A diurnal difference indicator for freeze-thaw monitoring from Ku band scatterometer applied within the Siberia II project.

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Abstract - We present and assess a diurnal difference indicator that is related directly to the seasonal freeze-thaw effects, focusing, in this paper, primarily on the onset of snowmelt and terrestrial thawing. In order to be able to provide a level of certainty with the indicator our approach is based upon the development, and application, of a noise model that accounts for instrument noise, speckle, spatial heterogeneity, "environmental" noise and the influence of azimuth angle at which the measurement was acquired.

Keywords: Freeze Thaw, K_u Band, Scatterometer, Siberia.

I. INTRODUCTION

The seasonal transition from frozen, to nonfrozen, conditions affects a number of terrestrial processes that cycle between winter, dormant, and summer, active, states [1]. Timely information on the state of the frozen- thawed surface may also be of direct benefit for other practical applications such as flood prediction, transportation, construction and oil or gas production.

In this study we focus on the Siberian biome which represents a significant part of the Earth's boreal biome and plays a critical role in the global climate.

The relatively short growing season within these high latitudes is significantly impacted by interannual variability in the onset of freeze and thaw and, within the boreal forest, directly influences atmospheric carbon sequestration in terms of CO_2 exchange. The significantly large Siberian wetland areas provide anaerobic soil conditions which not only allow for long term storage of carbon into histosols [2] but also methane, CH_4, emission during the active vegetation, or thawed period.

The onset of thaw is seen as a major factor that coincides with the boreal zones seasonal switch from a net source to a net sink of atmospheric carbon [3] and is directly relevant in the context of regional and global carbon cycles.

The high temporal sampling of the K_u band scatterometer on the QuikSCAT platform, and reasonable resolution offers the potential to investigate diurnal differences in the dielectric properties of the Earths surface. Sudden observed changes in backscatter intensity during the spring thaw period are related to a change of the scattering mechanism from volume to surface scattering (wet snow, surface water).

The Siberia II project area covers 308 million hectares and includes diverse regions from Taiga, Tundra and Steppe, includes diverse land cover, typography, and climatic zones, and as such offers a unique and challenging environment, and opportunity, to study and understand the physical processes involved in the dynamics of backscatter time series.

II. DATA

SeaWinds is a scanning dual spot beam scatterometer, launched in June 1999 aboard the QuikSCAT satellite [4]. Backscatter measurements are collected simultaneously at constant incidence angles of 46°, inner beam, and 54°, outer beam, with horizontal and vertical polarizations respectively, using a scanning dish antenna operating at 13.4 GHz (K_u-band). The antenna has a footprint size of roughly 25x25 km and scans over a swath of 1800 km, imaging thereby 90% of Earth's surface in one day.

The big advantage of SeaWinds compared to its predecessors is the extremely high temporal sampling rate. At high latitudes towards 75°N data can be acquired daily up to ten times during ascending and descending passes. Even at lower latitudes of 55°N it is possible acquire data 4 times daily. This greatly improves the capability to detect relatively short thawing periods and consequently leads to a better interpretation of the derived freeze-thaw information.

In the course of the Siberia II project [5] a processing chain has been developed and is currently operationally used for the extraction and re-gridding of backscattered measurements from SeaWinds [6]. The extracted data is reformed into time series that are allocated to unique, regular, grid points, with a 10km by 10km grid spacing. The complete Siberia II project area (50°N, 85°E to 75°N, 115 °E) covers approximately 43,000 grid points for which time series of backscattered measurements, currently extending from July 1999 to December 2003, have been generated.

Daily synoptic meteorological data, from the DS512 data set, comprising daily minimum and maximum ambient air temperatures, precipitation and snow depth measurements are available from World Meteorological Organisation (WMO) stations across the project area.

III. INDICATOR AND NOISE MODEL

The characteristics of the seasonal trend of global snow backscatter [7] include two distinct periods at the end of the snow season as the snow melts and there is a rapid decrease in backscatter, σ^0, as the snow cover is depleted and the landscape thaws, increasing permittivity and reflectivity results in an increase in backscatter. At the onset of snow melt diurnal changes in the snow pack, from a wet surface, or lossy wet snow pack, in the evening and refrozen snow pack in the morning, causes strong, up to 6dB [8], diurnal effects. The thaw indicator presented here relies upon the exploitation of this observed diurnal difference in σ^0.

