A multi-sensor multi-temporal approach to retrieving snow surface wetness from a combination of Sentinel-1 and Sentinel-3 data

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8th EARSeL workshop on Land Ice and Snow
7-9 February 2017, Bern, Switzerland

SnowBall project objectives and remote sensing of snow wetness

- The overall *SnowBall* project objective is to explore and develop methodology supporting the vision of developing a future service providing national authorities in Romania with hind-cast and real-time snow and avalanche information retrieved from earth observation data
- Project work includes development of algorithms and implementation of a prototype snow monitoring system
- Sentinel-1 and Sentinel-3 satellite data for snow surface wetness mapping based on:
  - Optical Wet Snow (OWS)
  - SAR Wet Snow (SWS)
  - Multi-sensor Wet Snow (MWS)
- Applications in flood warning and hydrological modelling

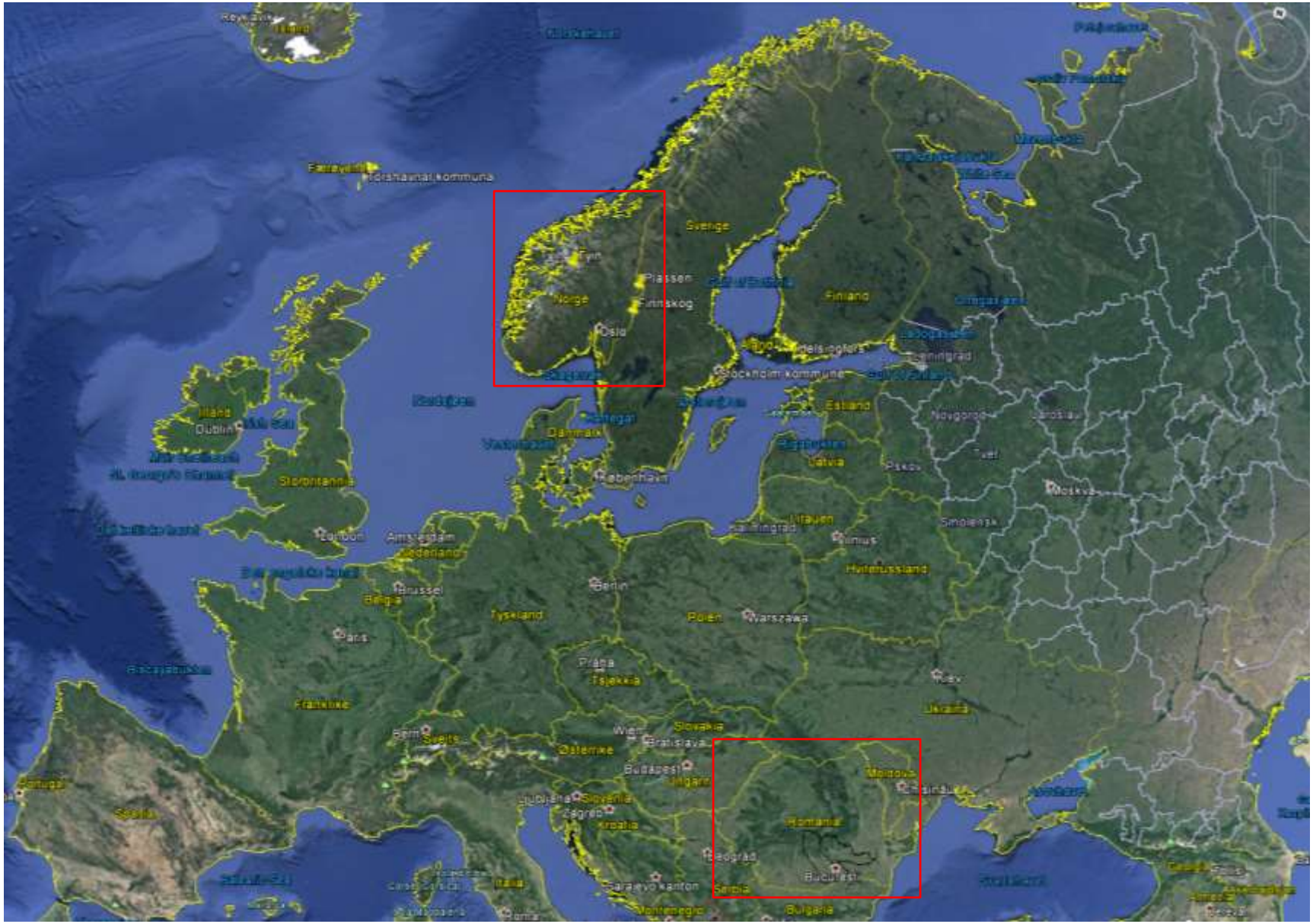


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SnowBall

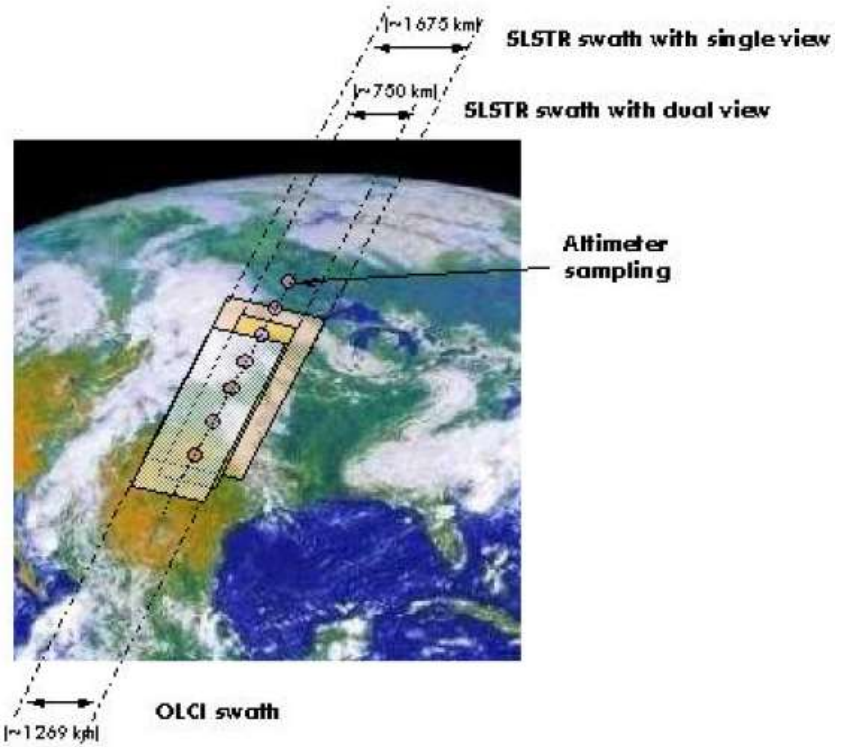
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Prototype product domains



Optical data sources

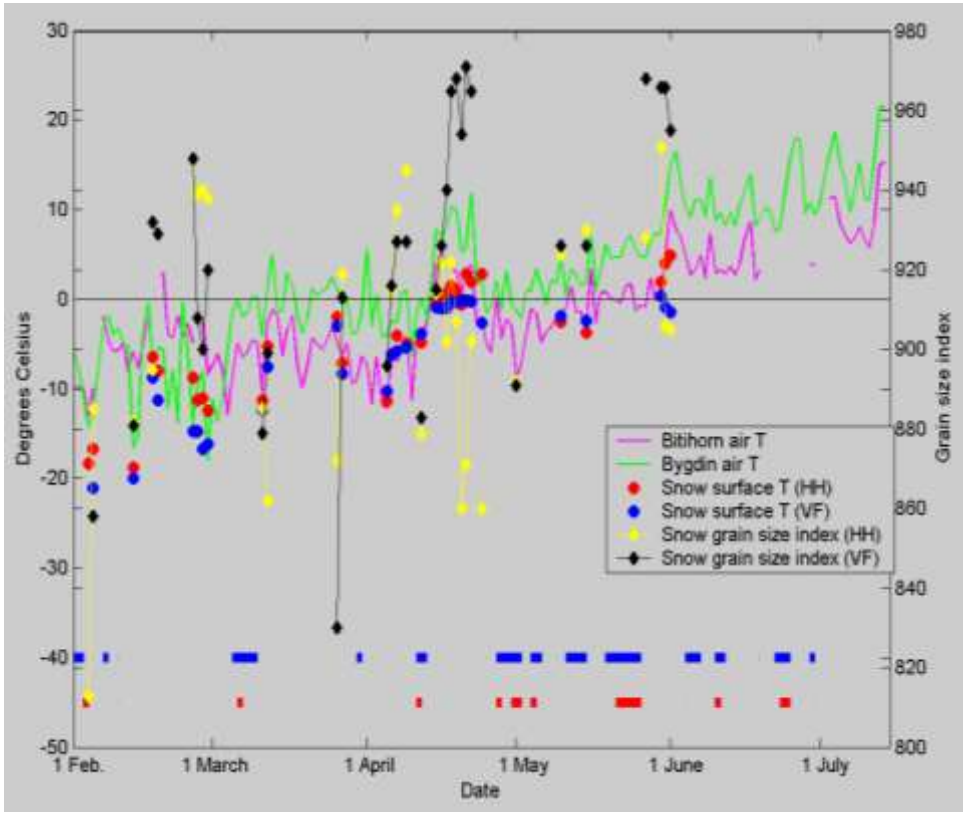
- Sentinel-3 Sea and Land Surface Temperature Radiometer (SLSTR)
  - Swath width 1675 km
  - 9 bands
  - Spatial resolution 500-1000 m
- Sentinel-3A launched 16 February 2016. Commissioning phase completed summer 2016 and ramp-up phase in late autumn 2016
- Used Terra MODIS until Sentinel-3 became available
- Suomi NPP VIIRS as backup



Band	λcenter [µm]	Δλ [µm]	SNR [-] / NeΔT [mK]	SSD [km]
S1	0.555	0.02	20	0.5
S2	0.659	0.02	20	0.5
S3	0.865	0.02	20	0.5
S4	1.375	0.015	20	0.5
S5	1.61	0.06	20	0.5
S6	2.25	0.05	20	0.5
S7	3.74	0.38	80 mK	1.0
S8	10.95	0.9	80 mK	1.0
S9	12	1.0	80 mK	1.0

Concept for retrieval of snow wetness retrieval from optical data

- Optical effective snow grain size (SGS) sensitive to liquid water content
- Analysis of the temporal development of the SGS together with surface temperature of snow (STS) might be used to infer whether the snow is dry or wet
- In situ measurements and empirical knowledge indicate that there is information related to snow liquid water (SLW) in the observations
- Have developed a decision tree algorithm to derive qualitative wetness categories



Field measured snow temperature, and satellite-measured snow temperature and effective snow grain size for Heimdalen test site in 2003. HH = Heimdalshø, VF = Valdresflya

