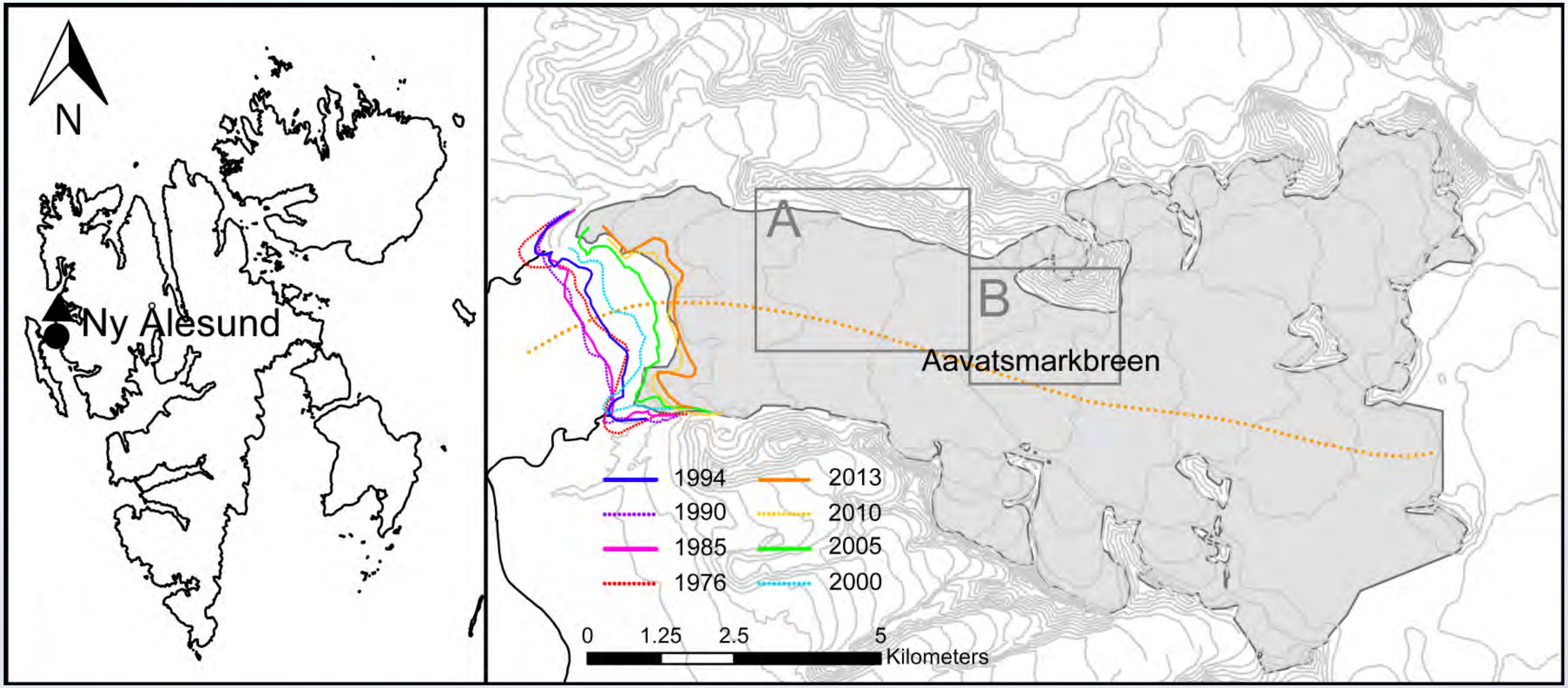
Flink, A. E., Noormets, R., Kirchner, N., Benn, D. I., Luckman, A., Lovell, H., Jan. 2015. The evolution of a submarine landform record following recent and multiple surges of tunabreen glacier, svalbard. Quaternary Science Reviews 108, 37-50.

Envisat ASAR
Wide Swath Mode (WSM)