To be able to provide a measure of certainty with this indicator it is necessary to account for all sources that may have an influence upon the indicator, and we therefore need to be able to clearly state that changes seen within the diurnal difference are significant changes and not due to solely to the influence of “noise” like effects.

It is important to be able to characterise these noise like effects for each location (grid point, *gp*) for which diurnal differences are calculated. Previous time series analysis [9] has shown that the backscattering coefficient can be expressed, as in (1) as the sum of its ‘true’ physical value σ_t^0 and a noise term $\sigma_{n,\varphi}^0$,

$$\sigma^0(\varphi) = \sigma_t^0 + \sigma_{n,\varphi}^0 \tag{1}$$

In this context the noise terms accounts for instrument noise, speckle, spatial heterogeneity, “environmental” noise and the influence of azimuth angle at which the measurement was acquired. If two measurements are acquired for the same location (grid point) from the same beam and very close in time (same orbit) our hypothesis is that environmental factors will not have changed significantly during this intervening period. If these two backscatter measures are then subtracted the ‘true’ term, σ_t^0 , is not present in ϑ any longer as it is eliminated by the subtraction. Therefore ϑ only represents the “noise” term as given in (2)

$$\vartheta = \sigma^0(\varphi_1) - \sigma^0(\varphi_2) \tag{2}$$

Since $\sigma^0(\varphi_1)$ and $\sigma^0(\varphi_2)$ are assumed to be mutually independent and normally distributed in the logarithmic dB-scale their difference will also be normally distributed, according to the central limit theorem. An estimate (3) of the standard deviation of the noise term from a population of observations (all 22164 processed orbits) provides a characteristic of the grid point location in terms of instrument noise, speckle, spatial heterogeneity and the influence of azimuth angle.

$$StDev(\sigma^0)_{gp} = \frac{StDev(\vartheta)}{\sqrt{2}} \tag{3}$$

The diurnal difference calculation is given simply by (4) using averaged local mean time morning and evening backscattered values at a grid point, and the thaw indicator is given in (5). The standard deviation used within the threshold is calculated, (6), from the estimation of the standard deviation of the noise for the observed grid point, $StDev(\sigma^0)_{gp}$, (time series location) taking into account the number of observations made with the morning (am) N_{am} and afternoon (pm) N_{pm} periods.

$$\Delta\sigma^0 = \sigma^0 am - \sigma^0 pm \tag{4}$$

$$\Delta\sigma^0 - 3StDev(\Delta\sigma^0) > 0dB \tag{5}$$

$$StDev(\Delta\sigma^0) = StDev(\sigma^0)_{gp}\sqrt{1/N_{am} + 1/N_{pm}} \tag{6}$$

The indicator, in (5), records when the diurnal change in σ^0 is significantly different, at the 99% confidence interval, and not due solely to the influence of “noise” like effects.

IV. EXAMPLE TIME SERIES.

For this paper we have selected a number of backscatter time series that are located at grid points lying within a Tundra landscape, as classified and identified from [10], and are collocated with an active WMO station. The selection of grid points within Tundra locations has been made since available meteorological data only records ambient air temperature and not soil, or surface temperature and selecting Tundra locations ensures meteorological measurements are likely to be directly related to, and provide a closer estimate to surface temperatures.

An extract from an example time series, for a location in the northern Siberian Tundra, is presented in Figure 2. In the top graph significant diurnal difference indicators, that satisfy (5), are noted by a red asterisk and can be seen to be in the order of 2 to 6 dB, as also noted in [7], [8].

The first vertical dashed line in the central graph in Figure 2. marks the approximate start of the snow melt, as confirmed by the rapid decrease in the depth of snow pack. The disappearance of the snow pack, second vertical line, is also noted by a dramatic change in the sense of the indicator, in line with theory presented in [7]. A warming event in early May, with the maximum daily temperature reaching 6°C, is seen to precede the onset of snowmelt, and is also recorded as a significant thaw indicator.

