Modelling Snow Water Equivalent distribution in the Alps: the activities in Aosta Valley

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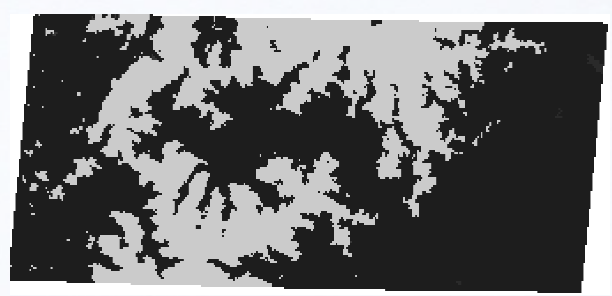
(4) - ETH - ZURICH

- **introduction**
- **SWE distribution at regional scale (3000 Km^2)**
- **SWE distribution at medium basin scale (120 Km^2)**
- **melt modelling**

SWE = SNOW HEIGHT x SNOW COVER x SNOW DENSITY

SWE [mm w.e.] = H_s [m] x SCA [m²] x ρ_s [kgm⁻³]



introduction

SWE distribution at regional scale (3000 Km^2)

SWE distribution at medium basin scale (120 Km^2)

melt modelling

SWE at regional scale

the aim is to know the evolution of total amount and distribution of SWE on the Aosta Valley during the winter time

it's used for the hydrological bullettin & it's an important information for summer drought crisis (e.g. Autorità di Bacino del Po)

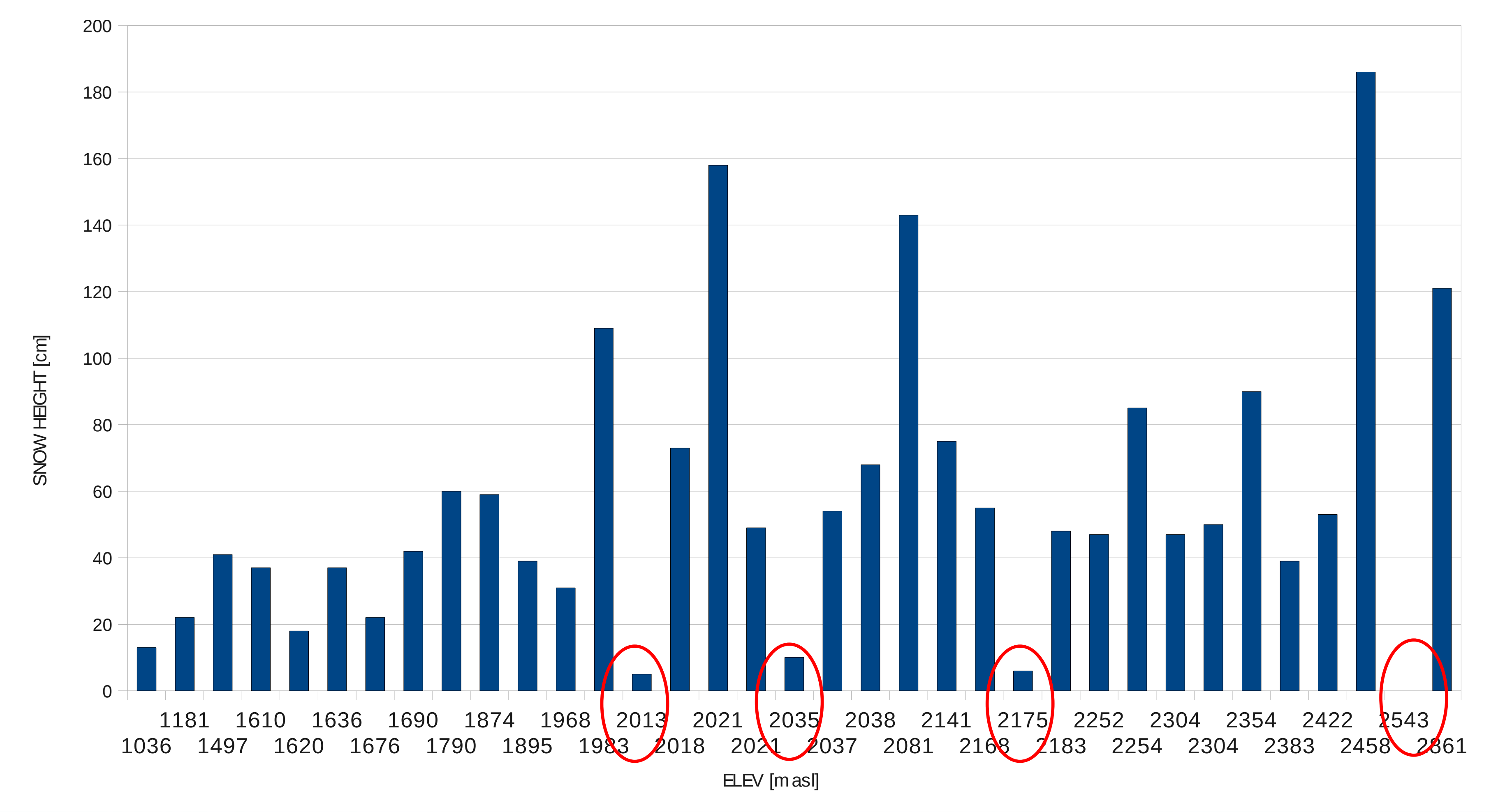
it's done with a monthly frequency from November to June

SWE = SNOW HEIGHT x SNOW DENSITY x SNOW COVER EXTENT

SNOW HEIGHT: from point measurements to distributed fields

Automatic snow height measurements point (ultrasonic depth gauge) in Aosta Valley (n=35)
... continuous measurements

SNOW HEIGHT: from point measurements to distributed fields



Data reliability !!

SNOW HEIGHT: from point measurements to distributed fields

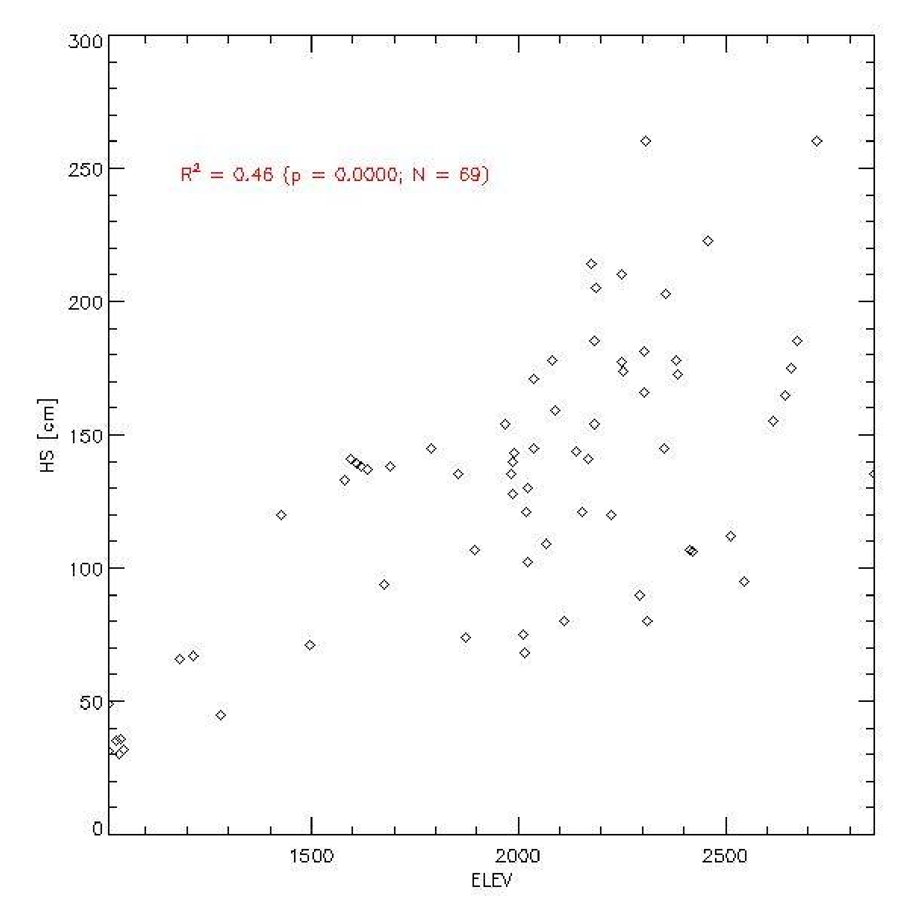
Data reliability !!

SNOW HEIGHT: from point measurements to distributed fields

How can we move from point measurements to a snow height value distributed all over the entire Aosta Valley?

SNOW HEIGHT: from point measurements to distributed fields

We try to find empirical relationships between snow height and some morphological parameters (e.g. at higher elevation we have a thicker snow height)



SNOW HEIGHT: from point measurements to distributed fields

We try to find **empirical relationships** between snow height and some morphological parameters

Steps

1) **model definition**: GLM: $y = \alpha + \beta_1 x_1 + \dots + \beta_n x_n + \varrho$

2) **selection** of the **morphological parameters** (x_1, x_2, ...) to include in the model (Akaike Information Criteria – AIC)

3) model **coefficients** (β_1, β_n, ...) **estimation** by bootstrap procedure

4) model evaluation by **cross validation** techniques (LGO and k-fold)

5) **analysis of** the crossvalidated **statistics** (R^2_{cv}, EF_{cv}, $RMSE_{cv}$)

SNOW HEIGHT: from point measurements to distributed fields

1) model definition: GLM: $y = \alpha + \beta_1 x_1 + \ldots + \beta_n x_n + \varrho$

2) selection of the morphological parameters (x_1, x_2, ...) to include in the model (Akaike Information Criteria - AIC)

DISTRIBUTED PARAMETERS
Elevation
Slope
Exposition
Northness index
Concavity/Convexity
Monthly Direct Radiation
Monthly Diffuse Radiation
Monthly Global Radiation
Monthly Direct Radiation Duration

SNOW HEIGHT: from point measurements to distributed fields

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→ **DEM** (Elevation, Slope, Exposition, Northness index, Concavity/Convexity)

SNOW HEIGHT: from point measurements to distributed fields

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Monthly Global Radiation
Monthly Direct Radiation Duration

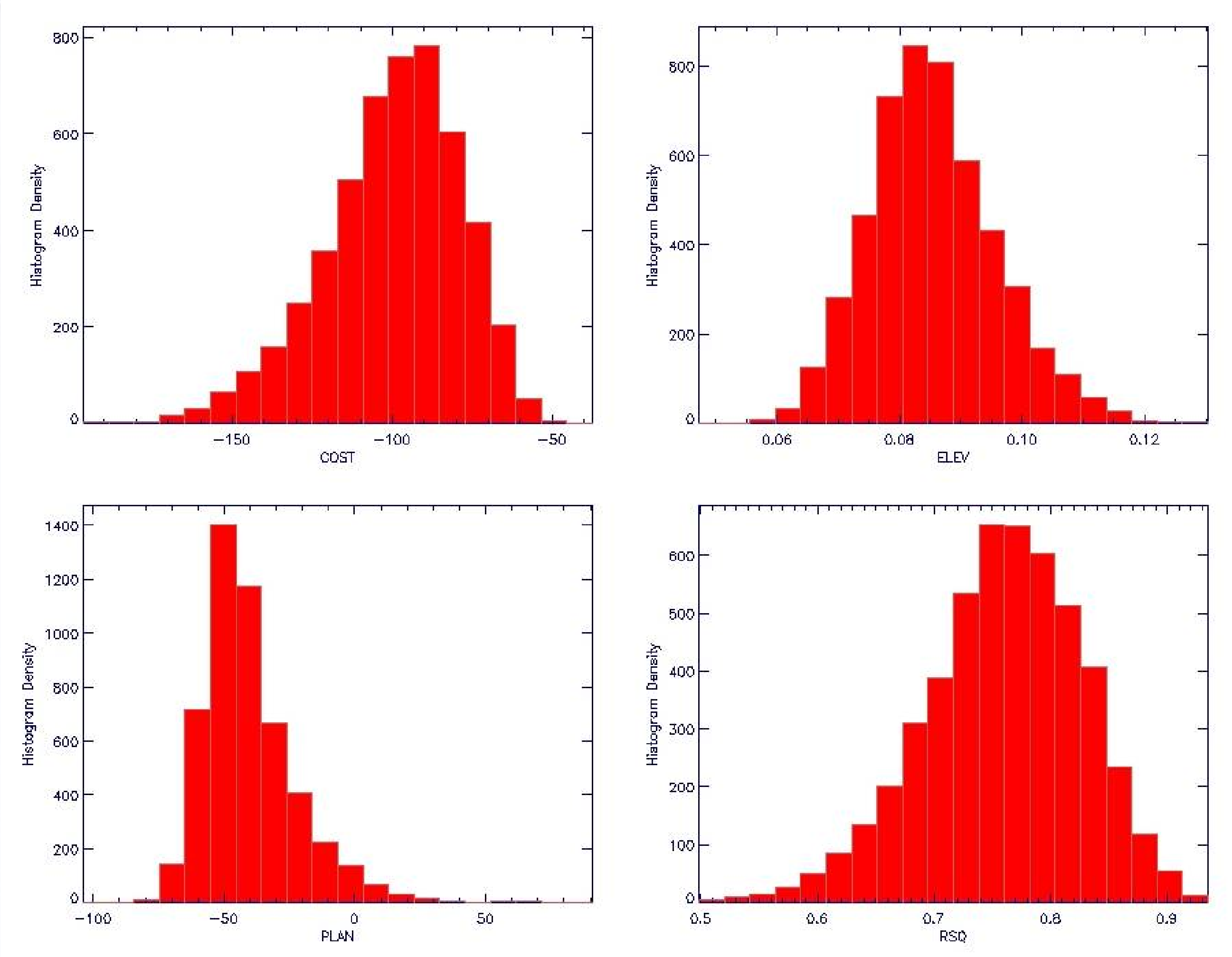
Elevation, Slope, Exposition, Northness index, Concavity/Convexity → **DEM**

Monthly Direct Radiation, Monthly Diffuse Radiation, Monthly Global Radiation, Monthly Direct Radiation Duration → **DEM + solar radiation model**

SNOW HEIGHT: from point measurements to distributed fields

November 2008: selected parameters by AIC:
SH = COST + β_1ELEV + β_2 CONC/CONV

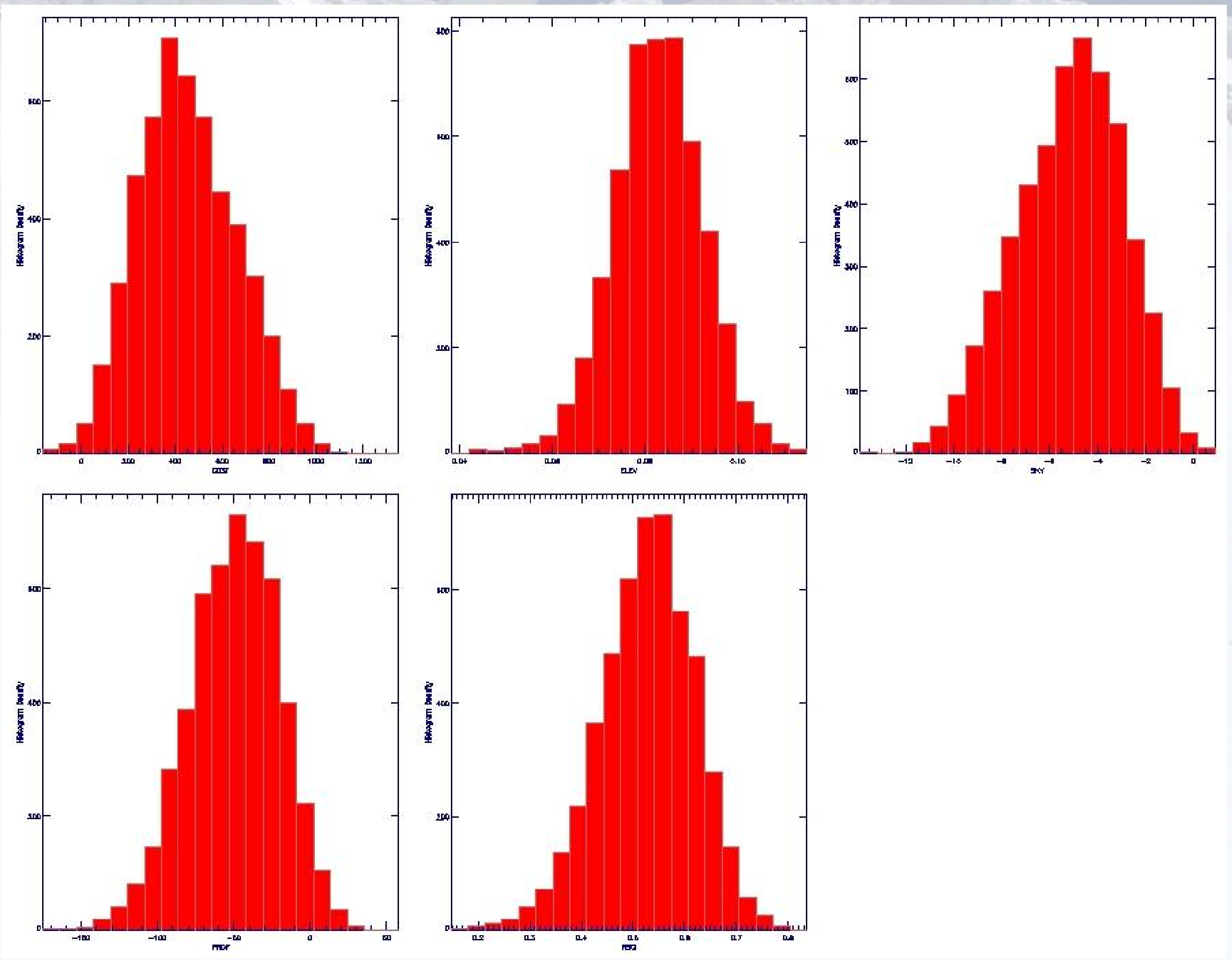
3) model coefficients (β_1,β_n , ...) estimation by bootstrap procedure



