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Characterization of Freeze-Thaw Process Heterogeneity with Spaceborne Radar

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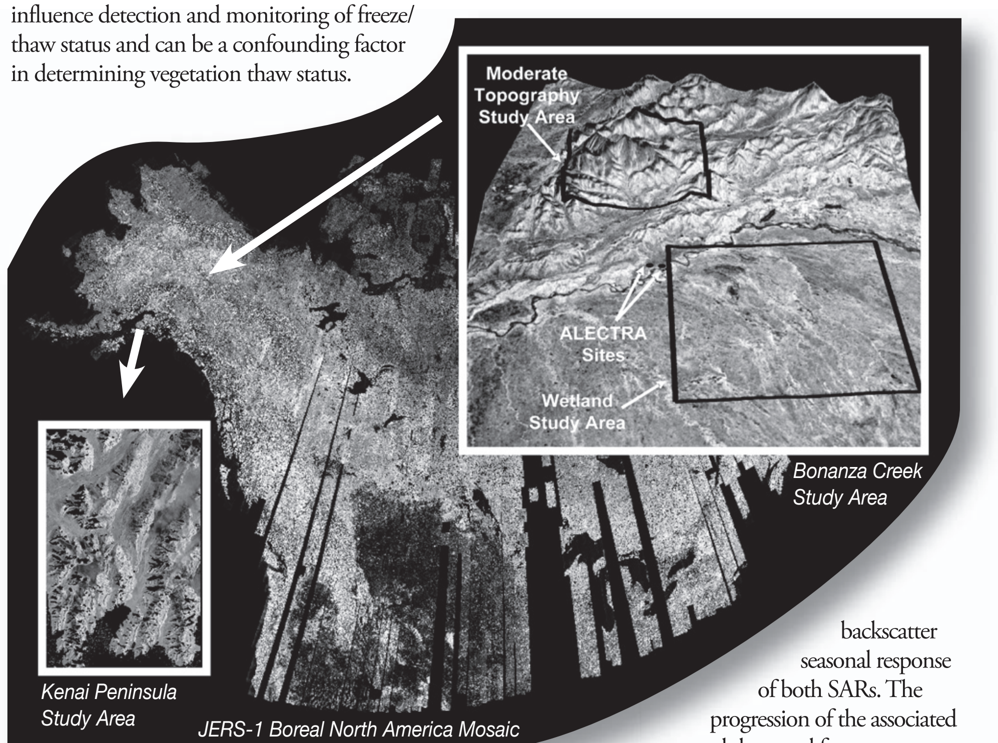
The landmass of the boreal high latitudes encompasses almost 30 percent of the global land area. Within these regions, a major portion of the Earth's carbon is stored in vegetation and in seasonally frozen and permafrost soils. The annual freeze/thaw cycle drives the length of the growing season in these landscapes and is a major factor determining annual productivity and associated exchange of CO_2 with the atmosphere. Accurate characterization of these processes can improve regional assessment of vegetation productivity and seasonal carbon dynamics. Satellite microwave remote sensing is sensitive to landscape freeze/thaw state and is an effective tool for this purpose since large inaccessible areas can be monitored on a temporal basis without limitations imposed by weather or daylight conditions. We have applied time series spaceborne Synthetic Aperture Radar (SAR) imagery from ESA's ERS-1/2 (C-band, 5.4 GHz, VV pol.), and JAXA's JERS-1 (L-band, 1.3 GHz, HH pol.) to assess the freeze/thaw state of the landscape and estimate growing season length.

Variations in seasonal freeze/thaw processes can be spatially and temporally complex. Landscape complexity can affect the timing of seasonal freeze/thaw transitions as a result of local-scale variations in land cover, snow cover, or topography, including elevation and slope aspect. We examined spatial and temporal characteristics of the seasonal freeze/thaw transitions over study areas in the Bonanza Creek and the Kenai Peninsula regions (see accompanying figure). The study areas encompass a variety of landcover classes and regions of low relief and moderate to complex topography within two different climatic zones, boreal continental and boreal maritime. The Bonanza Creek study area included two separate sites, a floodplain wetland site and a moderate topography site. The Kenai Peninsula study area encompasses a region of complex topography. Ancillary validation data, including data from long-term ecological study and other monitoring stations, regional land cover classifications and digital elevation model (DEM) information, were available for each site. JERS-1 SAR data employed were drawn from the data holdings generated as part of the North American component of the Global Boreal Forest Mapping project. The SAR data were radiometrically corrected and, where needed, terrain corrected using ASF's radiometric and terrain correction software. Imagery were processed to 100 meter spatial resolution.

