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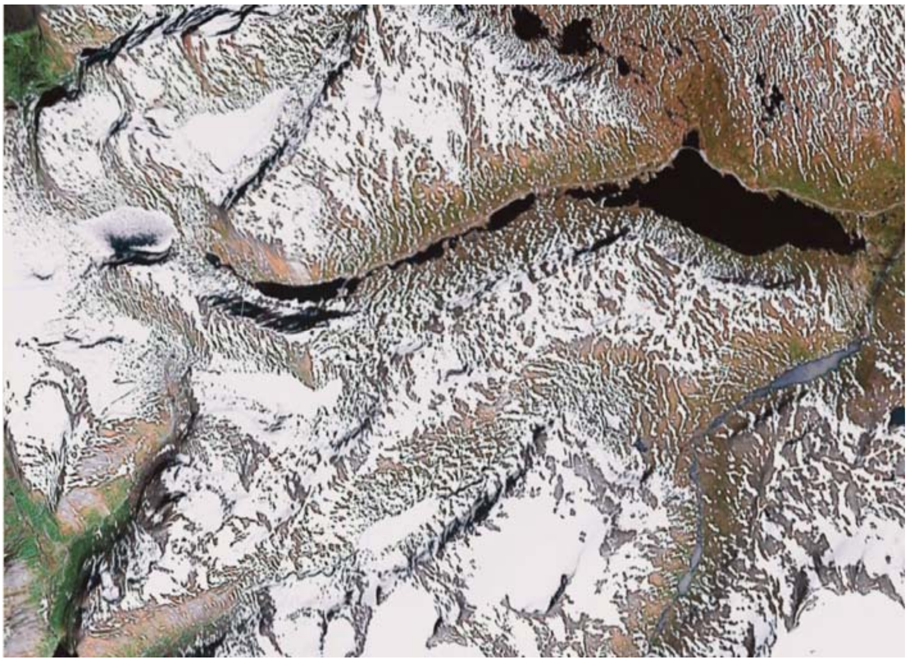
Note

Remote sensing of snow characteristics for avalanche warning

“Snøskred” project results from 2008-2009



Note no	SAMBA/09/10
Authors	Rune Solberg, Hans Koren and Bjørn Wangensteen
Date	22 March 2010
Contract	JOP.05.09.2 (Norwegian Space Centre)

Norsk Regnesentral

Norsk Regnesentral (Norwegian Computing Center, NR) is a private, independent, non-profit foundation established in 1952. NR carries out contract research and development projects in the areas of information and communication technology, applied statistical modelling and earth observation. NR has been a leading research and development institute in earth observation since Norway started to focus on this discipline in the beginning of the 1980's. The institute's main role has since then been to do research and development of methodologies for analysis of digital remote sensing data, in particular methodologies for semi-automatic and automatic classification, parameter retrieval and object recognition. Our vision is to perform research and development leading to new remote sensing methodologies for improved ways of environmental monitoring, natural resource mapping and other applications for public authorities and industry.

Norges Geotekniske Institutt

NGI (Norwegian Geotechnical Institute) is a leading international centre for research and consulting in the geosciences. NGI develops optimum solutions for society, and offers expertise on the behaviour of soil, rock and snow and their interaction with the natural and built environment. NGI works within the oil, gas and energy, building and construction, transportation, natural hazards and environment sectors. NGI is a private foundation with office and laboratory in Oslo, branch office in Trondheim and daughter company in Houston, Texas, USA. NGI was awarded Centre of Excellence status in 2002 and leads the International Centre for Geohazards (ICG).

NGI is the prime contractor of the project behind the work presented in this report.
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Norsk Romsenter

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Abstract

The work presented in this report is part of the project “Fjernanalyse i naturskade og urbane applikasjoner” co-funded by the Norwegian Space Center and carried out together with the Norwegian Geotechnical Institute (NGI). We here report on the work aiming to find a relationship between snow parameters derived from space-borne satellite data and in situ measured snow variables in order to build a model that allows the prediction of, e.g., snow grain type as measured in the field from the analysis of space-borne data. The focus of the study reported here has been simultaneous collection of in situ data and the acquisition of satellite data for establishing a relationship between avalanche-relevant variables and variables retrieved from the remote sensing data. Specifically, in situ measured surface snow grain characteristics have been compared to snow grain characteristics as derived from multispectral data from the MODIS satellite sensor. The satellite data study part of the work is presented in this report. Data from four test sites have been studied: three in the Strynefjell mountain range and a fourth site in the Oslo region close to Lillestrøm. Retrieval and analysis of snow variables from MODIS data was done for the two snow seasons 2007-2008 and 2008-2009, from December until May. Two cases of particular interest were found in each season. The observed snow grain size increased over a few days (typically 2-3 days), while snow surface temperature decreased. Due to the lack of simultaneous field measurements, it was not possible to confirm that these cases represent surface hoar. However, in one case surface hoar was observed coincidentally at Norefjell, and an analysis of corresponding satellite data from Norefjell showed an increase of SGS over a few days. The measurements in Lillestrøm will contribute to the establishment of an accurate relationship between observed snow grain size from satellite and snow grain size and shape as measured in the field. For further studies it is recommended to increase the number of in situ measurements significantly to get a reasonable chance of obtaining simultaneous measurements in situ and by satellite.

Keywords	Remote sensing, snow surface variables, avalanche
Target group	Avalanche research and warning
Availability	Open
Project number	220 390
Research field	Earth Observation
Number of pages	49

Contents

1 Introduction

The work presented in this report is part of the project "Fjernanalyse i naturskade og urbane applikasjoner" co-funded by the Norwegian Space Center (JOP.05.09.2) and carried out together with the Norwegian Geotechnical Institute (NGI). We here report on the work carried out in work package 2 "Forbedret snøskredvarsling med satellittdata". The main aim was to find a relationship between snow variables derived from space-borne satellite data and in situ measured snow parameters in order to build a model that allows the prediction of, e.g., snow grain type as measured in the field from the analysis of space-borne data. The parameters looked at were: snow grain size, snow surface temperature, and snow surface wetness. In the future it is hoped that such data can be integrated into avalanche warning routines. Special focus was given to the area around NGI's high-mountain station "Fonnbu" in the Strynefjell area.

Snow properties related to snow grain size and type at the surface are of special interest within the field of avalanche research and warning. In continental and inter-mountain avalanche climates weak layers or interfaces of the snow pack are the main cause of avalanches (Figure 1.1). Knowledge about such weak layers helps to increase the precision of avalanche forecasting. Some of these potential weak layers, such as surface hoar, form on the snow surface where they are preserved until burial.

Figure 1.1. Fractured and collapsed (left) and unfractured, intact (right) part of a weak layer of buried surface hoar. Photo credit: ASARC (Applied Snow and Avalanche Research), University of Calgary Canada. By courtesy of Prof. B. Jamieson, ASARC.

Optical satellite sensors measure reflected sunlight at different wavelengths in the visible and infrared part of the electromagnetic spectrum. The near-infrared region is sensitive to the optical grain size of the snow. Due to the distinct size and shape characteristics of potential weak layers such as, for example, surface hoar, their reflectance is quite different from other types of snow, such as new snow or melting snow (e.g., Bühler et al., 2009; Fily et al., 1999;

Nolin and Dozier, 2000). If the weather permits optical observations it should, therefore, be possible to detect such layers by remote sensing.

The focus of the pilot study presented here is the simultaneous collection of in situ data and the acquisition of satellite data in order to establish a relationship between avalanche-relevant variables and variables retrieved from the remote sensing data. Specifically, in situ measured surface snow grain characteristics are compared to snow grain characteristics as derived from multispectral data from the MODIS satellite sensor.

Data from four test sites have been studied so far. Three sites are located in the Strynefjell mountain range, Western Norway (Figure 1.2). On these sites it is possible to get satellite data without getting signals from vegetation, roads or other objects into the field of view for at least one MODIS pixel. However, due to the alpine terrain, topography will influence the signal measured by the satellite sensor. Two test sites (Fonnbu and Grasdalsvatnet are located in Grasdalen, close to the snow and avalanche research station Fonnbu of the Norwegian Geotechnical Institute (NGI). The third test site is situated at Breiddalsvatnet, a lake on the eastern side of the Strynefjell mountain. Here, the effects of the topography are eliminated.

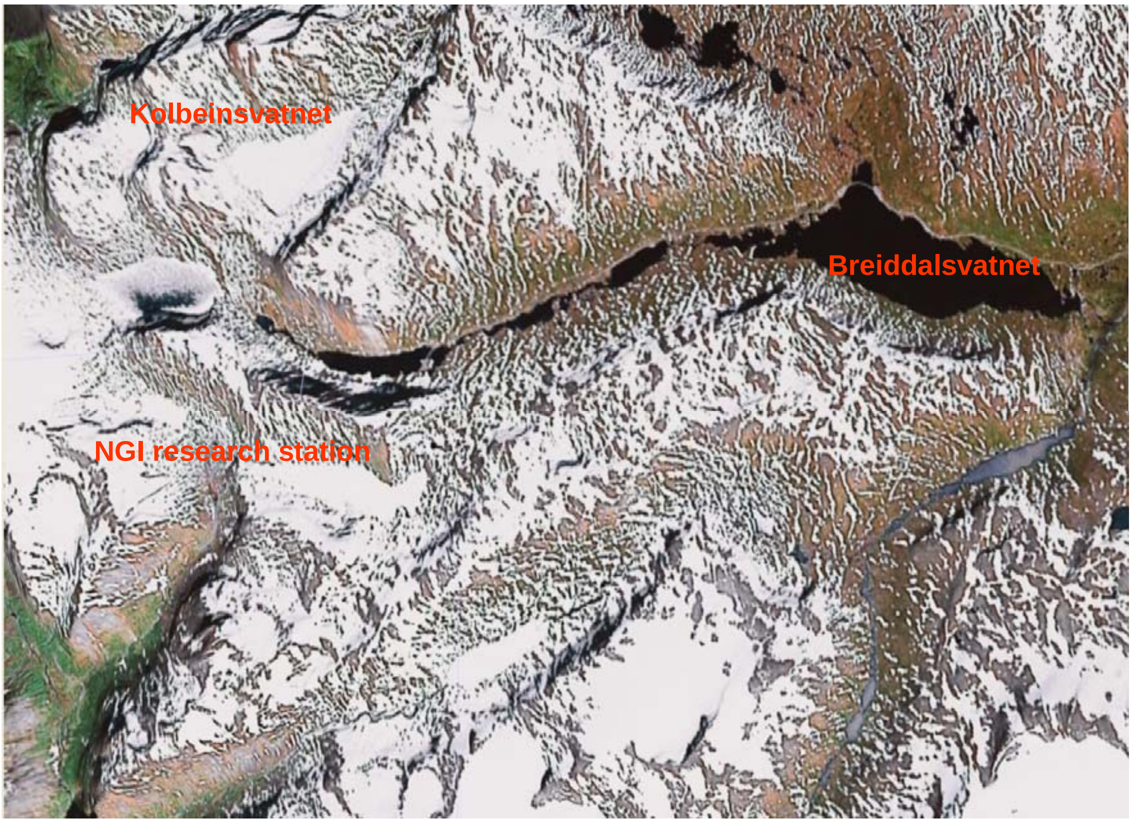


Figure 1.2. Location of the three test sites (Fonnbu, Grasdalsvatnet and Breiddalsvatnet) in the Strynefjell mountain range, Western Norway. Map source: GoogleEarth, 2009.

The test sites in the Strynefjell mountain range are quite far from the premises of the research institutes, which in practice limits the number of field measurements that can be taken during the snow season. Therefore, a fourth site in the Oslo region (close to Lillestrøm) was added in order to allow for quick response for fieldwork when the weather permits satellite data acquisition. The site is located in a flat agricultural area situated about 30 km north-east of Oslo, thus eliminating topographic effects.

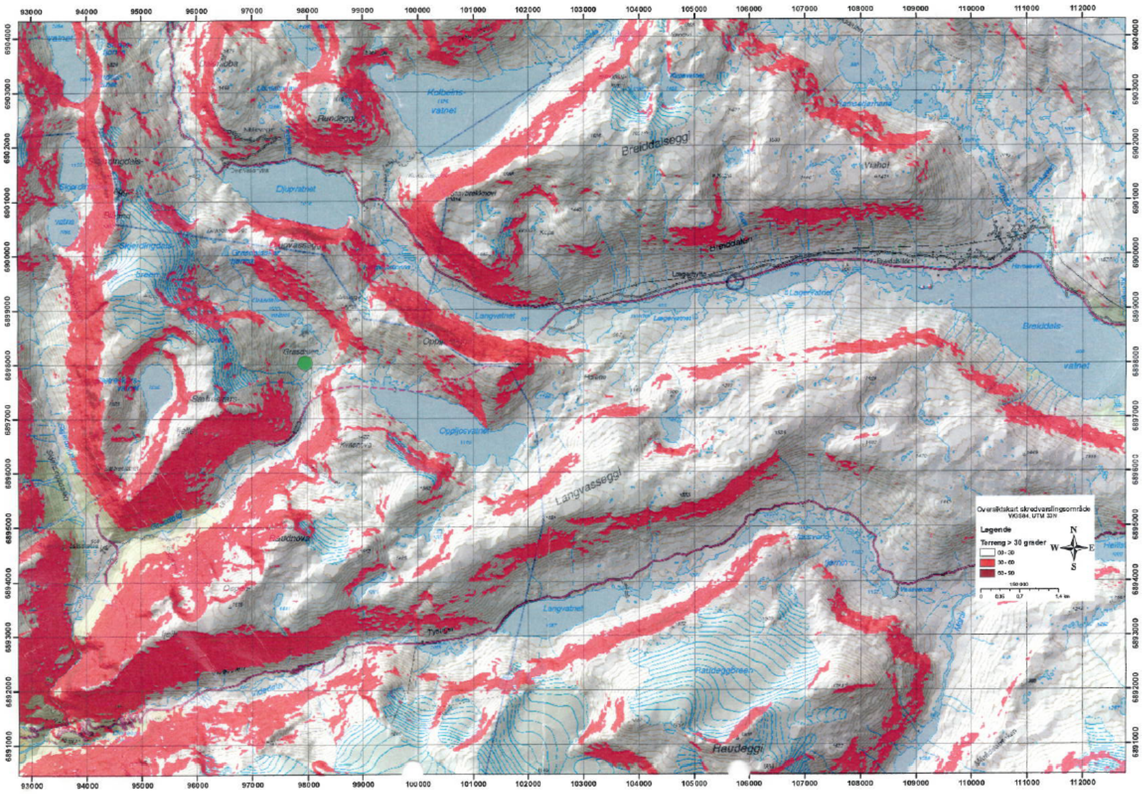


Figure 1.3. Steepness map for the test region. Source: Norwegian Geotechnical Institute

The pilot study shows that simultaneous in situ snow measurements and snow retrieval from MODIS data are possible for the selected test sites in Norway (Solberg et al. 2009). The data analysis work aim to establish a relationship between the satellite-observed apparent snow grain size variable and snow grain shape/size characteristics as measured in the field. Based on satellite and in situ data measured over some snow seasons, we intend to establish a snow grain evolution model. This model can then be used as an additional input variable to the avalanche forecasting model.

2 Algorithms for snow surface characterisation

2.1 Fractional Snow Cover

The optical Fractional Snow Cover (FSC) algorithm is based on an empirical reflectance-to-snow-cover model originally proposed for NOAA AVHRR by Østrem et al. (1979) and later refined in Solberg and Andersen (1994). The algorithm, also know as the Norwegian Linear Reflectance-to-snow-cover (NLR) algorithm, has later been tailored to MODIS data by NR. It retrieves the Fractional Snow Cover (FSC) for each pixel. The model is calibrated by providing two points of a linear function relating observed reflectance (or radiance) to fractional snow cover (see Figure 2.1). The calibration is usually carried out automatically by using calibration areas. Statistics from the calibration areas is then used to compute the calibration points for the linear relationship.

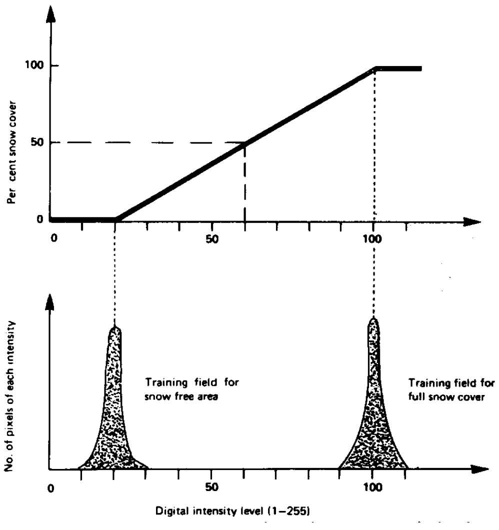


Figure 2.1. The Norwegian Linear Reflectance-to-snow-cover (NLR) algorithm illustrated. A pixel value is linearly transformed to a snow cover percentage. The algorithm is based on the assumption that the bare-ground reflectance is constant. (Andersen 1982)

A particular problem for practical use of the snow algorithm is clouds. NR has experimented with several approaches for cloud detection over snow-covered surfaces. The current best cloud detection algorithm is based on k-Nearest Neighbour (k-NN) classification of MODIS data. In a k-NN classifier a pixel, represented by a vector of band values, is assigned the label, which is most prevalent among the k-nearest labelled vectors from a reference set. A k-NN classifier is an asymptotically optimum (Maximum Likelihood) classifier as the size of the reference set increases (Duda et al. 2001).

More details about the NLR algorithm and cloud detection using the k-NN approach can be found in Solberg et al. 2006.

2.2 Snow Surface Wetness

We have developed an approach to infer wet snow from a combination of measurements of Surface Temperature of Snow (STS) and Snow Grain Size (SGS) in a time series of observations. The temperature observations give a good indication of where wet snow could be present, but are in themselves not accurate enough to provide sufficiently strong evidence of wet snow.