SNOW HEIGHT: from point measurements to distributed fields

December 2008: selected parameters by AIC:
SH = COST + β_1ELEV + β_2 SVF+ β_3 CONC/CONV

3) model coefficients (β_1,β_n , ...) estimation by bootstrap procedure

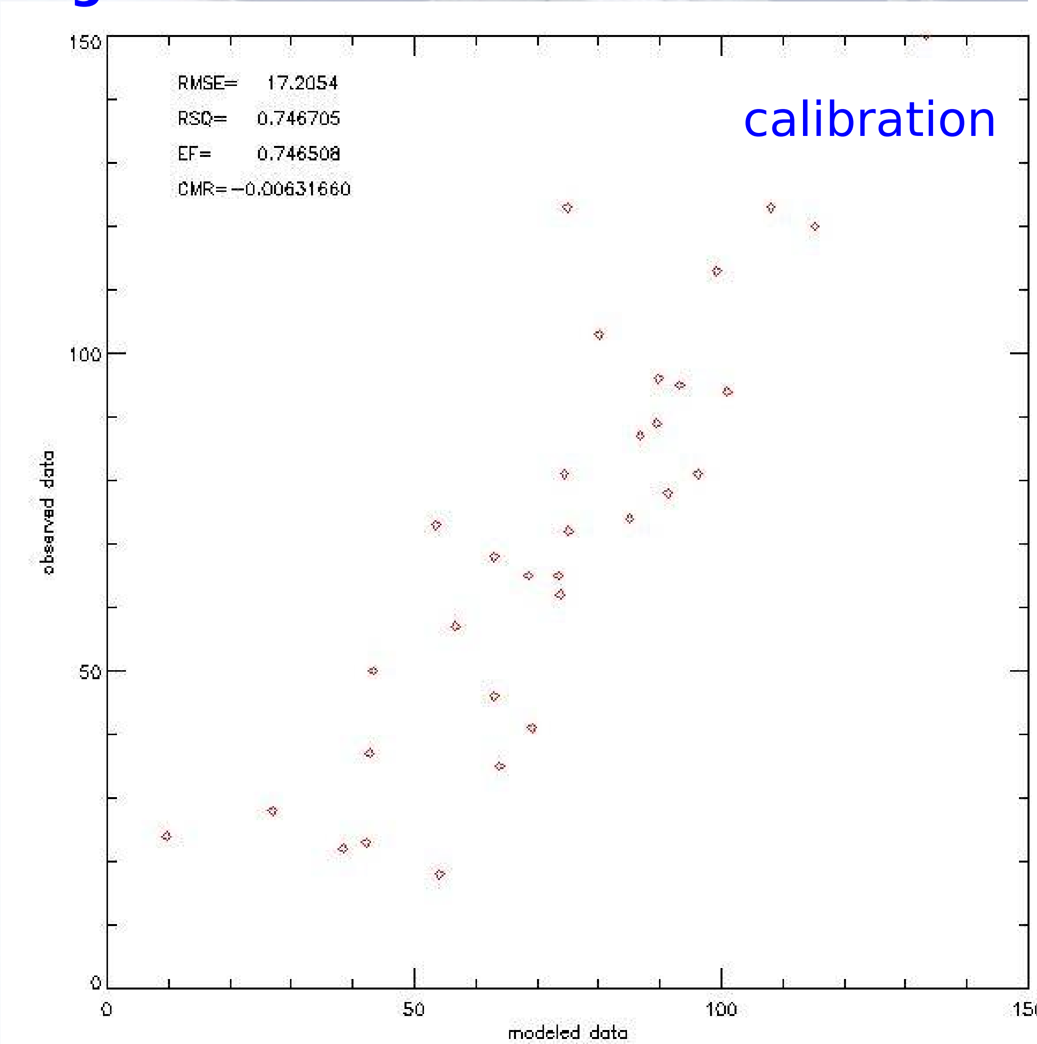


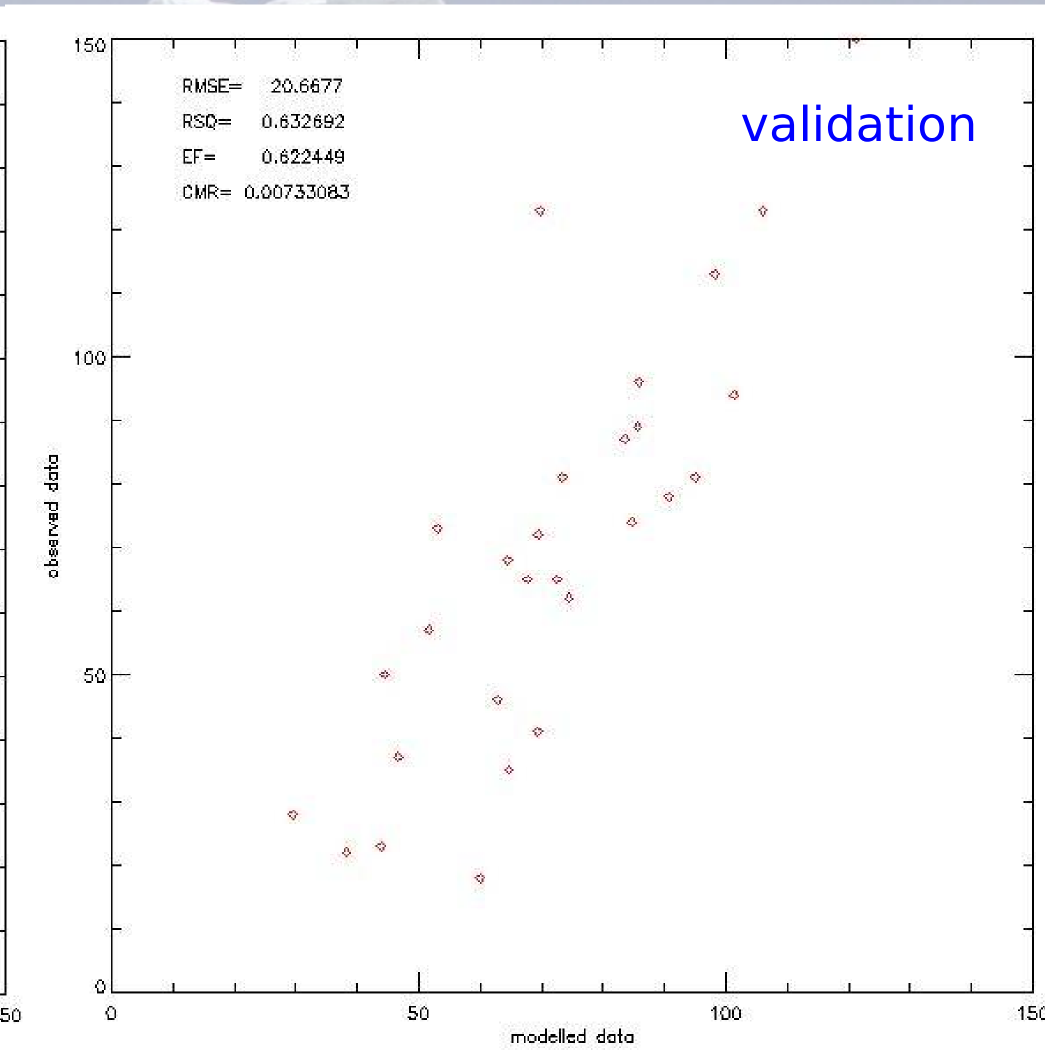
SNOW HEIGHT: from point measurements to distributed fields

4) model evaluation by cross validation techniques (LGO and k-fold)

5) analysis of the crossvalidated statistics (R^2_{cv}, EF_{cv}, $RMSE_{cv}$)

e.g. December 2008





SNOW HEIGHT: from point measurements to distributed fields

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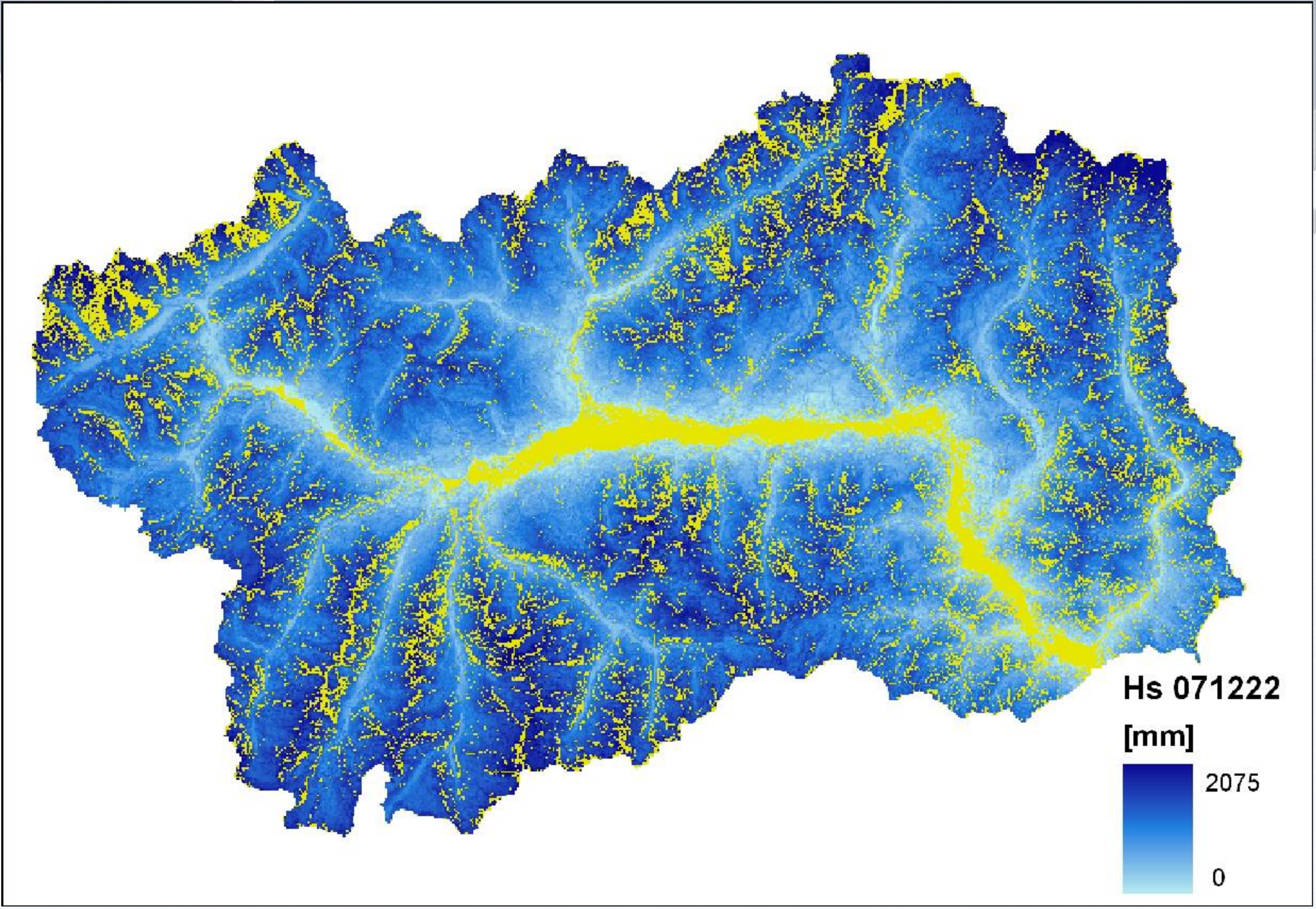
Model evaluation statistics in time

	$RMSE_{cal}$	$RMSE_{cv}$	R^2_{cal}	R^2_{cv}	EF_{cal}	EF_{cv}
mar 2008	51	62	0.518	0.440	0.507	0.158
feb 2008	33	41	0.467	0.409	0.461	-0.014
jan 2008	36	40	0.395	0.352	0.394	-0.148
....						
nov 2008	36	39	0.522	0.448	0.520	0.344
dec 2008	16	19	0.744	0.741	0.744	0.623
jan 2009		33		0.630		0.487
feb 2009		41		0.643		0.508
mar 2009		46		0.455		0.377
apr 2009		60		0.487		0.339
...						

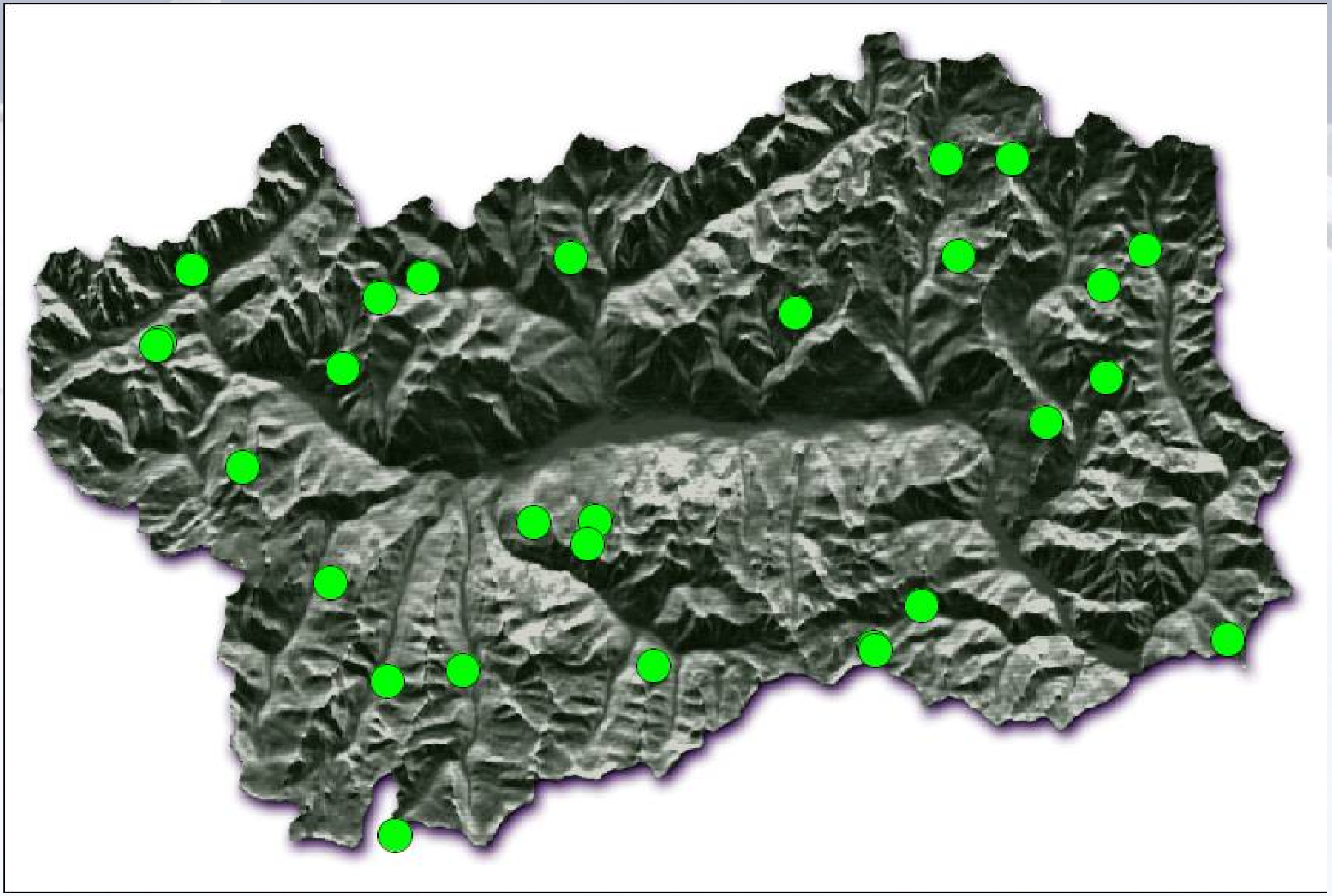
SNOW HEIGHT: from point measurements to distributed fields

