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Impact of the statistical method, training dataset, and spatial scale of post-processing to adjust ensemble forecasts of the height of new snow

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2 University of Oulu, Finland ; 3 Univ. Grenoble Alpes – INRAE, UR ETNA, Grenoble, France ; 4 NOAA Earth System Research Lab., Boulder, USA ; 5 Univ. Grenoble Alpes, CNRS, IRD, Grenoble INP, IGE, Grenoble, France ; 6 CNRM – Université de Toulouse – Météo-France – CNRS, GMAP, Toulouse, France, 7 Météo-France, DirOP/COMPAS, Toulouse, France



Context

- Forecasting the height of new snow:
 - Safety and economic concerns



- Meteo-France **automatic forecasts** currently available (website and smartphone apps) :
24h height of new snow =

$$\sum_{24h} \left(\text{Hourly NWP precipitation} \times \text{Density} \right)$$

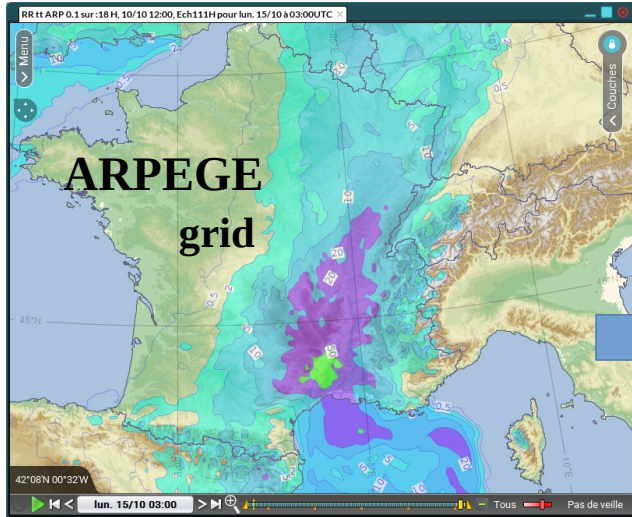
~~Compaction during snowfall~~

~~Possible melting~~

~~Rain on snow~~

→ **Severe biases**

Alternative : Physical modelling SAFRAN-Crocus

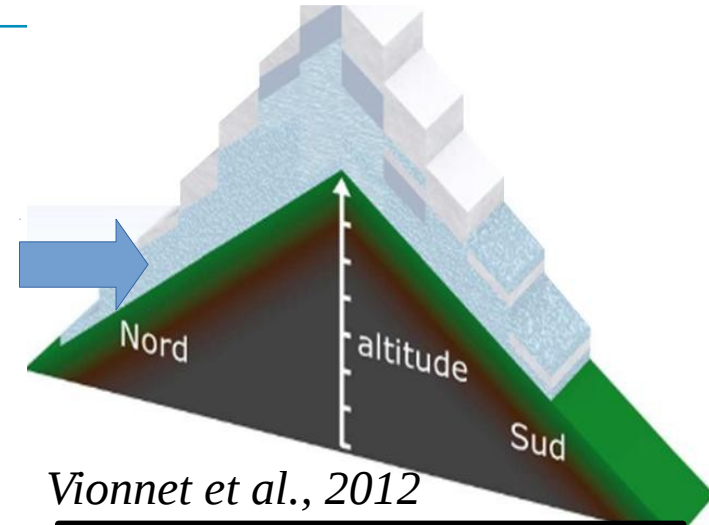


Durand et al., 1998



SAFRAN :

- Spatial aggregation of ARPEGE on *massifs* (~1000 km²)
- Adjust meteorological variables at various elevations



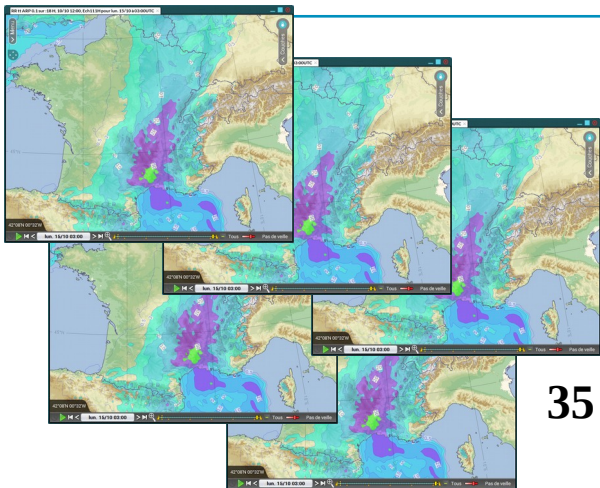
Vionnet et al., 2012

Crocus :

- Falling snow density = f(temperature, wind speed)
- Explicit mechanical compaction
- Melting (energy balance)
- Compaction due to liquid water (rain on snow)

