Distributed Mapping of SNTHERM-Modelled Snow Properties for Monitoring Seasonal Freeze/Thaw Dynamics

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EXTENDED ABSTRACT

The duration and meteorological history of winter and thaw periods in the boreal forest affect growing season duration and net ecosystem exchange (NEE). Forest canopies affect the transfer of energy from above the canopy to the forest floor, exerting important controls on energy, which in turn controls snow cover processes such as melting, densification, grain growth, wetting, and refreezing. These canopies thus affect both the remote sensing signature and the rate of supply of melt water to the soil system. Accurate monitoring of snow condition and forest energy state will detect long-term changes to the boreal forest and provide input for modeling both NEE and landscape hydrological processes. SNTHERM, a one-dimensional mass and energy balance model for predicting snowpack properties and processes (Jordan, 1991), forms the main modeling element of this work. SNTHERM calculates the components of the surface energy exchange and snow properties such as density, grain size, liquid water content and temperature for all snow layers. Previous work integrated SNTHERM with a canopy model to predict and validate the stand scale effects of forest canopy on the snow surface energy exchange (Hardy, et al. 1997; 1998). This work extends the stand scale modelling effort to a regional scale across a portion of central Saskatchewan, Canada. We spatially distribute SNTHERM and integrate it with ERS Synthetic Aperture Radar (SAR) remote sensing data to show the potential of SAR to provide a critical element for extending from local to regional scales. One goal of this study was to quantify the effect of the changing snowpack on the SAR backscatter dynamics, relative to the effect of soil and vegetation freeze/thaw dynamics.

For our modelling effort, we used data from the Boreal Ecosystem-Atmosphere Study (BOREAS), which included meteorological data (Shewchuk, 1997) and stand characteristic data (species, canopy closure, and tree height) available from http://www-eosdis.ornl.gov/BOREAS/boreas_home_page.html. Our approach involved creating a landscape cover classification map representing 54 unique landscapes based on tree species, height, and canopy closure in our 70 by 80-km modelling area in the boreal forest (**Figure 1**). We derived the regional classification map from available BOREAS remote sensing products and forest inventory data and used a segmentation approach as discussed by Woodcock and Harward (1992).

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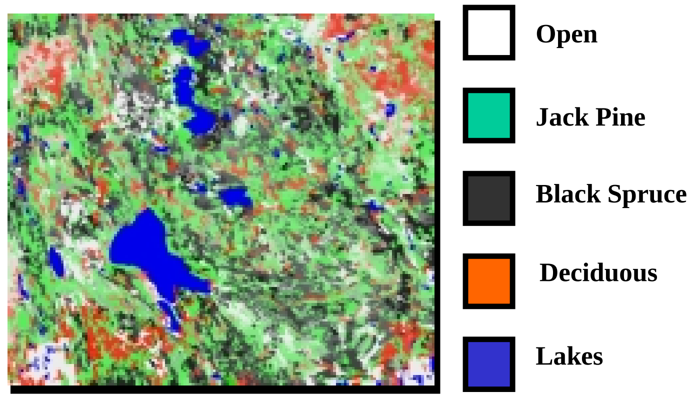

Figure 1. Derived landscape classification map. For the forested sites, the darker the tone the higher the canopy density or the taller the trees.

Spatial variations of energy input to the snowcover are complicated due to topography and forest cover; both which alter the radiation regime, turbulent fluxes, and influence snow distribution and ablation. To accurately model snow ablation in these environments, considerable effort was required to adjust meteorological data to represent the many different environments. For this study, we used meteorological data from stands of jack pine, black spruce, and deciduous aspen. We modified these data for each specific class based on species, canopy closure, and tree height. Li et al.'s (1995) canopy model predicted sub-canopy incoming solar radiation to the snow surface based on above-canopy measurements and canopy geometry. Reflected solar radiation was adjusted to account for forest litter beneath deciduous and coniferous canopies (Hardy et al., 2000). We adjusted wind speeds as measured above the canopy (VaO) to represent the reduced turbulent exchange in the forest according to an equation suggested by Dunne and Leopold (1978); VaF = (1 - 0.8 F) VaO, where VaF is the adjusted wind speed and F is the fractional forest cover (canopy density). Field measurements of snow and soil properties at the time of peak accumulation initialized the model. We ran the model for each landscape class using unique initialization parameters and temporal drivers. The modelling period began on February 23rd and continued through May 1st 1994. Processed output allowed us to spatially distribute the results for each hourly time step of the modelling period. Modelled snow properties distributed and mapped over the region include, depth, surface albedo, temperature, density, liquid water content, and grain size (**Table 1 and Figure 2**).

