Determination of the Freeze/Thaw Surface State from ERS-2 Backscatter Data

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Summary: The freeze/thaw cycle of the Earth's surface determines the timing and the length of the vegetation growing season. Applications like permafrost monitoring and climate studies require information on the freeze/thaw state, however, conventional methods such as temperature records from in-situ stations are often severely hampered by the low density of weather stations. In order to obtain a global dataset of the freeze/thaw cycle, satellite remote sensing methods provide a good means since their observations of albedo, temperature or backscatter can be used to infer surface freeze/thaw state. The aim of this work was to derive freeze/thaw state from backscatter measurements by the scatterometer on-board the European Remote Sensing satellites. The results were validated against different soil models and in-situ networks.

1. Introduction

About 50 million km^2 of the terrestrial northern hemisphere experience seasonal surface freezing and thawing processes. Globally, about two thirds of the Earth's landmasses are subject to this phenomenon. The freeze/thaw cycle of the Earth's surface determines the timing and the length of the vegetation growing season and has a high impact on the land-atmosphere carbon dioxide exchange. It affects seasonal snowmelt and associated soil thaw, runoff generation and flooding, ice break up in large rivers and lakes, and trace gas dynamics (KIMBALL et al. 2001). For applications like permafrost monitoring and climate studies, information on the freeze/thaw state of the surface is highly valuable.

It is therefore important to monitor the changes between the surface states. Conventional methods such as using temperature records from in-situ stations are often severely hampered by the low density of weather stations, especially in Canada and Siberia. In order to obtain a global dataset of the freeze/thaw cycle, satellite remote sensing methods provide a good mean since their observations of albedo, temperature, snow coverage or backscatter can be used to infer surface freeze/thaw state.

The Remote Sensing research group at TU Wien has developed methods to retrieve global freeze/thaw states of the Earth's surface from backscatter measurements obtained from microwave scatterometers (NAEIMI et al. 2012). The algorithm for the retrieval of the surface state was originally developed for data from the Advanced Scatterometer (ASCAT), covering the period from 2007 until present. Since geoscientific studies require data from different periods, it's desirable to have long time series available.

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The aim of this work was to investigate if the ASCAT surface state algorithm can also be applied on data from the scatterometer (ESCAT) on-board the European Remote Sensing (ERS) satellites in order to obtain prolonged freeze/thaw time series, despite the lower amount of available observations because of limitations in the observation geometry and technical problems during the mission. The algorithm requires a certain amount of observations under different conditions in order to derive a surface state, which made the data availability the largest factor of uncertainty when starting the work on the algorithm adaptation.
In the following, the algorithm behind the surface state determination will be explained, along with results for different climate and land cover regions. The results were validated against soil and surface temperature data from the Global Land Data Assimilation System (GLDAS) and in-situ networks, as well as against arctic freeze/thaw soil state from the National Snow and Ice Data Center (NSIDC).

2. Determination of the Surface State

The calculation of the surface state flag is done using a threshold-analysis method. In a first step, backscatter values normalized to a common incidence angle are compared to the ERA Interim surface temperature dataset in order to derive the so-called freeze/thaw parameters. In most cases, the relationship between the two datasets follows a certain trend: In winter, when the soil moisture is lower and the soil is frozen, backscatter values are lower than in summer, where a high soil moisture dominates most landscapes. However, this behavior varies depending on climatic conditions and land cover. If possible, a logistic function is fit to all observations between -10°C and +10°C, from which the freeze/thaw parameters can be derived.

