Freeze/Thaw Enhancement using Multi-Frequency Microwave Data

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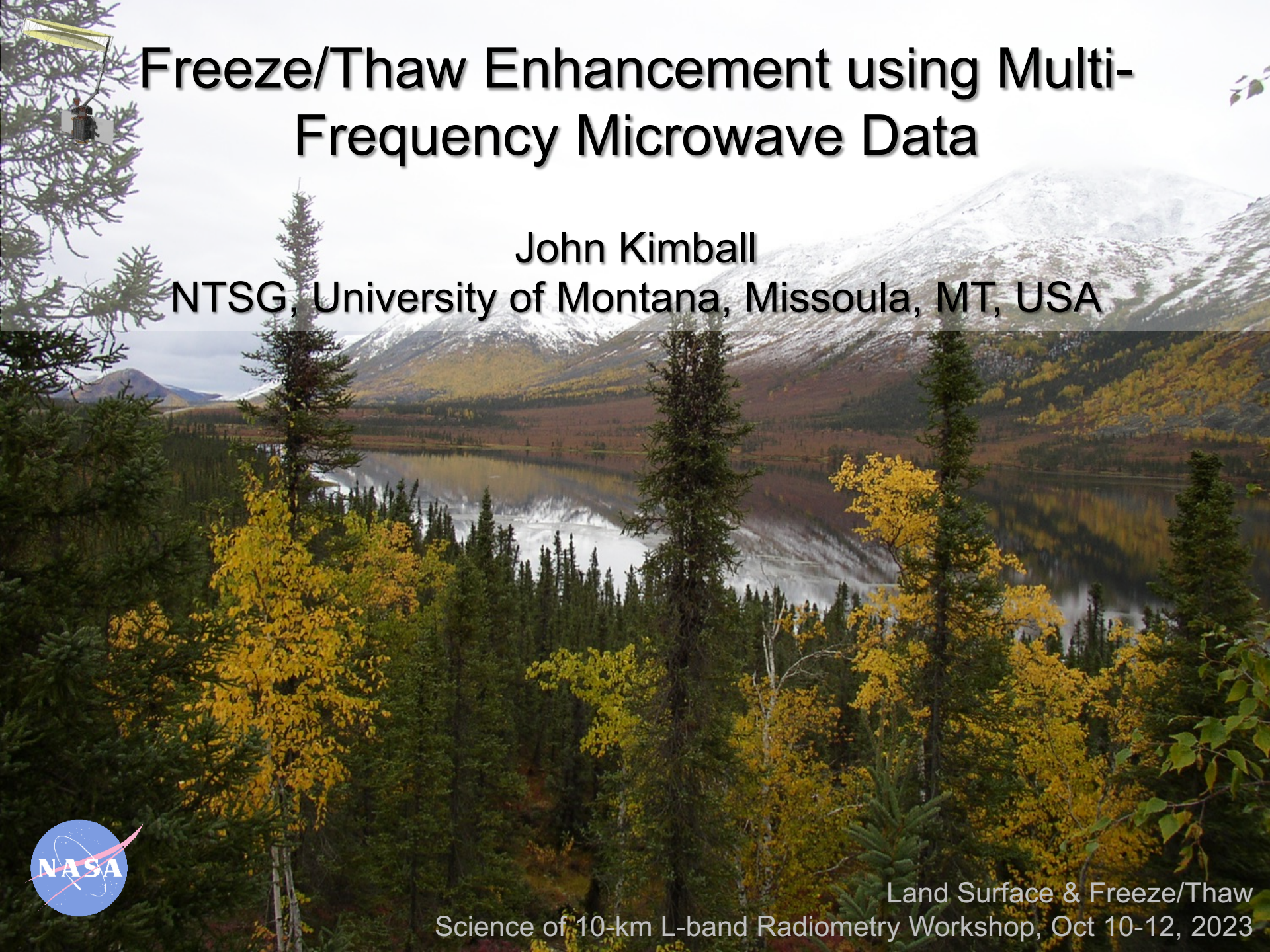


