Satellite remote sensing of snow wetness in Romania and Norway

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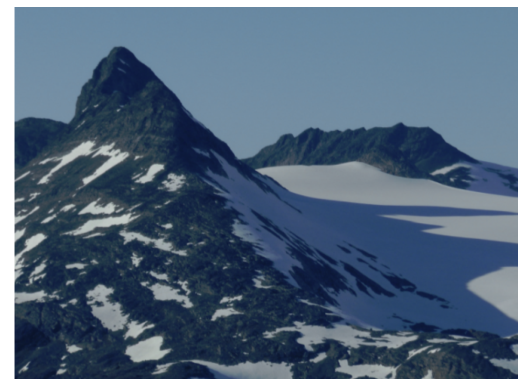
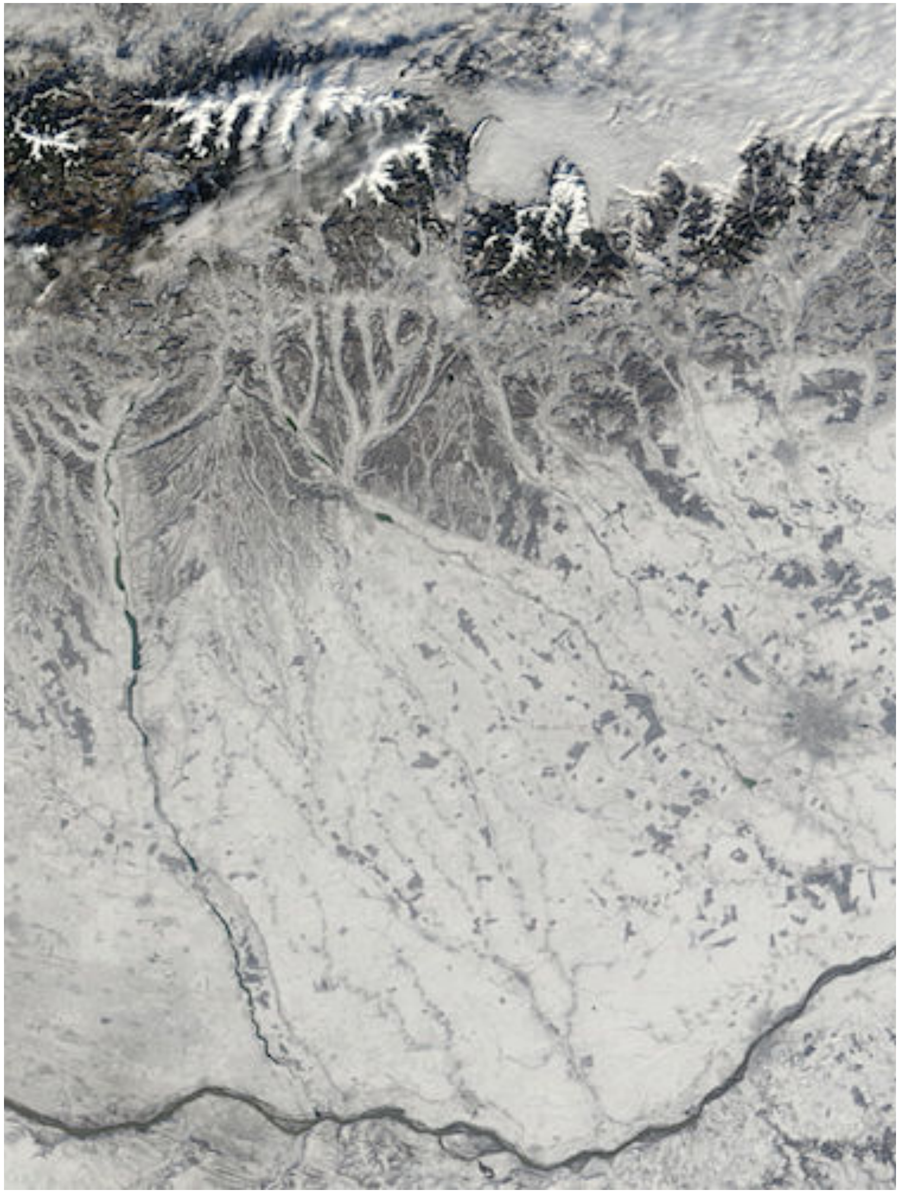


SnowBall Final Workshop, 27 April 2017,
Hotel Marshal Garden, Bucharest, Romania

Remote sensing of snow wetness in SnowBall

- 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 products:
  - Optical Wet Snow (OWS)
  - SAR Wet Snow (SWS)
  - Multi-sensor Wet Snow (MWS)
- Applications in flood warning and hydrological modelling



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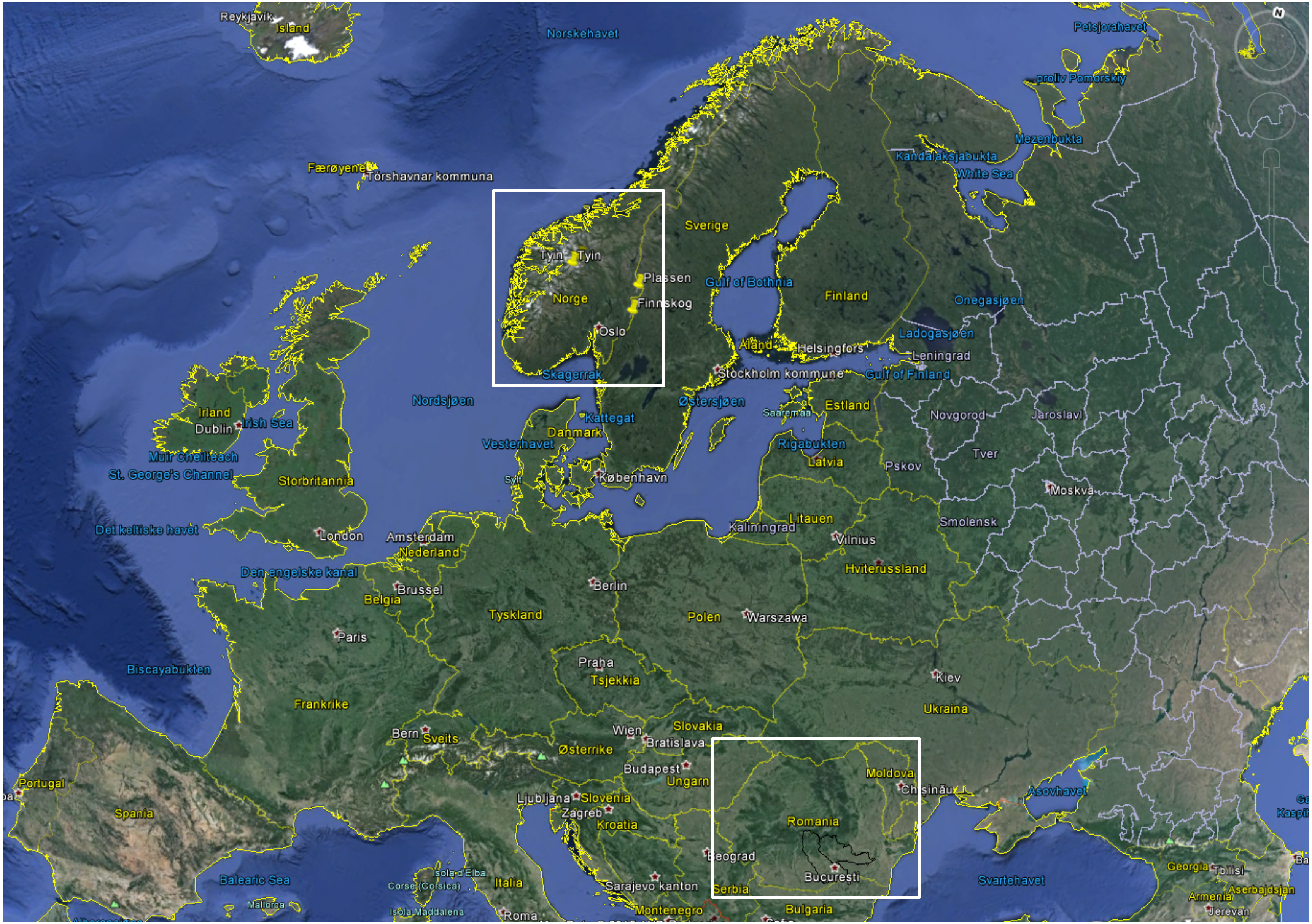
Prototype product domains



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

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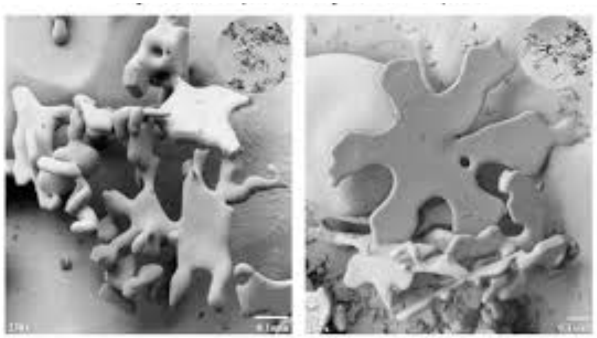
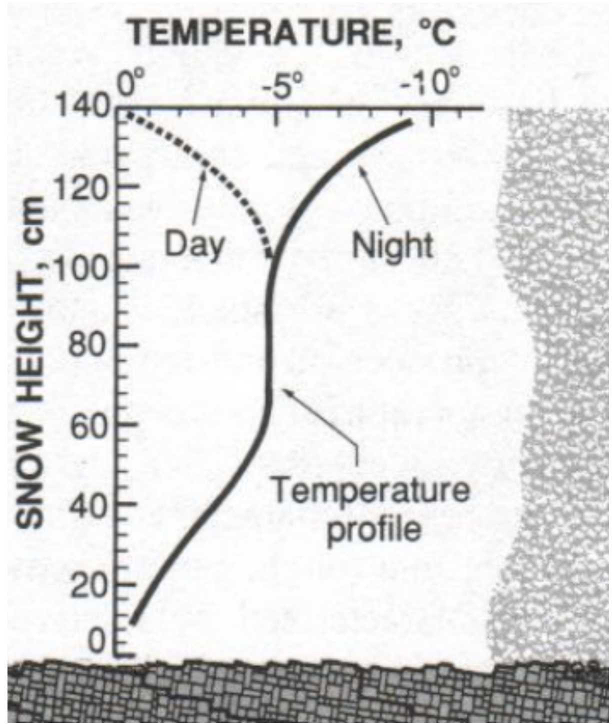
Wet snow metamorphism

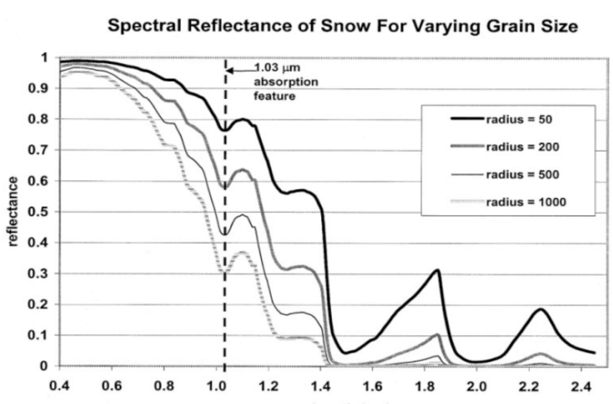
New snow

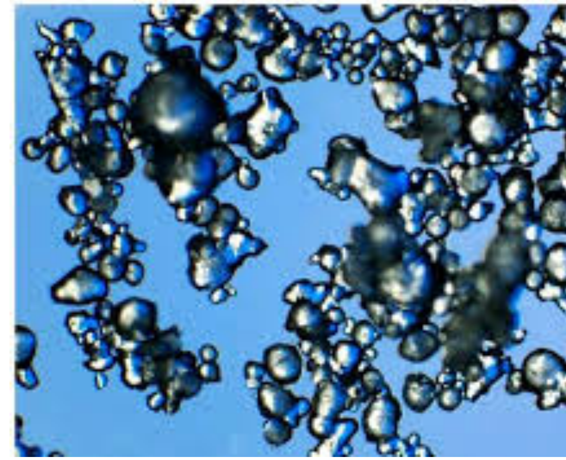


USDA

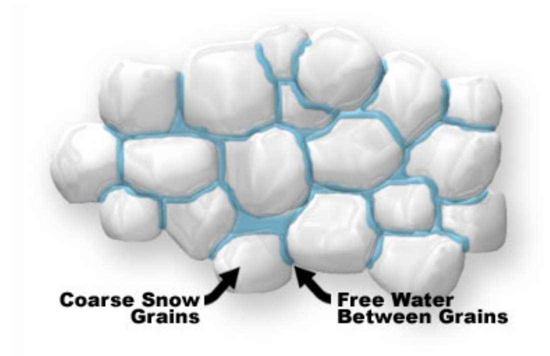
Dry snow metamorphism



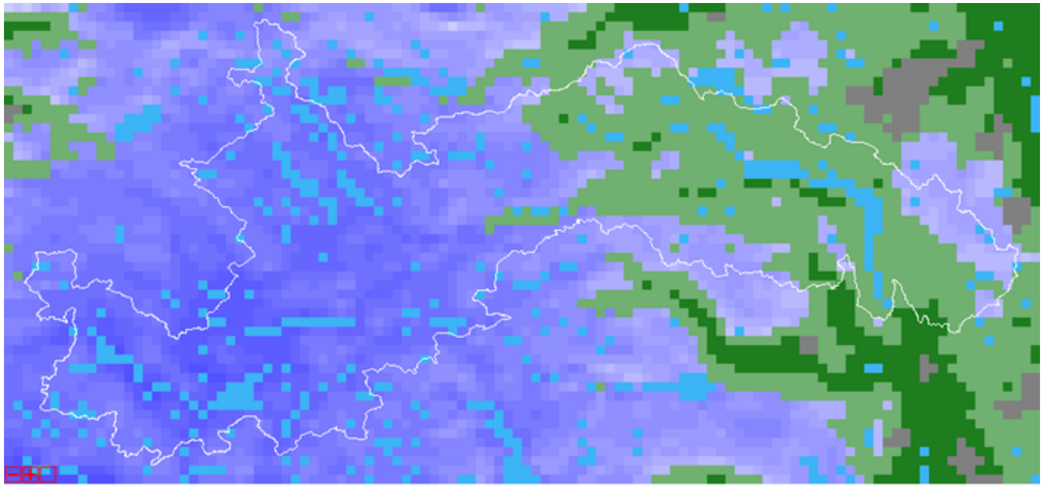




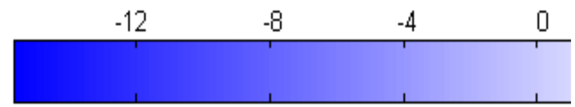
Wet snow

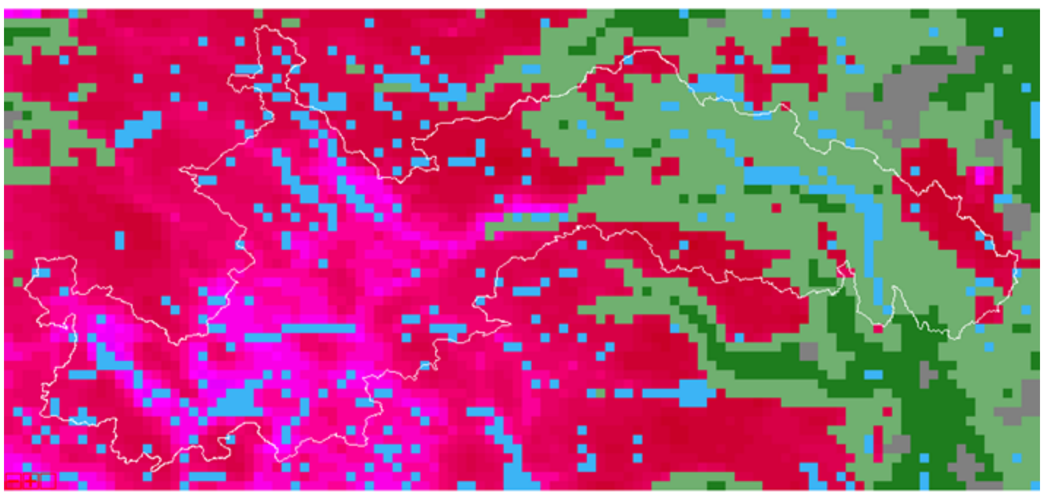


Snow surface temperature and snow grain size

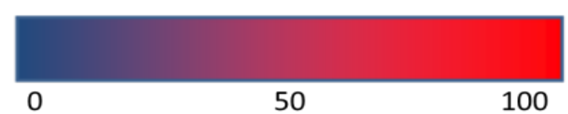


- Based on Key’s algorithm (split window + view angle correction)
- The retrieval algorithm requires that the emissivity of the surface is known. Therefore, we restrict the use to snow-covered surfaces
- At 0°C we found an accuracy of about 0.5°C in our test site