Results show that both C-band ERS-1/2 and L-band JERS-1 backscatter enabled characterization of freeze/thaw transition heterogeneity. However, the presence and status of snow cover strongly influence detection and monitoring of freeze/thaw status and can be a confounding factor in determining vegetation thaw status.



A change detection algorithm that examines the time series progression of radar backscatter relative to seasonal reference states was developed. The freeze/thaw classification algorithm was applied to the multi-temporal SAR data to develop state maps of each study area. Land cover composition, land cover classifications, and DEM information were merged with the SAR maps to examine spatial variability in freeze/thaw state as related to microclimate variations that arise from slope aspect, elevation, and land cover.

At Bonanza Creek, wetland vegetation in the floodplain study area thawed later and froze later than other vegetation classes in the domain. At the moderate topography study area, coniferous vegetation was seen to thaw earlier in springtime than the other vegetation classes. Slope aspect also gave rise to freeze/thaw transition complexity, with south facing slopes thawing earlier and freezing later than north facing slopes. At the Kenai Peninsula study area, snow melt dominated the backscatter seasonal response of both SARs. The progression of the associated seasonal thaw and freeze was clearly visible in the form of a "thaw wave" progressing from lower to higher elevations.

Although current SARs are capable of characterizing the spatial complexity associated with this important biophysical variable, they lack the temporal revisit capability necessary to accurately constrain the seasonality of the associated processes. Current lower resolution satellite microwave sensors (e.g., QuikSCAT, SSM/I) have the potential to resolve the timing of these seasonal transitions at the pan-Arctic scale, however, their ability to accurately resolve the finer (<25 km) spatial scales is less certain. These considerations underscore the importance of a combined temporal and spatial accuracy particularly for complex landscapes. ◆

Assessing the Potential for Wildfire Using ERS-2 SAR Imagery

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Wildfire is a common occurrence in boreal Alaska and natural resource agencies devote considerable resources to fire management and suppression. Currently, these agencies rely on the Canadian Forest Fire Danger Rating System's Fire Weather Index (FWI) for the assessment of the potential for wildfire. FWI is based solely on point-source weather data collected daily in a sparse network across the state of Alaska. Although currently invaluable, there are issues with the FWI system and the agencies recognize a need for improvement. Recent research (NASA grant NAS5-03113) has been conducted to enhance the prediction of wildfire potential in Alaska using satellite C-band (5.3 cm wavelength) synthetic aperture radar (SAR). SAR is sensitive to the moisture content of the features being imaged including vegetation and soils. The relationships between *in situ* soil moisture, C-band backscatter, and fire danger codes have been under investigation for several years at a variety of burned and unburned sites in interior Alaska. Focus has been on recently burned (0 - 7 years) boreal forests because they allow moisture in the organic ground surface layer to be measured directly from a satellite sensor without interference of the forest canopy and because they are a common feature across the Alaskan landscape. Comparisons of unburned forests to adjacent burned forests have revealed similarities in the temporal patterns of *in situ* moisture monitored throughout a fire season. Thus, soil moisture monitored from burned forests may be used as surrogates for unburned adjacent forests.

In our research to improve fuel moisture monitoring for fire danger prediction, we have focused on three approaches: 1) to use C-band SAR to initialize and calibrate the existing FWI codes; 2) to map soil fuel moisture directly across a burned landscape using SAR algorithms developed for different burn severity types; and 3) to map fuel moisture across a landscape using time-series analysis of SAR data. The first two of these approaches have been demonstrated and the third continues to be investigated.

