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Youngwook Kim

John S. Kimball
University of Montana - Missoula

Jinyang Du
University of Montana - Missoula

Joseph M. Glassy

Crystal L.B. Schaaf

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Youngwook Kim[1,*], John S. Kimball[1], Jinyang Du[1], Joe Glassy[2], and Crystal L. B. Schaaf[3]

[1]Numerical Terradynamic Simulation Group, The University of Montana, Missoula, MT 59812; *Corresponding author: youngwook.kim@ntsg.umt.edu

[2]Lupine Logic, Inc., Missoula, MT 59802;

[3]School for the Environment, University of Massachusetts Boston, Boston, MA 02125

UNIVERSITY OF MONTANA

NTSG Numerical Terradynamic Simulation Group

Abstract:

The freeze-thaw (FT) state parameter derived from satellite microwave remote sensing has been linked to changes in surface energy exchange, evapotranspiration, snowmelt dynamics, and vegetation phenology over northern lands affected by seasonal frozen temperatures. However, comprehensive studies of the spring FT transition on snowpack melt, surface energy exchange and vegetation activity over large regions are lacking. In this study, we use a satellite microwave remote sensing record of daily landscape FT dynamics derived at 6-km resolution from 36.5 GHz brightness temperature (T_b) retrievals from the NASA AMSR-E and JAXA AMSR2 sensors. The polar grid FT product is used with other complementary satellite records, including MODIS snow cover extent, shortwave broadband albedo and NDVI phenology to characterize the spring thaw transition season over Alaska for a selected 2004 study period. The satellite observations are corroborated using in situ station networks, including phenocam observations of snowpack depletion. We find that the spring FT transition coincides with a rapid decrease in land surface albedo, snowmelt and snow cover depletion. The increase in net solar radiation accompanying snow cover depletion reinforces surface warming and snowmelt, while the increase in plant-available moisture and available radiant energy coincides with the active growing season onset. The snowpack melt season identified by integrating satellite FT and snow cover records reveals the timing, extent and duration of wet snow conditions and associated shifts in surface albedo and NDVI. These results reveal linkages between FT related snowpack melt onset and associated changes in surface energy partitioning, and vegetation activity. Continuing observations from complimentary satellite sensors also provide for regional monitoring of climate related impacts on the terrestrial energy, water and carbon cycles.

Data and Methods:

AMSR-E/2 enhanced resolution Freeze/Thaw (FT) data record:

- [1]The Northern Hemisphere (NH) FT record was derived from similar, calibrated 36.5GHz, V-polarized (v-pol) overlapping brightness temperature (T_b) records from the NASA Advanced Microwave Scanning Radiometer for EOS (AMSR-E) and JAXA Advanced Microwave Scanning Radiometer (AMSR2); T_b and FT records were derived in 6-km resolution, polar EASE-grid projection format.
- The FT retrieval uses a modified seasonal threshold algorithm ([2]MSTA) that classifies daily T_b variations in relation to grid cell-wise FT thresholds calibrated using surface air temperatures (SAT) downscaled from coarser ERA-Interim reanalysis data using ancillary elevations (DEM) and environmental lapse rates;
- [2]FT classifications are categorized as discrete frozen (0) or non-frozen (1) values from satellite AM and PM overpasses; The AM/PM FT classifications are composited at daily intervals to define Frozen (AM & PM), Non-Frozen (AM & PM), Transitional (AM frozen; PM thawed) and Inverse-Transitional (AM thawed; PM frozen) states.

Satellite Snow Cover Extent (SCE) observations from MODIS:

- Daily SCE (0-100%) observations were acquired from the MODIS/Aqua Snow Cover Daily L3 Global product (MYD10A1, Version 6) at 500m resolution over Alaska; mean SCE retrievals were derived from good-quality (QC) pixels within each 6-km grid cell in polar EASE-Grid format.