Table 1. Modelled snow properties distributed and mapped over the region include depth, snow surface albedo, temperature, density, liquid water, and grain size. This table provides the key to the maps below. The images below show change in modelled snow surface properties from February 24 through April 12, 1994.

Property	Description	Unit	Range	Light	Dark
Albedo	Short-wave Albedo	Dimensionless	15 – 71	High	Low
Density	Surface Density	Kg m^{-3}	80 – 890	High	Low
Depth	Snowpack Depth	cm	0 – 34	Deep	Shallow
Temperature	Snow Temperature	K	240 – 274	Cold	Warm
Water	Liquid Water Density	Kg m^{-3}	0 – 40	Wet	Dry

A temporal series of ERS SAR images from spring 1994 of the same site in Canada integrated with this regional-scale modelling of snow properties, allowed assessment of landscape freeze/thaw dynamics on this regional scale (**Figure 3**). The difference between the mid-winter reference image and the temporal series of co-registered images yields change in backscatter relative to frozen conditions (middle row). A threshold-based change detection scheme was then applied to classify the landscape as frozen (black) or thawed (white), as presented in the bottom row. The spatial heterogeneity and the dynamic character of the thaw process are clearly discernable. Significant changes in SAR backscatter occurred between March 1 and 4 as widespread thaw occurred over the region, followed by a freezing event between March 4 and 7. The observed backscatter changes correlated with changes in modelled snow surface properties. Because of the marked difference in the physics of microwave scattering for open-water regions relative to land surfaces, the threshold-based scheme does not accurately classify the thaw transition for lakes. Accurate delineation of thaw dynamics for vegetated and non-vegetated land has been separately validated utilizing in situ measurements of vegetation and soil temperature (e.g. Way et al., 1997). Fusing remote sensing data with snow models allowed detailed characterization of spatial and temporal snowpack dynamics with maps depicting estimates of frozen landscape, thawed landscape, and open water.

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REFERENCES:

Dunne, T. and L. Leopold (1978) Water in Environmental Planning. San Francisco, CA: W.H. Freeman and Co.

Hardy, J., R. Melloh, P. Robinson and R. Jordan (2000) Incorporating effects of forest litter in a snow process model. *Hydrological Processes*, 14 (18): 3227-3237.

Hardy, J., R. Davis, R. Jordan, W. Ni and C. Woodcock (1998) Snow ablation modelling in a mature aspen stand of the boreal forest. *Hydrological Processes*, 12 (10/11): 1763-1778.

Hardy, J., R. Davis, R. Jordan, X. Li, C. Woodcock, W. Ni and J. McKenzie (1997) Snow ablation modeling at the stand scale in a boreal jack pine forest. *Journal of GeophysicalResearch*, 102 (N24), 29,397-29,406, December 26, 1997.

Jordan, R. (1991) A one-dimensional temperature model for a snow cover: Technical documentation for SNTHERM.89, *Spec. Rep. 91-16*, U.S. Army Corps of Eng., Cold Reg. Res. and Eng. Lab., Hanover, N.H.

Li, X., A. Strahler and C. Woodcock (1995) A hybrid geometric optical-radiative transfer approach for modelling albedo and directional reflectance of discontinuous canopies. *IEEE Trans. On Geoscience and Remote Sensing*, 33(2): 466-480.

Shewchuk, S (1997) Surface mesonet for BOREAS. *Journal of GeophysicalResearch*, 102 (N24), 29,077-29,082, December 26, 1997.

Way, J. B., R. Zimmermann, E. Rignot, K. McDonald and R. Oren (1997) Winter and spring thaw as observed with imaging radar at BOREAS. *Journal of Geophysical Research*, 102 (D24), 29,673-29,684, Dececember 26, 1997.

