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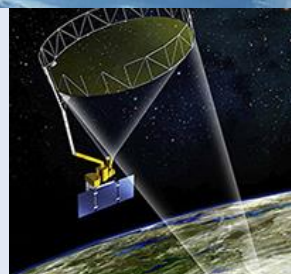
Developing an enhanced soil inversion model for regional permafrost monitoring

Yonghong Yi

Jet Propulsion Laboratory, California Institute of Technology, USA

ARCTIC – BOREAL VULNERABILITY EXPERIMENT



Climate change and regional permafrost monitoring

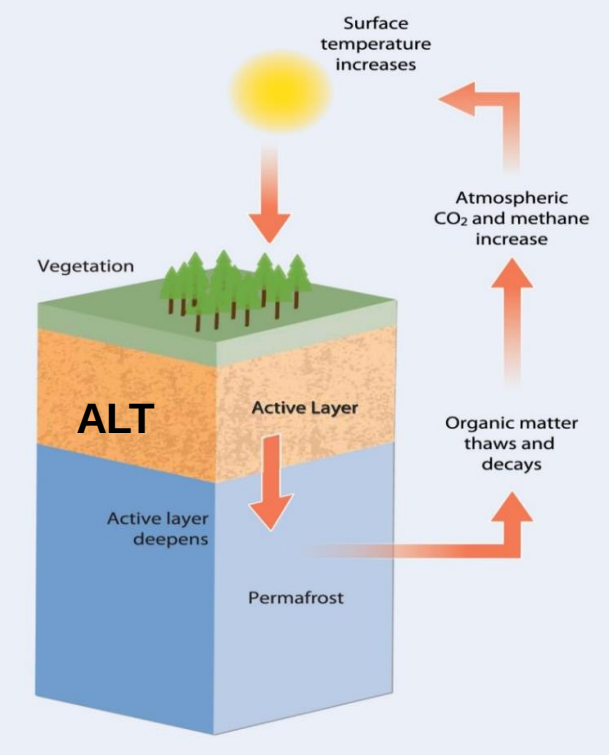
- ~**24%** of NH exposed land area overlain by permafrost.
- Potentially large carbon feedbacks with warming and permafrost degradation.

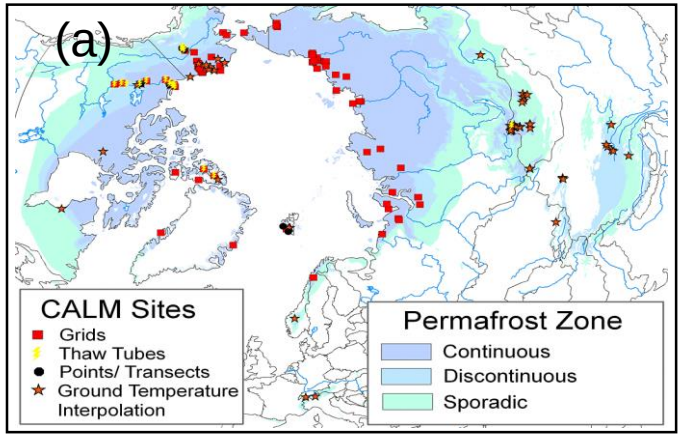
Permafrost soil organic carbon(0-3m): ~1672 PgC

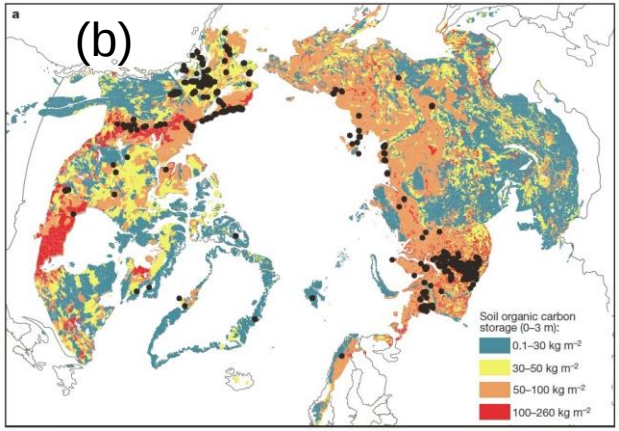
- Surface organic layer & soil moisture are first-order controls on active-layer seasonal freeze/thaw process

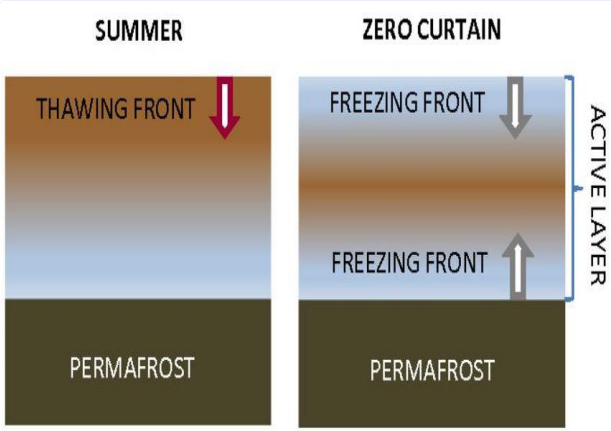
Active layer thickness (ALT): maximum thawing depth

Duration of zero-curtain period









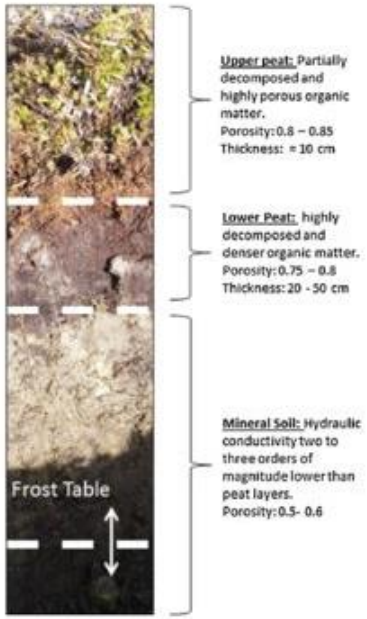
Pan-Arctic permafrost (a) and soil organic carbon (SOC, 0-3m) map (b)

Zona et al. 2016
Hugelius et al. ESSD, 2013

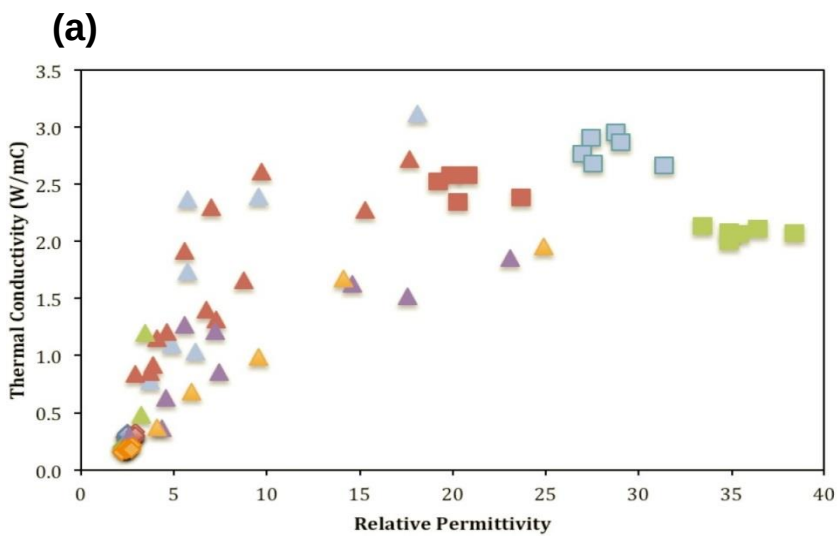
Using microwave remote sensing to map organic soil?

- Challenges in high-latitude soil moisture and permafrost modeling:
  - organic soil profile representation;
  - large variability in organic soil properties esp. at surface
- Dielectric constants are a function of soil texture (mineral, soil organic fraction) and soil water content ---- both are primary factors controlling soil thermal properties.

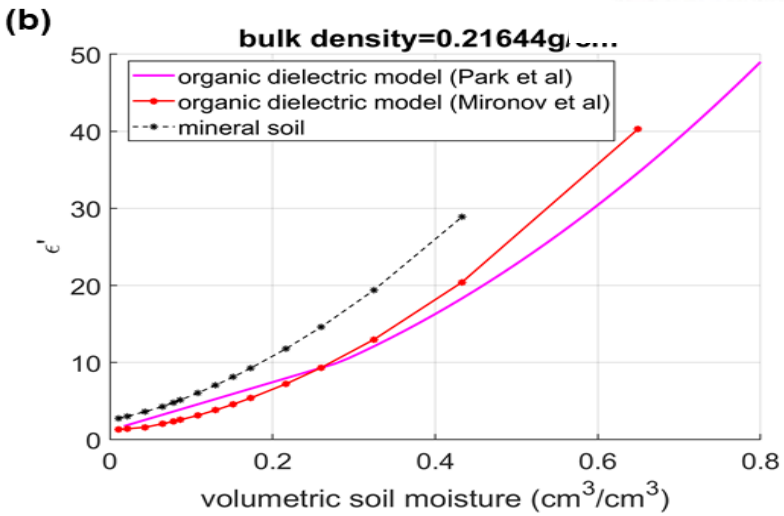
A tundra soil profile[1]



[1]Krogh 2017
[2]Rubin 2017



(a) Relationship between measured dielectric constant and thermal conductivity of sands[2]



(b) Large difference between organic and mineral soil dielectric properties

Objective & Outline

Objective: Explore potential of longwave microwave remote sensing to map regional variability in surface organic soils and permafrost properties (e.g. ALT).

Outline:

- Application of a remote sensing based permafrost model (RS-PM) in Alaska
- Sensitivity of L-band Tb & P-band radar to active-layer soil moisture
- Develop a coupled EM & permafrost model to utilize L-band Tb and P-band radar data.

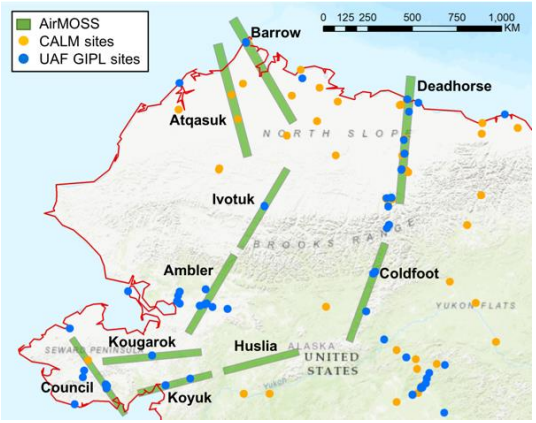
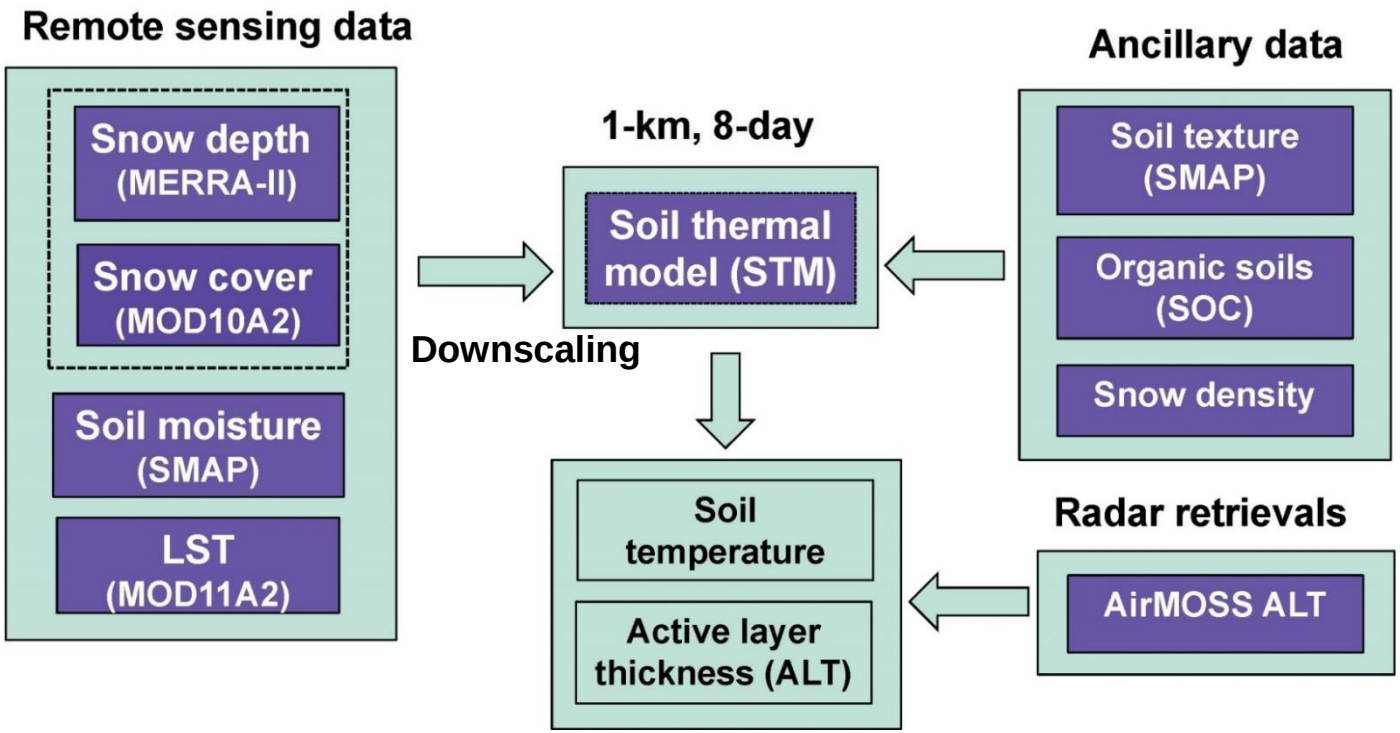


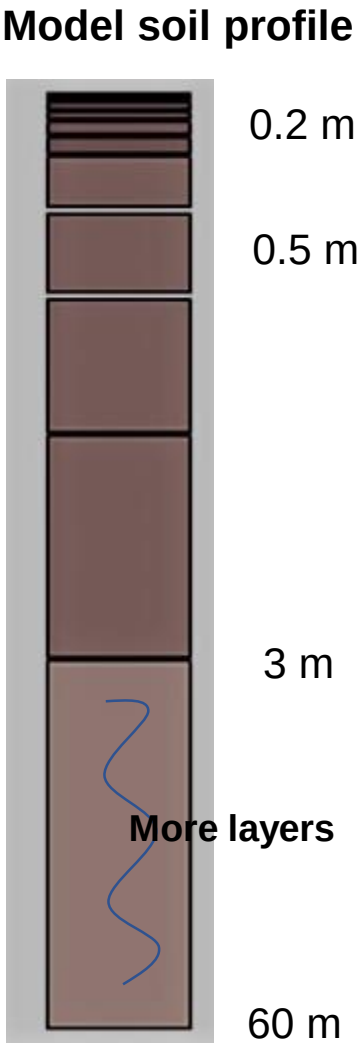
Fig. 1 AirMOSS flight lines in northern Alaska (2014/2015/2017)

Datasets:

- SMAP & Aquarius L-band Tb, 2014-2017
- AirMOSS P-band (430MHz) radar backscatter, 2014, 2015, 2017

A remote sensing data-driven permafrost model (RS-PM)





- Important factors affecting active layer thickness (ALT) include: snow cover, organic soils, soil water phase change etc.
- Simulate permafrost active layer dynamics by solving 1D non-linear heat transfer equation with phase change included.

