Informing Improvements in Microwave Freeze/Thaw Products using High-Resolution Temperature Data Over North America

Jeremy Johnston[1], Paul Houser[1], and Viviana Maggioni[1]

[1]George Mason University Fairfax

November 24, 2022

Abstract

Existing global FT records, derived from the Soil Moisture Active Passive (SMAP), the Advanced Scanning Microwave Radiometer (AMSR), and the Special Sensor Microwave Imager (SSM/I) produce relatively course spatial resolution (25-36km) binary FT classifications. These classifications can vary widely depending on the microwave bands used, topography, and land cover, leading to a somewhat ambiguous definition of 'frozen' and 'thawed' states. In this study, we assess the relationship between satellite observation derived FT products over North America compared to modeled near-surface temperatures and land surface temperature (LST) from the Geostationary Operational Environmental Satellite system (GOES). Utilizing the higher spatial resolution of these products (~4.5km), sub-grid scale variability and its relationship to courser microwave FT classifications was assessed. Through an analysis of spatial variability and uncertainty across North America, five focus study pixels each representing unique FT profiles were examined. These included pixels in: (1) Southern Plains (36, -97), (2) Tundra (61, -76), (3) Northern Forest (47, -74), (4) Northern Plains (52, -103), and Mountainous (38.9, -107.9). The model ensemble adequately captured near surface temperatures as they relate to FT classifications in Tundra, the Northern Plains, and Northern Forest regions. On average, 85.3% to 99.6% of sub-grid cells were below freezing when FT products classified the associated pixels as frozen. GOES - LST observations were shown to have the highest proportion of sub-grid cells below freezing on average, when classified as frozen by FT products (97.3% - 100%) across the same 3 focus locations. However, we also find that fractional FT products utilizing higher resolution data inputs, such as LST, would provide a considerable improvement in mountainous regions with high inter-grid cell heterogeneity, in regions characterized by ephemeral FT events (Southern Plains), as well as during freeze and thaw onset periods. These locations showed a significant reduction in the average temperature product frozen proportion associated with frozen classifications (as low as 5.8%). This study provides insight to improving representation of FT state and providing a clearer meaning of what constitutes a 'frozen' classification.

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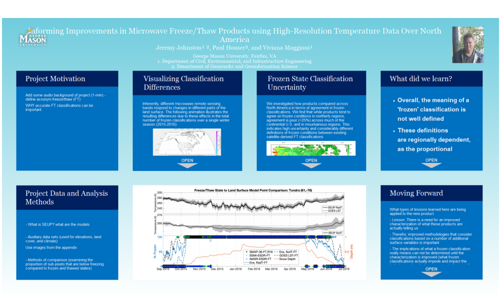

Jeremy Johnston, Paul Houser, and Viviana Maggioni

George Mason University, Fairfax, VA

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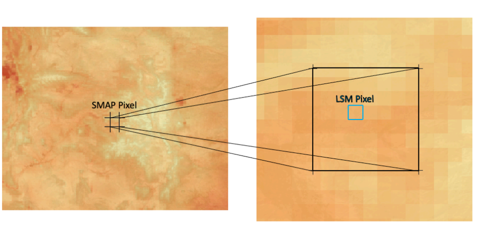
PROJECT MOTIVATION

Why is it important to measure the Earth's freeze/thaw state?

- Impacts to the global hydrologic cycle
- Caps plant growth and biogeochemical cycles
- Agricultural implications
- Impacts energy exchanges between the land surface and atmosphere
- Direct indicator of a changing climate

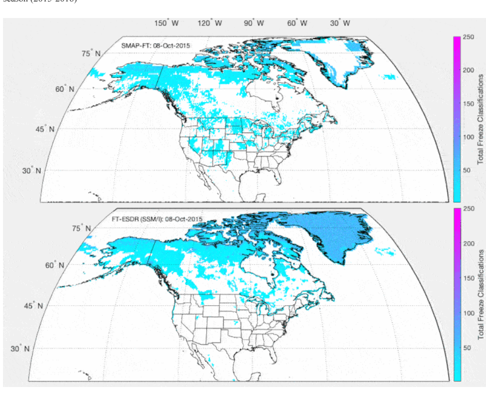


Why examine sub-pixel temperature?