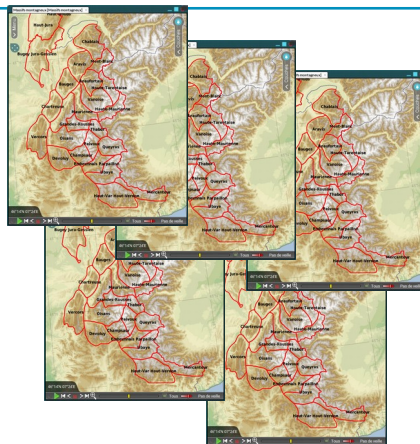
Ensemble forecasts PEARP-S2M

Experimental from 2014
Operational : october 2019

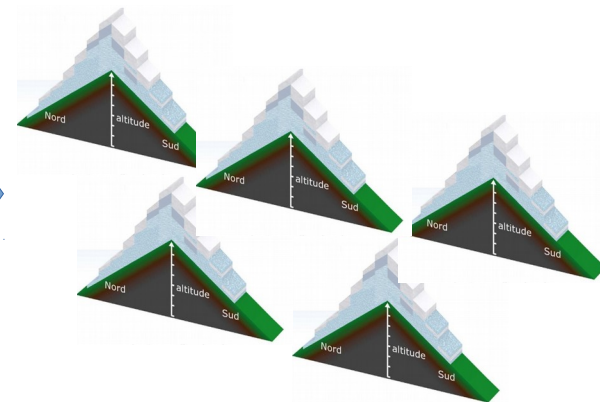


35 members

PEARP

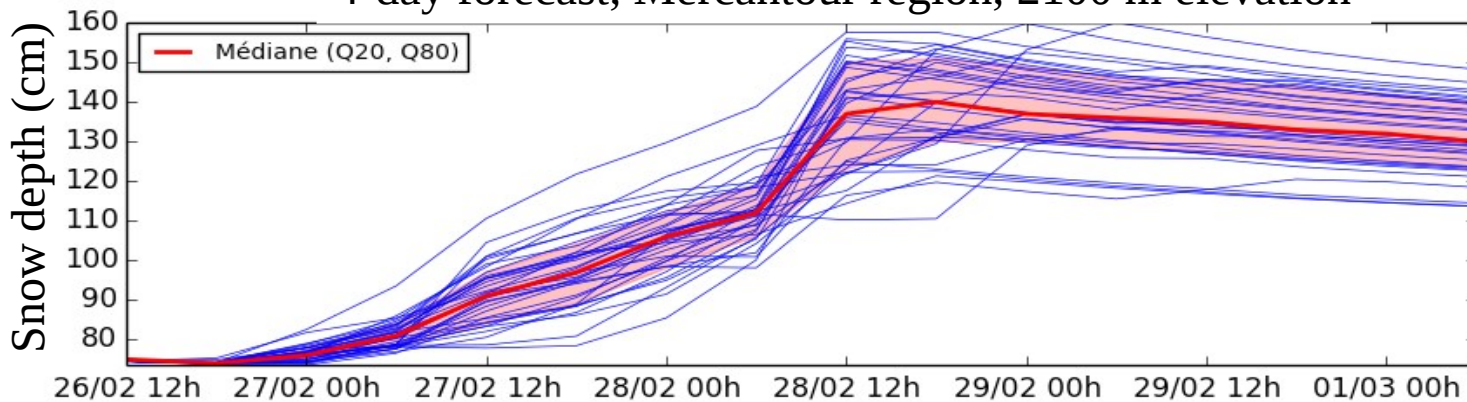


SAFRAN



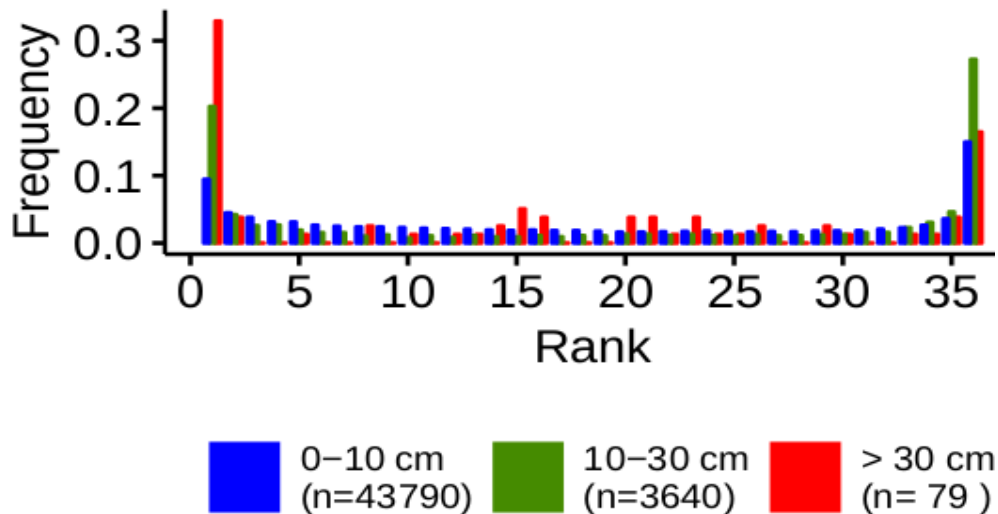
Crocus

4-day forecast, Mercantour region, 2100 m elevation



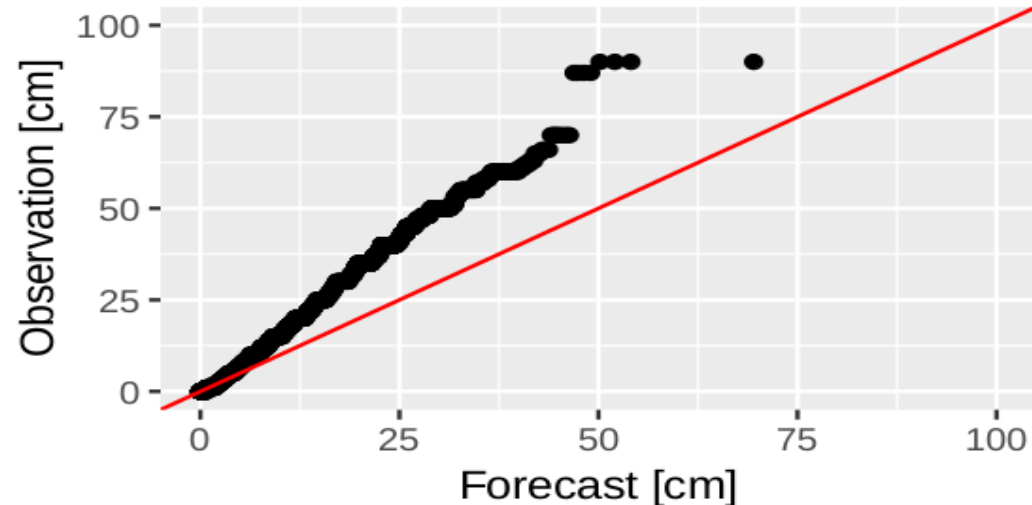
Vernay et al. 2015

Rank diagram



Underdispersion !

Quantile-Quantile plot



Bias !