V. SIGNIFICANT INDICATORS

The time series example clearly shows that there is a relationship between the onset of snowmelt, as noted by the increase maximum temperature above freezing, and the decrease in the depth of the snow pack and the occurrence of significant indictors.

The relationship between significant indicators, derived from time series generated over July 1999 to December 2003, and minimum and maximum ambient air temperature has been investigated for 5 grid points, located within the Siberian Tundra, each within 10km of an active WMO station.

Across the region consistent meteorological data is scarce, and generally, for active WMO stations only ambient air temperature measurements (T_{min}, T_{max}) are available. The results are presented as a scatter plot in Figure 1.

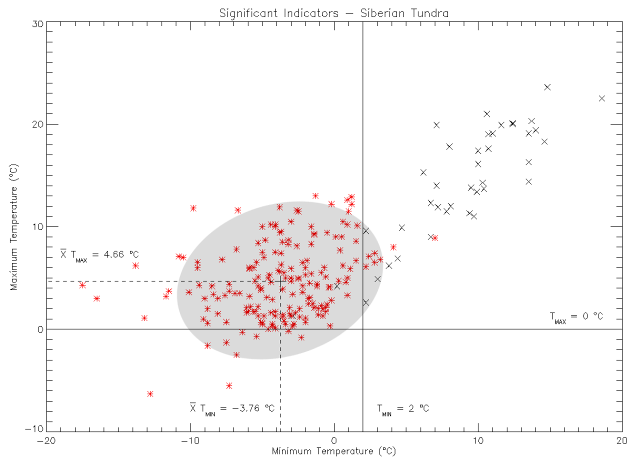

Figure 1. Significant daily difference indicator in relation to maximum and minimum ambient air temperature. Indicator derived over 5 Tundra locations throughout the period 19th July 1999 to 31st December 2003. Crosses (x) denote significant indicators occurring during non Spring period (>1st July and <31st December); asterisk (*) denote indicators occurring during Spring period (>1st January and < 30th June)

For the 5 locations a total of 5313 diurnal differences have been calculated (only significant indicators are presented and considered) of which 223 are significant according to (5). Two distinct clouds of points are noted. The cloud (40 points) in the upper right quadrant relates directly to significant diurnal differences (indicators) occurring in the defined non-spring thaw period and are marked as black crosses. The cloud (183 points) in the mid of the scatter plot relates to indicators observed throughout the winter and spring thaw period. The shaded ellipse describes the boundary of group, the centre determined by the mean of the temperatures, and the spread defined by two standard deviations.

Recalling that the temperature measurements are ambient air temperature, and not surface temperatures, we see that the majority of indicators lie within a clearly defined boundary. During the period, 1st January to 30th June inclusively, the probability of false alarm (Pfa) of observing an indicator, when the ambient air temperatures is outside the range $T_{min} < 2$ °C, $T_{max} > 0$°C, is 8.7%.

VI. CONCLUSION

In this paper we have presented a simple indicator that is sensitive to significant changes in diurnal backscatter. An investigation into the relationship between the occurrence of the indicator and daily minimum and maximum ambient air temperatures for Tundra locations reveals a strong relationship. With the mean values of T_{max} being 4.66 °C and T_{min} being –3.76°C, the indictors describes temperature conditions consistent for the onset of snowmelt.

Since 1999 SeaWinds on board QuikSCAT has, and continues, to provide reliable global observations of backscatter from both ocean and land surfaces. Taking into account the initial short term nature of the QuikSCAT mission which is now coming towards the end of year five of a planned two year mission, and the failure of its successor in October 2003 onboard Midori 2 (formally ADESO II), the future of spaceborne K_u Band Scatterometry is unfortunately somewhat uncertain.