- Binary classifications and the coarse resolution (>625 km^2 per pixel) of **satellite derived** freeze/thaw products limit the representation of surface conditions
- Little is known about what parts of the surface dominate the observed microwave (MW) signal in terms of observed freeze/thaw transitions
- Sub-pixel temperatures using higher resolution products, provide a window into the smaller-scale processes that are driving MW-based frozen classifications
- We want to identify what characteristics (e.g. vegetation, snow, soil or skin temperatures) are dominating the signal
- What does a 'frozen' classification really mean

VISUALIZING CLASSIFICATION DIFFERENCES

Inherently, different microwave remote sensing bands respond to changes in different parts of the land surface. The following animation illustrates the resulting differences due to these effects in the total number of frozen classifications over a single winter season (2015-2016)

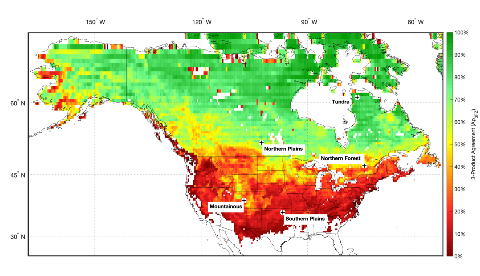


SMAP (top) and FT-ESDR SSMIS (bottom)

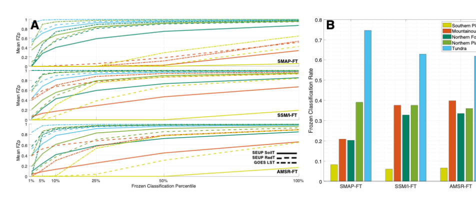
Observable differences in classifications are most prominent over the central and western United States (e.g., Montana, the Dakotas) as SMAP has considerably fewer frozen classifications in these regions

FROZEN STATE CLASSIFICATION UNCERTAINTY

We investigated how products compared across North America in terms of agreement in frozen classifications. We find that while products tend to agree on frozen conditions in northerly regions, agreement is poor (<25%) across much of the continental U.S. and in mountainous regions. This indicates high uncertainty and considerably different definitions of frozen conditions between existing satellite-derived FT classifications



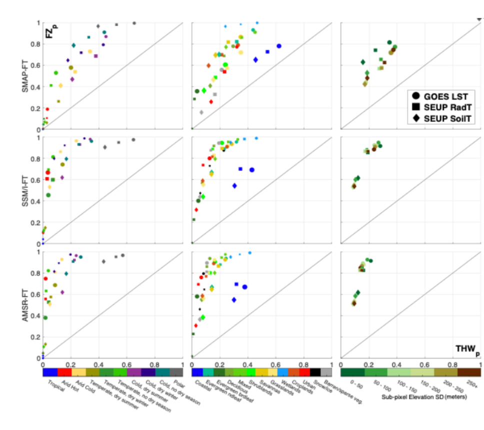
In order to investigate the factors driving these differences we performed a timeseries analysis of pixel specific temperatures and FT states. The analysis locations indicated (in above figure) were selected due to a wide range of vegetation, climate, and topographic profiles



The sub-pixel land surface characteristics and temperatures governing observed FT transitions are shown to vary depending on location. While clear FT transitions are captured at the surface and soil in the Tundra, temperate regions are shown to transition to 'frozen' in existing products when only a small propostion of the sub-pixel observed and modeled temperatures are below freezing (see timeseries figures)

WHAT DID WE LEARN?

- **Overall, the meaning of a 'frozen' classification is not well defined**



FZp/THWp indicate the proportion of sub-pixel temperatures below freezing when deemed frozen/thawed by MW products

- **These definitions are regionally dependent, as the proportional area modeled/observed to be below freezing (within the larger FT pixels) in order to result in frozen classifications varies widely depending on climate, topography, and vegetation**
- **In dry, mountainous, and more temperate regions, FT classifications are especially uncertain**
- **Frozen classifications are most consistent with sub-pixel skin temperatures, not soil**
- **Snow cover and wet snow have a considerable impact on FT states and the observed MW response of different bands**