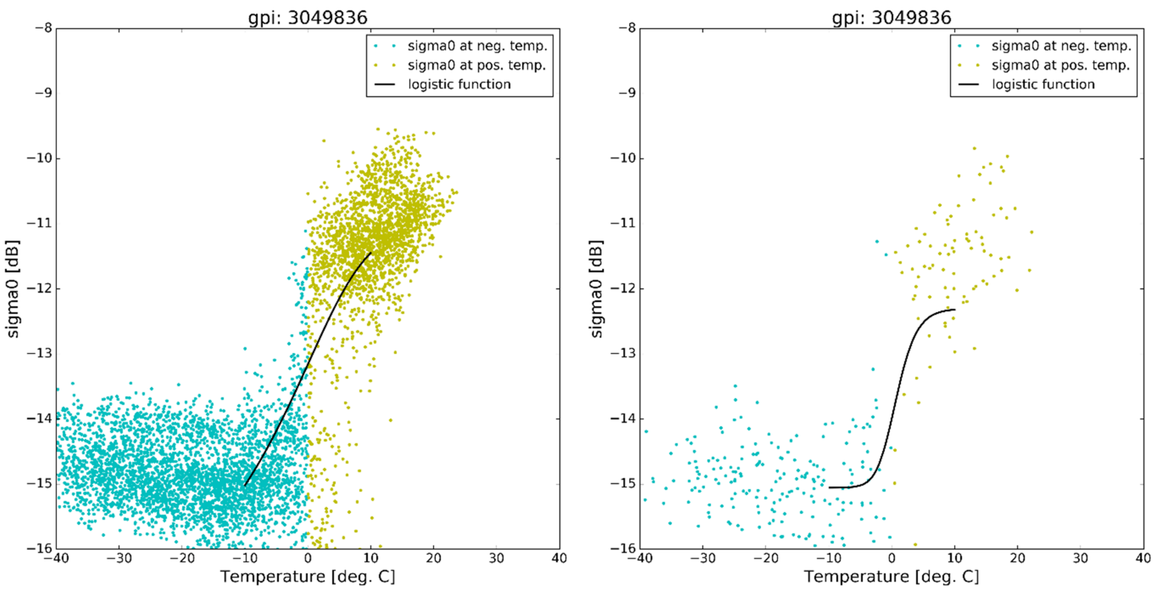

Fig. 1: Behavior of normalized backscatter against ERA Interim surface temperature for a grid point in Alaska, Happy Valley. (left: ASCAT, right: ESCAT)

A typical example for the backscatter-temperature relationship at higher latitudes is shown in Fig. 1. The chosen grid point is located in the Happy Valley, Alaska, at 69.16° northern latitude and 148.84° western longitude. This area shows low backscatter values in winter due to frozen soil, and high backscatter values due to vegetation growth and high soil moisture in summer. The two images show all ASCAT backscatter measurements from 2007-2013 (left) and all ESCAT measurements from 1997-2003 (right), respectively. The difference in the amount of observations is clearly visible. The logistic curves are displayed in black in the figure.

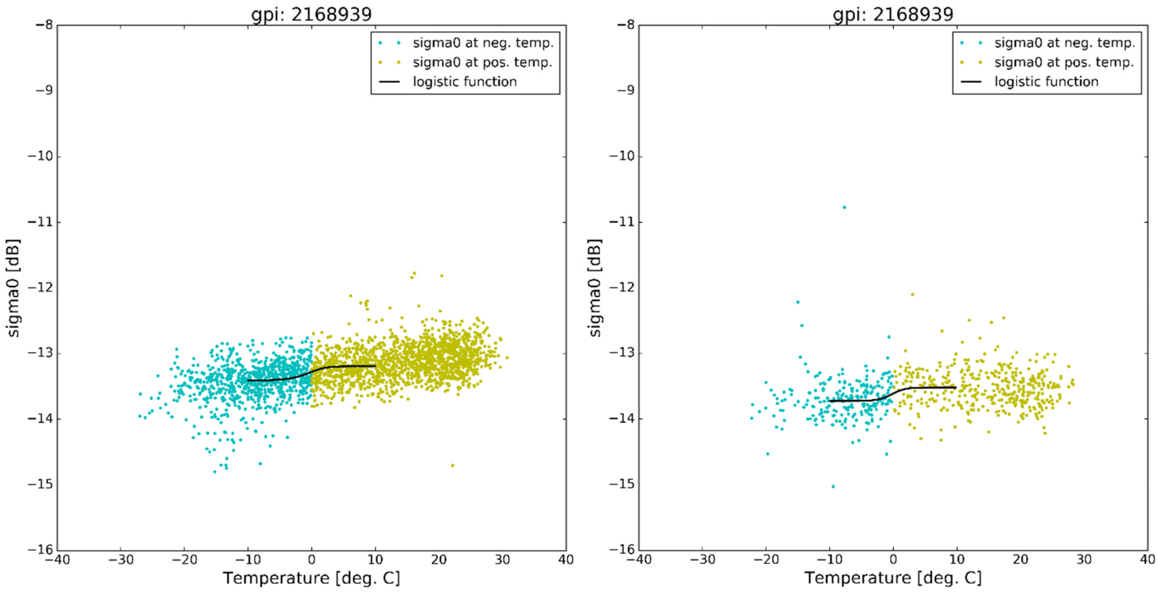

Fig. 2: Behavior of normalized backscatter against ERA Interim surface temperature for a grid point in China, Mazong Shan. (left: ASCAT, right: ESCAT)