Canadian and Alaskan resource managers have noted issues with the determination of the spring start-up values of one of the FWI codes, drought code (DC). DC is an index of moisture in the lower duff layer and it has a 52 day lag period, thus it is most affected by inaccurate start-up values. Another problem with the DC in Alaska is that of mid-summer variations in measured moisture values within permafrost regions that are not accounted for in the FWI system. We developed an algorithm relating ERS-2 SAR backscatter from recently burned forests to DC. By measuring the ERS-2 backscatter from a burn scar in spring, after snowmelt, we can predict the DC and use this value to initialize the weather-based DC. Figure 1 shows an example of this process for the Fort Greely weather station using ERS-2 backscatter from the neighboring 1999 Donnelly Flats burn. The DC based on the default spring initialization value of 15 is shown as the solid black line of Figure 1. By initializing the code in the spring *Continued on page 4*

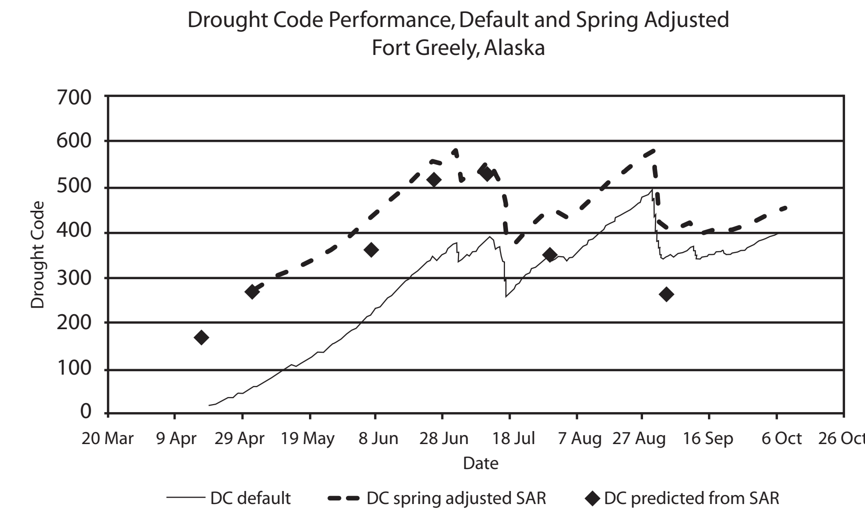
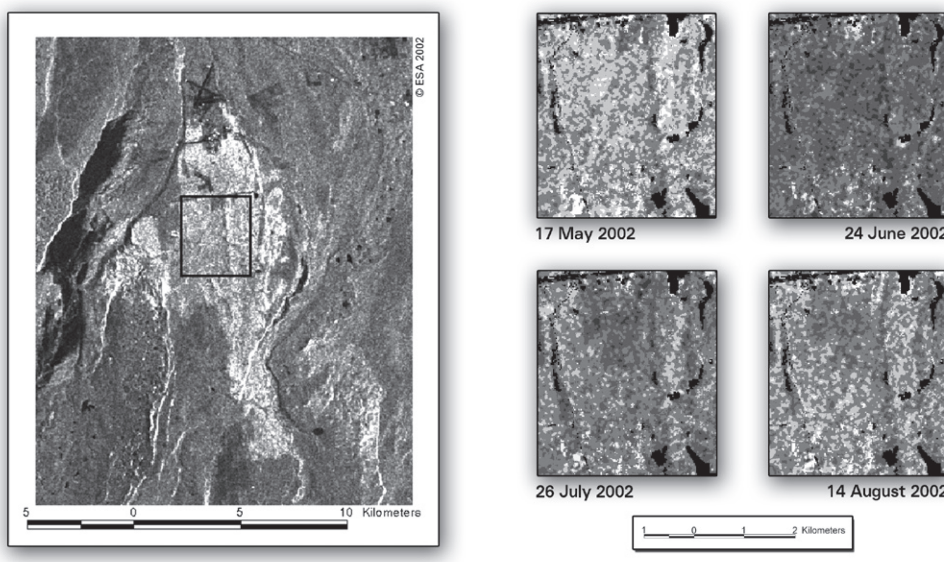


Figure 1. Plot of drought code (DC) values from the Fort Greely, Alaska, weather station using the default spring initialization of 15 (solid line) and the SAR backscatter spring initialization (dashed line). Individual date, SAR-derived, DC values are plotted for verification (diamonds).