PROJECT DATA AND ANALYSIS METHODS

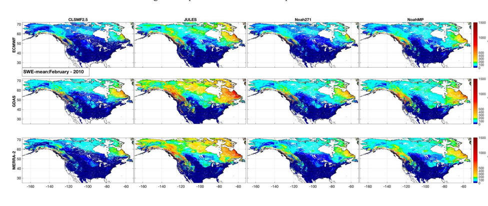
In order to meet the project objectives of asessing sub-FT pixel scale temperature processes, we utilized a number of different data inputs including both models and observations. This study was performed over the area of physical (North America) and temporal overlap (2015 - 2017) between the following datasets:

Freeze/thaw (FT) Products

In this study, we consider 3 satellite-based FT products. All products were derived from microwave radiometer observations via the Soil Moisture Active Passive (SMAP, L-band, Dunbar et al. 2018), Special Sensor Microwave Imager Sounder (SSMIS, Ka-band), and the Advanced Scanning Microwave Imager 2 (AMSR2, Ka-band). The latter two are derived as part of the FT Earth System Data Record (FT-ESDR, Kim et al. 2018). All products derive binary FT states from changes in the observed microwave emissions which are dependent on surface water content and state. These products are developed at relatively coarse 36km (SMAP) and 25km (FT-ESDR) resolutions.

The Snow Ensemble Uncertainty Project (SEUP)

The NASA SEUP project is an effort to examine and understand the existing gaps in our modeling of global snowpacks (R. S. Kim et al. 2020). This is being done through the use of several land surface models (Noah 2.7.1, Noah MP, JULES, and CLSMFv2.5) forced by operational input forcings (MERRA2, GDAS, and ECMWF). The output of this 12-member model ensemble consists of a wide range of variables. These include snow depths, snow water content, air, soil, and surface skin temperatures among others. The 5km outputs from this project were produced from 2008 - 2017. We use the outputs from these simulations to inform a reasonable range of temperature states in our comparison to observed FT states.

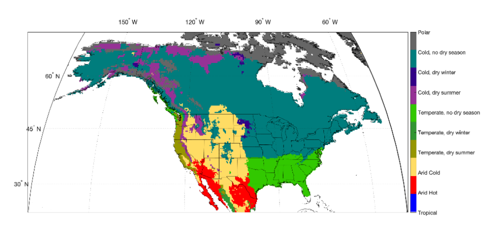


Land Surface Temperature Observations

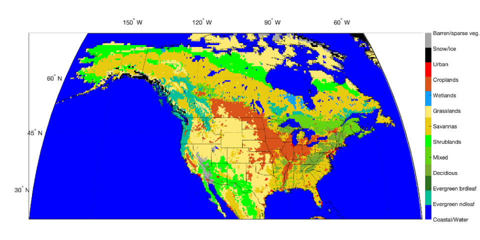
To supplement the model realizations, we also use land surface temperature (LST) retrievals derived by the Copernicus Global Land Service from GOES-East observations (Geostationary Operational Environmental Satellite). LST data was available at ~5km resolution using GOES thermal band observations at an hourly increments (Freitas et al. 2013).

Other Data Sets

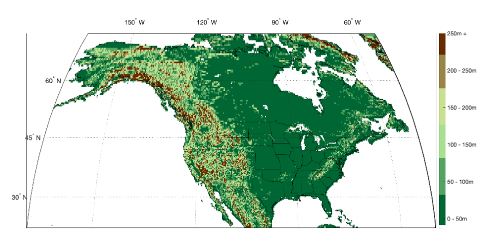
Climate classifications from Beck et al. 2018 were examined against temperature and FT states



MODIS derived land cover is also used to quantify the impacts of vegetative cover on classifications

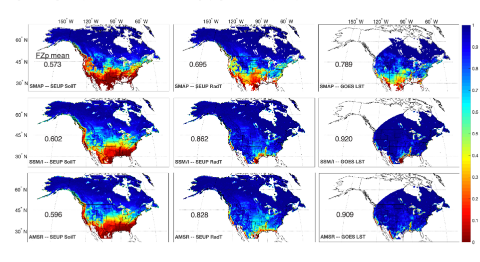


We also use the ASTER global digital elevation model to examine the relationship between FT classifications and sub-FT pixel topographic variability



