Ensemble forecasting of snowpack conditions and avalanche hazard

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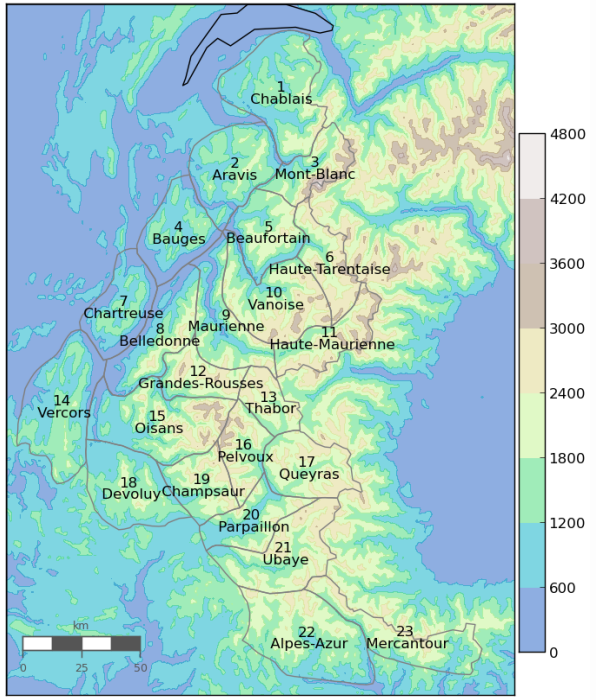
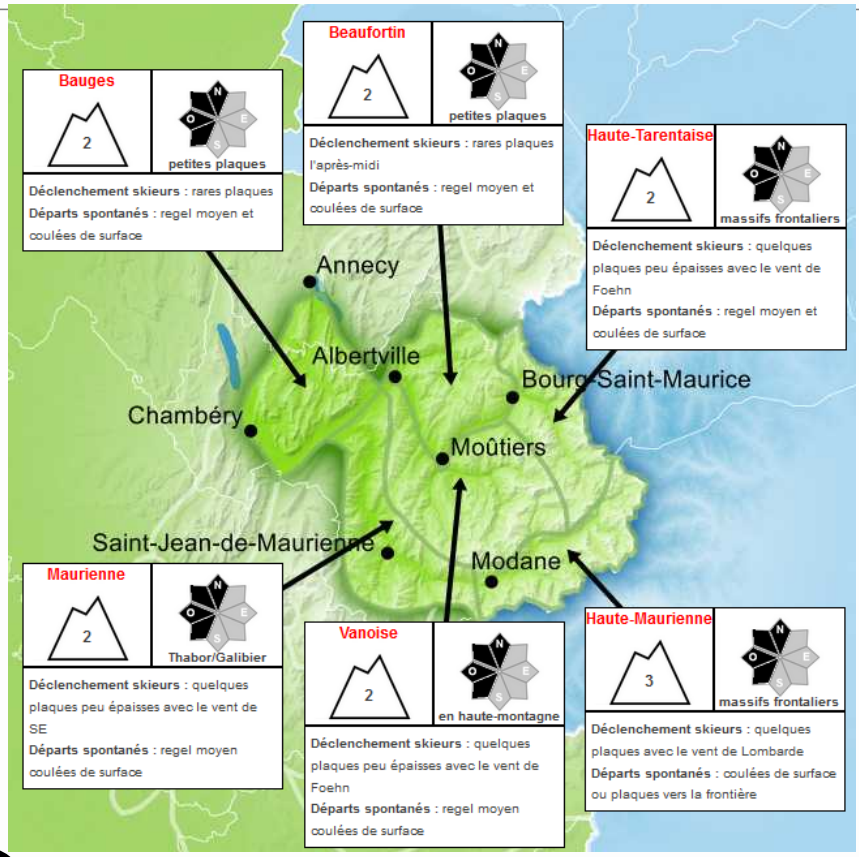
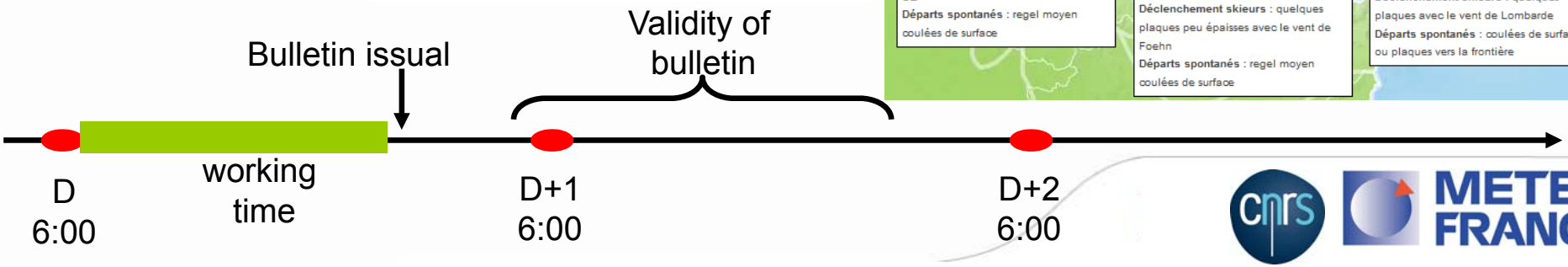
Avalanche bulletins in France