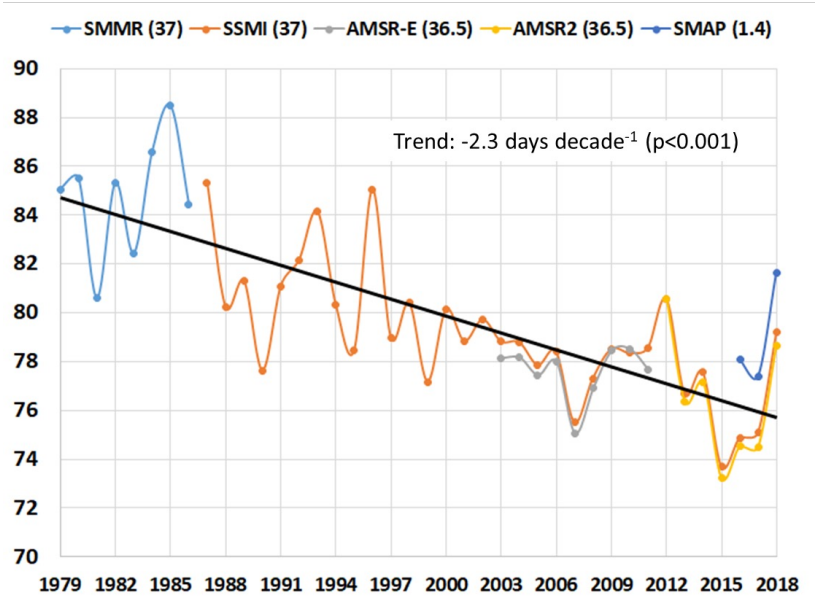
Land Surface & Freeze/Thaw
Science of 10-km L-band Radiometry Workshop, Oct 10-12, 2023

Motivation

- [1]Frozen conditions annually affect >50% of global lands & their eco-hydrology
- Frozen season is shrinking, fundamentally altering ecosystems & communities
  - Widespread permafrost thaw & increasing uncertainty in land C sink for Atm. GHGs
- Satellite microwave RS has strong freeze/thaw (FT) sensitivity; day/night & all-weather monitoring capability; however:
  - Lower frequencies (L-band) more sensitive to soil, but FT algorithms can have difficulty distinguishing from other features;
  - Current satellite sensors unable to fully capture FT complexity due to sub-optimal spectral, spatial or temporal coverage

❖ Potential to improve FT monitoring by exploiting multi-frequency measurements.

