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Snow cover prediction in the Italian central Apennines using weather forecast and land surface numerical models

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1. SYNOPTIC VIEW OF SNOW SEASONS 2019, 2020 AND 2021

In this paragraph we show 500 hPa geopotential height, 850 hPa air temperature, and surface precipitation anomalies for snow seasons 2018/19, 2019/20 and 2020/21.

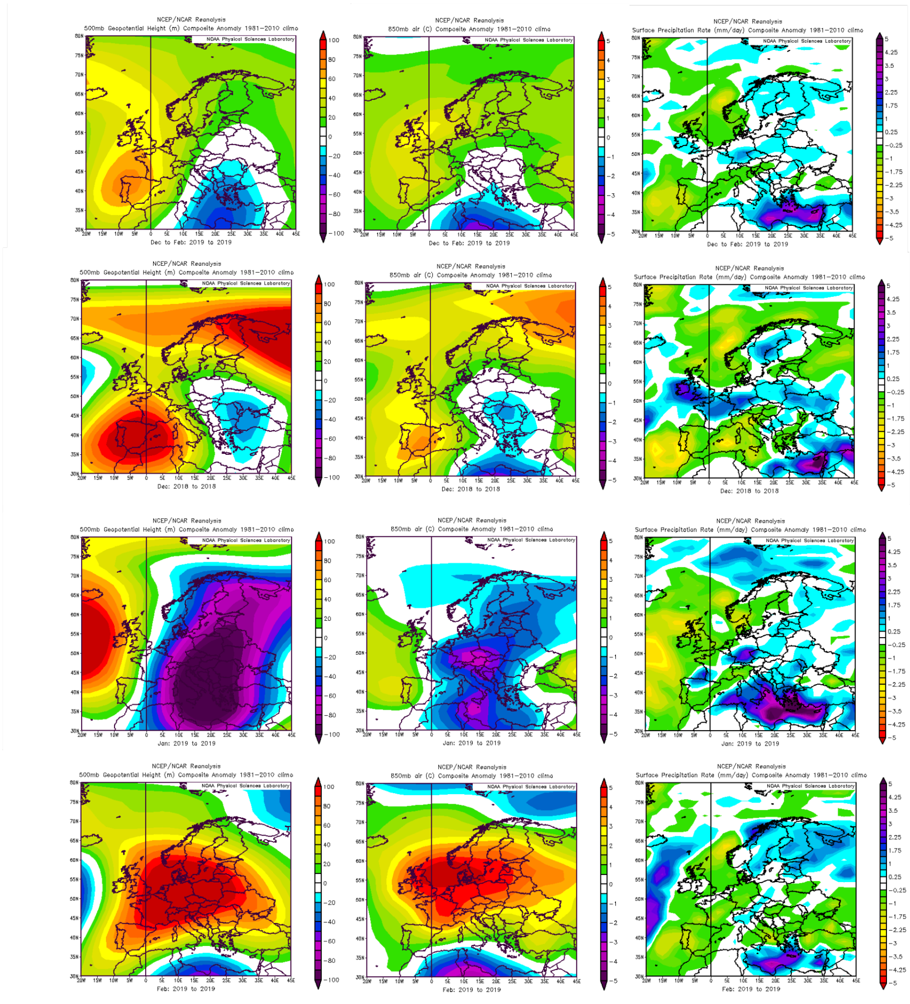

Fig. S1. Synoptic view of snow seasons 2018/19.