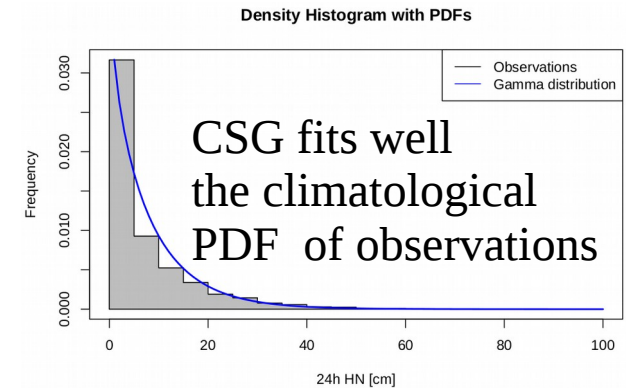
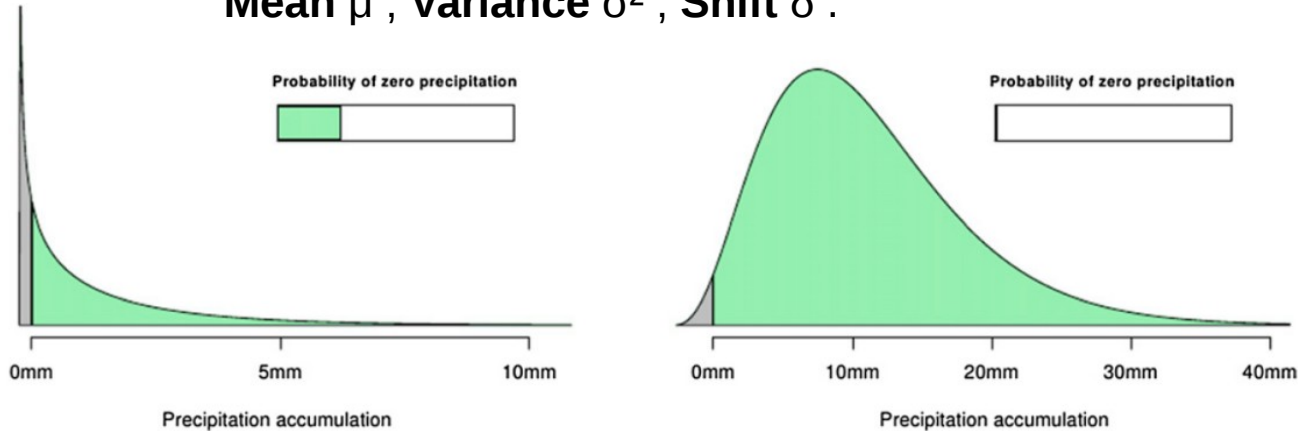
- Physical ensemble modelling of the snowpack improves the forecast of the height of new snow compared to:
 - **Direct NWP outputs** (*Champavier et al., 2018*)
 - **Deterministic systems** (*Vernay et al., 2015*)
- **Ensemble Model Output Statistics (EMOS)** are useful to forecast the height of new snow from direct ensemble NWP outputs (precipitation and temperature) (*Stauffer et al., 2018 ; Scheuerer and Hamill, 2019*)
- **Quantile Regression Forests (QRF)** can incorporate more predictors and have added value for precipitation forecasts (*Taillardat et al., 2019*)

Questions

- Can **Ensemble Model Output Statistics (EMOS)** improve the forecasts from physical modelling ?
 - What is the best training dataset ?
 - What is the spatial validity of the post-processing ?
- Can **Quantile Regression Forests (QRF)** improve the skill compared to EMOS ?

Statistical post-processing: method

- In *Nousu et al., NPG, 2019*, we apply the EMOS method used by *Scheuerer and Hamill (2015 ; 2018)* for precipitation forecasts:
 - We assume that the conditional distribution of the forecast HN to the raw ensemble forecasts follow a Censored Shifted Gamma (CSG) defined by 3 parameters :
Mean μ ; Variance σ^2 ; Shift δ .



- Regression model between CSG parameters and synthetic properties of the raw ensemble (**mean, dispersion, probability of 0 cm**)

Predictand :

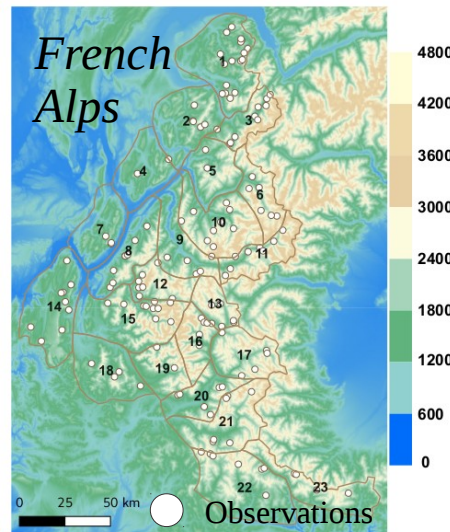
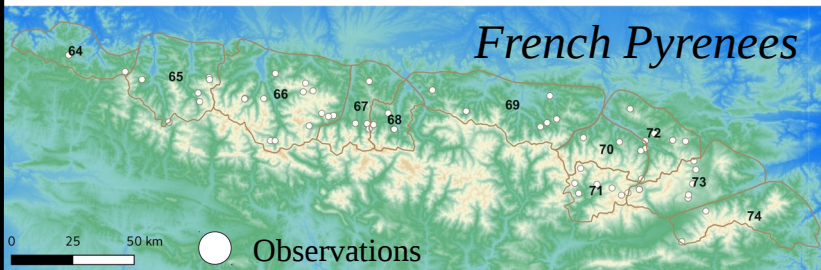
Network of local observations of the 24h height of new snow



Snow board

2 Predictor datasets: Ensemble forecasts PEARP-S2M

	Period	Members	Initial conditions	Resolution and physics
Reforecast	1994-2016	10	Unperturbed	Homogeneous
Real-time forecasts	2014-2017	35	Perturbed	Heterogeneous



Spatial scale of the calibration:

- Massif scale
- Station scale

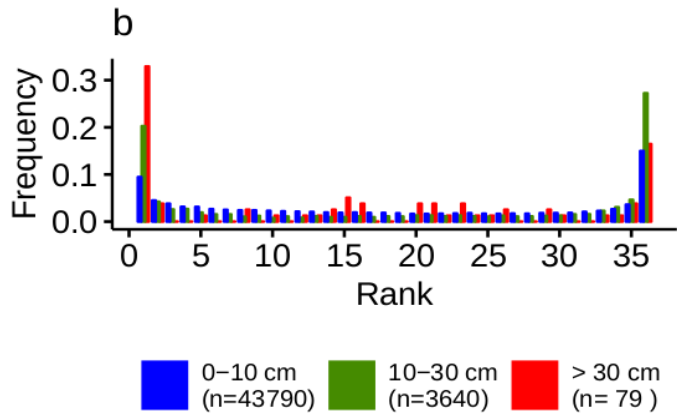
Evaluations :

- From real-time forecasts, winter **2017-2018**

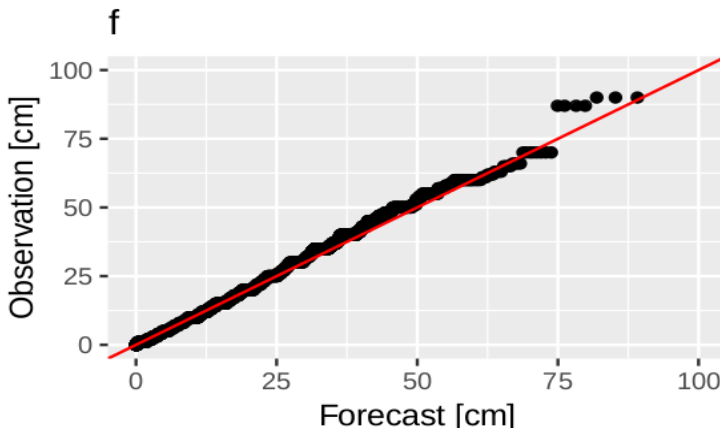
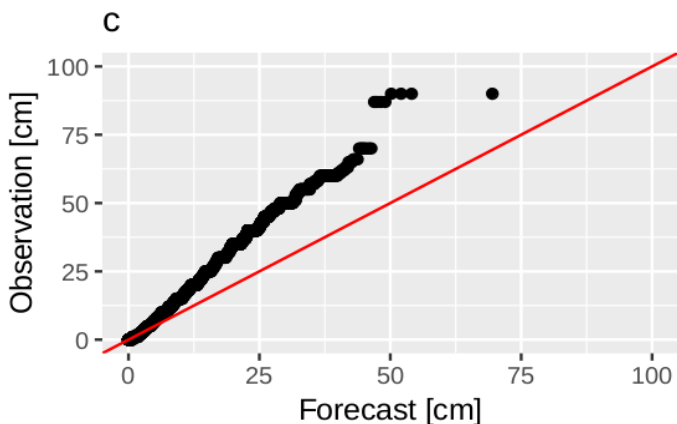
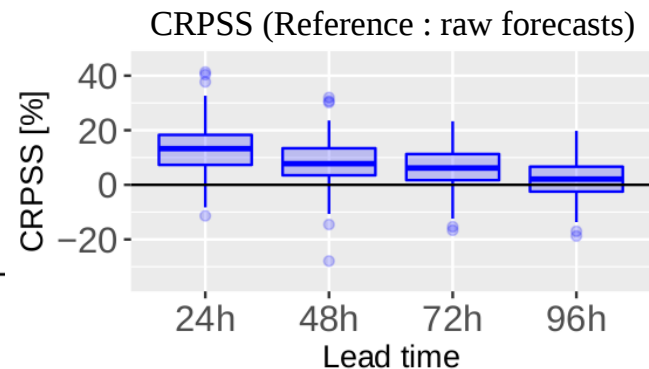
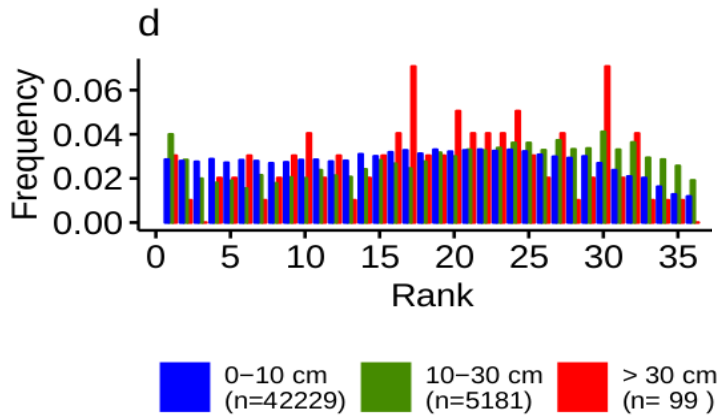


Training: reforecasts 1994-2016
Evaluation: real-time forecasts
2017-2018

Raw forecasts



Corrected forecasts



- Remove bias and underdispersion

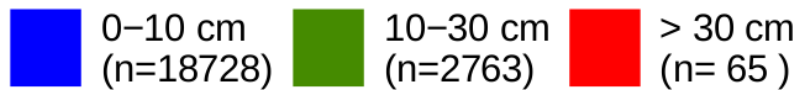
- Improvement of CRPS on most stations.

