

SPATIO-TEMPORAL MONITORING OF PERMAFROST REGION USING SAR REMOTE SENSING

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KEY WORDS: Synthetic Aperture Radar, ASAR Global Monitoring, Permafrost, Freeze/thaw

ABSTRACT:

Due to the high temporal sampling rate of ASAR Global Monitoring (GM) mode, it has a high application potential for analyzing freeze/thaw process in permafrost area. The aim of the study is to develop a robust and rigorous method for monitoring seasonal freeze/thaw cycles beyond the threshold approach. In order to use ASAR GM time series for analyzing freeze/thaw states, a least square fitting of piecewise step function is introduced. The thawing date can be determined by minimizing the sum of squared residuals between measured backscattering time series and a pre-defined step function. An experiment result for Siberian permafrost area illustrates that it can be a promising approach in monitoring permafrost ecosystems.

1. INTRODUCTION

Permafrost covers large areas of the Earth's land surface in the form of either continuous or discontinuous in occurrence. Permafrost ecosystem undergoes drastic seasonal changes due to the temperature variations. Active layer overlies permafrost thaws during the warmest part of the year. Consequently changes in freeze/thaw cycles can be an important indicator of spatio-temporal process of permafrost ecosystem. Although remote sensing of permafrost has been difficult due to overlain active layer, vegetation, and snow covers, several studies have reported on applications of active microwave sensors to detect freeze/thaw transitions in terrestrial ecosystems. Most of previous studies were carried out based on the C- and Ku-band scatterometer measurements due to their global coverage with high temporal resolution.

The C-band scatterometer sensors on board ERS satellites have been investigated for detecting the freeze/thaw states [Boehnke and Wisemann, 1996; Wisemann, 2000]. It provides complete coverage every three days at latitudes above 40° latitude. Studies on freeze/thaw cycles of interior Alaska and Siberia showed that changes in dielectric properties of frozen scatterer results in a decrease of backscatter for all land cover classes. Algorithms to monitor the freeze/thaw of the upper layer of the soils have been developed using the normalized radar cross section (NRCS) at 40° incidence angle. They are based on the change detection approaches that determine backscatter values exceeding the average of summer (thawed) and winter backscatter values.

On the other hand, the Ku-band NASA Scatterometer (NSCAT) data were used to detect freeze/thaw transitions at sites in the BOREAS study area in Canada [Frolking et al., 1999] and in Alaska [Kimball et al., 2001]. NSCAT had a broader swath width than the ERS-1 scatterometer and higher temporal resolution (twice-daily). In case of Ku-band, a strong decrease in backscatter was observed during spring thaw (4–6dB). Again, algorithms to monitor the freeze/thaw transitions using NSCAT were developed based on a temporal change detection of five-

day smoothed backscatter measurements. Although NSCAT operated for only about 9.5 months, a follow-on instrument, the SeaWinds scatterometer on board Quikscat, has similar characteristics to NSCAT. Bartsch et al. (2007) applied Quikscat data to detect thawing state in central Siberia. They developed a rigorous algorithm for detecting thaw events based on significance of diurnal changes during spring thaw. Compared to previous methods which depend on temporal change detection approaches with threshold values, it allows investigation of large regions without calibration by ground data and determination of thresholds.

SAR remote sensing allows Earth observation with high spatial resolution. But due to poor temporal resolution, there have been few studies on the practical application SAR data to detect freeze/thaw processes in the cold regions. The ENVISAT ASAR Global Monitoring (GM) mode can provide several measurements per week with varying incidence angles and 1 km resolution. Due to its high temporal sampling rate, ASAR GM mode has a high application potential for analyzing freeze/thaw process. However, radar backscatter behavior throughout the time series is rather complex and can be interpreted differently depending on the presence of snow and rapidly changing vegetation. The aim of the study is to develop a robust method for monitoring seasonal freeze/thaw cycles beyond the threshold approach. In Section 2, effective methods of extracting onset of freeze/thaw dates of permafrost areas from of ASAR GM data sets are presented. Experimental results on the estimation of freeze/thaw dates are discussed in Section 3. Finally, summary and concluding remarks are presented in Section 4.