However, if a rapid increase in the effective grain size is observed simultaneously with a snow surface temperature of approximately 0 °C, then this is a strong indication of a wet snow surface. The algorithm is described in detail in Solberg et al. 2004. A simplified version of the algorithm applied is expressed below (pixel indexing has been skipped for clarity):

```
if $SGS$(today) − $SGS$(recently) > SGStresh AND −2 < $STS$(today) < 1 then $MSSW$ = WET_SNOW
else if $SGS$(today) < BareGroundSGStresh then $MSSW$ = BARE_GROUND
else if $STS$(today) > 1)  then $MSSW$ = BARE_GROUND
else $MSSW$ = DRY_SNOW
```

The algorithm also illustrates how bare ground is inferred from temperature observations above 0°C and a rapidly developing negative gradient for SGS (both due to appearance of bare ground patches at the sub-pixel level).

The calculated SGS index does not give the precise physical size of the snow grains, but is an indication of the grain size. The value of the SGS index increases with increasing grain size. For a pixel totally covered with snow, the SGS index is a good indication of the grain size. Bare ground gives a low value for the SGS index. This means that for a pixel only partly covered with snow, we could measure a low SGS index even for large snow grain sizes. A decreasing value of SGS could mean newly fallen snow or increasing snow-free area.

For STS there is a similar problem. With a snow temperature of 0°C, the snow will start to melt and the temperature will stop increasing. For a pixel only partly covered with snow, the temperature of the snow-free area will influence, resulting in measured STS values above 0°C. This would usually mean that the snow is wet, but if the snow-free area is sufficiently large, one can measure an average positive temperature for the pixel even if the snow is cold and dry.

Therefore, a good estimate of SSW is valid only for pixels completely covered with snow. An accurate FSC map should be used to restrict the pixels classified. We assume that the SSW estimate is reasonable good even if there are small areas of bare ground included.

Experiments with the snow wetness algorithm have confirmed that the approach of combining STS and SGS, analysed in a time series of observations, can be used to infer wet snow, including giving an early warning of snowmelt start. Air temperature measurements from meteorological stations confirm the maps produced in general. The main problems observed are related to clouds. In some maps it is observed that dry and cold snow is more frequent close to clouds. One could imagine that this is because the clouds have kept the sunlight away – hence the snow has not been warmed. But it might as well be that parts of the clouds have not been detected such that the cloud temperature is partly included. The problems are typically associated with transparent clouds.

2.3 Surface Temperature of Snow

The Surface Temperature of Snow (STS) algorithm is based on an approach proposed by Key et al. (1997). In a comparison study by Amlien and Solberg (2003), this algorithm was identified as one of the best single-view techniques for retrieval of STS for polar atmospheres, and it can be applied on Terra MODIS as well as NOAA AVHRR data.

The absorption of the radiation in the atmosphere depends on the wavelength, and the difference between the brightness temperatures in two channels will therefore yield information about the atmospheric attenuation (Strove et al. 1996; Coll et al. 1994). The split-window technique aims at eliminating the atmospheric effects by utilizing this difference. The surface temperature T is estimated as a weighted sum (or difference) of the brightness temperatures observed. The split-window equation for AVHRR utilizes T_{11} measured in band 4 at 11 µm and T_{12} measured in band 4 at 12 µm:

$$T = b_0 + b_1 T_{11} + b_2 T_{12}$$

The split-window technique is only sensitive to the effect of the atmospheric water vapour, and not to other atmospheric gases or aerosols. The atmospheric influence on the split-window equation depends on the composition of the atmosphere, and the method must therefore be calibrated for different atmospheres.

Coll's modification of the split-window algorithm was proposed in order to avoid the need of several calibration sets. It is a global non-linear equation for global-scale application. Derivation of regionally optimized linear algorithms has been demonstrated for mid-latitude conditions, but not for colder atmospheres. Coll's equations are given by:

$$\begin{aligned} T &= T_{11} + A(T_{11} - T_{12}) + B \\ A &= b_0 + b_1 (T_{11} - T_{12}) \\ b_0 &= 1.00 \quad b_1 = 0.58 \quad B = 0.51 \end{aligned}$$

Key's algorithm for NOAA AVHRR data (Key et al. 1997) is a modification of the simple split-window technique. An additional correction term addresses the variation of the view angle θ along a scan line and its effect of the atmospheric path length. The algorithm expresses the surface temperature as

$$\mathrm{T_s} = b_0 + b_1 T_{11} + b_2 \left(T_{11} - T_{12}\right) + b_3 \left(T_{11} - T_{12}\right)\left(\sec\theta - 1\right)$$

The calibration coefficients depend on the temperature interval and the satellite sensor.

2.4 Snow Grain Size

For SGS we have used a normalized grain size index based on work by Dozier (1989) and followed by experiments by Fily et al. (1997). MODIS bands 2 and 7 have been used as this index has been shown to be less sensitive to snow impurities.

The original algorithm proposed by Dozier (1989) was based on Landsat Thematic Mapper (TM) data. The problem of radiometric terrain effects, the influence of slopes on the reflected light, is minimized by using ratios between two channels as an index for grain size. A number of ratios of the form

$$R_{ij} = \frac{TM_i - TM_j}{TM_i + TM_j}$$

have been tested. We have selected the R47 as the best. Fily (1997) reported that the measured data matches the theoretical curves well.

The ratio approach is a simple method. Signals from two channels are sufficient and information about the terrain is not needed (as it is with several other methods). Published studies do not give a calibrated ratio. One specific ratio value does not give an exact snow grain size value. It is also a problem how to define the grain size. However, the ratio can be used as an index of grain size; the ratio increases with increasing grain size up to the point of saturation.

The wavelengths of the Landsat TM/ETM+ bands are:
- Band 4: 0.775 – 0.900 μm
- Band 7: 2.09 – 2.35 μm

The MODIS bands closest to these are:
- Band 2: 0.841 – 876 μm
- Band 7: 2.105 – 2.155μm

MODIS band 2 has a spatial resolution of 250 m and band 7 has 500 m. This means that the grain size index R27 can be computed with 500 m resolution.

Studies of calculated grain size from the R27 ratio show that the index is well suited for monitoring the changes in grain size due to precipitation and temperature changes. The index increases with increasing temperature and gets a lower value when new snow has fallen.

The grain size index for snow for MODIS images lies between ca. 0.7 and 1.0. Bare ground of different kinds gives low index values. 0.7 is not an exact threshold value for snow. Somewhere around 0.7 the index shows that there is probably some snow on the ground. To be sure that the index represents snow grain size, one should use a snow cover retrieval algorithm in addition to check that the ground is fully snow covered.

3 Satellite measurements

Data from four test sites have been studied. Three sites are located in the Strynefjell mountain range, Western Norway. Two of the test sites (Fonnbu and Grasdalsvatnet, cf. Figure 1.2) are located in Grasdalen. The third test site is situated at Breiddalsvatnet, a lake on the eastern side of the Strynefjell mountain. A fourth site in the Oslo region (close to Lillestrøm) was added to allow for quick response for fieldwork when the weather permits satellite data acquisition.

Field measurements of snow surface characteristics were carried out on approximately two-weekly basis at the three different sites in the Strynefjell area starting in January and continued until mid-April 2009. The Lillestrøm site was established later in the season and was measured a few times between mid March and the end of April.

3.1 Snow season 2008, Strynefjellet

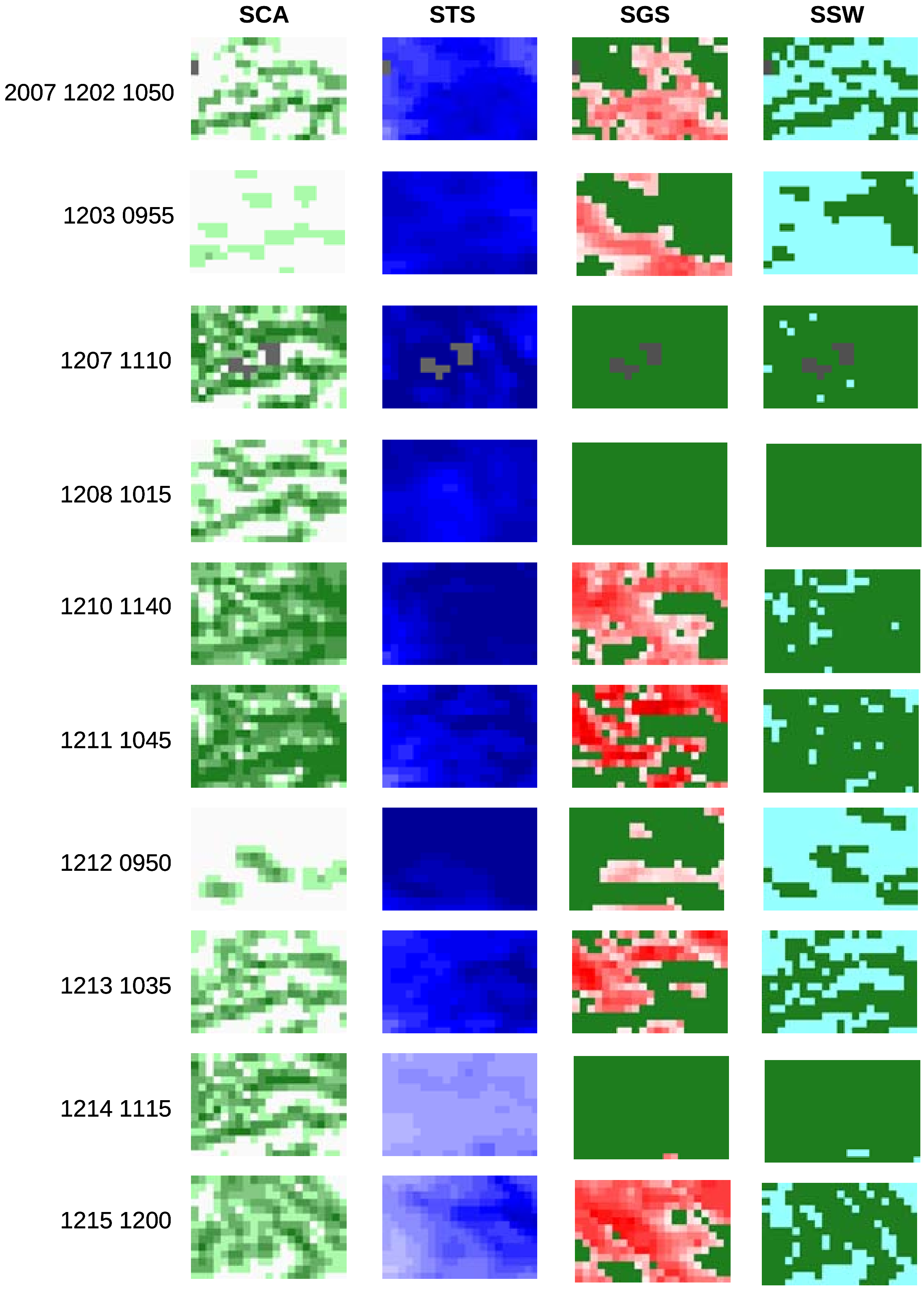
The figures below show the retrieved Fractional Snow Cover (FSC), Surface Temperature of Snow (STS), Snow Grain Size (SGS) and Snow Surface Wetness (SSW) for an area on Strynefjellet for the winter/spring season in 2008 and 2009. Date and time of satellite data acquisition is shown to the left.

FSC is shown in white for 90-100%, 0-10% is shown in dark green, and between 10 and 90% the snow cover is shown in nuances of green.

STS is shown in blue with dark blue for low temperatures and lighter blue, up to approximately white at 0 °C. Temperatures above 0 °C indicate that there is influence from bare ground. This is shown in red, dark red and black.

SGS is shown in red. Light red means a grain size index of 0.8 and the colour gets darker with increasing index. In the SGS plots from Breiddalsvannet, the SGS values are multiplied by 100. The green colour indicates that the SGS value is so low that it probably is influenced by bare ground. For the months from December to February, the green area is probably too large because of low sun and a defect in channel 7 in the MODIS detector (see Chapter 4).