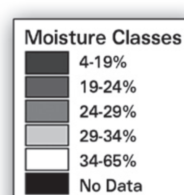


Figure 2. Maps showing individual date patterns of surface soil moisture for the Donnelly Flats 1999 burn. Reference image to left is from 17 May 2002 with black box showing subsetted area. Unburned areas were not mapped and are shown as black in the subset. The entire burn was mapped, but the figure shows an enlarged area for viewing purposes

Use of SAR to Improve Paleo-Climate Investigations at Lake El'gygytgyn, Siberia

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A time-series of more than 450 combined ERS-2, RADARSAT-1, and Landsat-7 scenes acquired between 1998 and 2001 was analyzed to develop a fairly complete picture of lake ice dynamics on arctic Lake El'gygytgyn, NE Siberia (67.5°N, 172°E). This 14 km^3 lake partially fills a meteorite impact crater formed 3.6 million years ago and is home to an ongoing paleo-environmental coring project. The duration of lake ice cover and the onset of lake ice breakup are important both to interpretations of the archived sediment core record and to future drilling projects that will use the ice as a stable platform. Ice formation, snowmelt, and ice breakup were found to occur in late October, mid-May, and early July, respectively (Table 1). These data were used to validate a one-dimensional, energy-balance lake-ice model, which can now be used to hindcast paleoclimate based on core proxy information. SAR backscatter from the lake ice also revealed unusual spatial variations in bubble content that were found to indicate the level of biological productivity in the sediments directly beneath the ice, with the highest productivity located in the shallowest (0 – 10 m) as well as the deepest (170 – 175 m) regions of the lake. The fact that large spatial variations in biological productivity exist in the lake has important implications for selecting the locations of future sediment cores. This article gives an overview of how SAR facilitated these findings; the complete analysis can be found in Nolan, *et al* (2003).

Table 1. Important dates of lake ice dynamics derived from SAR.

Winter	Onset of Lake Ice Freezing	Onset of Lake Ice Snowmelt	Onset of Lake Ice Moat Formation	Completion of Lake Ice Melt
1997-1998	No Data	< 8 July	< 8 July	8 July – 9 Aug
1998-1999	> 6 Oct	17 May – 18 May	24 June – 4 July	28 July – 13 Aug
1999-2000	16 Oct – 19 Oct	8 May – 11 May	23 June – 2 July	16 July – 19 July
2000-2001	18 Oct – 20 Oct	14 May - 17 May	20 June – 23 June	13 July – 17 July

What first caught our interest when analyzing these SAR scenes of the lake was the unexpected area of high backscatter near the center of the lake (Figure 1), reminiscent of a bullseye target. This pattern forms every winter, with only minor annual variations. Our interpretation of this phenomenom is that bubbles accumulate within the lake ice here and act as scatterers, reflecting energy back towards the sensor. As more bubbles accumulate throughout the winter, the backscatter increases, until it finally saturates the signal. Another region of high backscatter exists over the shallow shelves surrounding the deeper lake water. Subsequent field work has confirmed that the pattern of backscatter observed here also matches the distribution and concentration of bubbles within the lake ice. What is causing the bubbles? On the shelves (<5m deep), it is clear that the water is warmer and more life exists here, and it is respiration and decomposition of this life that generates bubbles. The story is less certain for the center of the lake, but our final interpretation was that a thin convective current exists in the lake that brings warm (near 4° C), dense water from the shelves to the deepest part of this bowl-shaped lake. This flow carries with it biota, which are then trapped at the bottom, and either respire or decompose there, leading to bubble formation. That spatial distributions in biological productivity exist within the lake is important to choosing and interpreting a sediment coring location; we hope to recover a 3.5 million climate record from this lake during IPY and have already received approximately half the money required to fund this multimillion dollar international project.

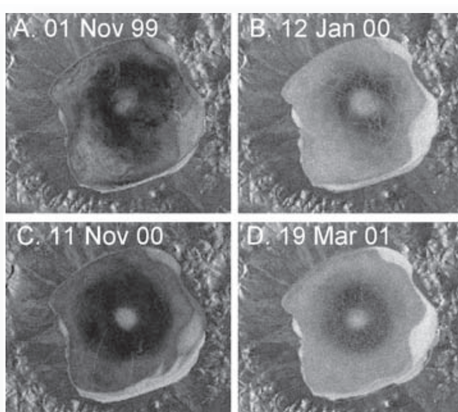

Figure 1. Time-series of SAR scenes from winter 1999-2000 and 2000-2001. Even in the first few weeks of lake ice formation (November), a bullseye pattern can be seen to form in both winters. Year-to-year variations are minor, but in 2000-2001, it can be seen that the bullseye feature was more prominent. The spatial scale of these sub-scenes is roughly 20 km on a side.