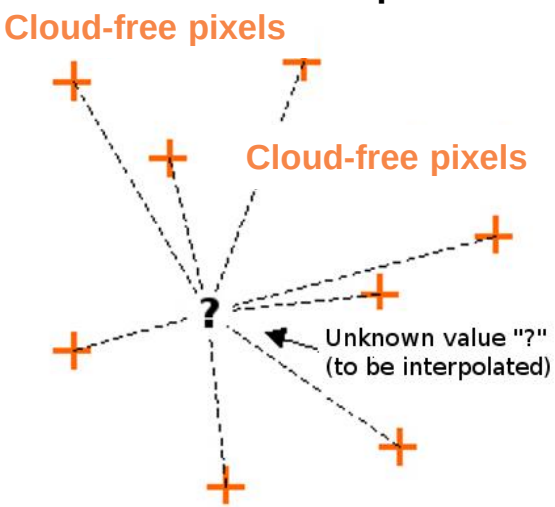
Source: Yi et al. TC 2018

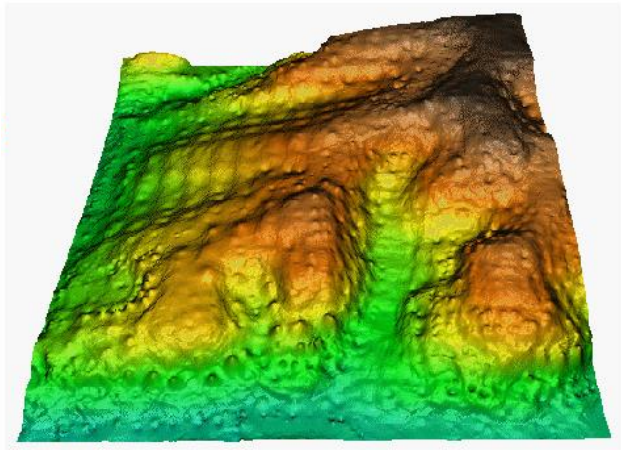
Developing a regional fine-resolution (1km) snow depth product

Methods: design an elevation-based spatial filter to:

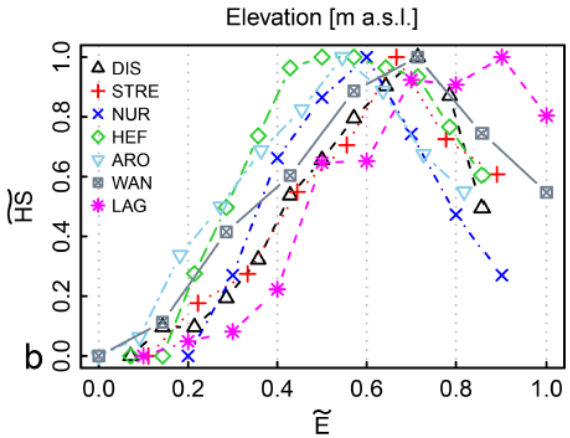
- Predict snow occurrence for cloud-contaminated pixels in MODIS SCE images.
- Downscale MERRA-2 snow depth to 1km using cloud filtered MODIS SCE and DEM data.

Spatial interpolation



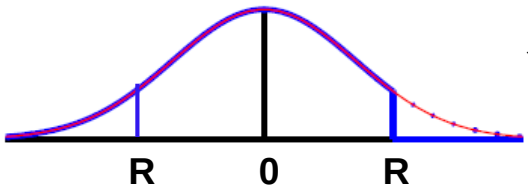


Elevation-dependence of snowd



SCE: snow cover extent
snowd: snow depth

A truncated Gaussian filter



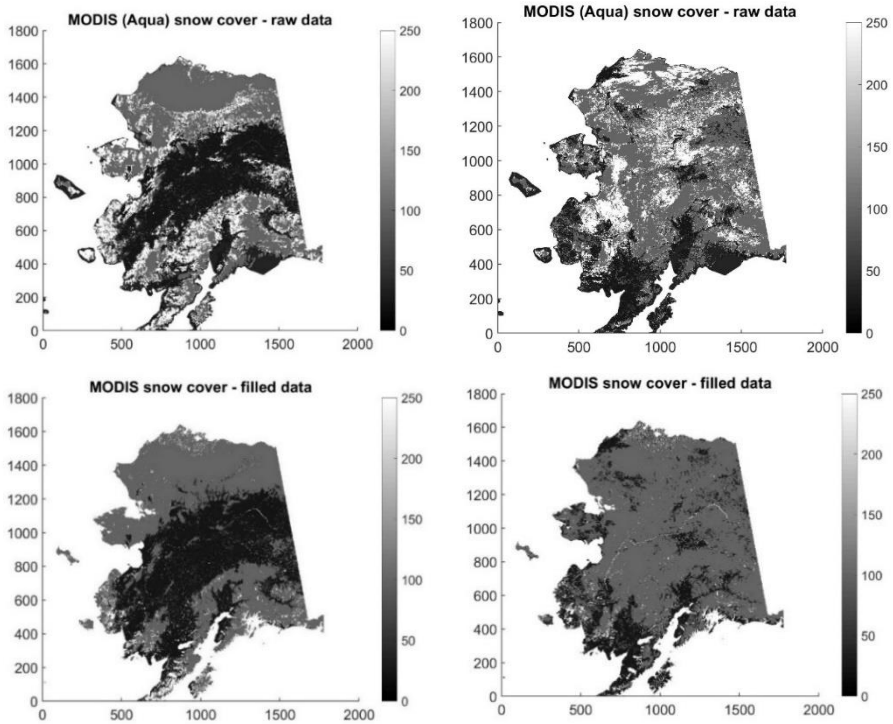
$$W(d) = \begin{cases} 0; & if\ d \geq R \\ \exp\left[-\alpha\left(1-\left(\frac{d}{R}\right)^2\right)\right]; & if\ d < R \end{cases}$$

Source: Thornton et al. J. Hydrology, 1997; Grunewald et al. TC, 2014; Yi et al. TC 2019

A fine-resolution (1-km) snow product for Alaska from 2001 to 2017

Snow cover extent

2007/05/01-2007/05/08 **2007/11/06-2007/11/13**

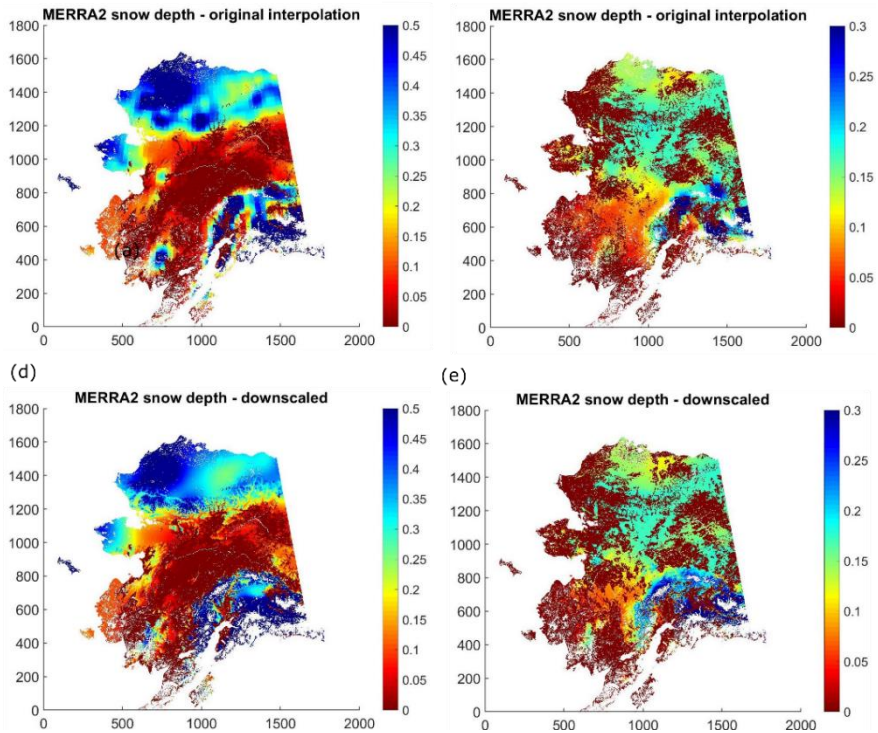


Black: no snow; dark gray: snow; white: clouds

- **Terra vs Aqua MODIS SCE cloud filtering accuracy >80%**

Snow depth

2007/04/23-2007/04/30 **2007/09/30-2007/10/07**

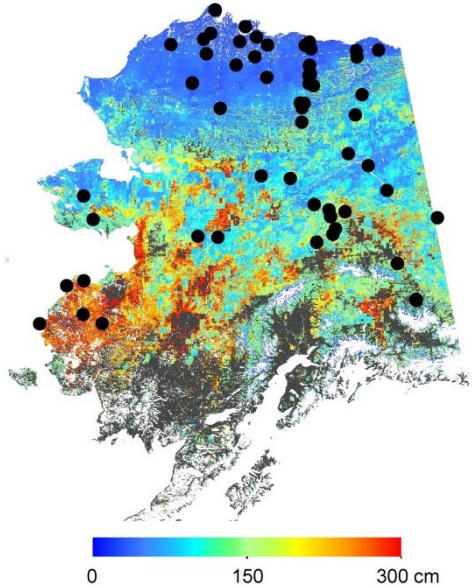


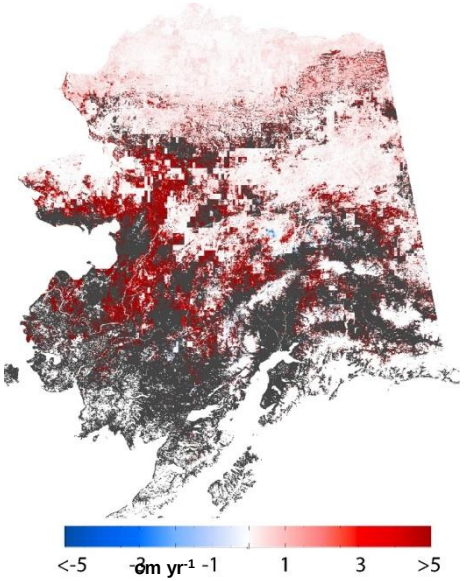
- **RMSEs (Arctic Alaska)=0.16m; errors linked with elevation discrepancy (site vs 1km grid)**

Source: Yi et al. TC, 2019

Simulated active layer thickness and uncertainty in Alaska

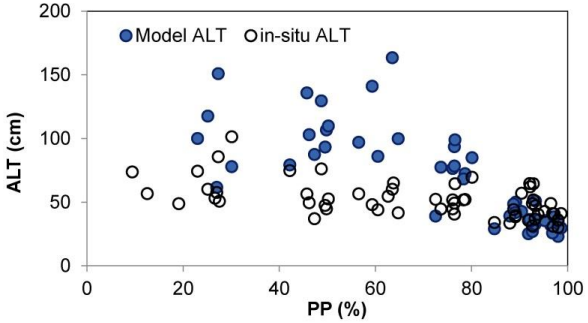
RS-PM simulated active layer thickness (ALT, 2001-2015)

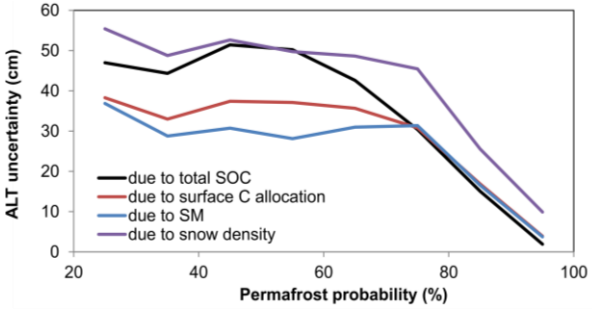




ALT mean

ALT trends





- Strong coupling between snow cover, soil moisture and SOC profiles leads to large uncertainties in model ALT estimates esp. in discontinuous permafrost region.

Model ALT sensitivity to SOC content and vertical distribution

- Larger ALT sensitivity to SOC uncertainty and warming in areas with low SOC;
- Better characterizing spatial and vertical SOC distribution will improve permafrost model accuracy.