MODIS Albedo and NBAR products:

- The MODIS Terra/Aqua Albedo 500m daily L3 Global product (MCD43A3, Version 6) was processed to acquire the mean Albedo of good-quality pixels within each 6-km polar EASE-grid cell and time step over Alaska, including surface shortwave broadband white-sky albedo (WSA) and black-sky albedo (BSA).
- The MODIS Terra/Aqua Nadir BRDF-Adjusted Reflectance (NBAR) daily L3 global 500m product (MCD43A4, V6) was processed by averaging good quality red and near-infrared (NIR) bands at each time step within each 6-km polar EASE-Grid cell over Alaska; NBAR data were used to compute NDVI and fPAR.

Satellite based NDVI and Start of Season (SOS) phenology products:

- The annual SOS phenology over Alaska was derived from the Vegetation Index and Phenology (VIP) NDVI yearly global 0.05Deg product (CMG V004). (https://lpdaac.usgs.gov/dataset_discovery/measures/measures_products_table/vipphen_ndvi_v004)

Definition of snow cover presence and wet snow duration:

- Daily snow cover presence/absence was determined for each 6-km grid cell using the MODIS MYD10A1 SCE record and a 50% threshold;
- [3]Wet snow duration [days] was derived as the duration of FT classified transitional conditions with snow cover (SCE) presence from Jan-Jun 2004 over Alaska. Missing MODIS SCE data were gap-filled using prior day retrievals;

Surface radiation observations used for energy balance analysis:

- The NOAA Climate Data Record (CDR) for Extended AVHRR Polar Pathfinder (APP-x) in 25-km EASE-Grid format (ftp://data.ncdc.noaa.gov/cdr/appx/) was used to derive daily Surface downwelling shortwave radiation (R_dn_short) [w/m[2]] over Alaska.

In-situ snow cover and canopy phenology:

- PhenoCam pictures of local snow cover and canopy phenology for selected Alaska sites were obtained from automated, near-surface daily imaging (https://phenocam.sr.unh.edu/webcam/).

Methods:

(1) NBAR NDVI = $\frac{NIR_{Ref}-Red_{Ref}}{NIR_{Ref}+Red_{Ref}}$, where NIR_{Ref}=NBAR NIR, Red_{Ref}=NBAR Red;

(2) The Amount of absorbed Photosynthetically Active Radiation (APAR)=0.45 * R_dn_short * fPAR, where fPAR≈ $\frac{(NDVI-NDVI_{min})}{(NDVI_{max}-NDVI_{min})}$ (Gutman & Ignatov. 1998. *IJRS*). $NDVI_{max}$ and $NDVI_{min}$ set to 0.95 and 0.05 (Mu et al., 2007. *RSE*);

(3) Blue-Sky Albedo (BLSA) derived as: f_{diff}*WSA + (1-f_{diff})*BSA (Wang et al., 2012. *RSE*), where f_{diff}=diffuse skylight ratio. f_{diff} is assumed as 0.5;

(4) Rsnet=R_dn_short – outgoing shortwave radiation (OSR), where OSR=BLSA * R_dn_short;