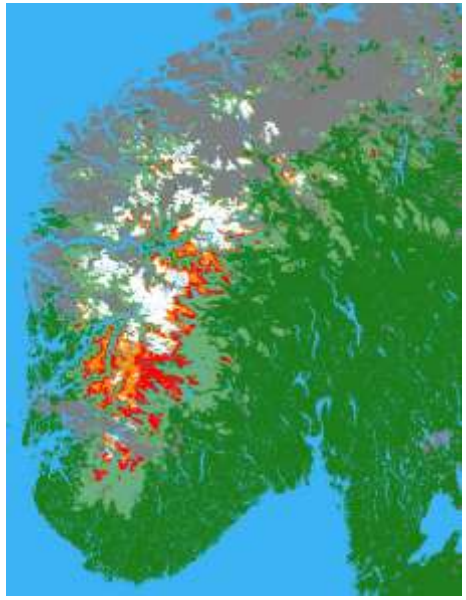
OWS examples from southern Norway in 2015



4 March 2015



9 April 2015



5 June 2015

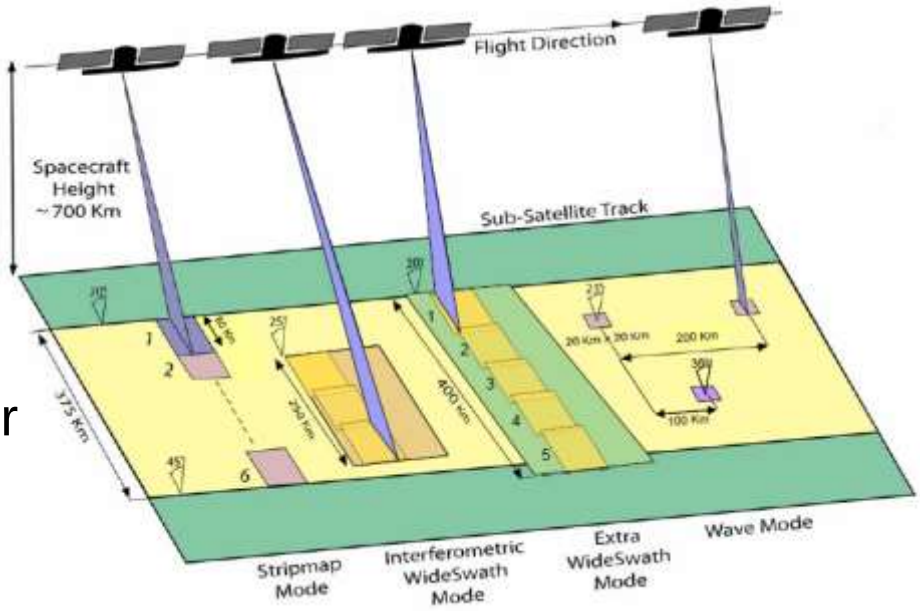


4 July 2015

Snow wetness class	Colour
Dry	
Moist	
Wet	
Very wet	
Soaked	

SAR data source

- Sentinel-1:
  - Sentinel-1A launched 3 April 2014
  - Sentinel-1B launched 25 April 2016
- The C-band SAR operates in four modes:
  - Strip Map Mode (SM)
  - Interferometric Wide Swath (IW)
  - Extra-Wide Swath Mode (EW)
  - Wave-Mode (WV)
- Primary mode for land is IW:
  - Single-look complex (SLC): 2.3 × 17.4 m
  - Ground Range Detected (GRD): 10 × 10 m; looks 5 × 1

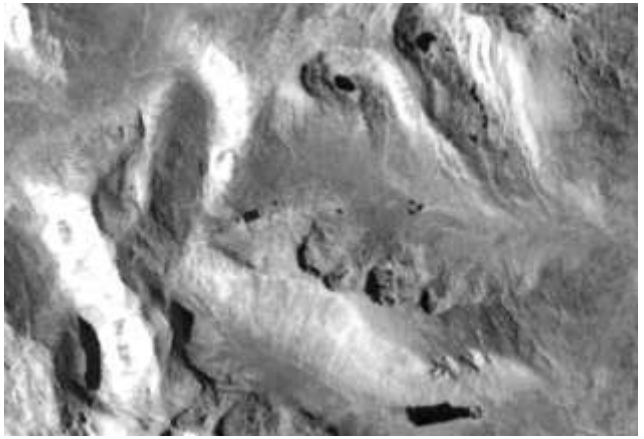




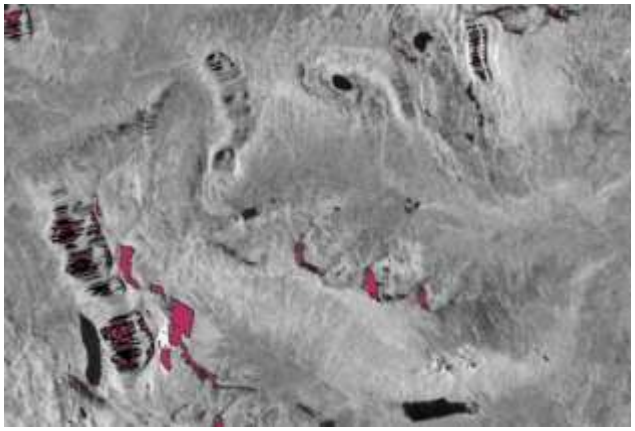
SAR wet snow algorithm

1. Conversion of the SAR data (digital numbers) to gamma naught.
2. Multi-looking to reduce speckle noise. The number of looks we apply depends on the desired output resolution. We have applied 6×6 looks (corresponding to a desired pixel spacing of 50 × 50 m).
3. Conversion to terrain-corrected gamma naught (flattening gamma) backscatter normalization by following the approach proposed by Small (2011).
4. Computation of layover and shadow masks.
5. Geocoding using the range-Doppler algorithm.
6. Construction of daily mosaic images and reference image.
7. Computation of VV-polarization ratio images, i.e. daily mosaic image versus the reference image.
8. Thresholding of ratio images to detect wet-snow. If the difference is more than 4 dB, the pixel is classified as wet-snow.
9. Masking of layover and shadow areas.

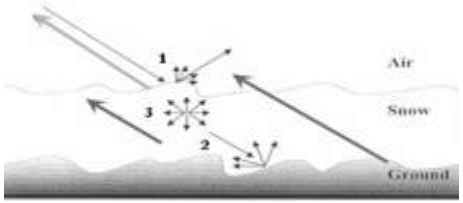
Currently, the algorithm supports Sentinel-1 GRD and Radarsat-2 SCN/SCW/SLC SAR images.



The gamma-naught (γ^0) image Radarsat-2 ultra-fine HH



Flattening gamma radiometric terrain corrected Radarsat-2 ultra-fine HH image. Red areas indicate shadow areas.

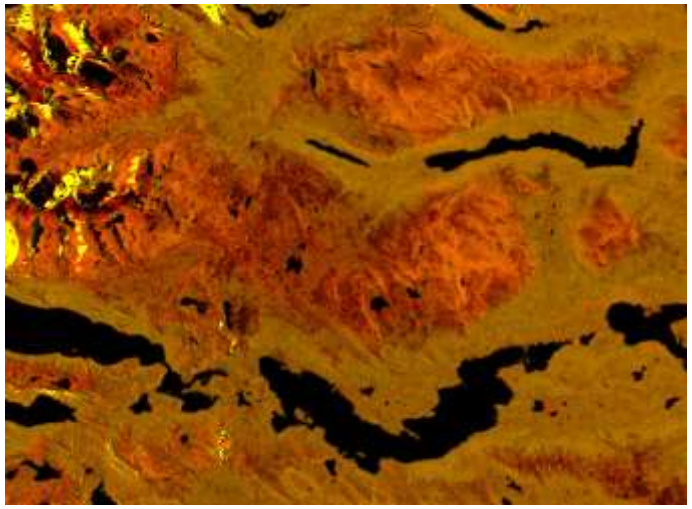


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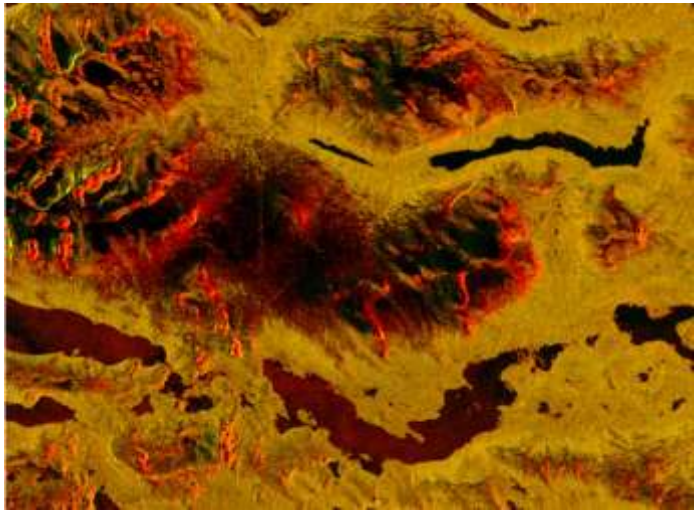
SnowBall

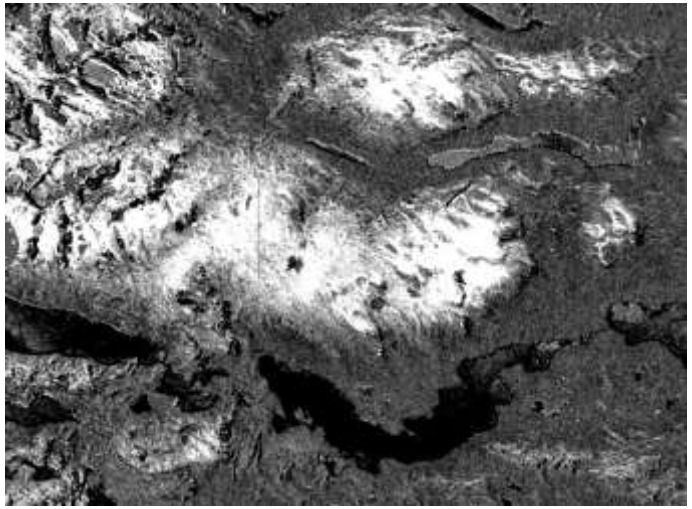
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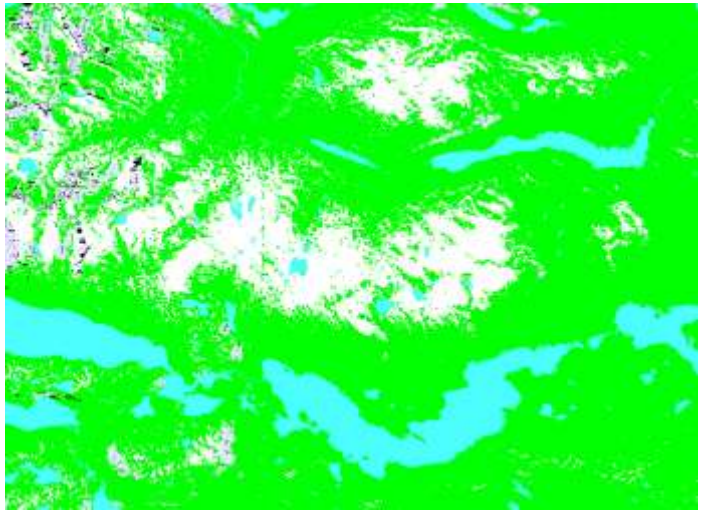
SAR wet snow map 29 June 2015