Results of model application



SWE = SNOW HEIGHT x SNOW DENSITY x SNOW COVER EXTENT

SNOW DENSITY: from point measurements to distributed fields



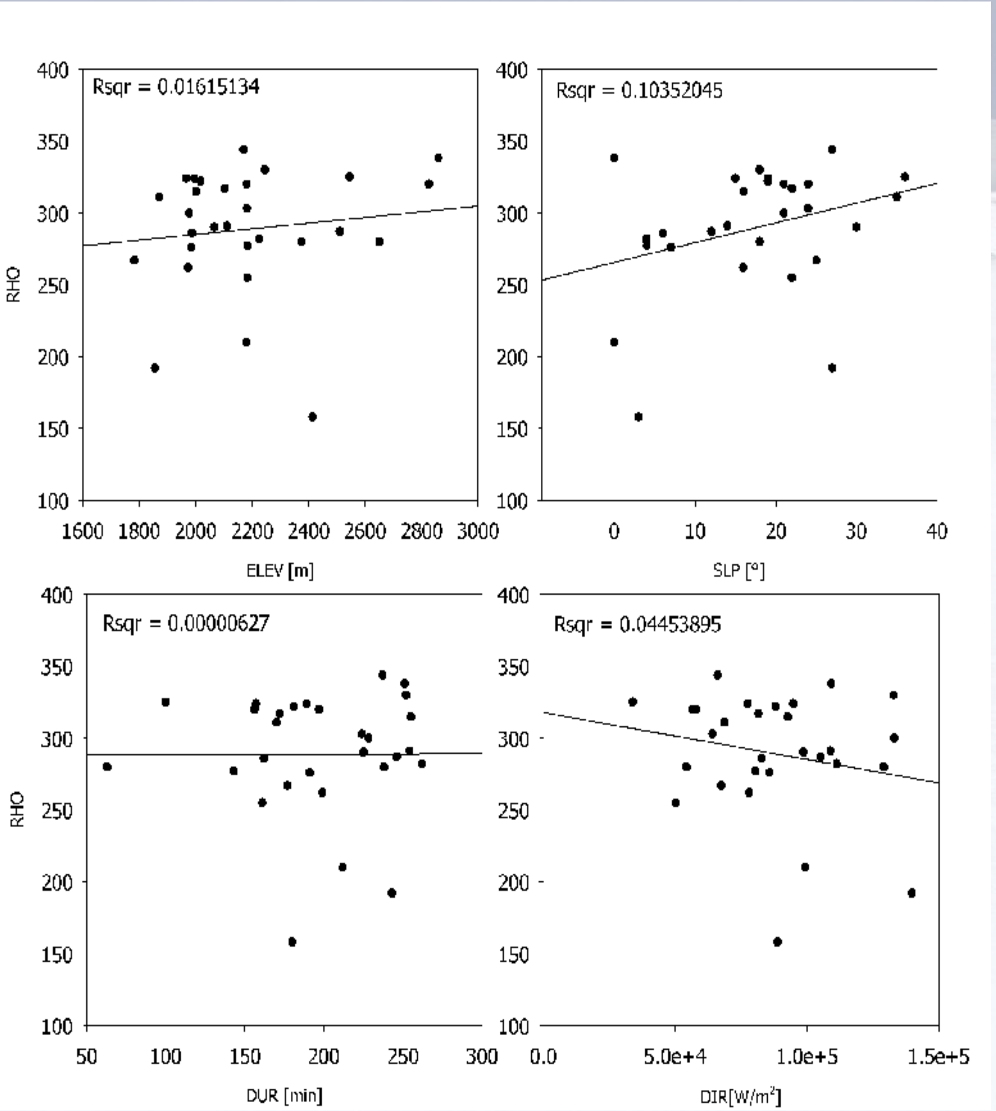
Manual measurements from snow pits, made for snow avalanches risk

SWE = SNOW HEIGHT x SNOW DENSITY x SNOW COVER EXTENT

SNOW DENSITY: from point measurements to distributed fields

in theory we can use the same modelling approach used for snow height

... in practice we have



...1) weak relationships with distributed parameters

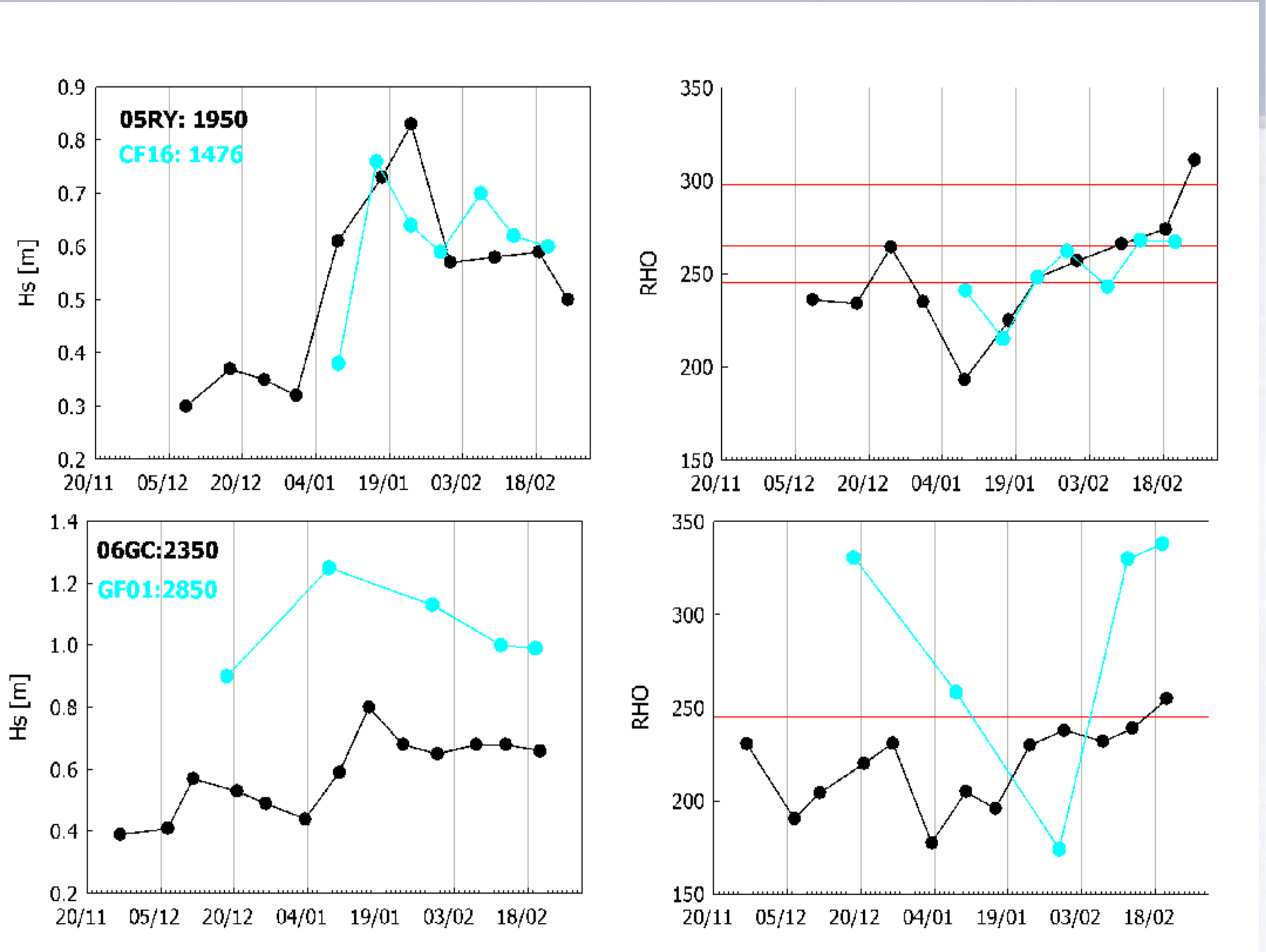
SWE = SNOW HEIGHT x SNOW DENSITY x SNOW COVER EXTENT

SNOW DENSITY: from point measurements to distributed fields

in theory we can use the same modelling approach used for snow height

... in practice we have

...2) bigger data reliability problems



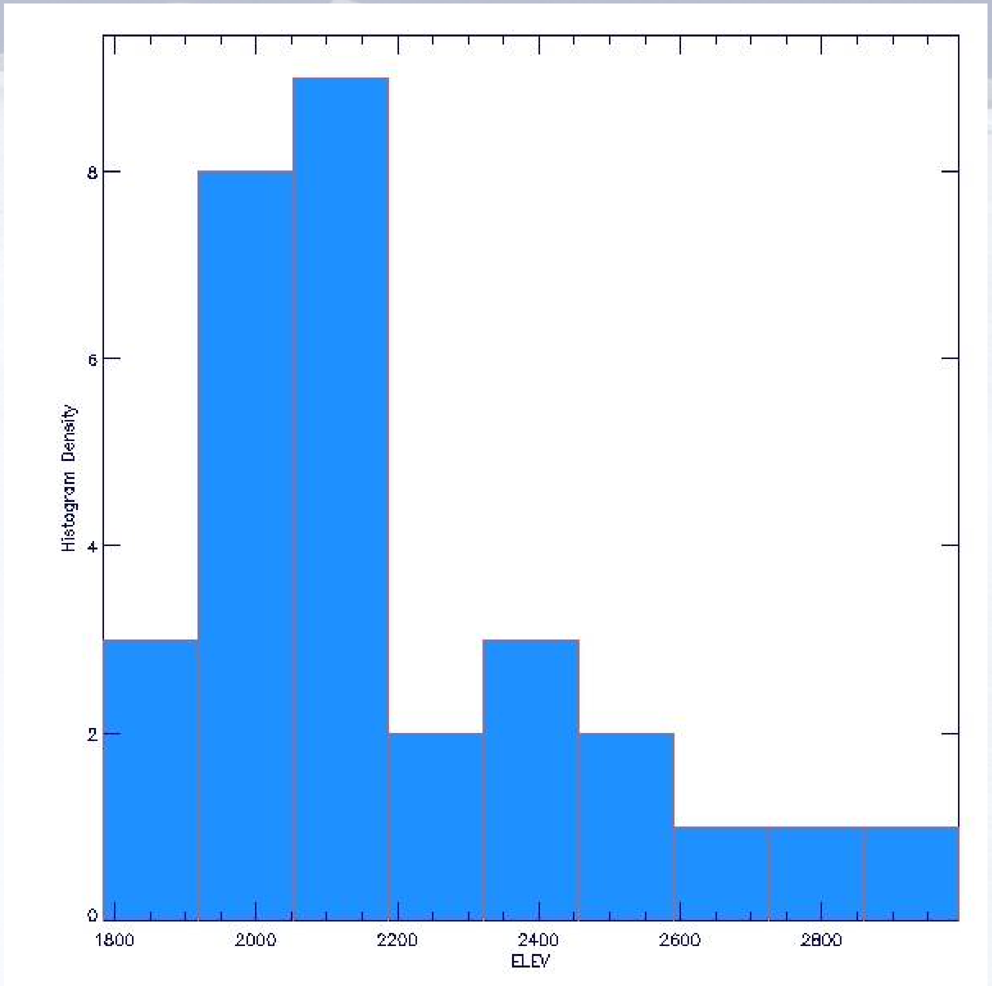
SWE = SNOW HEIGHT x SNOW DENSITY x SNOW COVER EXTENT

SNOW DENSITY: from point measurements to distributed fields

in theory we can use the same modelling approach used for snow height

... in practice we have

...3) bad distribution of measurement points



SWE = SNOW HEIGHT x SNOW DENSITY x SNOW COVER EXTENT

SNOW DENSITY: from point measurements to distributed fields

So we used monthly means of measured data ... one value applied on all Aosta Valley

Dec	2007	229 [Kgm^{3}]
Jan	2007	242
Feb	2007	298
Mar	2007	324
Apr	2007	366
May	2007	390
...		
Nov	2008	205
Dec	2008	281
Jan	2009	310
Feb	2009	320
Mar	2009	351
Apr	2009	394

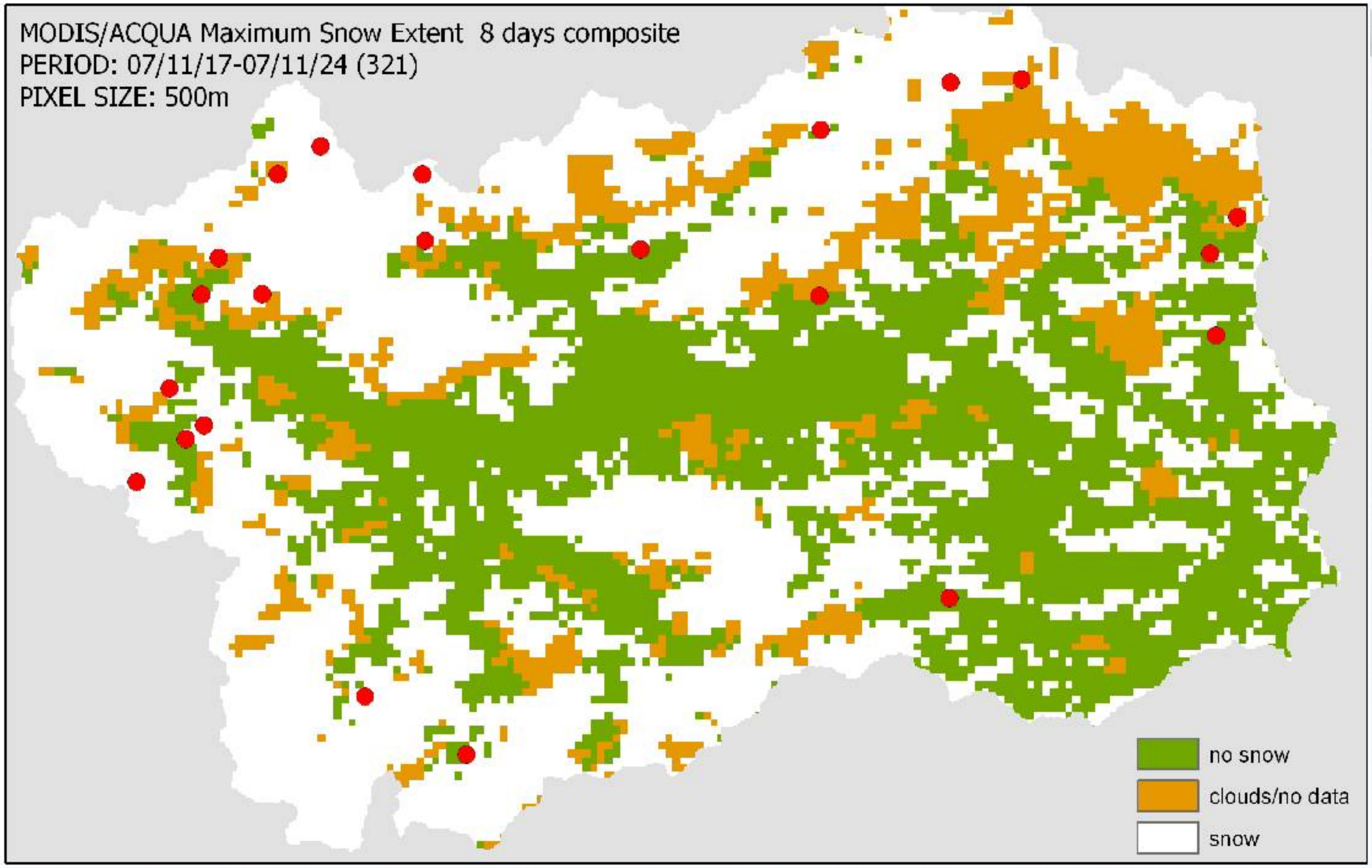
SWE = SNOW HEIGHT x SNOW DENSITY x SNOW COVER EXTENT