Woodcock, C. and V. Harward (1992) Nested-hierarchiacal scene models and image segmentation. *International Journal of Remote Sensing*, 13(16): 3167-3187.

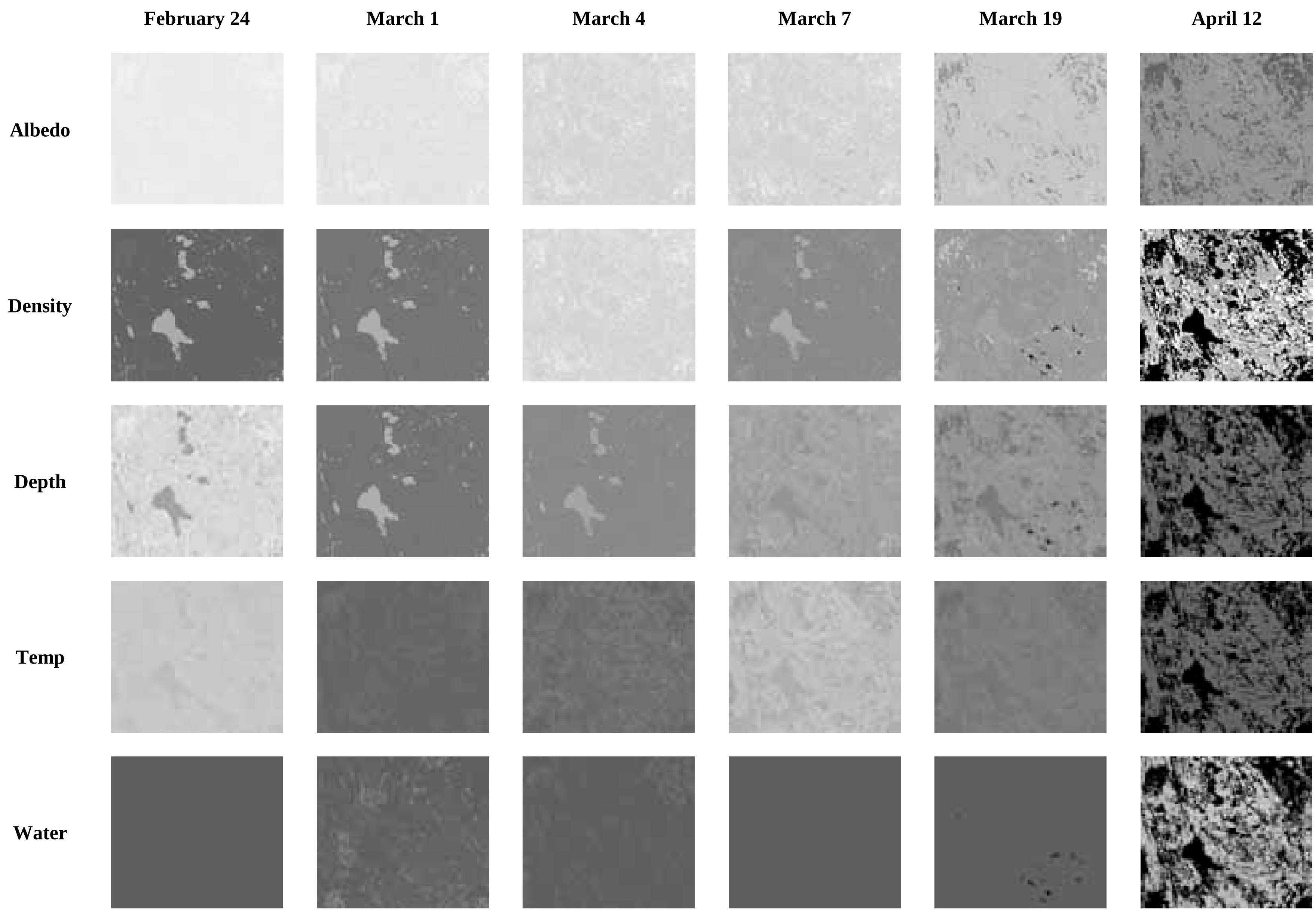

Figure 2. Time series of snow property maps. Table 1 provides the key to the relative value of the grey scale.