VII. ACKNOWLEDGEMENTS

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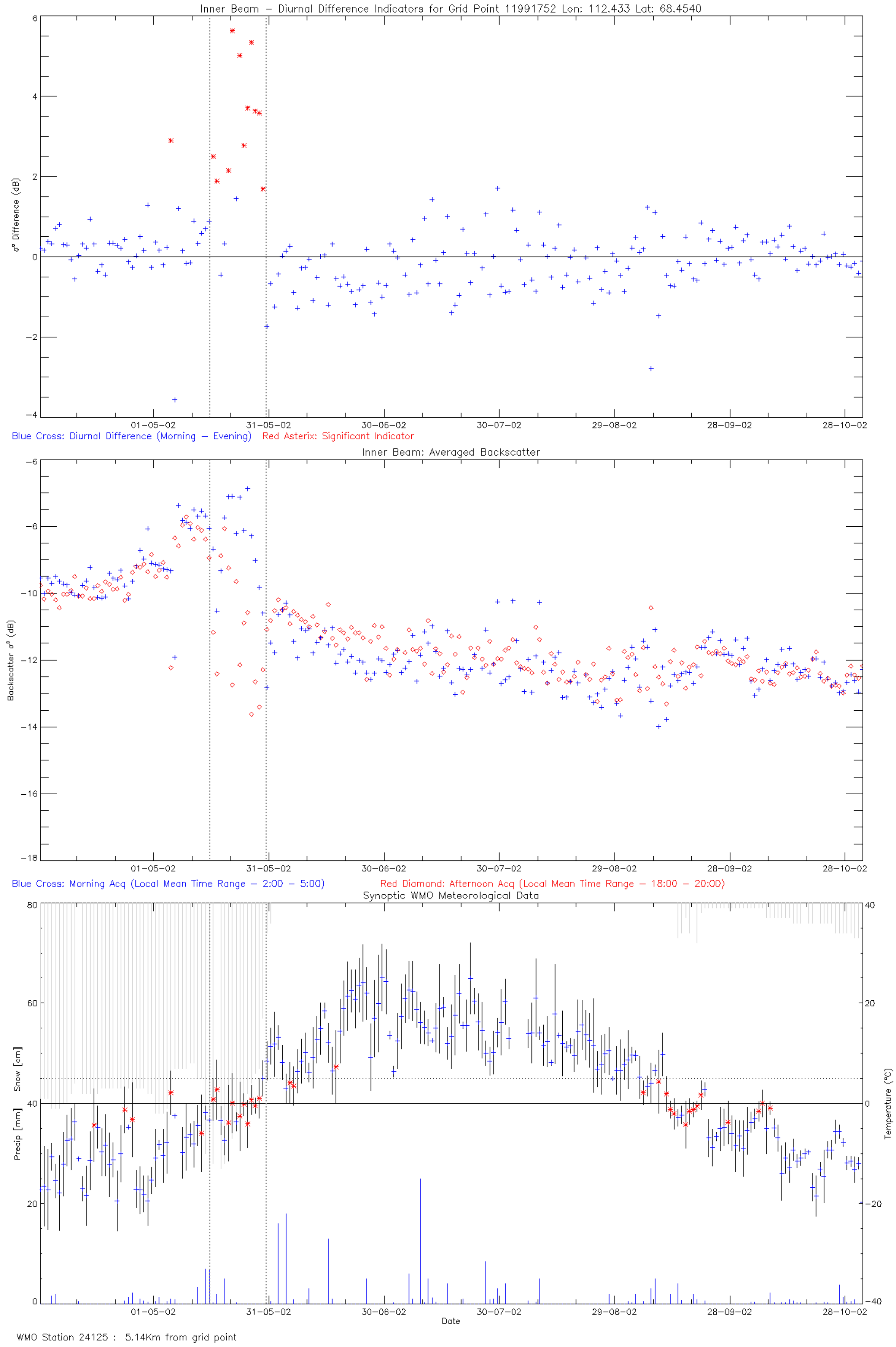

Figure 2. Backscattering coefficient σ^0 in decibel and meteorological time series for a Tundra region in Northern Yakutiya (112.4°E, 68.5°N). Bottom: synoptic meteorological data (minimum/maximum ambient air temperature, precipitation and snow); Center: Inner Beam K_u-band σ^0_{HH} morning acquisitions, local mean time range 02:00 to 05:00 (blue crosses), σ^0_{HH} evening acquisitions, local mean time range 18:00 to 20:00 (red diamonds); Top: diurnal difference morning and evening σ^0_{HH} acquisitions (blue crosses) – significant indicator red asterisk. Vertical dashed lines are a visual guide to mark the start and cessation of the observed decrease in snow pack