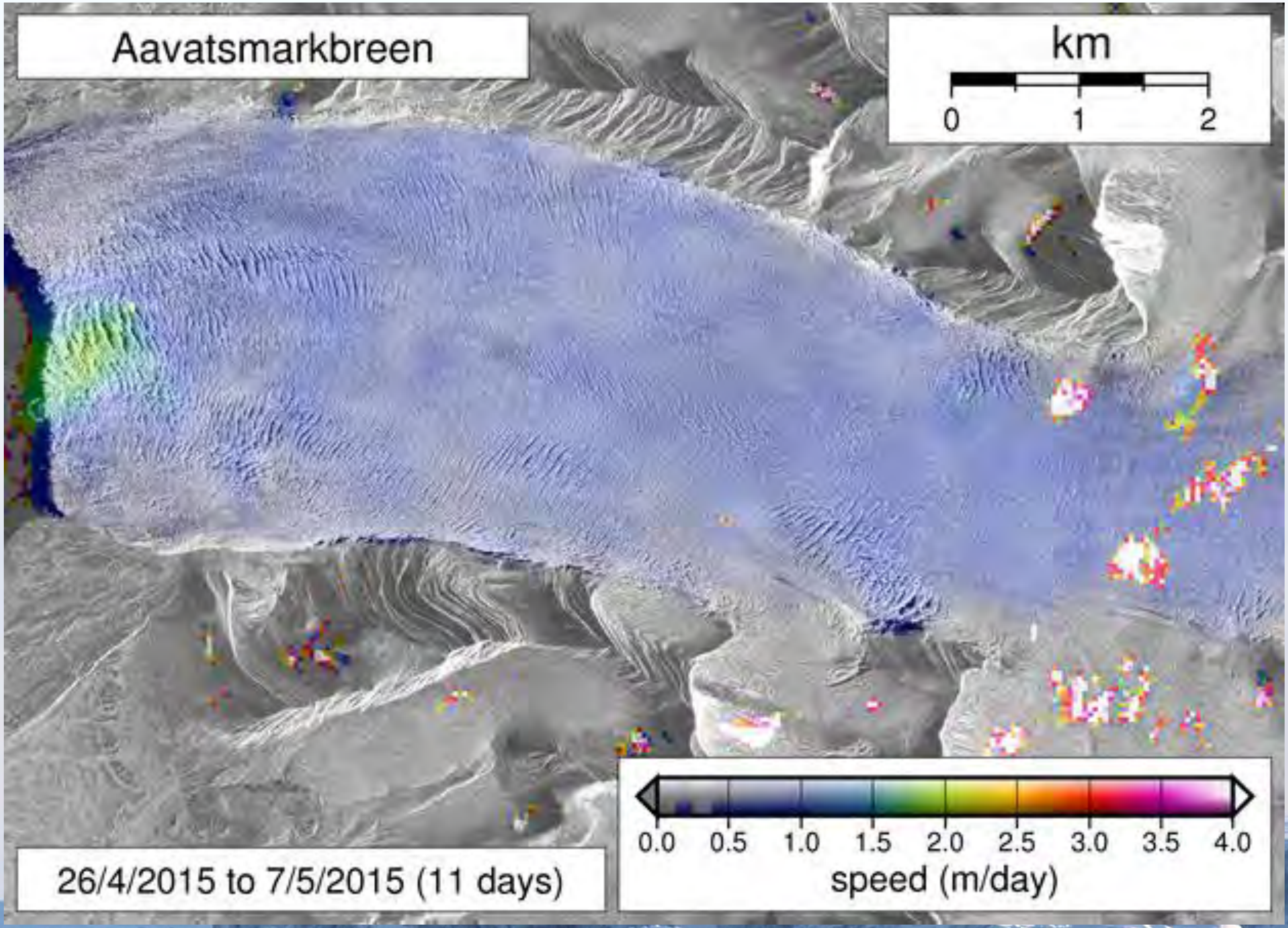
Dobrowolskibreen
& Nathorstbreen

Aavatsmarkbreen



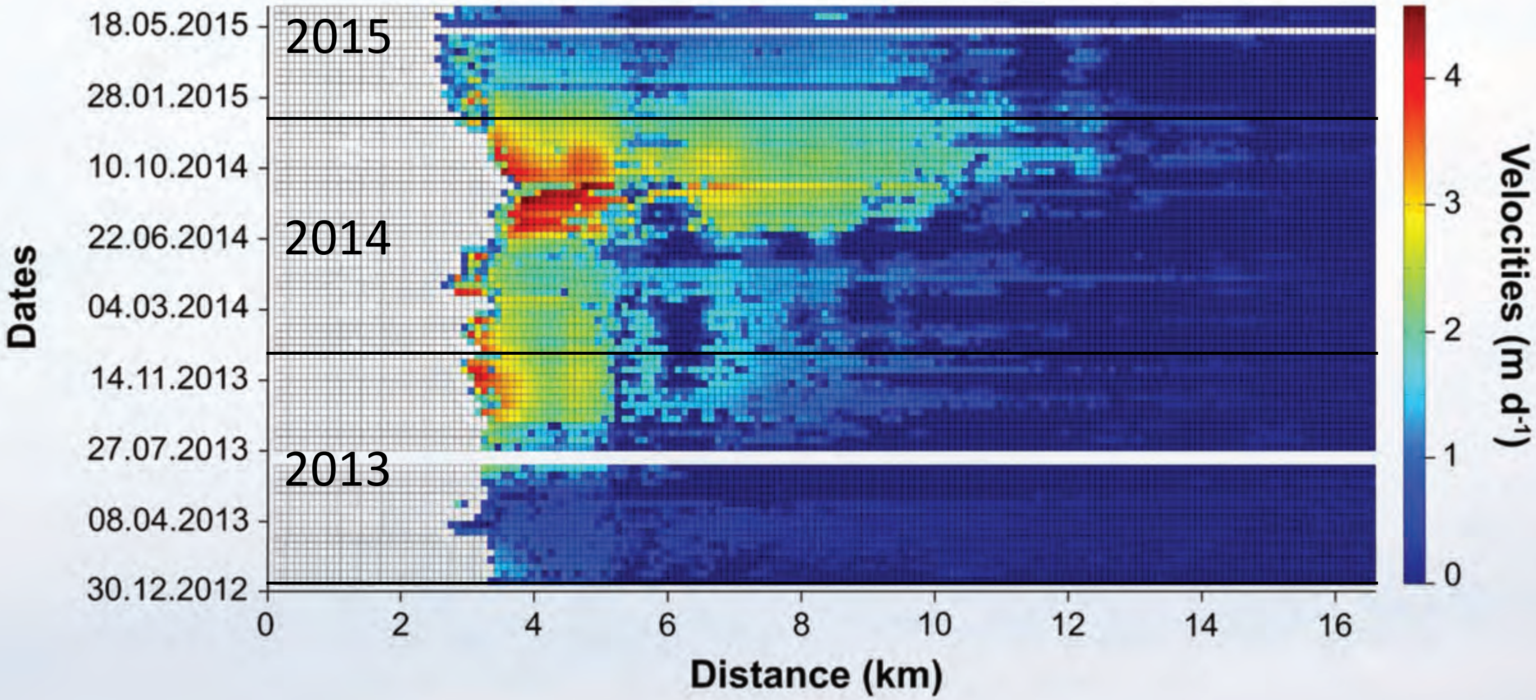
- Two known previous advances: ~1920 and ~1980
- Falls within the Kronebreen TerraSAR-X image frame
  - So became one of the CRIOS study glaciers