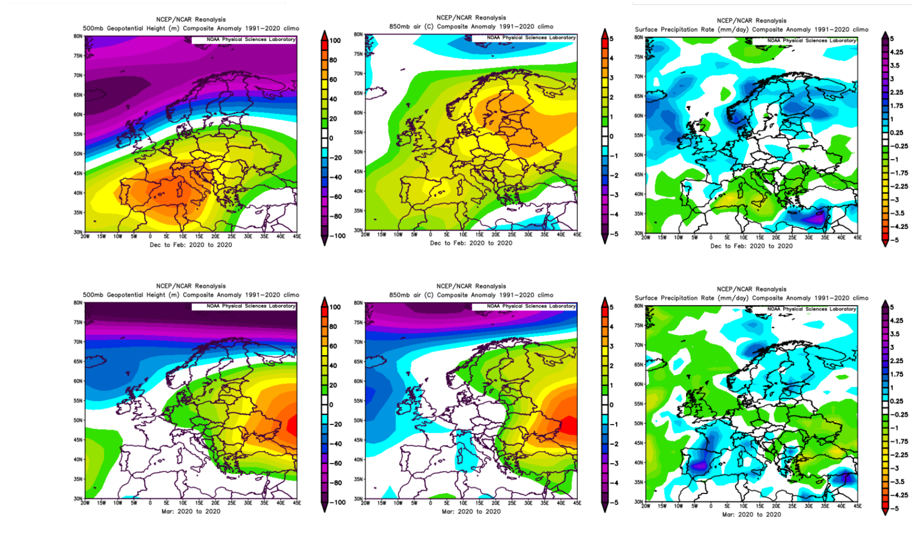

Fig. S2. Synoptic view of snow seasons 2019/20.

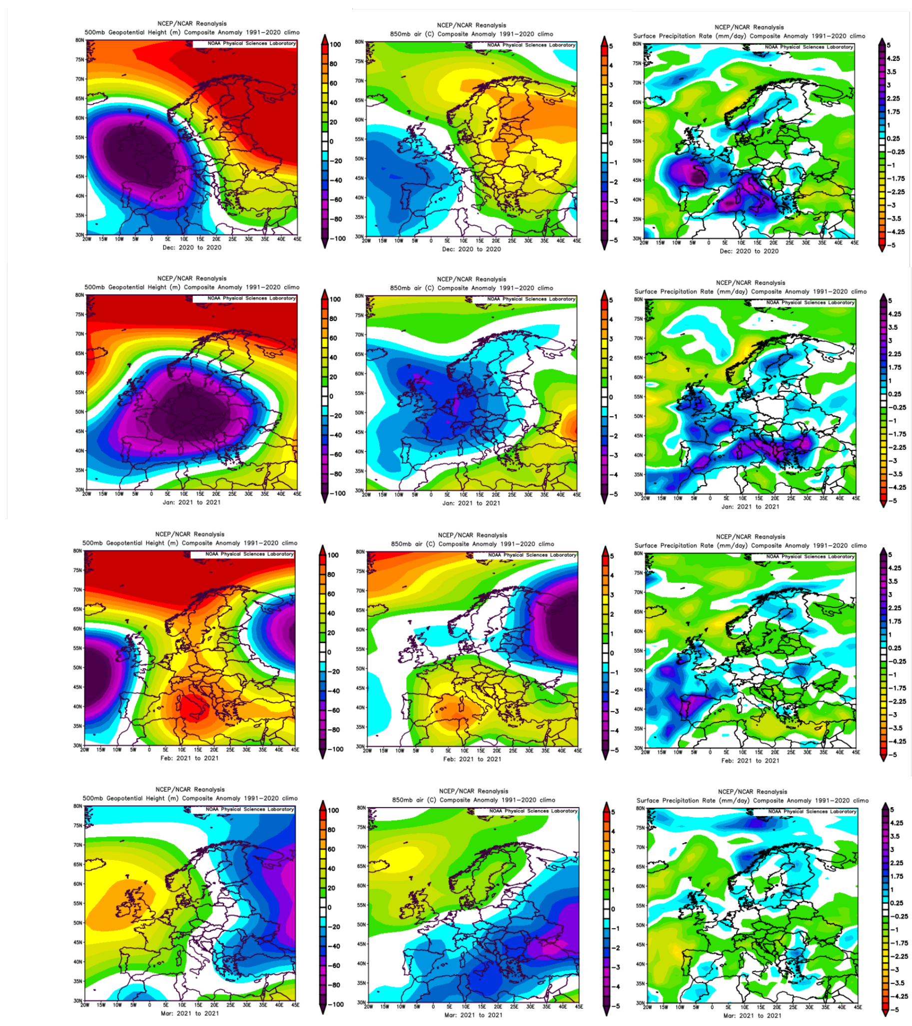

Fig. S3. Synoptic view of snow seasons 2020/21.