SSW is showing dry, cold snow (colder than -2 °C) in cyan. Dry snow closer to 0 (colder than –0.5 °C), is shown in blue. The development of SGS since last measurement is indicated by the colour. Increasing SGS is shown in dark blue, constant SGS in normal blue, and decreasing in cyan. If there are no SGS data from the nearest days, the colour is even lighter blue. Snow close to 0 °C (between -0.5 and +0.5) is shown in yellow/orange. Increasing SGS is in red, constant in orange, decreasing in yellow and unknown in light yellow). The green colour shows snow cover that is well below 100%. The algorithm checks the values for SCA, STS and SGS, and marks bare ground if a valid value for SSW cannot be calculated.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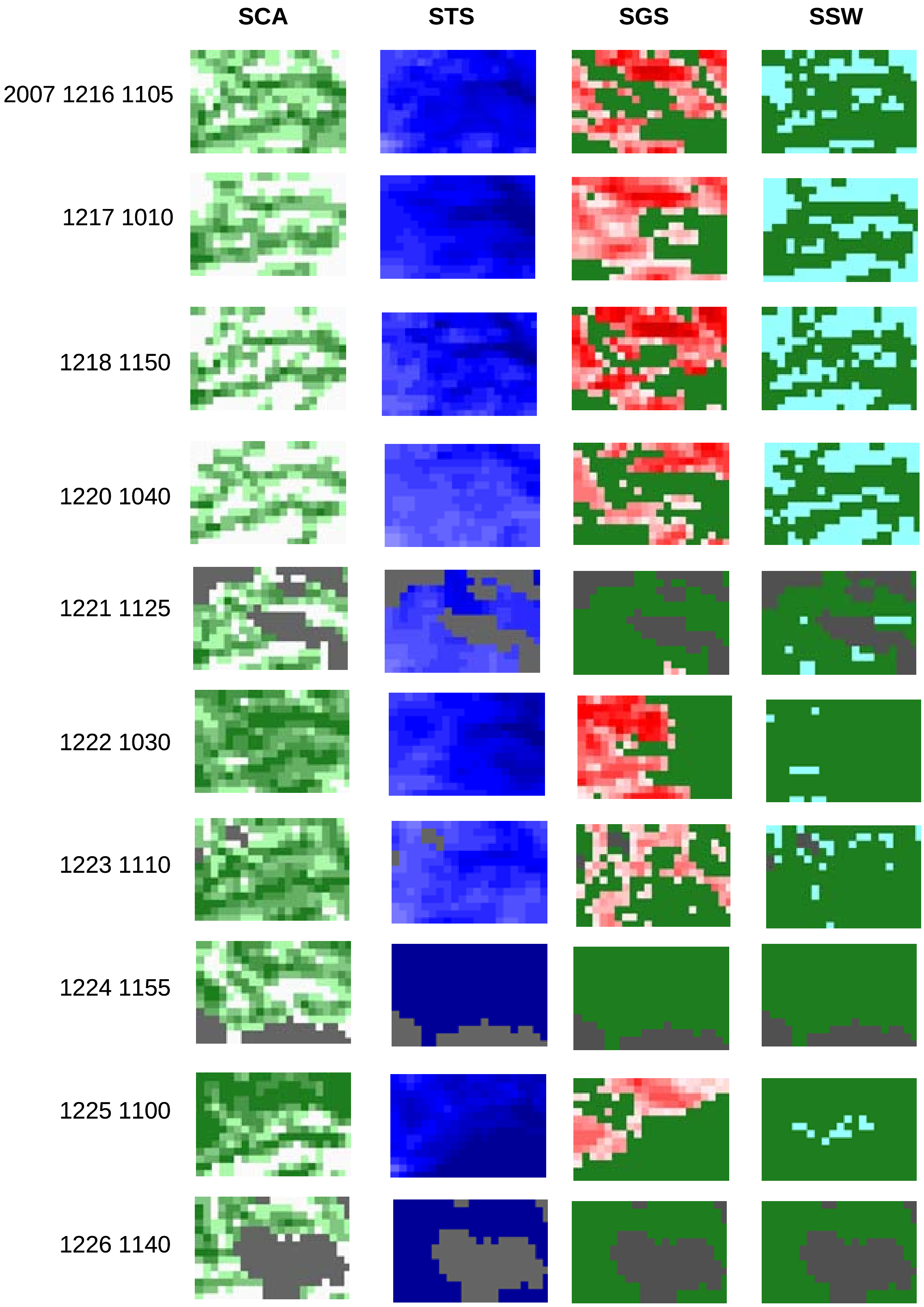
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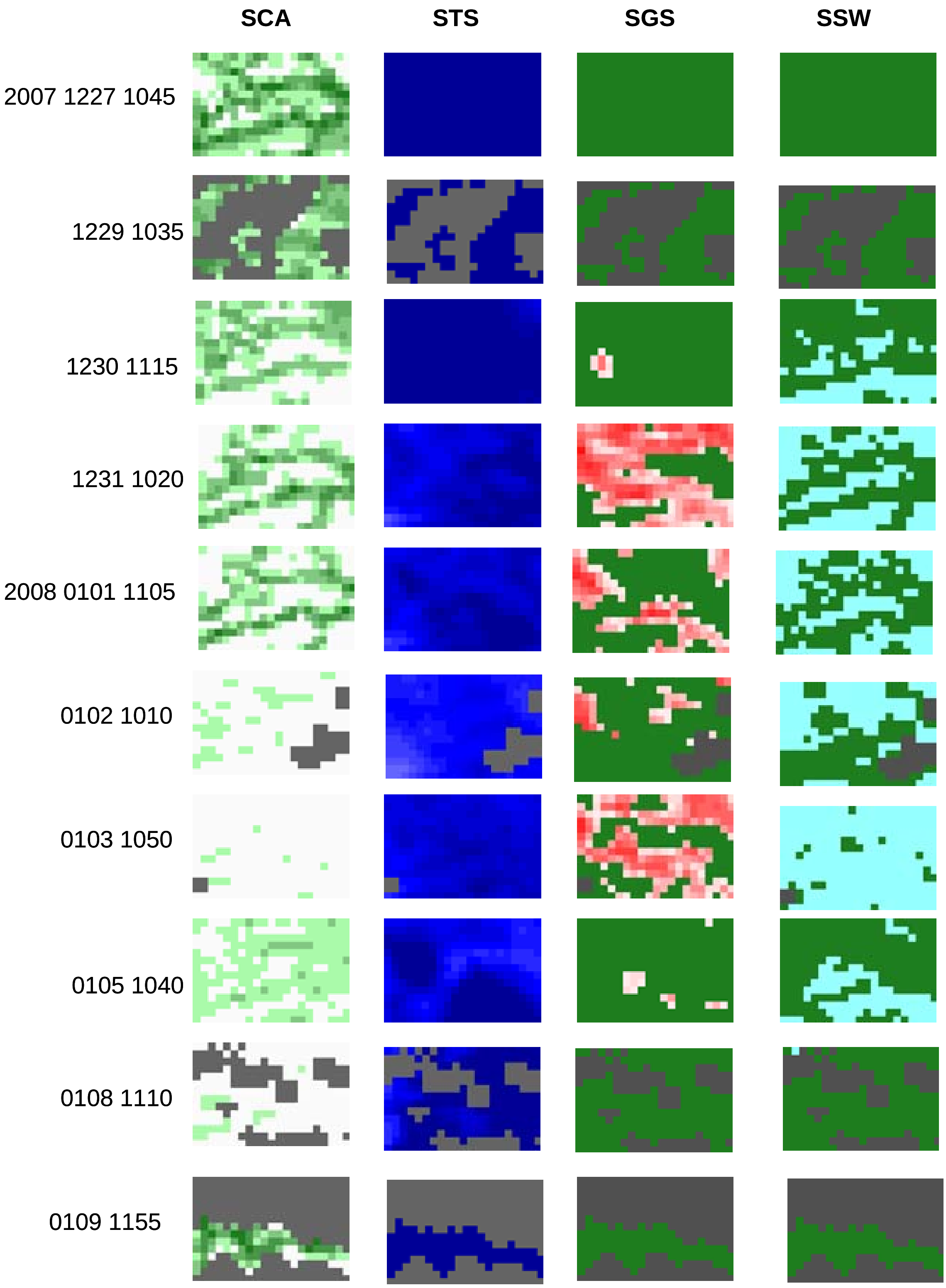
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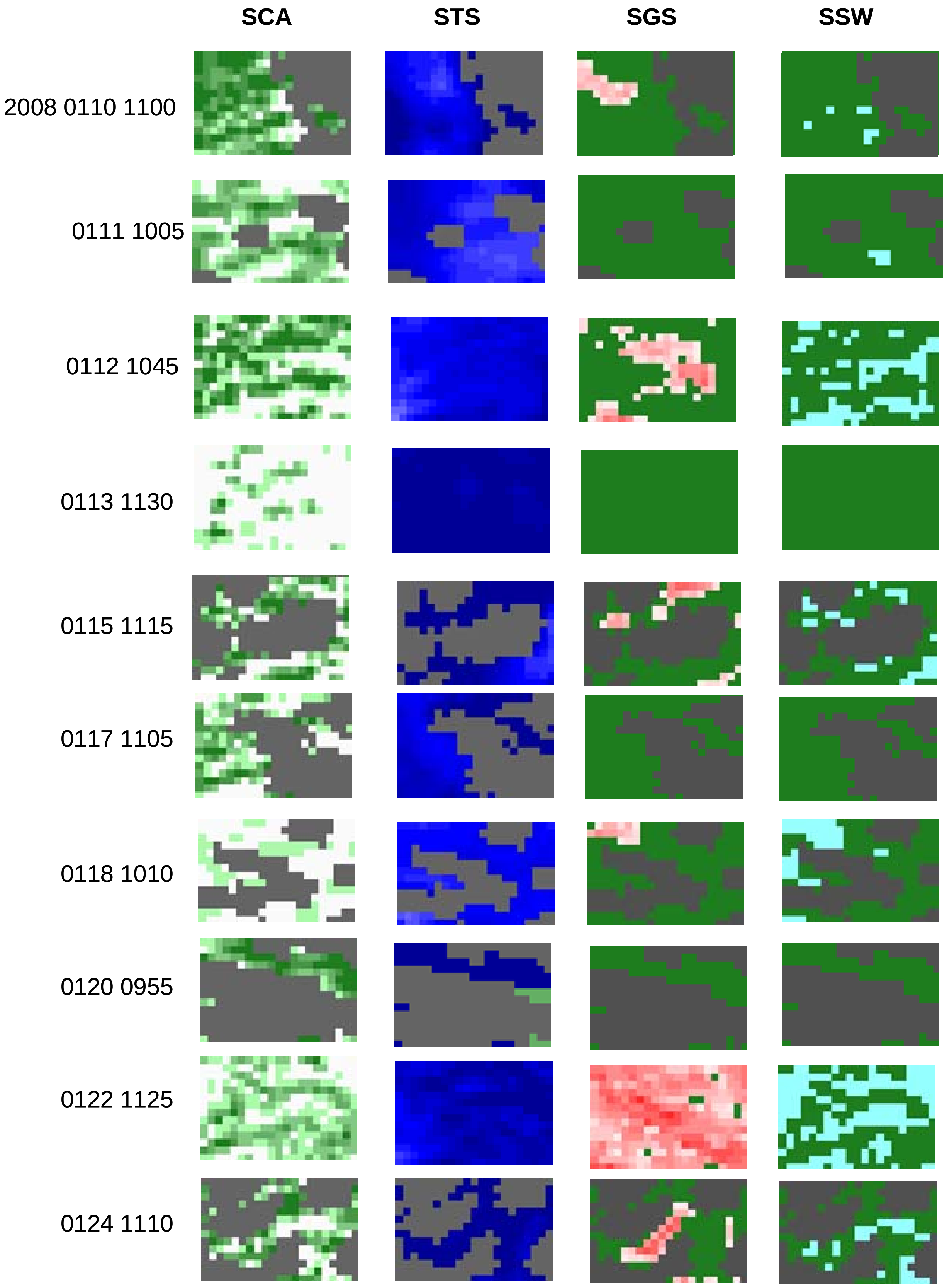
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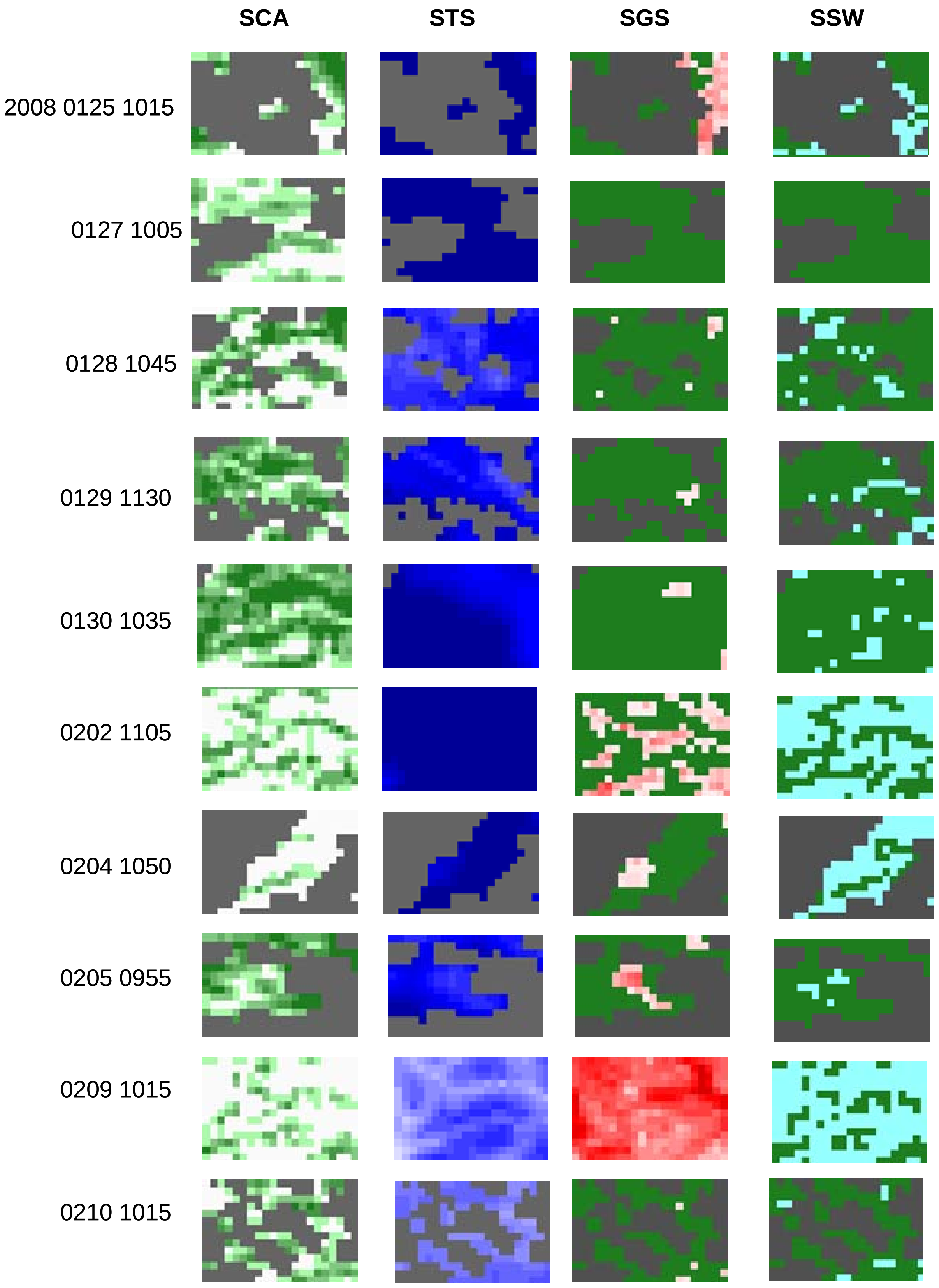
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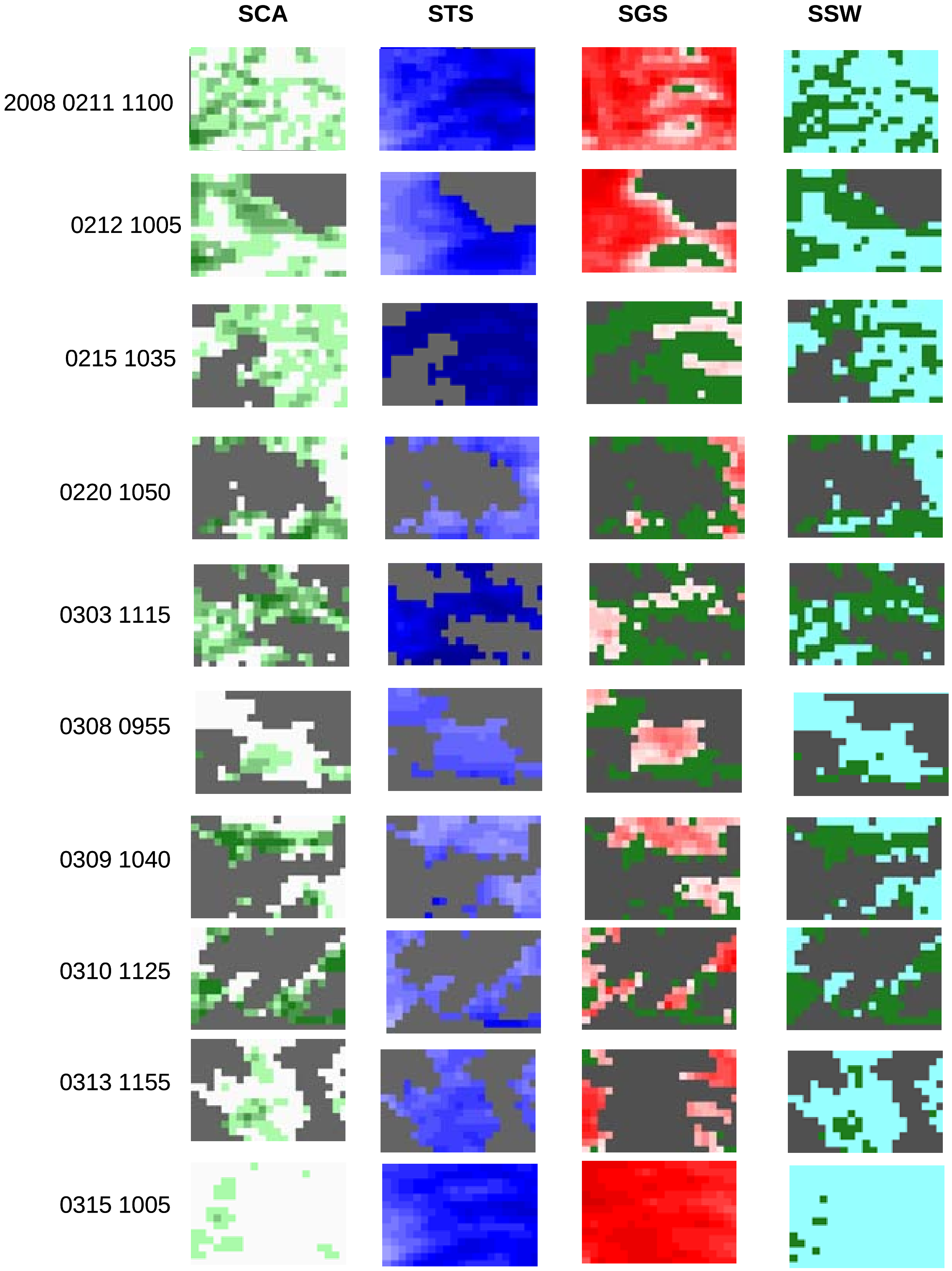
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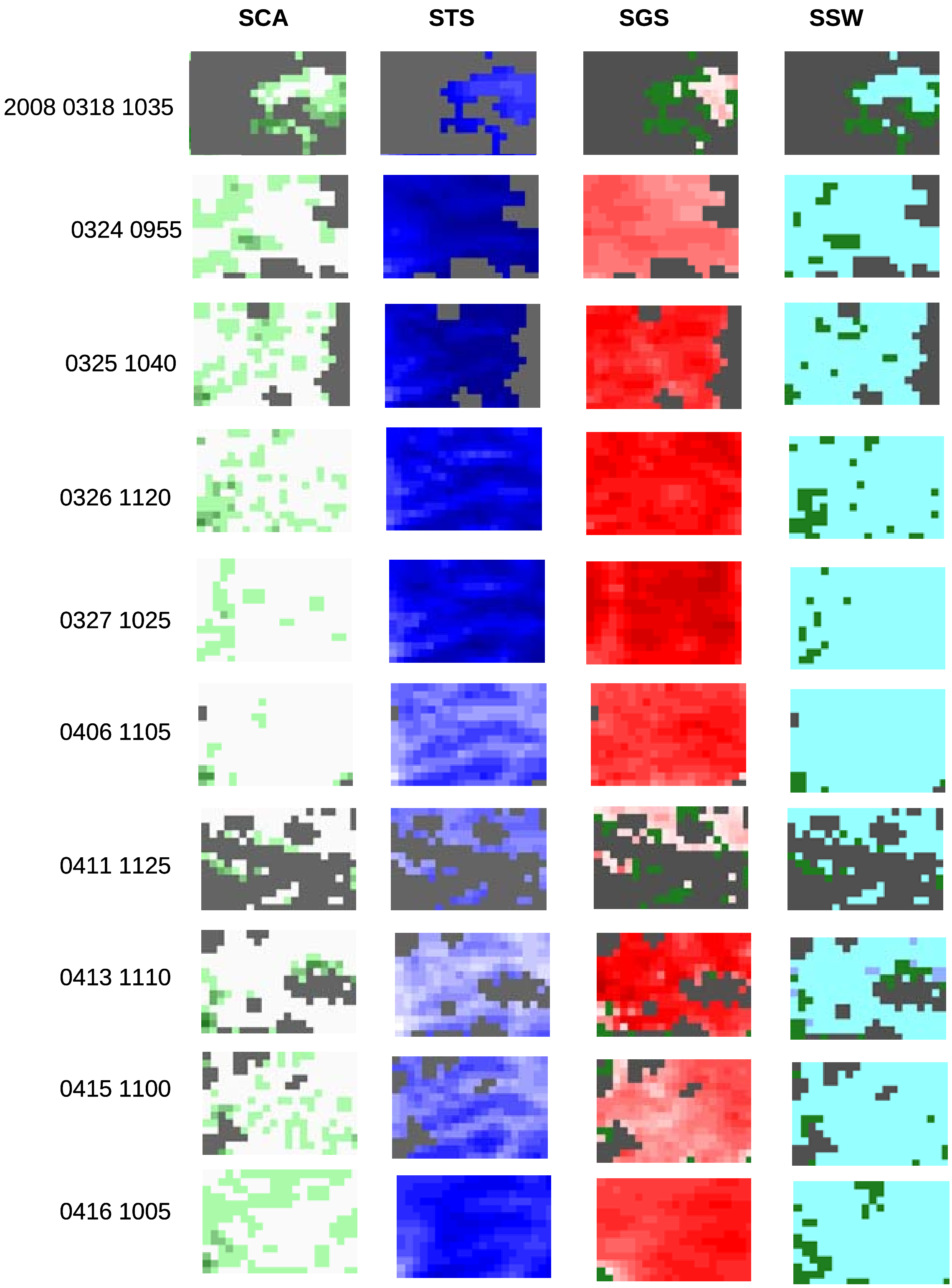
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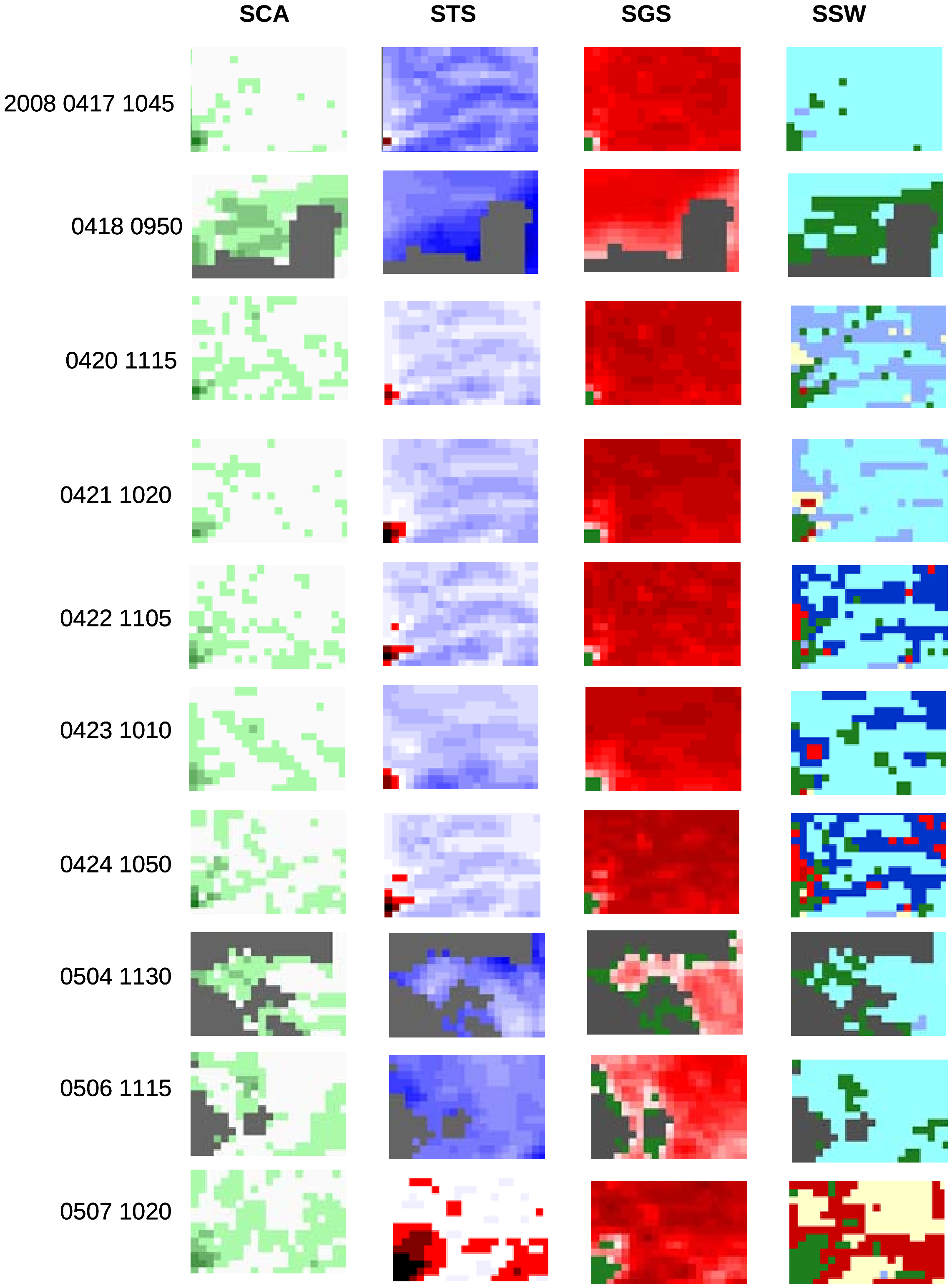
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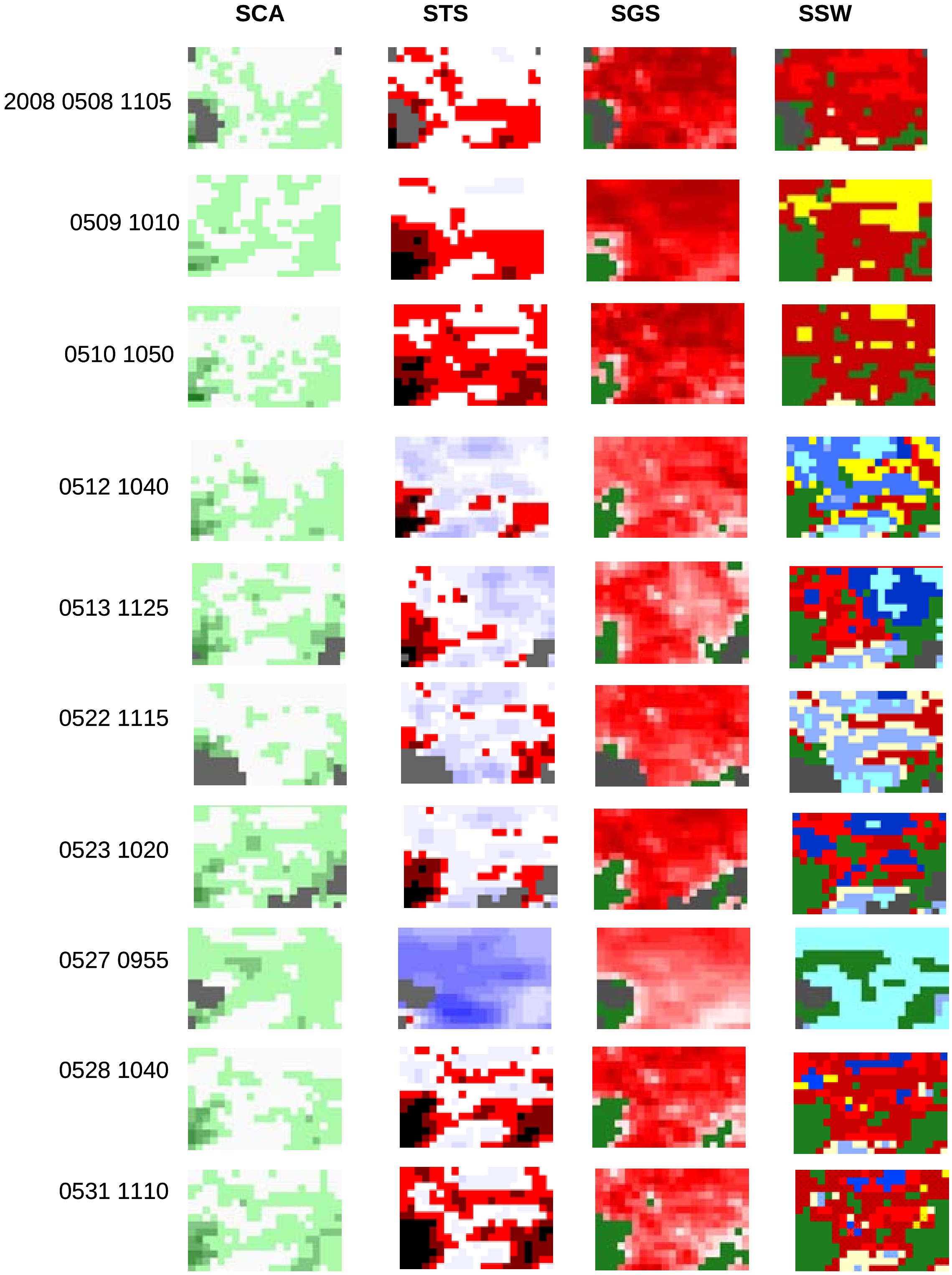
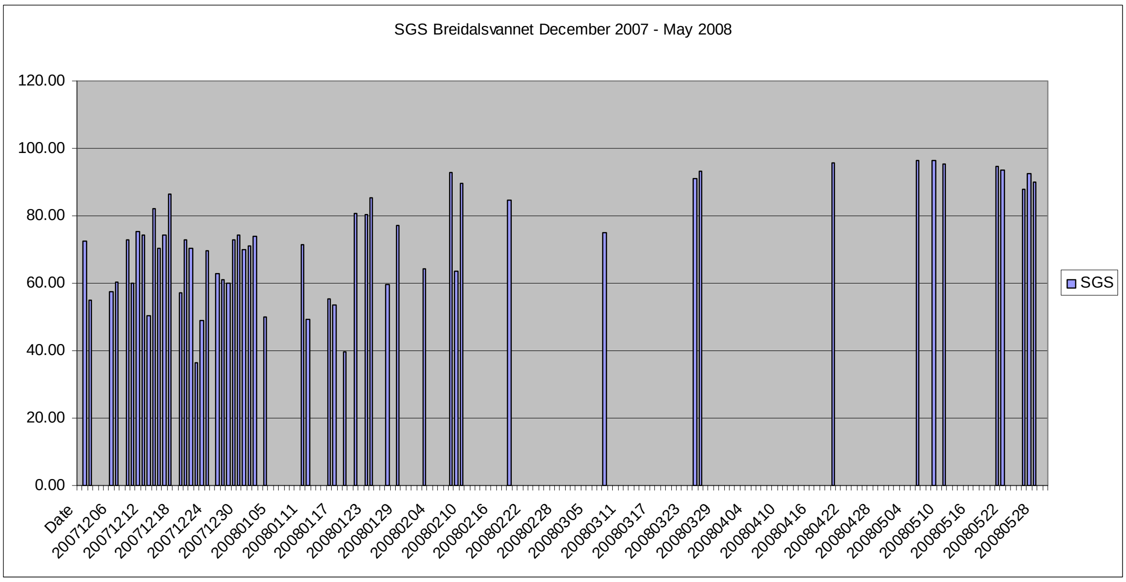