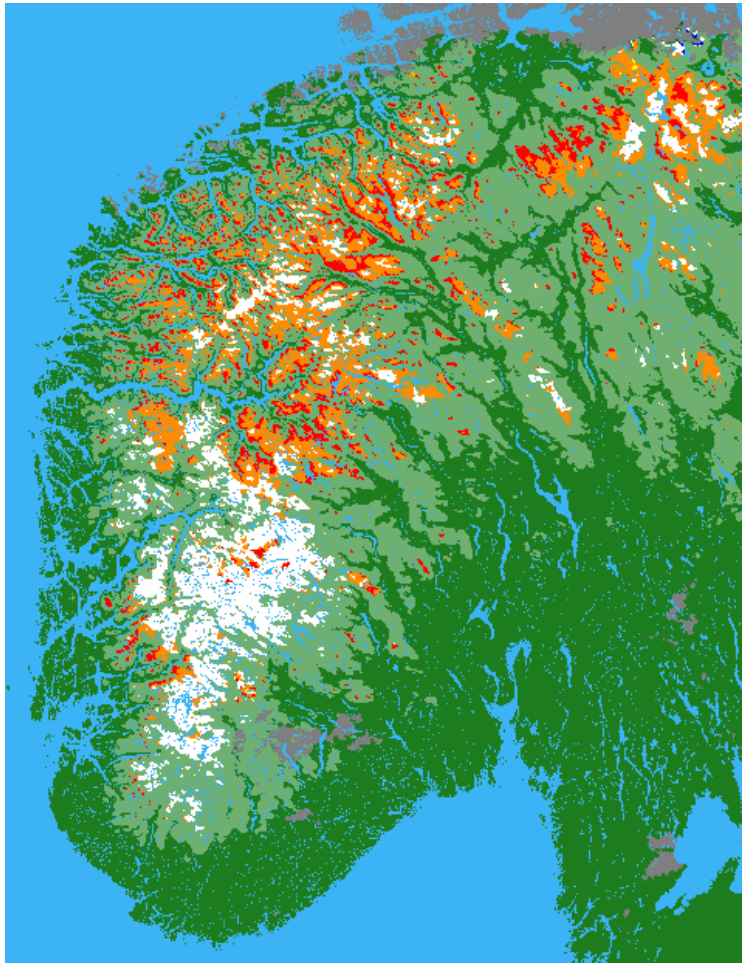
R: VV
G: VH
B: 0



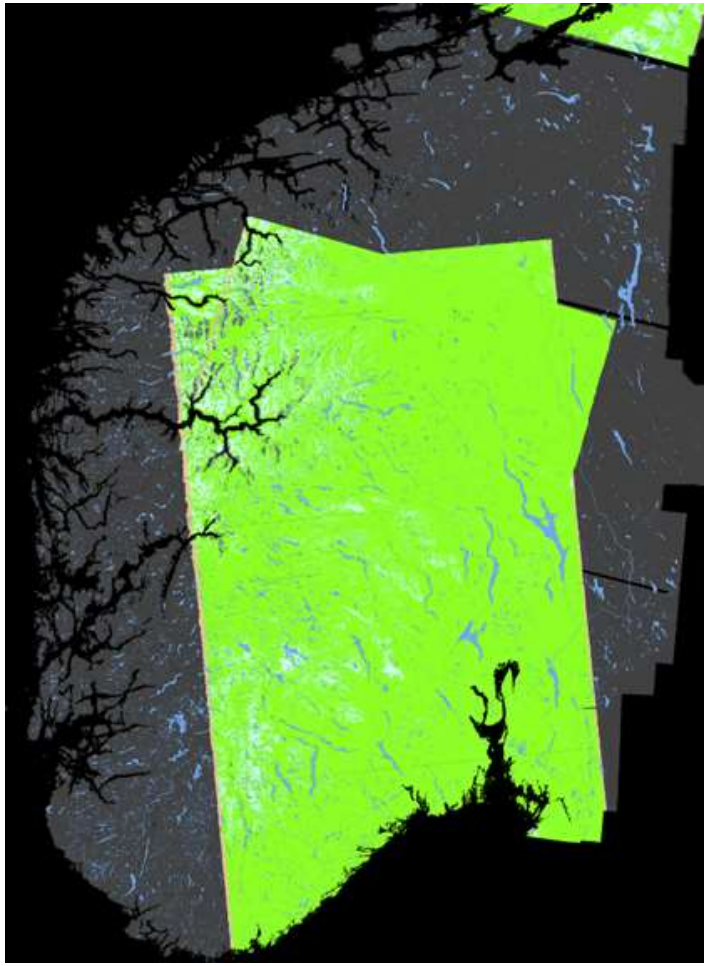




Something to gain from combining optical and SAR?



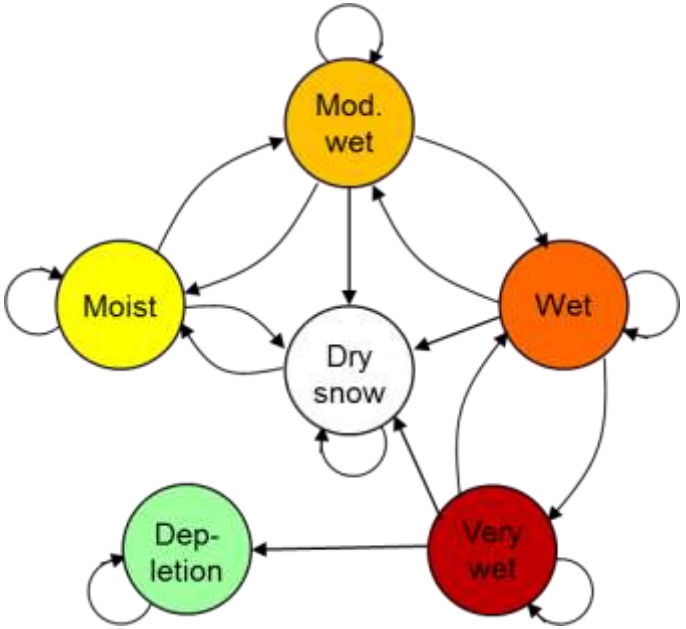
OWS from Terra MODIS, 20 April 2015



SWS from Sentinel-1, 20 April 2015

Multi-sensor multi-temporal algorithm

- State model with five wetness classes, based on a hidden Markov model (HMM)
- *Initial* and *transition probabilities* determined from seasonal snow wetness probabilities based on the optical product or, better, climatological data
- The time series of wetness estimates are smoothed with a Savitzky-Golay filter to extract the seasonal wetness trend
- Multi-sensor algorithm accepts two wetness products, optical product and SAR
- The optical product provides an estimate of the liquid water content, while the SAR wetness product gives a binary variable
- The *likelihood* for each state, given the input signal and assumed to be Gaussian, is found through experimentation or from ancillary data (training)
- Using the Viterbi algorithm, the most likely sequence of states is found based on the input data time series



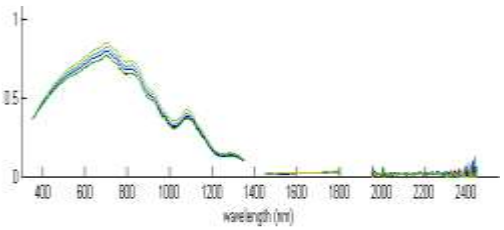
$$p(X^t|E^t = S_i)$$

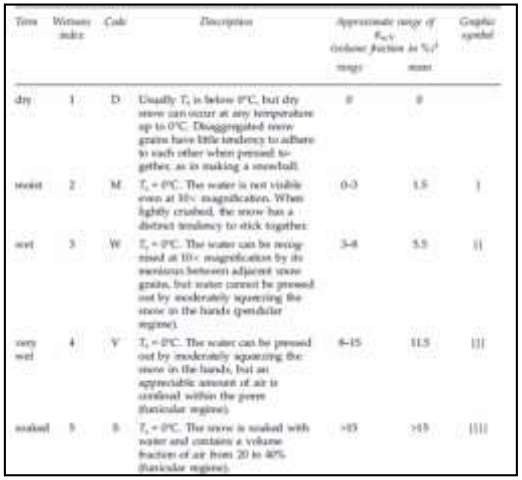
$$p\left(E^t = S_i \middle| E^{t-1} = S_j\right)$$

Ongoing calibration validation work

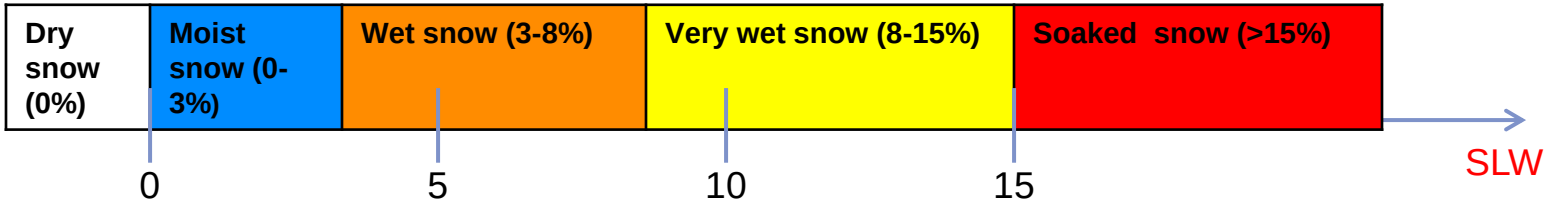
- Previous OWS product included qualitative classes only
- Field measurements of snow spectra and SGS (ASD FS), and snow liquid water (Denoth probe) content are currently used to refine the retrieval algorithm to confirm with “Int. class. of seasonal snow on the ground” standard