Global mean annual frost days from satellite microwave radiometry

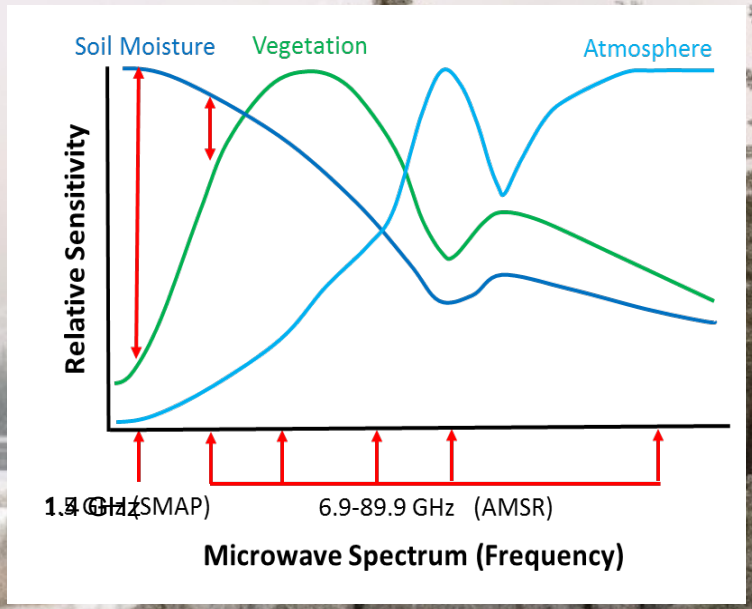


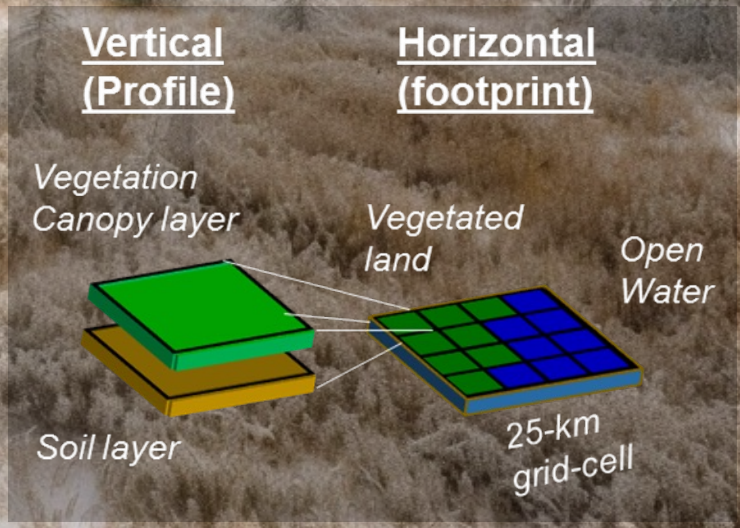
✓ Addresses NASA Decadal Survey science & application priorities for ecosystems, hydrology & climate [E1, E3, H1-2, C-8]

Source: [1]Kim et al. 2017. *ESSD 9;* [2]Schuur et al., 2018. *Ann. Rev. Ecol. Syst. 49*

Value of Multi-frequency Microwave Measurements for FT Classification

- Large dielectric contrast in landscape liquid water abundance during FT transitions
- Satellite footprint is a complex mixture of different land cover features with unique FT signatures
- Different frequencies (1.4-37 GHz) have varying footprint sizes & sensitivity to different landscape features
- Potential added-value by exploiting complimentary frequencies:
  - Spatial enhancement
  - Distinguish unique FT signals from different features