Figure 3.1. Time series of FSC/SCA, STS, SGS and SSW for the period December 2007 until May 2008.



Figur 3.2. The development of SGS for one 1 km² area at Breiddalsvannet for the 2008 season. The scale is grain size index multiplied by 100.

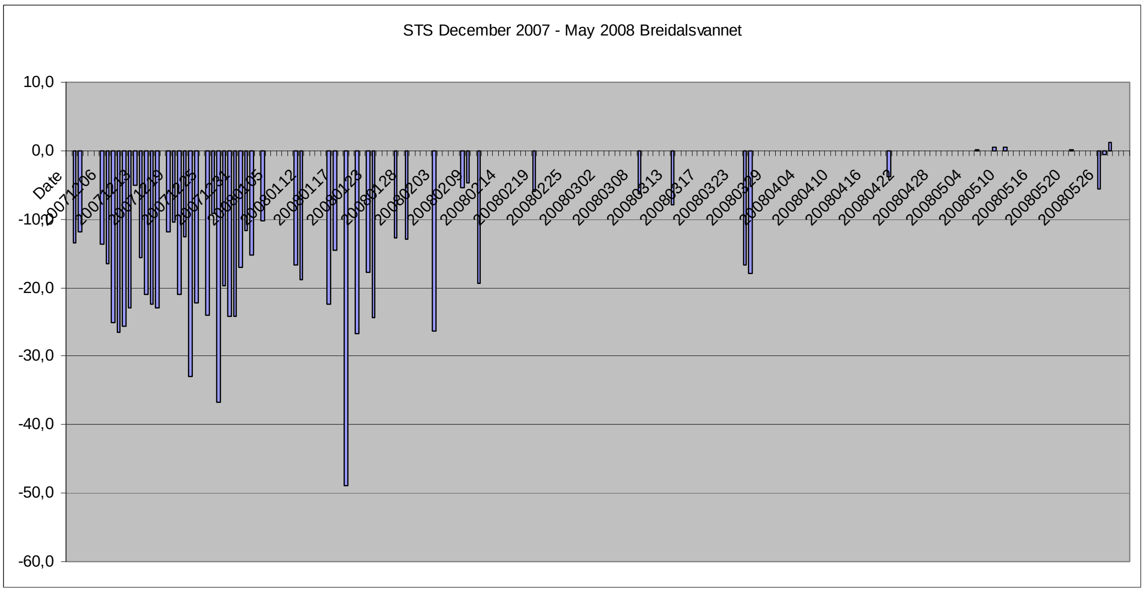
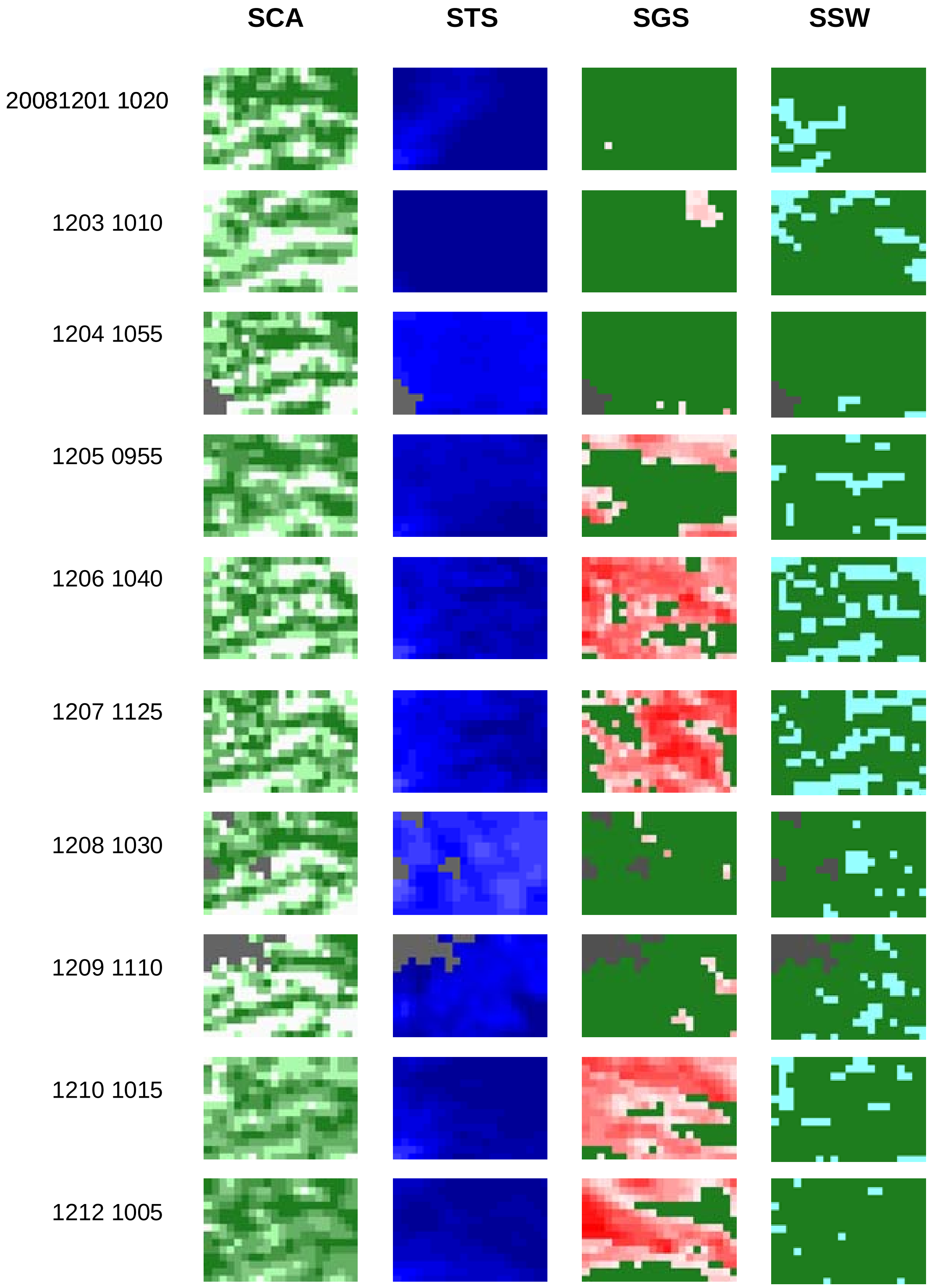
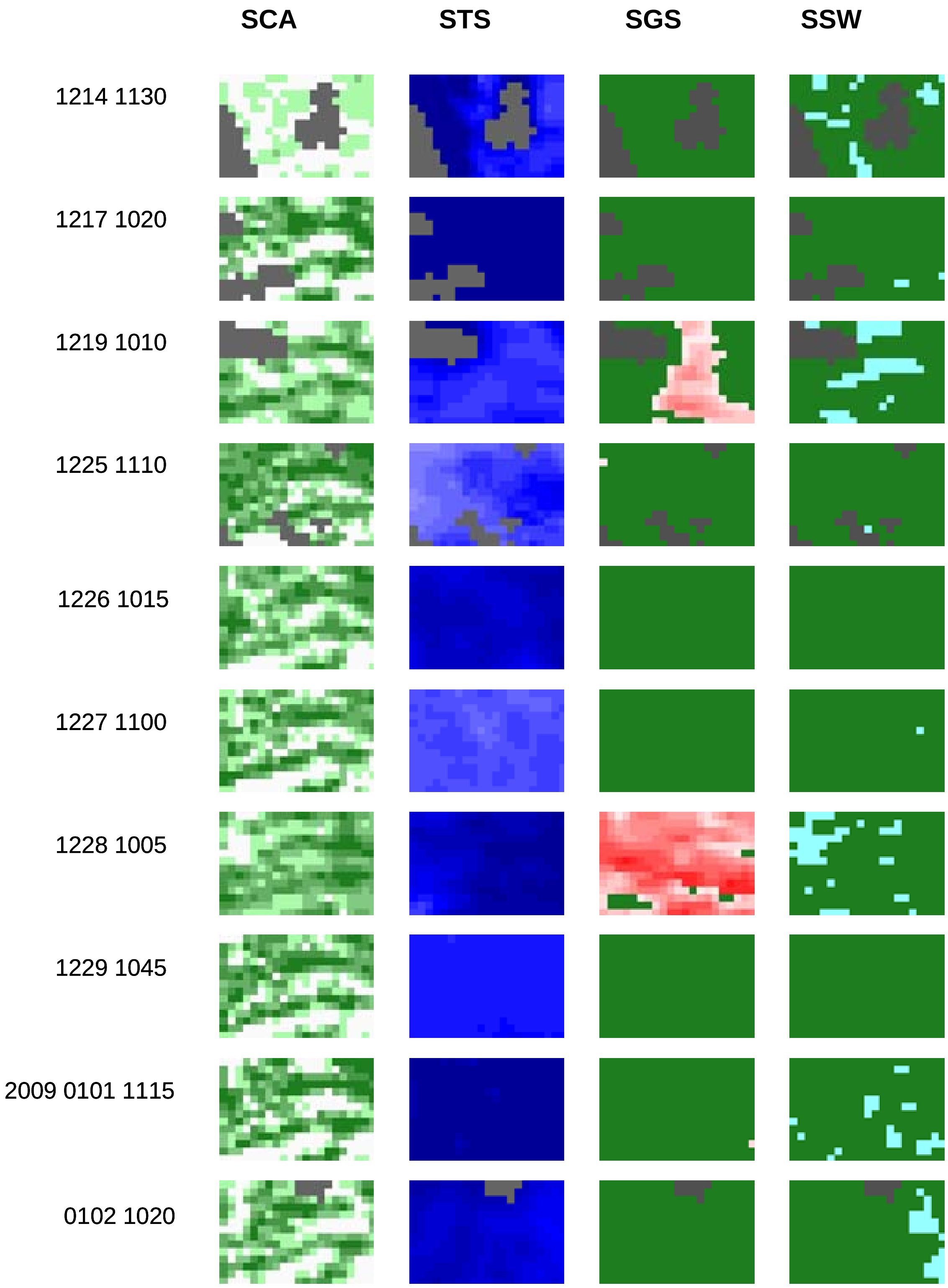


Figure 3.3. The development of STS for the area at Breiddalsvannet for the 2008 season.