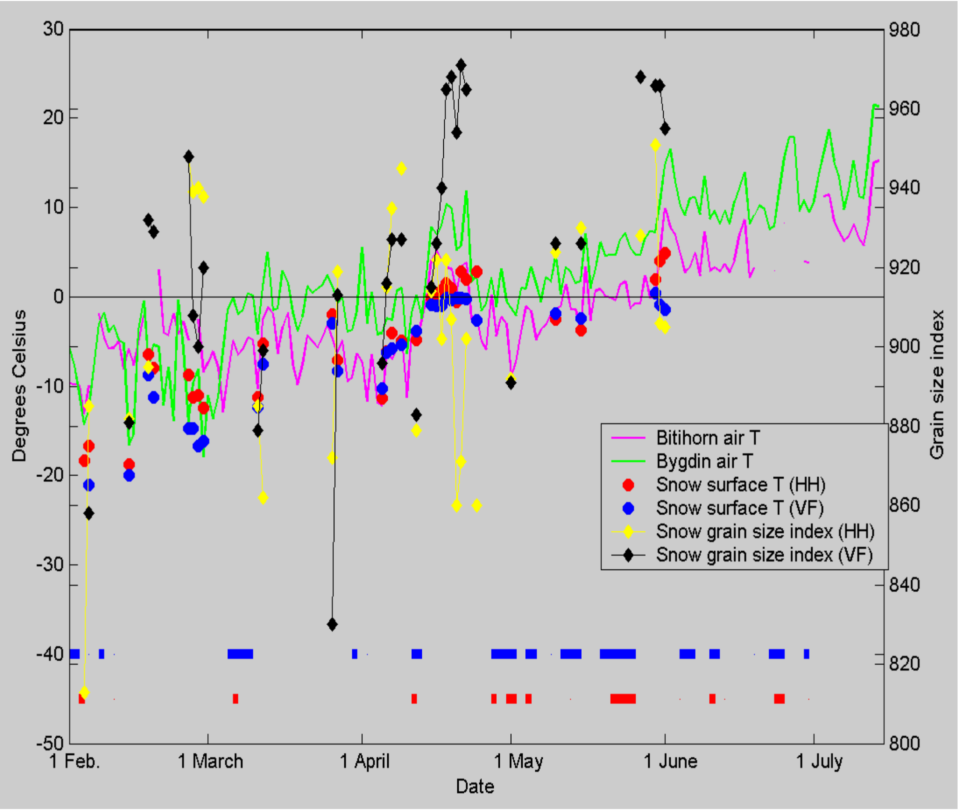


- Algorithm based on the property that NIR reflectance is sensitive to grain size
- Field measurements show clear correlation with in situ measured snow grain size



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



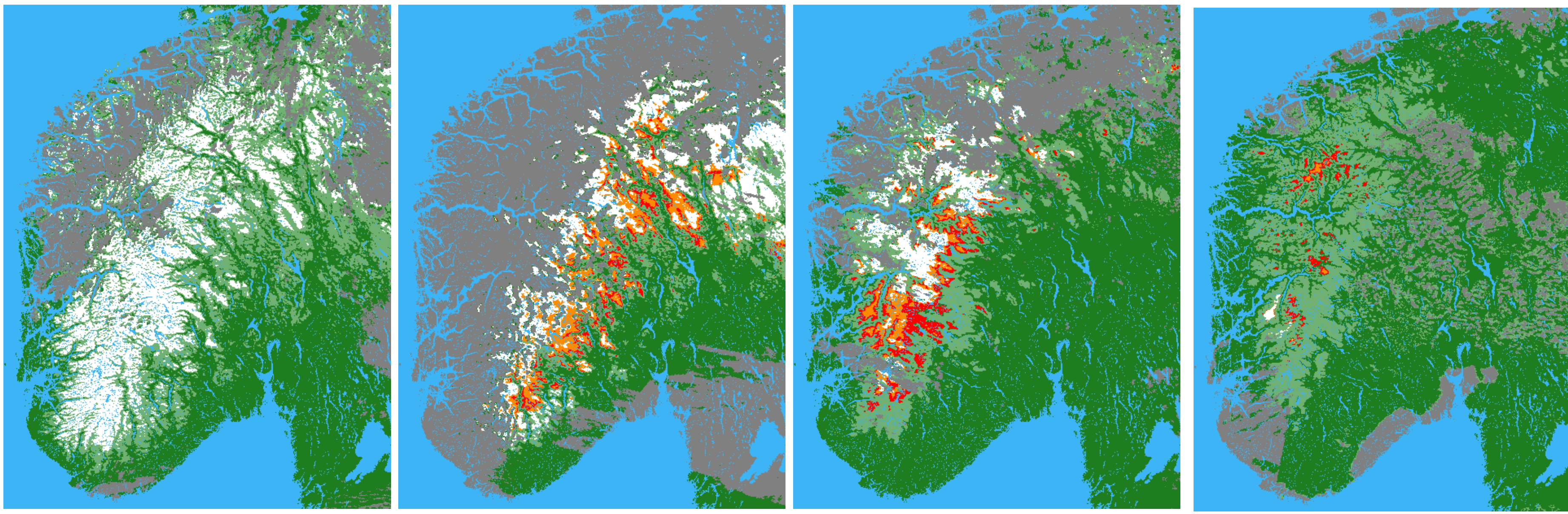
Field measured snow temperature, and satellite-measured snow temperature and effective snow grain size for Heimdalen test site in 2003. HH = Heimdalshø, VF = Valdresflya

“Int. class. of seasonal snow on the ground”

Term	*Wetness index*	*Code*	*Description*	*Approximate range of $\theta_{w,V}$ (volume fraction in %)*[1] *range*	*mean*	*Graphic symbol*
dry	1	D	Usually T_s is below 0°C, but dry snow can occur at any temperature up to 0°C. Disaggregated snow grains have little tendency to adhere to each other when pressed together, as in making a snowball.	0	0	
moist	2	M	T_s = 0°C. The water is not visible even at 10× magnification. When lightly crushed, the snow has a distinct tendency to stick together.	0–3	1.5	|
wet	3	W	T_s = 0°C. The water can be recognised at 10× magnification by its meniscus between adjacent snow grains, but water cannot be pressed out by moderately squeezing the snow in the hands (pendular regime).	3–8	5.5	||
very wet	4	V	T_s = 0°C. The water can be pressed out by moderately squeezing the snow in the hands, but an appreciable amount of air is confined within the pores (funicular regime).	8–15	11.5	|||
soaked	5	S	T_s = 0°C. The snow is soaked with water and contains a volume fraction of air from 20 to 40% (funicular regime).	>15	>15	||||

Colour	**Wetness category**
	Dry
	Moist
	Wet
	Very wet

OWS examples based on MODIS for southern Norway in 2015



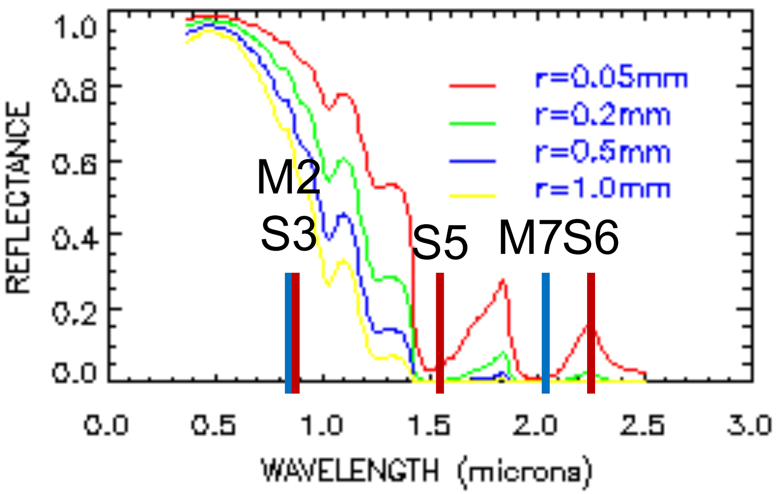
4 March 2015 | 9 April 2015 | 5 June 2015 | 4 July 2015

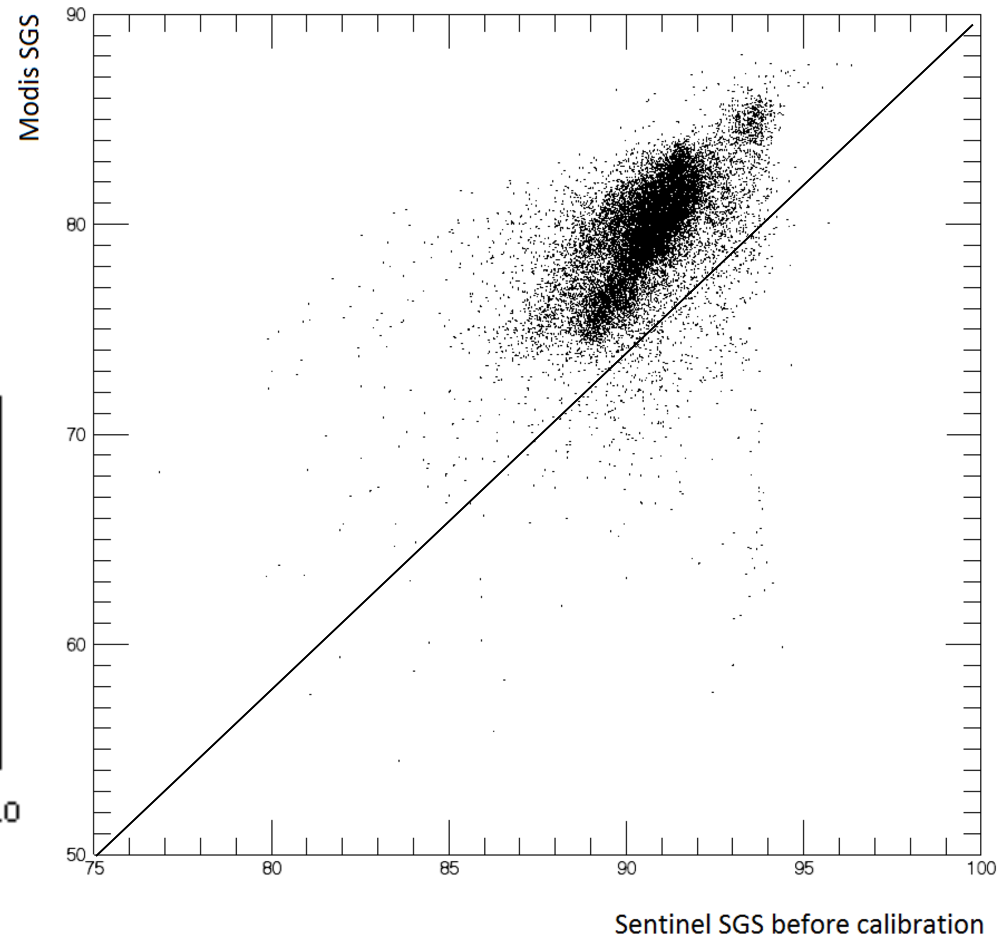
Colour	Wetness category
	Dry
	Moist
	Wet
	Very wet

Porting optical algorithm to Sentinel-3

R47
M27
S35

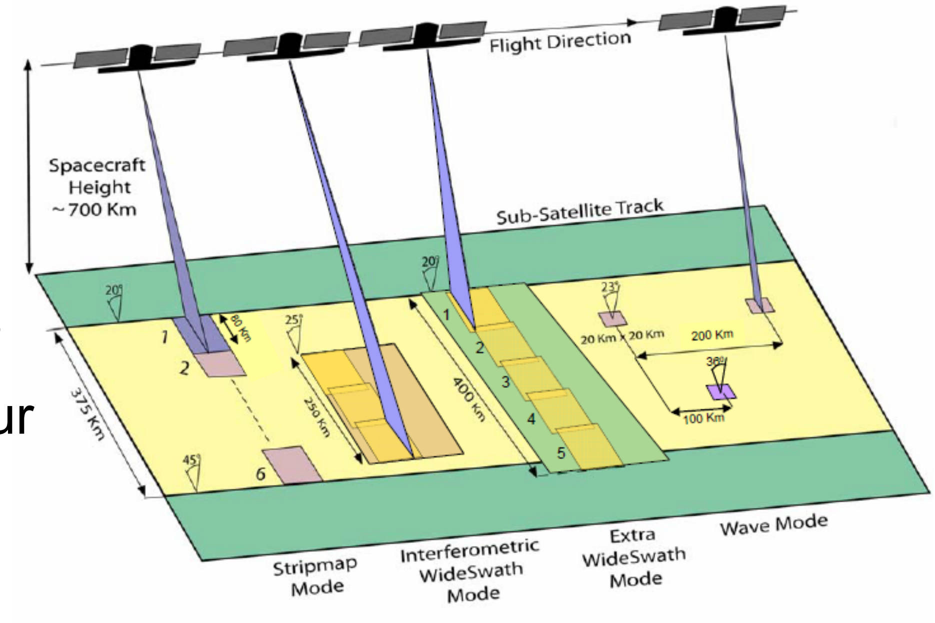
$$R_{ij} = \frac{TM_i - TM_j}{TM_i + TM_j}$$





SAR data source

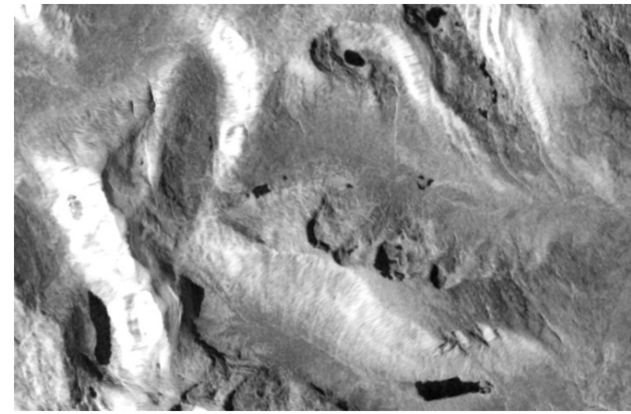
- Sentinel-1:
  - Sentinel-1A launched 3 April 2014
  - Sentinel-1B launched 25 April 2016
- The C-band SAR operates in four modes:
  - Strip Map Mode (SM)
  - Interferometric Wide Swath (IW)
  - Extra-Wide Swath Mode (EW)
  - Wave-Mode (WV)
- Primary mode for land is IW:
  - Single-look complex (SLC):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



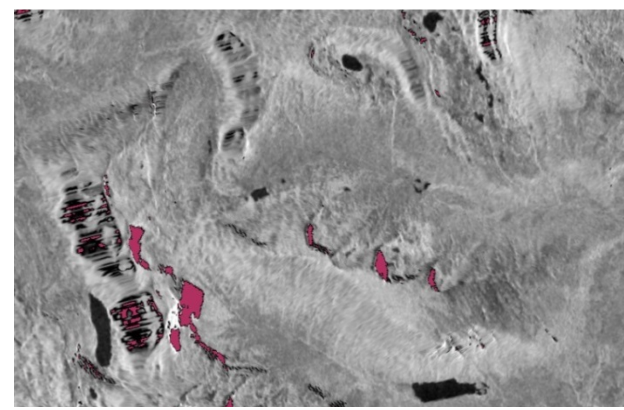
SAR wet snow algorithm

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 (difference approach inspired by Nagler and Roth, 2000).
9. Masking of layover and shadow areas.

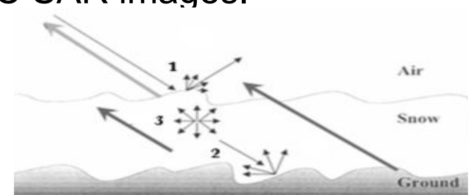
Currently, the algorithm supports Sentinel-1 GRD and Radarsat-2 SCN/SCW/SLC SAR images.