Comparison Methods

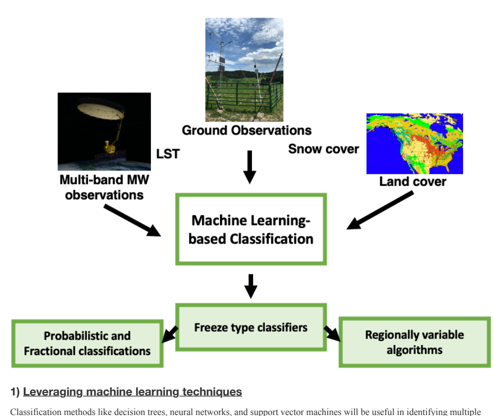
We examine temperature distributions relative to the freezing point within sub-pixels (~5km) that are contained within the larger FT pixel footprints (36km, 25km). Identifying the average proportion of cells below freezing when deemed both frozen and thawed. These values are computed spatially through the entire period, as well as at specific focus study pixels. Values are also separated depending on climate, land cover, and topographic variability using the aforementioned data sets.



Average proportion of sub-pixel temperature cells below freezing, when classified as frozen

MOVING FORWARD

This research has identified a need for improved characterization of freezing and thawing processes. Therefor, work towards new methodologies is ongoing to better capture and classify these processes. Some new methods being employed include:



1) Leveraging machine learning techniques

Classification methods like decision trees, neural networks, and support vector machines will be useful in identifying multiple classification types beyond binary states (e.g., frozen soil and skin, frost, snow, thawed surface/frozen soil etc.)

2) Varying classification techniques regionally to ensure consistent frozen state definitions

This can be aceived by using current change detection and thresholding approaches in northern regions, while leveraging LST and other land surface variables in mountainous and southerly regions could allow fractional frozen classificaitons and help to avoid false freeze classifications

3) Data Fusion

These results suggest that the combination of MW bands, the use of land surface temperature, as well as the integration of other land surface variables (i.e., topography, land cover) will enable multiple FT classifications (think distinguishing a frost event from a mid-winter hard freeze in the tundra)

DISCLOSURES

This research is supported through the NASA Terrestrial Hydrology Program (THP 2016), grant number NNX17AL38G

The authors would like to thank member of the NASA Snow Ensemble Uncertainty Project (SEUP) group for their feedback and contributions to the data used in this study. The freeze/thaw data used in this study are available through the National Snow and Ice Data Center (NSIDC), SEUP model outputs are available via a George Mason University server (contact Dr. Paul Houser, phouser@gmu.edu for access), and GOES hourly land surface temperature is available through the Copernicus Global Land Service (https://land.copernicus.eu/global/themes/energy). Additional land surface variables from MODIS (500m land cover) and ASTER (30m elevation) are also available via NASA's Earthdata Search system (https://search.earthdata.nasa.gov)

AUTHOR INFORMATION

Jeremy M. Johnston received the B.S. and M.S. degrees in 2017 and 2019, respectively, from George Mason University, Fairfax, VA, USA, where he is currently working toward the Ph.D. degree in environmental and water resources engineering within the Department of Civil, Environmental and Infrastructure Engineering. His PhD research focuses on the development of improved observation and classification of freeze/thaw processes using remote sensing techniques.

He previously has worked as an Undergraduate Researcher as part of the OSCAR program, and as an Intern with the Alaska Center for Energy and Power. He currently holds the role of Graduate Research Assistant with George Mason University where he has authored multiple articles investigating current freeze/thaw datasets. His research involves the application of remote sensing data to aid in global water resource management, land surface monitoring, and utilizing in-situ data to support and develop more efficient human systems at the city scale. His research interests include the use of multi-scale sensing techniques (satellite, in situ, and UAV) to contribute to the understanding of global hydrologic and energy cycling as well as toward monitoring a changing climate.

For more information on this project, please contact Jeremy at jjohns60@gmu.edu

Paul R. Houser received the B.S. and Ph.D. degrees in hydrology and water resources from the University of Arizona, Tucson, AZ, USA, in 1992 and 1996, respectively.