3.2 Snow season 2009, Strynefjellet

The colour coding below is the same for this season as explained in Section 3.1.

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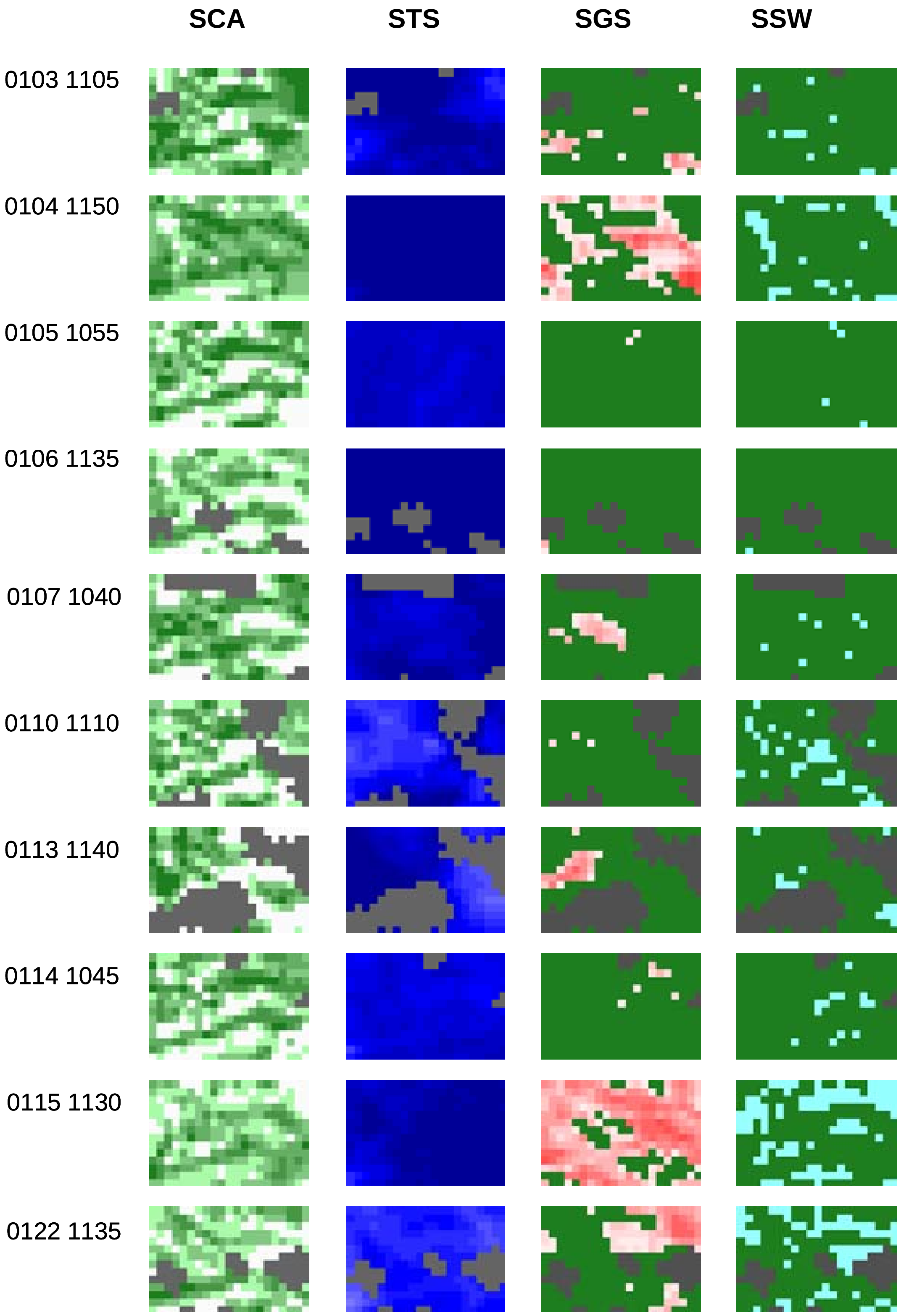
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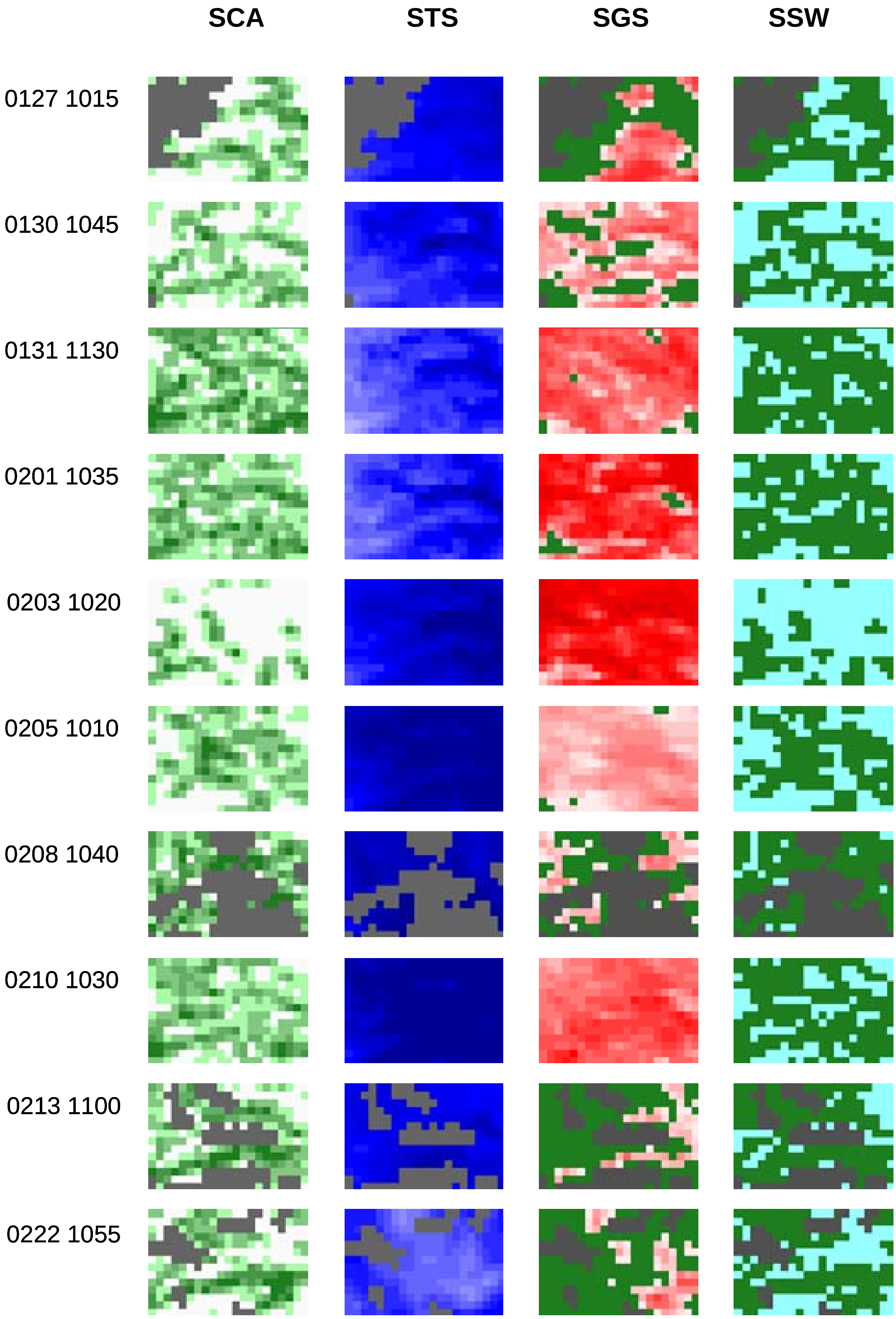
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0203 1020
0205 1010
0208 1040
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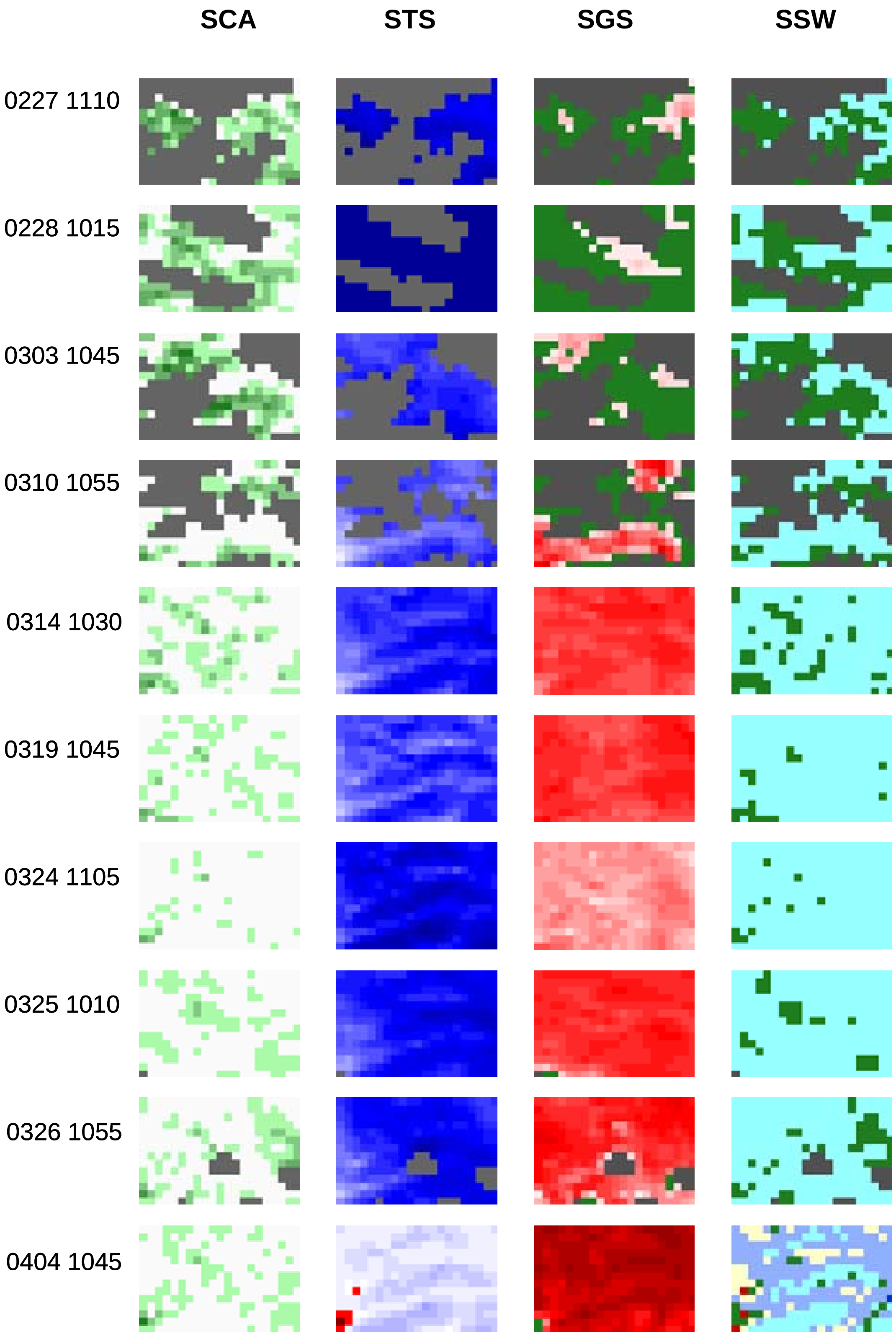
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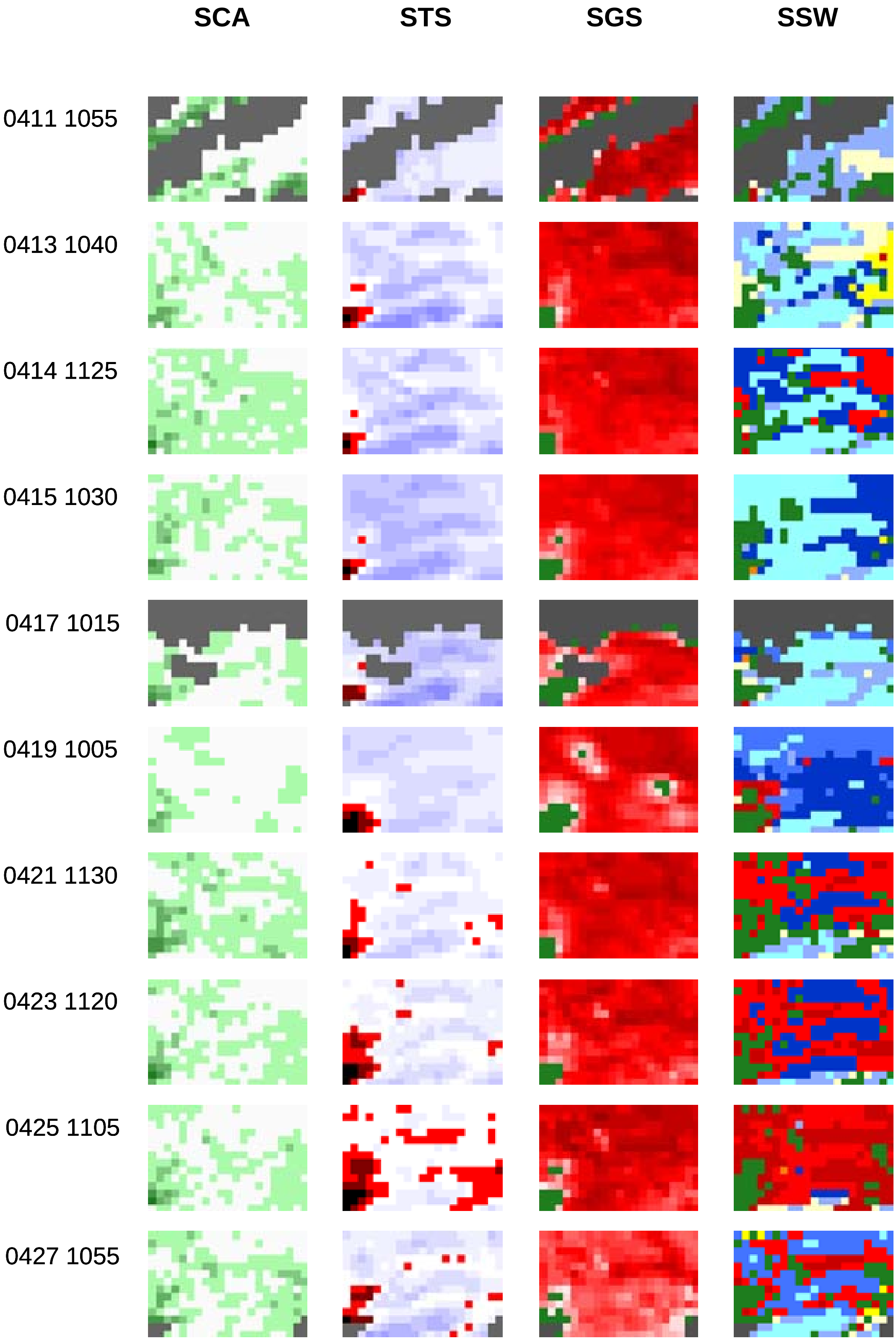
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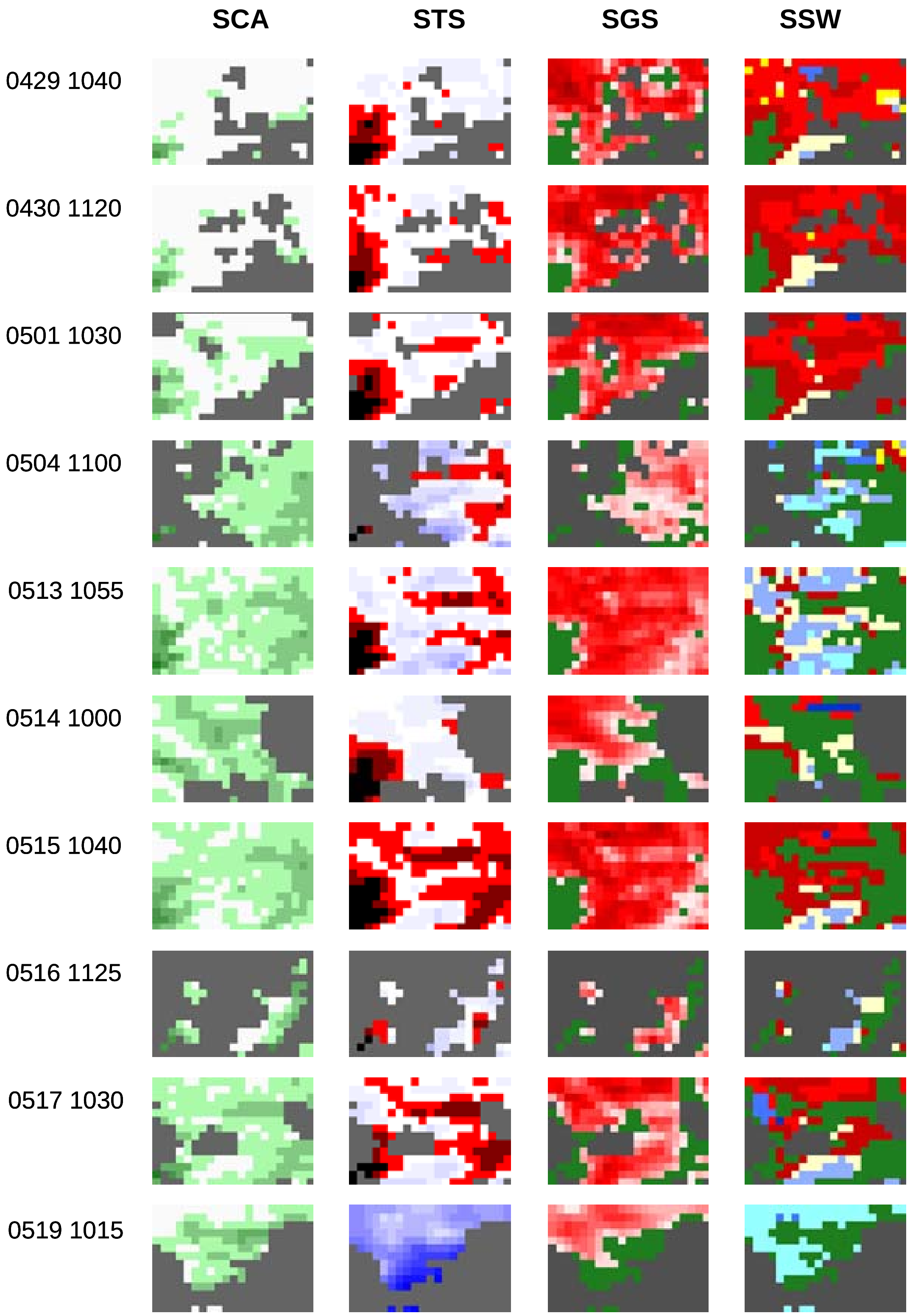
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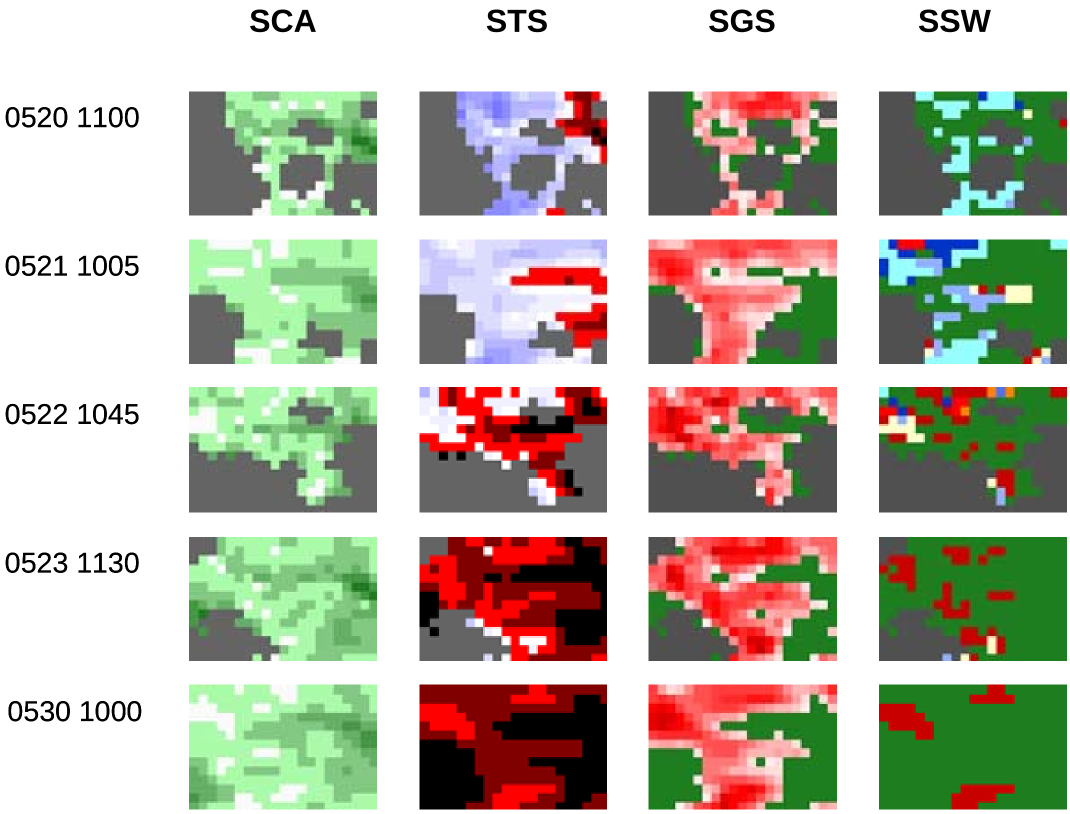
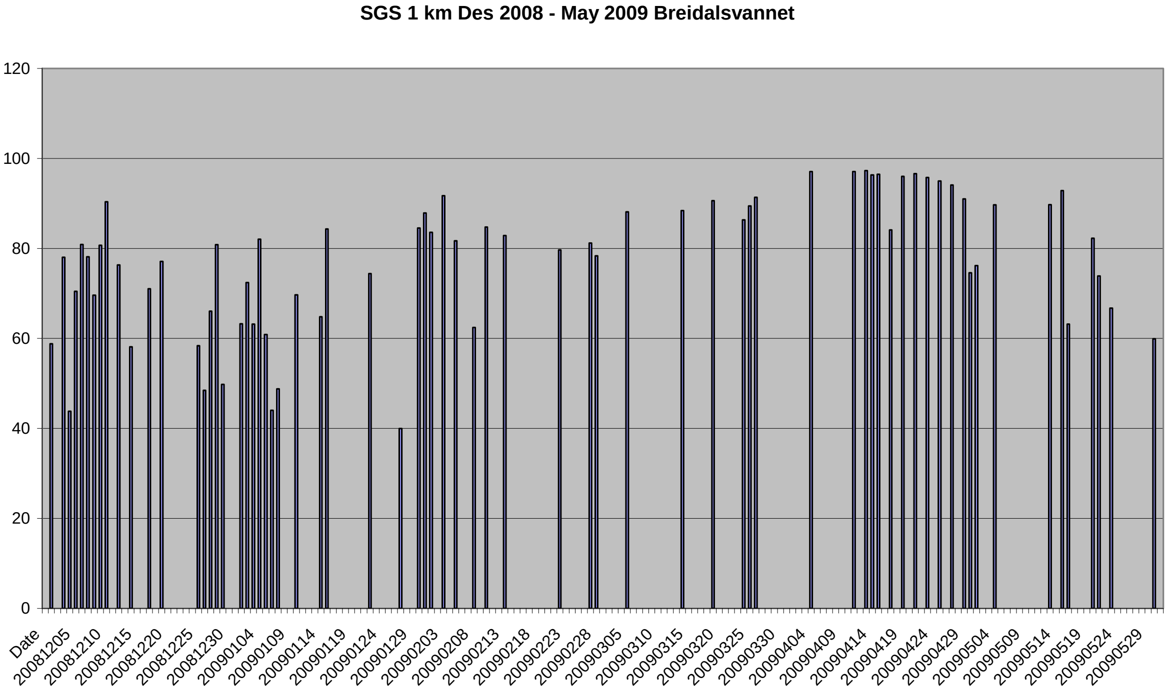