2. METHODOLOGY

The selected study site is Yakutsk area of the eastern Siberia which spans from 61°N to 64°N and from 122°E to 133°E as shown in Figure 1. The principal idea is that the freeze/thaw cycles are estimated based on long time series. In order to facilitate the temporal analysis of ASAR GM data, all images

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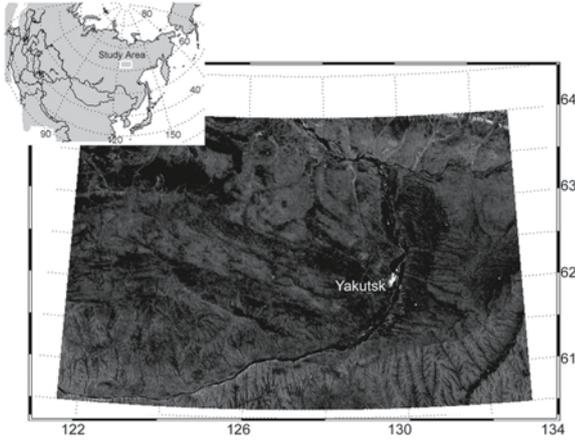


Figure 1. Location of the study area and mean backscattering coefficient of ASAR GM data of the study area.

are resampled to a fixed grid with an interval of 15 arc seconds and stored in time series files. The grid and data structure were designed for global processing. The time series files contain, for each acquisition, the date and time of acquisition, the backscattering coefficient in decibels, and the local incidence angle. Due to the large swath width of GM mode, the incidence angles range between 20° and 40°. Consequently, in the preprocessing step, incidence angle normalization has been applied to remove the incidence angle dependency. Normalization has been carried out by fitting a linear model to the backscatter data [Pathe et al., 2009], to get an estimate of the slope in units of decibels per degree incidence angle which characterizes the decrease of the radar backscatter from near range to far range. The new backscatter values were calculated for a mean reference incidence angle of 30°, such as:

$$\sigma^0(30) = \sigma^0(\theta) - \beta(\theta - 30), \quad (1)$$

Where $\sigma^0(30)$ is the normalized backscatter expressed in decibels, $\sigma^0(\theta)$ is the uncorrected radar backscatter, β is the slope of the regression line of the linear model fitted to $\sigma^0(\theta)$ time series data, and θ is the local incidence angle. Figure 2 shows a time series of GM normalized backscattering coefficient for the grid point of 130.32°E and 63.15°N in the