An example where the discrimination of frozen and unfrozen soil is almost impossible is a grid point in Mazong Shan, in the Gobi desert (41.76° northern latitude, 97.25° eastern longitude, Fig. 2). This area is characterized by an extreme climate with very cold winters and very hot summers, with temperatures ranging from -40°C to +40°C. The soil is extremely dry and there is no vegetation cover due to very low precipitation. Since the backscatter values from dry and frozen soil are about the same level, surface state changes are not clearly observable in this region.
If it is possible to fit a logistic curve, a set of parameters can be derived that are later used in the threshold-analysis. Those parameters include the mean backscatter level in summer and winter, the freeze/thaw threshold, which is found by calculating the inflection point of the logistic function, and the days of the year when the transition between winter and summer and summer and winter happens.
Those freeze/thaw parameters are then used to set up decision trees for the determination of the surface state flag (SSF). The SSF can take on the following values, which are displayed in the given color in the following:

- unfrozen (yellow)
- frozen (cyan)
- snowmelt/water on surface (green)
- permanent ice (purple)
- unknown (grey)

Fig. 3 shows the decision tree, which checks the observed backscatter value (σ_{40} in the figure) with six thresholds that are previously defined using the freeze/thaw parameters. Based on the season in which the backscatter value was observed, the decision tree returns the SSF.

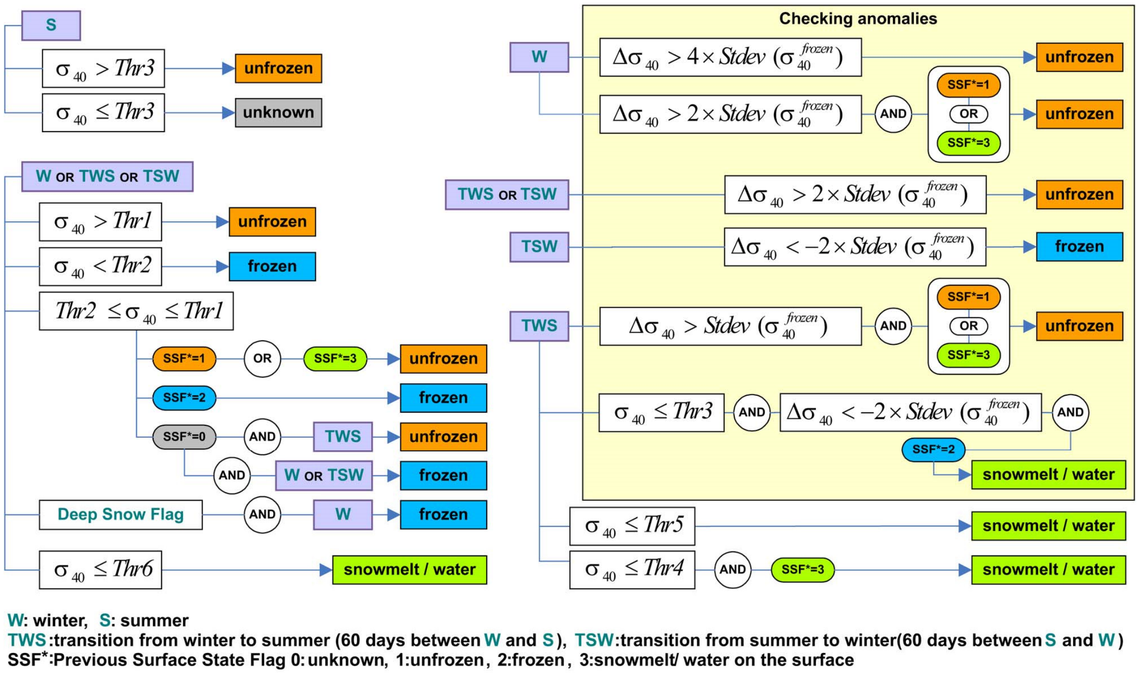

Fig. 3: Decision tree which returns the SSF for an observed backscatter value normalized to 40° incidence angle (σ_{40}) (NAEIMI et al. 2012)

The first run of the SSF algorithm with ESCAT backscatter data produced incorrect results. The main reason for these results were differences between the ASCAT and ESCAT input data format. After some adaptation of the code that does the data handling, the output for ESCAT SSF time series looked promising and the analysis and validation of the results was started.

3. Results of the Surface State Flag Determination

Fig. 4 shows example time series of surface states for a grid point in Russia, derived from ASCAT (left) and ESCAT (right), respectively. The grid point is located at 54.58° northern latitude and 36.73° eastern longitude in an area dominated by cold continental climate without a dry season, covered mostly with croplands. The SSF time series show very good agreement with the corresponding backscatter time series and the minimum and maximum temperature curves from the Met Office Hadley Centre (CAESAR et al. 2006).
Different climate and land cover regions were selected to compare the ESCAT surface state flags with those retrieved from ASCAT backscatter data. The overall outcome shows very satisfying results, contradicting the expectation that the low data availability might prevent a successful determination of the surface state from ESCAT data.