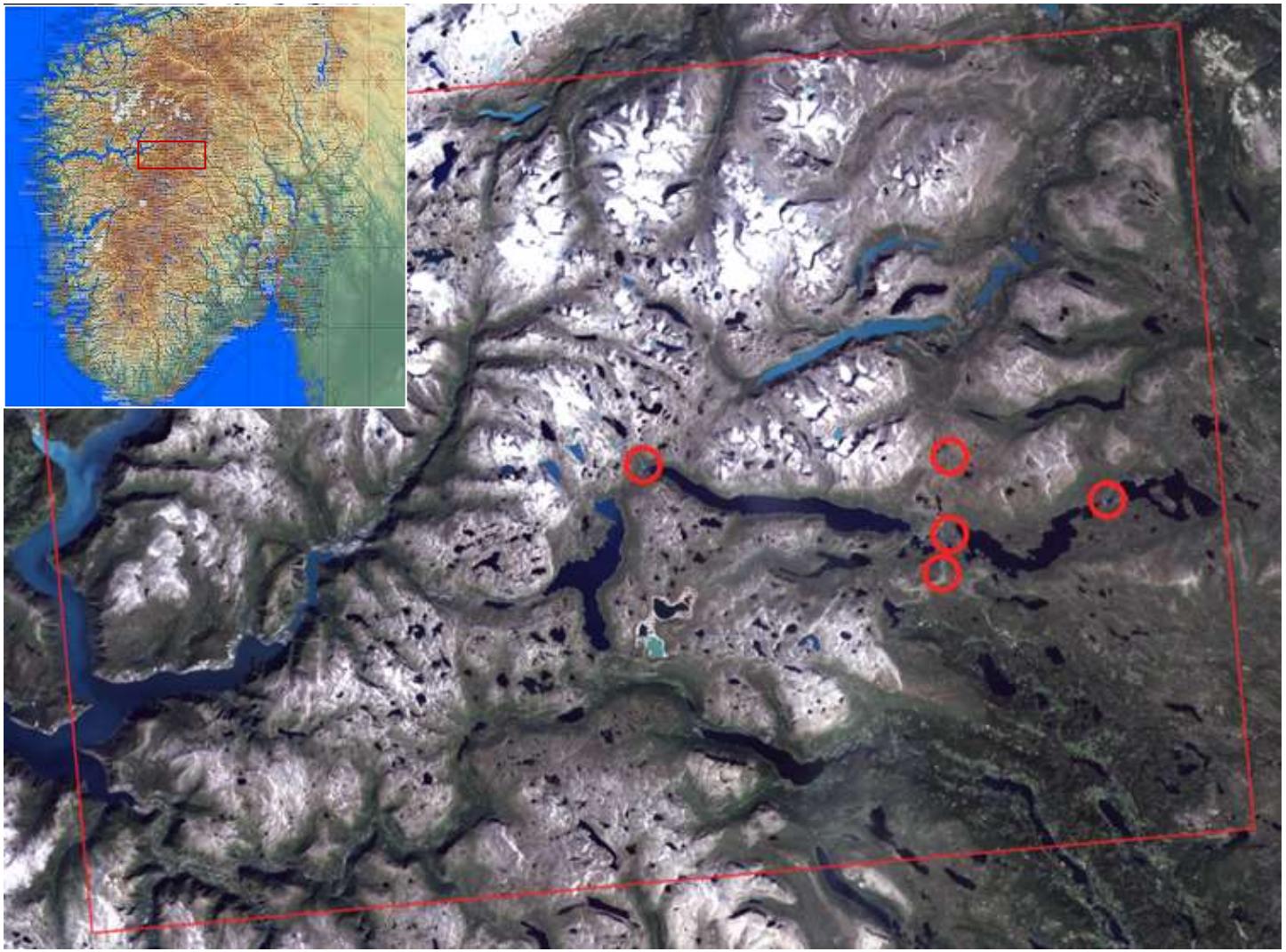




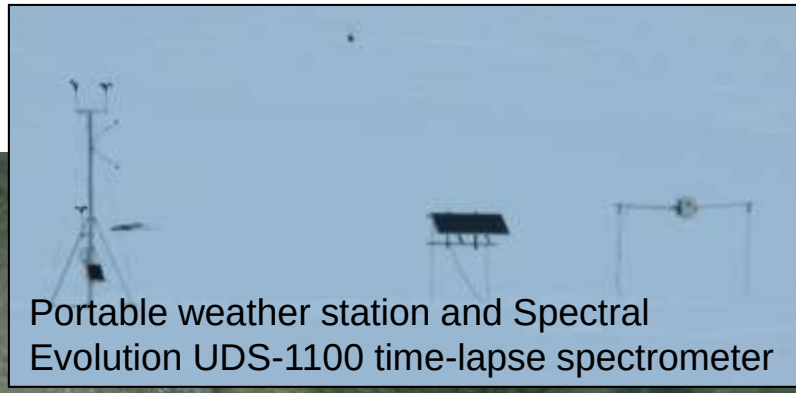
Int. class. of seasonal snow on the ground



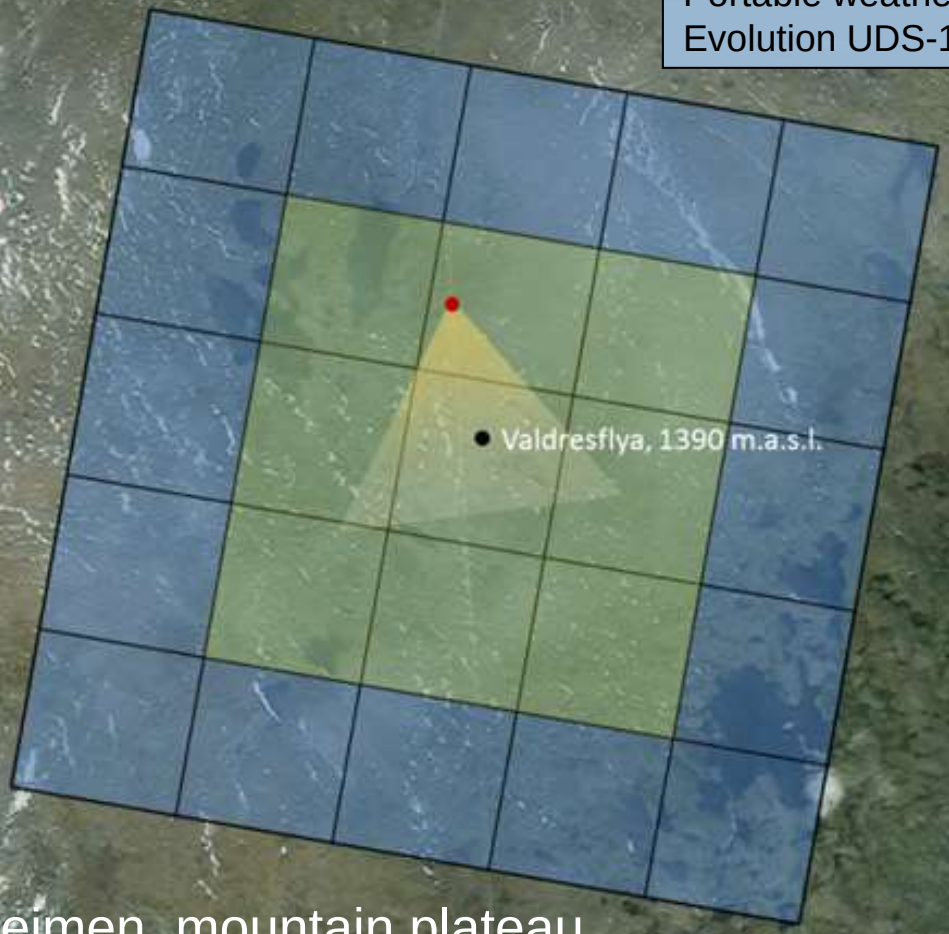
Test region Norway: Jotunheimen



Cal/val site Valdresflya

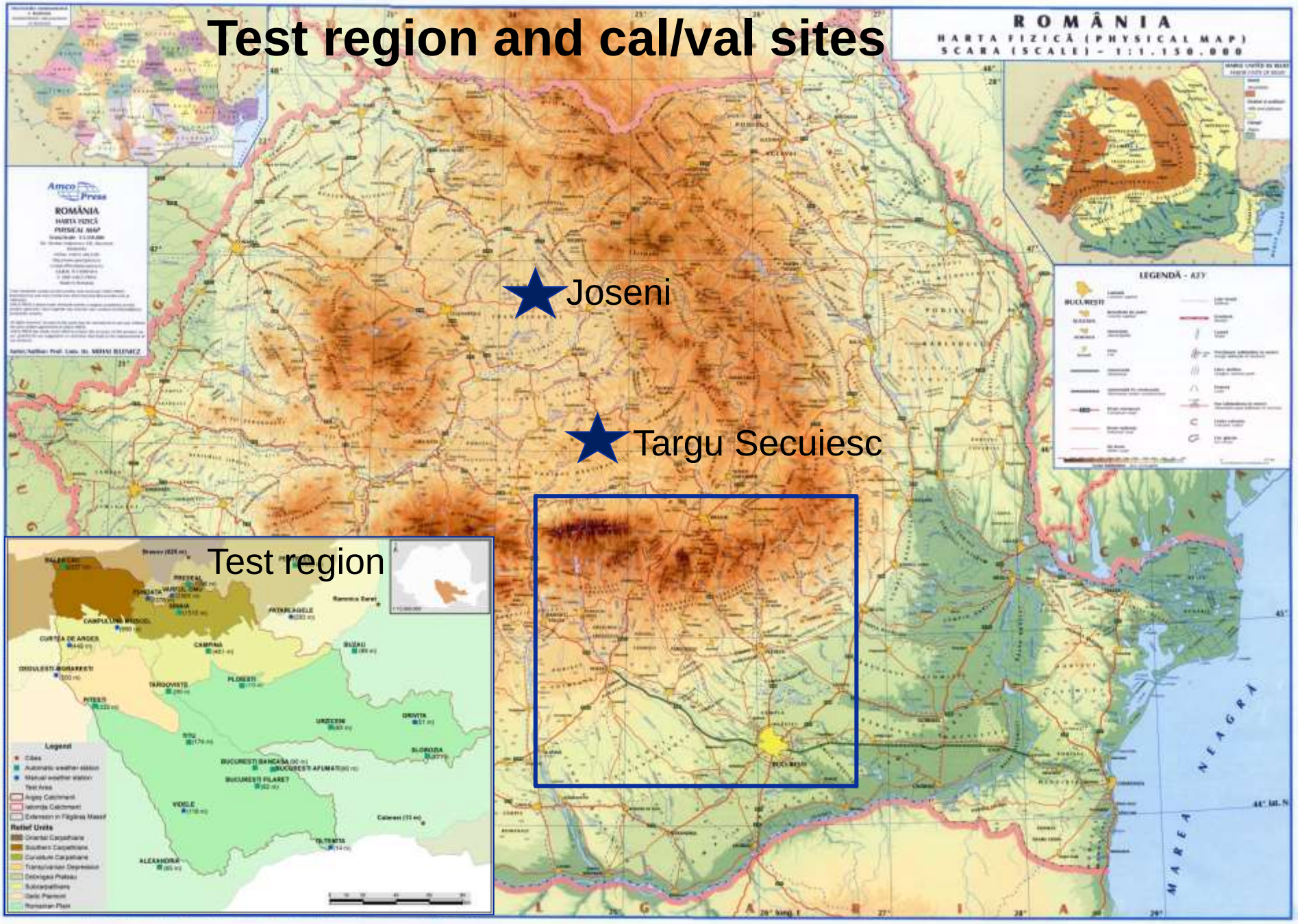


Portable weather station and Spectral Evolution UDS-1100 time-lapse spectrometer



Valdresflya, Jotunheimen, mountain plateau, 1200-1400 m a.s.l., total area 265 km^2

Test region and cal/val sites



Cal/val site Joseni



Cal/val site Targu Secuiesc





Targu Secuiesc, 571 m.a.s.l.