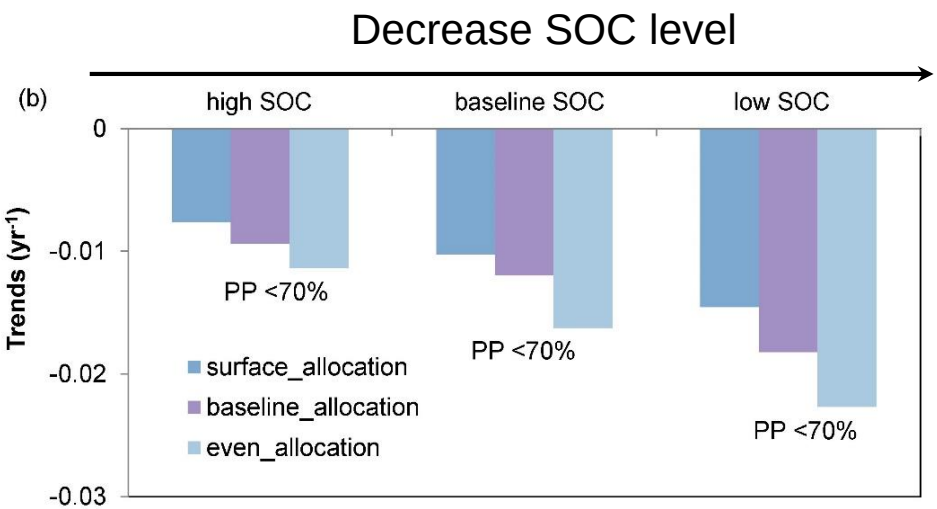


Fig.1 Sensitivity of Permafrost extent (ALT<3m) to SOC & its profile (PP: Permafrost probability)

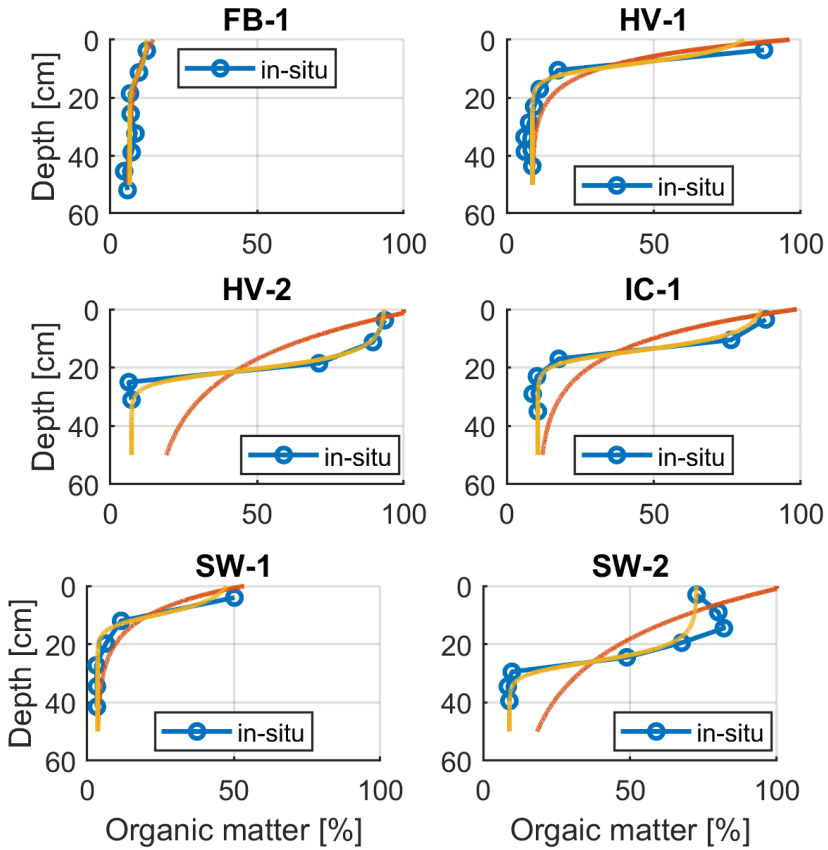
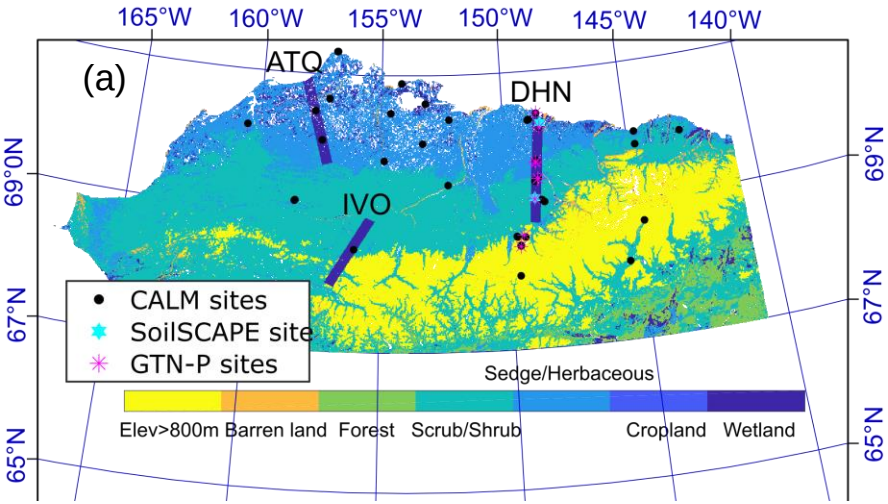
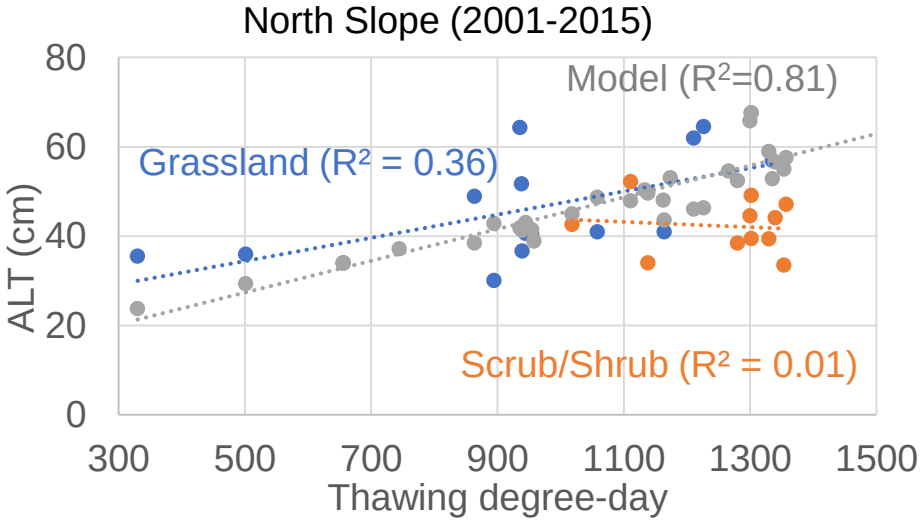


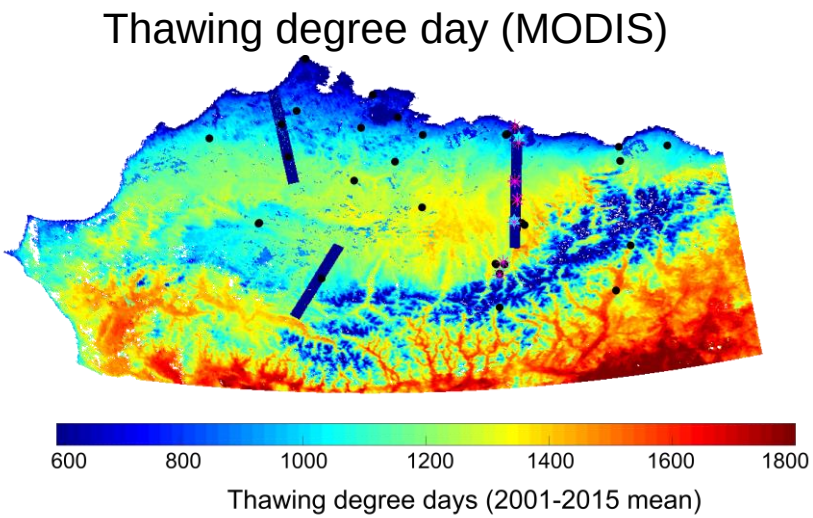
Fig.2 In-situ soil organic matter (%) profile in Alaska North Slope (Bakian-Dogaheh in prep).

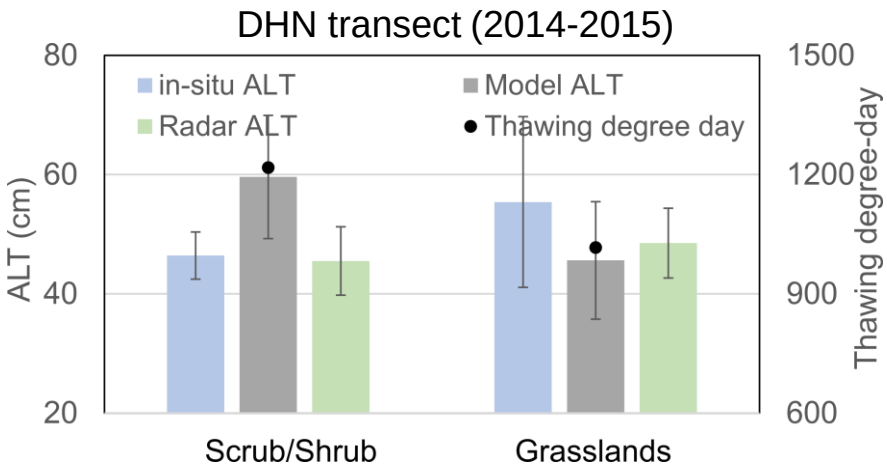
SOC(%) ~= SOM(%) × 58%

ALT responses to surface thermal loading for different tundra types





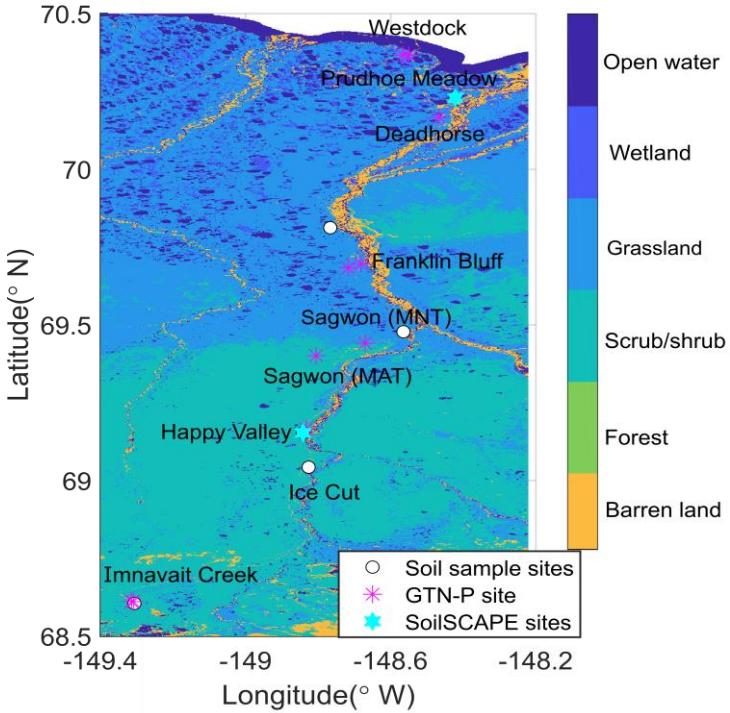




- Different tundra types show different response to surface thermal loading, likely due to different SOC properties and SM profile.

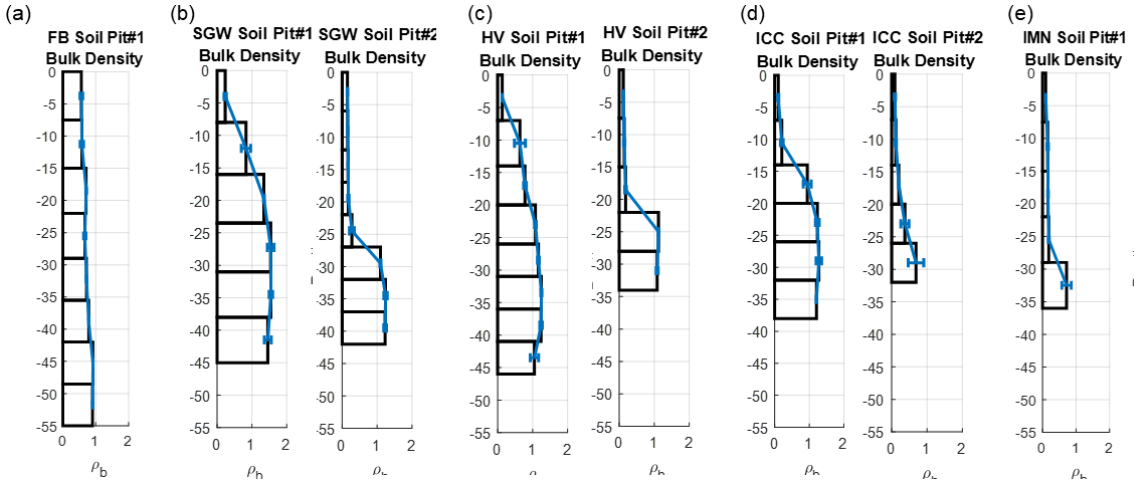
Organic soil profile properties in Alaska North Slope (DHN)

DHN transect (North Slope, AK)

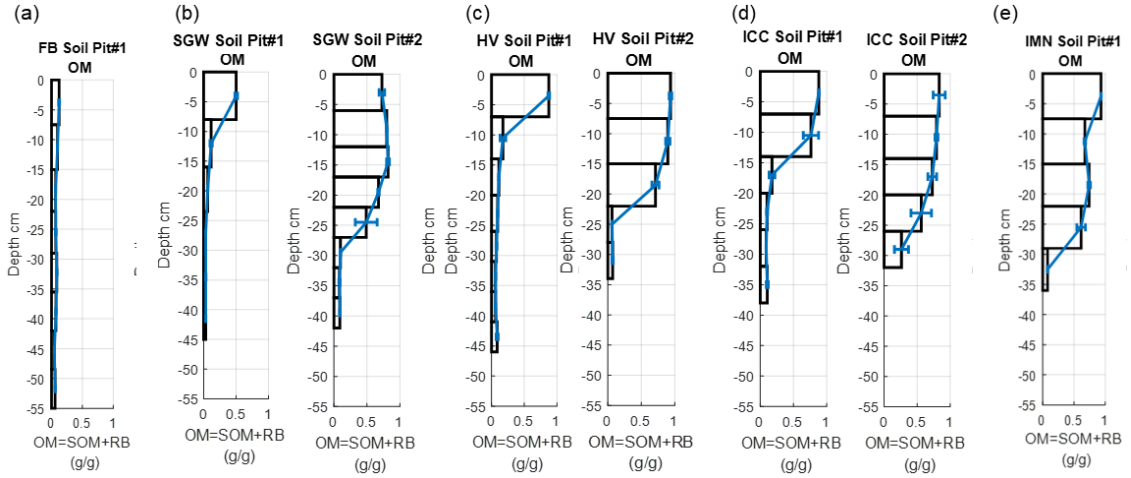


Tussock tundra (Arctic AK)

- Bulk density and organic matter (OM) concentration affect organic soil hydraulic properties.