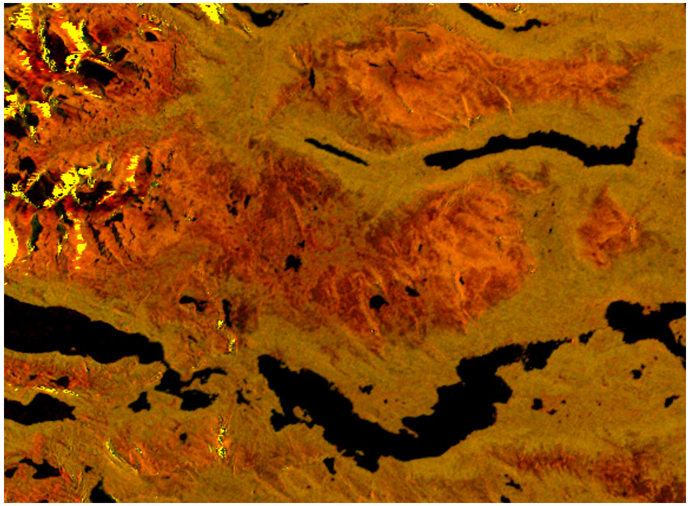
The gamma-naught (γ^0) image Radarsat-2 ultra-fine HH.



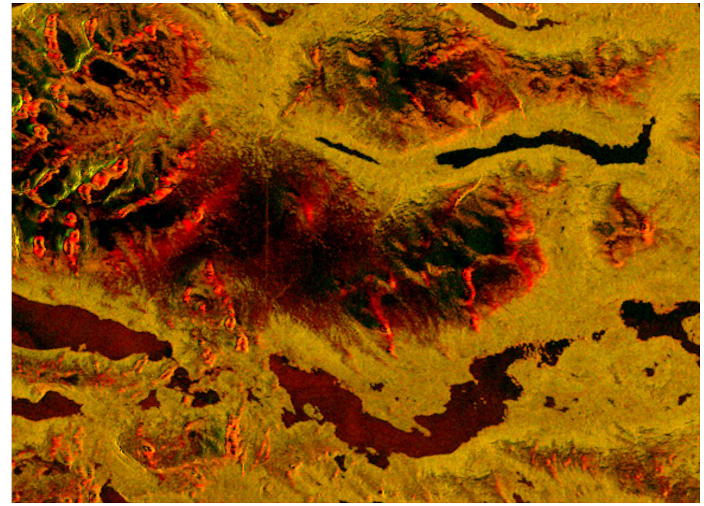
Flattening gamma radiometric terrain corrected Radarsat-2 ultra-fine HH image. Red areas indicate shadow areas.

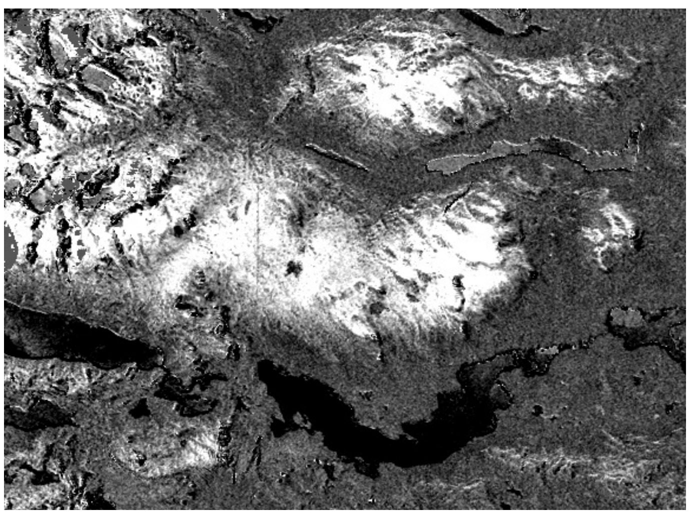


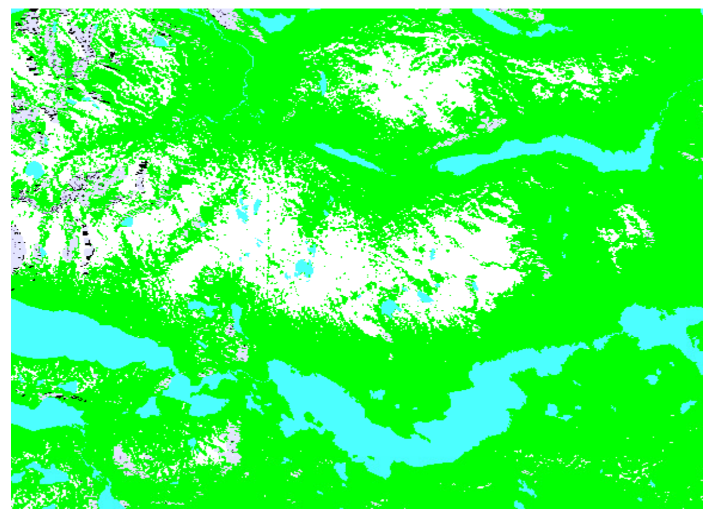
SAR wet snow map 29 June 2015


Reference

R: VV
G: VH
B: 0


New observation


Difference


Snow map

Colour	Class
(green)	Dry snow or no snow
(white)	Wet snow

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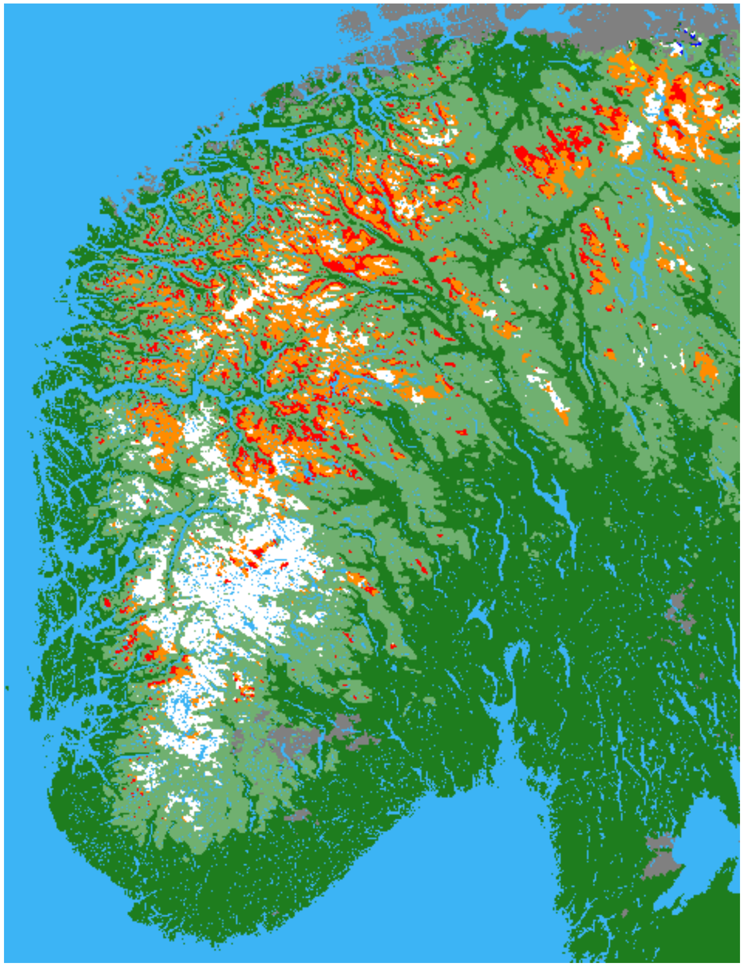
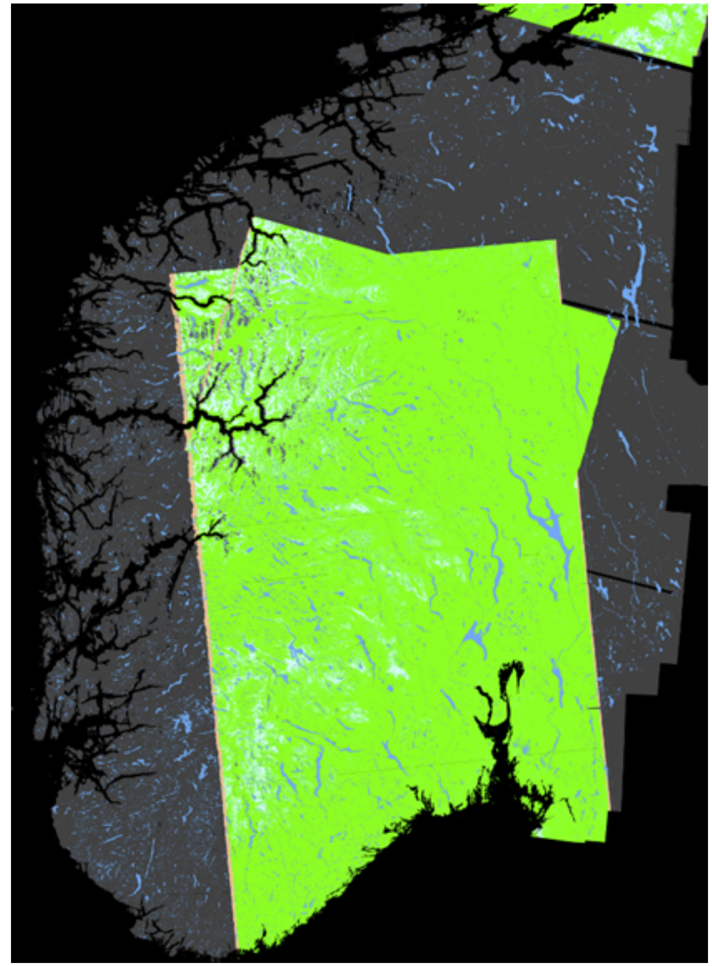
Something to gain from combining optical and SAR?



OWS from Terra MODIS, 20 April 2015



SWS from Sentinel-1, 20 April 2015

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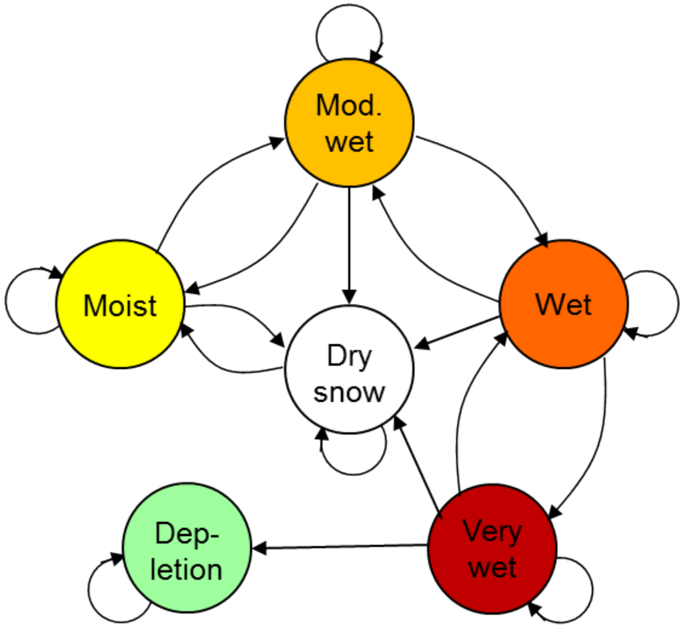
Multi-sensor multi-temporal algorithm

- 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
- 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 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 from ancillary data (training)
- Using the Viterbi algorithm, the most likely sequence of states is found based on the input data time series