Figure 3.4. Time series of FSC/SCA, STS, SGS and SSW for the period December 2008 until May 2009



Figur 3.5. The development of SGS for one 1 km² area at Breiddalsvannet for the 2009 season. The scale is grain size index multiplied by 100.

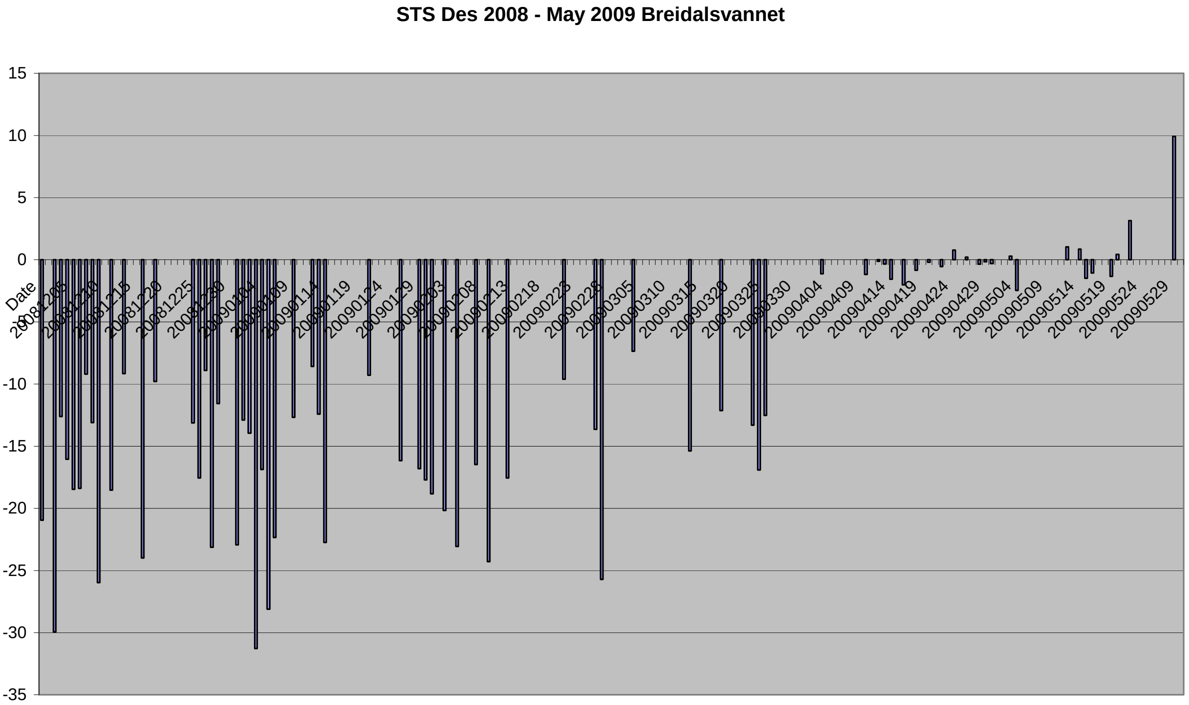


Figure 3.6. The development of STS for the area at Breiddalsvannet for the 2009 season.

3.3 Snow measurements in Romerike, 2009

A search was done on maps and aerial photos to find a possible test area near Oslo. The area should be as flat and as large as possible without vegetation like trees and bushes. To retrieve snow grain size from MODIS images, the area should at least be 500 m × 500 m. For retrieval of temperature and wetness, the area should be at least 1 km × 1 km. It is almost impossible to find areas of sufficient size near Oslo. After selection of some possible locations at Romerike, the sites were inspected. Only two were found usable, one at Egner and one at Jølsen. The sites are marked in Figure 4.7. The site at Jølsen was found to be best. It is completely flat, and close to 1 km^2 without tall vegetation.

3.3.1 Field measurements

Field measurements were done with spectrometer (ASD FieldSpec Pro spectroradiometer) in addition to registration of the temperature of air and snow, and snow density and wetness. The measurements were done on days without clouds at satellite passage. During the measurements at Egner 16 March, clouds appeared, and covered the area at the time of satellite passage. One measurement was done at Sogn, close to NR on a day when snow just had been falling. On this day the snow grains were small and had some sharp edges. They were somewhat stuck together, but not frozen together in large aggregates. The other days, the grains were frozen together in lumps of 3-4 mm size and larger. One could distinguish rounded units of about 1 mm size. The field measurements are summarised in Table 3.1.

Table 3.1. Field measurements of temperatures and snow grain size

Location	**Date**	**Air temp (°C)**	**Snow temp (°C)**	**Snow surface**	**Grain size min. (mm)**	**Grain size aggregated (mm)**
Egner	16.03.09	+6.5	0	Beginning crust	≤ 1	3-4
Jølsen	19.03.09	+3.7	0	Crust, hard	≤ 1	≥ 3-4
Jølsen	24.03.09	+0.5	0	Crust, ~5 cm	1-2	≥ 2-4
Sogn	29.03.09	+4.9	0	New, dry snow 2-5 cm above crust	0.3-1	-
Jølsen	01.04.09	-	-	Wet above weak crust	≤ 1	≥ 2-4

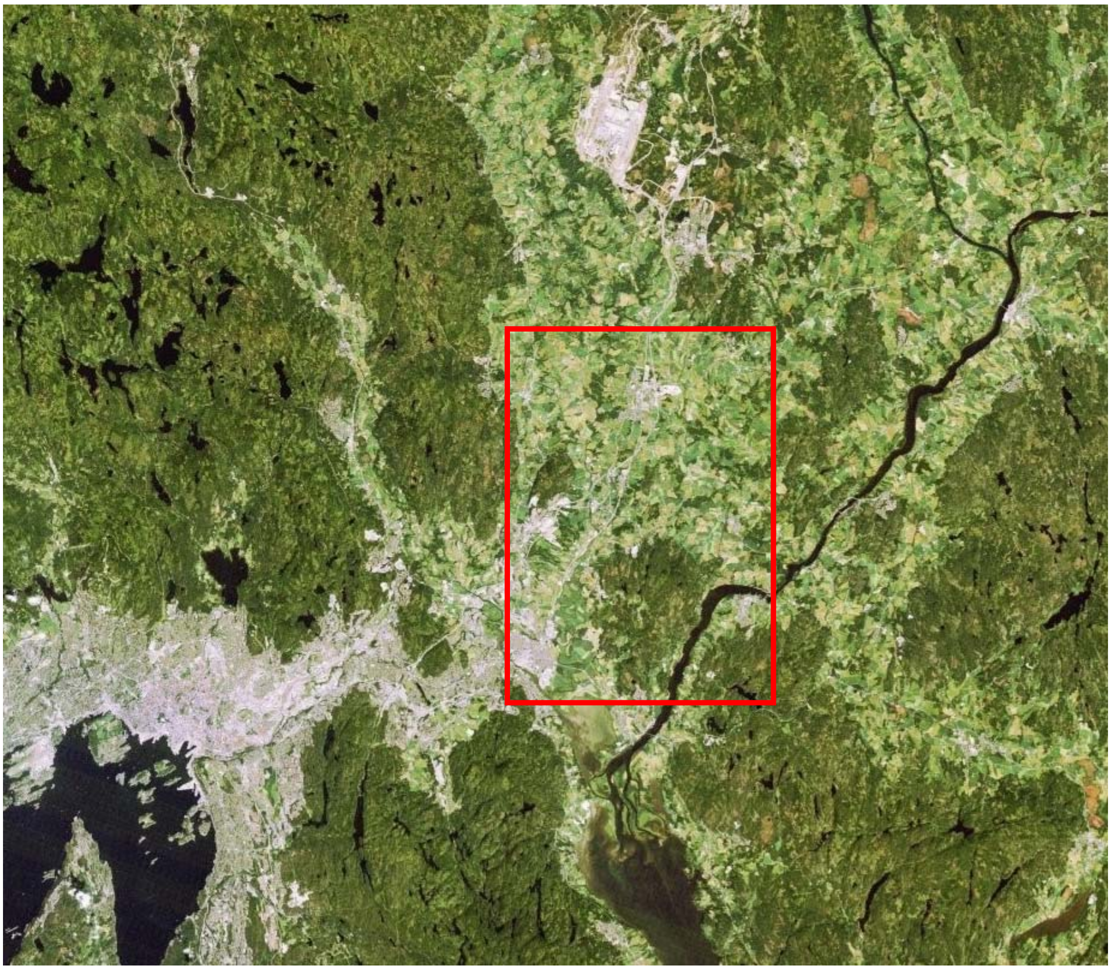


Figure 3.7. Region in Romerike where suitable test sites where searched. Oslo is to the left. Gardermoen airport in the north

3.3.2 Satellite measurements

A region of 13 km × 18 km was searched for potential satellite measurement sites in Romerike. The site should be flat and without forest and infrastructure. The location of the region is shown in Figure 3.7. A closer view of the region is shown in Figure 3.8, where the test sites at Jølsen and Egner are marked. As one can see, there are forested areas in the south. Parts of the town Lillestrøm is in the south western corner, and the town Kløfta is in the centre of the upper part of the region. The rest of the region is mainly farm land with open, cultivated fields. However, in many places there are small forested areas and trees along the borders of the fields. This means that there are very few open areas with size of at least 500 m × 500 m, and practically none of size of 1 km × 1 km. Therefore, the results from the satellite measurements will differ from the measurements at Stynefjellet without vegetation and buildings. The measured FSC values will be slightly too low for the whole region, especially in the forests and populated areas. The measured SGS values will also be lowered by the presence of vegetation and buildings, but it will be possible to detect the trends of increasing and decreasing grain size in the open areas. There will also be influence from vegetation on the measured surface temperature.