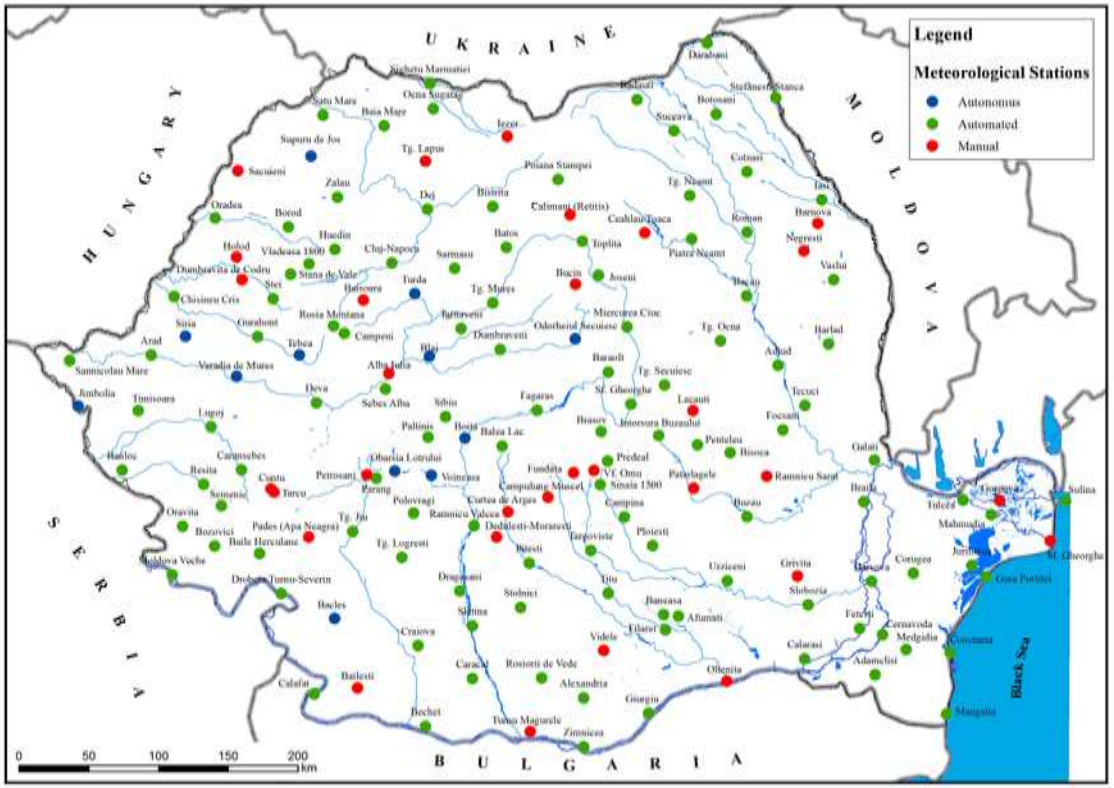
Fagaras and Sinaia region, Southern Carpathian



- Snow spectrum (field spectrometer)
- Snow grain size (contact spectroscopy)
- Snow liquid water (dielectric probe)
- Snow density (weight of 1 dm^3)
- Snow depth (snow stick)

Large-scale evaluation of wet snow products

- Purpose: Evaluate product quality in general
- The general behaviour of the product can be reasonably evaluated against the temporal development of the air temperature
- Supplementary snow depth (and snow cover) measurements are useful
- 158 weather stations covering the whole product domain



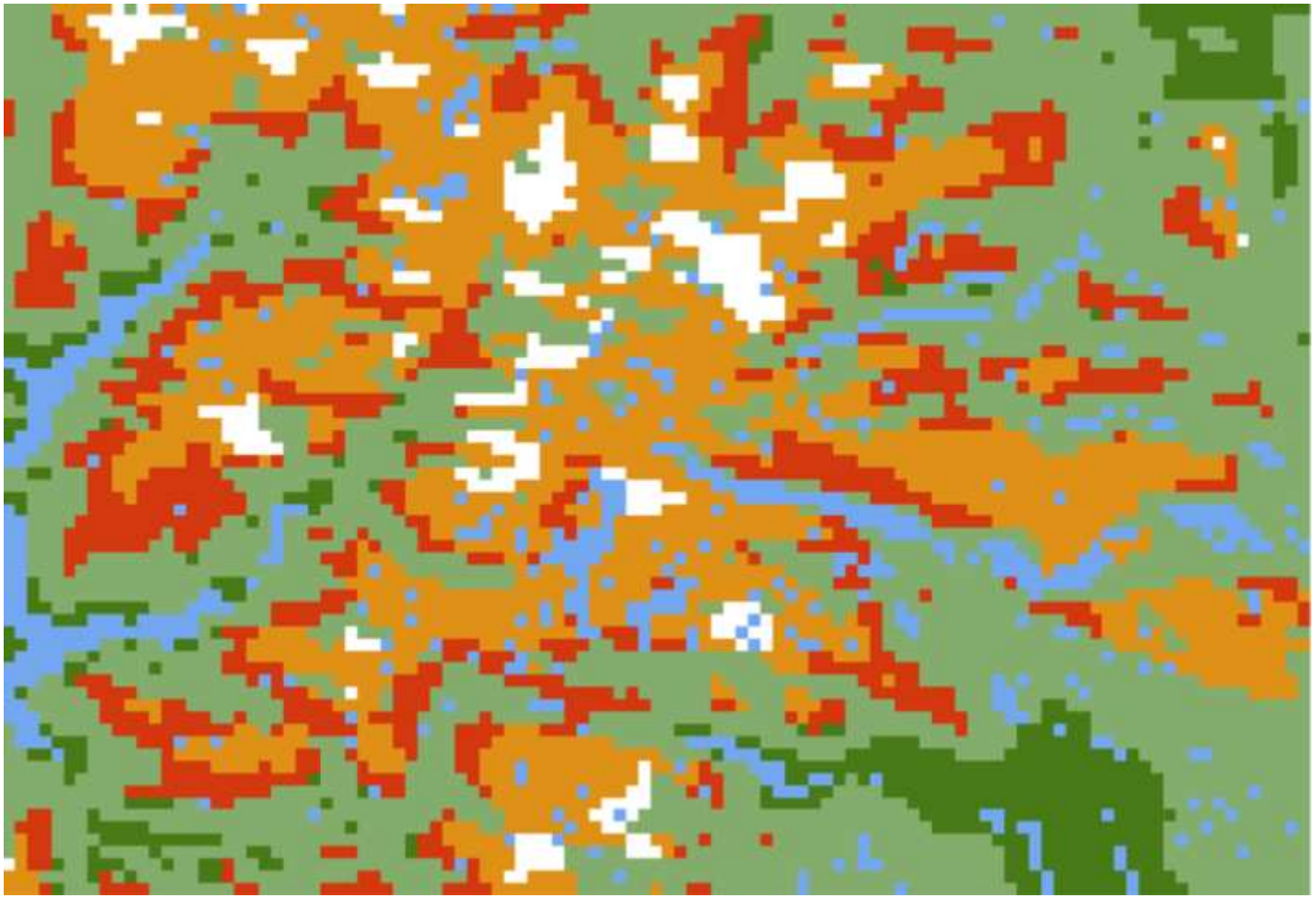
Romanian weather stations network

Jotunheimen: Weather station air temperature versus OWS, 2015

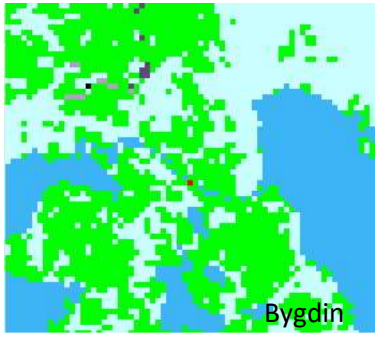
Satellite ac.		Valdresflya				Bitihorn				Bygdin				Eidsbugarden				Vinsteren-Bjørnhølen			
Date	Time	W	08:00	Ac	14:00	W	08:00	Ac	14:00	W	08:00	Ac	14:00	W	08:00	Ac	14:00	W	08:00	Ac	14:00
11.03	10:55	D	-9.0	-5.9	-4.1	D	-6.9	-3.2	-1.2	D	-7.3	-3.8	-3.1	D	-9.2	-7.2	-4.9	D	-8.6	-5.6	-3.5
08.04	11:20	D	-3.3	-3.4	-1.3	D	-8.8	-7.8	-6.0	D	-1.8	0.2	0.2	D	-2.5	1.4	0.7	D	-1.5	-0.2	-0.5
17.04	11:10	D	-2,6	-0.9	4.8	D	-5.9	-5.1	-4.6	W	0.1	1.4	3.6	D	-2,7	-0.7	1.5	W	0.4	2.2	3.5
19.04	11:00	W	0.6	5.6	6.1	W	-0.2	2.4	4.1	-	2.9	7.0	8.4	D	-1.5	3.1	5.0	S	3.6	7.9	6,4
20.04	10:10	W	8.3	7.7	6.4	-	4.4	4.8	3.4	-	4.8	6.6	8.9	W	4.2	9.8	8.4	-	-1.0	5.7	5.0
27.04	10:15	D	0.1	1.9	6.5	D	-3.9	-1.2	1.5	-	-5.2	-1.1	3.9	D	-7.6	-3.9	1.9	-	-4.6	-4.2	0.0
14.05	10:55	W	1.6	1.2	2.8	-	-3.4	1.4	0.6	-	2.2	6.8	4.1	W	0.5	2.0	3.8	-	0.4	1.7	2.7
15.05	11:35	D	0.8	8.4	2.6	-	-2.5	5.8	4.9	-	-1.2	1.4	2.4	S	1.6	9.8	6.0	-	-0.9	2.4	3.4
05.06	11:55	W	0.9	5.0	4.5	S	-0.9	4.7	4.2	-	2.4	6.2	6.1	W	3.8	8.1	8.8	-	4.1	6.4	7.7
08.06	10:50	W	3.8	4.4	5.1	-	-2.7	0.3	1.5	-	3.8	5.9	6.2	-	5.5	6.3	6.5	=	4.9	6.7	7.9
13.06	11:05	W	10.4	5.1	5.5	+	-0.1	1.3	2.8	+	4.2	7.1	7.2	-	6.9	7.6	9.6	=	6.7	8.1	9.2
16:06	10:00	D	2.0	4.2	6.2	-	-0.8	1.8	2.7	-	3.4	5.3	7.3	-	6.1	6.9	8.9	=	5.4	8.4	11.1
16.06	11:35	W	2.0	6.6	6.2	-	-0.8	2.1	2.7	-	3.4	5.7	7.3	-	6.1	8.1	8.9	=	5.4	10.2	11.1
20.06	11:15	S	14.2	15.6	9.0	-	7.0	6.1	8.5	=	7.5	10.2	12.2	-	9.7	13.1	12.1	=	9.9	12.0	15.1
27.06	11:20	S	10.4	9.6	12.7	-	4.9	15.6	10.3	=	9.6	14.4	16.0	-	9.2	18.2	15.7	=	9.3	14.7	16.1

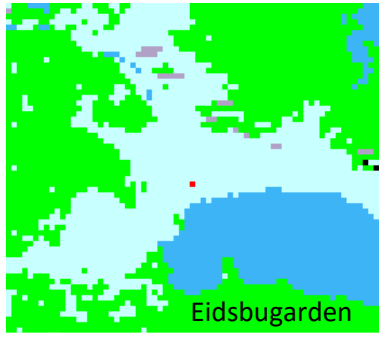
OSW map retrieval results (W) and corresponding air temperature measurements in the morning (08:00), closest to the acquisition time (Ac) and in the afternoon (14:00) for the five weather stations. All times are given in UTC. The retrieval results are shown colour coded as well as with letters (D = Dry, M = Moist, W = Wet, V = Very wet and S = Soaked snow). When there is no OSW retrieval result, other classes are shown ('+' = Cloud, '-' = Partly snow-covered ground and '=' = Bare ground (no snow)).