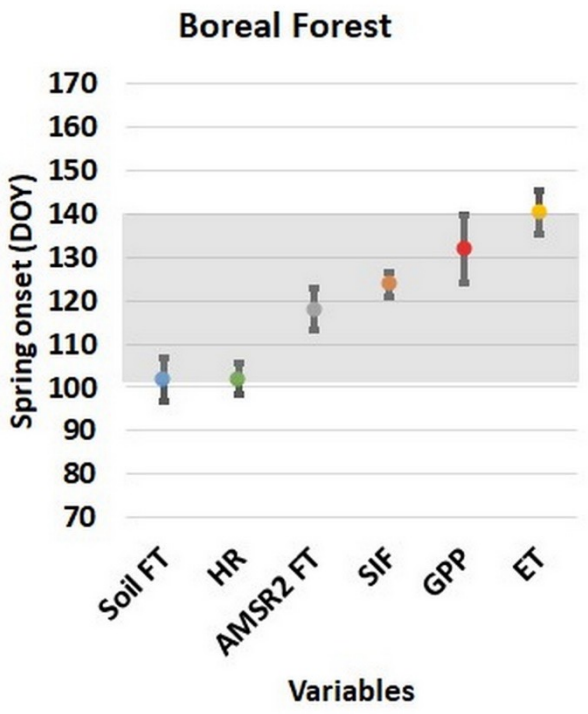




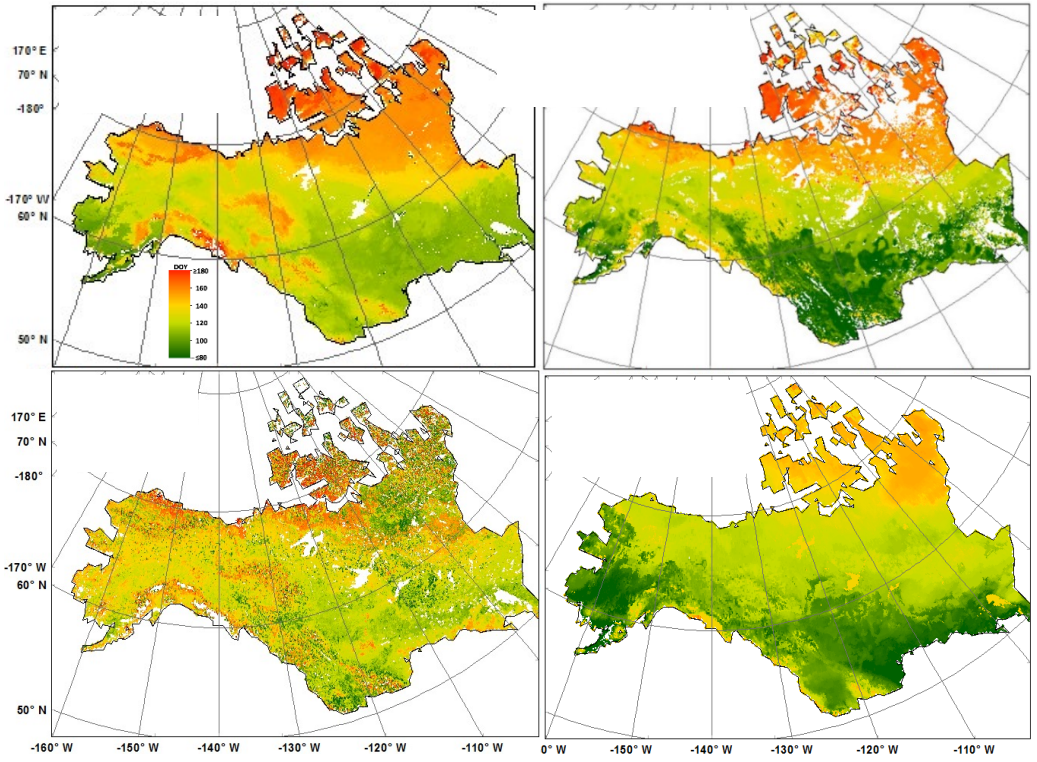
Requirement: Near-contemporaneous nested sampling across frequencies

Different Landscape Elements have Unique FT Signatures

- Different soil & surface thaw timing drives seasonal lags in PSN (SIF) & respiration, affecting ecosystem C-sink activity;
- Early soil thaw & respiration prior to surface thaw & PSN onset can lower C-sink;
- Multi-frequency retrievals can distinguish unique surface & soil FT constraints.



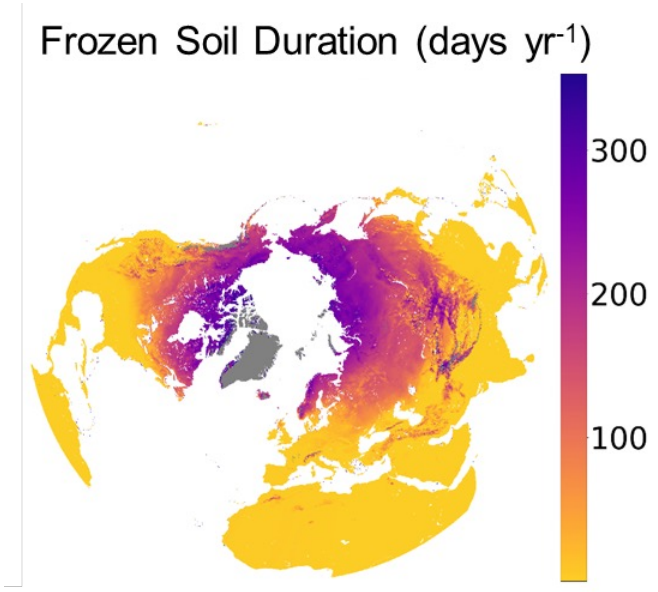
Order of spring thaw & ecosystem onset events (2018)