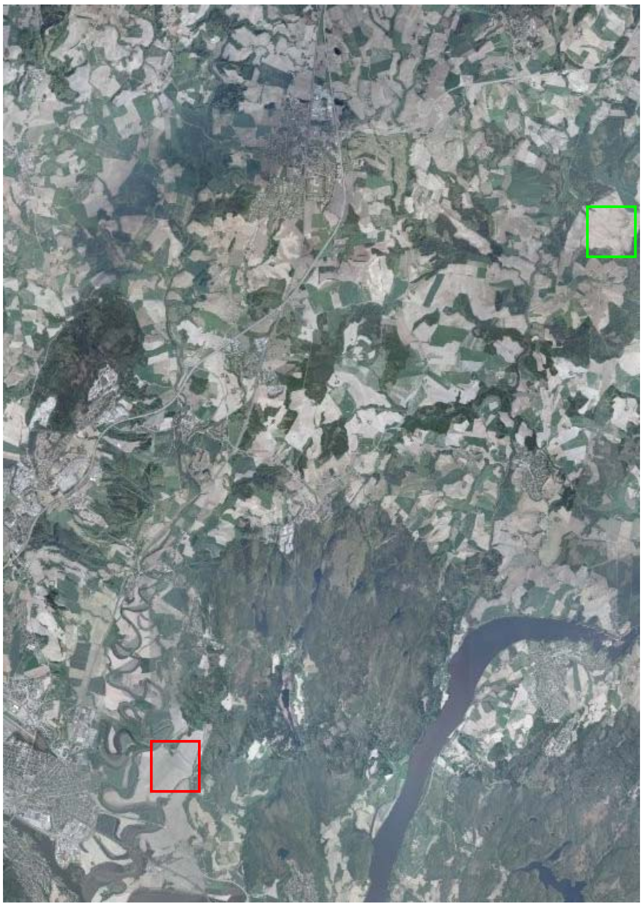
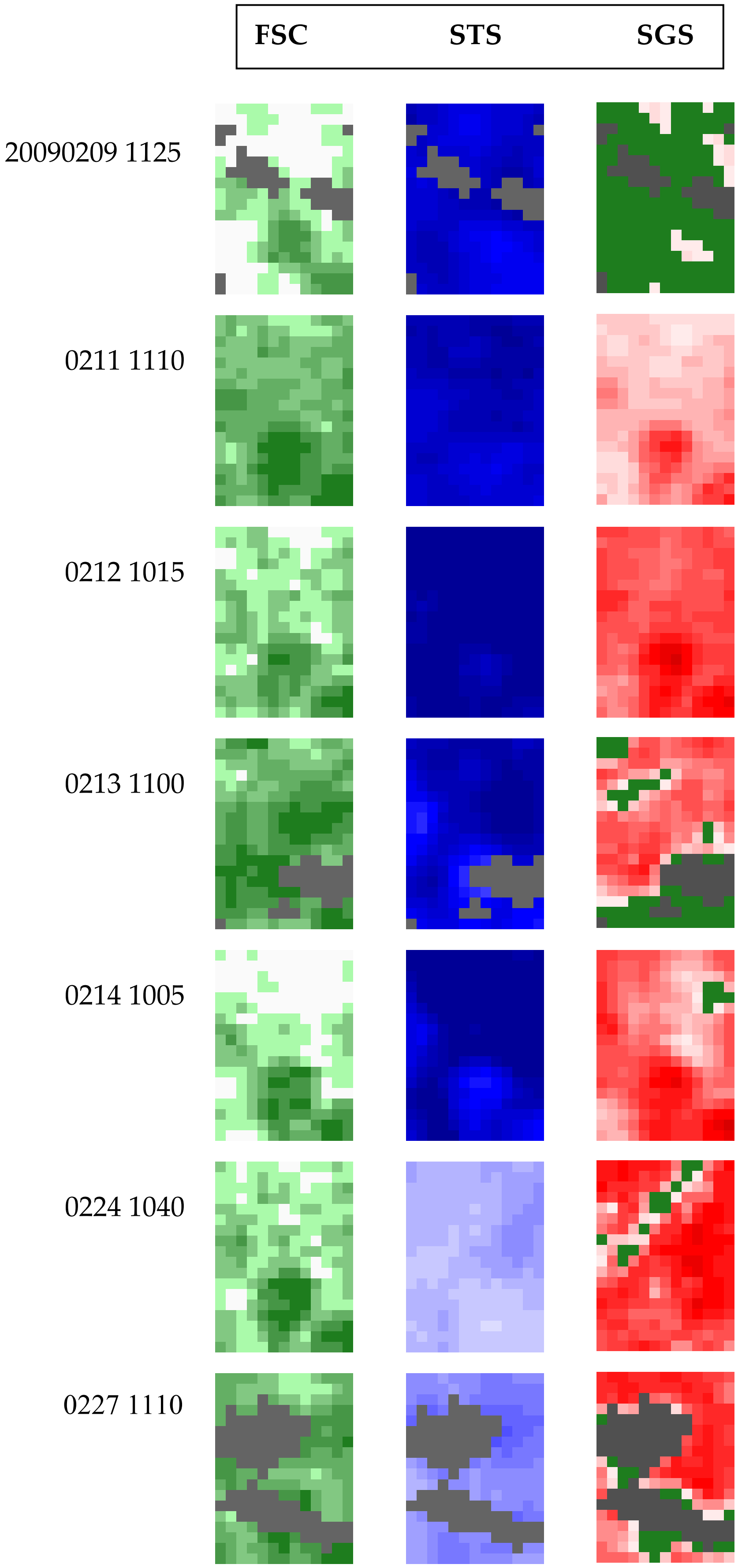


Figure 3.8. Romerike test site. A 1 km² pixel at Jølsen is marked in red, and at Egner in green.

In Figure 3.8 a pixel of size 1 km² is marked at Jølsen. This is the position of a pixel after geographic correction of the satellite image. In the original image, there is no pixel covering this area exactly. The value of the corrected pixel will be influenced by the values of surrounding original pixels. The positions of the original pixels will vary from image to image, so the influence on the corrected Jølsen pixel will be different from day to day. The corrected pixel covers mostly open fields, but there are also some trees inside it. From day to day the influence of the surrounding vegetation will vary, and therefore one cannot use the corrected SGS values as an exact measure of the snow grain size at Jølsen. But as the main part of the pixel and the nearest surrounding areas are open fields, the measured SGS gives a reasonable correct picture of the development of the snow grain size.

In Figure 3.9 the measured values of FSC, STS and SGS are shown for the region for the time period from 9 February until 11 April. Before and after this period, there was too little snow to obtain results of interest. Because of the low FSC values, no reasonable SSW values were measured in the time period.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SGS
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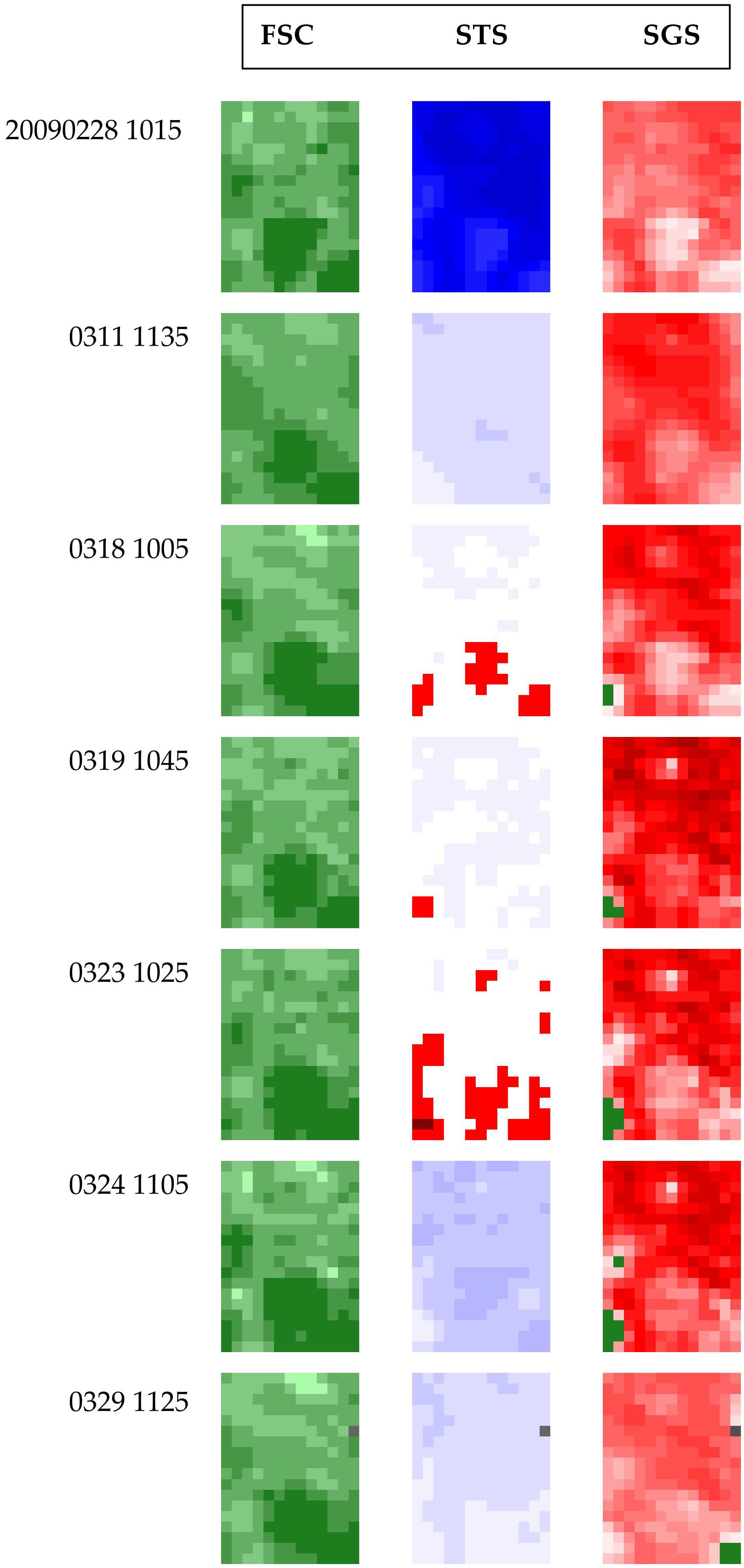
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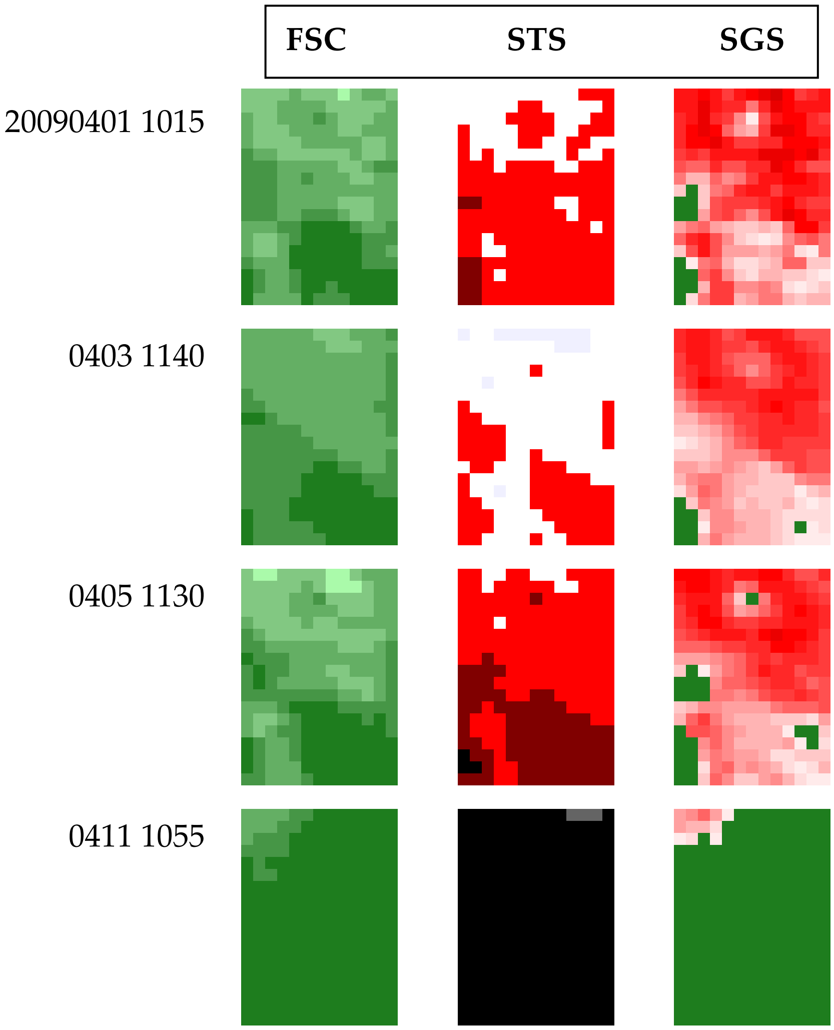


Figure 3.9. Development of FSC, STS and SGS for Romerike test area from 9 February until 11 April 2009

The development of SGS and STS at Jølsen test area is shown in Figure 3.10 and 3.11.

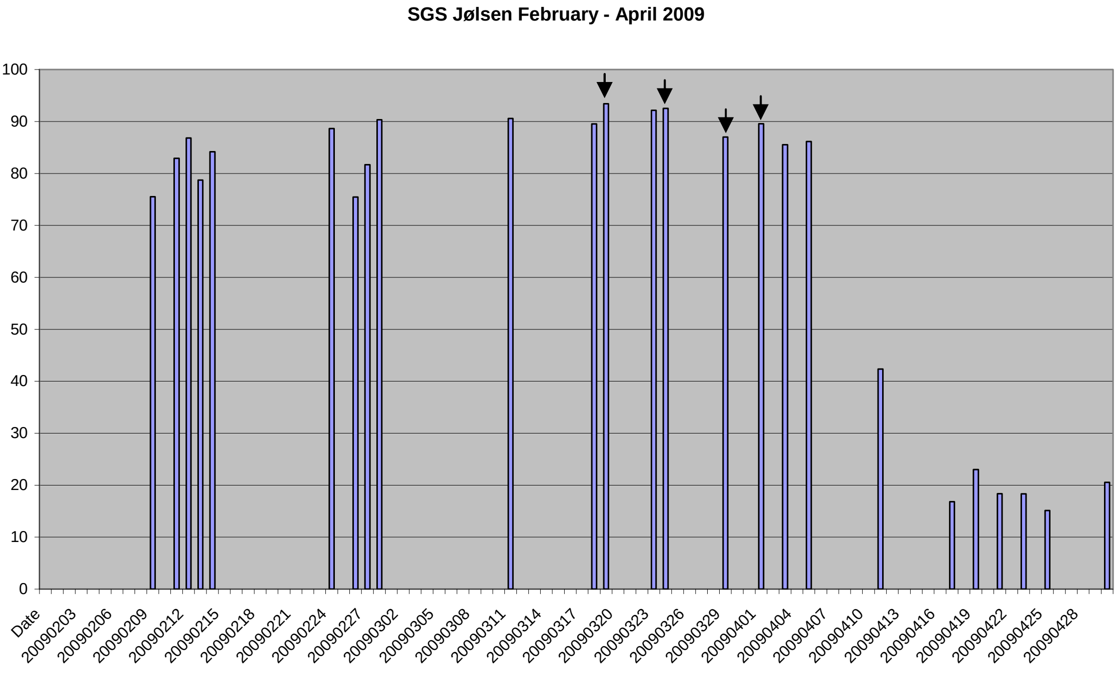


Figure 3.10. Development of snow grain size index at Jølsen for February – April 2009. Days of field measurements are marked with arrows.

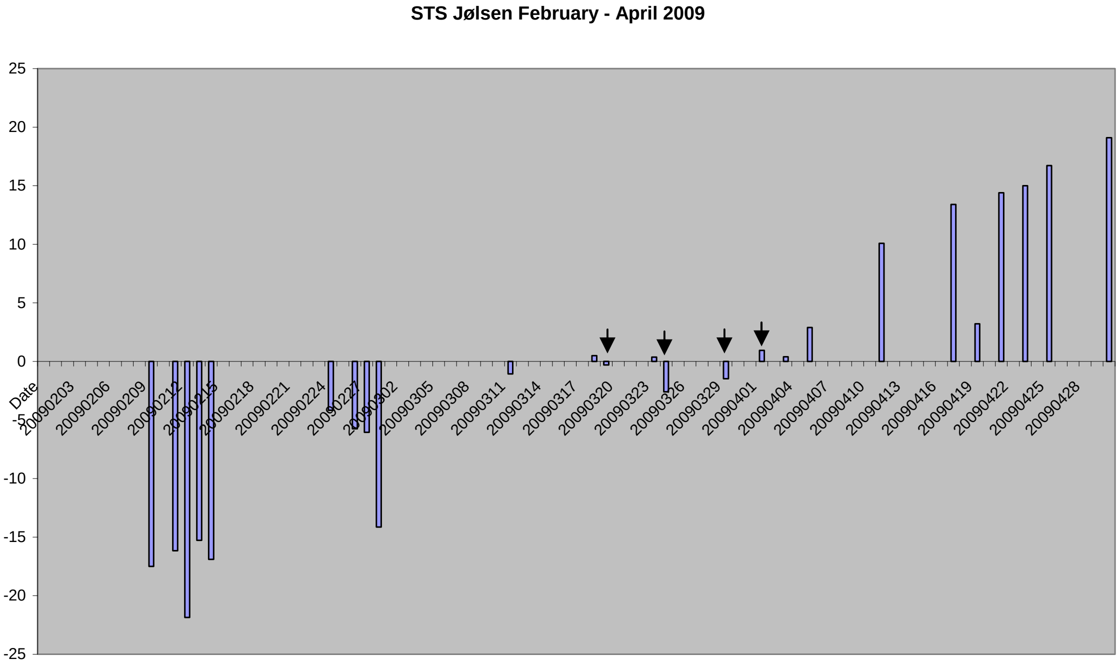


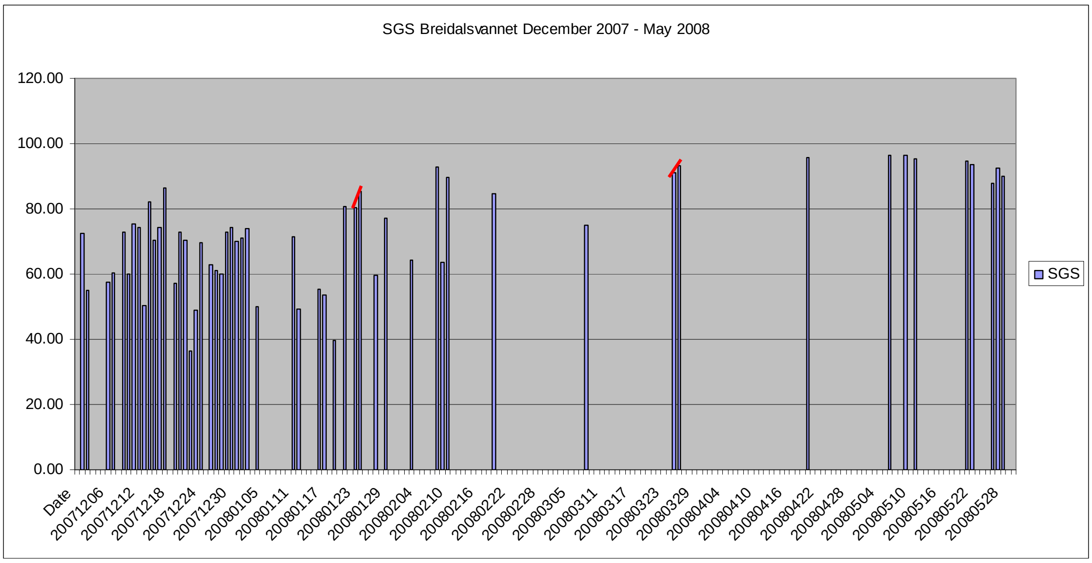
Figure 3.11. Development of snow surface temperature at Jølsen for February – April 2009. Days of field measurements are marked with arrows.