MODIS SNOW COVER DATA: MOD10A2

Maximum snow cover extent

8 day composite

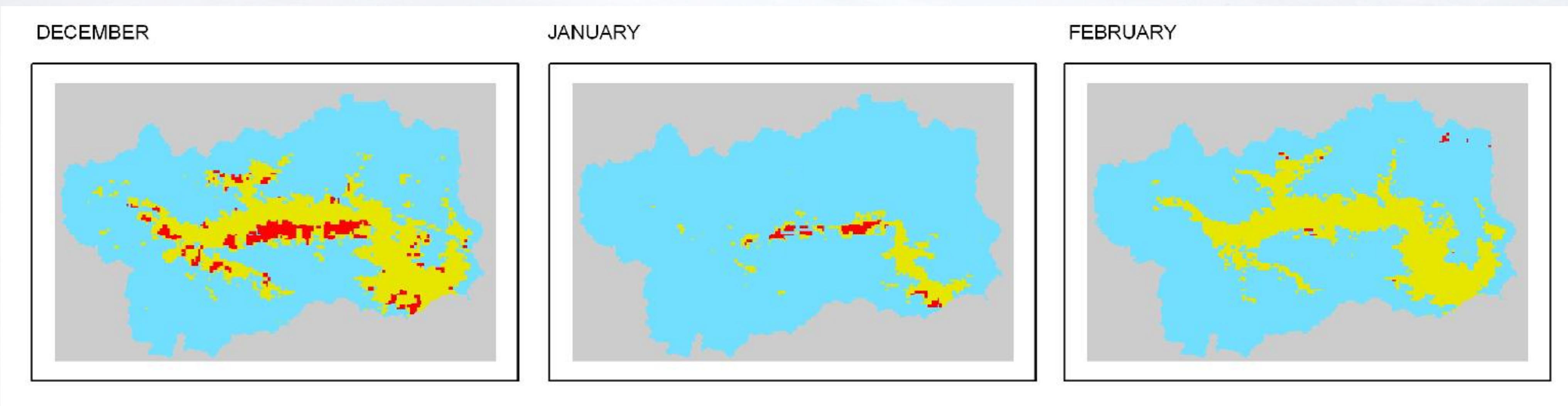
500 m spatial resolution



SWE = SNOW HEIGHT x SNOW DENSITY x SNOW COVER EXTENT

MODIS SNOW COVER DATA: MOD10A2

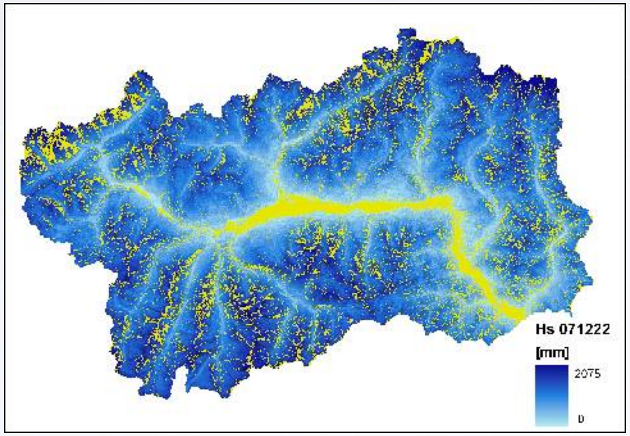
Snow cover extent temporal evolution (early winter 2008)



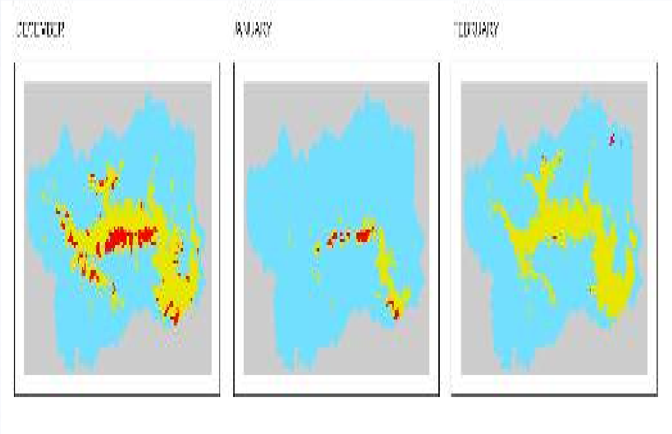
SWE = SNOW HEIGHT x SNOW DENSITY x SNOW COVER EXTENT

Example: December 2007

Snow Height x mean density value **Snow cover extent** **SWE**



x



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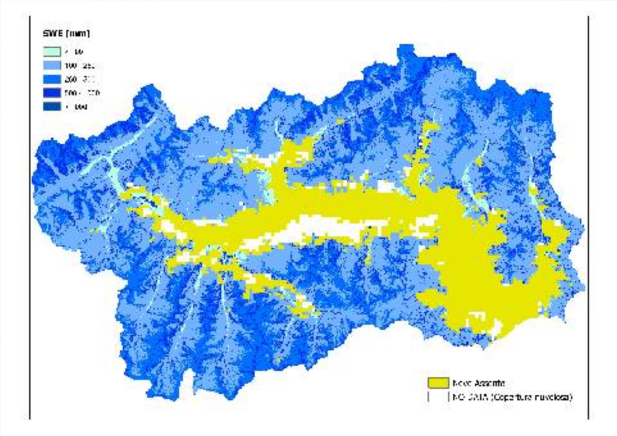

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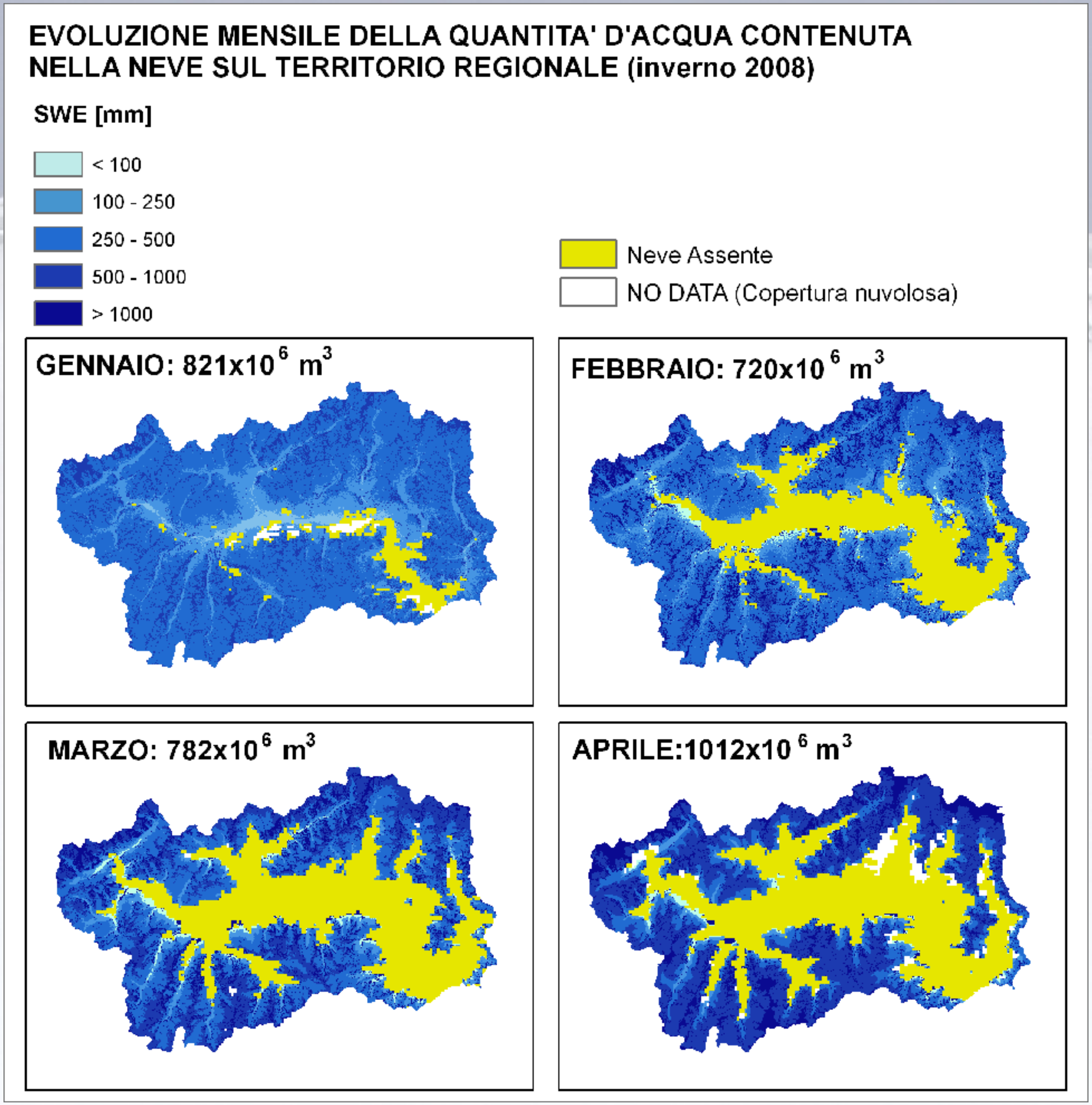
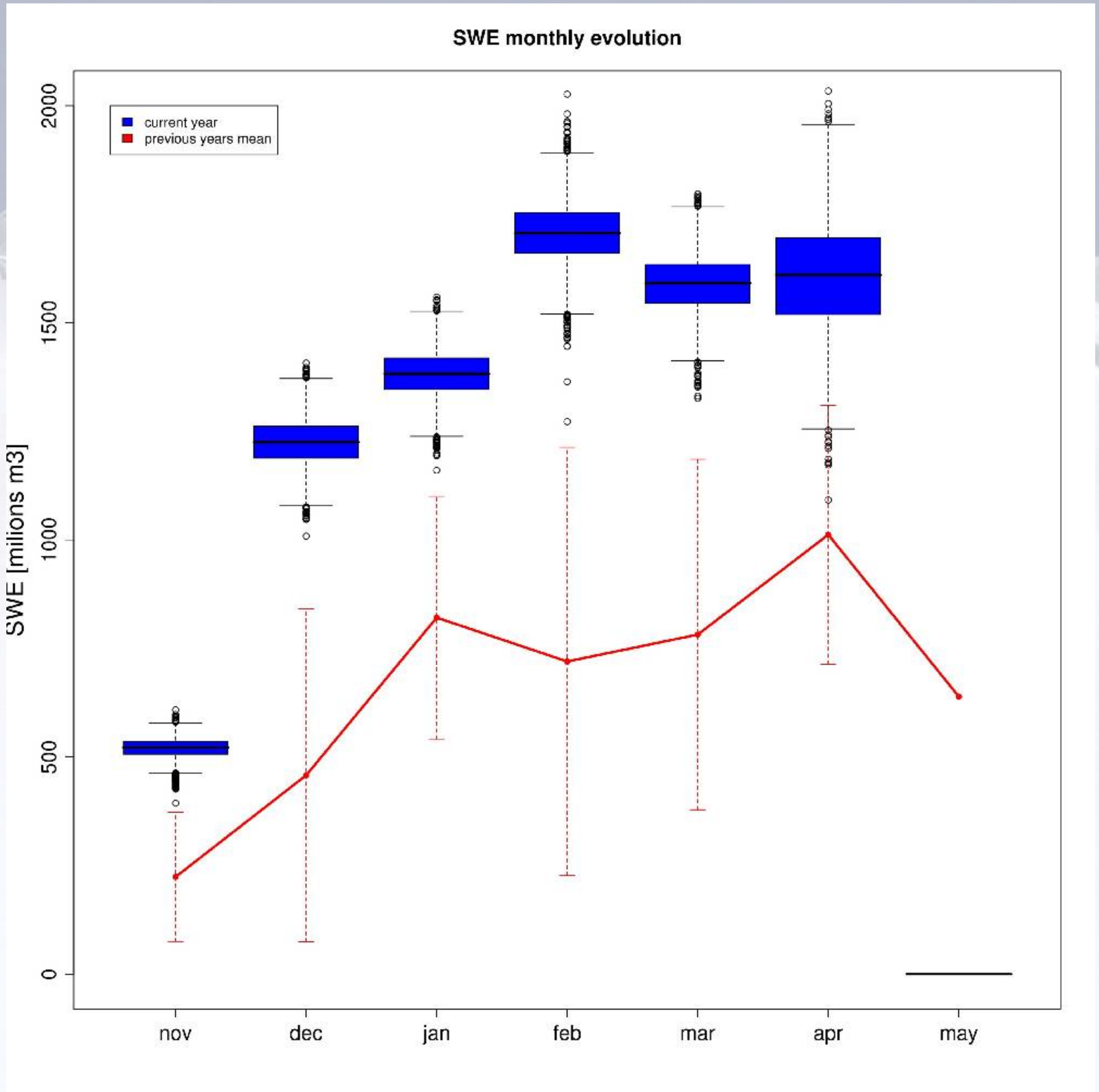


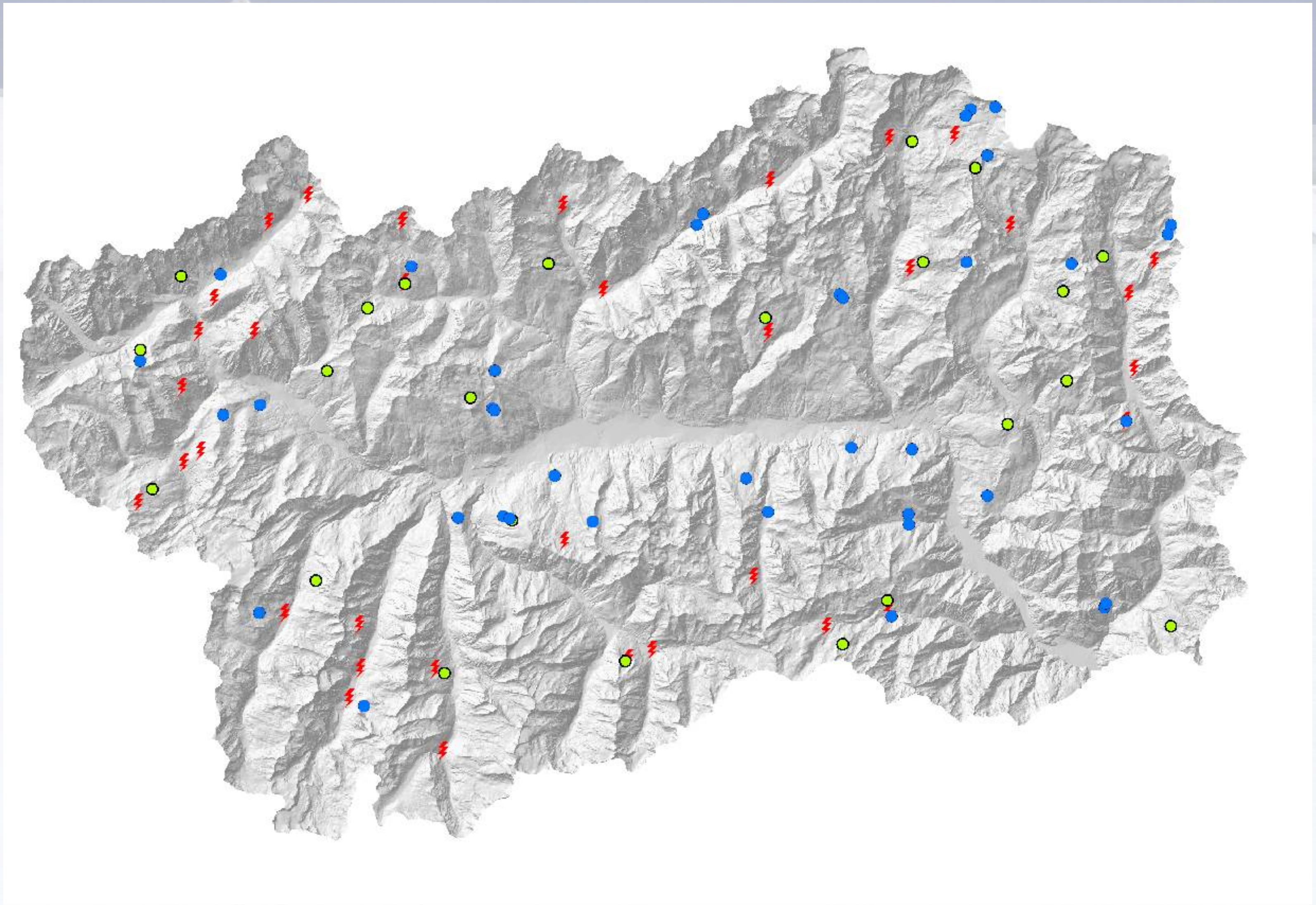
SWE = SNOW HEIGHT x SNOW DENSITY x SNOW COVER EXTENT