He is currently a Professor with the Department of Geography and Geoinformation Science, George Mason University, Fairfax, VA, USA, where he is the Codirector of the Center for Energy Science and Policy. He is an expert in local to global land surface-atmospheric remote sensing, in situ observation and numerical simulation, development and application of data assimilation methods, and global water and energy cycling. His research interests include integrating energy and water research across traditional disciplines (e.g., nexuses) that transition theoretical research to academic/public education and real-world application.

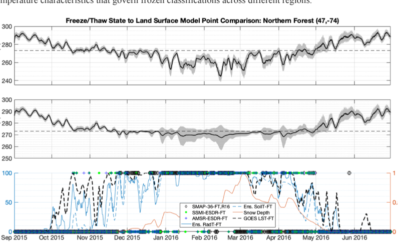
Viviana Maggioni received the B.S. and M.S. degrees from the Politecnico of Milan, Milan, Italy, in 2003 and 2006, respectively, and the Ph.D. degree from the University of Connecticut, Storrs, CT, USA, in 2012, all in environmental engineering.

She is currently an Assistant Professor of Environmental and Water Resources Engineering with George Mason University, Fairfax, VA, USA. In particular, she is interested in the application of remote sensing techniques to estimate and monitor hydrological variables. Her work has direct applications in water resources management, weather and climate prediction, as well as agriculture and irrigation practices. Her research interests include the intersection of hydrology and remote sensing.

Dr. Maggioni is currently a Deputy Chair of the AGU Precipitation Committee and an Associate Editor of the Journal of Hydrometeorology and Journal of Hydrology.

ABSTRACT

Freeze-thaw (FT) processes at the Earth's surface can have a considerable effect on carbon, energy, and hydrologic cycles at a global scale. Therefor an accurate representation of FT is valuable to adequately monitor, understand, and model these processes. Current methods to monitor FT cycles primarily rely on microwave brightness temperature observations via satellites. Existing global FT records, derived from the Soil Moisture Active Passive (SMAP), the Advanced Scanning Microwave Radiometer 2 (AMSR2), and the Special Sensor Microwave Imager (SSM/I) produce relatively course spatial resolution (25-36km) binary FT classifications. In this study, we assess the relationship between satellite-based FT products over North America compared to modeled surface radiative temperature and top-layer soil temperatures (0-10 cm). Additionally, hourly land surface temperature (LST) from the Geostationary Operational Environmental Satellite system (GOES) are also compared to FT classifications. Utilizing the higher spatial resolution of these products (~5km), sub-grid scale variability and its relationship to courser microwave FT classifications is assessed. FT classifications are matched to model outputs and GOES observations by quantifying the proportion of sub-grid cells below freezing within larger FT product pixels. We examine product agreement and the relationship of observed FT state to sub-pixel temperatures to land cover, climate, and topography. Classifications are shown to vary widely depending on these variables, leading to a somewhat ambiguous definition of frozen and thawed states. Additionally, through the analysis of spatial variability and FT uncertainty across North America we compare five focus study pixels – each representing a unique FT profile. The results suggest that current products are able to characterize FT transitions accurately and with a consistent sub-freezing surface characteristic in northerly regions. However, uncertainty associated with FT classifications is shown to increase as latitude decreases. Our results also suggest that fractional FT products, utilizing higher resolution data inputs such as LST, would provide a considerable improvement in mountainous regions with high inter-grid cell heterogeneity, in regions characterized by ephemeral FT events (i.e. regions < 40 °N), as well as during freeze and thaw onset periods. This study provides insight to improving representation of surface FT state by providing a clearer definition of the sub-pixel scale temperature characteristics that govern frozen classifications across different regions.



REFERENCES

H. E. Beck, N. E. Zimmermann, T. R. McVicar, N. Vergopolan, A. Berg, and E. F. Wood, "Present and future Köppen-Geiger climate classification maps at 1-km resolution," Scientific Data, vol. 5, no. 1, Art. no. 1, Oct. 2018, DOI: 10.1038/sdata.2018.214.