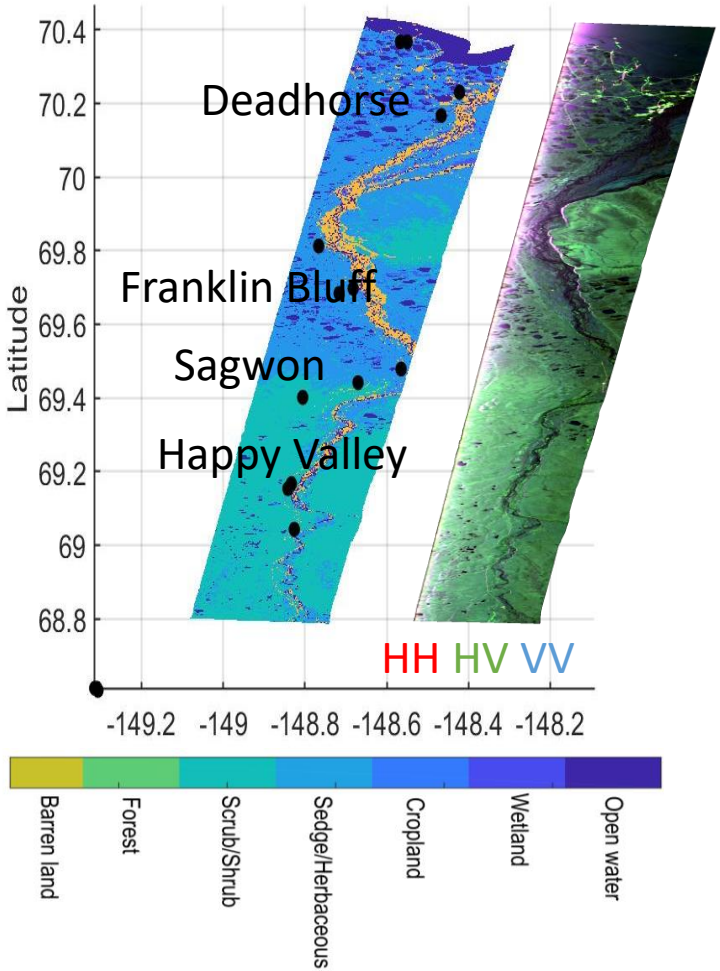
North **Bulk density (g/cm³)** South



OM concentration (g/g)

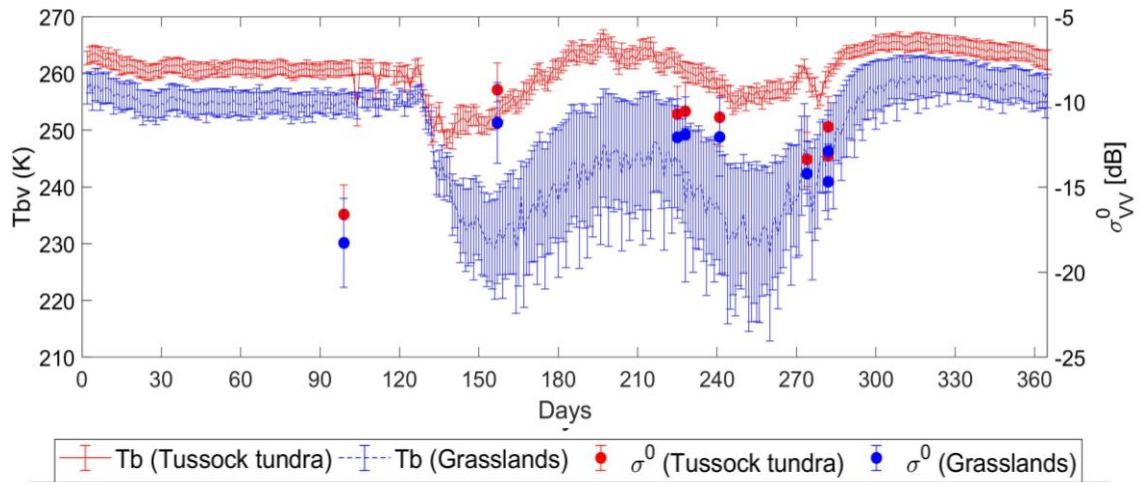
Sensitivity of L-band Tb and P-band radar to active-layer soil moisture

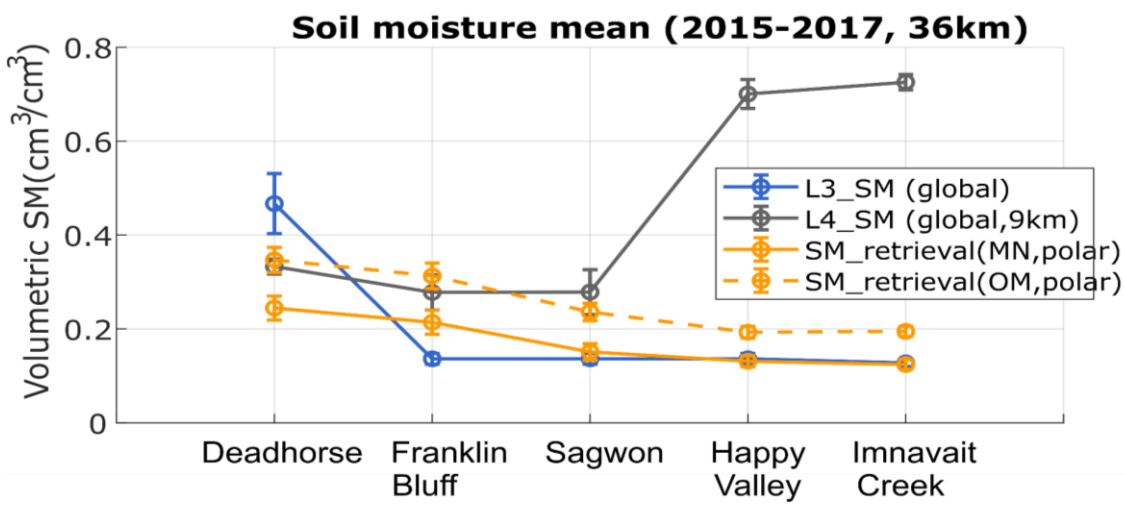
- Different behavior in Tb and radar backscatter indicate different active-layer SM profiles between tundra types.



AirMOSS (430 MHz, 2017/08/13)

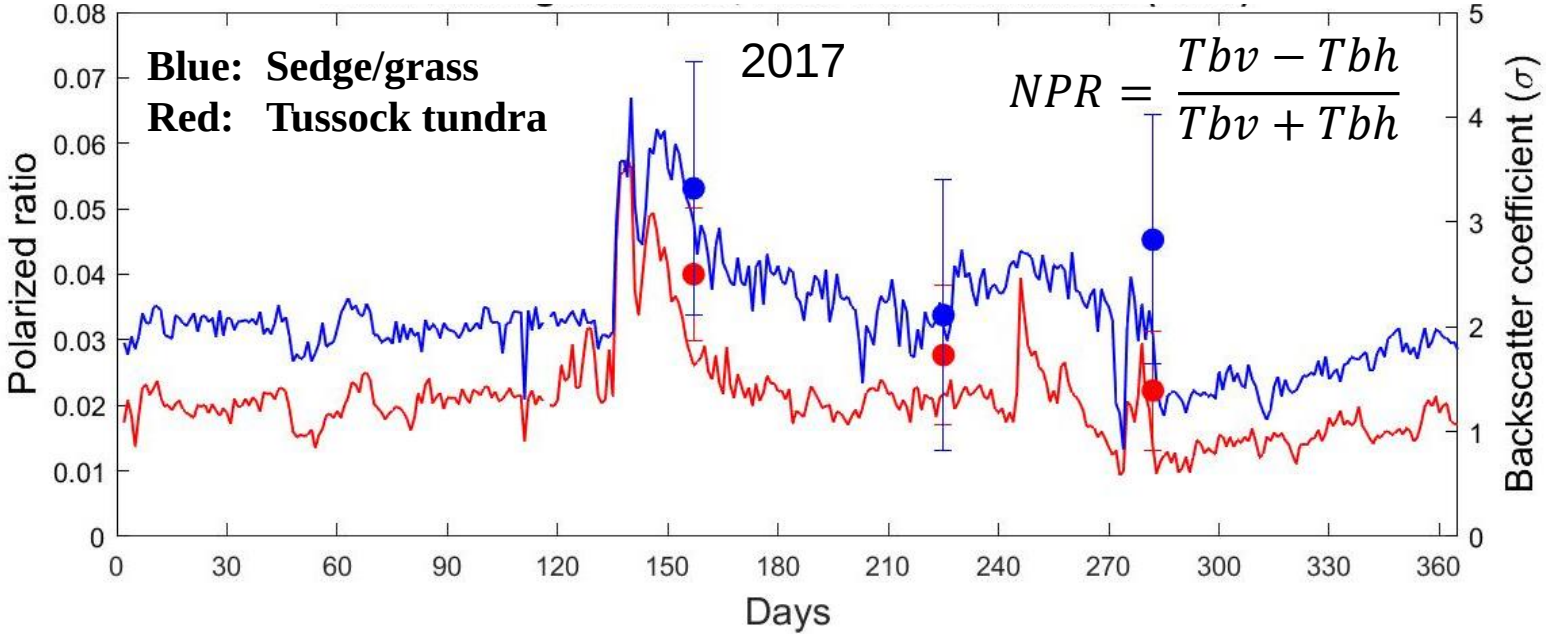
Mean SMAP Tb vs AirMOSS σ^0_{VV} (2014-2017)



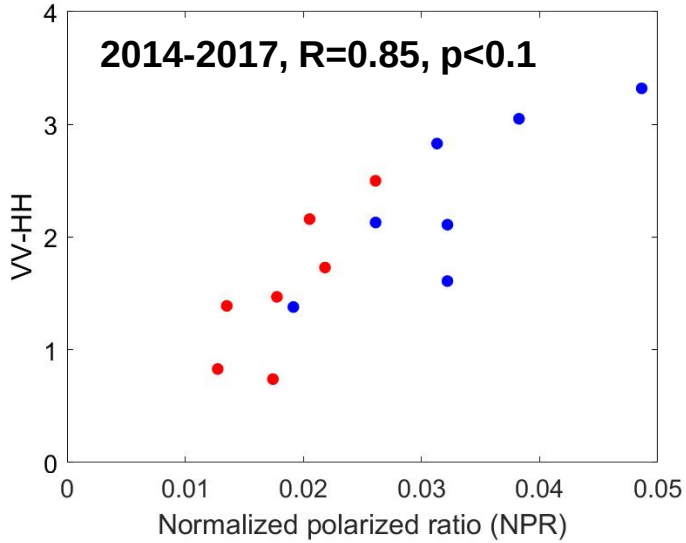


Relations between L-band NPR and P-band radar backscatter

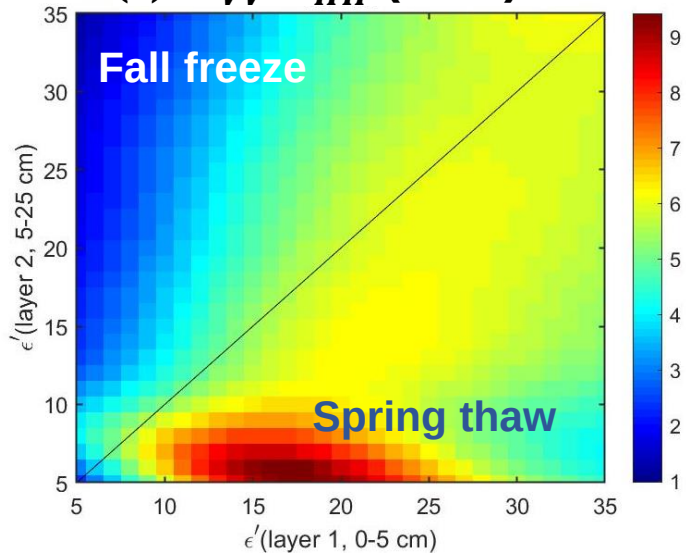
(a) Normalized polarized ratio (SMAP) vs σ^0_{VV}-σ^0_{HH} (AirMOSS)