2. SNOW WATER EQUIVALENT DERIVATION

The density data collected daily by the Meteomont service at the snow fields unfortunately refers only to the snowpack top layer, thus they are not representative of the mean snowpack density. To overcome this problem and be able to use the snowpack top density observations to calculate the snow water equivalent and use it for validation, we used an independent dataset of snowpack vertical profiles, still provided by the Meteomont service, to find a relation between the top and mean snowpack density values. The new dataset consists of 138 vertical stratigraphies of the snowpack properties done almost weekly during snow seasons 2018/19, 2019/20 and 2020/21, which include the snow density of each layer identified in the snowpack. The stratigraphies are often done in avalanche prone terrains by traveling units, which look for critical snowpack conditions. For this reason the stratigraphies are not always representative of a large area, thus we decided to not use them to validate our model simulations directly, but to derive a linear relation between the snowpack top layer density and the mean snowpack density. Thus for each vertical profile we calculated the mean density and we extracted the density of the top layer. Then we compared top and mean density obtaining a correlation coefficient equal to 0.7 (Fig. S4), and we found the following linear relation:

$$\rho_m = 1.1\rho_t + 55.5 \tag{S1}$$

where ρ_m and ρ_t are mean and top snowpack densities in kgm^{-3}. Substituting to ρ_t the density coming from the daily Meteomont dataset we were able to estimate the corresponding ρ_m. Then we calculated the snow water equivalent (SWE) according to the relation:

$$\mathrm{SWE} = \rho_m h_s \tag{S2}$$

where h_s is the measured snow height in meters, and use it for the validation of WRF-Noah and WRF-Alpine3D simulations.

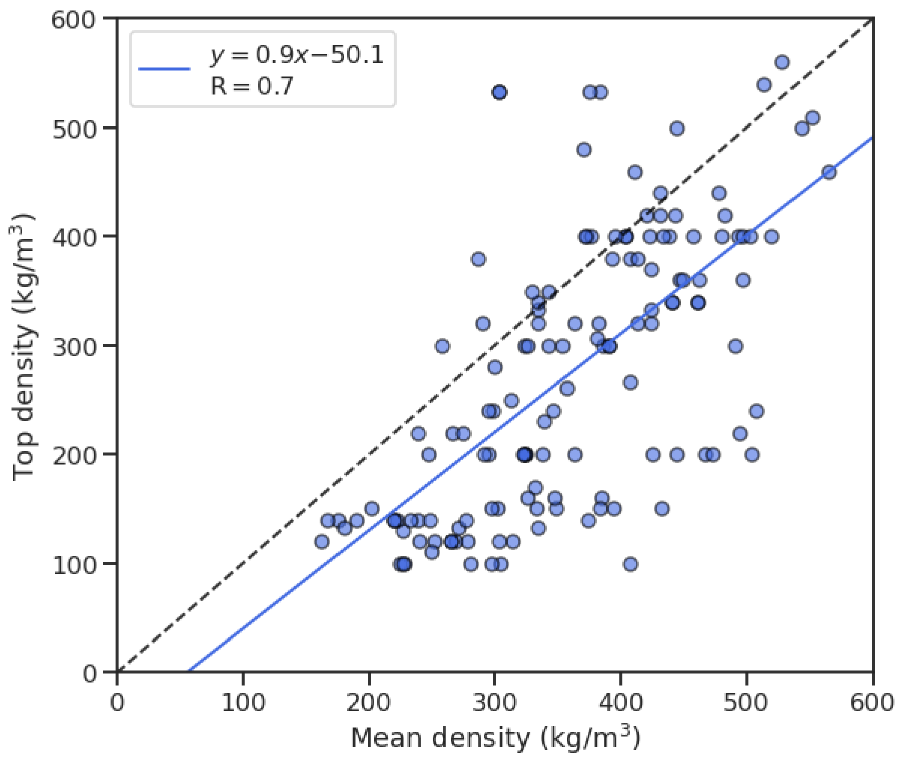

Fig. S4. Comparison between top and mean snowpack density of 138 vertical stratigraphies of the snowpack properties done during snow seasons 2018/19, 2019/20 and 2020/21 by the Meteomont service.

3. SENSITIVITY TEST OF ALPINE3D

In order to find the best Alpine3D configuration for our case study, we designed a sensitivity test limited to snow season 2020/21. It consisted in making point simulations of the snow cover evolution at the measurement sites using different parametrizations for atmospheric stability, new snow density and snow albedo in the SNOWPACK model. We tested all the possible combinations of the parametrizations reported in Table S1, and we decided to use in our WRF-Alpine3D simulations NEUTRAL, ZWART and LEHNING_1 parametrizations for atmospheric stability, new snow density and snow albedo, respectively, as the simulation obtained using this combination presented the best agreement with observed snow height in terms of MBE, MAE and R . The scores obtained for the snow height estimation are shown in Table S2, where we reported only the combinations that presented a MAE smaller than 18 cm and a MBE between -1 cm and 1 cm.

Table S1. Alpine3D tested parametrizations.