- Larger improvement at short lead times

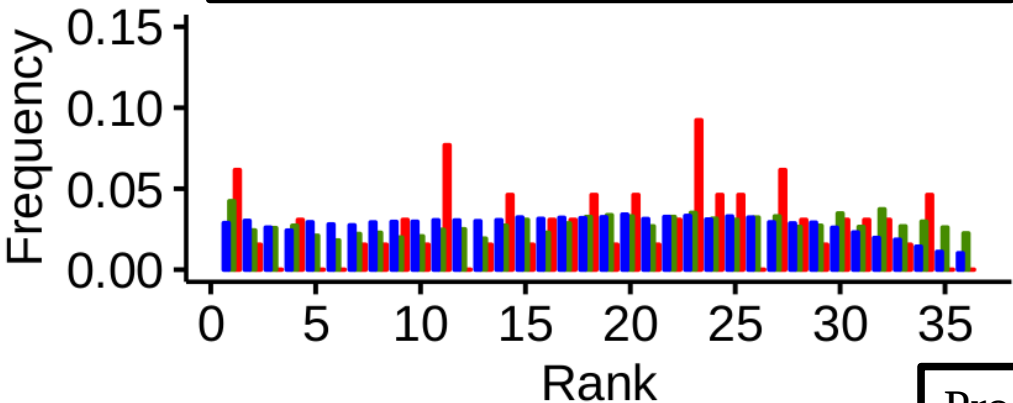


Sensitivity to training dataset

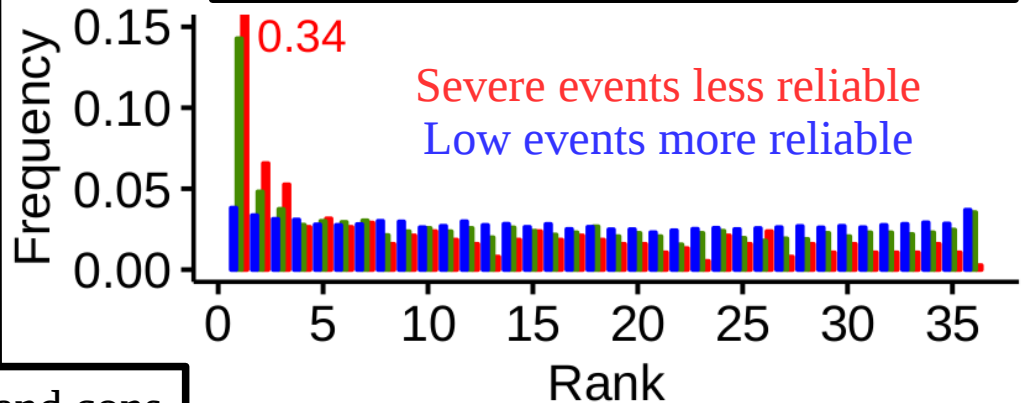
Nousu et al., NPG, 2019



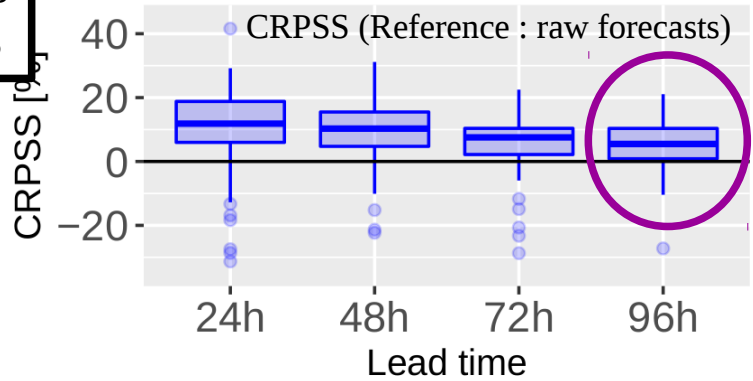
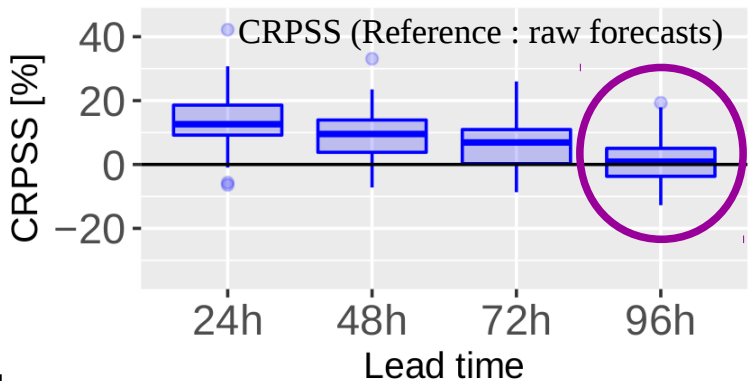
Training: reforecasts 1994-2016
Evaluation: real-time forecasts 2017-2018



Training: real-time forecasts 2014-2017
Evaluation: real-time forecasts 2017-2018



Pros and cons
on both sides



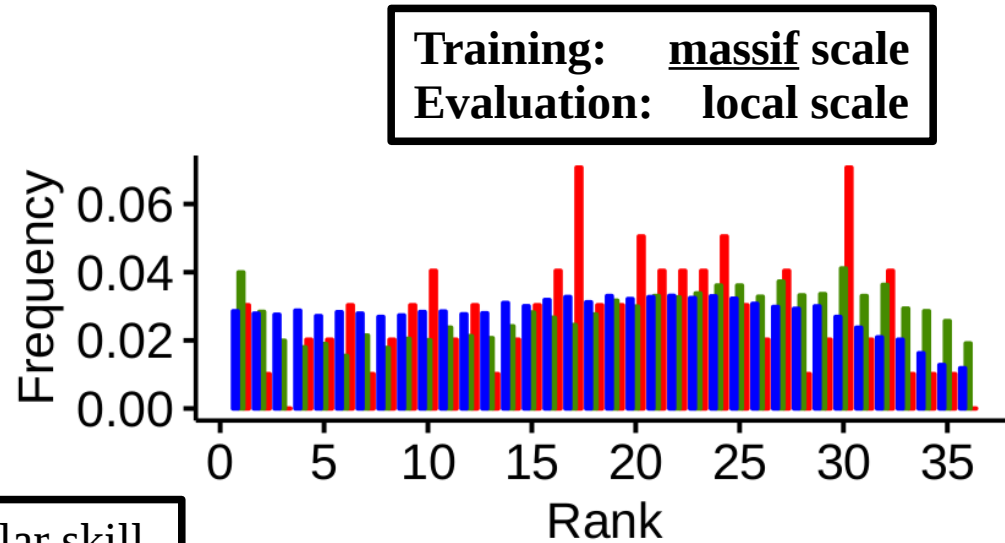
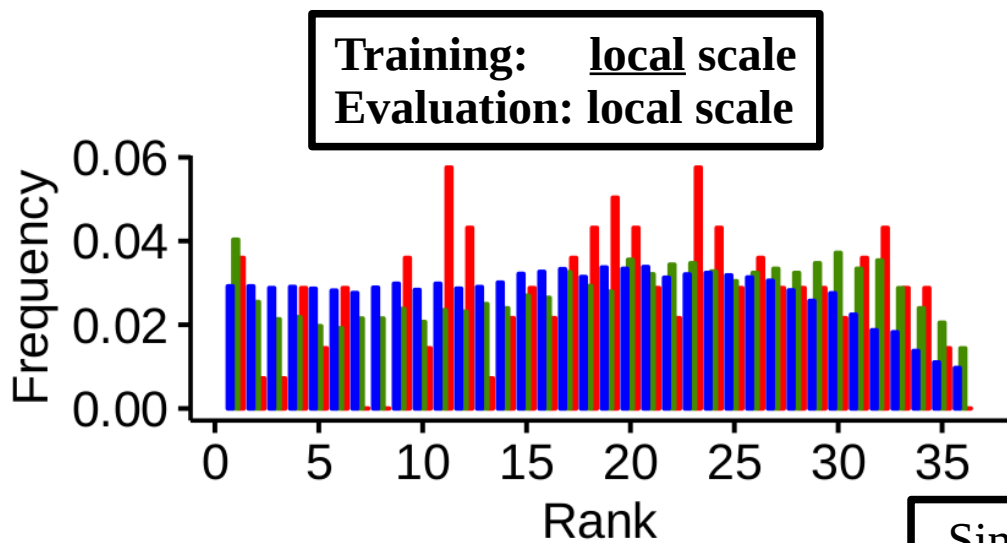
Better skill at the longest lead time