SWE at regional scale future developments

1) improve the network of snow density field measurements

SWE at regional scale future developments



SWE at regional scale future developments

1) improve the network of snow density field measurements

2) continuous measurements of parameters which can be related to snow density

SWE at regional scale future developments

2) continuous measurements of parameters which can be related to snow density:

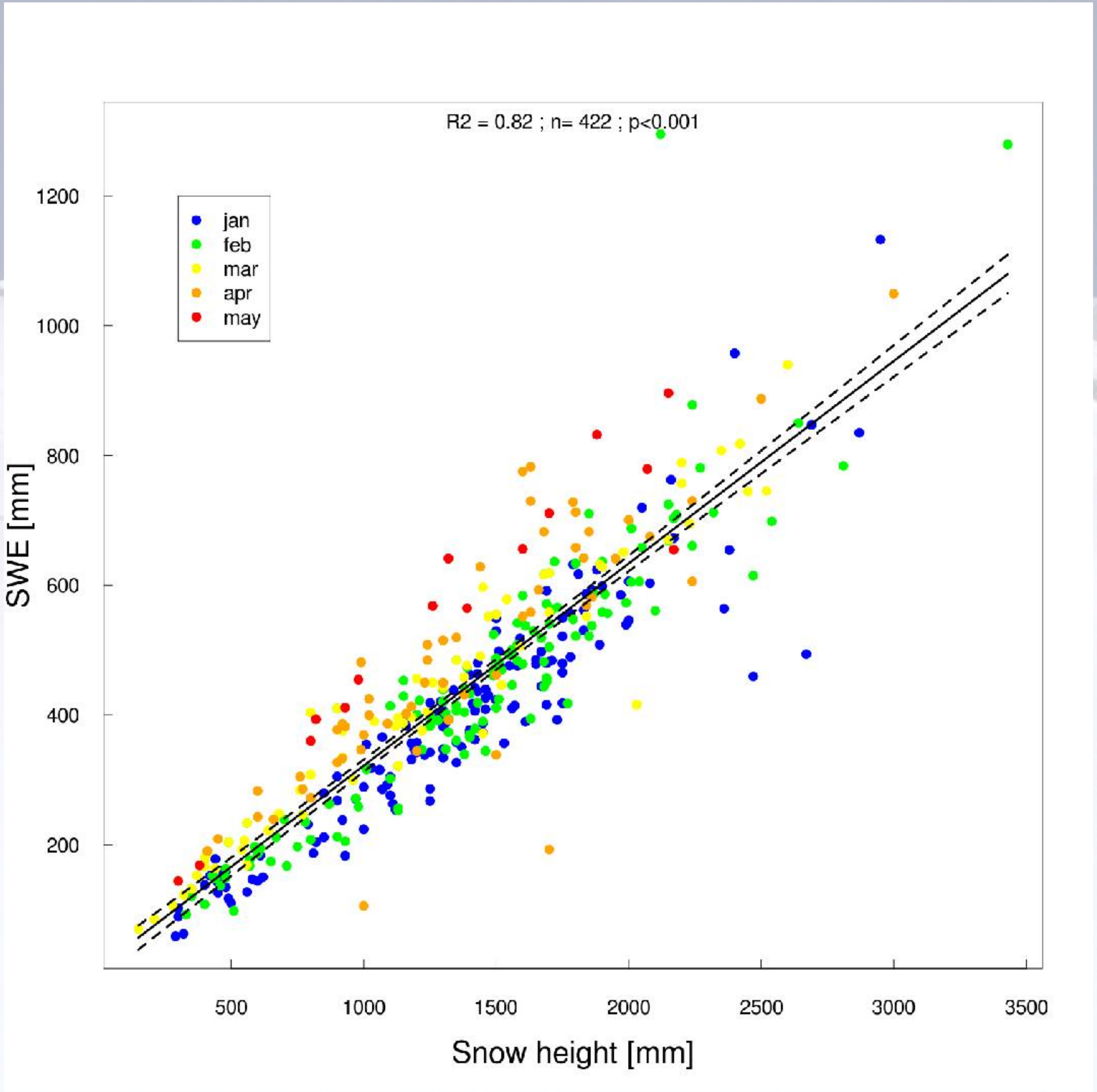
CS616 – Water content reflectometer (sensors for soil humidity)

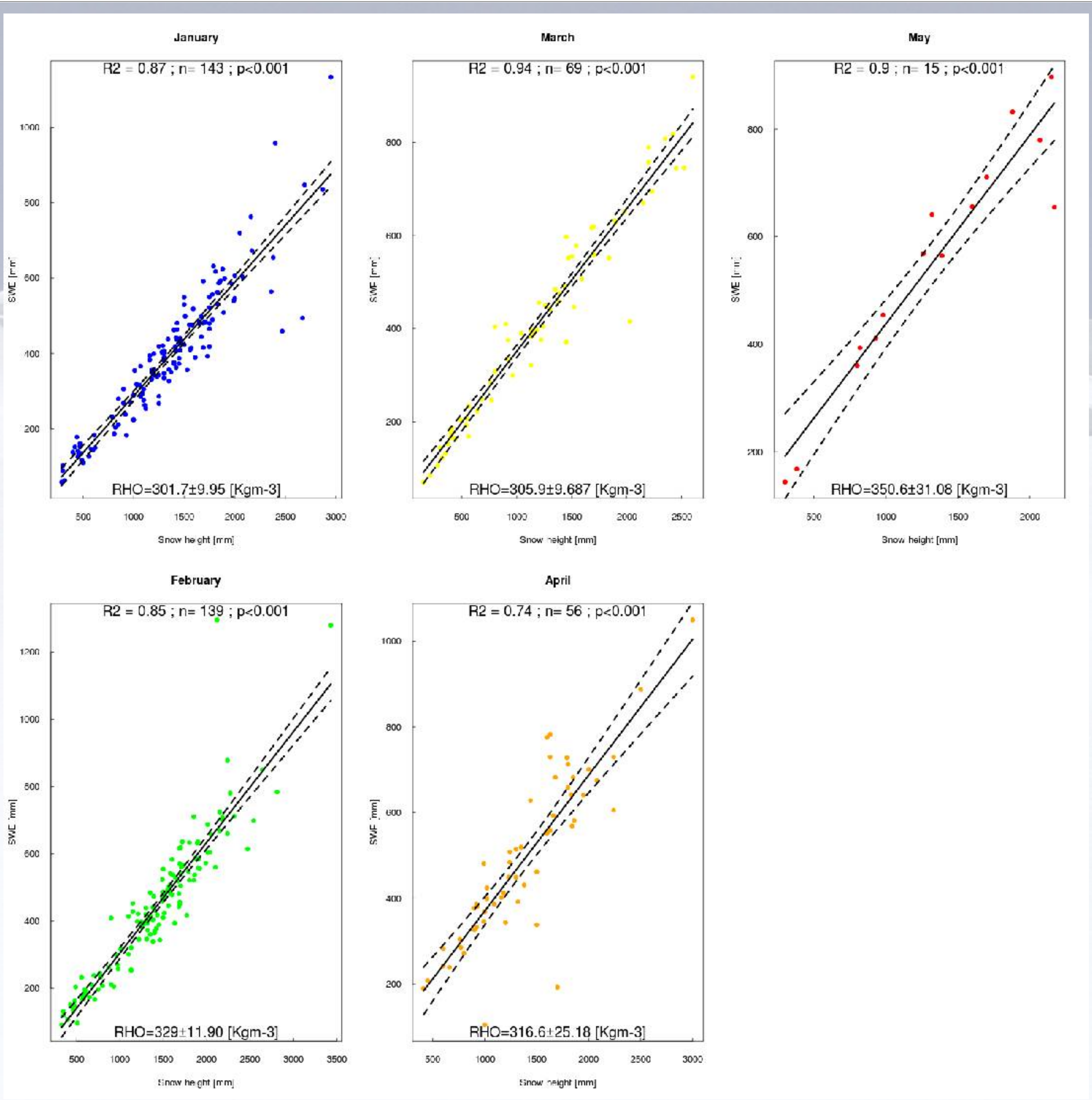
SWE at regional scale future developments

1) improve the network of snow density field measurements

2) continuous measurements of parameters which can be related to snow density

3) use of empirical relationships between SWE and Snow Height


R2 = 0.82 ; n= 422 ; p<0.001
jan
feb
mar
apr
may
SWE [mm]
Snow height [mm]
200
400
600
800
1000
1200
500
1000
1500
2000
2500
3000
3500


January
R2 = 0.87 ; n= 143 ; p<0.001
RHO=301.7±9.95 [Kgm-3]
March
R2 = 0.94 ; n= 69 ; p<0.001
RHO=305.9±9.687 [Kgm-3]
May
R2 = 0.9 ; n= 15 ; p<0.001
RHO=350.6±31.08 [Kgm-3]
February
R2 = 0.85 ; n= 139 ; p<0.001
RHO=329±11.90 [Kgm-3]
April
R2 = 0.74 ; n= 56 ; p<0.001
RHO=316.6±25.18 [Kgm-3]

SWE at regional scale future developments

1) improve the network of snow density field measurements
2) continuous measurements of parameters which can be related to snow density
3) temporal resolution of the elaboration
4) retrieval of informations at subpixel resolution (unmixing + use of MOD10A1 FSC)
5) take into account the effect of forest on snow height and snow density

introduction

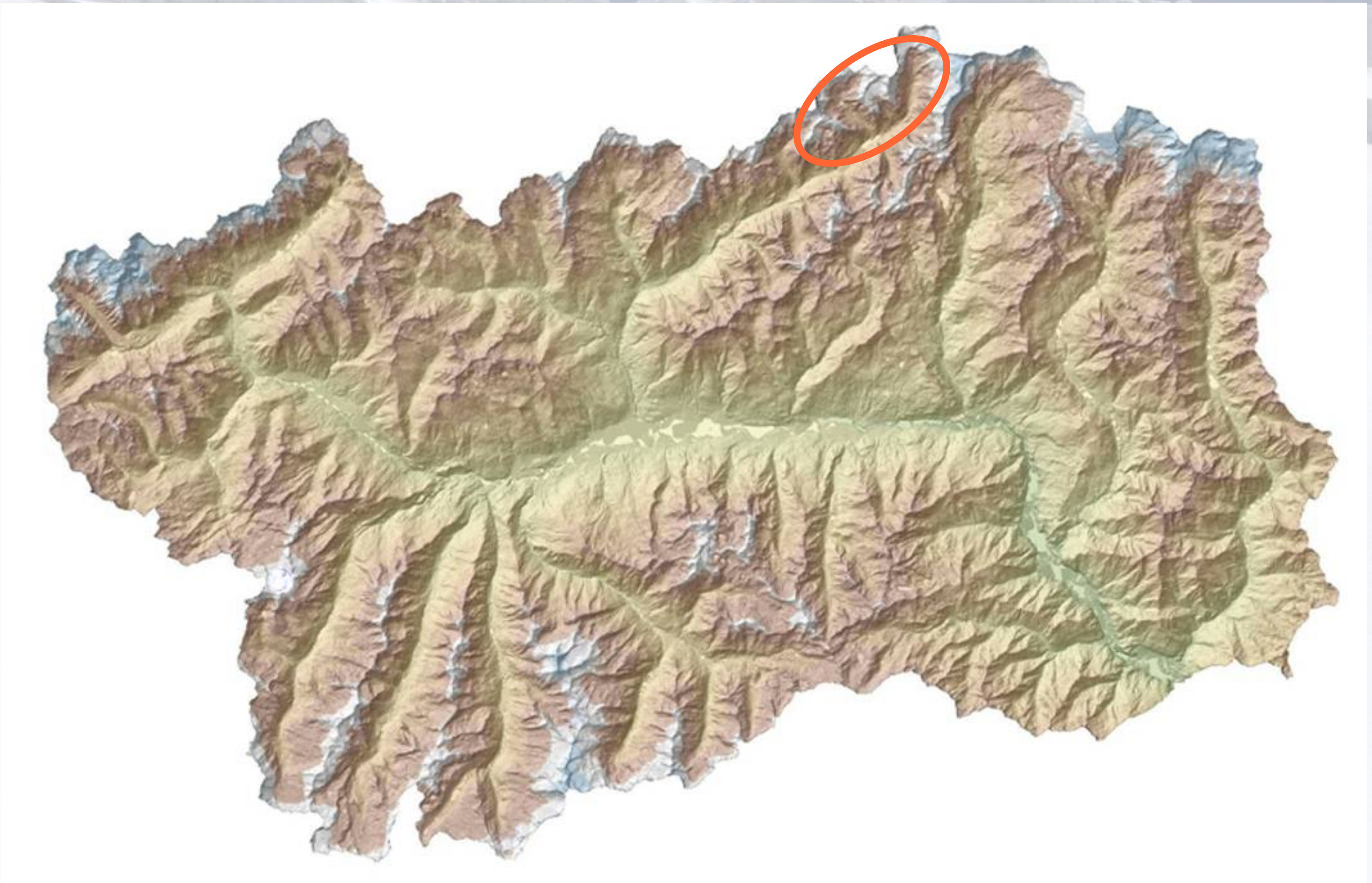
SWE distribution at regional scale (3000 Km^2)

SWE distribution at medium basin scale (120 Km^2)

melt modelling

Valpelline (120 Km^2):

basin with the biggest dam in the Aosta Valley (105 millions of m^3) hydro power production (CVA spa)



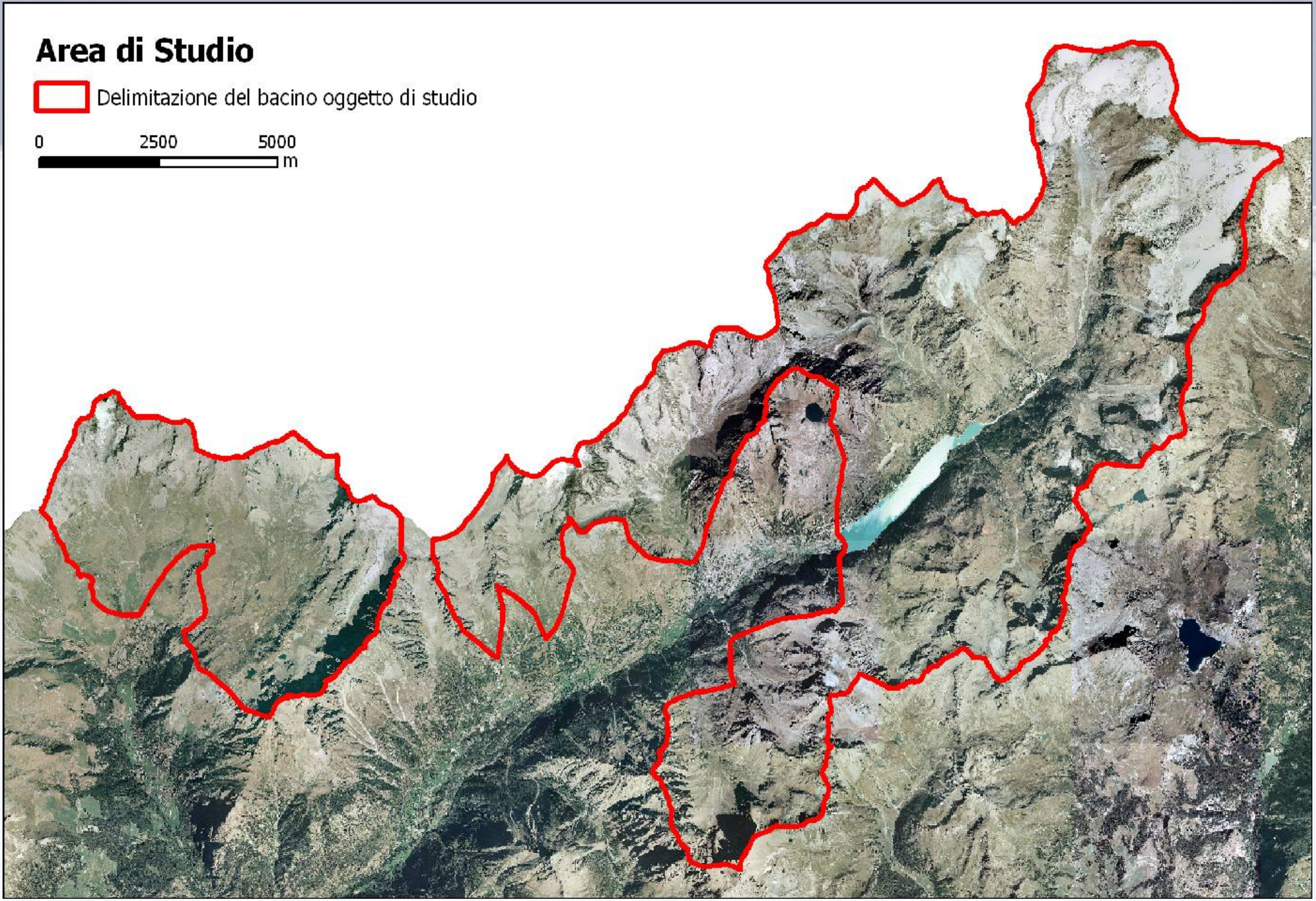
SWE at medium scale

the aim is to know the total amount of water stored in snow at the beginning of the melting season (late may – june)