Aavatsmarkbreen



Aavatsmarkbreen

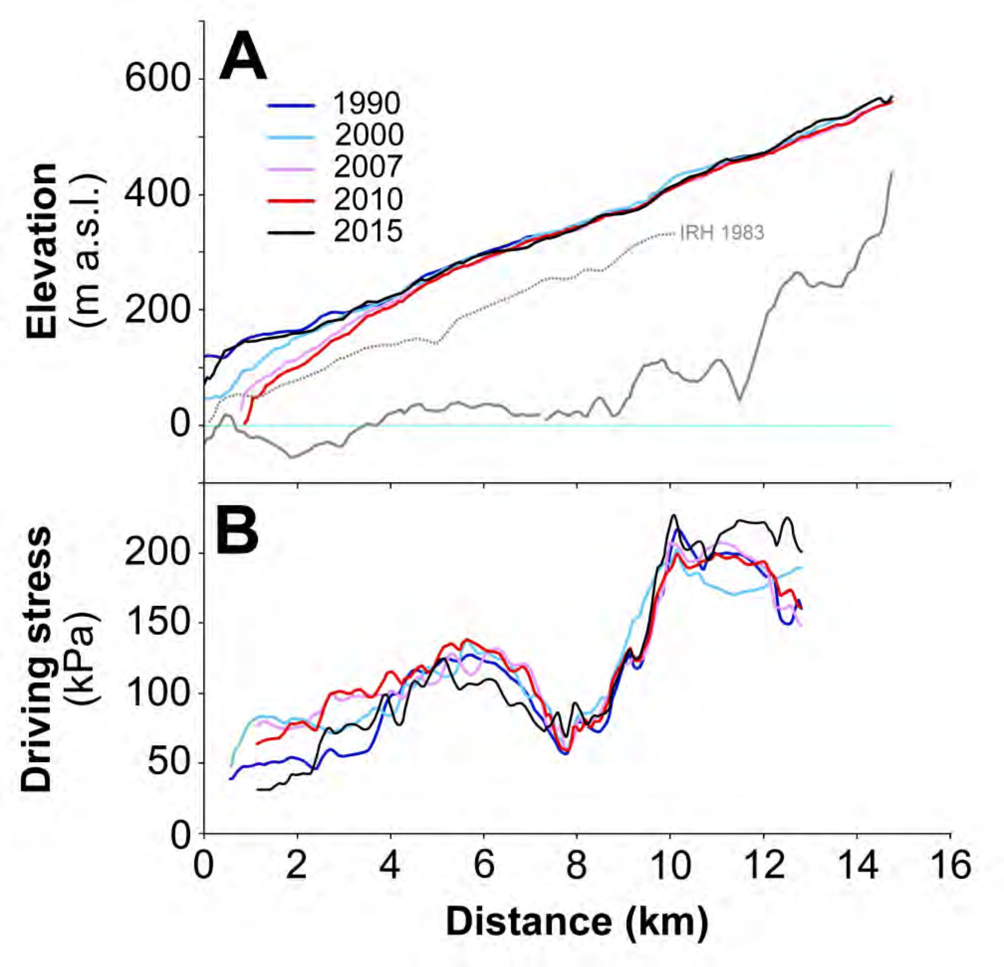
Centre-line speeds through the surge



- Surge propagates up-glacier
- Seasonal aspect to velocities
- Second summer involves more of the upper glacier