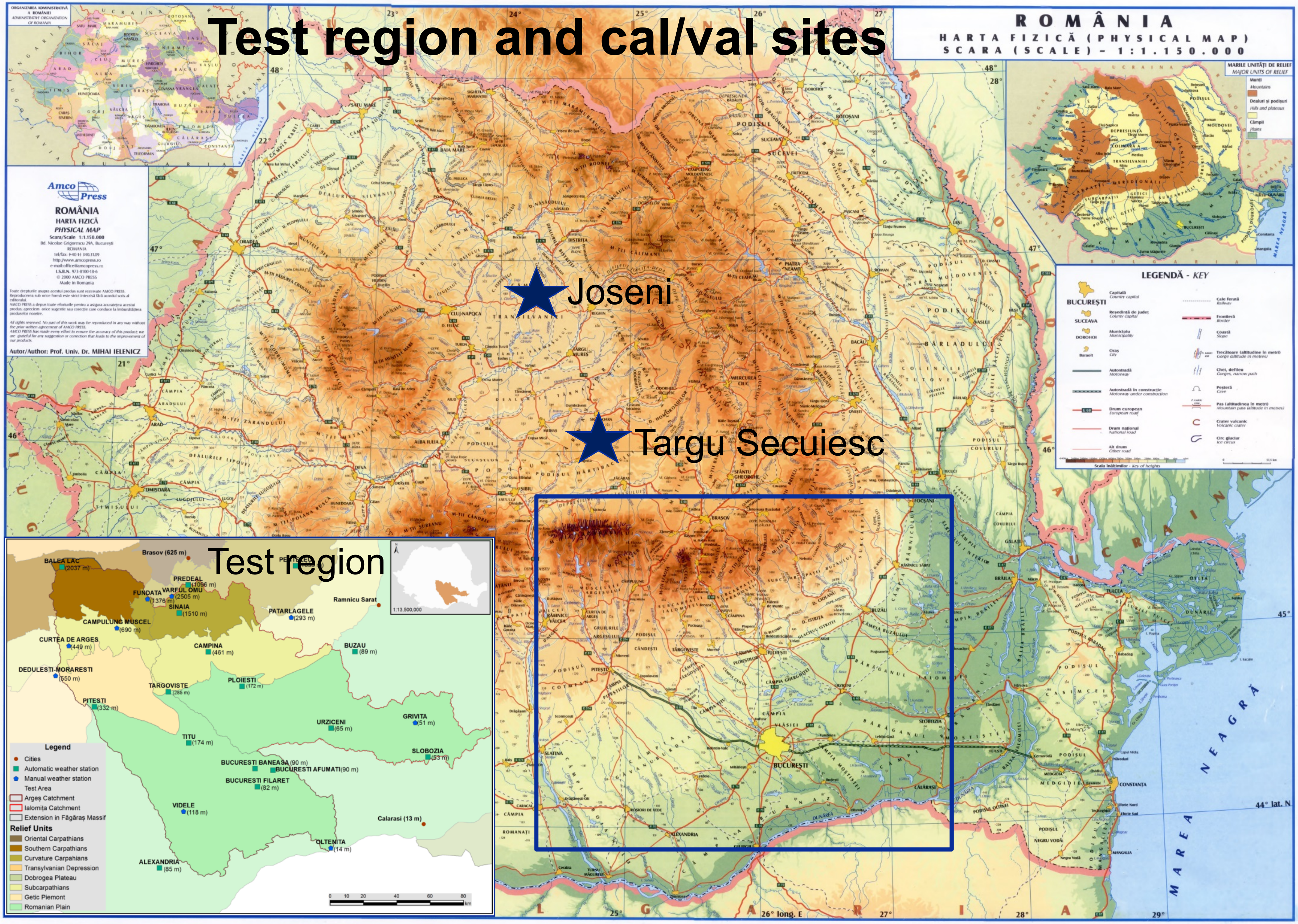
$$p(X^t | E^t = S_i)$$

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

Calibration and validation (cal/val) activities

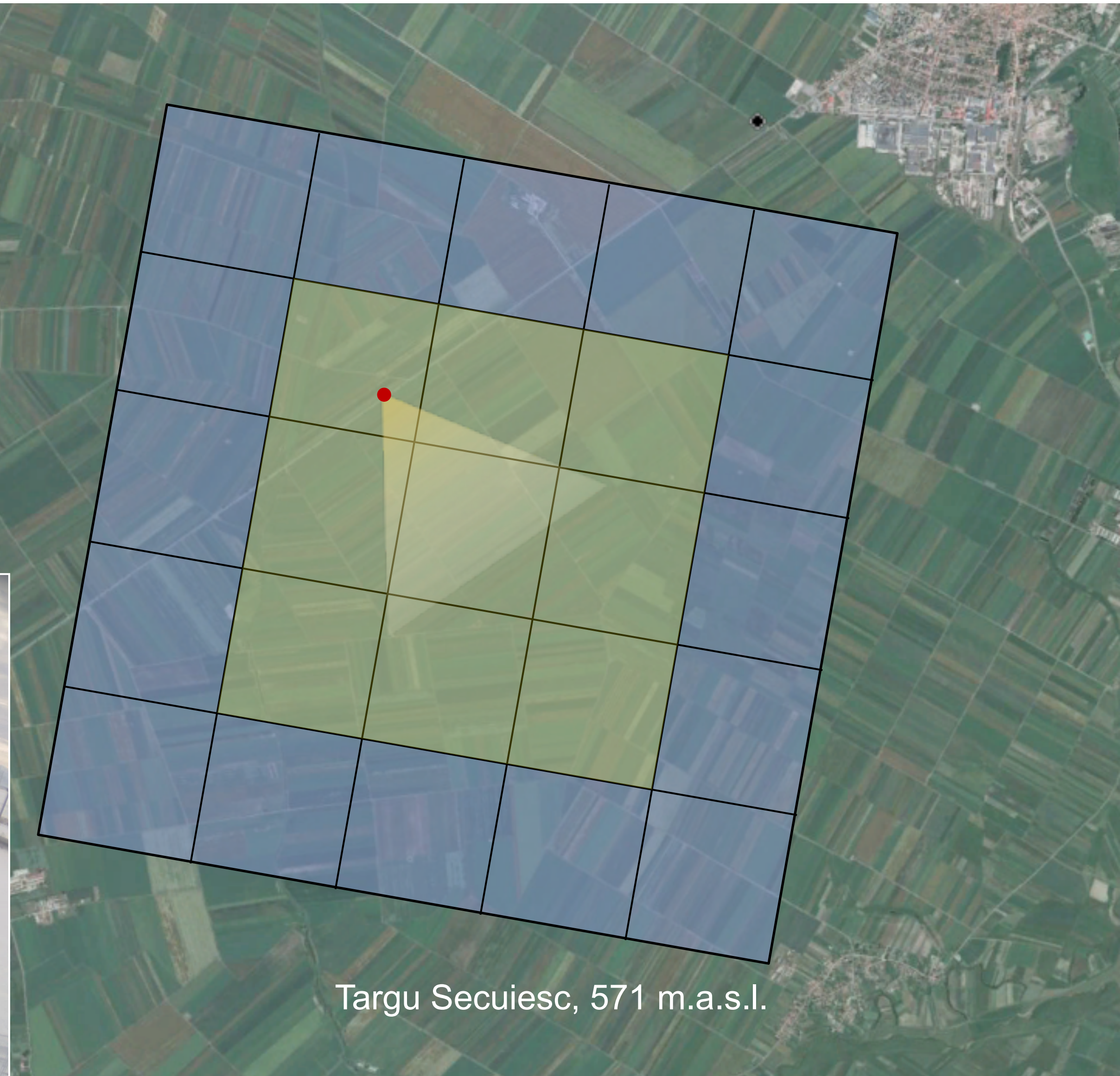
- Objectives: To calibrate an algorithm and validate its performance
- Calibration: Determine the relationship between satellite measurements and physical (or categorical) entities. Aiming for a quantitative product
- Validation: Compare and analyse satellite retrieval results and independent in situ measurements
- Taking place through tree winters: 2015-2017

Test region and cal/val sites



Cal/val site Joseni

Cal/val site Targu Secuiesc



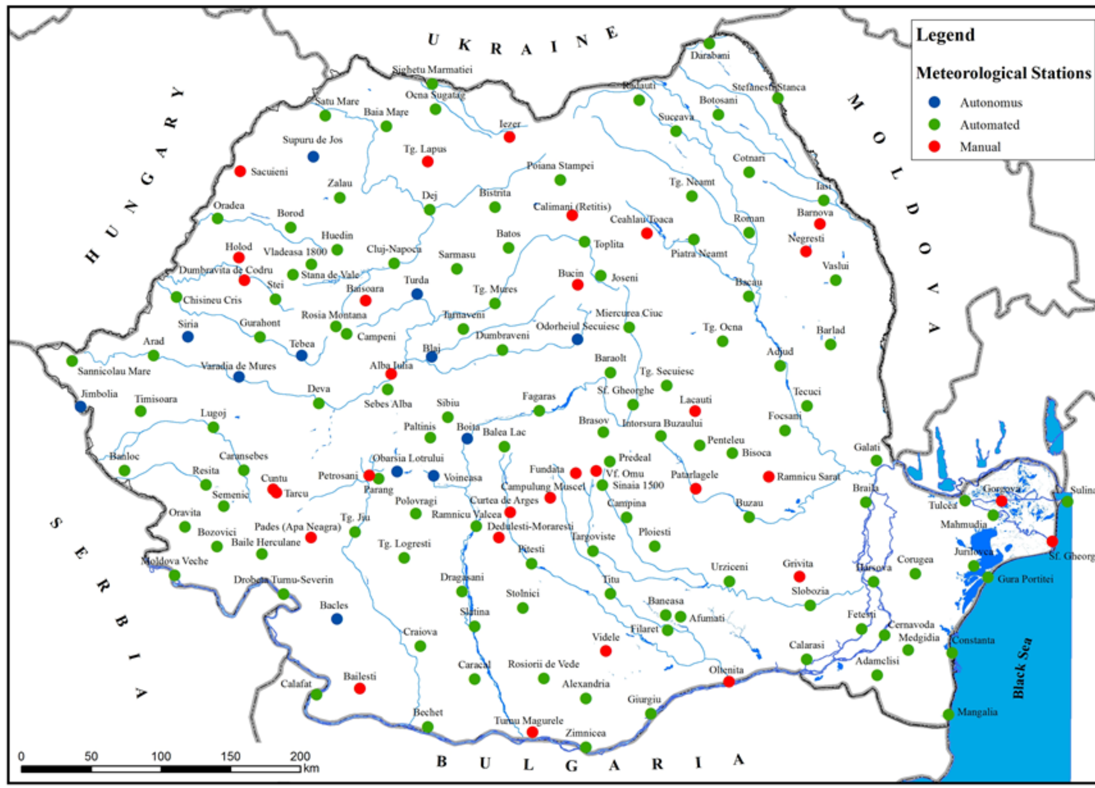
Fagaras and Sinaia region, Southern Carpathian

- 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)

Fieldwork in Southern Carpathian
31 January 2017

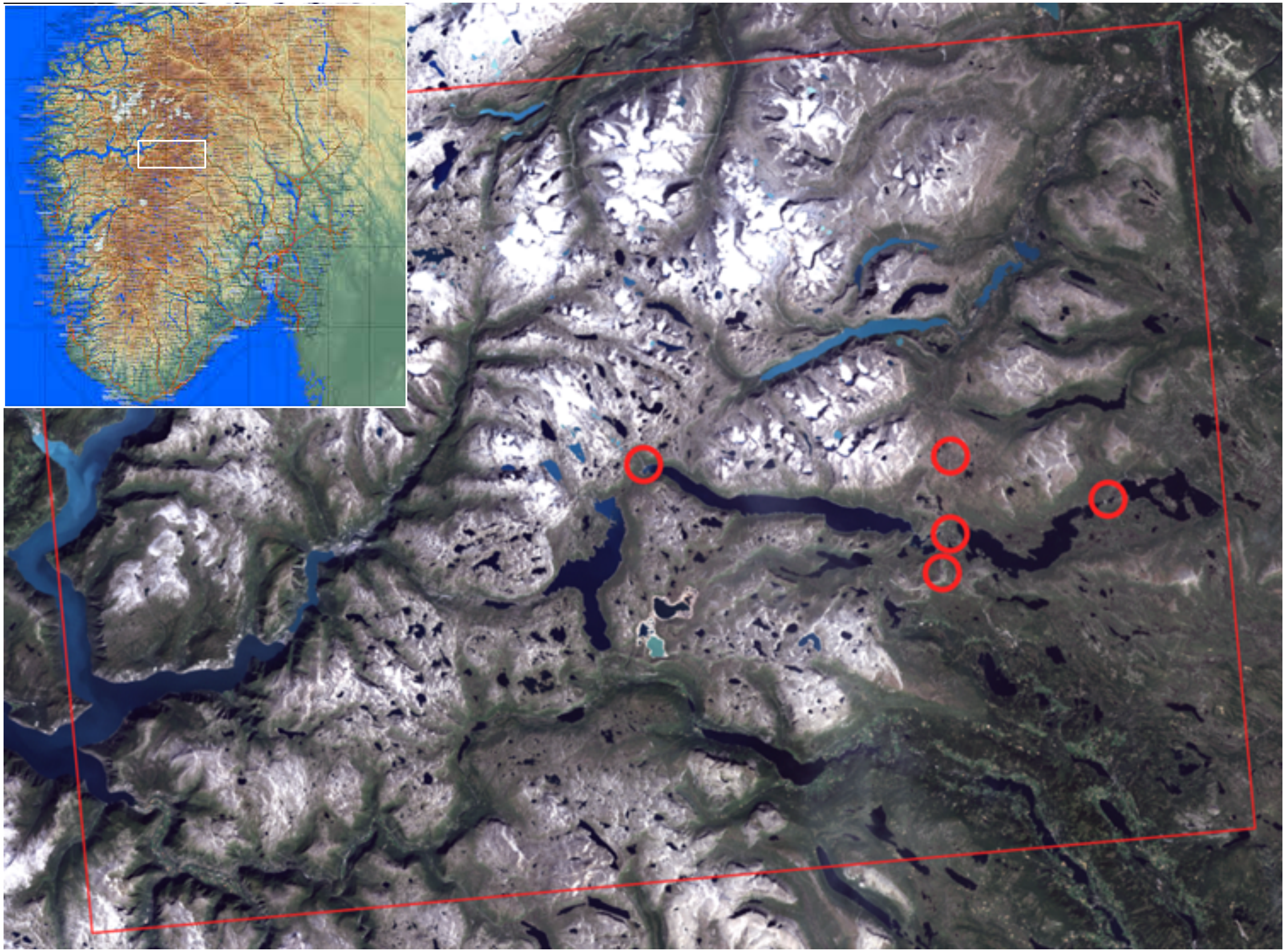
Large-scale evaluation of wet snow products

- 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

Test region Norway: Jotunheimen



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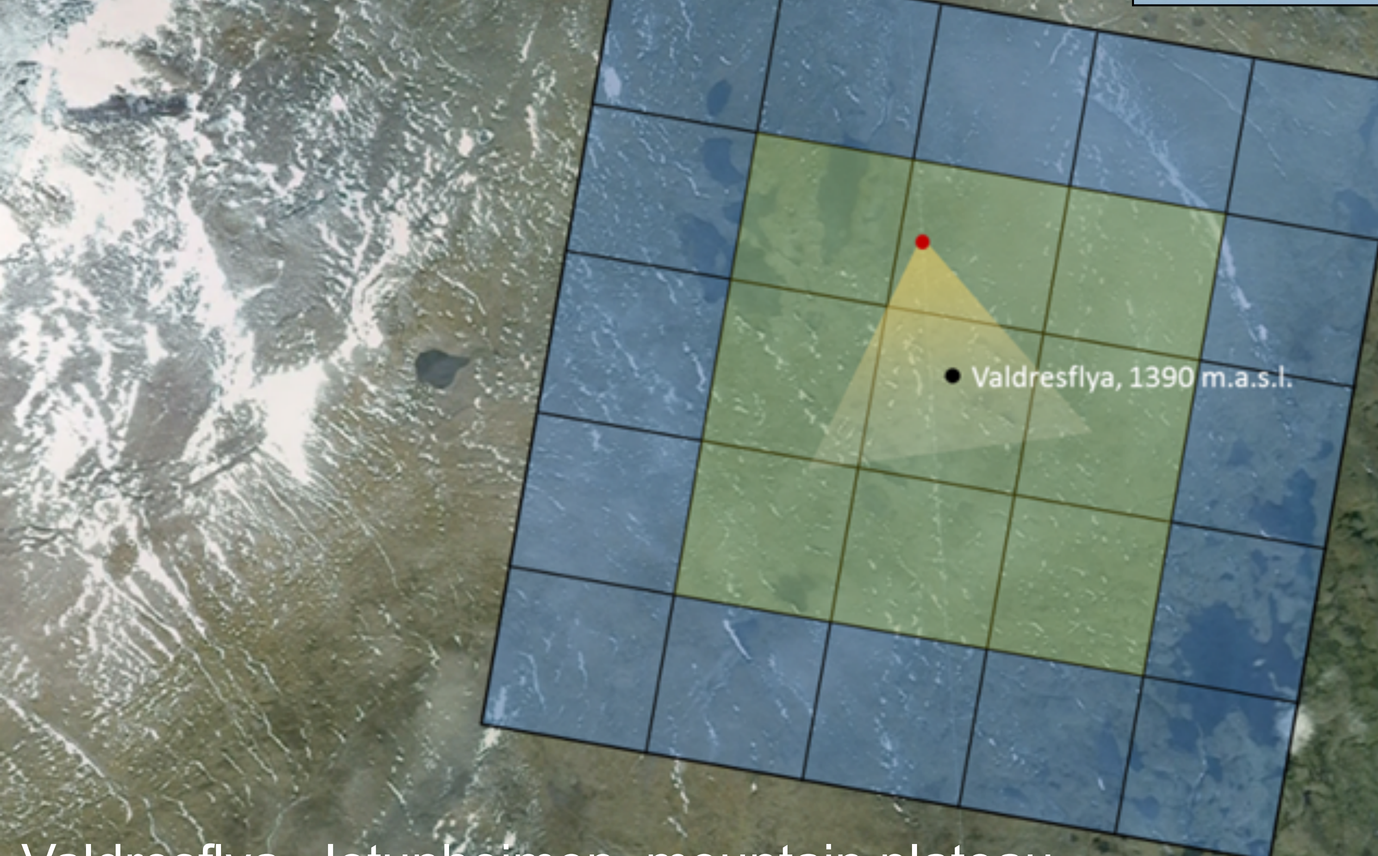
Cal/val site Valdresflya

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



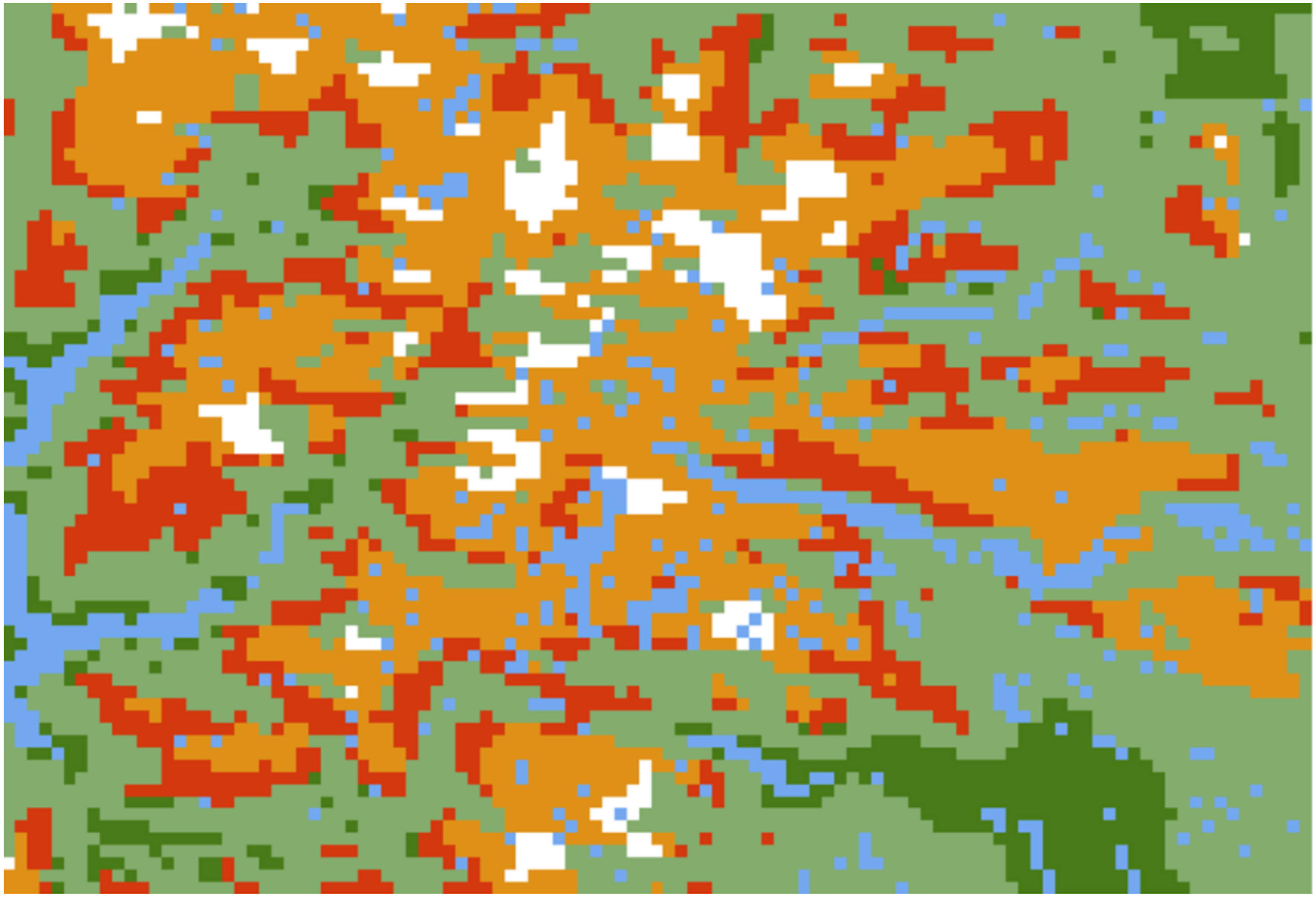
Valdresflya, Jotunheimen, mountain plateau, 1200-1400 m a.s.l., total area 265 km^2