The estimation of SWE is coupled with the application of a distributed melt model

it's used to plan and optimise hydro power production

Valpelline (120 Km^2)



Valpelline (120 Km^2)

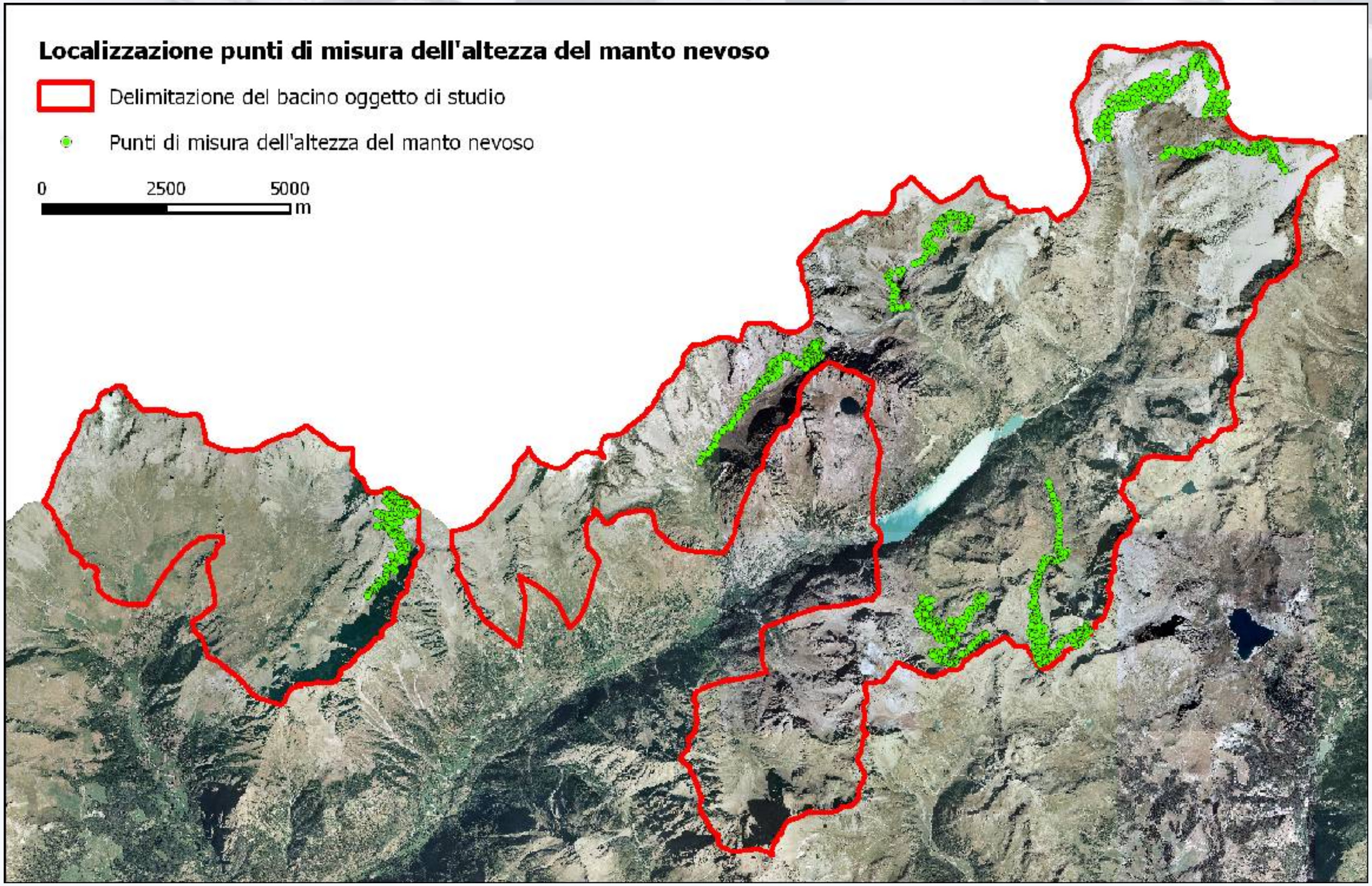
- **SWE is modelled for late spring (maximum accumulation)**

- **DATA SET: single field campaign (measures of snow height and snow density)**

Valpelline (120 Km²)

- SWE is modelled for late spring (maximum accumulation)

- DATA SET: single field campaign (measures of snow height and snow density)

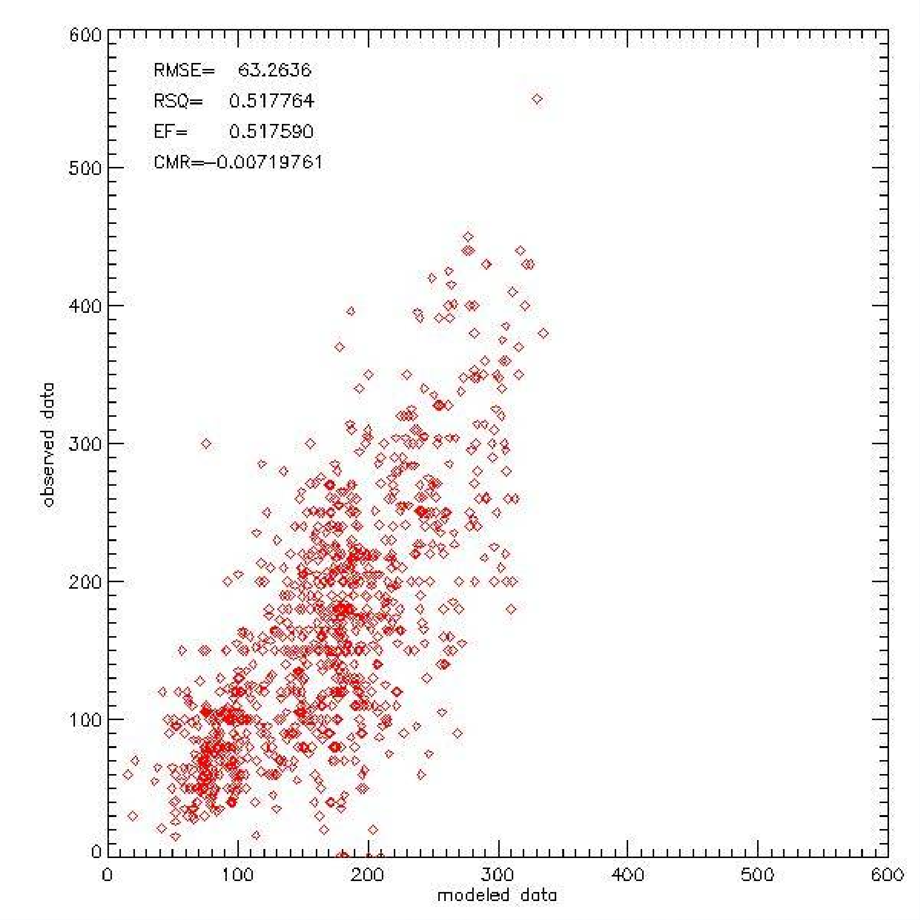


Valpelline (120 Km^2)

SWE is modelled with the same method used at regional scale but:

1) we have better distributions of point measurements

2) we have a bigger number of sampling points (900 SH data + 30/40 SD data



Valpelline (120 Km^2)

SWE is modelled with the same method used at regional scale but:

1) we have better distributions of point measurements

2) we have a bigger number of sampling points (900 SH data + 30/40 SD data

3) we can distribute SD data as well (avoiding the use of a mean)

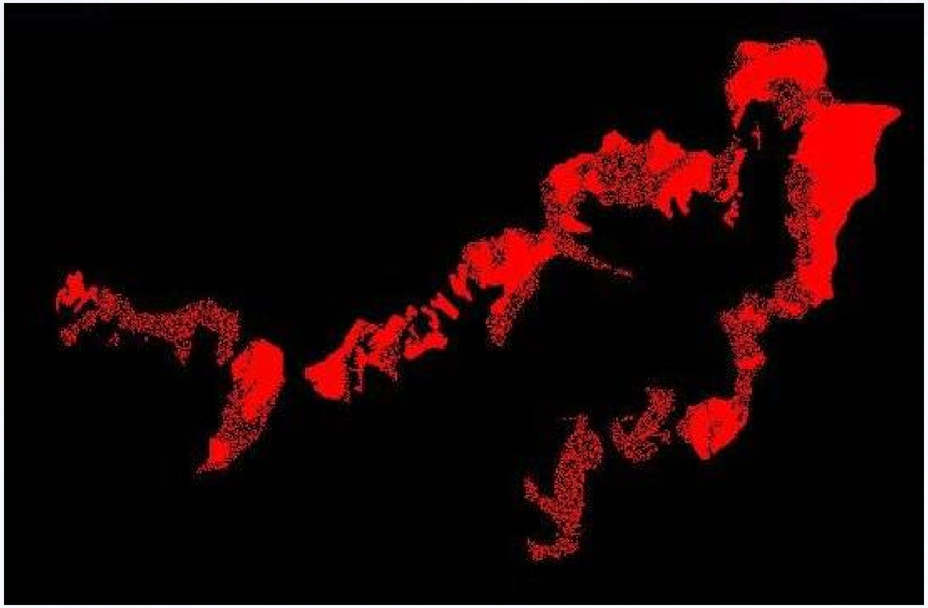
4) SCA can be estimated by:

- **the photo interpretation of oblique terrestrial images collected during field campaign**
- **using MODIS FSC data (MOD10A2) ... but the spatial resolution can be too coarse**

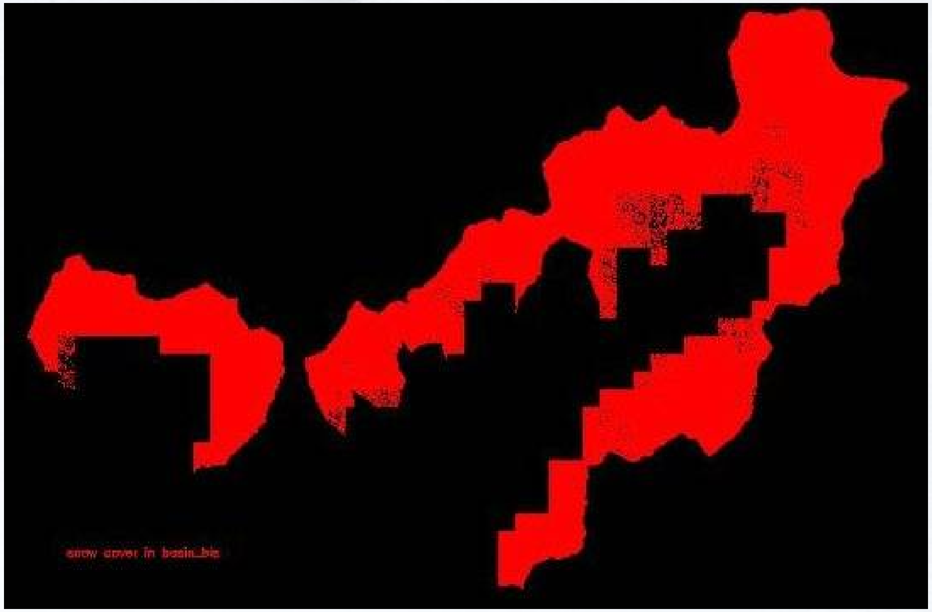
Valpelline (120 Km^2):

SWE is modelled with the same method used at regional scale but:

2008 SCA: photo interpretation

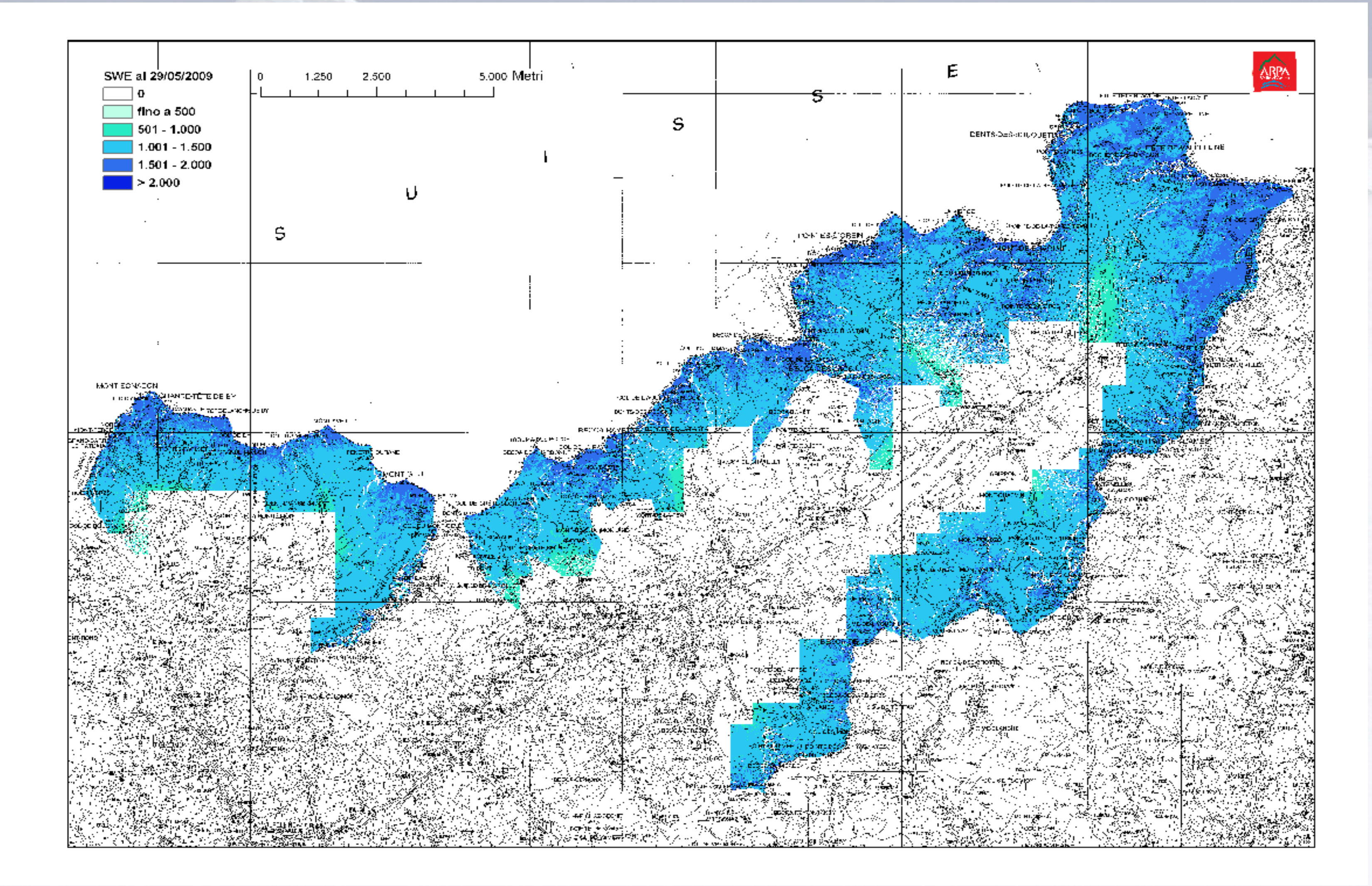


2009 SCA: MOD10A1 FSC



Valpelline (120 Km^2):