In order to obtain an impression not only for one grid point at a time but for a larger area, the SSF time series are plotted region-wise, meaning that the SSF time series of all grid points of one 5° x 5° region ("cell") are displayed above each other.

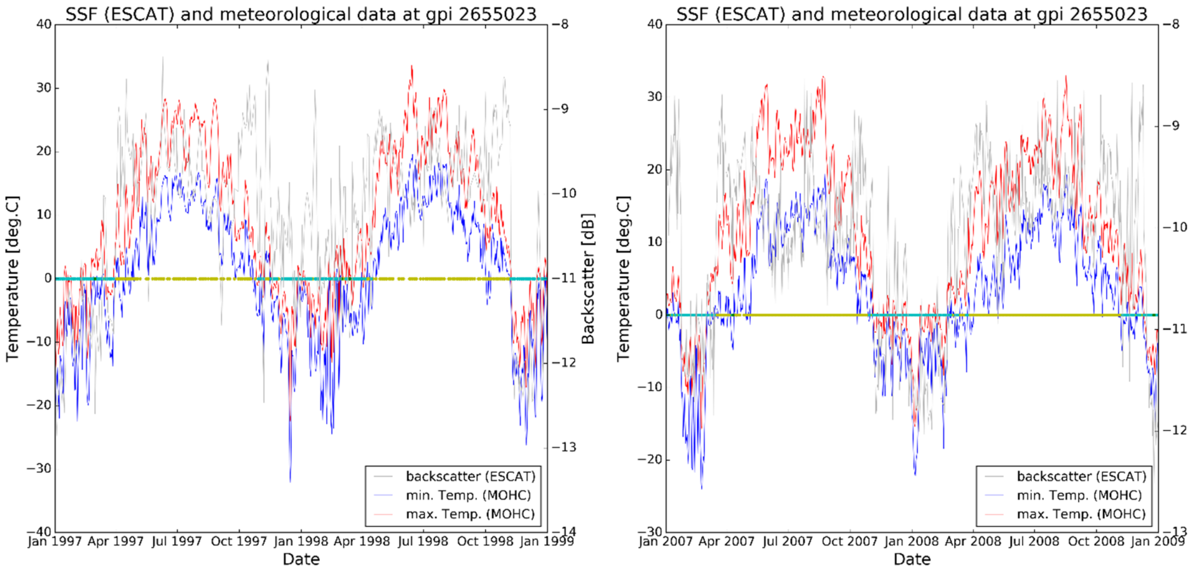

Fig. 4: SSF time series from ASCAT and ESCAT data compared to the corresponding backscatter data from ASCAT and ESCAT and minimum/maximum temperature data from the Met Office Hadley Centre

Fig. 5 and Fig. 6 show the location and results for a region in northern Canada (70-75° northern latitude, 110-115° western longitude; cell 500). The land cover in this area mainly consists of grasslands, only some smaller areas show barren or sparsely vegetated land. According to the Koeppen-Geiger climate map, the region is dominated by polar Tundra climate (PEEL et al. 2007). The surface is frozen for most time of the year, only during summer there is an unfrozen period of about two-three months. A few grid points show only frozen conditions throughout the year. Before every unfrozen period, most of the grid points show a melting period of about two weeks. In some parts of the area, the frozen period is interrupted by short-term melting events.

The Surfaces State Flags derived from ASCAT and ESCAT data show very similar patterns. In the ESCAT results (Fig. 6, left), the data gap due to a failure of the gyroscopes is visible from 2001 onwards.

Fig. 7 shows the location of a selected region in temperate climate in northwestern Germany, the Netherlands and Belgium (50-55° northern latitude, 5-10° eastern longitude; cell 1360). This region experiences warm summers and no dry season, and is characterized by heterogenous land cover, including mixed forest, croplands, natural vegetation mosaics, and urban areas. The heterogenous land cover reflects as vertical changes in the two plots shown in Fig. 8, that means that there are visible differences in the surface state between the different grid points. The frozen period lasts about two months in this region. This long duration is unexpected due to the influence of the Gulf Stream on the climate of the area surrounding the North Sea. However, the SSF algorithm is designed to flag untrusted soil moisture values, which are retrieved from backscatter values that might have been measured over frozen soils. The risk of flagging too many values is accepted in order to provide a reliable soil moisture product.