(b) NPR vs σ^0_{VV}-σ^0_{HH}

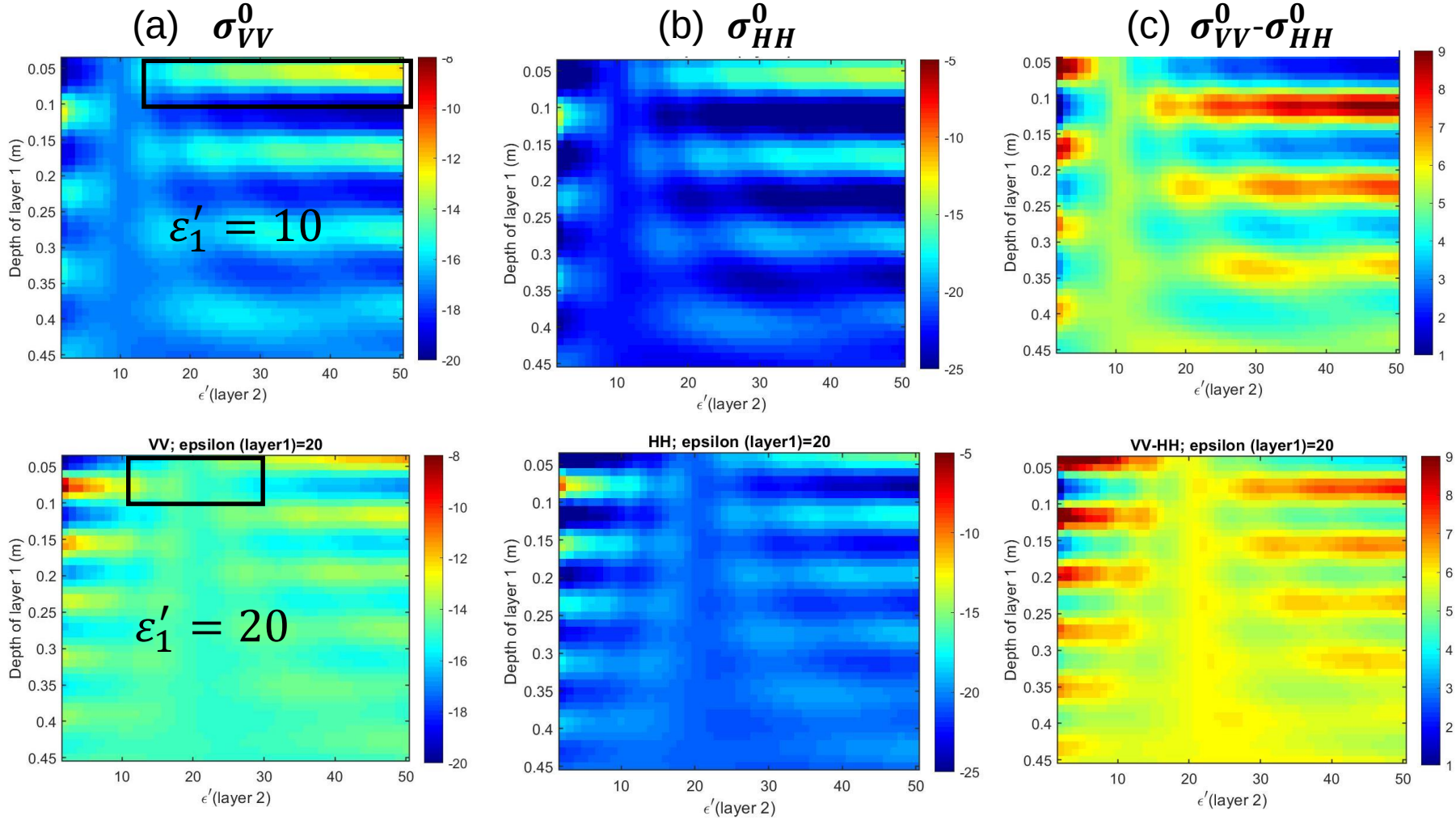


(c) σ^0_{VV}-σ^0_{HH} (SPM)



P-band radar sensitivity to active-layer soil moisture profile (SPM)

- SPM model setup: 3-layer structure: layer1 - layer2 – frozen layer;
- Tussock tundra: A drier surface overlying on a wetter subsurface



Developing a coupled EM and hydrology model for permafrost retrievals

Electromagnetics (EM) modeling

$$\epsilon = (1-\phi)\epsilon_{soil} + \theta\epsilon_{water} + (\phi-\theta)\epsilon_{air}$$

Tb: Tau-omega model
Radar: Small perturbation method (SPM)[1]

[1]Tabatabaeenejad et al. 2015; Chen et al. 2019

Permafrost modeling

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[K\left(\frac{\partial\psi}{\partial z}+1\right)\right]$$

$$C\frac{\partial T}{\partial t} + L\theta\frac{\partial w}{\partial t} = \frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right)$$

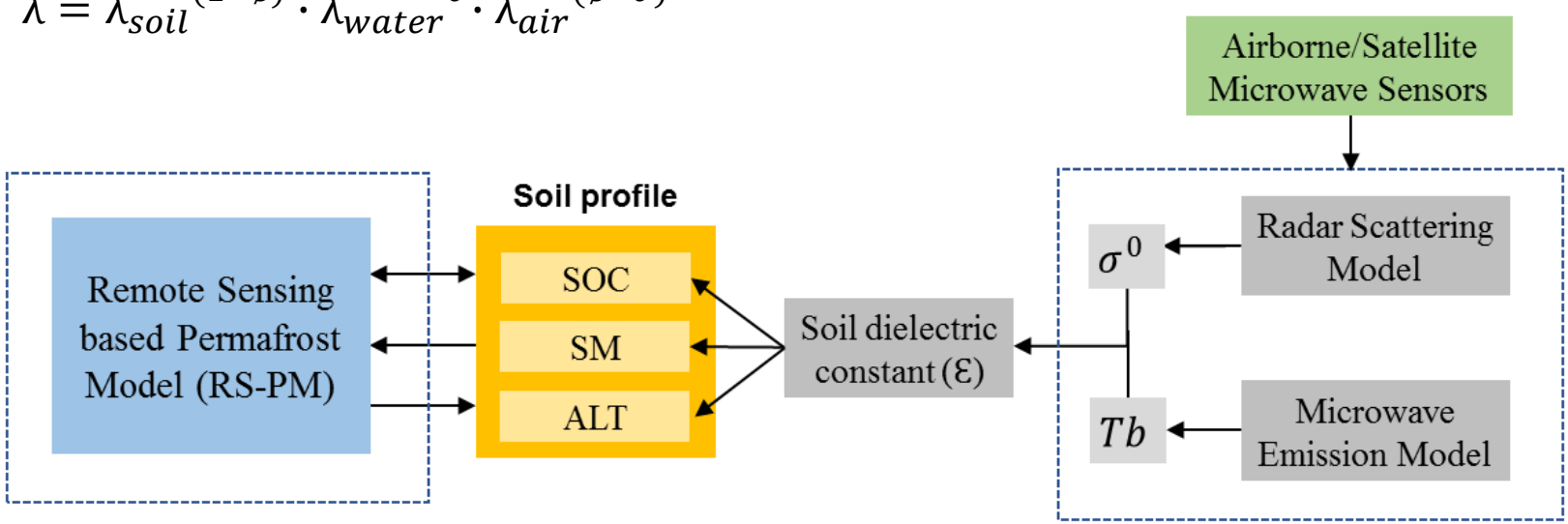
$$\lambda = \lambda_{soil}{}^{(1-\emptyset)} \cdot \lambda_{water}{}^{\theta} \cdot \lambda_{air}{}^{(\emptyset-\theta)}$$

Permafrost hydrology model (PHM)[2]:

5 snow layers
23 soil layers, 0-60m

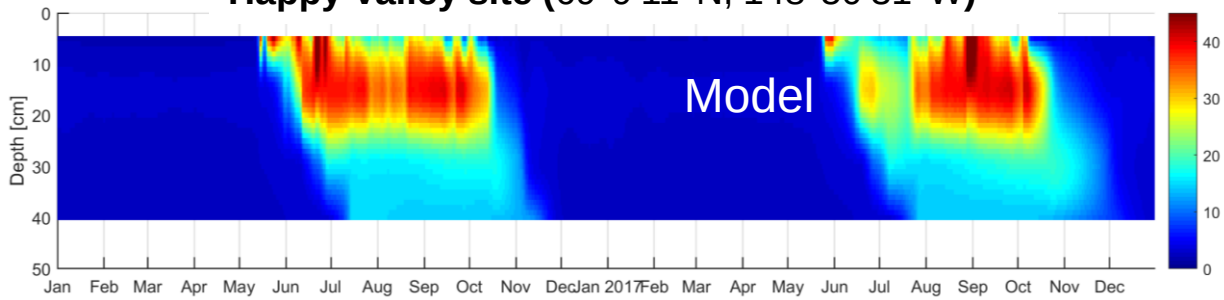
K : hydraulic conductivity
λ : thermal conductivity

[2]Rawlins et al 2013; Yi et al. 2015

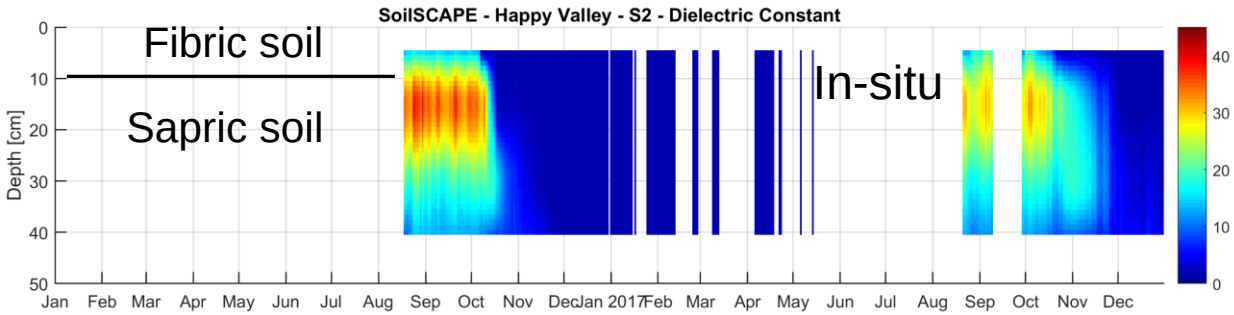


Simulated sensitivity of soil dielectric profile to surface organic soil

Happy Valley site (69°9'11''N, 148°50'31''W**)**

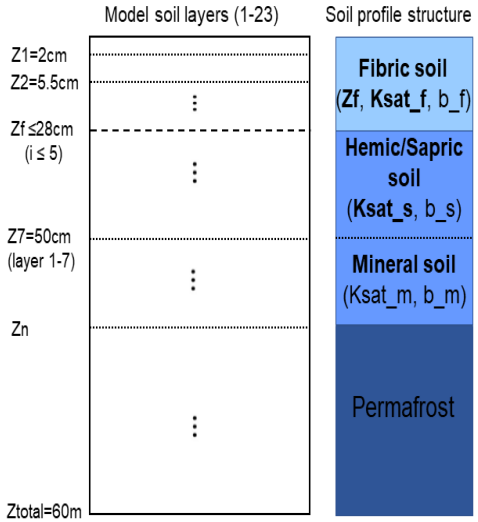


SoilSCAPE site (S1)
R=0.92
RMSE=5.25

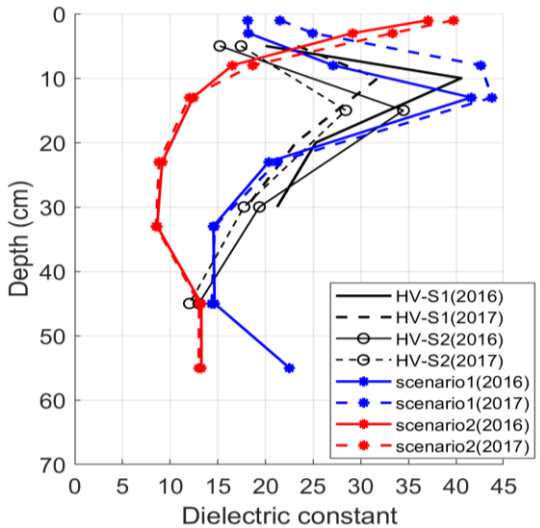


SoilSCAPE site (S2)
R=0.94
RMSE=4.35

(a) PHM model layer setup



(b) Thawed dielectric profile



Model set up:

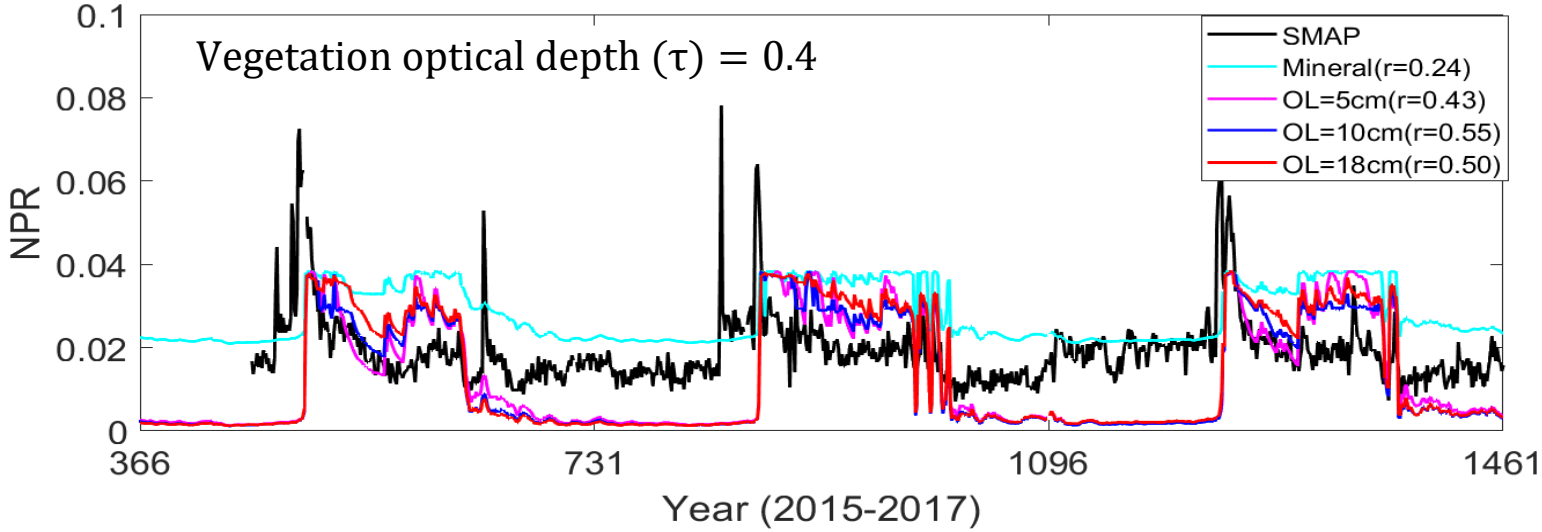
- Scenario 1: fibric organic soil overlying on sapric organic soil
- Scenario 2: ~40 cm sapric soil