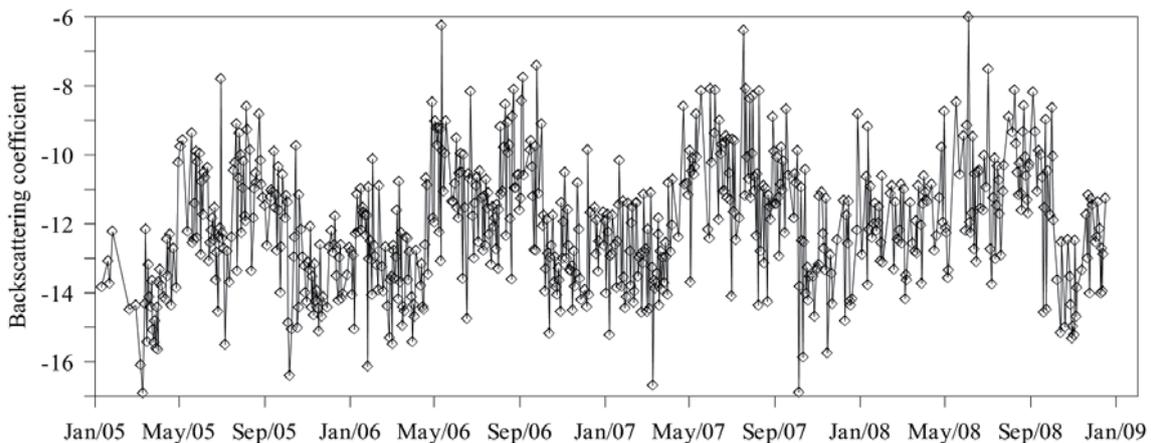


Figure 2. Normalized backscatter time series for two test sites in Yakutsk.

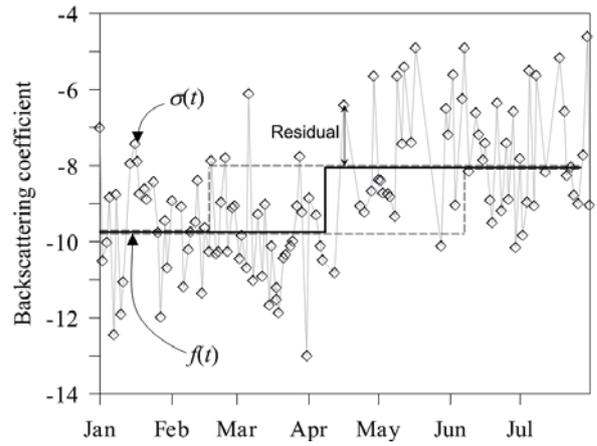


Figure 3. Concept of fitting of piecewise step function to GM normalized backscatter time series.

East side of Lena river. Although time series of ASAR GM data are quite noisy, one can find seasonality in temporal backscattering coefficients. Backscattering coefficients obtained in summer season show higher values than those obtained in winter season. However, temporal change detection approaches with threshold values can hardly be applicable because of the high noise in backscattering time series and fluctuating seasonal backscatter patterns according to different land cover types and climate conditions.

In order to use ASAR GM time series for analyzing spring/autumn transition states, a least square fitting of piecewise function is introduced in this study as shown in Figure 3. A step function for timing spring transition period can be defined as:

$$f(t) = \begin{cases} \sigma_W^0, & t < \tau_S \\ \sigma_S^0, & t \geq \tau_S \end{cases}, \quad (2)$$

where, σ_W^0 and σ_S^0 represent mean values for a winter and summer period, respectively. Then, the spring transition date τ_S can be determined by minimizing the sum of squared residuals:

$$\min[\sum\{\sigma^0(t) - f(t)\}^2]. \quad (3)$$

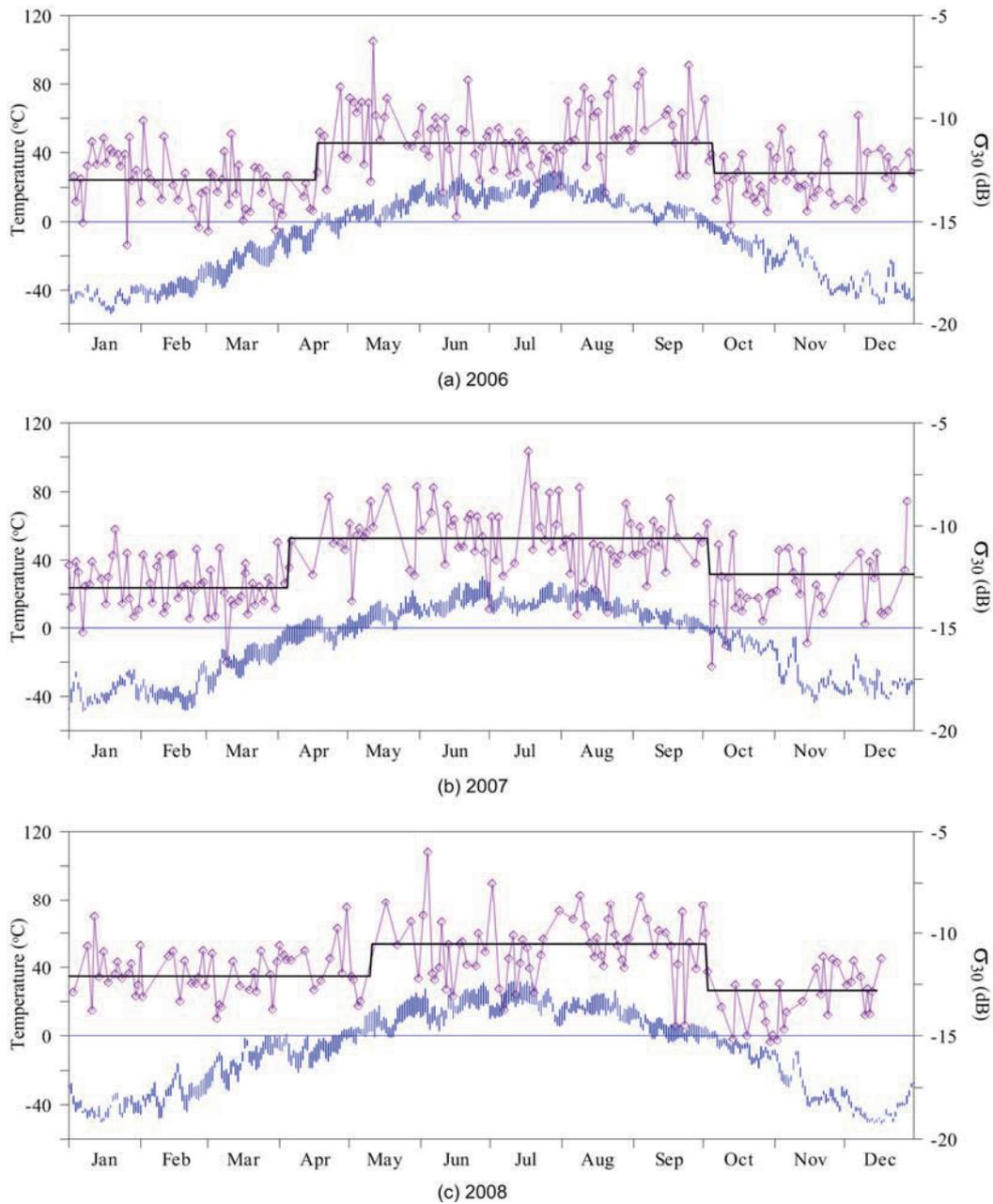


Figure 3. Piecewise function (black line) fitted to ASAR GM time series (red line) given in Figure 2 and nearest ECMWF air temperature data (blue line).

Timing of autumn transition τ_A can be obtained in the same way by fitting a piecewise function $g(t)$ to the GM time series

$$g(t) = \begin{cases} \sigma_S^0, & t < \tau_A \\ \sigma_W^0, & t \geq \tau_A \end{cases} \quad (4)$$

3. EXPERIMENTAL RESULTS

Figure 3 shows examples of determined piecewise function for timing freeze/thaw states of the year 2006-2008 from ASAR GM time series given in Figure 2. For validation of the proposed method, ECMWF (The European Centre for Medium-

Range Weather Forecasts) air temperature data obtained from nearest grid point are also plotted in Figure 3. Dates correspond to a jump discontinuity of the piecewise function indicate seasonal transition inferred in ASAR GM time series, which can be interpreted as freeze/thaw dates in permafrost ecosystems. Estimated freeze/thaw dates reveal good agreements with the general freeze/thaw transition of mean daily air temperatures. Figure 4 shows a preliminary map of the timing of the estimated thawing event for Yakutsk test site of the year 2006-2008 study periods. Early thaw event can be recognized for the year 2007. It is possibly related to the most recent occurrence of El Niño event which started in September 2006 and lasted until early 2007. On the other hand, late spring thaw were observed for year 2008. However, more detailed verification on the proposed method is required for further analysis on evolution of freeze/thaw cycles.