- Provided for « massifs », typical scale 1000 km^2
- Issued every day around 16:00 local time, valid for coming day







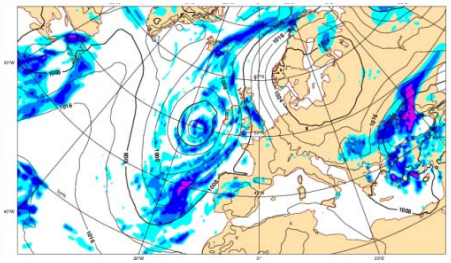
Avalanche bulletins in France

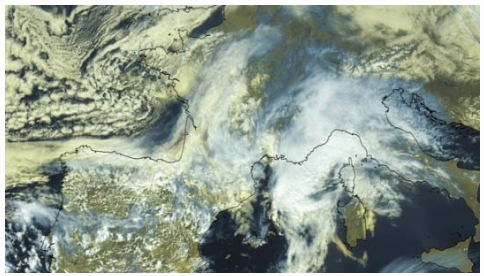
- Things that matter :
  - Meteorological observations
  - Meteorological forecasts from Numerical Weather Prediction models
  - Snowpack observations (profiles, avalanche activity, etc)
  - Snowpack modelling (driven by past and future meteorological conditions)

Meteorological analysis and forecast : full model chain

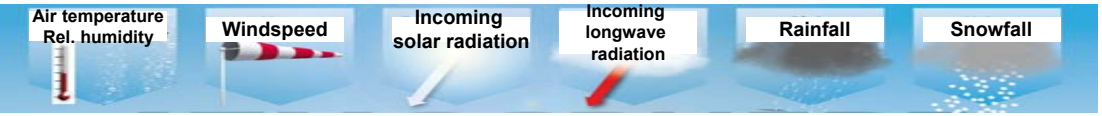
- Modelling chain SAFRAN – SURFEX/ISBA-Crocus – MEPRA (S2M)

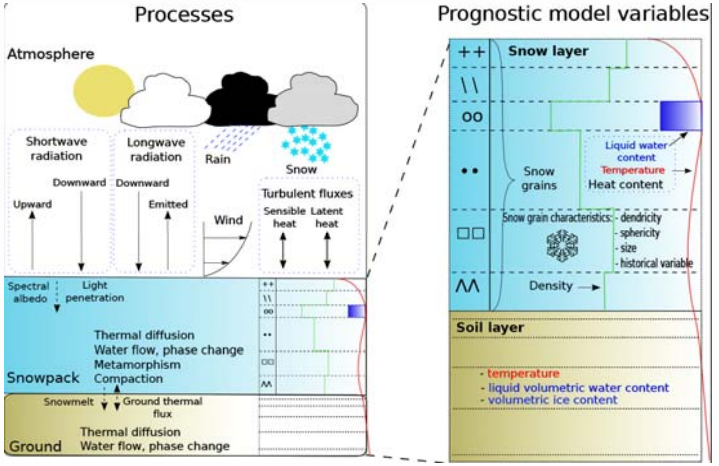
Durand et al, 1992, 1999
Vionnet et al, 2012
Lafaysse et al, 2013