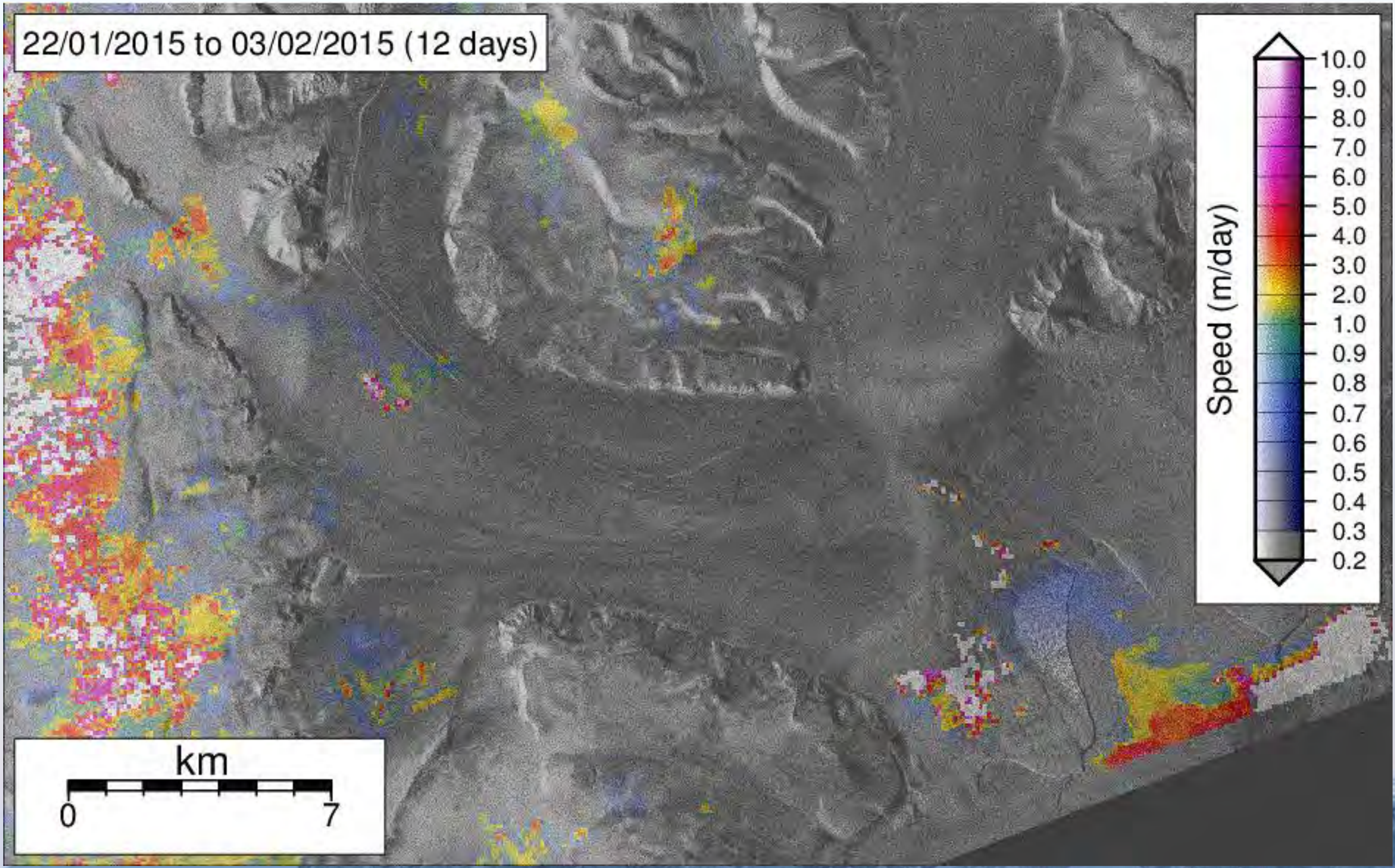
Aavatsmarkbreen

Elevation changes

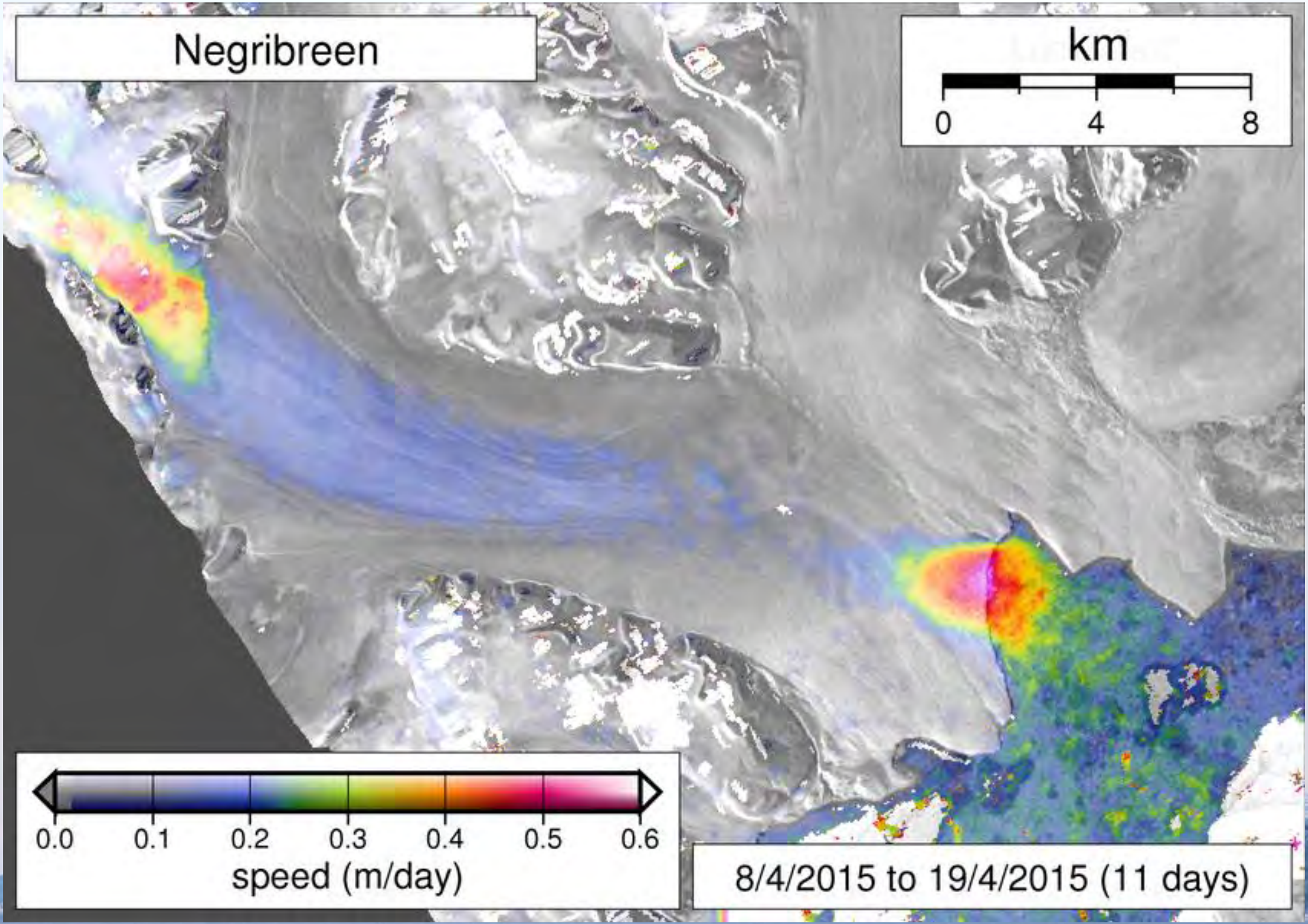


- DEMs from aerial stereo-photogrammetry, ASTER and TanDEM-X
  - – No clear reservoir growth
- Surge development
  - – Initiated by lower glacier steepening
  - – Sustained by routing of meltwater through crevasses