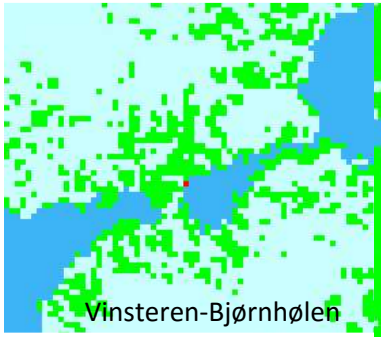
OSW based on MODIS from 20 April 2015 acquired at 10:10 UTC

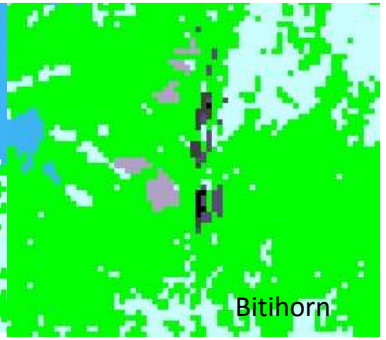


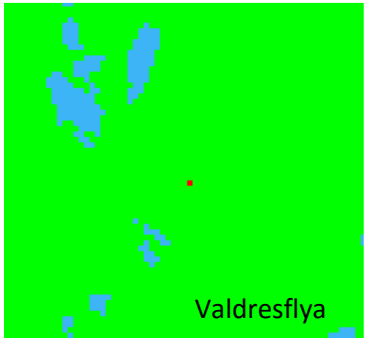
Jotunheimen: Weather station air temperature versus SWS 30 April 2015

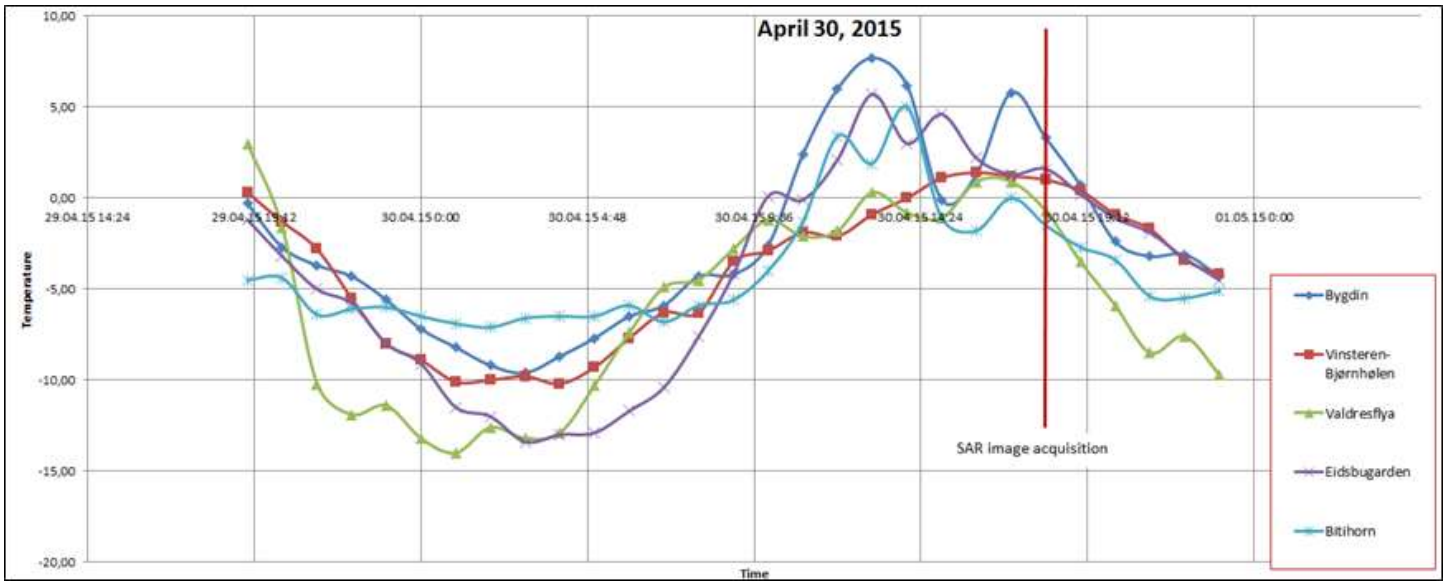




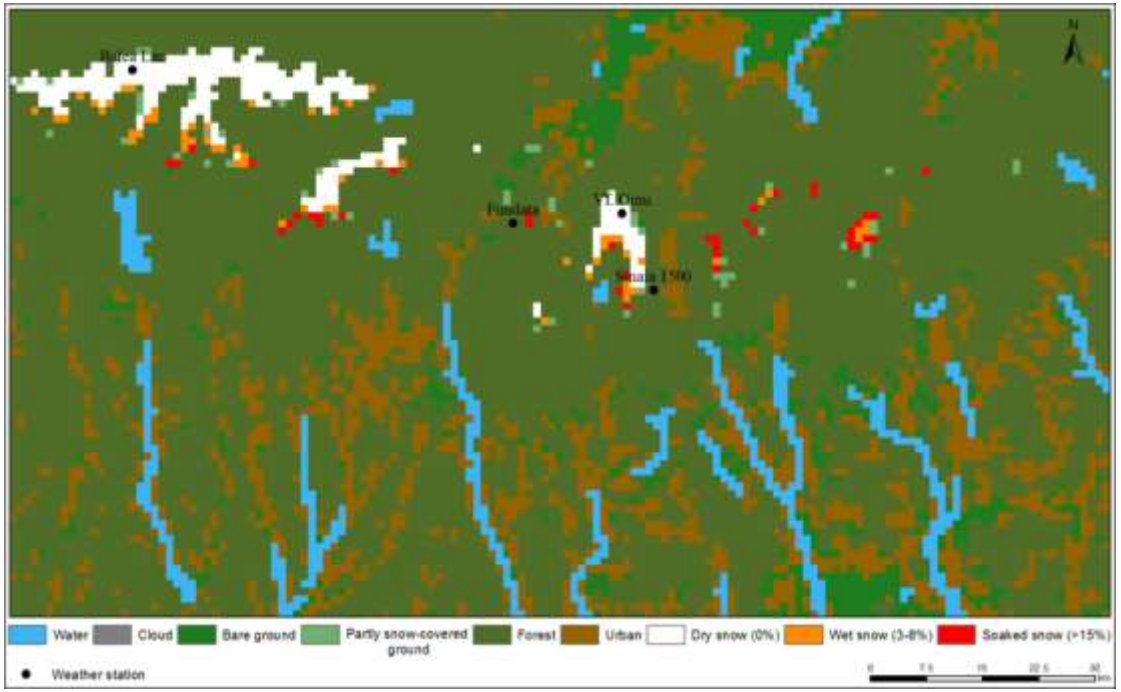


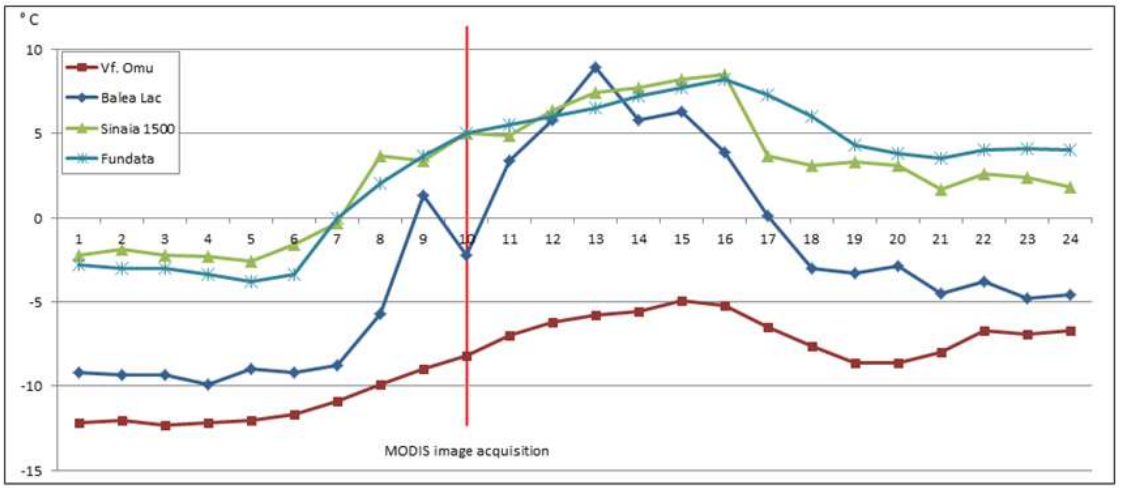




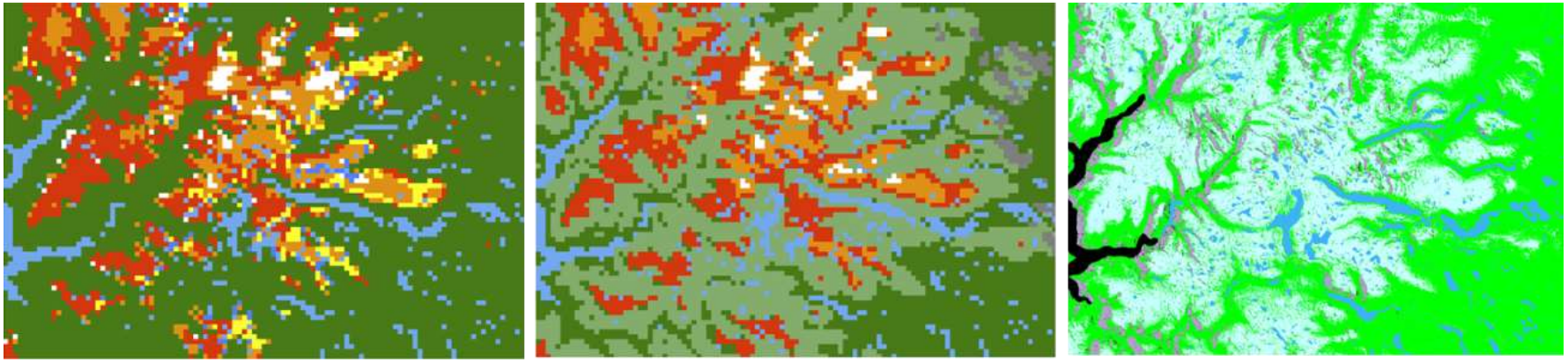


Southern Carpathian: OSW based on MODIS from 10 April 2015 acquired at 09:30 UTC

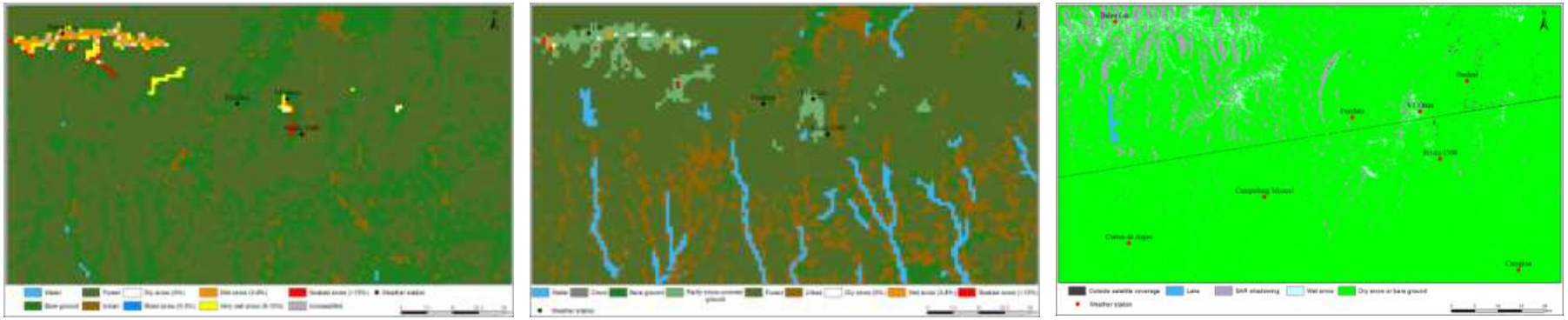




Version 1.0 products 2015



Jotunheimen: Multi-sensor wet snow map for 16 June 2015 (left), optical wet snow map for the same day (middle) and SAR wet snow map for 17 June 2015 (right).