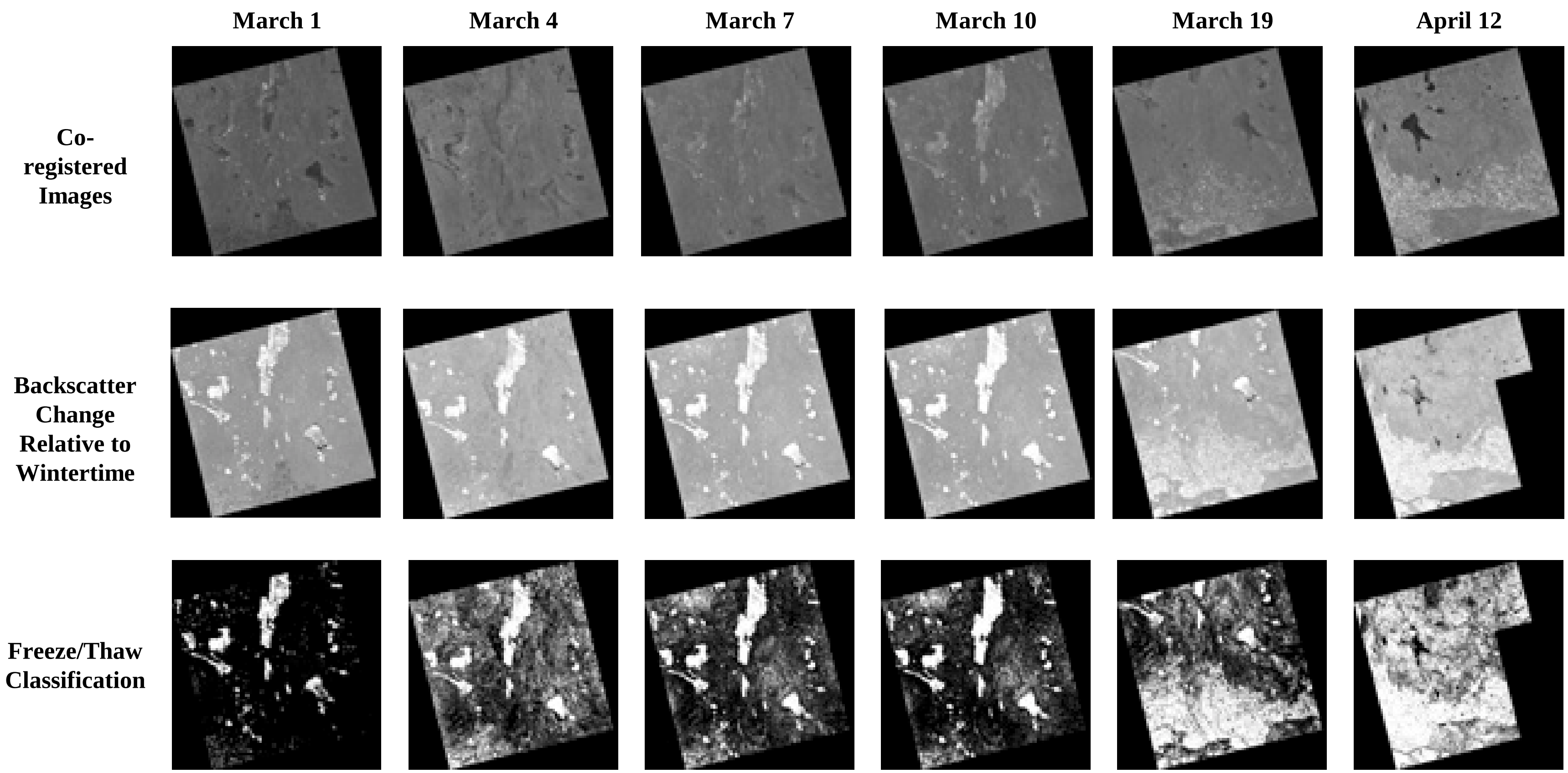

Figure 3. Time series of ERS-SAR images.