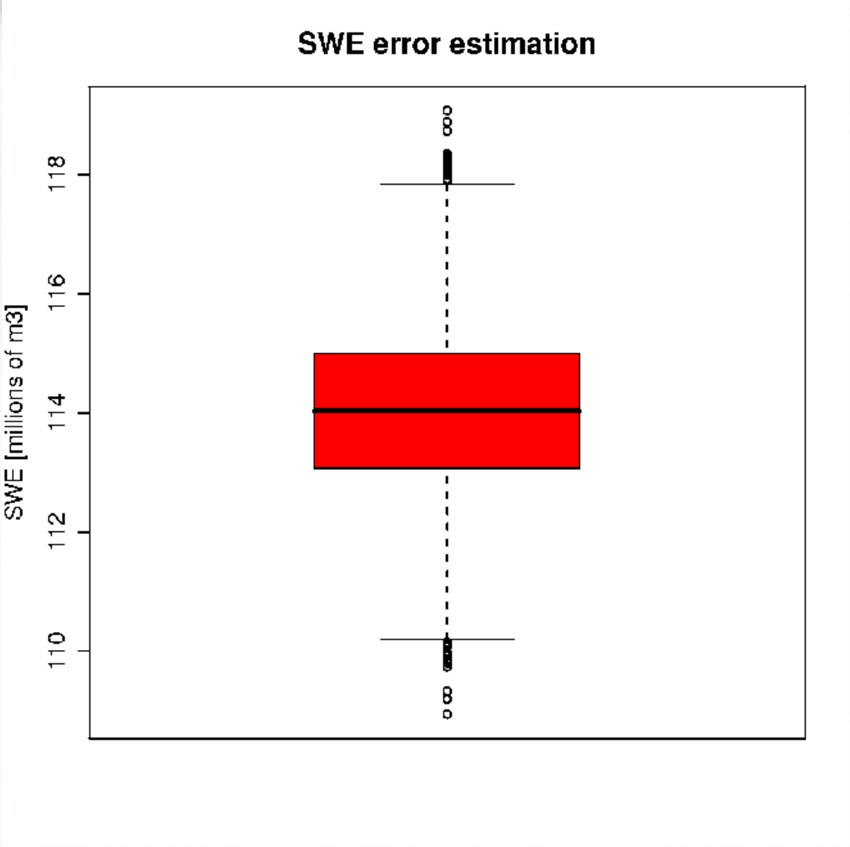
SWE = SNOW HEIGHT x SNOW DENSITY x SNOW COVERED AREA



Valpelline (120 Km^2):

SWE = SNOW HEIGHT x SNOW DENSITY x SNOW COVERED AREA

25/05/2009 SWE



introduction

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SWE distribution at medium basin scale (120 Km^2)

melt modelling

Snow and Glaciers melt modelling in Valpelline

ETI model: Distributed Enhanced Temperature-Index Melt Model (ETI) including the Shortwave radiation balance (Pellicciotti et al 2004, JoG)

Snow and Glaciers melt modelling in Valpelline

ETI model: Distributed Enhanced Temperature-Index Melt Model (ETI) including the Shortwave radiation balance (Pellicciotti et al 2004, JoG)

$$M = Tf \cdot T + AF \cdot (1-\alpha) \cdot I \qquad T > T_t$$

T: air temperature

I: shortwave incoming radiation

α: albedo

The model melts snow/ice when air temperature is above 1°C (T_t).

Melt rate is determined by air temperature, shortwave incoming radiation and albedo

INPUT DATA:

1) air temperature

2) precipitation

3) initial SWE

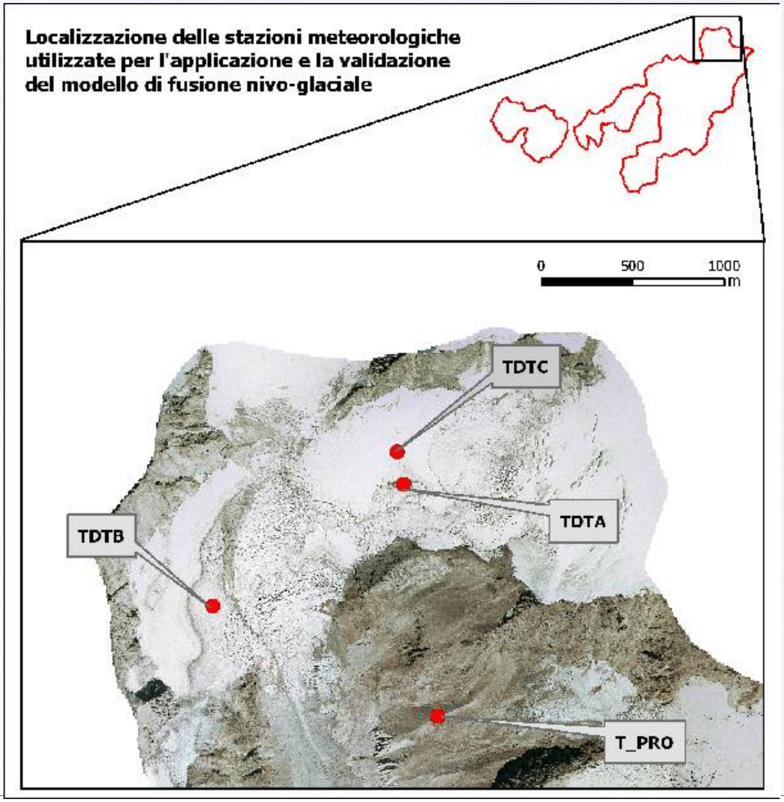
Snow and Glaciers melt modelling in Valpelline

ETI model: Distributed Enhanced Temperature-Index Melt Model (ETI) including the Shortwave radiation balance (Pellicciotti et al 2004, JoG)

Snow and Glaciers melt modelling in Valpelline

2006 application on Tza de Tzan glacier

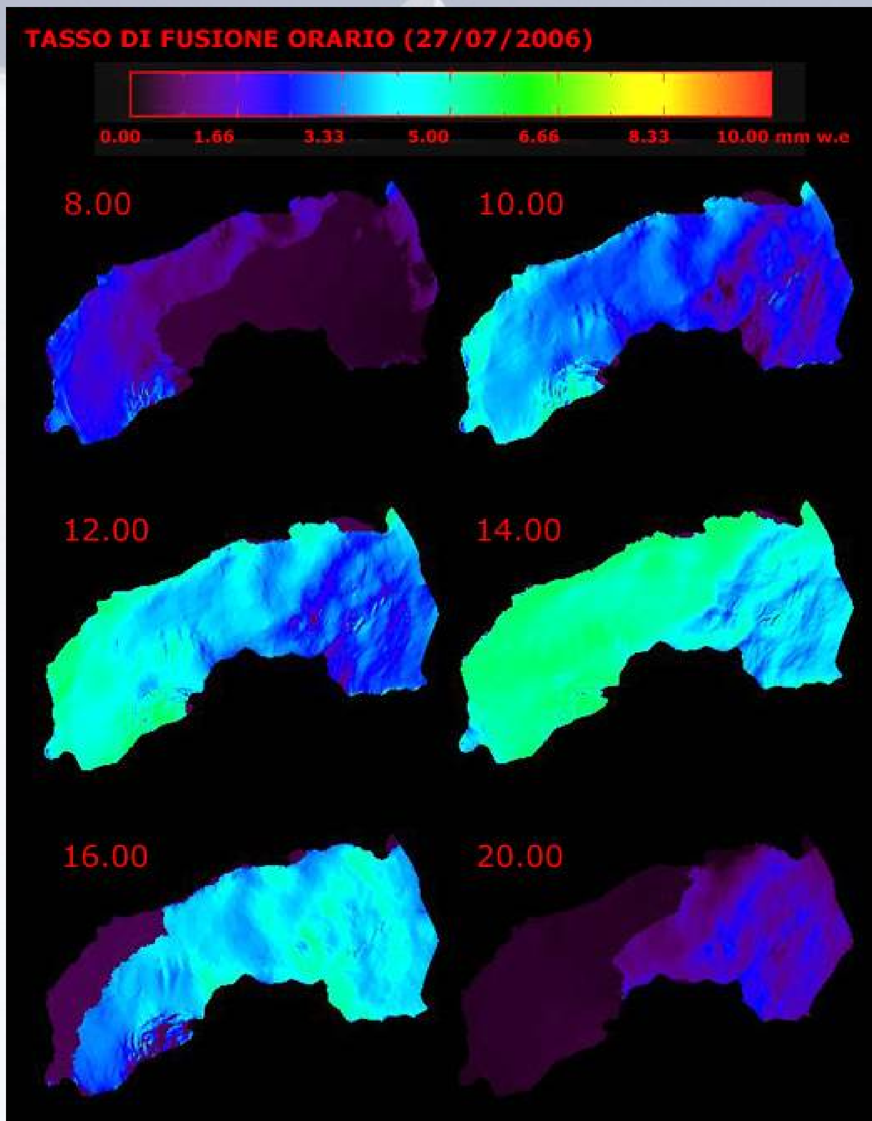
2007 + 2008 application on entire basin

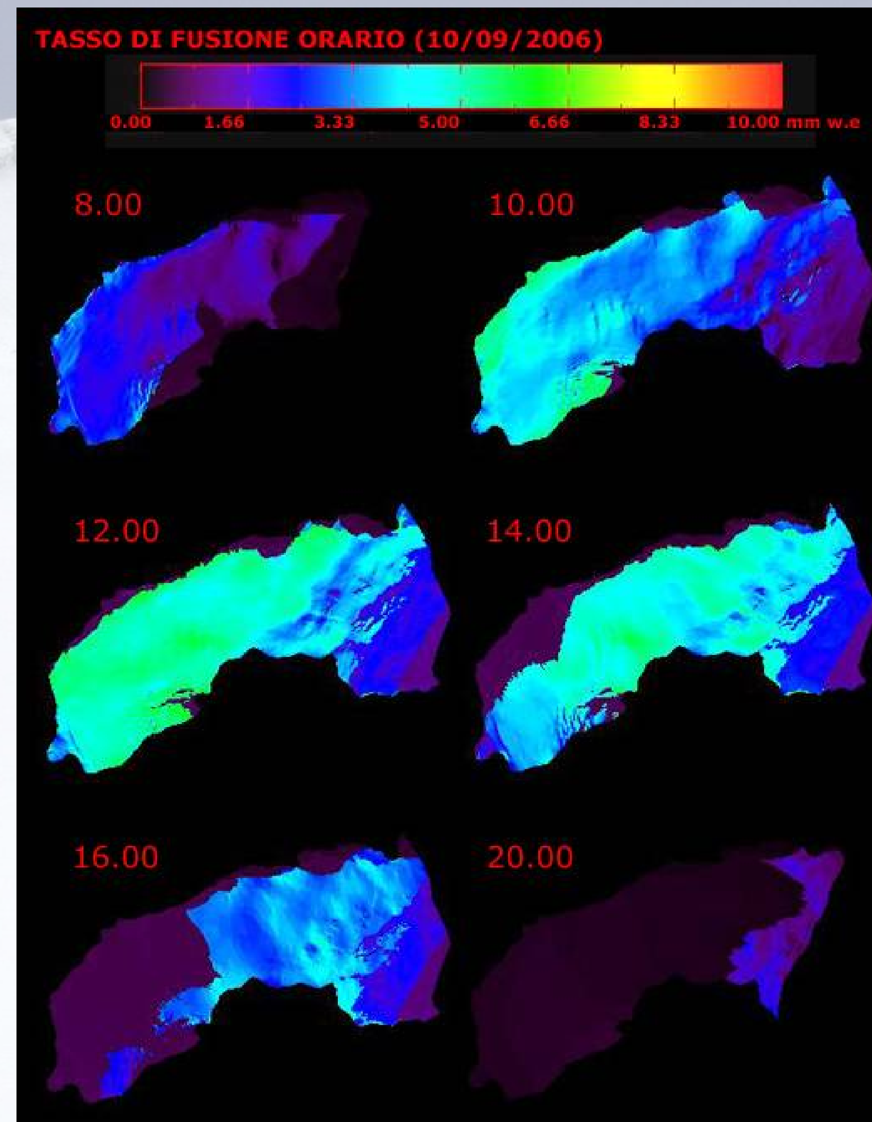


Weather station installation and ablation measurements during summer (UDG and stakes)

Snow and Glaciers melt modelling in Valpelline

2006 application on Tza de Tzan glacier: examples of model output





Snow and Glaciers melt modelling in Valpelline

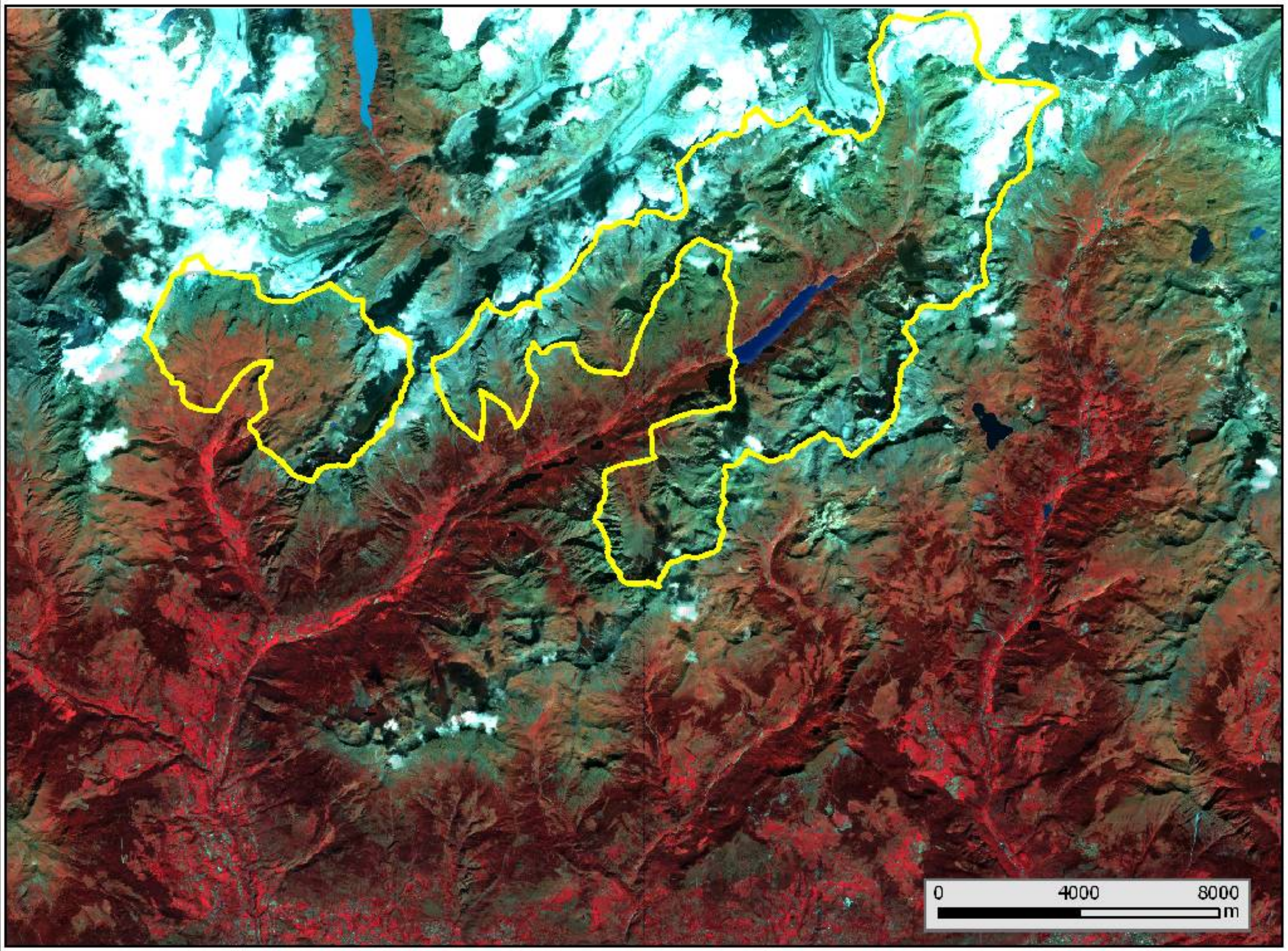
2006 application on Tza de Tzan glacier: model validation