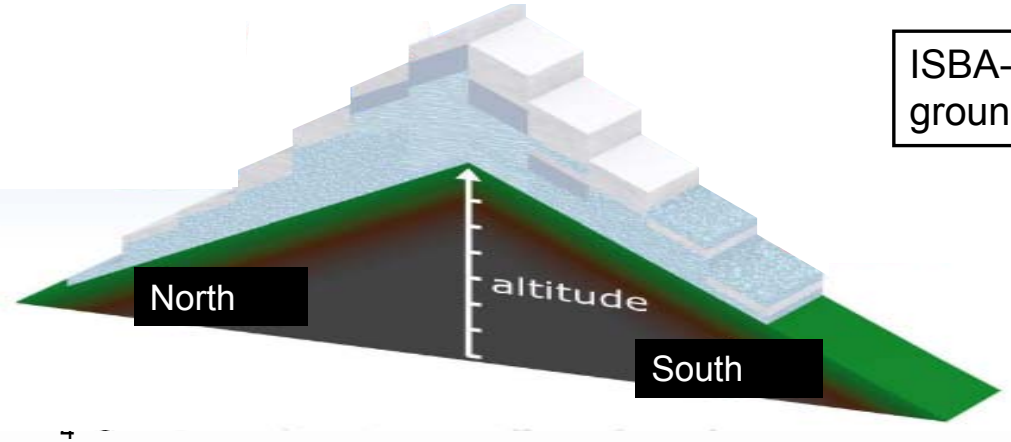


SAFRAN : analysis and forecast at the « massif » scale



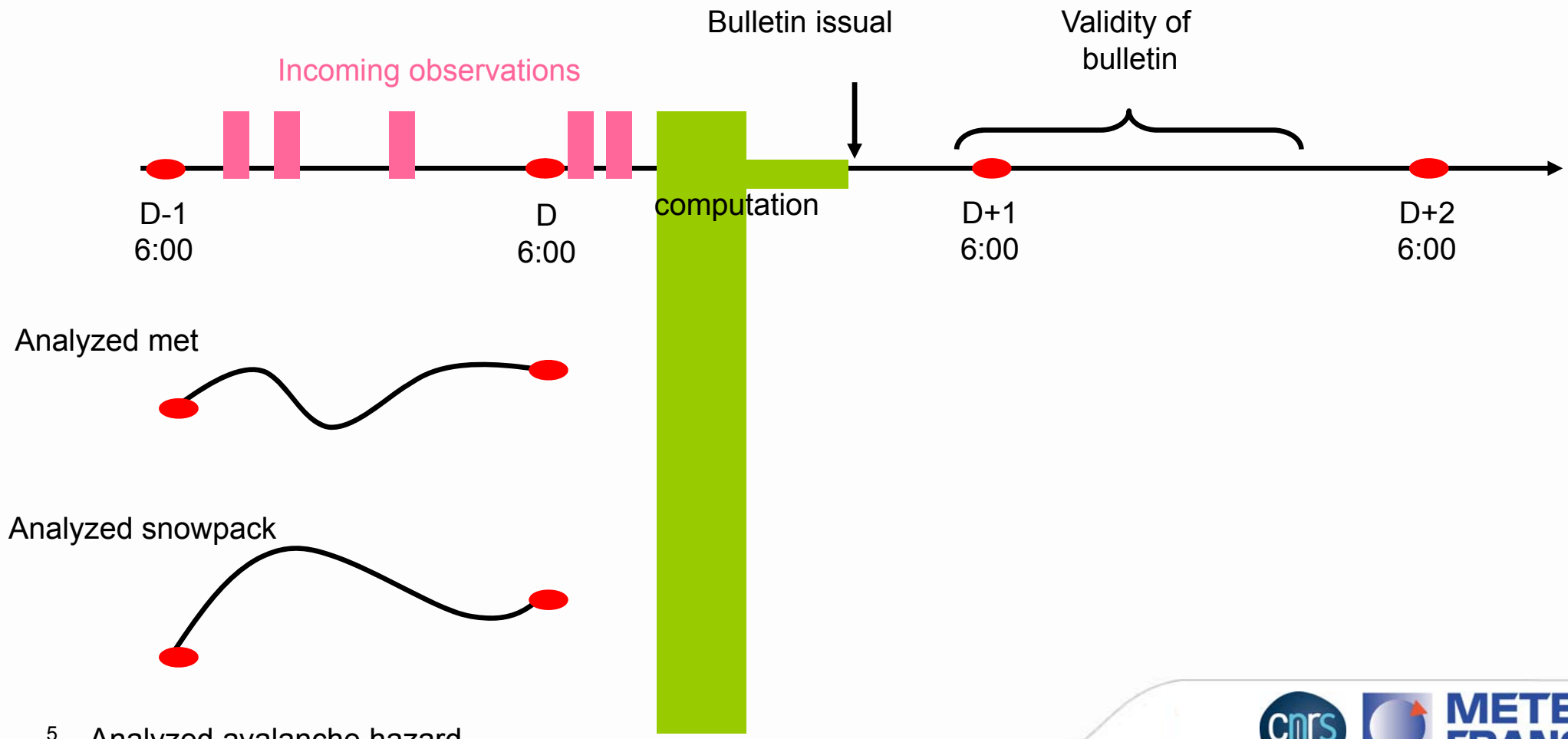


ISBA-Crocus : coupled ground/snowpack model



MEPRA : expert system analyzing Crocus output in terms of spontaneous and artificial avalanche hazard : provides massif scale hazard level (from 0 to 8)