Jotunheimen: Weather station air temperature versus OWS from MODIS, 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



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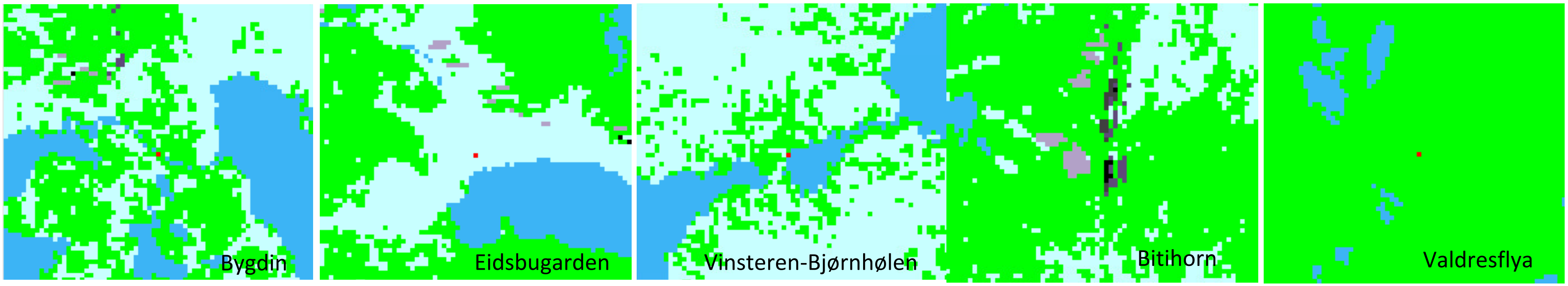
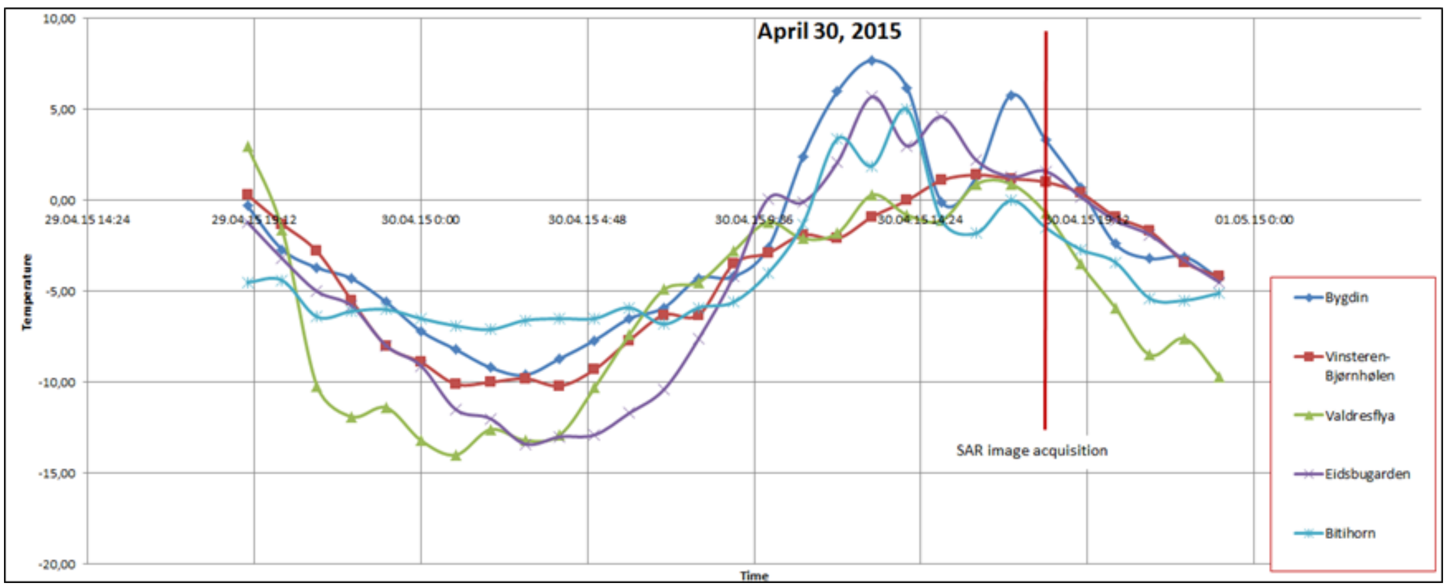
Jotunheimen: Weather station air temperature versus SWS 30 April 2015





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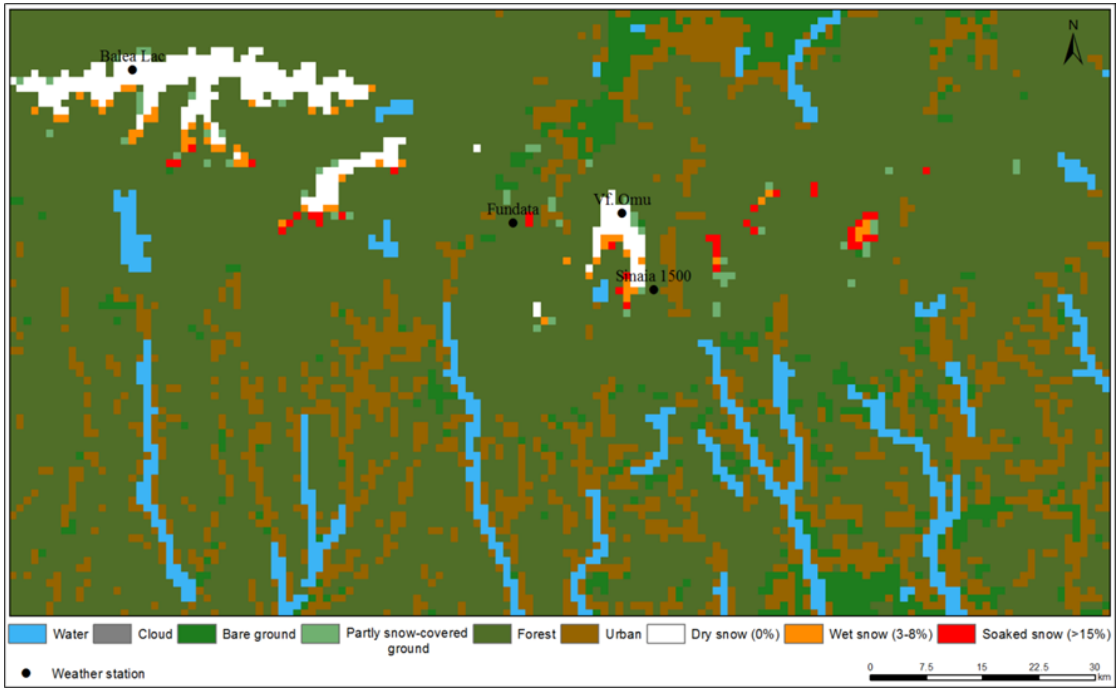
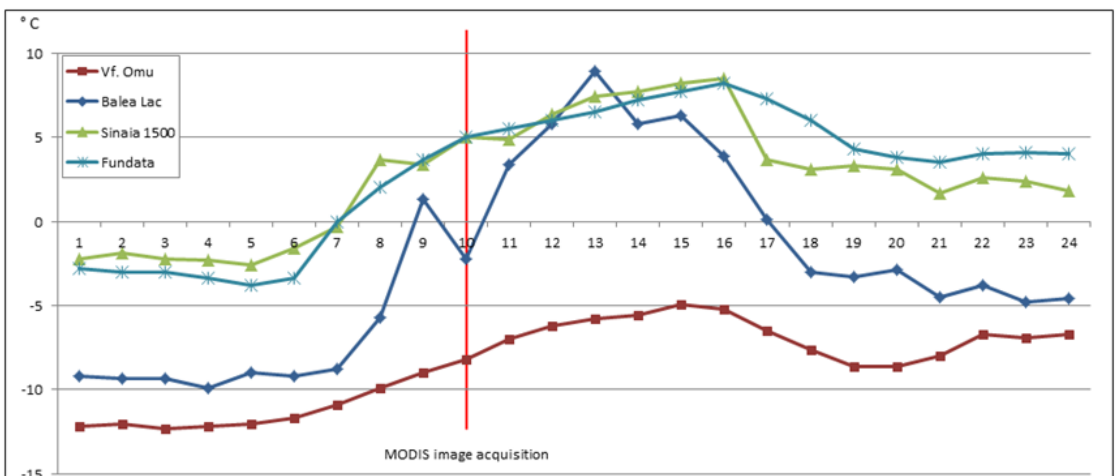
Southern Carpathian: OSW based on MODIS from 10 April 2015 acquired at 09:30 UTC





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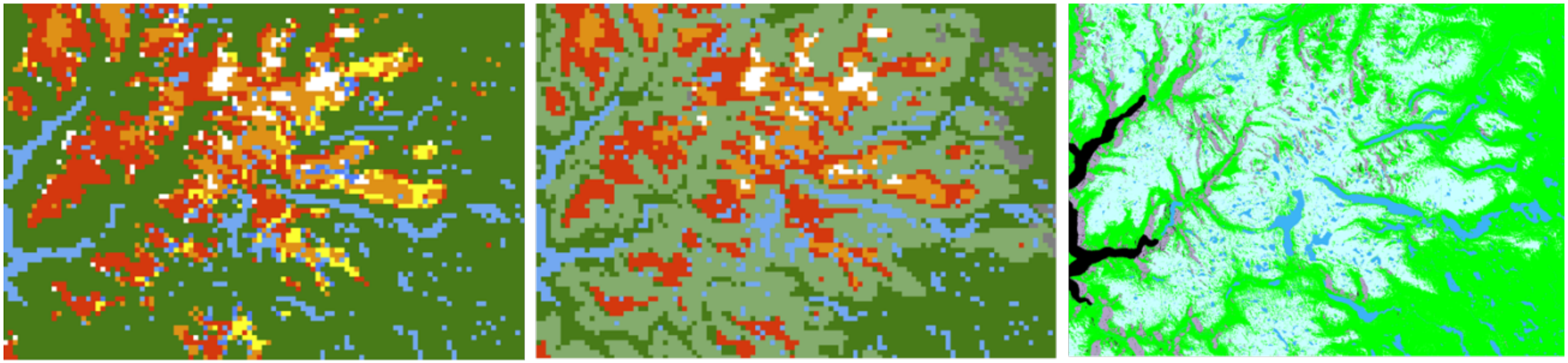
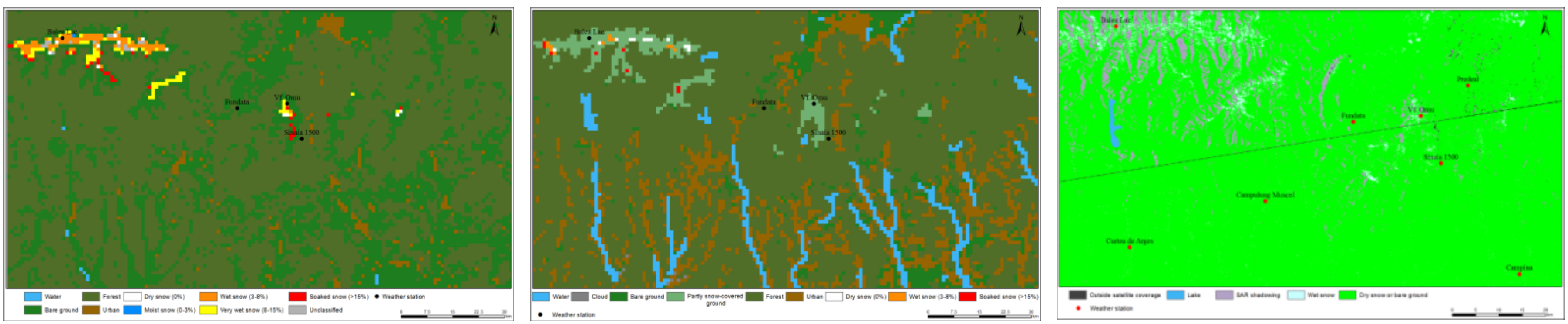
METEO ROMÂNIA ADMINISTRAȚIA NAȚIONALĂ DE METEOROLOGIE

Version 1.0 products 2015

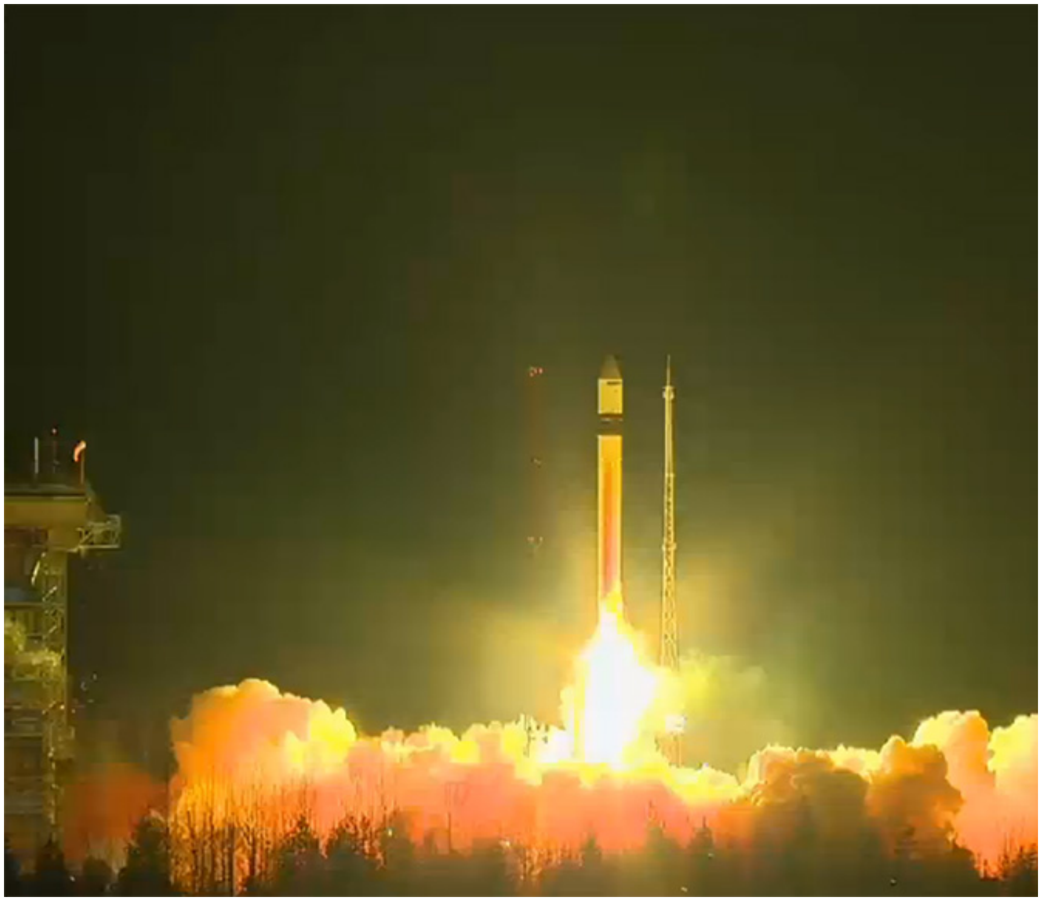


Jotunheimen: Multi-sensor wet snow map for 16 June 2015 (left), optical wet snow map for the same day (middle) and SAR wet snow map for 17 June 2015 (right).