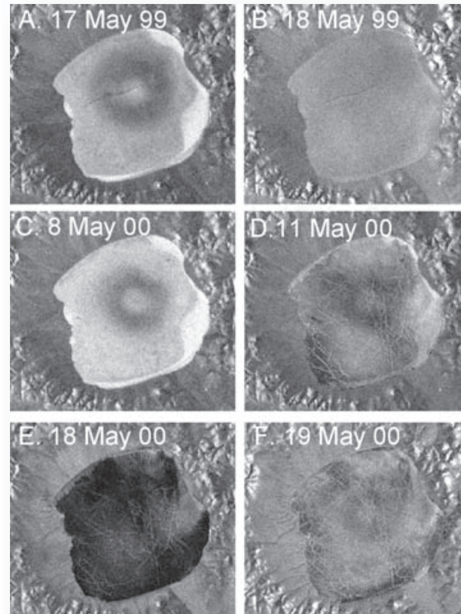

Figure 2. SAR scenes showing snowmelt. The upper two rows of images show that the onset of snowmelt can be determined to within a day, based on the disappearance of the bullseye feature, as described in the text. Freeze events were also observed, as seen in the 18-19 May SAR comparison when the bullseye feature comes partially back into view.

A valuable side benefit to the ice bubble dynamic is that it allowed us to pin down the onset of snow melt to within a day or two each year. Figure 2 shows the onset of snow melt in two different years. What's happening here is that during winter, when the snow is cold and dry, microwaves penetrate through it without much loss, largely reflecting only from the lake ice bubbles below. Once snowmelt begins, however, the liquid water in the snow prevents penetration through it and the backscatter changes remarkably and no longer shows the bullseye pattern representing the lake ice bubbles. We used information like this to construct a history of lake ice formation and decay, which we subsequently used to confirm that the lake-ice model we are using here is accurately representing reality. It seems clear from the biogeochemistry of shallow cores obtained thus far that the lake ice has remained intact for thousands of years at a time in the past. Thus, anything that improves our understanding of lake ice dynamics will aid in core interpretations and SAR has thus far been an important tool towards this end.

Nolan, Matt, et al, 2003. Analysis of Lake Ice Dynamics and Morphology on Lake El'gygytgyn, Siberia, using SAR and Landsat. J. Geophys. Research, 108 (D2) 8062, doi:10.1029/2001JD000934. ◆

Assessing the Potential for Wildfire Using ERS SAR Imagery

continued

with SAR from a 2 May 2004 image (dashed line), the DC jumps from 55.6 to 271, indicating much drier (higher DC indicates drier status) conditions than what weather alone was predicting. SAR-derived DC values are plotted throughout the summer on Figure 1 showing that the new DC curve is more in line with what was observed from the SAR sensor until late July when the SAR sensor shows the site as getting wetter, while DC continues to climb. This dramatic increase in moisture observed in the SAR may be due to melting of frozen ground layers.

The second approach that we investigated was to map spatially varying soil moisture across a burned landscape. To do this, a combination of Landsat and C-band SAR was used. Maps shown in Figure 2 show soil moisture within a burned boreal forest and how it changes over the 2002 summer. The maps were created from ERS-2, C-band imagery using algorithms developed that relate surface soil moisture to ERS-2 backscatter. The technique involves subdividing the burn scar by burn severity class and then applying SAR algorithms developed for each of three burn severity classes (light, moderate, and severe) to convert backscatter to soil moisture. To categorize sites by burn severity to the ground, Landsat data and field collections were used. Dividing the sites in this way reduces errors due to variation in surface roughness, revegetation, and soil type, all of which influence SAR backscatter and all of which are affected by burn severity.

The maps were validated with independent *in situ* data which resulted in an overall 13.1% rms error. This soil moisture retrieval technique represents a first step in landscape scale monitoring of surface soil moisture and research is ongoing to expand to unburned areas. The retrieval of fuel moisture information from SAR imagery represents an innovative technique which would allow fire managers to directly assess the potential for wildfire over large regions at high spatial resolution. Such moisture monitoring has applications not only for fire danger assessment but also for modeling carbon gas exchange, net primary productivity, and assessing possible effects of a changing climate on hydrologic regimes. ◆

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