1) **Ablation Stakes and AWS measurements**
2) **Snow cover extent during ablation season**
3) **Discharge measurements made by CVA (hydro-power company)**

Snow and Glaciers melt modelling in Valpelline

2006 application on Tza de Tzan glacier: model validation

Immagine SPOT del 24/09/07 utilizzata per la delimitazione della copertura nevosa (composizione IRFC)

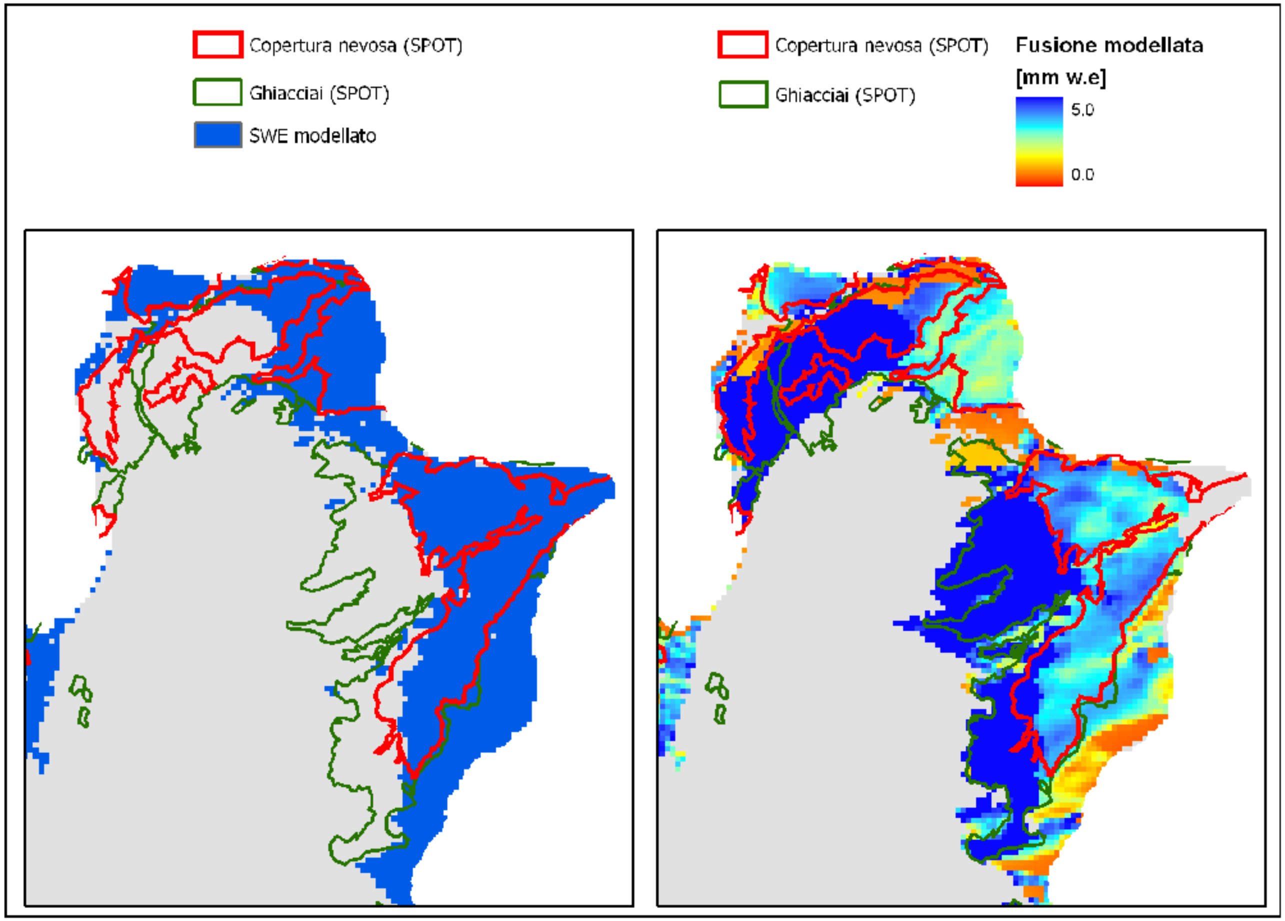


Snow cover extent during ablation season:

high resolution SPOT image

Snow and Glaciers melt modelling in Valpelline

2006 application on Tza de Tzan glacier: model validation

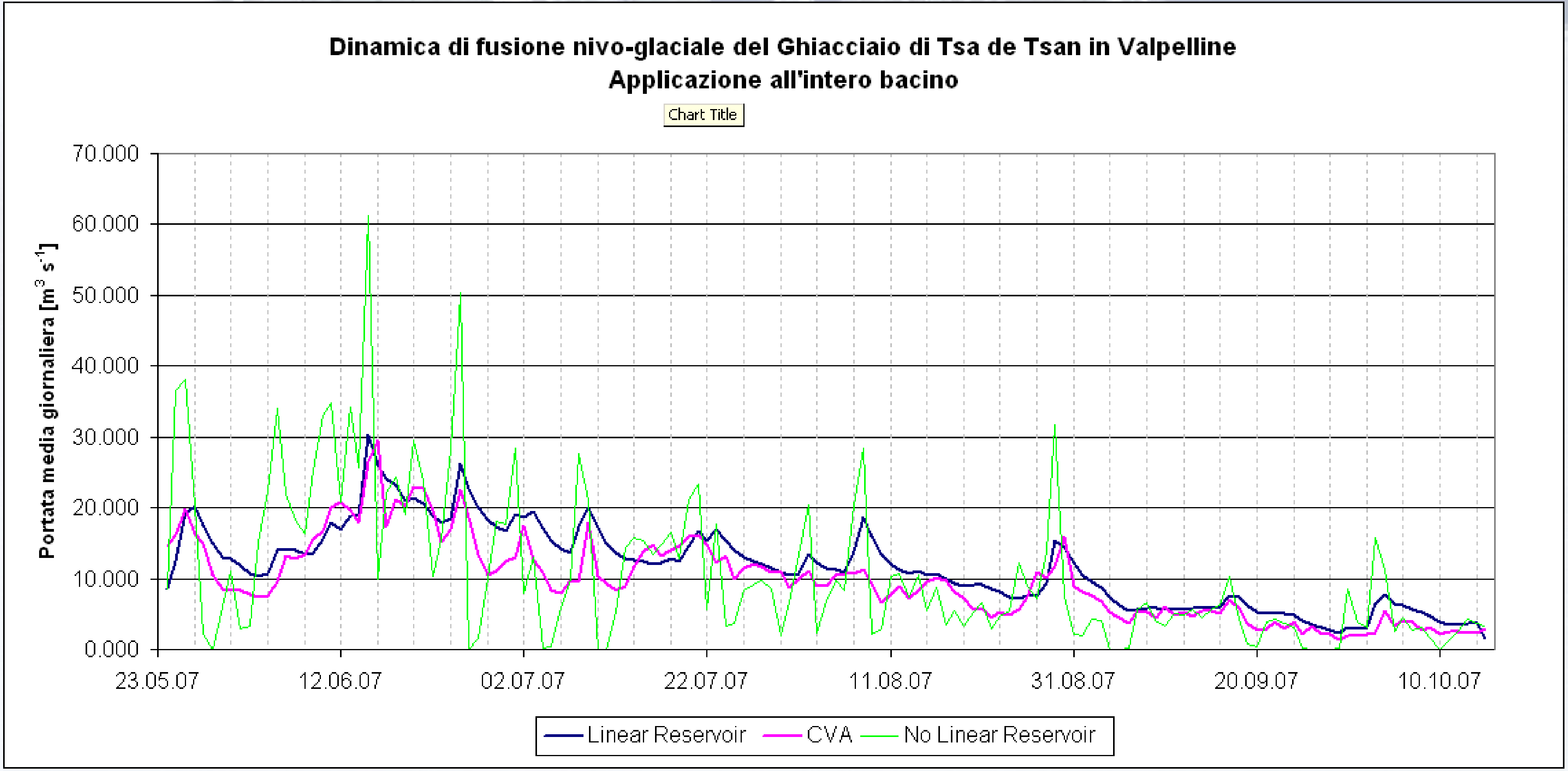


Snow cover extent during ablation season:

high resolution SPOT image

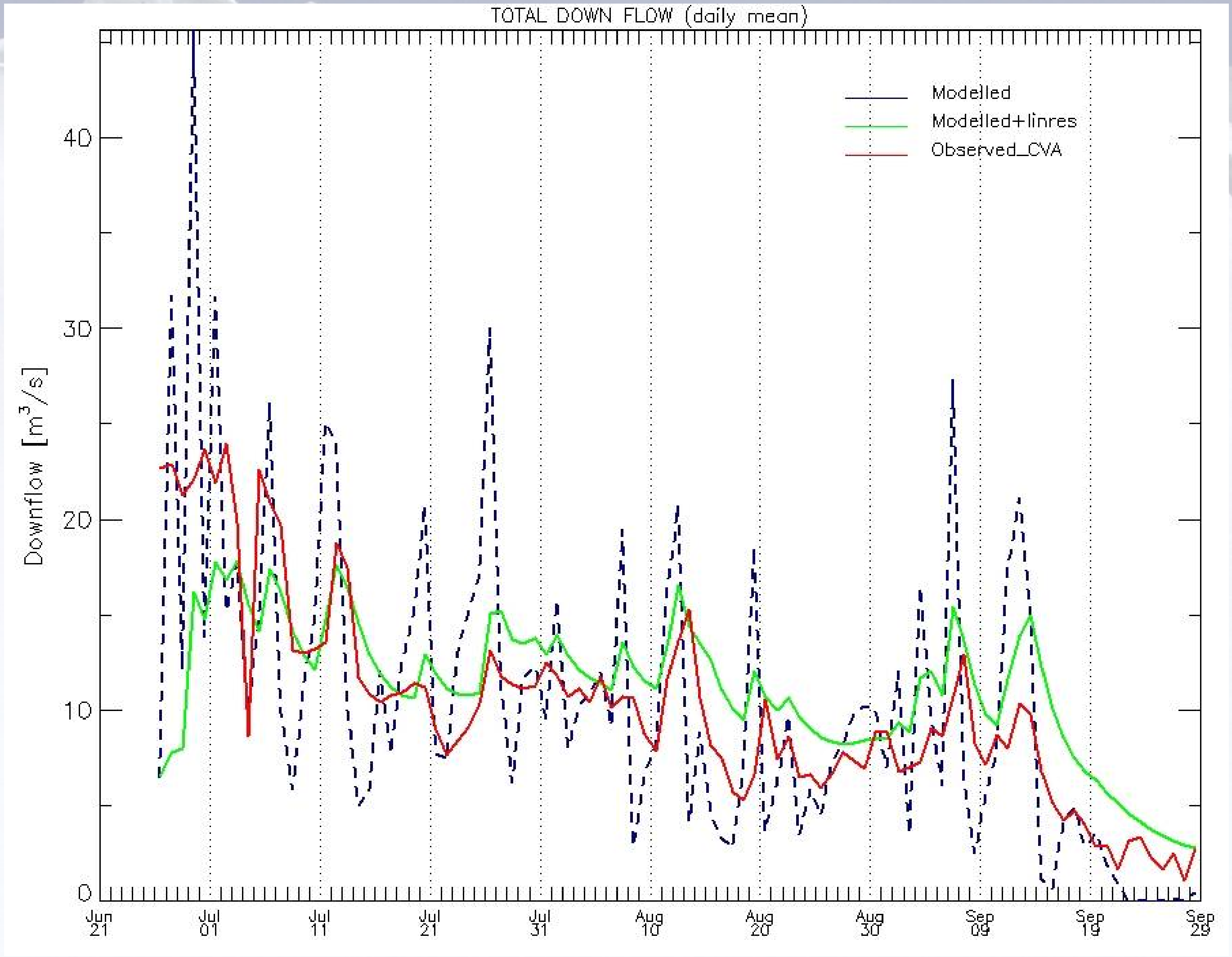
Snow and Glaciers melt modelling in Valpelline

2007 application on the entire basin.
Daily discharge measured by CVA: model validation



Snow and Glaciers melt modelling in Valpelline

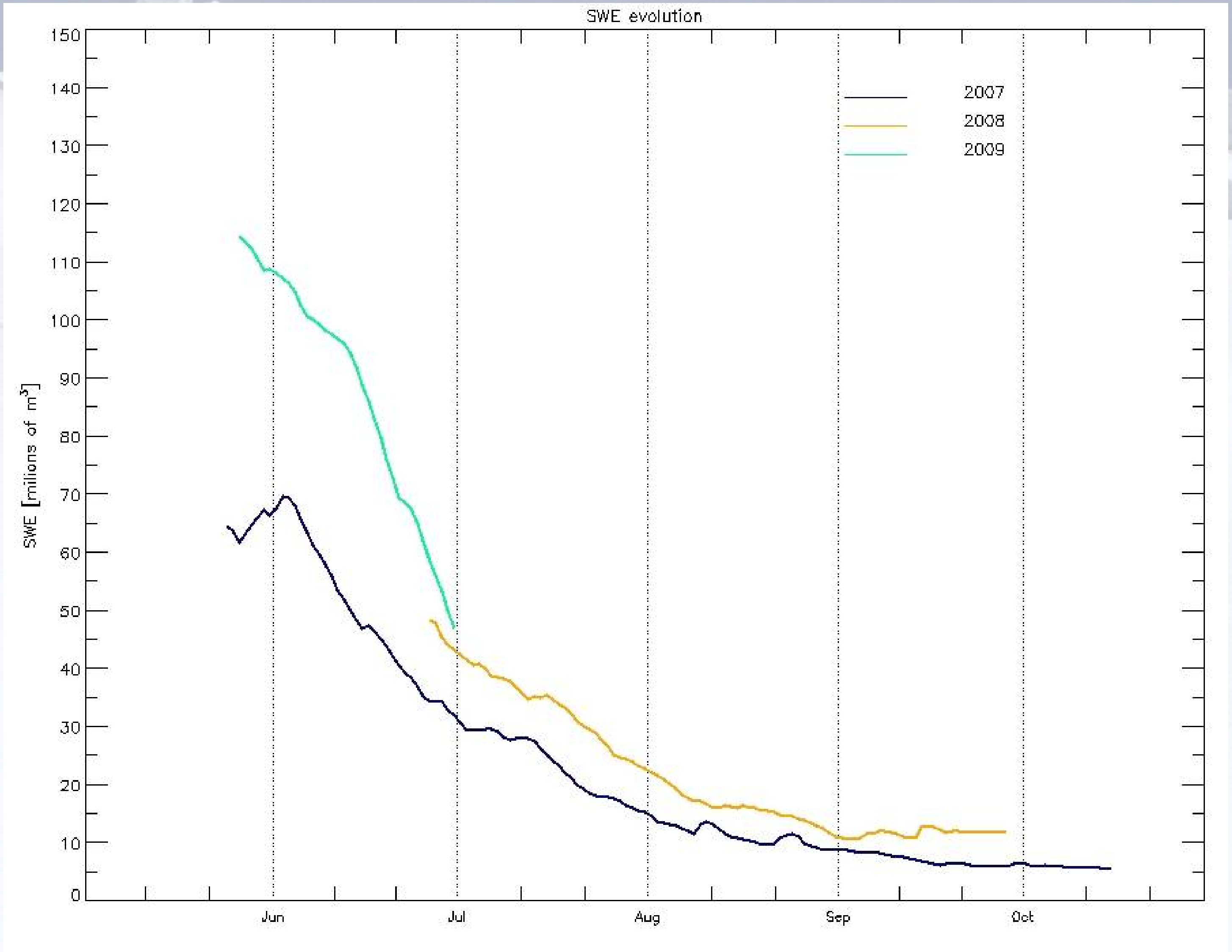
2008 application on the entire basin.
Daily discharge measured by CVA: model validation



Snow and Glaciers melt modelling in Valpelline

SWE evolution on the entire basin

(preliminary results including 2009 snowy winter)



Snow and Glaciers melt modelling in Valpelline

Future developments

1) sensitivity analysis of model parameters (e.g. temperature and precipitation gradients and linear reservoir parameters)

2) model optimization against observed discharge data


ARPA
Valle d'Aosta
... thank you