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

Sentinel-3 era starts late autumn 2017



16 February 2016

Sentinel-1, 2 and 3 family

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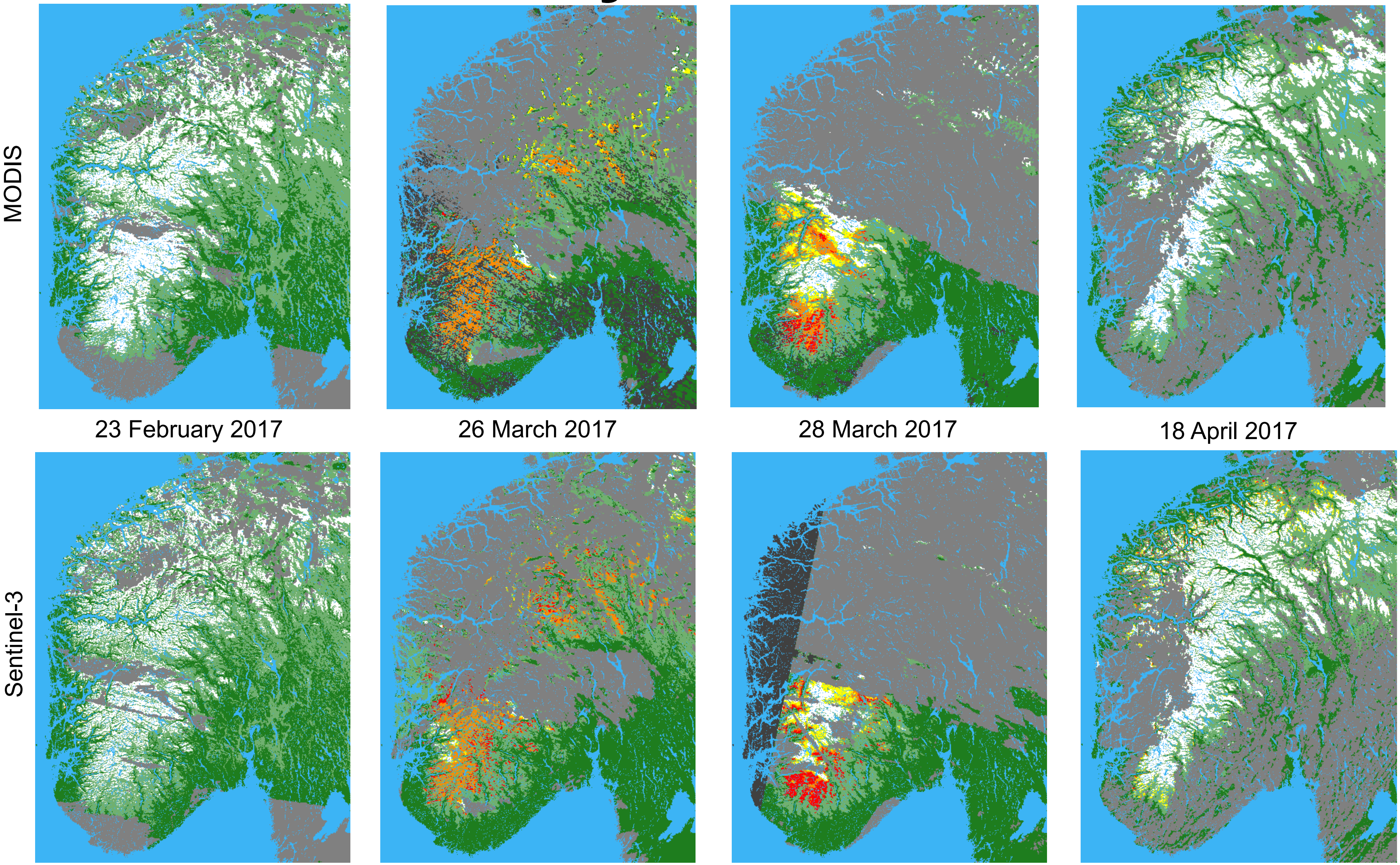
METEO ROMÂNIA ADMINISTRAȚIA NAȚIONALĂ DE METEOROLOGIE

Southern Norway, winter 2017



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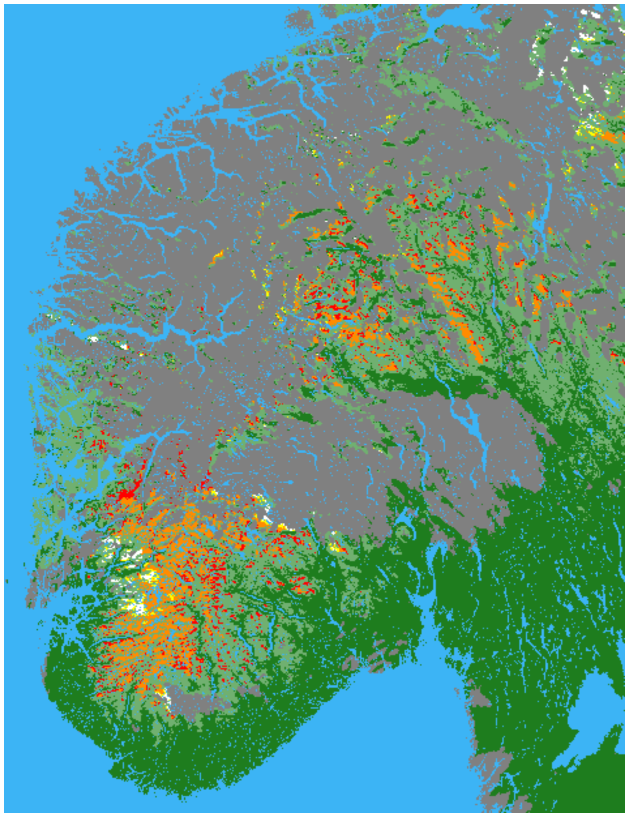
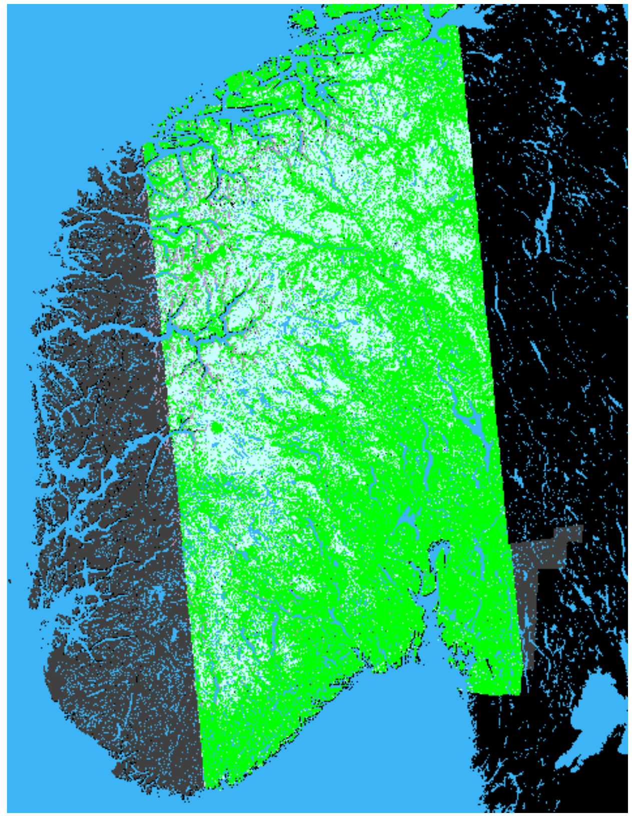
METEO ROMÂNIA
ADMINISTRAȚIA NAȚIONALĂ DE METEOROLOGIE

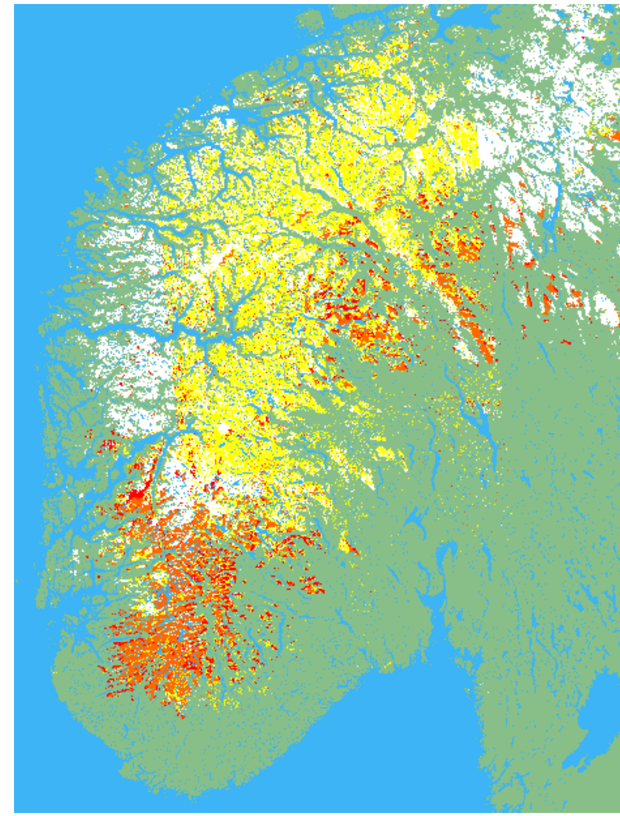
Wet snow event 26 March 2017



OWS Sentinel-3



SWS Sentinel-1



MWS Sentinel-1 + Sentinel-3

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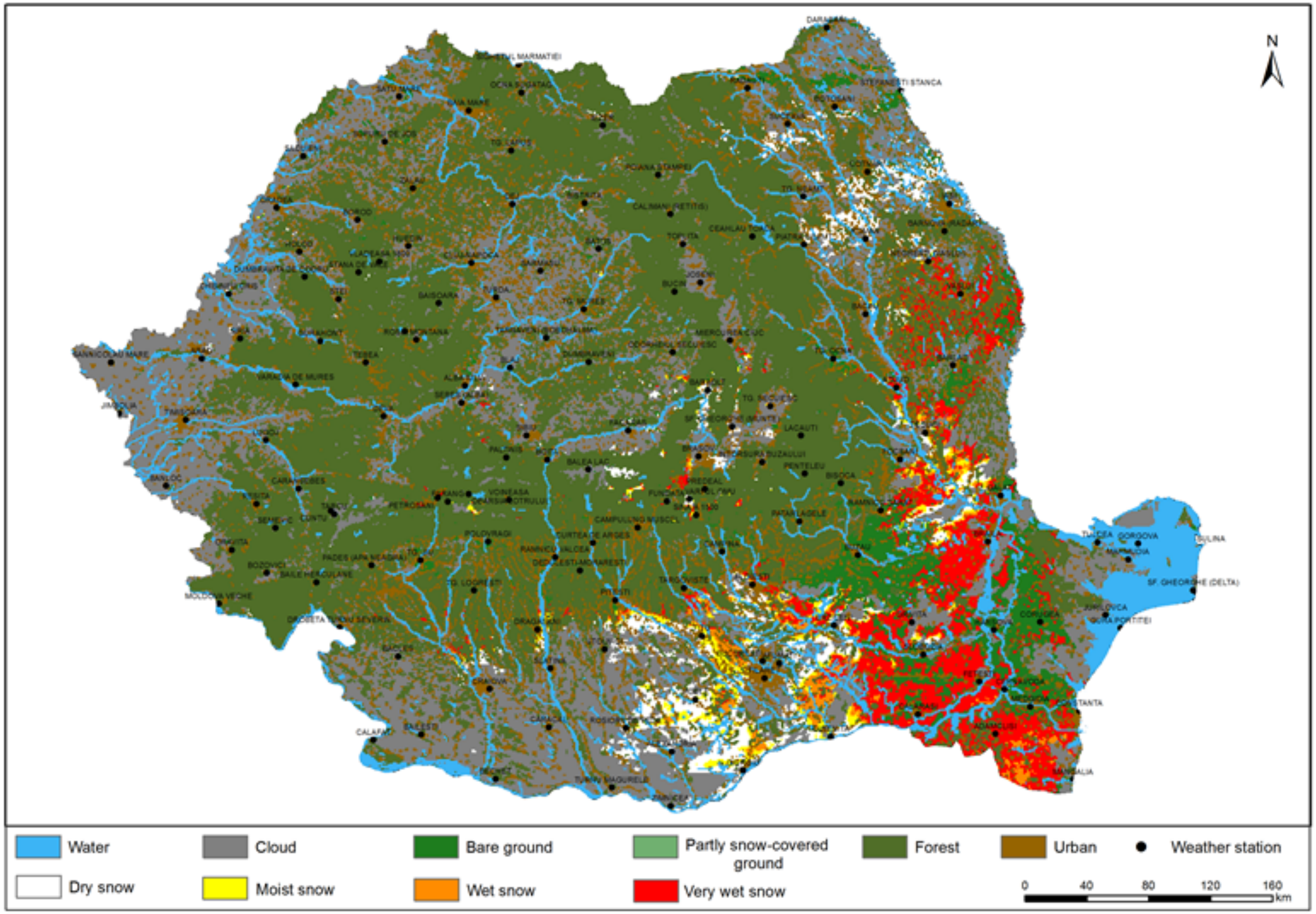
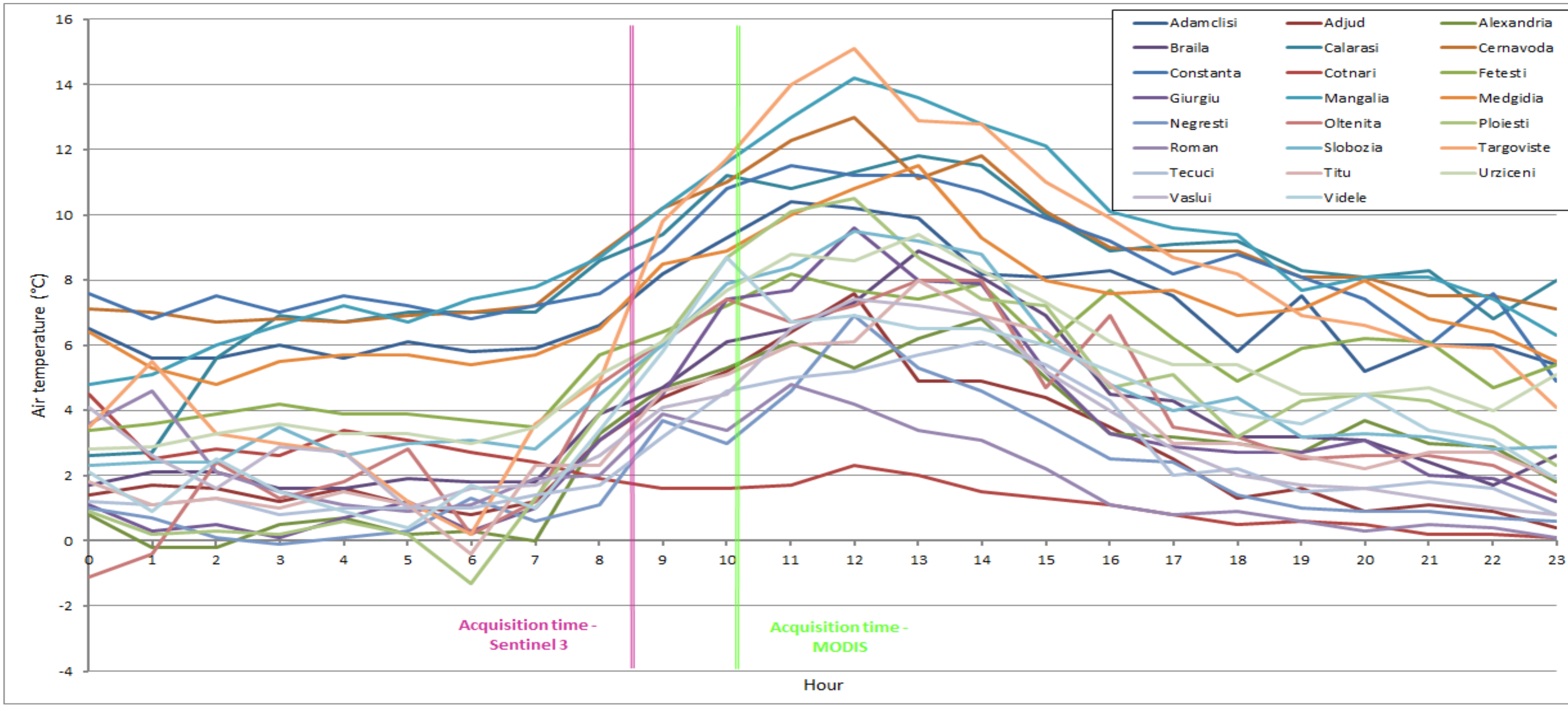
METEO ROMÂNIA ADMINISTRAȚIA NAȚIONALĂ DE METEOROLOGIE