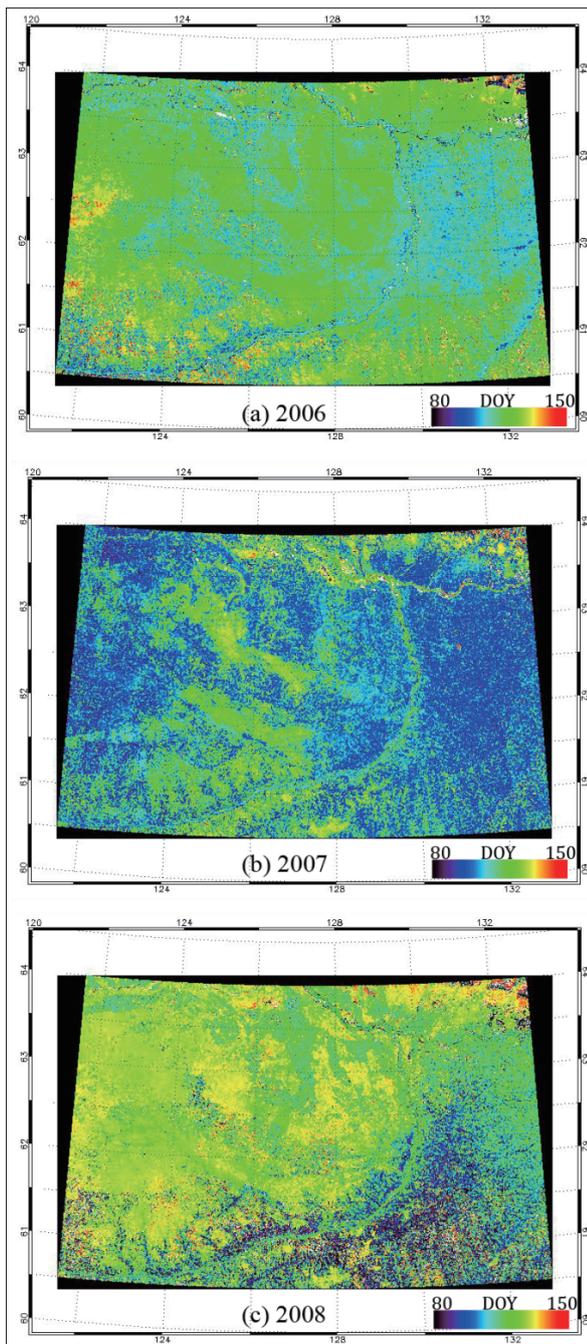


Figure 4. Experimental results of ASAR GM derived maps of the onset of thawing for (a) 2006, (b) 2007, and (c) 2008.

4. CONCLUSION

In this study, an effective method of extracting onset of freeze/thaw dates of permafrost areas from of ASAR GM data sets is presented based on a least square fitting of piecewise step function to the GM time series. An experiment result over Siberian permafrost area illustrates that it can be a promising approach in monitoring permafrost ecosystems. Moreover, the method proposed in this study has a good potential for analyzing temporal changes of any other noisy time-series data sets.

Since the estimated thawing event derived from ASAR GM data are exclusively based on temporal changes of backscatter,

studies on relating radar derived parameters to fundamental environmental processes in permafrost ecosystem should be further evaluated. This paper is a progress report presenting the experimental results carried out in and around the Yakutsk area in the eastern Siberia within the ESA DUE Permafrost project. The capabilities of satellite data with respect to operational monitoring of permafrost ecosystem are continuously been analyzing and further results will be discussed in the near future. Particularly, land cover types of permafrost environment and their temporal evolutions will be investigated on the basis of the classification of multi-modal, multi-frequency polarimetric SAR data sets.

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