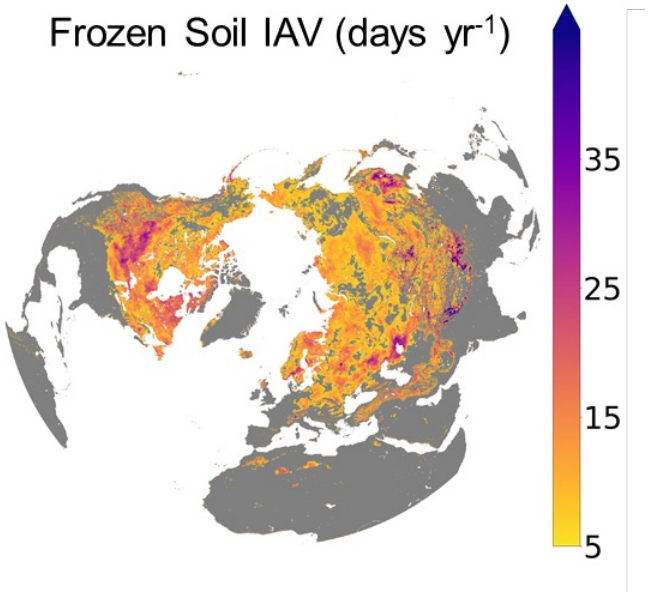


Source: Kim et al. *JGR (in review)*

Example Application: Satellite Multi-frequency Tb Observations for Soil FT Classification

- Approach: ML (UNet) model using overlapping Tbs from SMAP (1.4 GHz) & AMSR (18.7, 36.5 GHz) to classify daily soil (0-5cm depth) FT dynamics (2016-2020)
- Combined Obs. (SMAP+AMSR) gave significant performance gain over single-sensor or single-frequency methods.
  - Mean accuracy >90%
  - Distinguished soil FT from other landscape features
- Constraints:
  - Different sensor geometry & overpass times (e.g. AMSR: 0130/1330; SMAP: 0600/1800)
  - 9-km grid unable to resolve finer FT heterogeneity
  - Ground truth for model training & validation