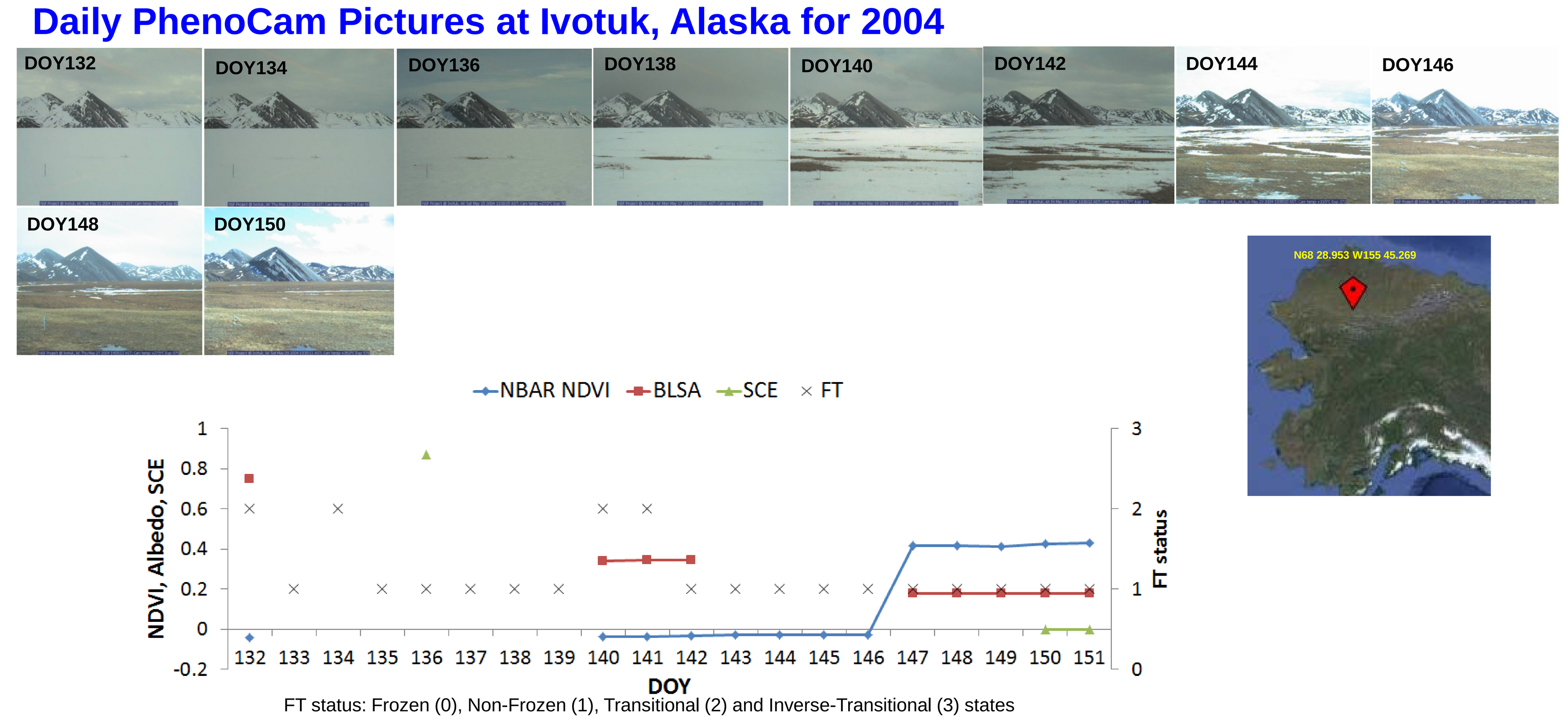
(5) Primary spring thaw date within each grid cell determined as the first day for which 12 out of 15 consecutive days from January to June were classified as non-frozen from the 6km AMSR FT record;

(6) Primary albedo decrease date determined from Optimal Edge detection approach using Gaussian Kernel convolution of daily 6km MCD43A3 BLSA. missing MODIS data gap-filled using prior day retrieval;

(7) Primary NDVI increase date determined from Optimal Edge detection approach using Gaussian Kernel convolution of daily 6km MCD43A4 NBAR NDVI. missing MODIS data replaced with prior day retrieval.

Results:

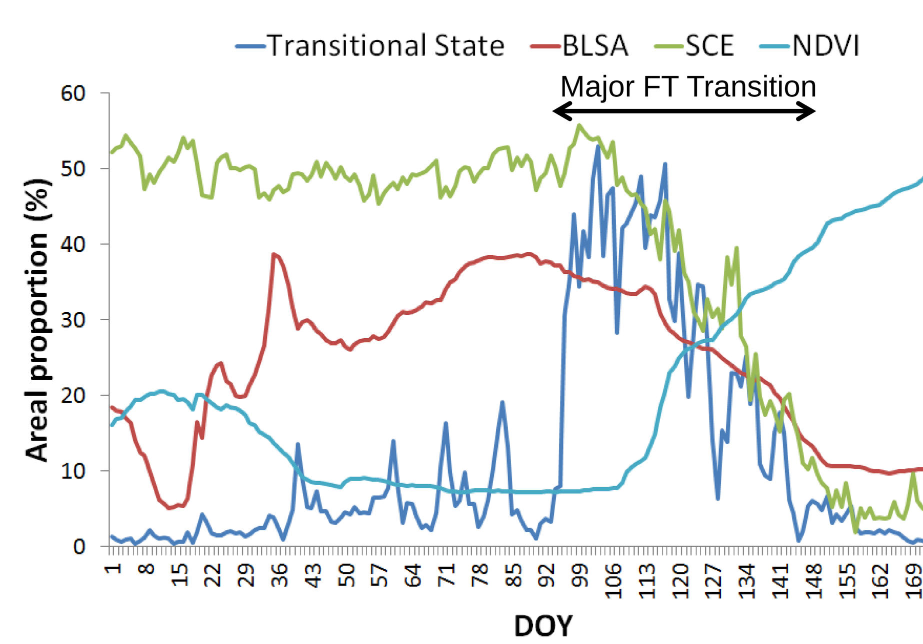
Daily PhenoCam Pictures at Ivotuk, Alaska for 2004

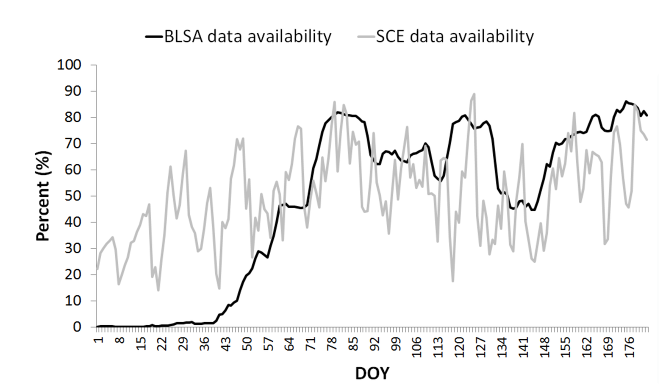


FT status: Frozen (0), Non-Frozen (1), Transitional (2) and Inverse-Transitional (3) states

- The combined satellite observations show that landscape thawing coincides with spring snowmelt and snowpack depletion (**above**); MODIS SCE and BLSA decrease coincides with AMSR FT thawing, which precedes NBAR NDVI spring onset (**left plot**); the satellite observations are also consistent with local phenocam observations of spring snowpack depletion for a selected tundra site (**top** and **lower right**).

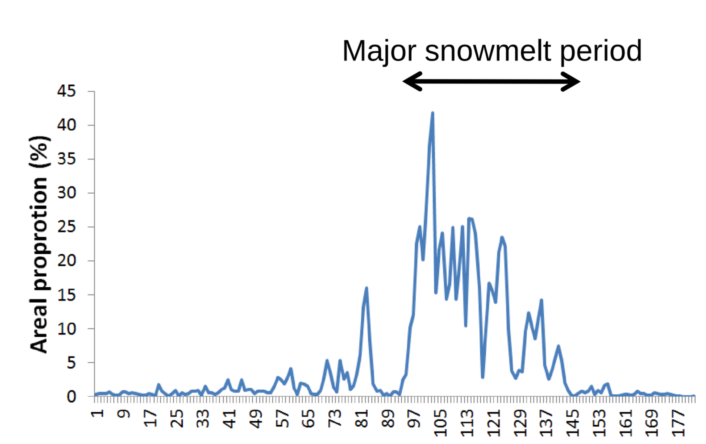
Alaska spring FT transition and areal mean SCE, BLSA and NDVI:



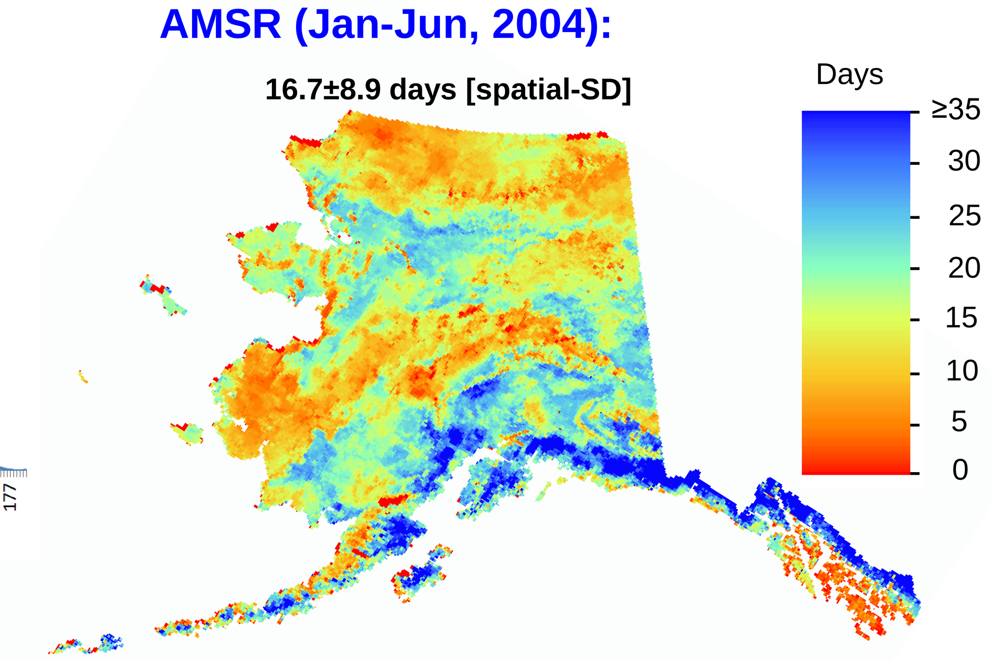


- High MODIS snow cover albedo (BLSA) occurs before the major AMSR FT transitional period;
- FT transitional period (~DOY90-150) coincides with BLSA and SCE decrease, while surface thawing and albedo, and SCE decreases facilitate vegetation (NDVI) spring green-up over Alaska (**left**);
- MODIS SCE and BLSA data availability varies over Alaska with larger data gaps in winter due to persistent clouds and low light levels (**right**).

Alaska areal proportion of daily snowmelt extent for 2004 :

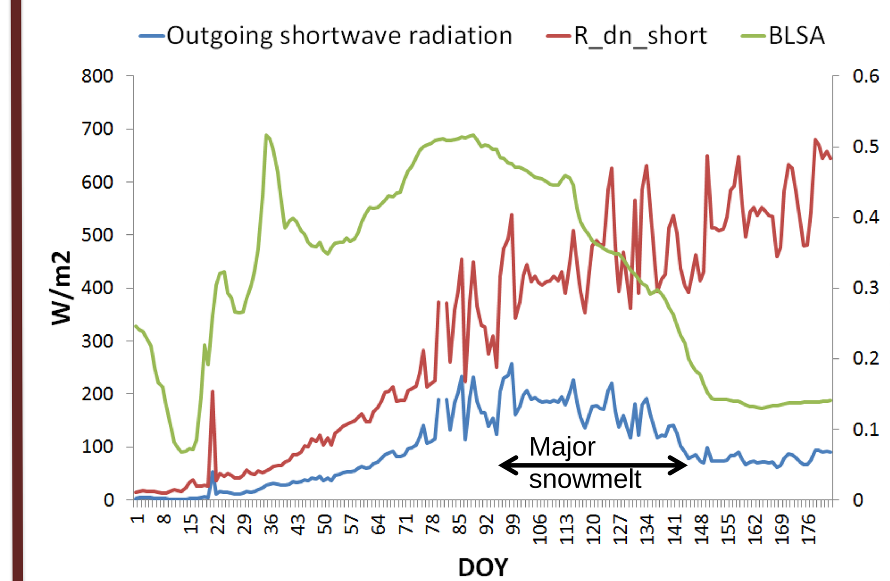


Alaska wet snow duration from MODIS and AMSR (Jan-Jun, 2004):