OWS from Sentinel-3, 4 February 2017



NR SnowBall METEO ROMÂNIA ADMINISTRAȚIA NAȚIONALĂ DE METEOROLOGIE

OWS from Sentinel-3, 4 February 2017



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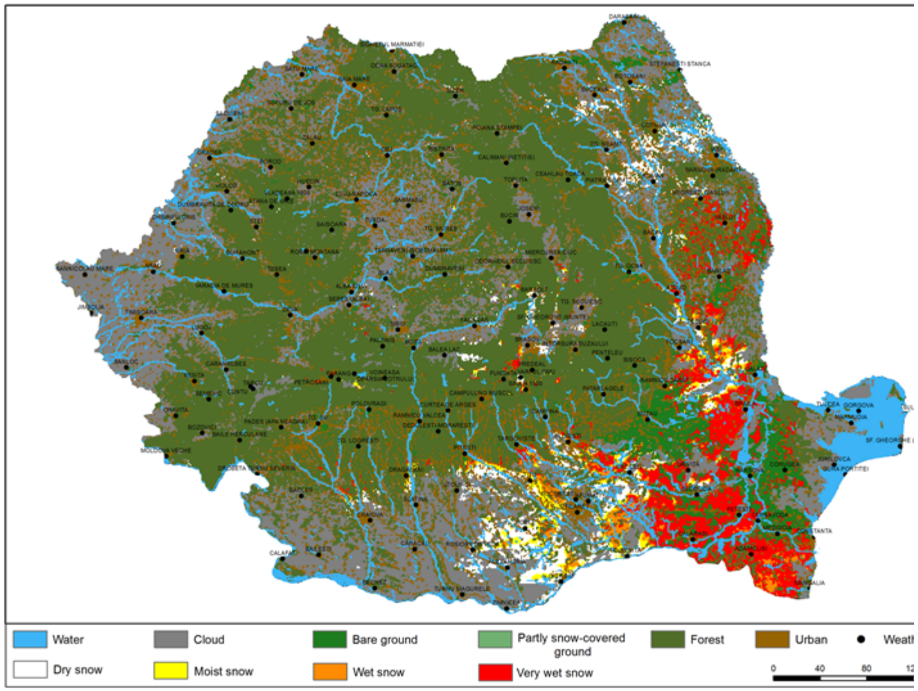
METEO ROMÂNIA ADMINISTRAȚIA NAȚIONALĂ DE METEOROLOGIE

OWS from Sentinel-3, 4 February 2017

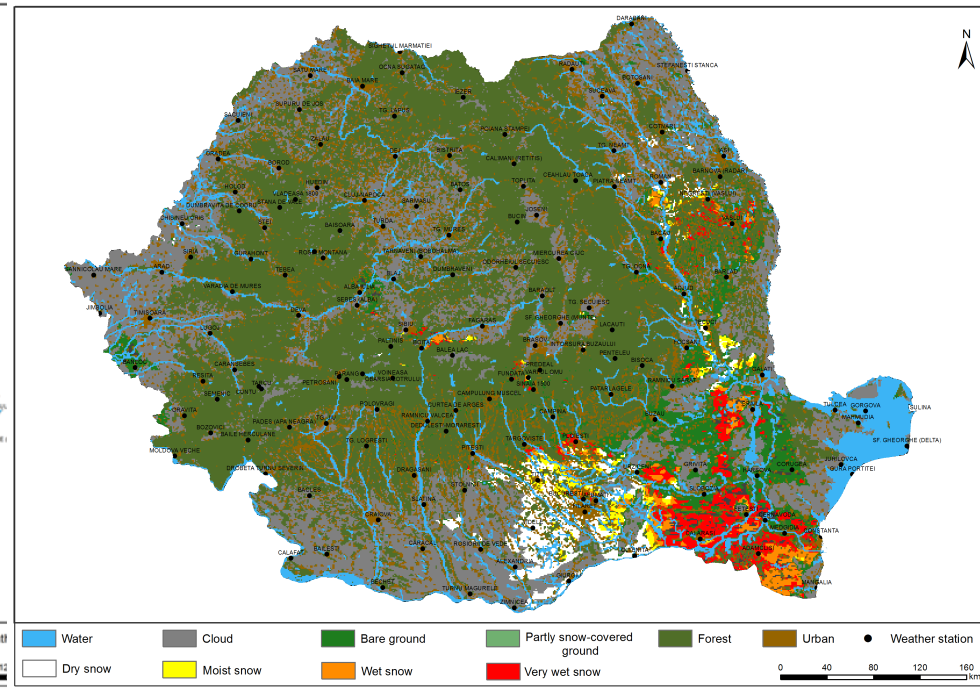
Weather station	04.02.2017							
	W S-3	W MODIS	SD (6:00)	SCE (6:00)	8:00	Ac. – S-3	Ac. – MODIS	14:00
Adamclisi	V	V	4	10	6.6	8.2	9.3	8.2
Adjud	V	+	3	10	3.1	4.4	5.2	4.9
Alexandria	+/D	+	11	10	3.3	4.7	5.3	6.8
Braila	V	+	7	7	3.9	4.7	6.1	8.1
Calarasi	V	V	6	10	8.6	9.4	11.2	11.5
Cernavoda	=	=	No data	//	8.8	10.2	11.0	11.8
Constanta	=	=	<1	5	7.6	8.9	10.8	10.7
Cotnari	=	=	<1	6	1.9	1.6	1.6	1.5
Fetesti	V	V	4	6	5.7	6.4	7.2	7.9
Giurgiu	D	D	17	10	3.1	4.5	7.4	7.9
Mangalia	+	+	0	0	8.7	10.2	11.6	12.8
Medgidia	V	V	5	10	6.5	8.5	8.9	9.3
Negresti	W	W	2	10	1.1	3.7	3.0	4.6
Oltenita	D	D	17	10	4.8	6.1	7.4	8
Ploiesti	+	V	4	10	3.9	6.1	8.7	7.4
Roman	+/D	+	2	7	2	3.9	3.4	3.1
Slobozia	=	=	<1	5	4.5	6.0	7.9	8.8
Targoviste	=	=	<1	0	4.9	9.8	11.7	12.8
Tecuci	+	M	1	8	1.7	3.2	4.6	6.1
Titu	M	W	10	10	2.3	4.6	5.1	6.9
Urziceni	+	-	3	8	5.1	6.1	7.7	8.3
Vaslui	V	V	5	10	2.6	4.1	4.5	6.9
Videle	D	D	13	10	3.4	5.8	8.7	6.5

METEO ROMÂNIA ADMINISTRAȚIA NAȚIONALĂ DE METEOROLOGIE

OWS from Sentinel-3 and MODIS, 4 February 2017



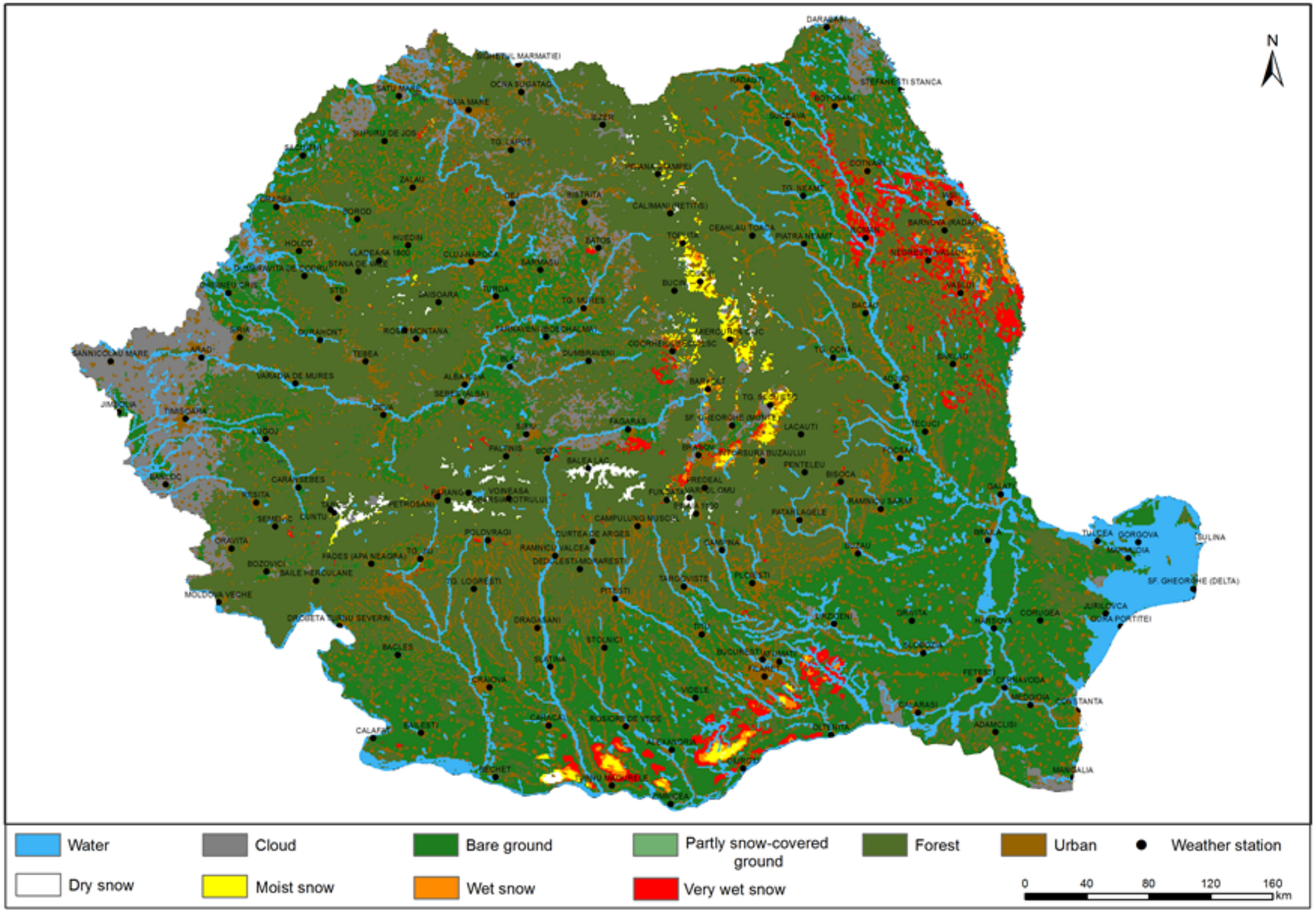
Sentinel-3



MODIS

NR SnowBall METEO ROMÂNIA ADMINISTRAȚIA NAȚIONALĂ DE METEOROLOGIE

OWS from MODIS, 22 February 2017



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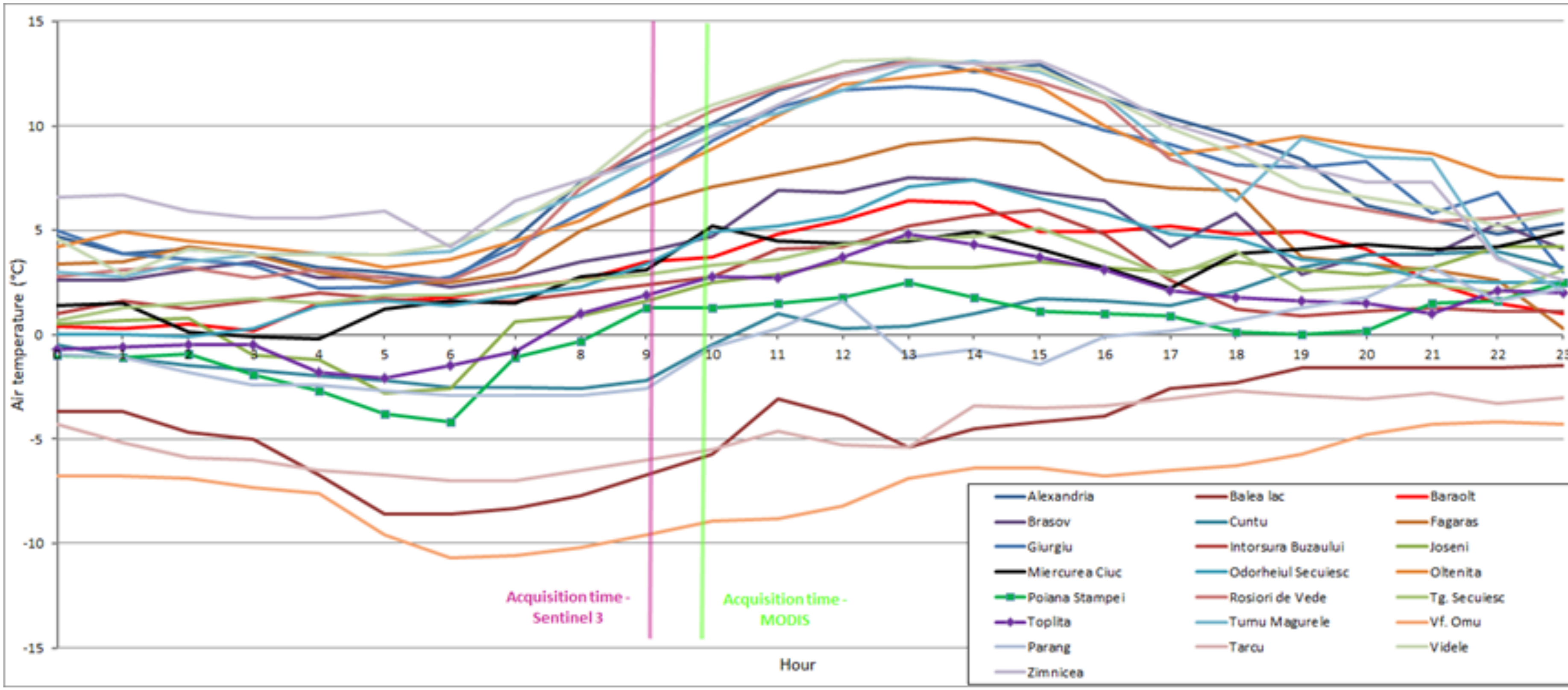
METEO ROMÂNIA ADMINISTRAȚIA NAȚIONALĂ DE METEOROLOGIE