S. Dunbar, X. Xu, A. Colliander, K. McDonald, E. Podest, E. Njoku, J. S. Kimball, Y. Kim, C. Derksen, "SMAP - Algorithm Theoretical Basis Document (ATBD) - Level 3 Radiometer Freeze/Thaw Data Products. (Revision B)." 2018.

S. C. Freitas, I. F. Trigo, J. Macedo, C. Barroso, R. Silva, and R. Perdigão, "Land surface temperature from multiple geostationary satellites," International Journal of Remote Sensing, vol. 34, no. 9–10, pp. 3051–3068, May 2013, DOI: 10.1080/01431161.2012.716925.

M. Friedl, D. Sulla-Menashe, MCD12Q1 MODIS/Terra+Aqua Land Cover Type Yearly L3 Global 500m SIN Grid V006 [Data set]. NASA EOSDIS Land Processes DAAC. 2019. Accessed 2020-08-10 from https://doi.org/10.5067/MODIS/MCD12Q1.006

M. L. Goulden, J. W. Munger, S.-M. Fan, B. C. Daube, and S. C. Wofsy, "Measurements of carbon sequestration by long-term eddy covariance: methods and a critical evaluation of accuracy," Global Change Biology, vol. 2, no. 3, pp. 169–182, 1996, DOI: 10.1111/j.1365-2486.1996.tb00070.x.

J. Johnston, V. Maggioni, and P. Houser, "Investigating the Relationship Between Satellite-Based Freeze/Thaw Products and Land Surface Temperature," IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, pp. 1–25, 2019, DOI: 10.1109/JSTARS.2019.2926942.

J. Johnston, V. Maggioni, and P. Houser, "Comparing global passive microwave freeze/thaw records: Investigating differences between Ka- and L-band products," Remote Sensing of Environment, vol. 247, p. 111936, Sep. 2020, DOI: 10.1016/j.rse.2020.111936.

J. S. Kimball, K. C. McDonald, S. W. Running, and S. E. Frolking, "Satellite radar remote sensing of seasonal growing seasons for boreal and subalpine evergreen forests," Remote Sensing of Environment, vol. 90, no. 2, pp. 243–258, Mar. 2004, DOI: 10.1016/j.rse.2004.01.002.

R. S. Kim et al., "Snow Ensemble Uncertainty Project (SEUP): Quantification of snow water equivalent uncertainty across North America via ensemble land surface modeling," to be published.

Y. Kim, J. S. Kimball, J. Glassy, and K. C. McDonald. MEaSUREs Global Record of Daily Landscape Freeze/Thaw Status, Version 4, Boulder, Colorado: NASA National Snow and Ice Data Center Distributed Active Archive Center, 2017. Accessed on: July 16, 2018. [Online]. Available: https://doi.org/10.5067/MEASURES/CRYOSPHERE/nsidc-0477.004.

NASA/METI/AIST/Japan Spacesystems, and U.S./Japan ASTER Science Team. ASTER Global Digital Elevation Model V003 [Data set]. NASA EOSDIS Land Processes DAAC. 2019. https://doi.org/10.5067/ASTER/ASTGTM.003

G.-Y. Niu and Z.-L. Yang, "Effects of Frozen Soil on Snowmelt Runoff and Soil Water Storage at a Continental Scale," J. Hydrometeor., vol. 7, no. 5, pp. 937–952, Oct. 2006, DOI: 10.1175/JHM538.1.

T. L. Rowlandson et al., "Capturing agricultural soil freeze/thaw state through remote sensing and ground observations: A soil freeze/thaw validation campaign," Remote Sensing of Environment, vol. 211, pp. 59–70, Jun. 2018, DOI: 10.1016/j.rse.2018.04.003.

J. B. Shanley and A. Chalmers, "The effect of frozen soil on snowmelt runoff at Sleepers River, Vermont," Hydrological Processes, vol. 13, no. 12−13, pp. 1843–1857, Sep. 1999, DOI: 10.1002/(SICI)1099-1085(199909)13:12/13<1843::AID-HYP879>3.0.CO;2-G.

X. Zhang and S. Sun, "The impact of soil freezing/thawing processes on water and energy balances," Adv. Atmos. Sci., vol. 28, no. 1, pp. 169–177, Jan. 2011, DOI: 10.1007/s00376-010-9206-0.