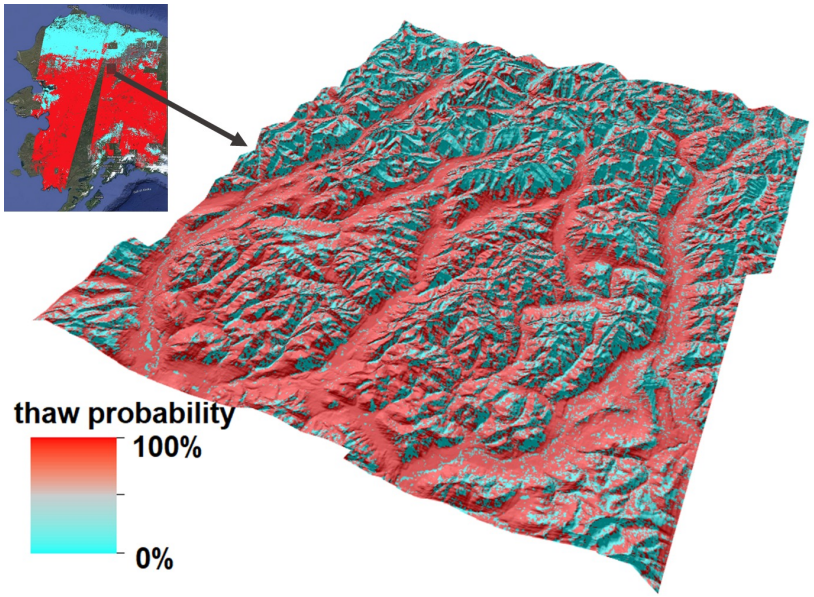




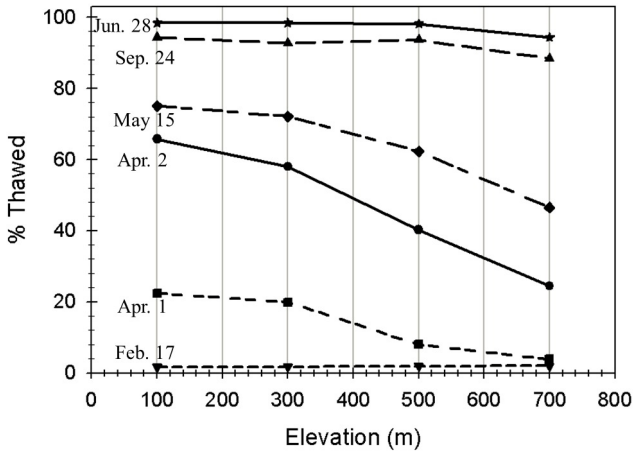
Source: Donahue et al. 2023. *Fontiers in Big Data and AI*

Need for Spatial Enhancement

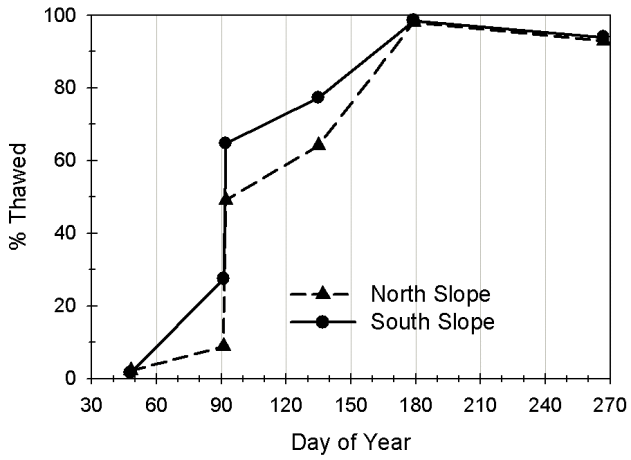
- Large FT heterogeneity due to soil-terrain & land cover complexity
- Approx. scales of variability: 25-km (biome); 10-km (ecoregion); 1-km (landscape); 30-100m (local)
- Greater FT heterogeneity during seasonal transitions
- Potential spatial enhancement by exploiting higher frequencies or active/passive Obs.