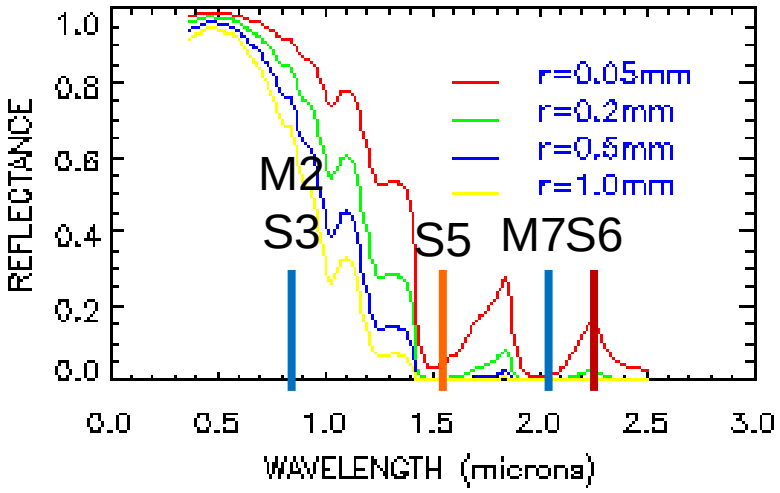


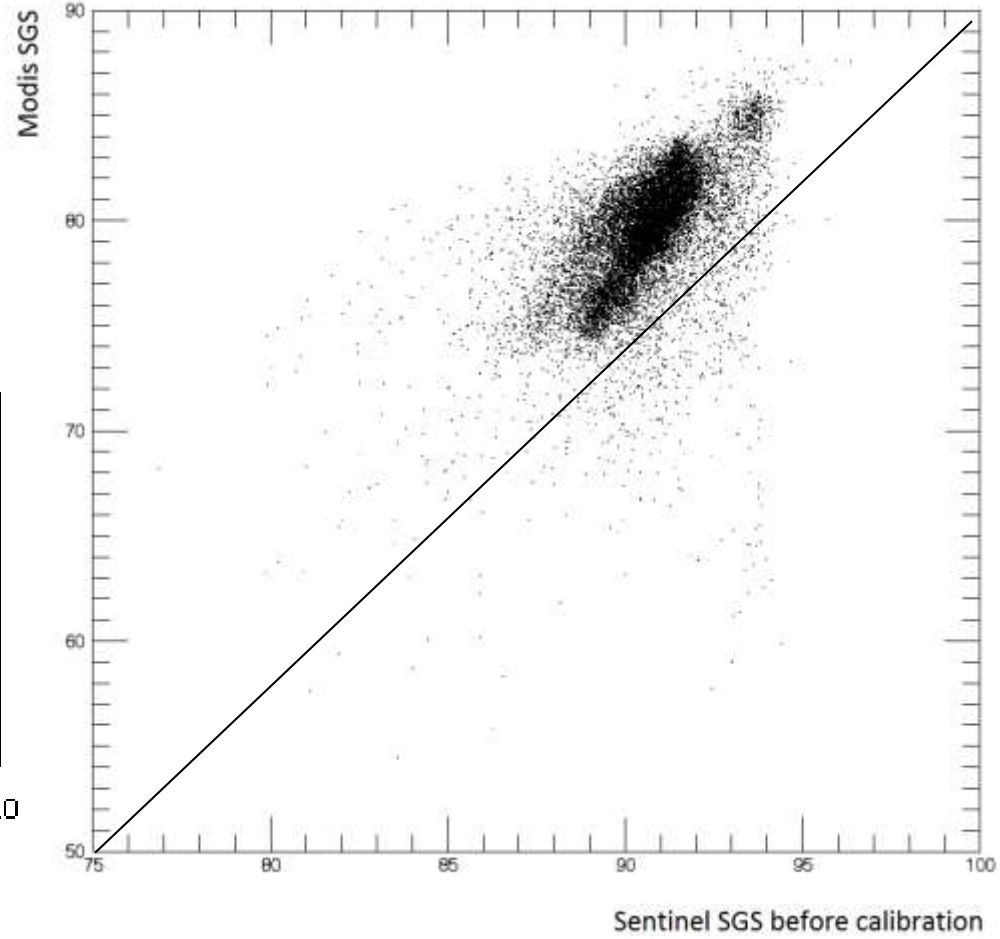
Southern Carpathian: Multi-sensor wet snow map (left), optical wet snow map (middle) and SAR wet snow map (right) for 24 April 2015

Porting optical algorithm to SLSTR

R47
M27
S35

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





Southern Norway, winter 2016-2017

MODIS



6 December 2016



8 December 2016



19 December 2016

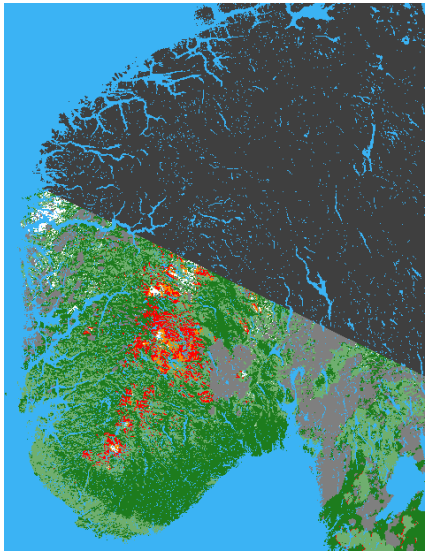


18 January 2017

SLSTR

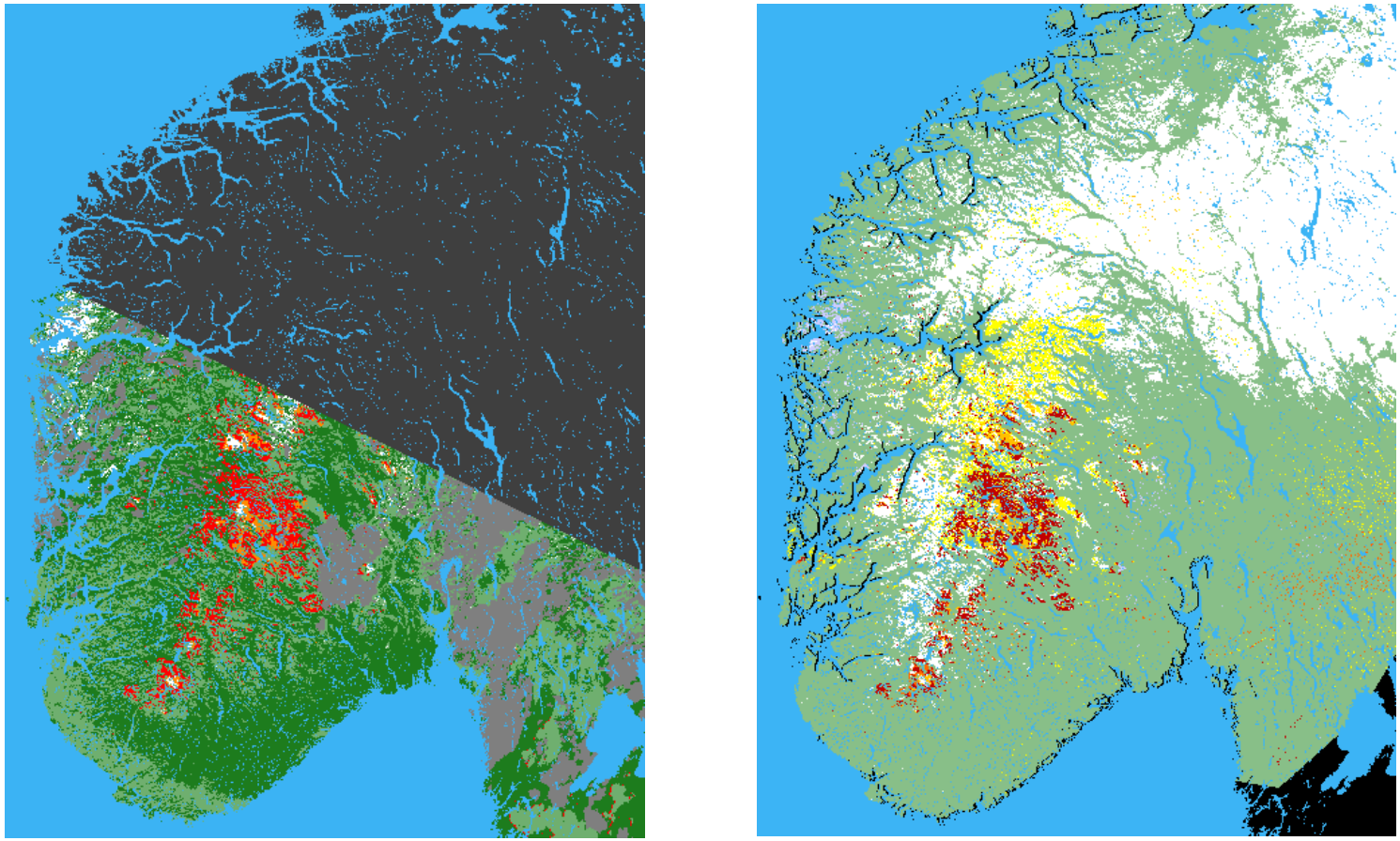








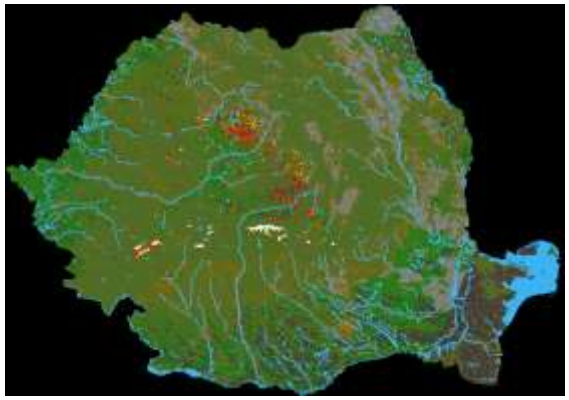
Preliminary multi-sensor results: Sentinel-1 (SAR) + Sentinel-3 (SLSTR)