4 Interpretation of the satellite measurements

Retrieval of FSC, STS, SGS and SSW has been done for the two snow seasons 2007-2008 and 2008-2009, from December until end of June. The results from June have not been interpreted as there was not much snow left and the images just show bare ground and temperatures above 0°C.

4.1 Strynefjellet

In 2008 the winter was long and cold. The snow was mostly dry until 7 May when a sudden increase in temperature led to a large increase in SGS and snow wetness. The snow became wet during the following days. Then a period of colder weather created dry snow in some areas, but not for long. At the end of May the snow was wet.



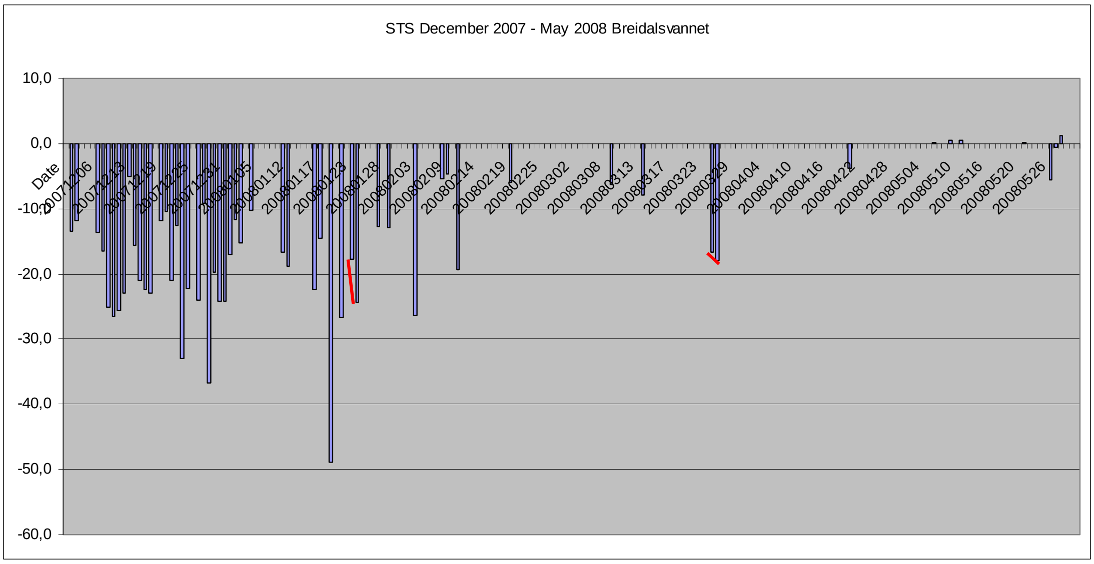


Figure 4.1. SGS (top) and STS (bottom) for the season 2007-2008. Two special cases of simultaneous interesting development of SGS and STS have been marked with red lines

Figure 4.1 shows observed SGS and STS through the 2007-2008 snow season. As we are in particular interested in situations where surface hoar might have been created, we are searching situations where SGS increases over a few days simultaneously with cold temperatures. As surface hoar is usually created under cold, clear sky conditions, there is a good chance to actually observe the phenomenon. Two cases seem of particular interest in the diagrams: around 23 January and around 25 March. SGS is increasing from one day to the next, and the temperatures are cold (and the sky is clear as we have observations). The development of SGS and STS is indicated by red lines.

In 2009 there was cold weather with dry snow until 26 March. The next observation is 4 April and then the temperature and grain size have increased, but there were no really wet snow before 21 April. From then on there are several colder and warmer periods, with changing dry and wet snow. At the end of May the snow is wet and much of it has melted.

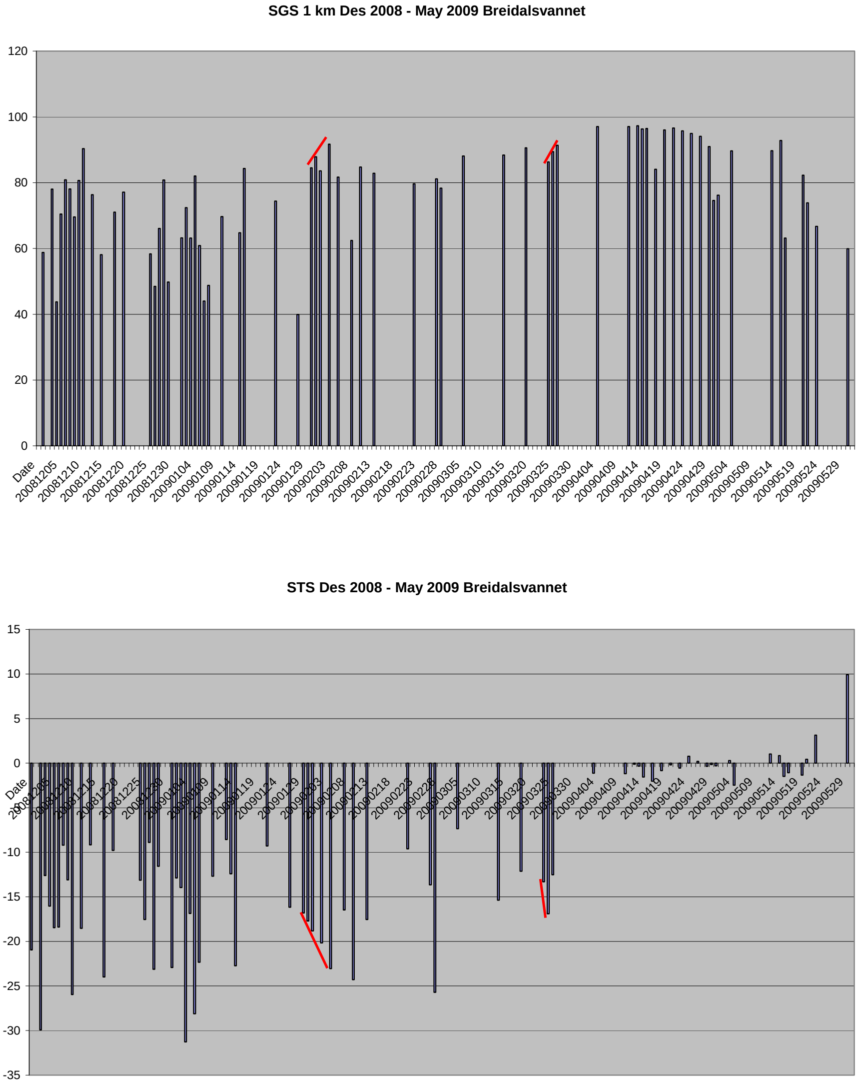


Figure 4.2. SGS (top) and STS (bottom) for the season 2008-2009. Two special cases of simultaneous interesting development of SGS and STS have been marked with red lines

For 2009, there are also two cases of particular interest: around 30 January and around 20 March. SGS increases over a few days in all three cases simultaneously with a parallel drop in STS.

For both snow seasons, it has not been possible to get the SGS development confirmed by in situ measurements. The web camera at NGI's field station Fonnbu does not provide sufficient spatial resolution of the snow surface to observe surface hoar with reasonable confidence. Also, the field measurements did not take place exactly simultaneously with the interesting cases. Furthermore, the field measurements usually took place at longer intervals so it has not been possible to get snow development from one day to the next confirmed.

By coincidence, one of the authors (H.K.) went skiing at Norefjell the weekend 30 January–1 February and surface hoar was observed. The photo in Figure 4.3 was taken at about 900 m above sea level on the western side of Norefjell, a couple of kilometres south of Tempelseter. We do not know whether the weather situation was similar within such a large region that the Norefjell observation gives an indication for Strynefjellet as well. Anyway, we analysed satellite data for Norefjell as well for development in SGS and STS.

Figure 4.3. Snow surface at Norefjell 31 January 2009

Figure 4.4 shows the SGS index measured from satellite for a 15 km ×15 km area covering Norefjell for the days 27, 30 and 31 January. There were clouds on 1 February.

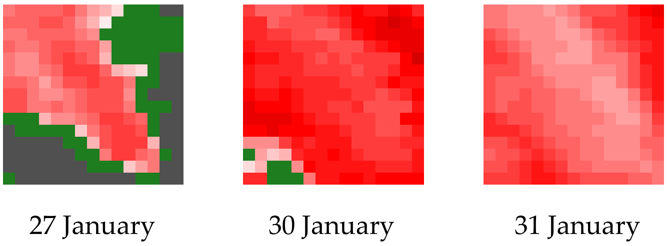


Figure 4.4. SGS for Norefjell at the end of January 2009

One can see that there is an increase of SGS from between 27 and 30 January, and a decrease the next day. For the pixel where the photo was taken, the development of SGS and STS is shown in Table 4.1.

Table 4.1. SGS and STS at photo location

Date	**27 Jan**	**30 Jan**	**31 Jan**
SGS	0.868	0.911	0.880
STS	-13.8	-8.6	-6.3

While the temperature was steadily increasing, the SGS had a maximum value on the 30th, and had a lower value on the day with the surface hoar. At the photo location, there is an open area, a couple of hundred meters wide, with some single trees here and there. Around there is forest on all sides. This means that it is not only the snow that affects the retrieved grain size index of at this position. However, the same tendency of a maximum on the 30th can be seen all over the area, also where there are no trees. There are no photos or field measurements of the surface on the 30th, so it is difficult to get the SGS increase confirmed. Anyway, a clear surface hoar situation was at least observed in situ.

4.2 Romerike

From Figure 3.9 one can see that the measured FSC is low (too low) in the whole period and especially in the forested areas, as expected. There is a cold period until the end of February. From 11 March the temperature is rising, and gets close to 0 °C from the 18th. The grain size is increasing.

The field measurements from 19 and 24 March show large grains. Between 24 and 29 March there is snowfall. The grain size has decreased on the 29th. This can bee seen for the whole area in Figure 3.9 and for Jølsen in Figure 3.10. This is reflected in the field measurement at Sogn. The field measurements show 0 °C in the snow all days, while the satellite measurements show temperatures somewhat below zero. At 1 April both satellite and field measurements show increased grain size. The satellite measurements show snow temperature above zero for a large part of the test area. This is due to melting of the snow, and areas of bare ground appearing in the fields.

4.3 Feasibility of SGS retrieval

One first experience was that starting as early as December creates problems. We had little previous experience of using the snow retrieval algorithms on images taken before the beginning of March. Because of the low solar elevation, the measured signals from reflected light are low. There are large shaded areas, and the areas oriented away from the sun receive little light. The retrieved FSC is too low in general. This influences the computation of SSW, which gives no valuable result when FSC is well below 100%.

MODIS channel 7, which has been used in retrieval of SGS, has a defect. This is shown as stripes in the images. One scan covers ten 1 km pixels in the flight direction, so there are ten lines across the image per scan. One can see that there is a difference in the signals from the ten lines. Roughly one can say that five of the lines give lower values than the other five. The difference is not large, and is not detectable in the late spring and summer when the solar elevation is large and the signals are high also in channel 7. In the winter, however, the differences are large relative to the total signal and have great influence on the SGS values.

In Figure 4.5 one can see the stripes in the image showing SGS for part of southern Norway. This makes it difficult to estimate the development of SGS from MODIS images at this time of the year. The stripes will change position on the Earth from day to day, and an increase in SGS value for one area could be caused by the position of the stripes and not by actual increasing grain size. Therefore, one should be careful drawing conclusions about changes in the SGS during the darkest parts of the winter.

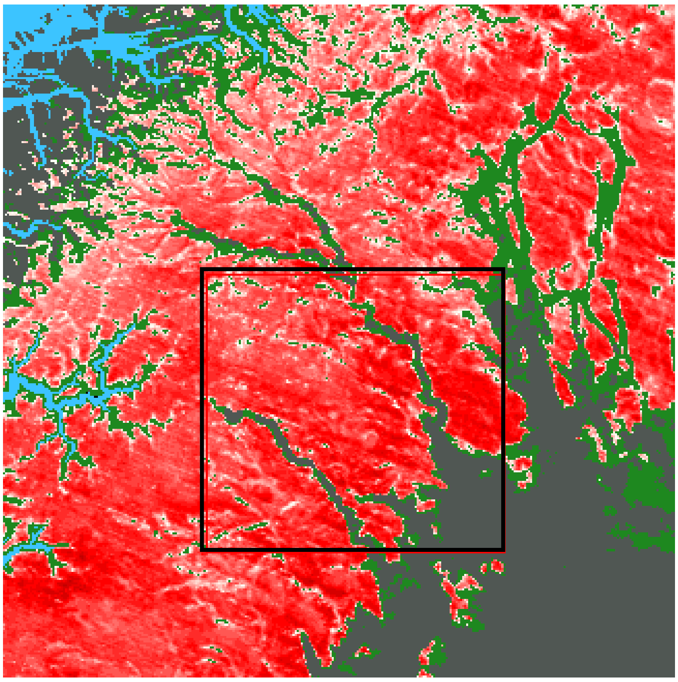


Figure 4.5. SGS for 30 January 2009, showing striping due to channel 7 defect

Looking at the plots of SGS (Figures 3.2 and 3.5), one can see that the values go up and down and are often very low in the darkest period. This may be caused by the channel 7 defect, but also by the effects of the solar elevation.

Clouds might cause problems when they are not covering the complete area. The cloud detection algorithm is not perfect, and there may be problems at the border of the clouds. If the clouds are larger than estimated, there may be errors in the estimation of STS and SGS near the cloud borders. This can be seen in a number of the images. In the SGS image for 26 March 2009, one can see low SGS values near the clouds, while the values are higher than for 25 March away from the clouds. This can also be caused by cloud shadows on the ground.

5 Conclusions

Measurements of snow grain size and type at the surface are of special interest within the field of avalanche research and warning. In continental and inter-mountain avalanche climates weak layers or interfaces of the snow pack are the main cause of avalanches. Optical satellite sensors measure reflected sunlight at different wavelengths in the visible and infrared part of the electromagnetic spectrum. The near-infrared region is sensitive to the optical grain size of the snow. Due to the distinct size and shape characteristics of potential weak layers such as, for example, surface hoar, their reflectance is quite different from other types of snow, such as new snow or melting snow. Surface hoar is often created under clear sky conditions, so chances of observing snow crystal growth are fairly good.

The focus of the pilot study behind this report has been simultaneous collection of in situ data and the acquisition of satellite data for establishing a relationship between avalanche-relevant variables and variables retrieved from the remote sensing data. Specifically, in situ measured surface snow grain characteristics have been compared to snow grain characteristics as derived from multispectral data from the MODIS satellite sensor. The satellite data study part of the work has been presented in this report.

Data from four test sites have been studied. Three sites are located in the Strynefjell mountain range, Western Norway. Two of the sites are close to the snow and avalanche research station Fonnbu of NGI and the third is situated at Breiddalsvatnet. In the latter case, the effects of the topography are eliminated. A fourth site in the Oslo region (close to Lillestrøm) was added in order to allow for quick response for fieldwork when the weather permits satellite observations. The site is located in a flat agricultural area about 30 km north-east of Oslo, thus eliminating topographic effects.

Retrieval and analysis of FSC, STS, SGS and SSW from MODIS data has been done for the two snow seasons 2007-2008 and 2008-2009, from December until May. The darkest part of the snow season (in particular December and January) gives somewhat unreliable results due to low solar elevation. It is hard to determine whether there is full snow cover from FSC, and the SGS index contains a significant component of noise due to the slightly variable sensitivity of MODIS channel 7 detectors.

Two cases of particular interest were found in the 2007-2008 dataset and two cases in the 2008-2009 dataset. The observed SGS increased over a few days (typically 2-3 days), while STS decreased. Due to the lack of simultaneous field measurements, it was not possible to confirm that these cases represent surface hoar. However, in one case surface hoar was observed coincidentally at Norefjell, and an analysis of corresponding satellite data from Norefjell showed an increase of SGS over a few days.

The measurements in Lillestrøm started too late in the season to observe surface hoar. However, variable grain size was measured in the field with corresponding variability in SGS. These data can therefore contribute to the establishment of an accurate relationship between observed SGS from satellite and snow grain size and shape as measured in the field.

For further studies of snow surface properties measured from satellite, and in particular the development of surface hoar, it is recommended to increase the number of in situ measurements significantly to get a reasonable chance of obtaining simultaneous measurements in situ and by satellite. It is also recommended to continue the studies at Jølsen in the Lillestrøm area to establish a model for the relationship between variables measured in situ and from the satellite data.

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