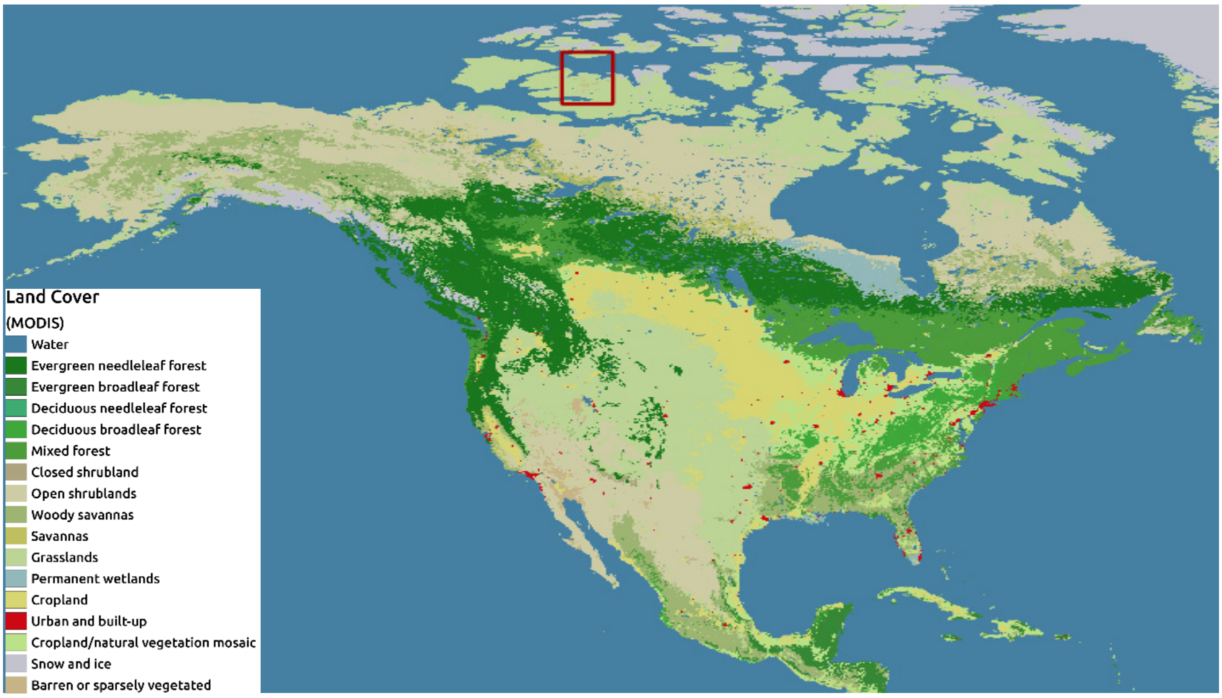

Fig. 5: Location of cell 500

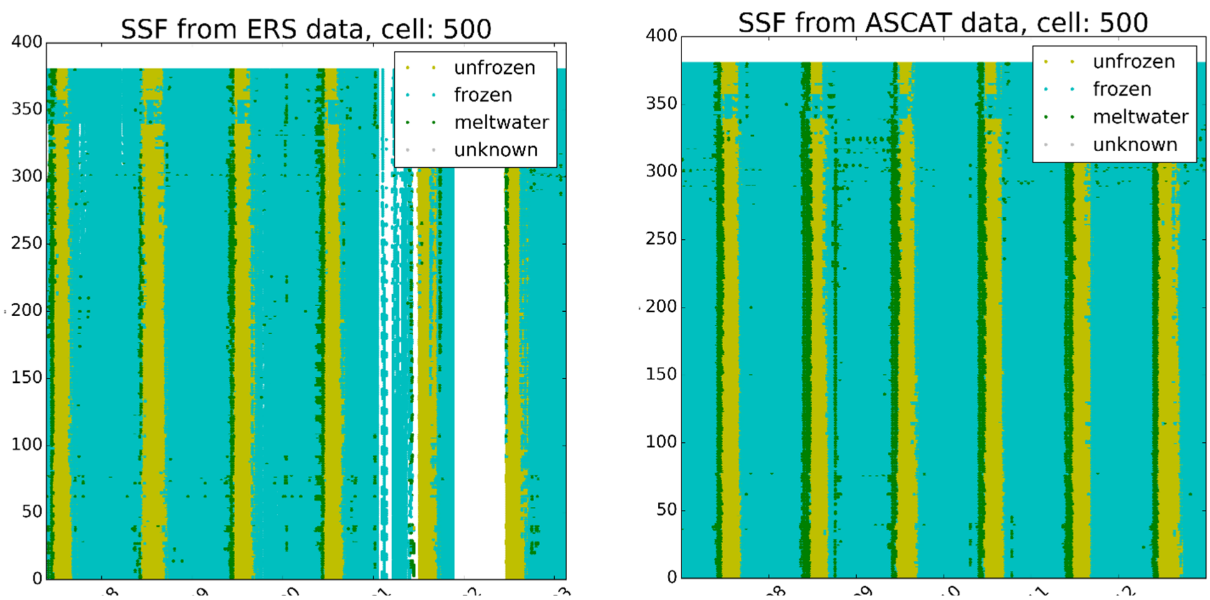

Fig. 6: SSF time series plot for cell 500, determined from ESCAT (left) and