Atmospheric stability	New snow density	Snow albedo
RICHARDSON	LEHNING_NEW	LEHNING_0
NEUTRAL	LEHNING_OLD	LEHNING_1
MO_MICHLMAYR	BELLAIRE	LEHNING_2
MO_STEARNS	ZWART	SCHMUCKI_GSZ
MO_HOLTSLAG	PAHAUT	SCHMUCKI_OGS
MO_LOG_LINEAR	NIED	NIED
MO_SCHLOEGL_UNI		

Table S2. Scores obtained in the snow height estimation for the combinations that presented a MAE smaller than 18 cm and a MBE between -1 cm and 1 cm.

	MBE (cm)	MAE (cm)	R
MO_STEARNS-NIED-PAHAUT	0.41	17.7	0.75
MO_STEARNS-NIED-ZWART	0.37	17.7	0.76
NEUTRAL-LEHNING_0-BELLAIRE	-0.90	17.6	0.74
NEUTRAL-LEHNING_0-LEHNING_NEW	-0.78	17.6	0.75
NEUTRAL-LEHNING_0-NIED	-0.16	17.7	0.74
NEUTRAL-LEHNING_0-ZWART	-0.70	17.3	0.75
NEUTRAL-LEHNING_1-LEHNING_NEW	0.21	17.7	0.74
NEUTRAL-LEHNING_1-NIED	0.63	18.0	0.73
NEUTRAL-LEHNING_1-ZWART	0.38	17.4	0.75

4. NEW SNOW DENSITY AND ALBEDO PARAMETRIZATIONS

ZWART

The following C++ code implements the ZWART parametrization for new snow density in SNOWPACK:

```
VW = std::max(2., VW);
RH = RH/100.;
static const double beta01=3.28, beta1=0.03;
static const double beta02=-0.36, beta2=-0.75, beta3=0.3;
double arg = beta01 + beta1*TA + beta2*asin(sqrt(RH)) + beta3*log10(VW);
if(TA>=-14.) arg += beta02;
rho_hn = pow(10., arg);
```

LEHNING_1

The following C++ code implements the LEHNING_1 parametrization for snow albedo in SNOWPACK:

```
double mf = 0.;
static const double av = 0.77;
static const double Cta = -0.0052, Cv = 0.0056 ;
static const double Clwc = -3.0, Crho = -0.0003;
static const double Cmf = -0.032;
static const double Crb = 0.06, Cdd = 0.017;
static const double Csp = 0.021, Ctss = 0.0084;
static const double Cswout = -6.8e-5;
static const double Cta_tss = -1.1e-5;
if (Edata.mk%100 > 19) {
mf = 1.;
}
const double Alb1 = Crho*Edata.Rho + Clwc*Edata.theta[WATER]
+ Cdd*Edata.dd + Csp*Edata.sp
+ Cmf*mf + Crb*Edata.rb +  Cta*Ta + Ctss*Tss
+ Cv*Mdata.vw+ Cswout*Mdata.rswr + Cta_tss*Ta*Tss;
Alb = av + log(1.0 + Alb1);
```

5. SNOW WATER EQUIVALENT THRESHOLD FOR MODIS LAND USE CLASSIFICATION

In this paragraph we show the values we used for W_{max} according to MODIS 20 classes land use classification.

Table S3. MODIS land use classes and corresponding W_{max}.

Class Index	Vegetation type	W_{max} (m)
1	Evergreen Needleleaf Forest	0.08
2	Evergreen Broadleaf Forest	0.08
3	Deciduous Needleleaf Forest	0.08
4	Deciduous Broadleaf Forest	0.08
5	Mixed Forests	0.08
6	Closed Shrublands	0.03
7	Open Shrublands	0.035
8	Woody Savannas	0.03
9	Savannas	0.04
10	Grasslands	0.04
11	Permanent Wetlands	0.015
12	Croplands	0.04
13	Urban and Built-Up	0.04
14	Cropland/Natural Vegetation Mosaic	0.04
15	Snow and Ice	0.02
16	Barren or Sparsely Vegetated	0.02
17	Water	0.01
18	Wooded Tundra	0.025
19	Mixed Tundra	0.025
20	Barren Tundra	0.02

6. ELEVATION DIFFERENCES BETWEEN MODEL AND REALITY

In this paragraph we compare real and model elevation for all the variables collected at the automatic and manual measurement sites. Figure S5 and Table S4 show that the elevation for wind speed, snow depth and incoming shortwave radiation sensors is underestimated in the model. The elevation difference is particularly evident above 1000 m a.s.l., where the model elevation is smoothed compared to the reality because of the kilometric-scale of the WRF grid. This have a particular impact on the wind speed, which results to be considerably underestimated at high elevation.