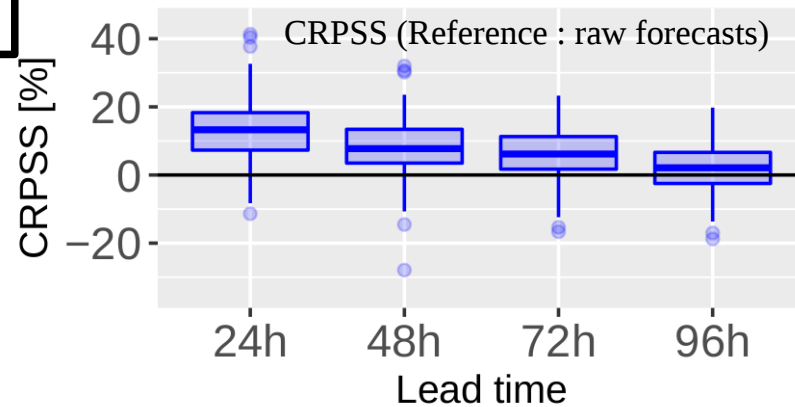
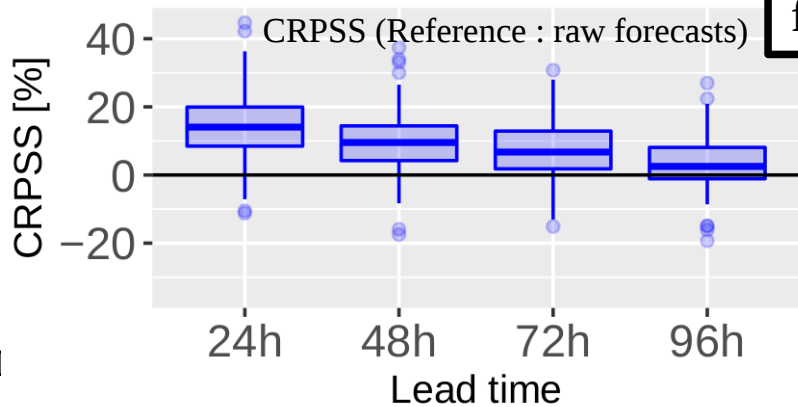
Sensitivity to spatial scale

Nousu et al., NPG, 2019

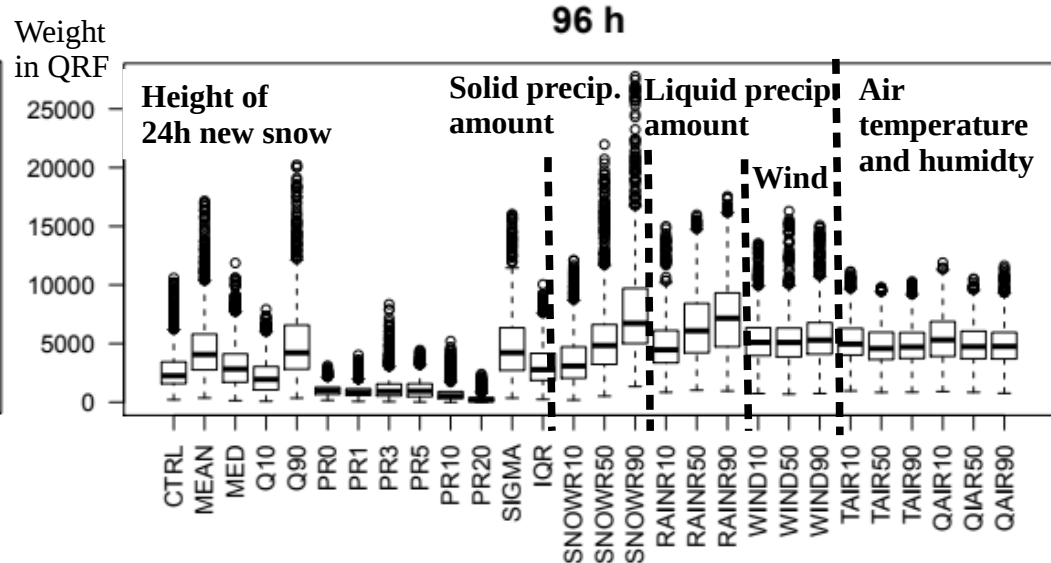
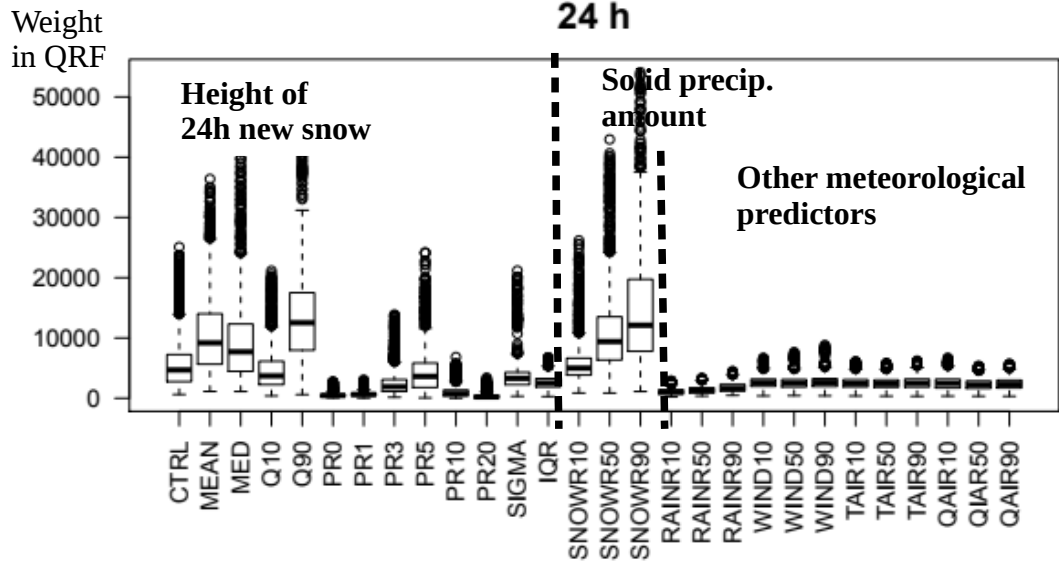
0–10 cm (n=18728) 10–30 cm (n=2763) > 30 cm (n= 65)