Implication:

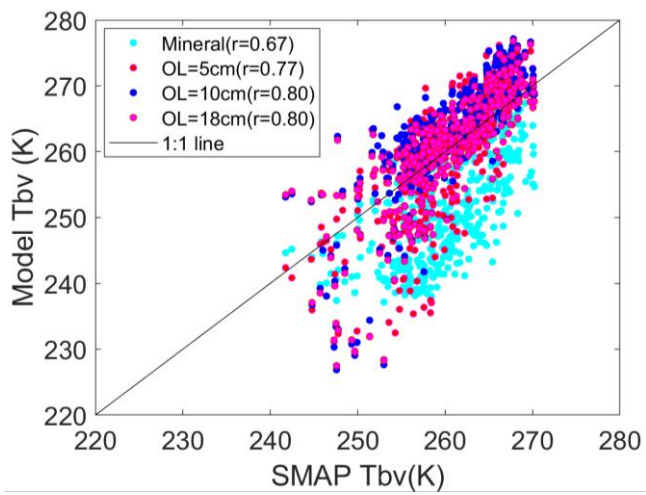
Large differences in dielectric profile indicates large difference in Tb and radar backscatter

Simulated L-band Tb sensitivity to surface soil moisture

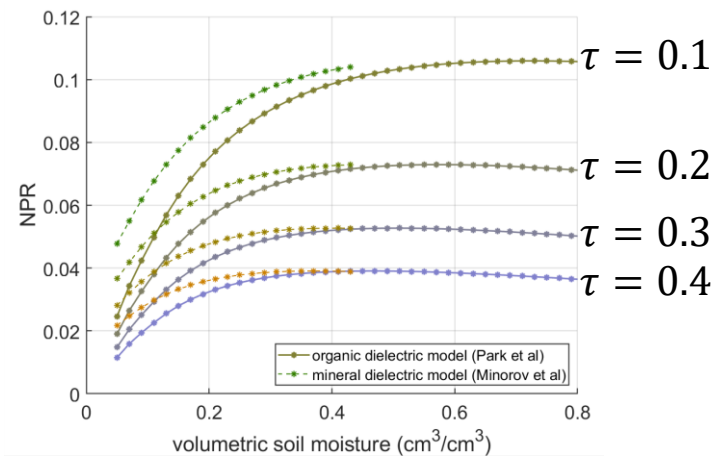
Model vs SMAP NPR time series



Tbv (thawing-season)



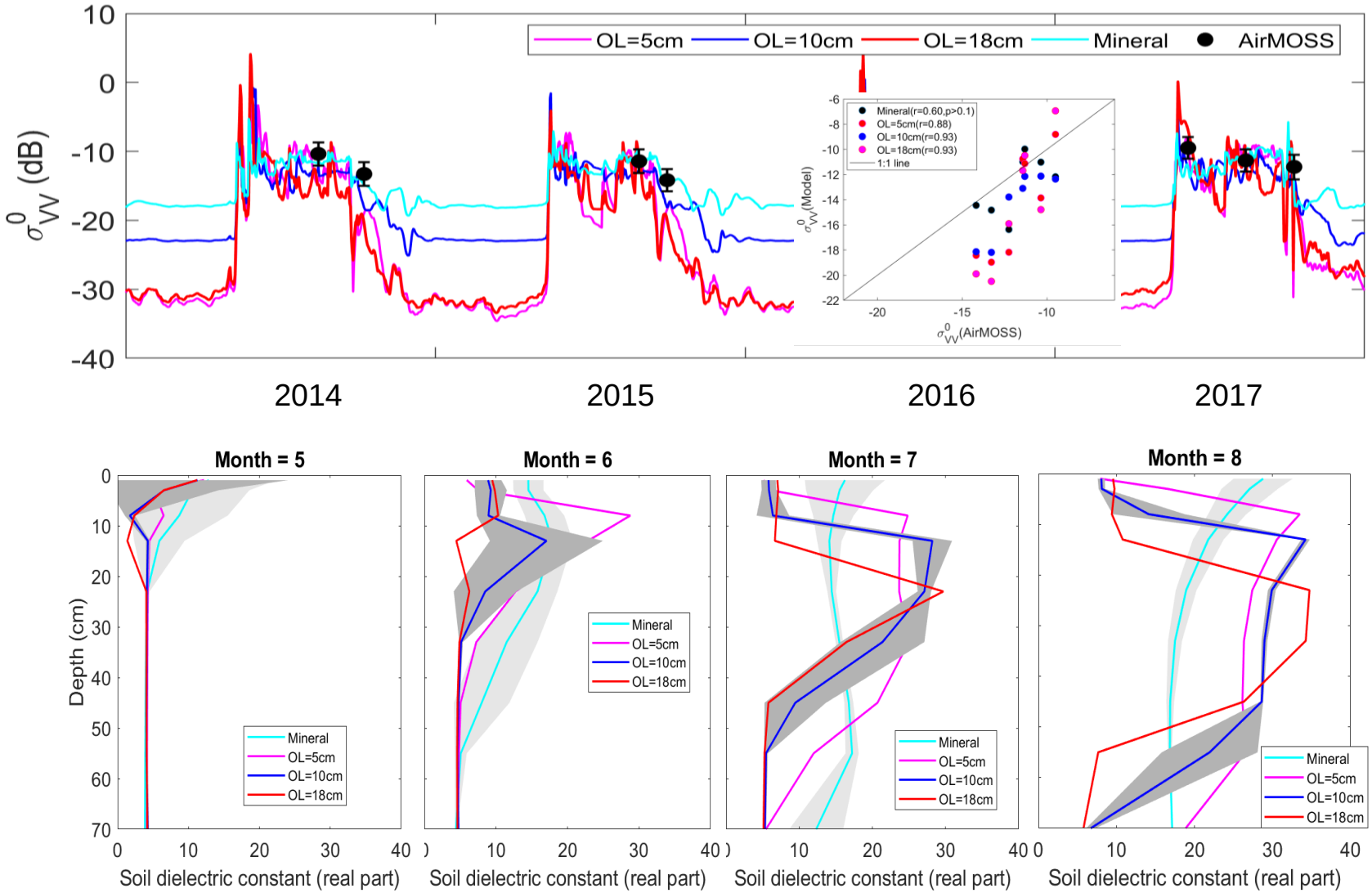
NPR sensitivity to VSM



- Without surface organic layer, model indicates a wetter surface and less variable surface SM, resulting in lower Tb & reduced variability in NPR.

Simulated P-band Radar sensitivity to active-layer soil moisture

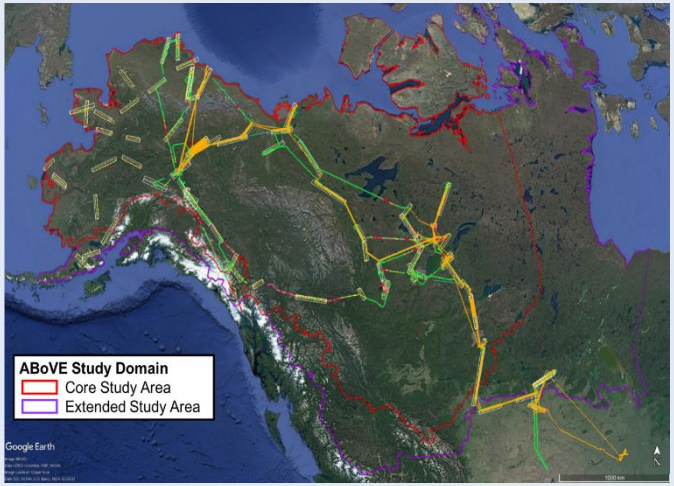
Model vs AirMOSS σ^0_{VV} (2014-2017)



- Surface organic soil affects active-layer thawing & SM distribution.
- Reduced variability in P-band radar backscatter without surface organic soil.

Summary & Conclusions

- **ALT and active-layer SM profile are very sensitive to surface organic layer; L-band radiometer and P-band radar can detect this sensitivity.**
- **Joint use of L- and P-band data may be needed for accurate ALT and SM retrievals due to compensating factors affecting P-band radar backscatter.**
- **An accurate organic soil dielectric model is critical for Arctic SM retrieval and permafrost modeling.**



ABoVE airborne campaign (2017)

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C cycle modeling
(back up)

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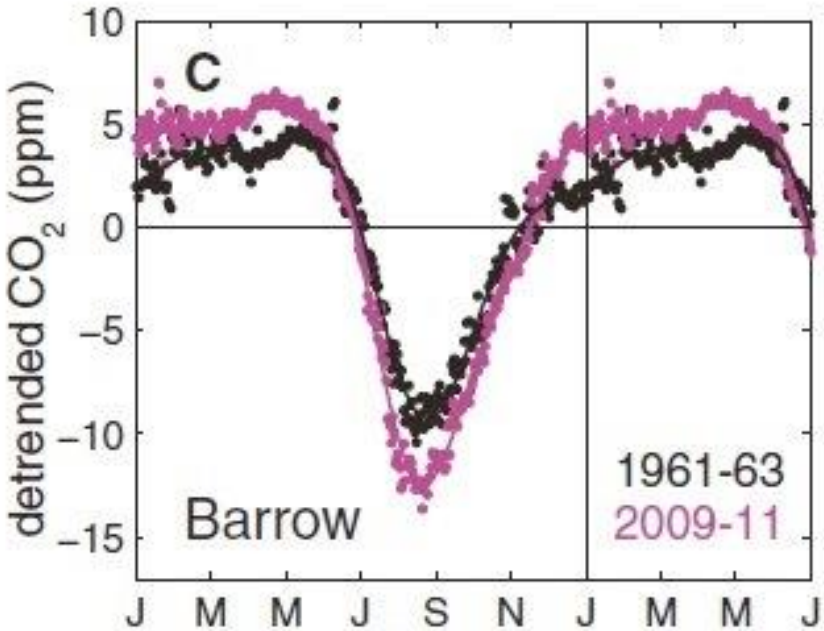
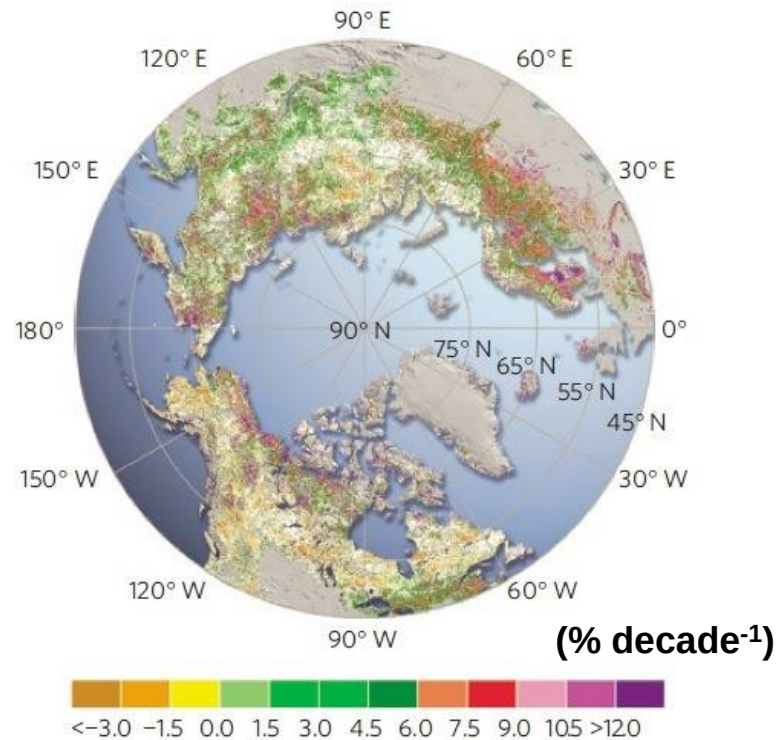
Enhanced seasonal carbon exchange of northern ecosystems

CO_2 seasonal cycle at Barrow, AK[1]



Trends of growing-season NDVI[2]