Terrain elevation vs thaw timing



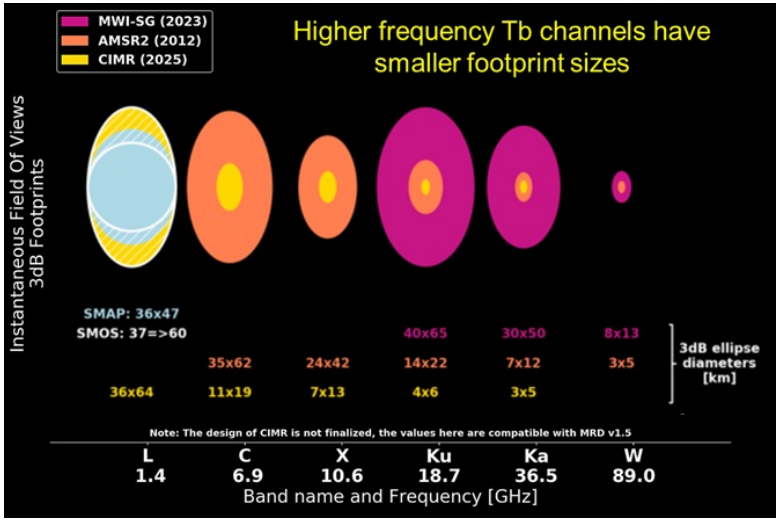
Terrain aspect vs thaw timing

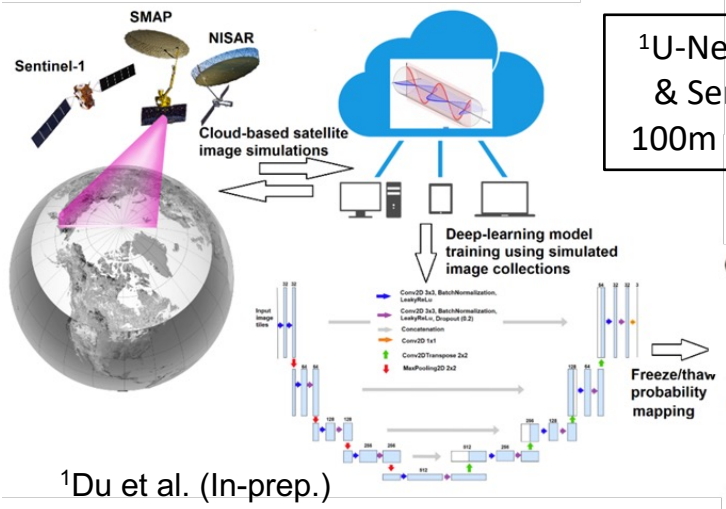


Source: Du et al. 2014. *TGRS 53, 1; Podest et al. 2014. TGRS 52, 11.*

Spatially Enhanced FT Retrievals using Satellite Multi-Freq. & Active/Passive Microwave Data

- Combine smaller footprint Obs. from higher frequency Tb or SAR data (e.g. C-band) with larger footprint, but higher temporal repeat Tbs (L-band).
- Capable of spatial enhancement & gap-filling, with better performance than single-Freq./sensor methods
- Common methods:
  - ML (e.g. RF, [1]U-Net)
  - Data fusion algorithms ([4]ST-Cokriging, [2]Tb Disaggregation, [3]active-passive covariation)
  - Hyper-resolution LSM/RTM data assimilation ([5]HydroBlocks-RTM)
- Constraints: resource intensive, esp. for model development





[1]U-Net using SMAP Tb & Sentinel-1 SAR for 100m daily FT mapping

[1]Du et al. (In-prep.)

[2]Yao et al. 2019. *JSTARS* 12, 9; [3]Jagdhuber et al. 2019. *RSE* 225; [4]Yang et al. 2021. *RSE* 255; [5]Vergopolan dt al. *RSE* 242;

Desired Science Traceability Elements for FT

Science Measurement Reqs:

- Distinguish FT constraints to land water mobility & ecosystem processes with 80% mean accuracy
- Daily monitoring to capture FT transitions bounding potential growing season in northern ecosystems (≥45˚N)
- Day-night sampling to distinguish transient thaw/refreeze & frost events affecting vegetation growth, surface soil & snow conditions
- ≤10 km resolution to capture ecoregion (Min.) to local landscape (Opt.) behavior;
- Capture full seasonal cycle & inter-annual variability

➢ Improved over current satellite microwave radiometers (AMSR, SMOS, SMAP); better L-band performance than CIMR; better temporal sampling than SARs (Sentinel-1, NISAR, ROSE-L)

Sensor Functional Reqs:

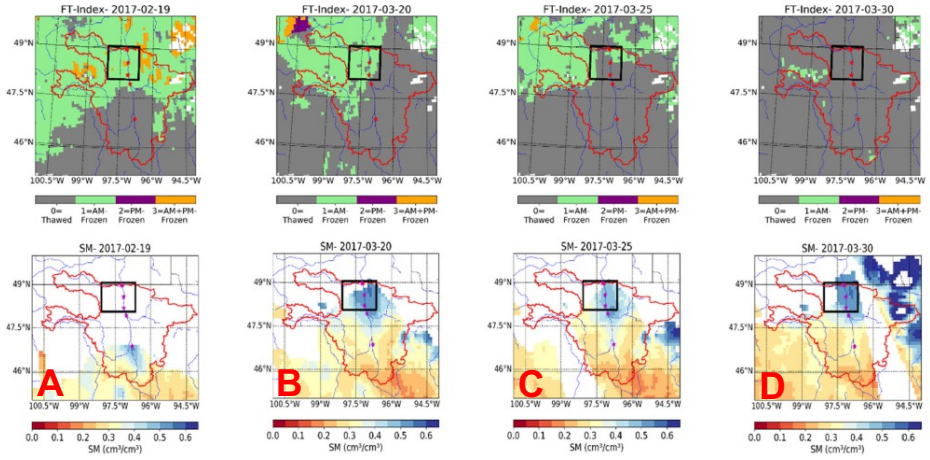
- Multi-frequency sampling (Ka, Ku, X, C, L-band; V/H-Pol) to distinguish landscape FT components (ground, snow/ice, Vegetation)
- Sun-synchronous polar orbit with daily predawn (~0300-0600) & mid-day (~1500-1800) sampling to capture diurnal heating/cooling & daily variability
- <2-hr sample delay across Tb frequencies for each orbital pass to minimize diurnal drift
- Spatially nested footprint with geolocation accuracy ≤ 1/10 FOV footprint for each Freq.
- Constant incidence angle (35-55˚) for Pol. discrimination (low end) & signal quality (high end) for Veg., surface, soil
- Radiometric accuracy: 0.5-2K at 1.4 GHz (dependent on Tb Freq. & dynamic range)
- RFI mitigation for <10% data loss to preserve space/time continuity
- Minimize Faraday rotation (L-band, full Pol.)
- 3-year mission (minimum)

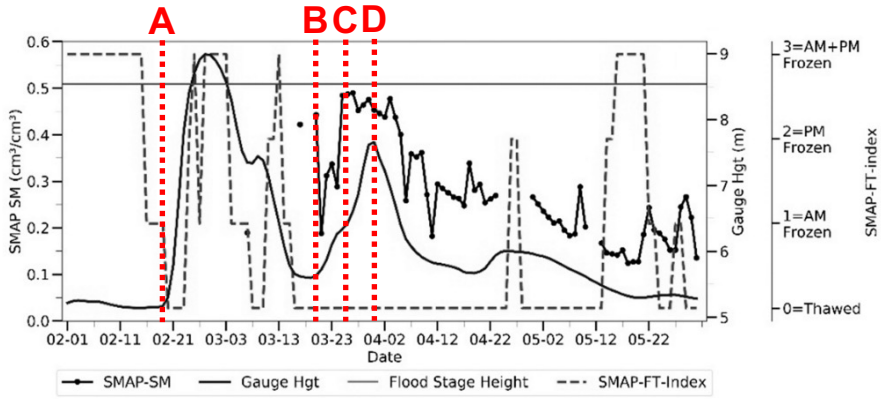
Potential Application: Flood Early Warning & Monitoring

- Anomalous thaw events are leading indicators of cold season flooding
- Flood risk affected by rate of thawed area increase in both snow & soil
- Constraint: Small basin size relative to SMAP footprint; distinguishing snow & soil FT conditions

❖Potential Advance: All-weather daily monitoring of snow wetness, soil FT & SM conditions with enhanced spatial resolution.

[1]Cold season flood early warning from SMAP (Red River North Basin, ND, USA, 2017)





Anomalous Thaw & SM increase provided up to 5-day leading indicators of subsequent river flooding

[1]Davitt et al. 2019. *IEEE JSTARS* 12, 8

Thank You!