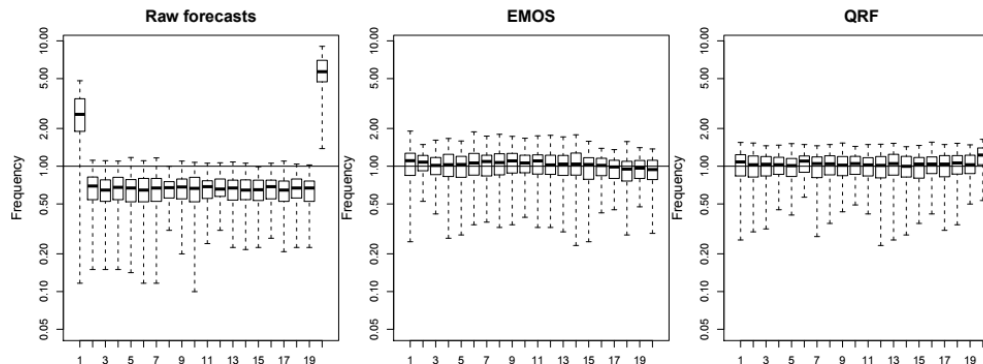
Similar skill
for all criteria



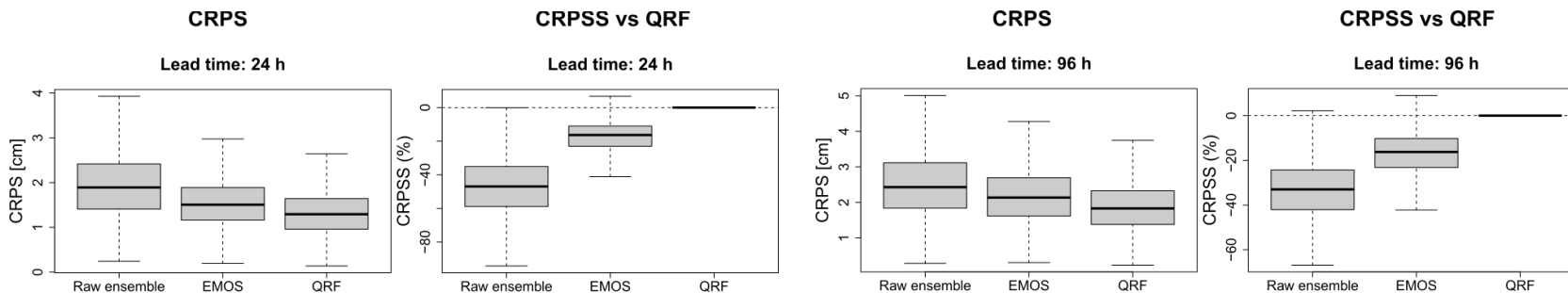
- Limitation of EMOS :
 - When all raw members expect 0 cm of snow but some rainfall, EMOS always forecast 0 cm (it does not account for potential errors in the rain-snow limit elevation)
- QRF has been tested with a large set of variables as predictors
 - It is shown that rainfall amount and temperature are useful predictors to be associated with the simulated new snow depth, **especially at the longest lead times**



- The **statistical properties** of the post-processed are **satisfactory** in both cases (flat rank histograms for both EMOS and QRF)