ASCAT (right) backscatter values. This region is located in polar Tundra climate in an area dominated by grasslands

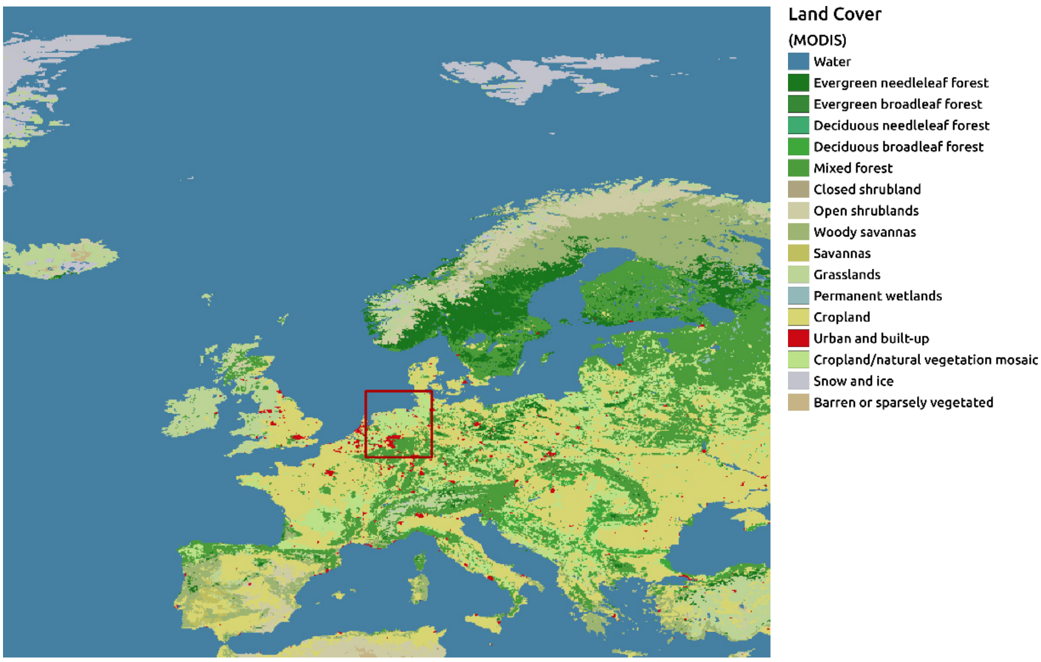

Fig. 8: Location of cell 1360.