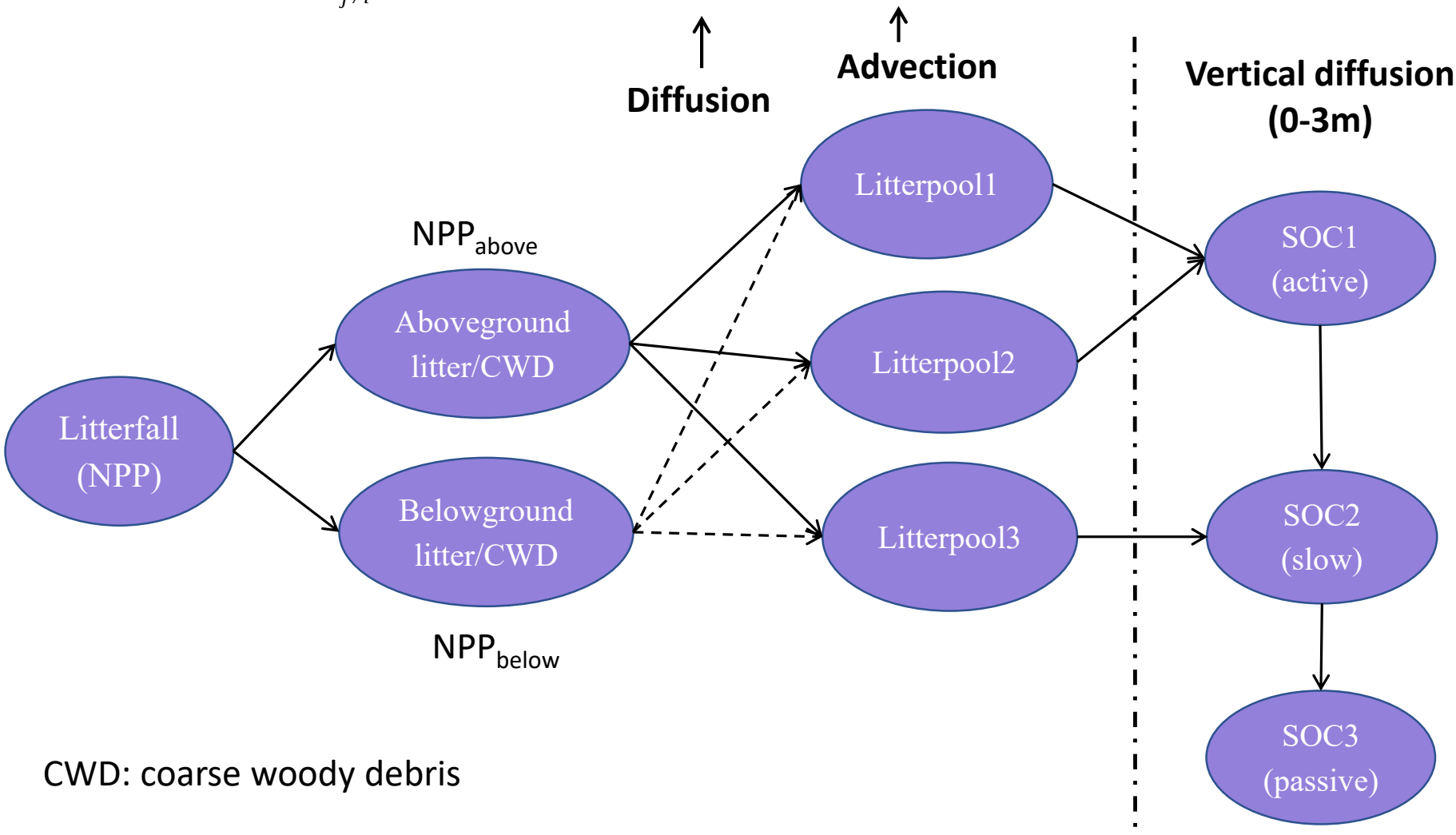
- Is the enhanced CO_2 seasonal cycle primarily due to increasing photosynthesis?

[1] Graven et al. Science, 2013; [2]Xu et al. Nature Climate Change, 2013

Incorporating a vertical SOC decomposition model

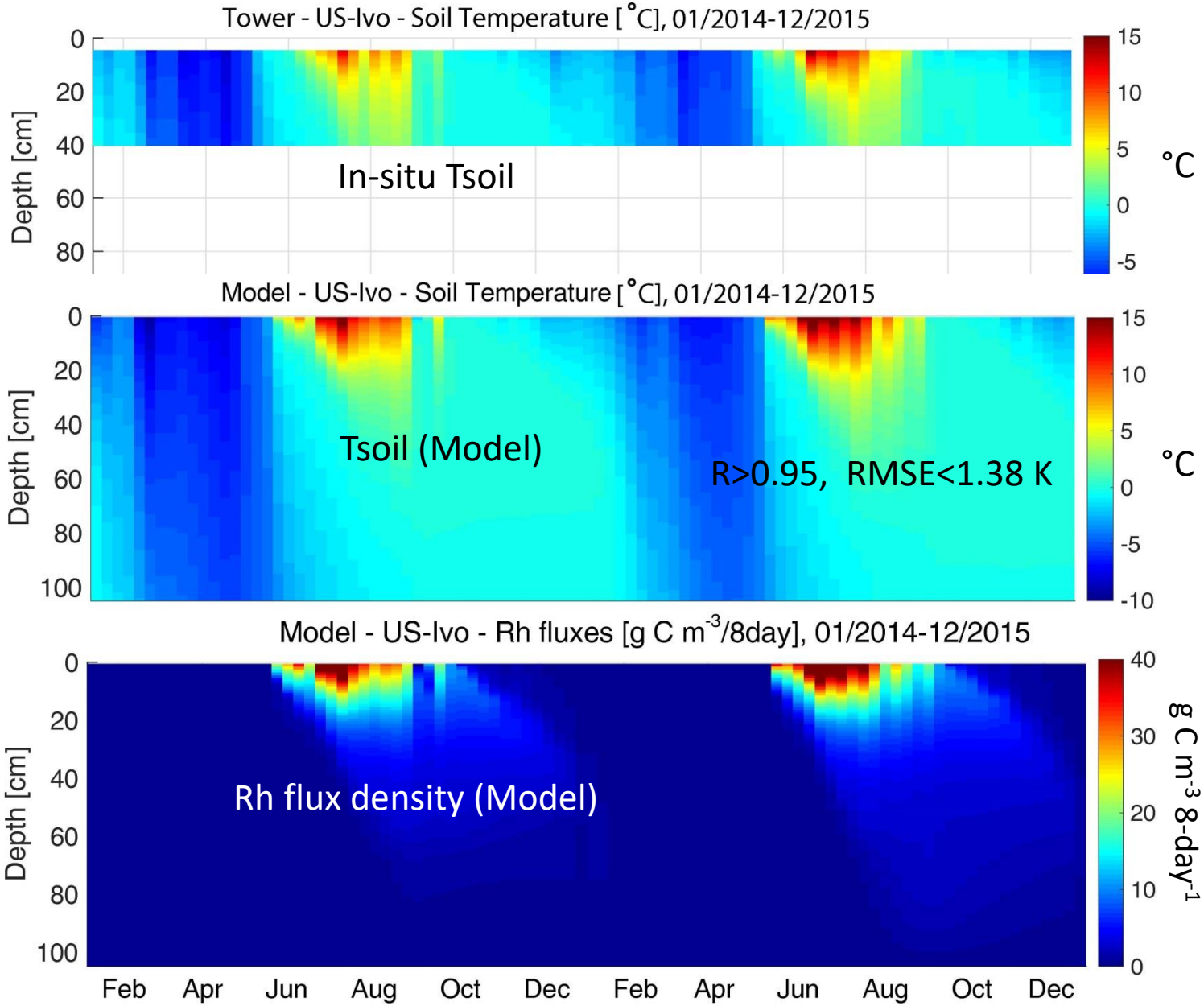
- **Introducing vertical dimension to each SOC pool (Elzein & Balesdent, 1995):**

$$\frac{\partial C_i(z)}{\partial t} = R_i(z) + \sum_{j \neq i}^{n} \partial_{ji} k_j(z) C_j(z) + D \frac{\partial^2 C_i(z)}{\partial z} - v \frac{\partial C_i(z)}{\partial z} - k_i C_i$$



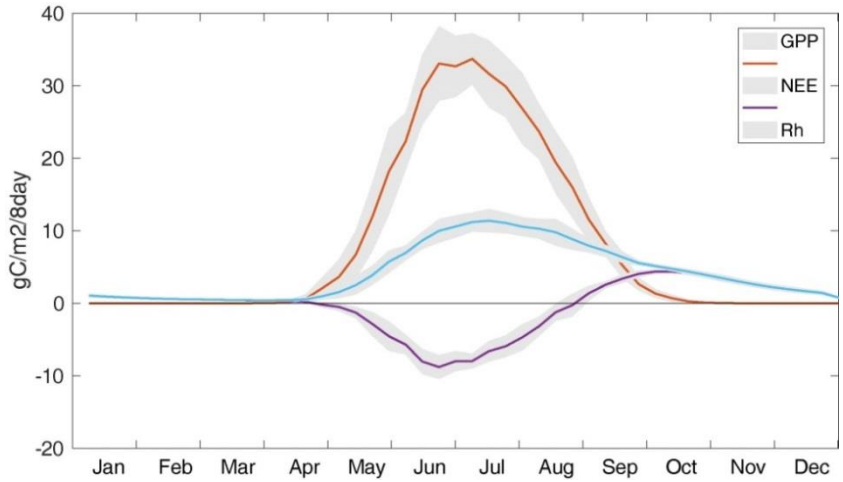
CWD: coarse woody debris

Soil temperature dynamics and heterotrophic respiration (Ivotuk, AK)

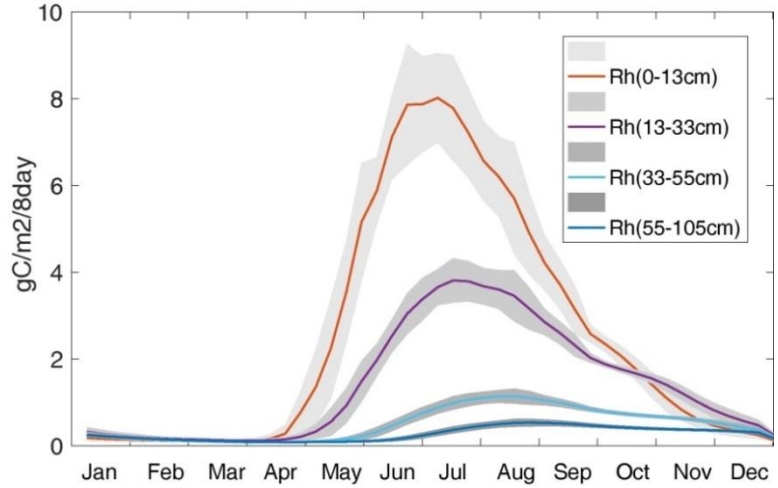


Regional C flux simulations in Alaska (2001-2015)

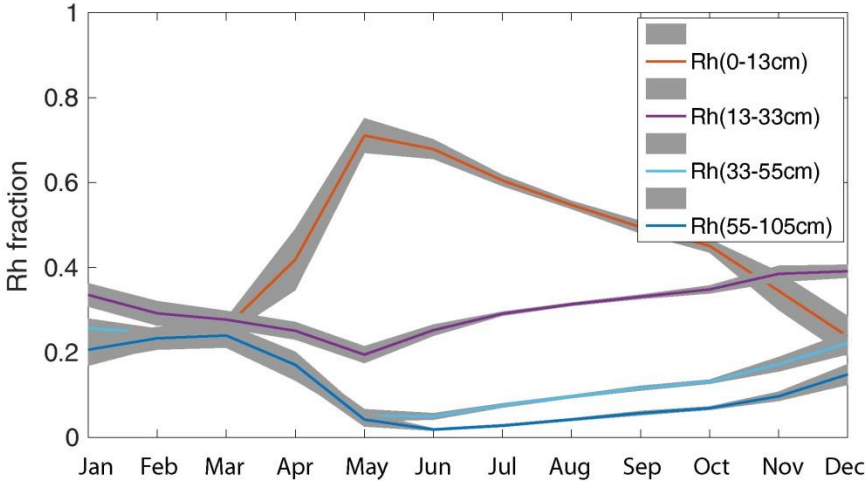
Simulated C fluxes (regional mean)



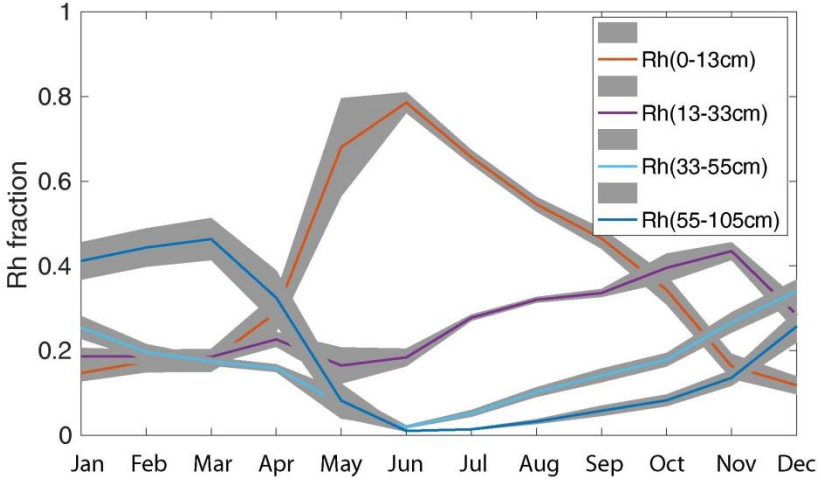
Simulated Rh fluxes (regional mean)