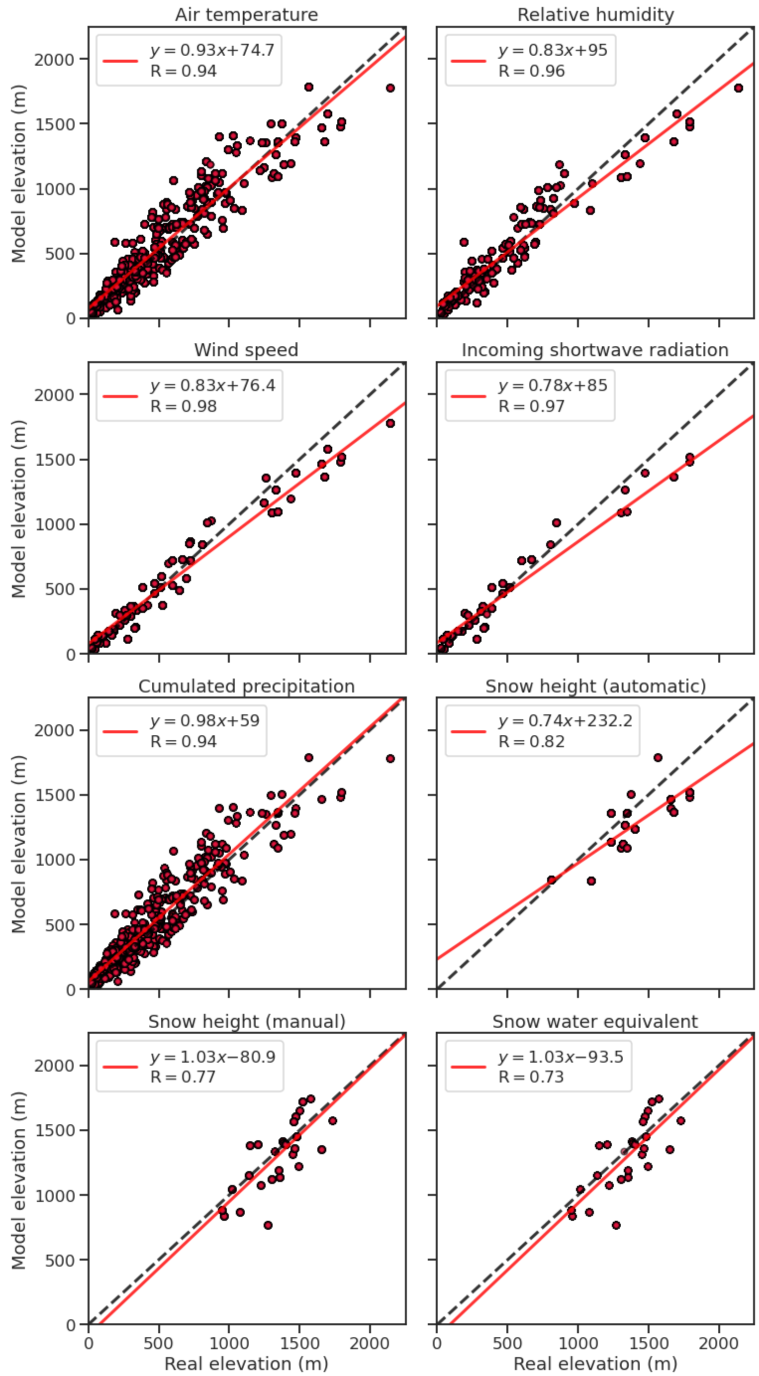

Fig. S5. Comparison of real and model elevation for all the variables collected at the automatic and manual measurement sites.

Table S4. Mean bias error (MBE), mean absolute error (MAE) and correlation coefficient (R) of model elevation for all the variables collected at the automatic and manual measurement sites.

	MBE (m)	MAE (m)	R
Air temperature	42	102	0.94
Relative humidity	14	99	0.96
Wind speed	-28	95	0.98
Incoming shortwave radiation	-18	93	0.97
Cumulated precipitation	52	98	0.94
Snow depth (automatic)	-126	171	0.82
Snow depth (manual)	-41	141	0.77
Snow water equivalent	-51	150	0.73