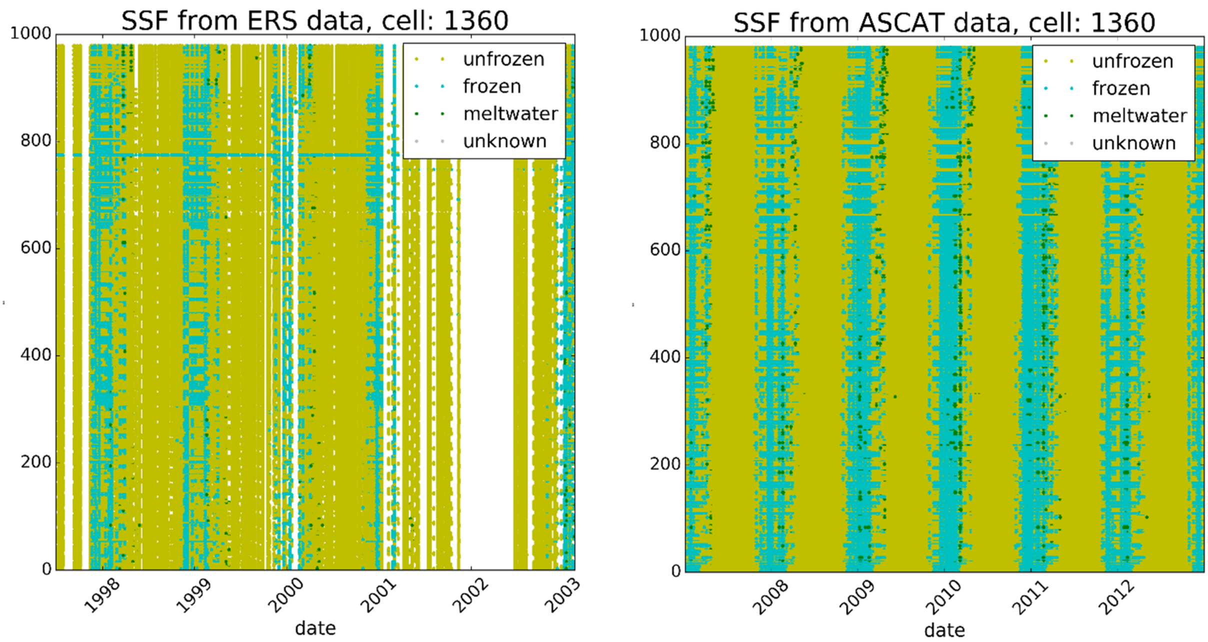

Fig. 7: SSF time series plot for cell 1360, determined from ESCAT (left) and ASCAT (right) backscatter values. This cell is located in temperate climate, in an area with very heterogeneous land cover

4. Validation and Discussion of the Results

The ESCAT surface state flags were validated against soil and surface temperature data from the Global Land Data Assimilation System (GLDAS) and in-situ networks, as well as against arctic freeze/thaw soil state from the National Snow and Ice Data Center (NSIDC). All validations show very good coherence between the datasets.

The validation against GLDAS data was furthermore divided into different periods, namely summer, winter, and the two transition periods between summer and winter (TZ1) and winter and summer (TZ2, Fig. 9 and Fig. 10). Blue and yellow bars show the percentage of corresponding observations in both datasets, either frozen or unfrozen surface. Red and green bars mean contradicting observations: red shows the percentage of SSF: frozen and GLDAS: unfrozen, green shows the percentage of SSF: unfrozen and GLDAS: frozen observations. Fig. 9 shows that the SSF determination works best in summer and winter in polar climate, when the freeze/thaw conditions are not as complex as in spring and fall, when the Earth's surface is exposed to multiple thawing and refreezing events in short time intervals. However, the performance of the algorithm is still sufficiently high in the transition periods. Similar results were observed for most of the test regions.

The validation of the SSF in temperate climate against GLDAS is shown in Fig. 10. This region is influenced by the Gulf Stream, and the soil is not permanently frozen during winter. Thawing and refreezing periods alternate depending on the weather situation.

The transition periods are defined as the period ±30 days around the transition day. In some regions, especially at lower latitudes or close to the sea, this definition might not be suitable, since winter is not a season of permanent frozen conditions there (Fig. 10). Especially in those regions, a quite large number of unfrozen states is classified during winter, which suggests re-defining the transition periods. Considering this in the algorithm might deliver improved results for the surface state flag.

Building on the successful adaptation of the SSF algorithm for ESCAT data, the research on the algorithm shall be further continued. An assessment of the reliability of the computed SSF values could be valuable for different applications, by providing a confidence flag for each surface state flag. SSF values in summer and winter will be given higher reliability values than SSF values in the transition periods.

The SSF algorithm is based on ERA-Interim model temperature data. Since a model can never fully represent the true natural conditions, it would be very interesting to replace the model data with suitable land surface temperature observations, which might be available in the near future.

Thanks to this successful adaptation, the surface state time series can be extended to the end of the twentieth century. Since the freeze/thaw states of the Earth's surface are becoming more and more important for the understanding of our environment and the counteraction against climate change, this time series extension provides important data for numerous research areas.