Rh fraction for areas with PP ≤ 33%



Rh fraction for areas with PP ≥ 69%

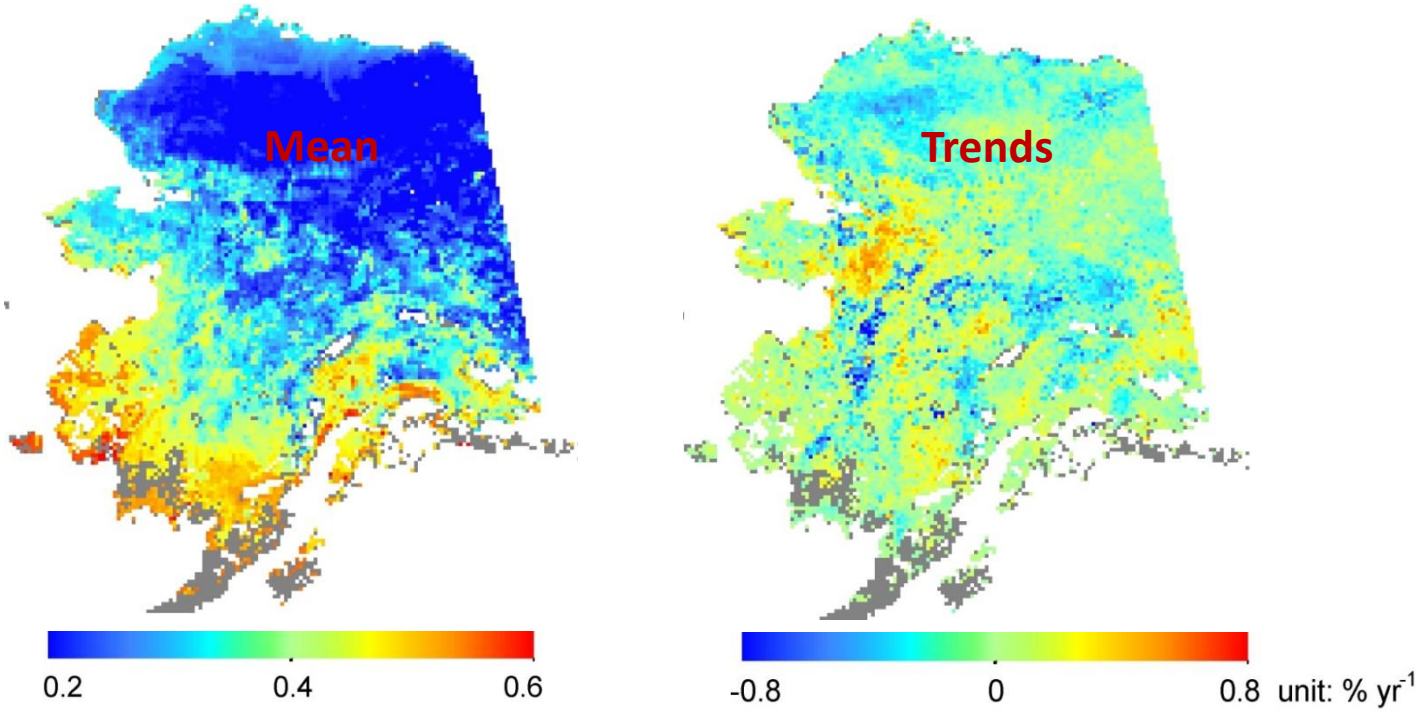


- In more continuous permafrost areas, soil respiration occurs more at deeper soils and shows stronger seasonality.

PP: permafrost probability

Regional pattern and trends of surface soil respiration in Alaska (fall, 2001-2015)

Rh fraction from surface (0-13cm) during fall (Oct-Nov)



- Rh in different permafrost zones likely respond differently to surface warming and snow cover changes.

Summary

Future work:

- Developing a methodology integrating in-situ data, GPR and airborne/satellite radar measurements to improve permafrost model soil parameterization.
- Using integrated modeling framework to understand soil F/T process and controls on cold-season soil carbon emissions.

References:

- Yi, Y. et al.: Characterizing permafrost soil active layer dynamics and sensitivity to landscape spatial heterogeneity in Alaska, *The Cryosphere*, 2018.
- Yi, Y. et al, The role of snow cover affecting boreal-arctic soil freeze-thaw and carbon dynamics, *Biogeosciences*, 12, 5811-5829, 2015.

ARCTIC – BOREAL VULNERABILITY EXPERIMENT

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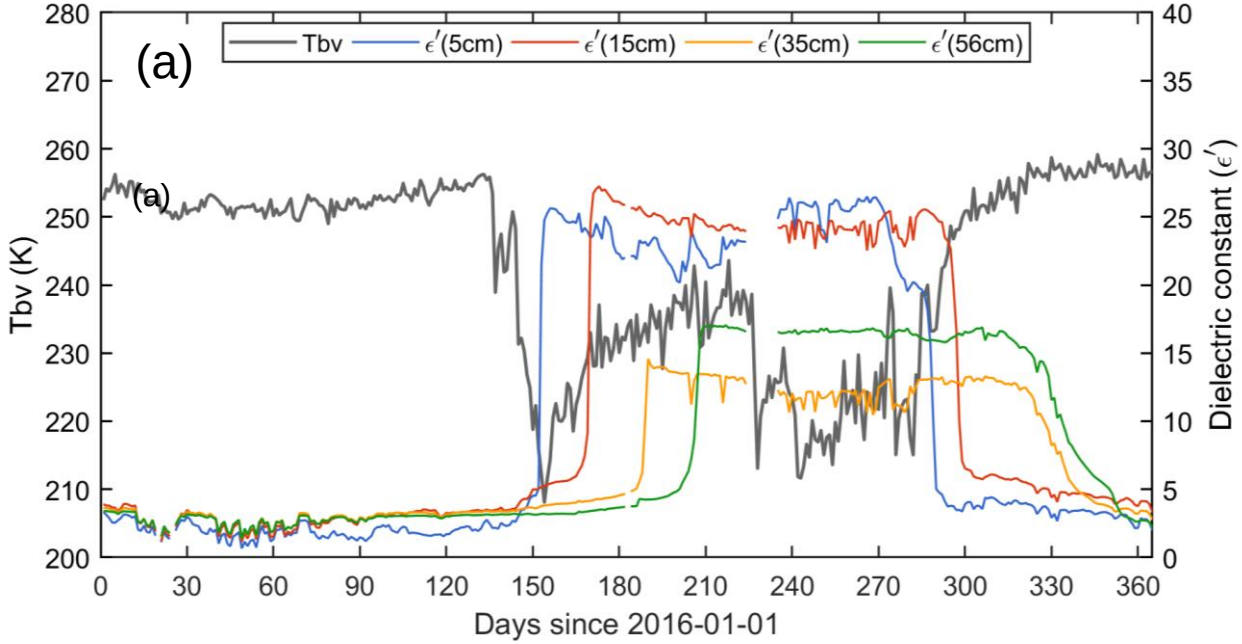
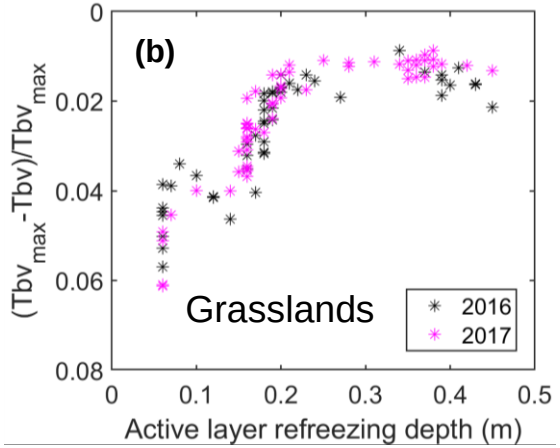
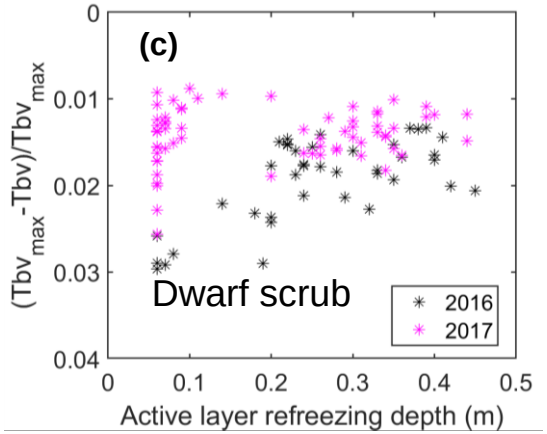
Sensitivity of L-band Tb to active layer refreezing in Arctic tundra



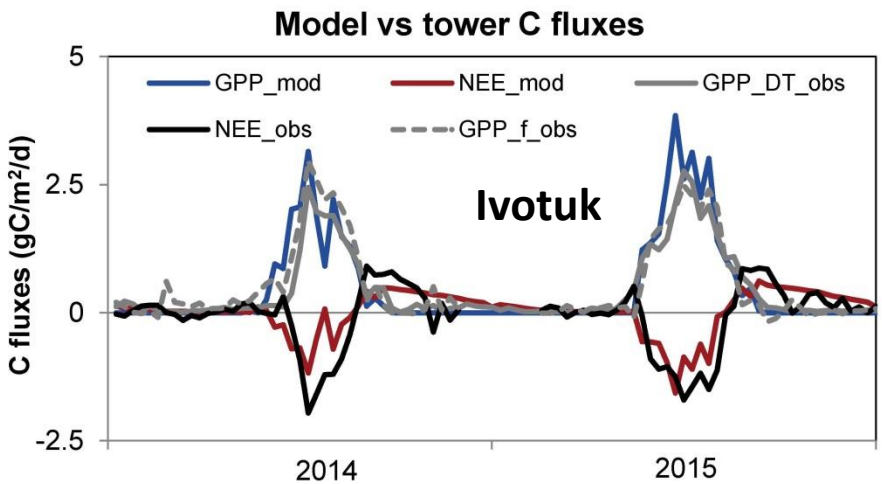


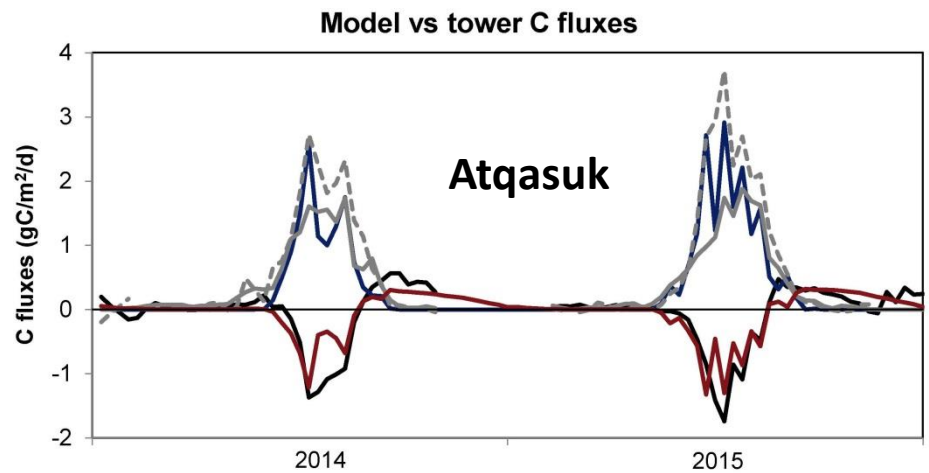


(a) SMAP Tb vs. in-situ soil dielectric constant at Prudhoe Meadow SoilSCAPE site. (b&c) relations between a Tb index and active layer refreezing depth at two tundra types.

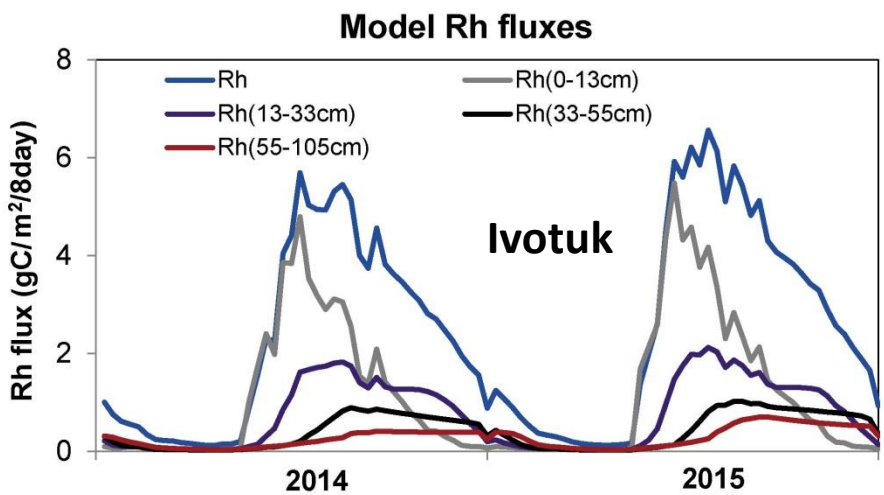
- Soil dielectric constant can effectively indicate soil water phase change;
- L-band Tb responds to active layer freezing with depth up to ~20 cm (depending on soil profile).

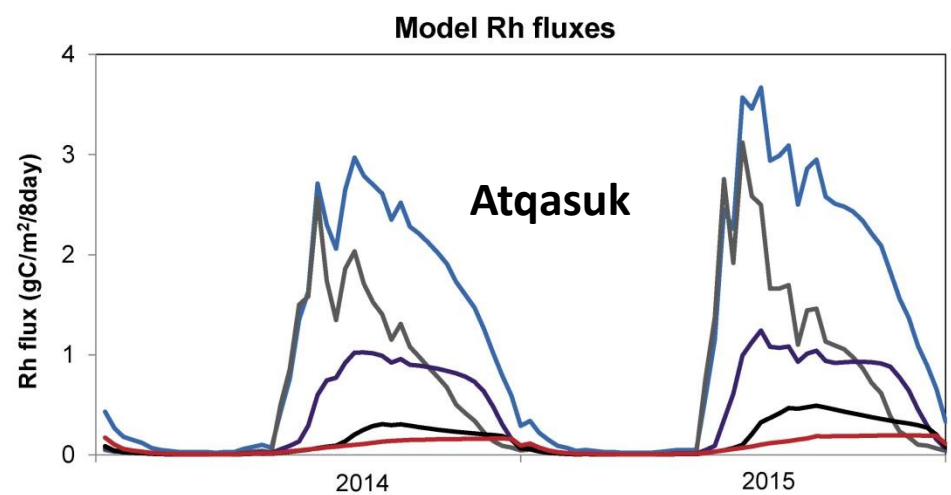
Model simulated C fluxes for Alaska tundra (Ivotuk & Atqasuk)





GPP: R>0.9, RMSE<0.35 gC/m^2/day; NEE: R>0.84, RMSE<=0.38 gC/m^2/day





- Key factors affecting soil heterotrophic respiration (Rh): 1) GPP; 2) soil temperature dynamics