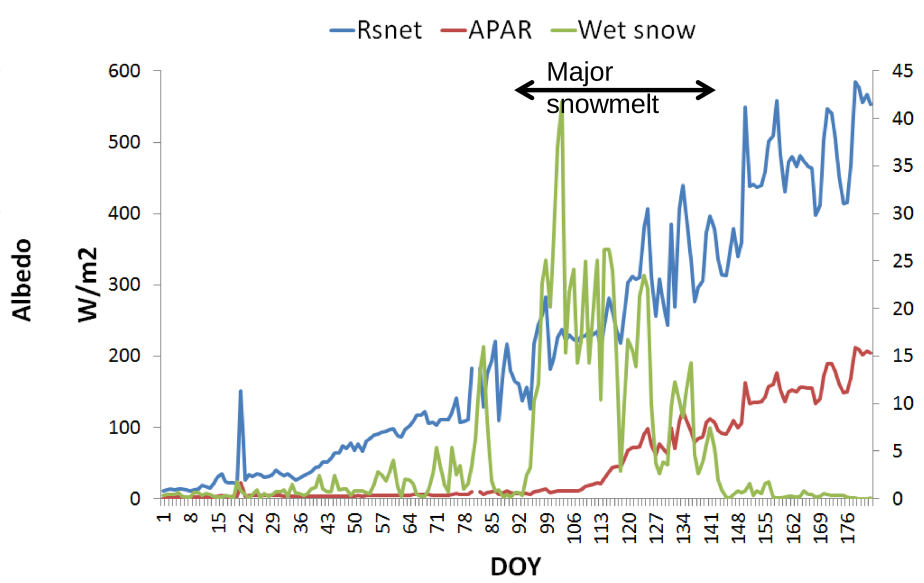


- Daily areal proportion of wet snow conditions from the combined MODIS SCE and AMSR FT records shows extensive snowmelt over Alaska from ~DOY95-145 over Alaska for the 2004 record (**left**);
- The longest wet snow duration occurs in southern Alaska maritime climate zones, characterized by extensive winter precipitation, transient snowcover conditions at lower elevations and relatively deep snowpacks at upper elevations, with frequent thawing and refreezing; other Alaska subarctic and arctic climate zones are characterized by cold, dry winter conditions and relatively shallow snowpacks with a much shorter wet snow period in spring (**right**).

Satellite derived daily mean albedo and surface shortwave energy flux over Alaska for 2004:

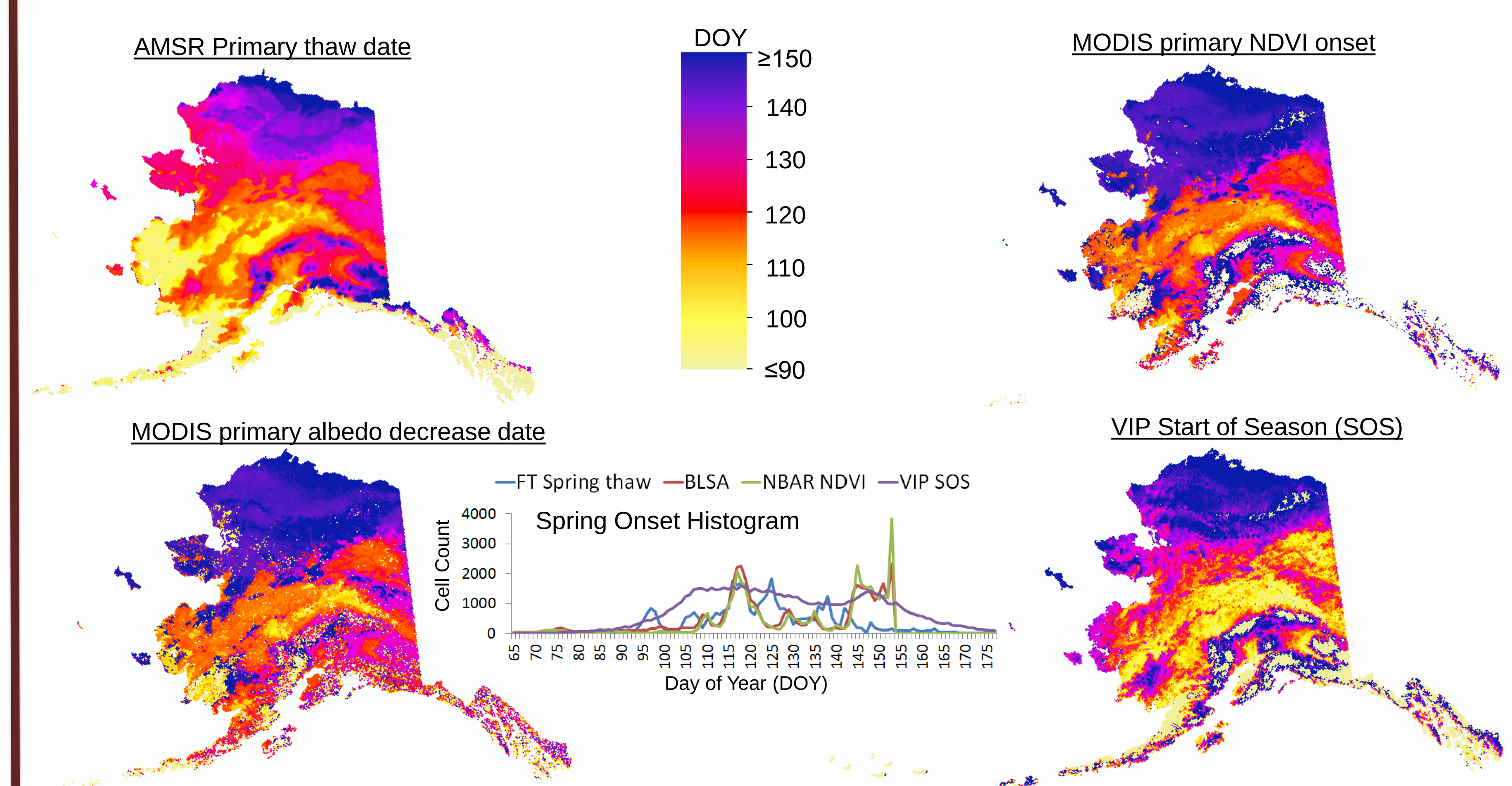


Daily mean net shortwave energy flux, APAR, and wet snow area proportion over Alaska for 2004:



- The active spring snowmelt period coincides with a rapid decline in surface albedo (BLSA); the associated decline in outgoing shortwave radiation occurs despite increased solar radiation (R_dn_short) loading (**left**), which reinforces energy available for melt;
- A rise in surface net solar radiation coincides with an increase in plant-available moisture from snowmelt and canopy APAR to support spring growing season onset (**right**).

Alaska primary spring onset from multi-satellite observations:



- The 6-km AMSR FT record shows enhanced delineation of the spring thaw pattern over Alaska relative to a similar, but coarser (25-km) resolution [2]global FT environmental data record;
- The AMSR primary spring thaw pattern is similar but precedes MODIS BLSA and NDVI changes and SOS.

Conclusions:

- Complementary satellite microwave and optical-IR remote sensing records indicate that the spring FT transition is closely linked to seasonal changes in surface albedo, snowmelt and snow cover depletion, and growing season onset over Alaska;
- The spring thaw onset coincides with snowmelt and a rapid increase in plant-available moisture and net radiation, which initiates and sustains the active growing season;
- Continuing, overlapping and long-term data records from complementary satellite sensors provide for regional monitoring of climate related impacts on the seasonal energy budget and associated water and carbon cycle linkages.

References

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3. **Kim, Y.**, J.S. Kimball, D. A. Robinson, & C. Derksen. 2015. New satellite climate data records indicate strong coupling between recent frozen season changes and snow cover over the high northern latitudes. *Env. Res. Lett.*, 10, 084004.

Acknowledgements

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