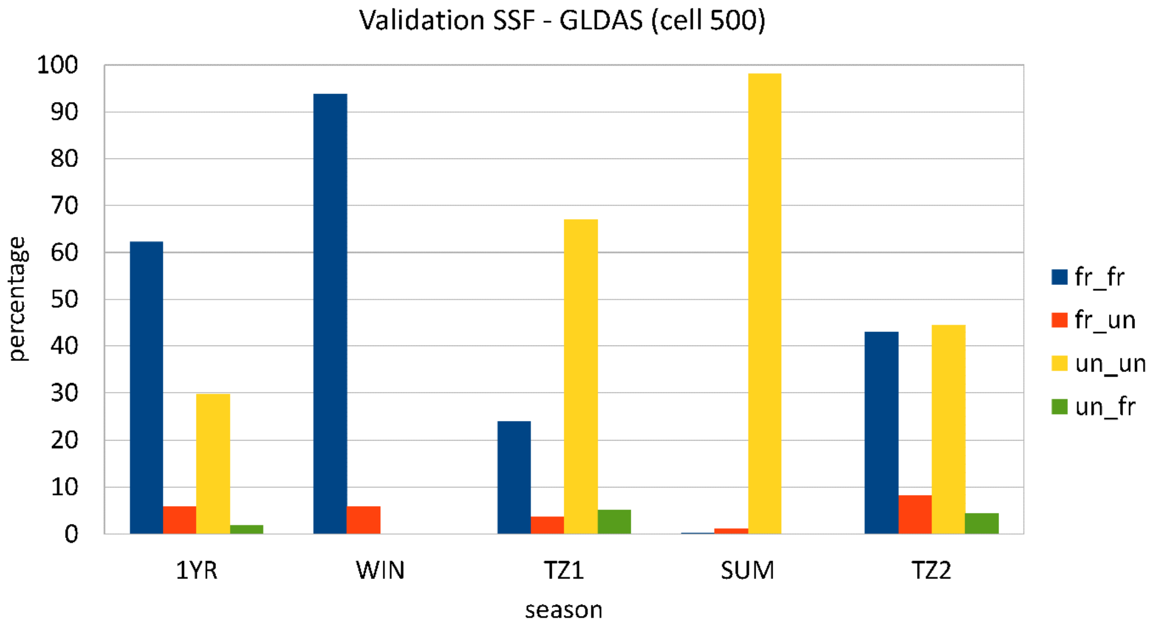

Fig. 9: Results of the validation of ESCAT SSF and GLDAS, divided into seasons. Cell 500 is situated in northern Canada, in polar Tundra climate. The region is covered by grasslands

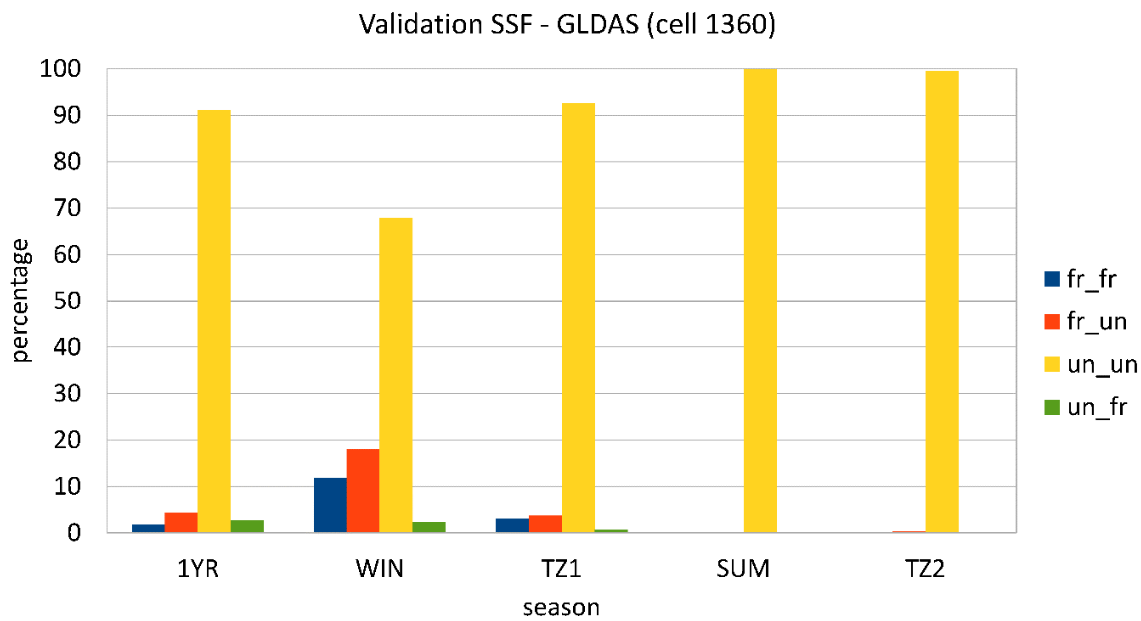

Fig. 10: Results of the validation of ESCAT SSF and GLDAS, divided into seasons. Cell 1360 is situated in Europe, in temperate climate influenced by the Gulf Stream. The land cover in this region is heterogenous; it includes mixed forests, croplands, and urban areas

5. References

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