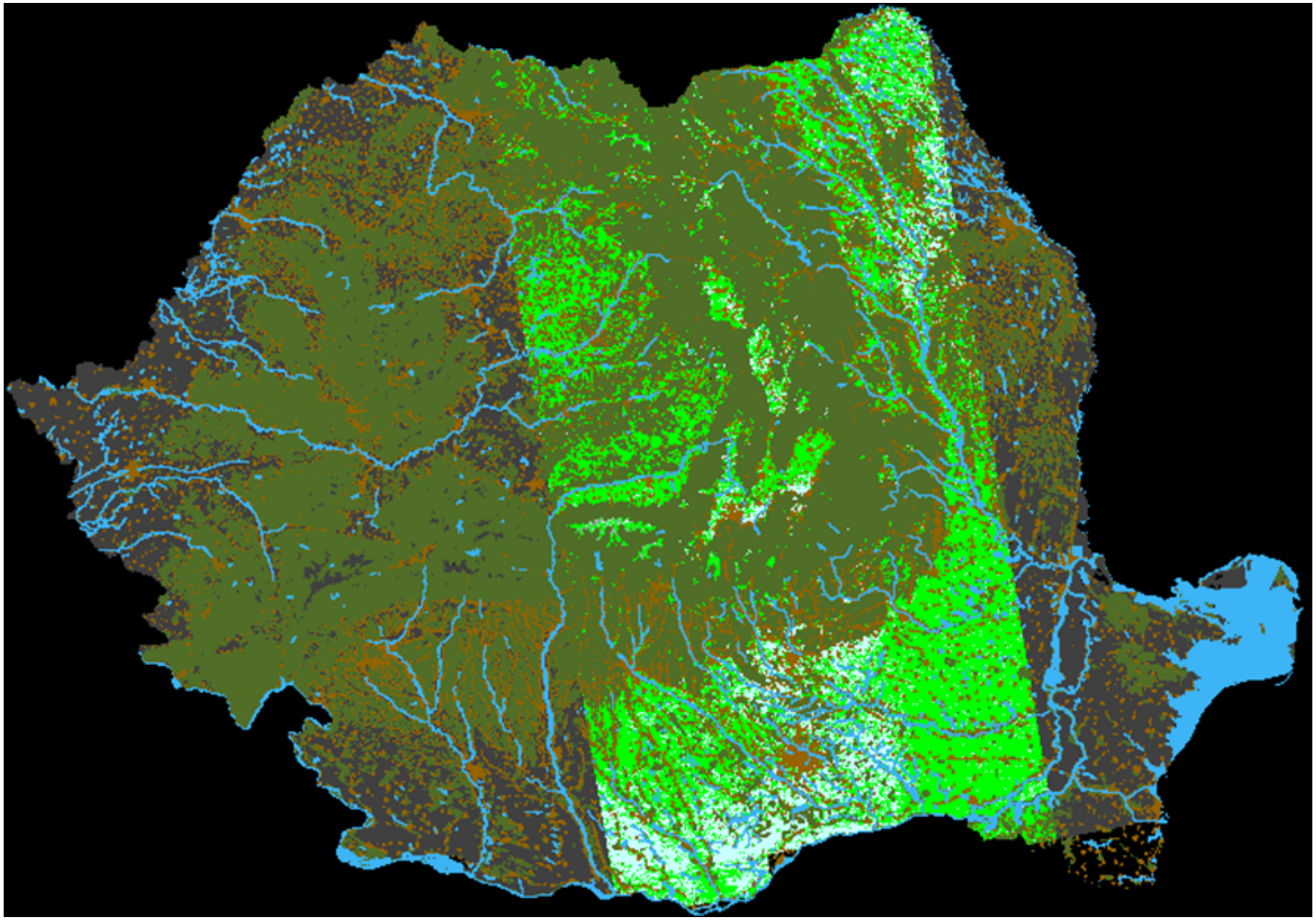
OWS from MODIS, 22 February 2017



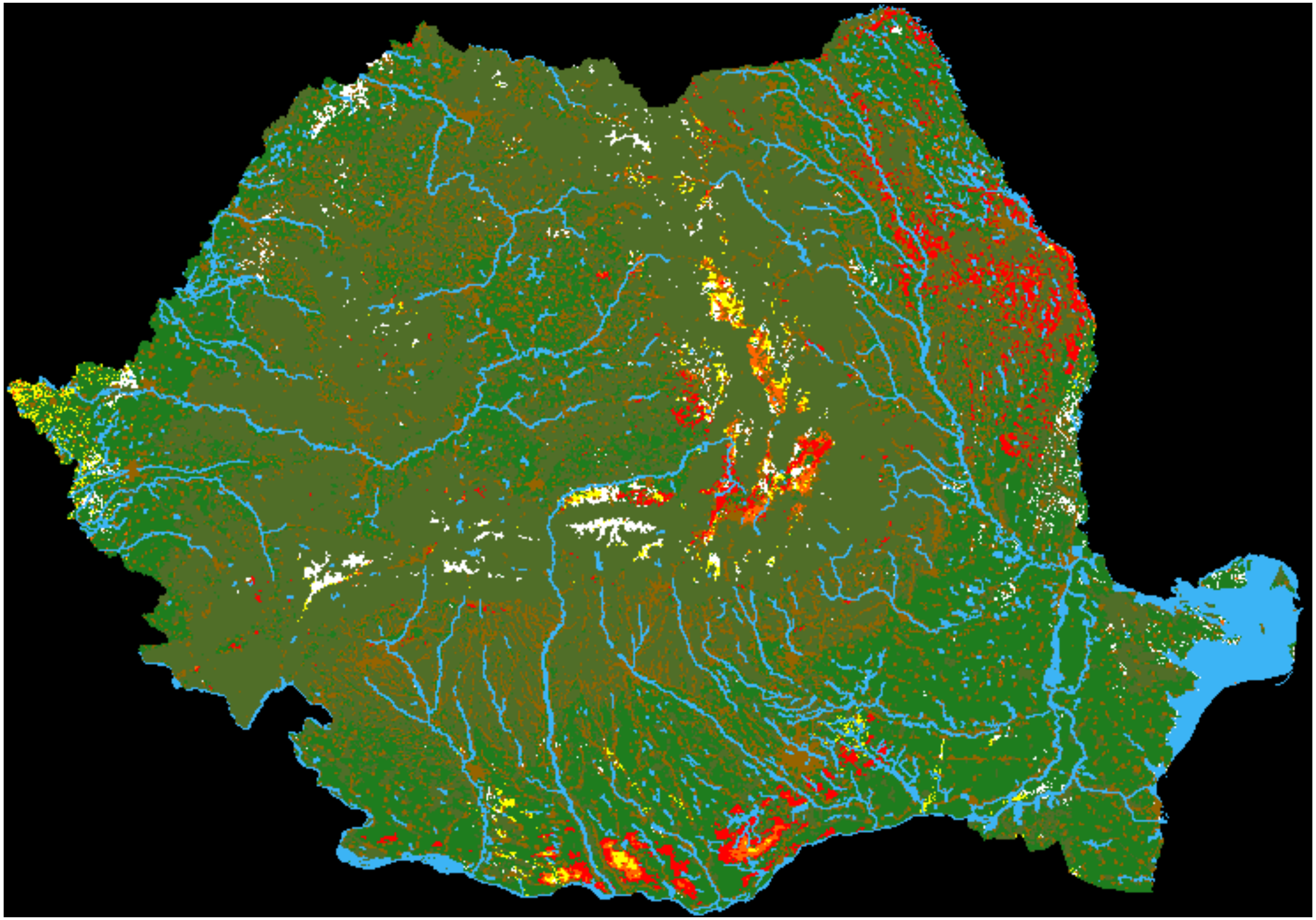
OWS from MODIS, 22 February 2017

Weather station	22.02.2017							
	W S-3	W MODIS	SD (6:00)	SCE (6:00)	8:00	Ac. – S-3	Ac. – MODIS	14:00
Alexandria	=	=	0	0	7.3	8.7	10.1	12.6
Balea Lac	D	D	158	10	-7.7	-6.7	-5.7	-4.5
Baraolt	M	W	8	10	2.6	3.5	3.7	6.3
Brasov	V	+	2	10	3.5	4.0	4.7	7.4
Cuntu	D	D	65	10	-2.6	-2.2	-0.5	1.0
Fagaras	=	=	<1	3	5	6.2	7.1	9.4
Giurgiu	V	V	5	10	5.8	7.1	9.3	11.7
Intorsura Buzaului	+	+	18	10	2	2.4	2.8	5.7
Joseni	M	M	5	10	0.9	1.6	2.5	3.2
Miercurea Ciuc	V	W	10	10	2.8	3.1	5.2	4.9
Odorheiul Secuiesc	V	V	5	10	2.3	3.4	4.9	7.4
Oltenita	=	=	<1	10	5.5	7.4	8.9	12.7
Poiana Stampei	M	D	4	1	-0.3	1.3	1.3	1.8
Rosiori de Vede	=	=	<1	10	7	9.1	10.7	13.0
Tg. Secuiesc	V	+	3	10	2.6	2.9	3.3	4.7
Toplita	W	M	8	5	1	1.9	2.8	4.3
Turnu Magurele	V	V	5	10	6.7	8.3	10.0	13.1
Vf. Omu	D	D	45	10	-10.2	-9.6	-8.9	-6.4
Vf. Parang	D	D	70	10	-2.9	-2.6	-0.6	-0.7
Vf. Tarcu	D	D	65	0	-6.5	-6.0	-5.5	-3.4
Videle	=	=	0	6	7.2	9.7	11.0	13.0
Zimnicea	=	=	1	0	7.4	8.3	9.5	13.0

SWS from Sentinel-1, 18 February 2017



MWS from Sentinel-1+Sentinel-3, 22 February 2017



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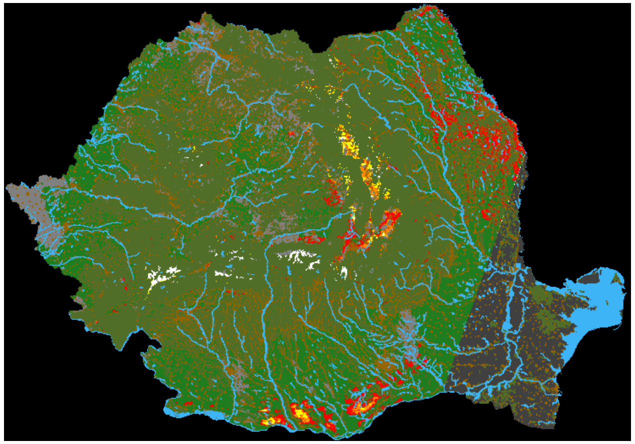
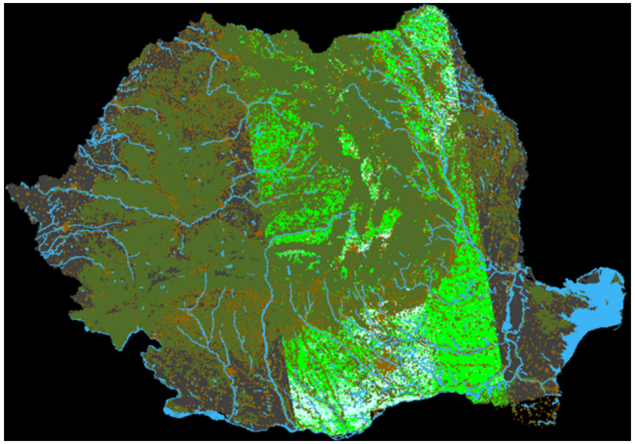
METEO ROMÂNIA ADMINISTRAȚIA NAȚIONALĂ DE METEOROLOGIE

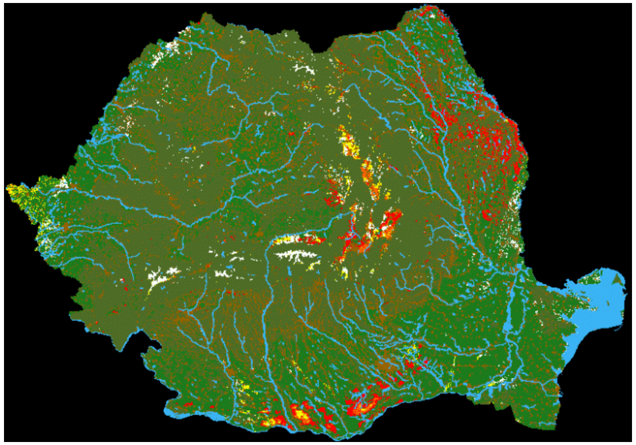
All from S1+S3, 22/18 February 2017



OWS, Sentinel-3



SWS, Sentinel-1



MWS, Sentinel-1 + 3

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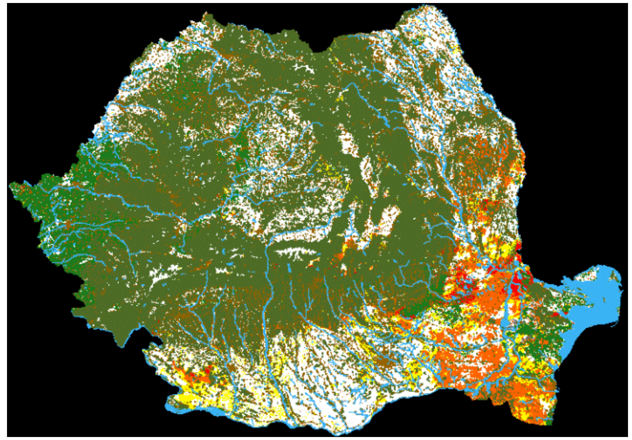
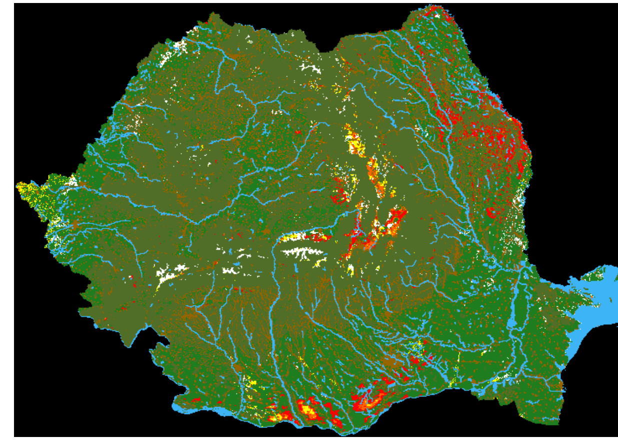
ADMINISTRAȚIA NAȚIONALĂ DE METEOROLOGIE

OWS Sentinel-3 time series 2017

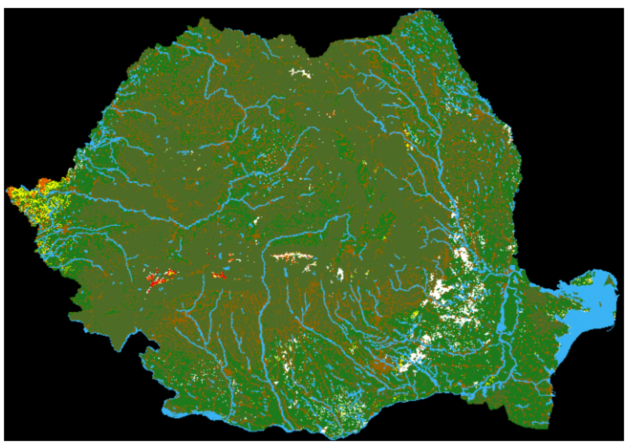
21 January 2017



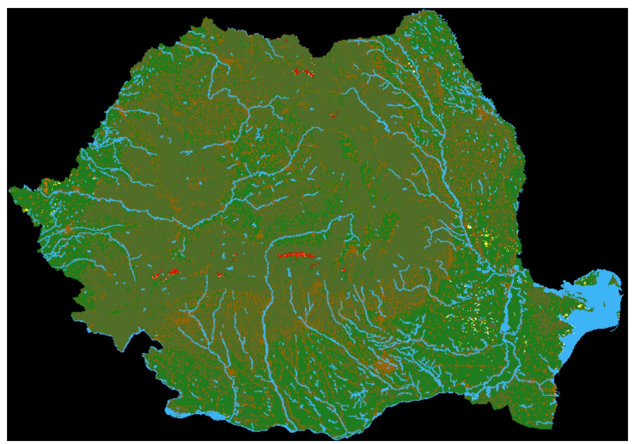
3 February 2017



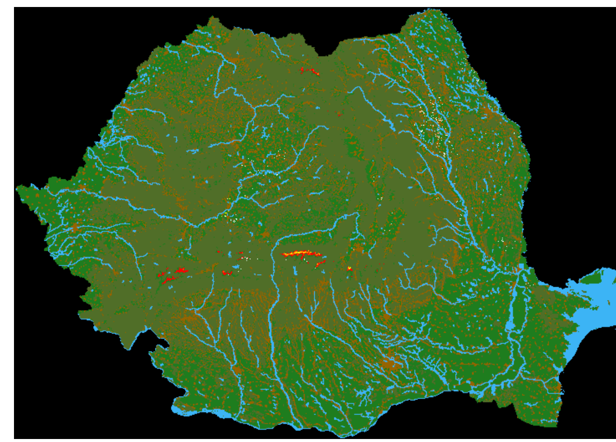
22 February 2017



5 March 2017



29 March 2017



10 April 2017

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METEO ROMÂNIA ADMINISTRAȚIA NAȚIONALĂ DE METEOROLOGIE

Conclusions

- Developed three products for snow wetness monitoring by Sentinel-1 & Sentinel-3:
  - Optical Wet Snow (OWS)
  - SAR Wet Snow (SWS)
  - Multi-sensor Wet Snow (MWS)
- Algorithms and products have been tested and advanced through three snow seasons (2015-2017)
- Diagnostic snow campaigns and calibration/validation carried out in both countries
- Product performance matches quite well with in situ data:
  - 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
- Algorithms and products close to a mature state for operationalisation

Thank you!

The project is supported by a EEA Grants Norway