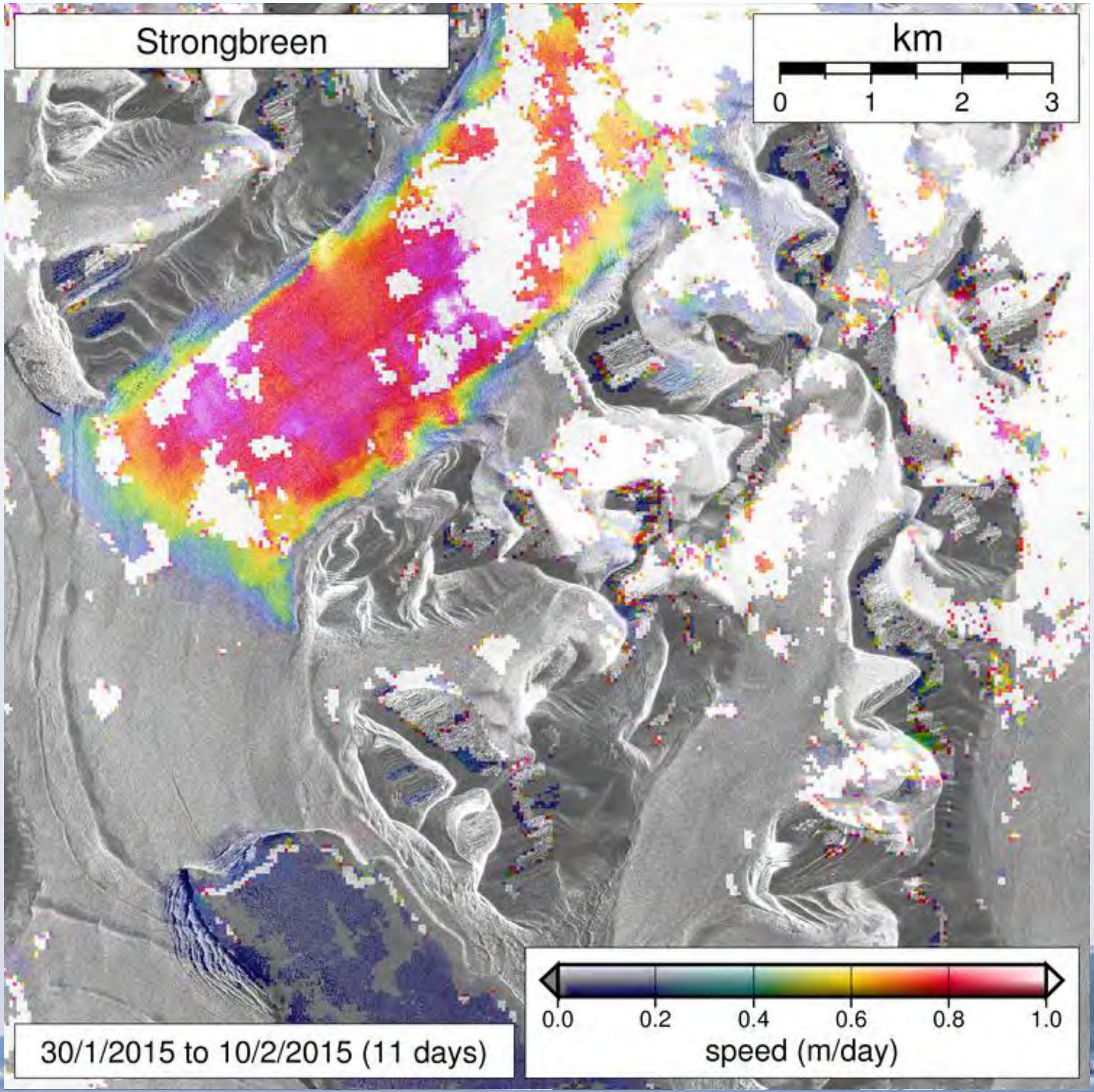
Negribreen Sentinel-1



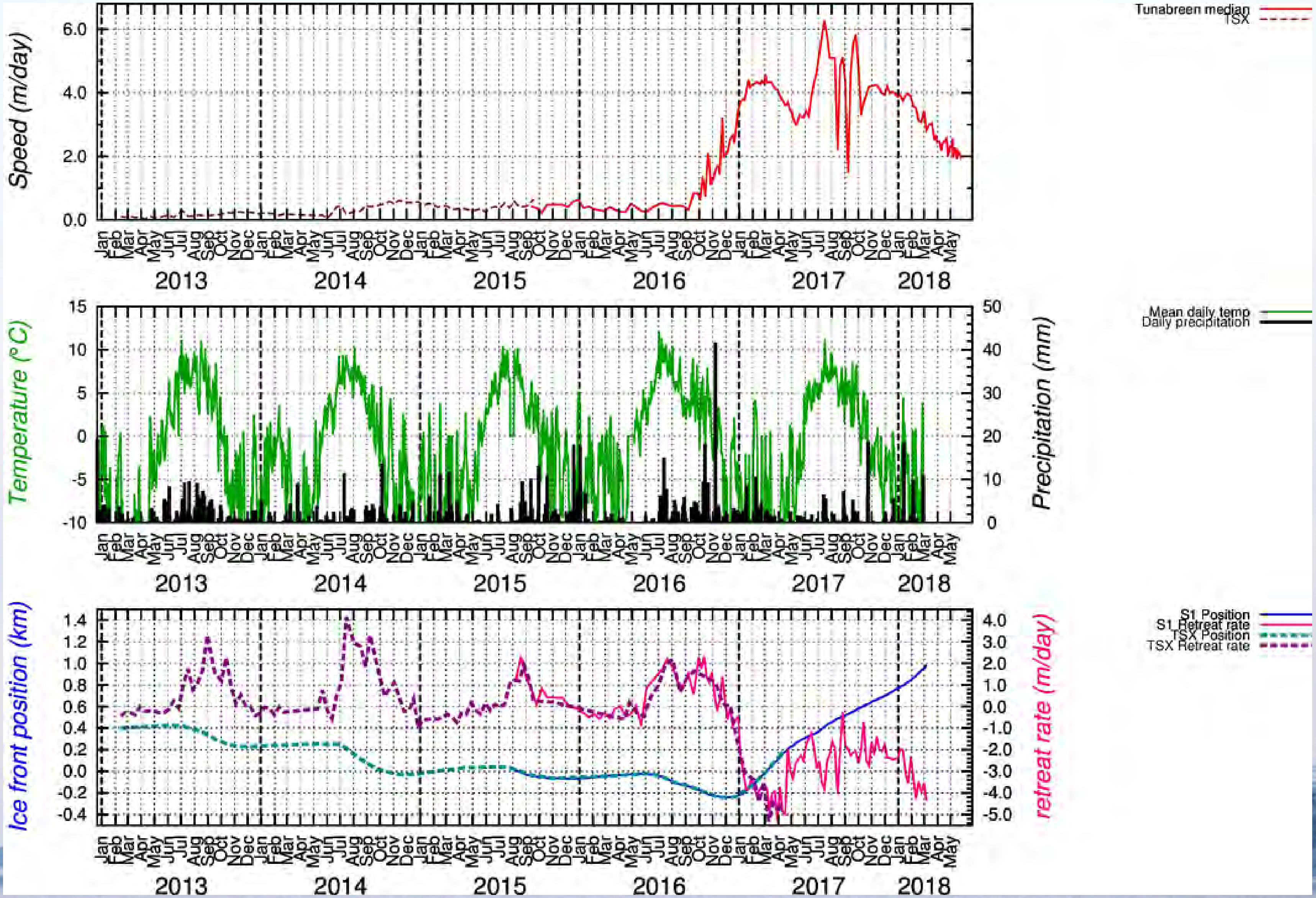
Negribreen TerraSAR-X



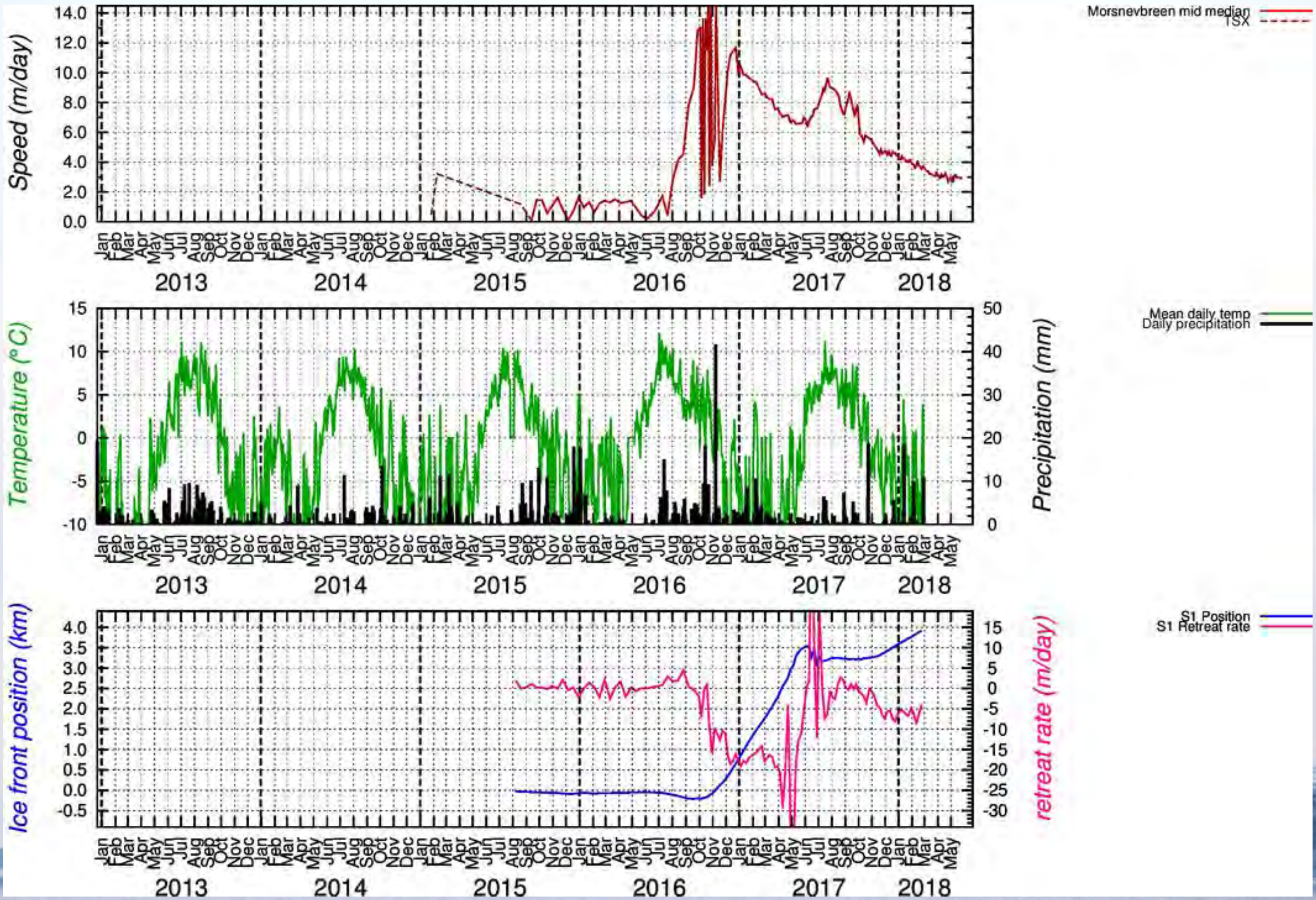
Morsenevbreen



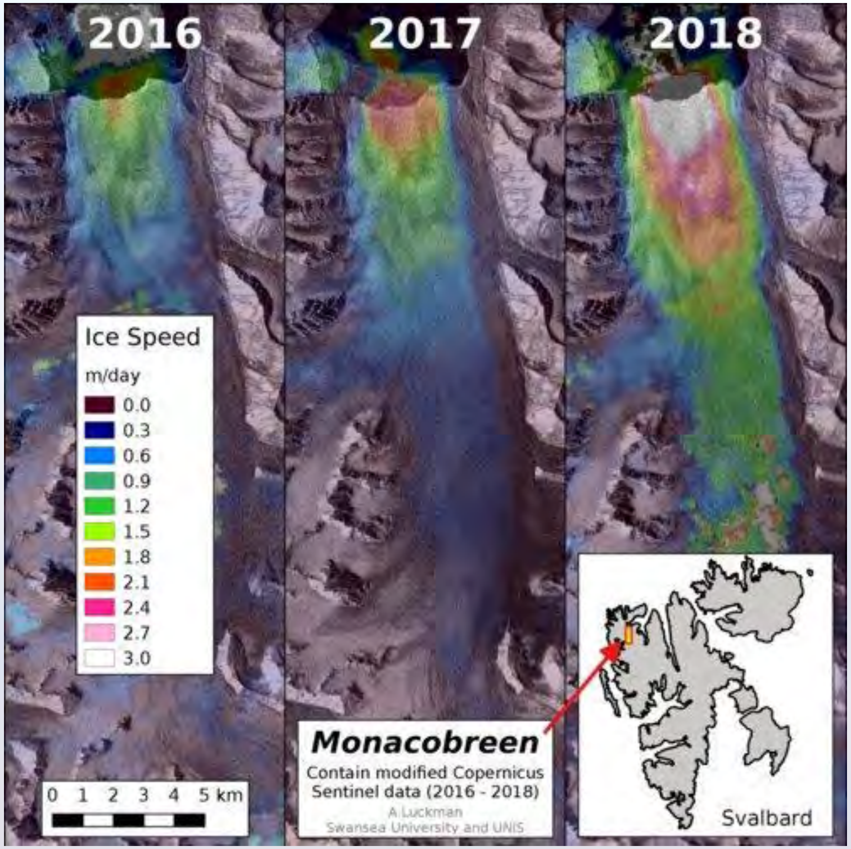
Tunabreen surge



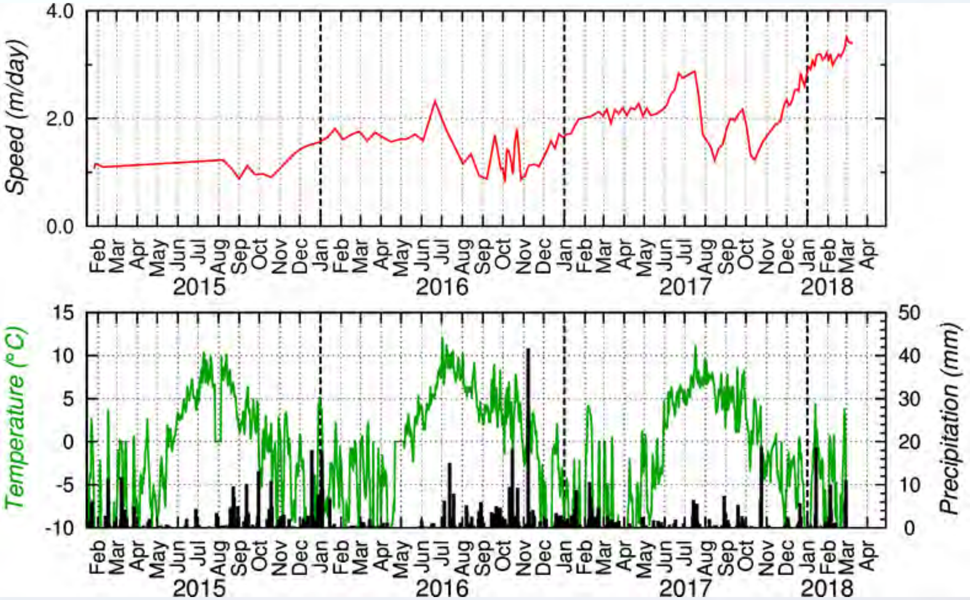
Morsnevbreen surge



Monacobreen surge



Contain modified Copernicus Sentinel data (2016 - 2018)
A Luckman
Swansea University and UNIS



- Monacobreen is the most recent Svalbard surge
  - Last surged in the 1990’s
- Maybe another early trigger?

Finale

- Ice surface speed is an essential climate variable
  - Soon you will master feature tracking methods
- Data availability has never been better
  - Thanks largely to ESA and NASA
- We understand calving better now
  - But watch project CALISMO
- Surges are fascinating
  - And maybe they are happening more often