19 December 2016

Romania, winter 2016-2017

MODIS



11 December 2016

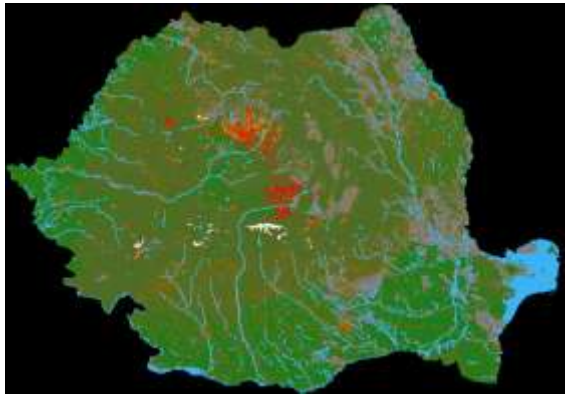


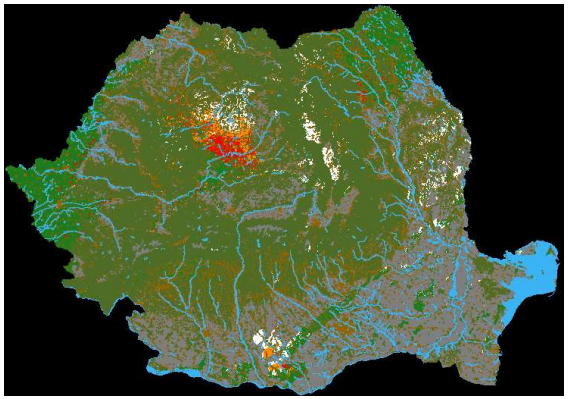
27 December 2016



24 January 2017

SLSTR







NR

SnowBall

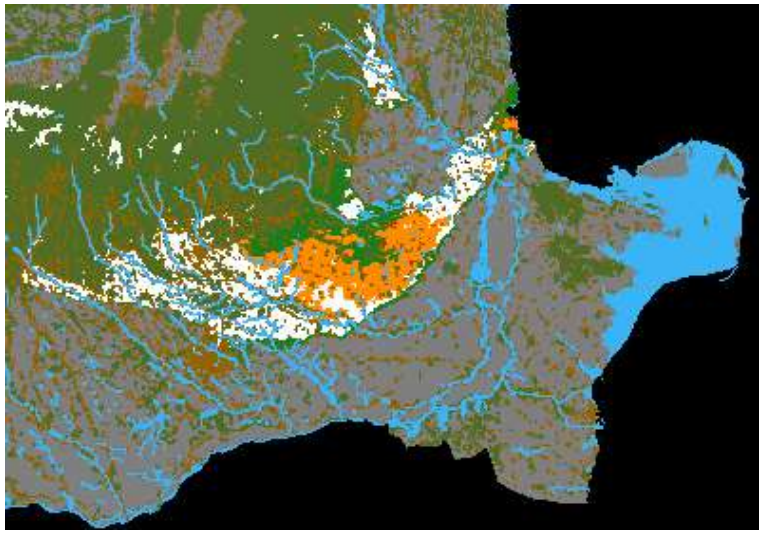
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Fieldwork in Southern Carpathian 31 January 2017



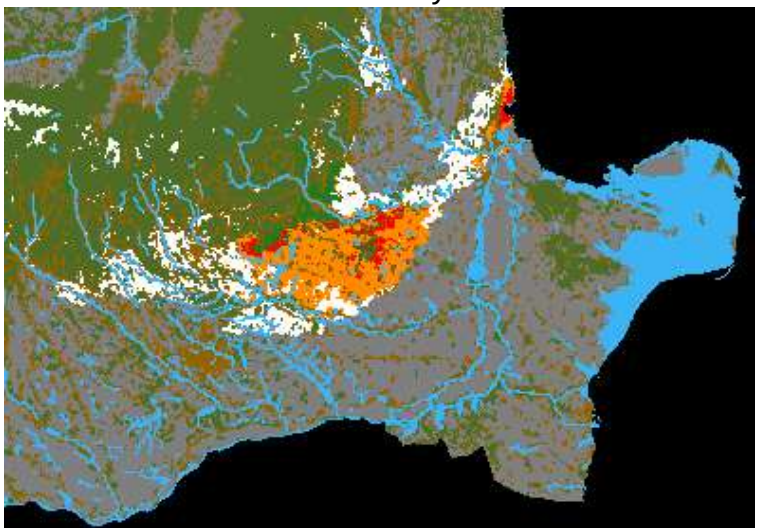
South-East Romania, 24 January 2017

MODIS

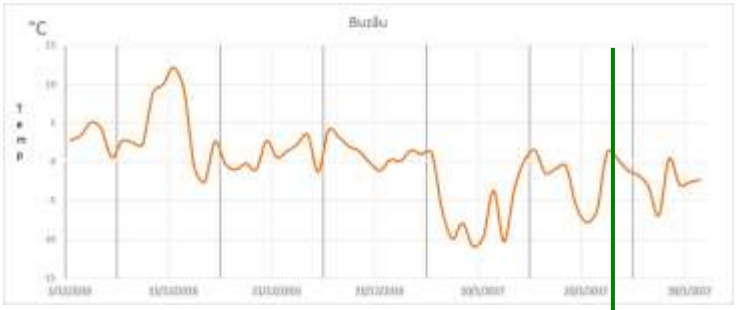


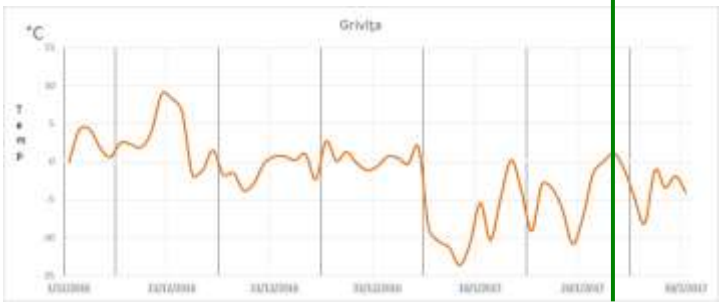
24 January 2017

SLSTR

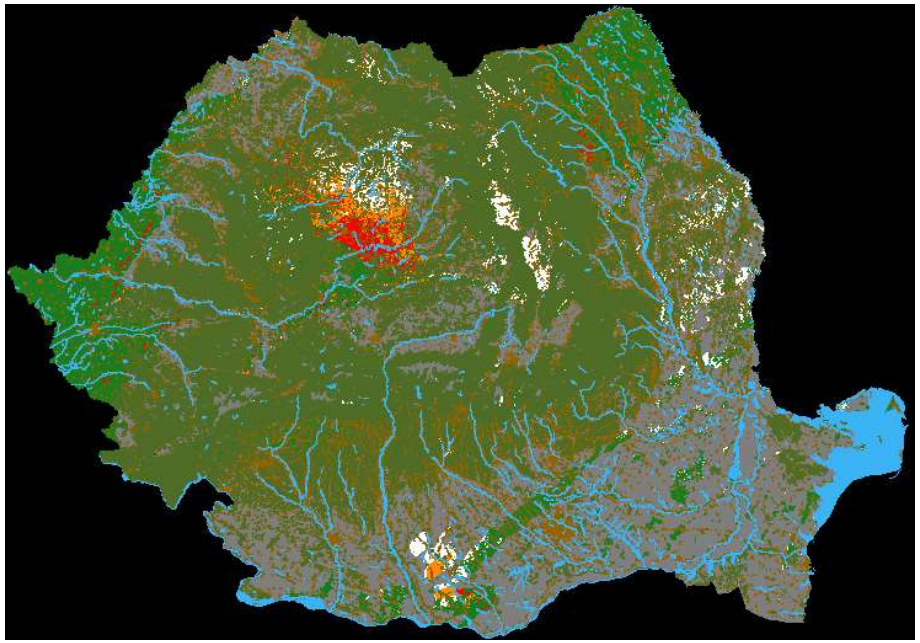


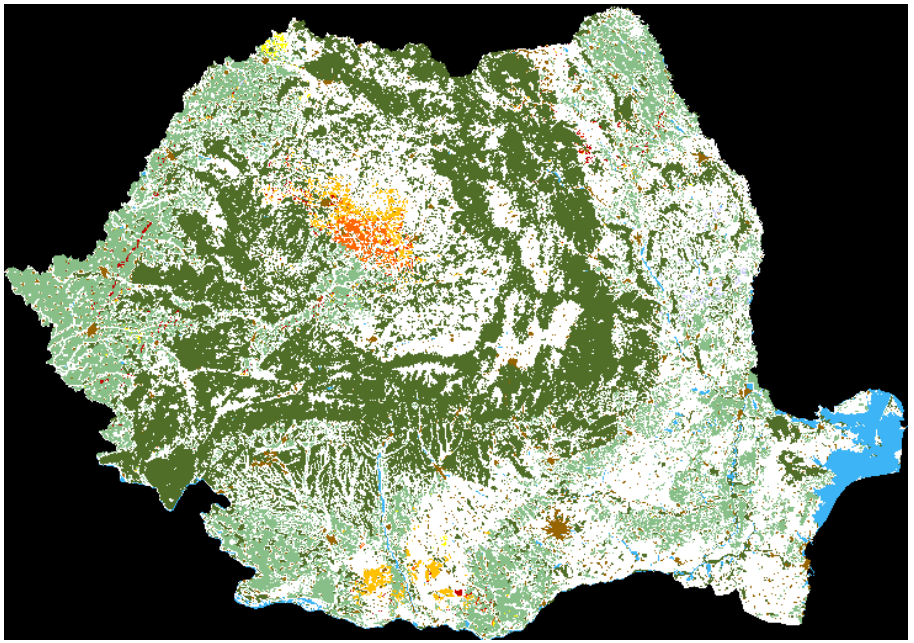






Preliminary multi-sensor results: Sentinel-1 (SAR) + Sentinel-3 (SLSTR)





27 December 2016



Preliminary conclusions

- First winter and spring, 2015, has been analysed for Romania and southern Norway (Sentinel-1 SAR & MODIS). Was followed up by 2016 mostly in Norway, lack of snow in Romania.
- Third winter, 2017, shows extensive snow cover in the Romanian plains. Southern Norway has so far lowest snow mass in ~60 years. Snow season covered with both MODIS and Sentinel-3 plus Sentinel-1 SAR.
- All seasons include in situ measurements of SLW (vol. %), aiming for quantitative characterisation of the snow wetness classes.
- The optical-based (OWS) maps were in general consistent with the air temperatures:
  - In most cases retrieval results of dry snow corresponded with air temperatures below freezing point.
  - Retrieval results of one of the wet-snow classes corresponded with air temperatures above freezing point.
  - The highest temperatures usually gave the wettest snow classes.
- A different snow grain size index has been established for SLSTR, and preliminary calibration is done to MODIS grain size sensitivity
- Full characterisation of SLSTR performance to be completed in the spring aiming for an SLW-calibrated product

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Thank you!



The project is supported by EEA Grants Norway