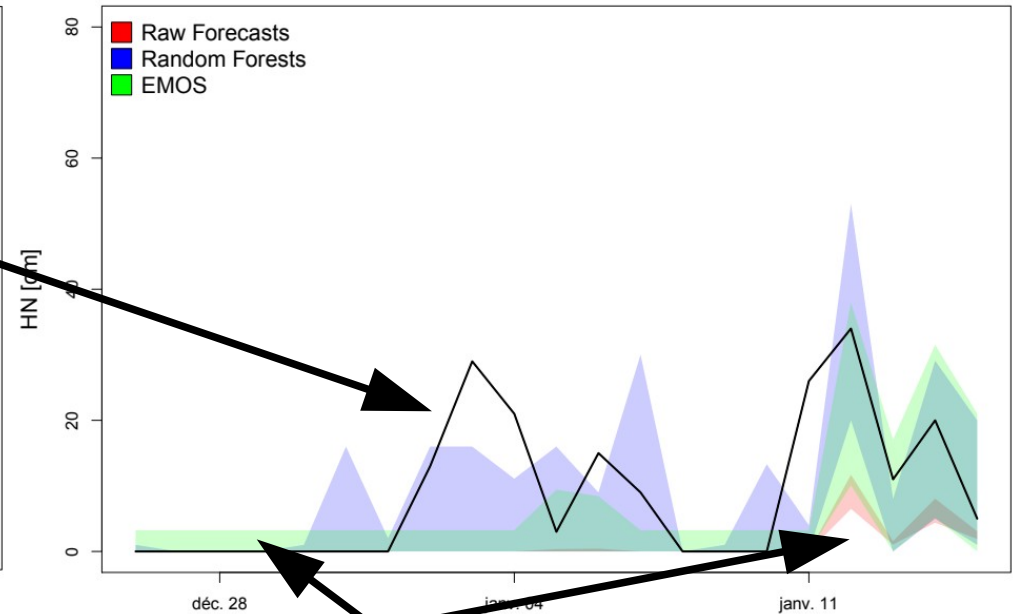
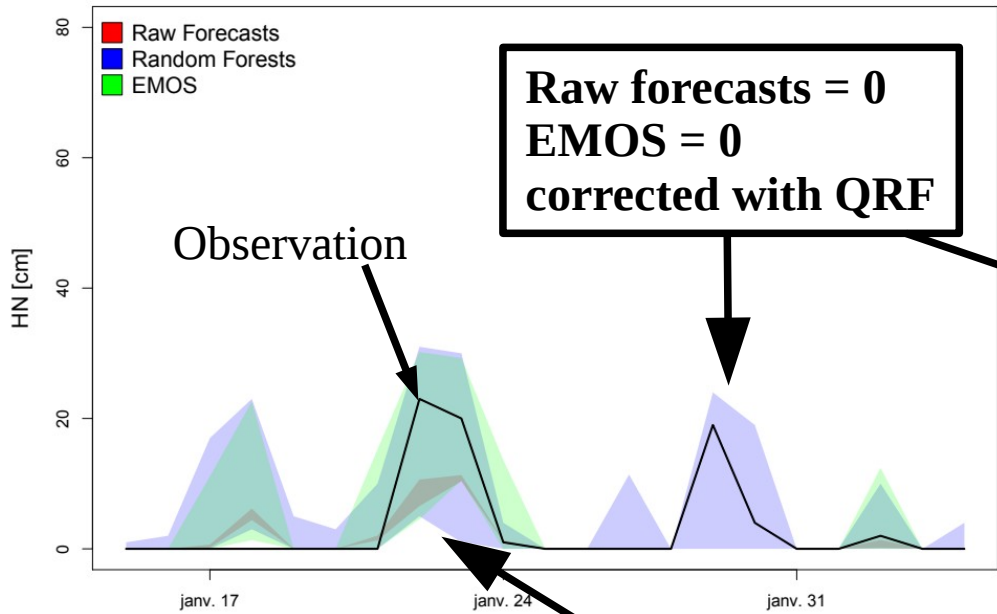
- A **significant improvement of CRPS is obtained with QRF** in theoretical experiments based on the 22-year reforecast dataset (22* [21-year training, 1-year validation])
 → Better predictive power



- Illustrations on specific cases (24h lead time forecasts):

Station 74134400 – 2000-01-15 – 2000-02-04

Station 73034400 – 2015-12-26 – 2016-01-15



**Raw forecasts = 0
EMOS = 0
corrected with QRF**

EMOS and QRF both correct the underdispersion and bias of raw forecasts

On dry days, QRF provides a lower spread than EMOS

Conclusions

- Raw ensemble forecasts + snowpack modelling provide predictive but ***biased and underdispersive*** forecasts not well suited for **automated products**.

- **Ensemble Model Output Statistics (EMOS)** improve the forecasts from physical modelling.
 - What is the **best training dataset** ?
 - ***Long reforecasts*** improve the ***reliability*** of the post-processed forecasts for the severe and ***unusual events***
 - *But they should be **more homogeneous** with the operational system (initial perturbations)*
 - What is the spatial validity of the post-processing ?
 - ***Spatial consistence of biases*** allows to apply corrections at the massif scale (1000 km²)

- **Quantile Regression Forecasts (QRF)**
 - Better predictive skill in theoretical experiments thanks to other predictors
 - Further work required to test the robustness when transferred to real time forecasts

More details for the EMOS results in our main reference:

Nousu, J.-P., Lafaysse, M., Vernay, M., Bellier, J., Evin, G., and Joly, B.: Statistical post-processing of ensemble forecasts of the height of new snow, *Nonlin. Processes Geophys.*, 26, 339–357, <https://doi.org/10.5194/npg-26-339-2019>, 2019.

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Scheuerer, M. and Hamill, T. M.: Statistical Postprocessing of Ensemble Precipitation Forecasts by Fitting Censored, Shifted Gamma Distributions, *Mon. Weather Rev.*, 143, 4578–4596, <https://doi.org/10.1175/MWR-D-15-0061.1>, 2015.

Scheuerer, M. and Hamill, T. M.: Generating Calibrated Ensembles of Physically Realistic, High-Resolution Precipitation Forecast Fields Based on GEFS Model Output, *J. Hydrometeorol.*, 19, 1651–1670, <https://doi.org/10.1175/JHM-D-18-0067.1>, 2018.

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Stauffer, R., Mayr, G. J., Messner, J. W., and Zeileis, A.: Hourly probabilistic snow forecasts over complex terrain: a hybrid ensemble postprocessing approach, *Adv. Stat. Climatol. Meteorol. Oceanogr.*, 4, 65–86, <https://doi.org/10.5194/ascmo-4-65-2018>, <https://www.adv-stat-clim-meteorol-oceanogr.net/4/65/2018/>, 2018.

Taillardat, M., Fougères, A., Naveau, P., and Mestre, O.: Forest-based and semi-parametric methods for the postprocessing of rainfall ensemble forecasting, *Weather Forecast.*, in press, <https://doi.org/10.1175/WAF-D-18-0149.1>, 2019.

Vernay, M., Lafaysse, M., Merindol, L., Giraud, G., and Morin, S.: Ensemble Forecasting of snowpack conditions and avalanche hazard, *Cold. Reg. Sci. Technol.*, 120, 251–262, <https://doi.org/10.1016/j.coldregions.2015.04.010>, 2015.