Current operations : deterministic meterological forecast



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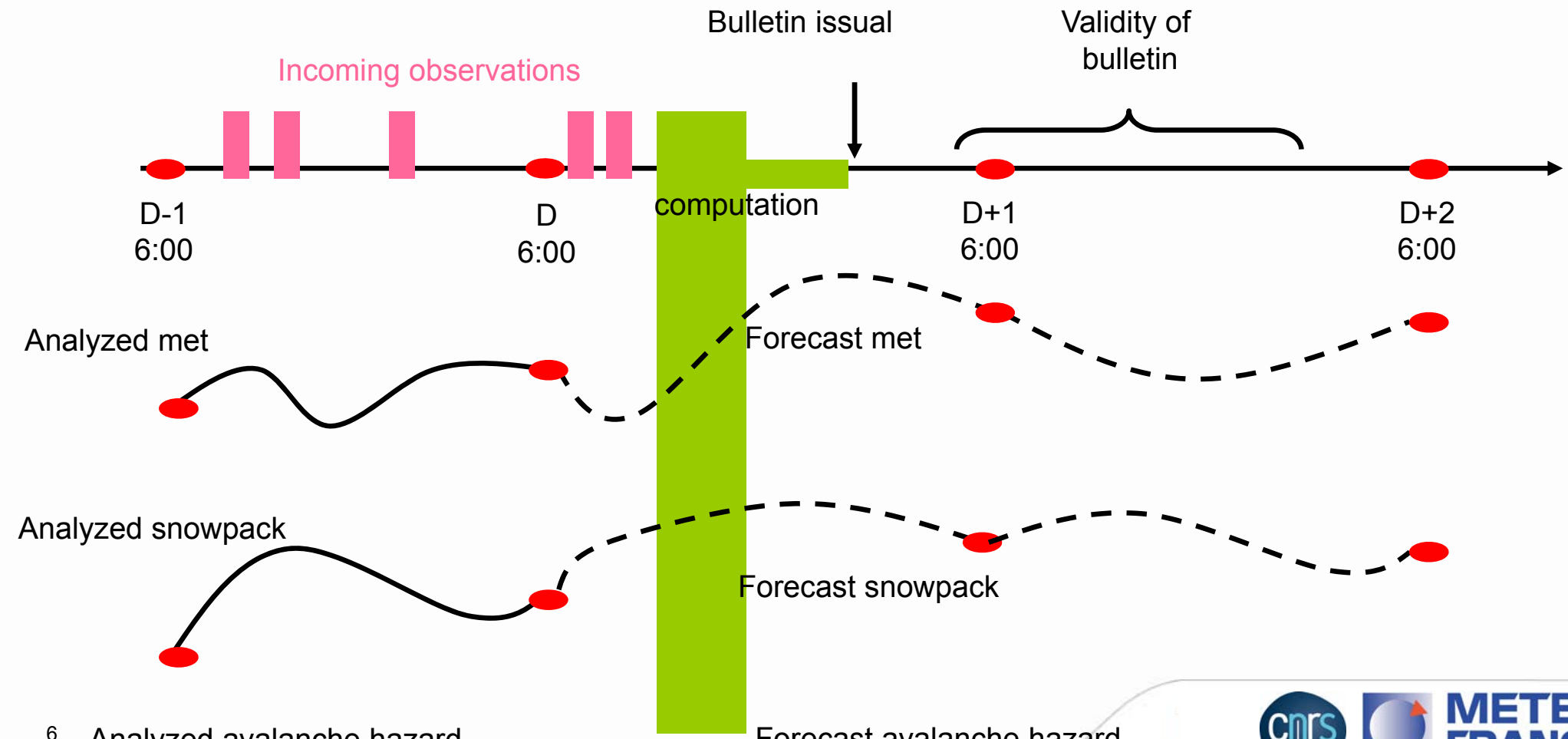

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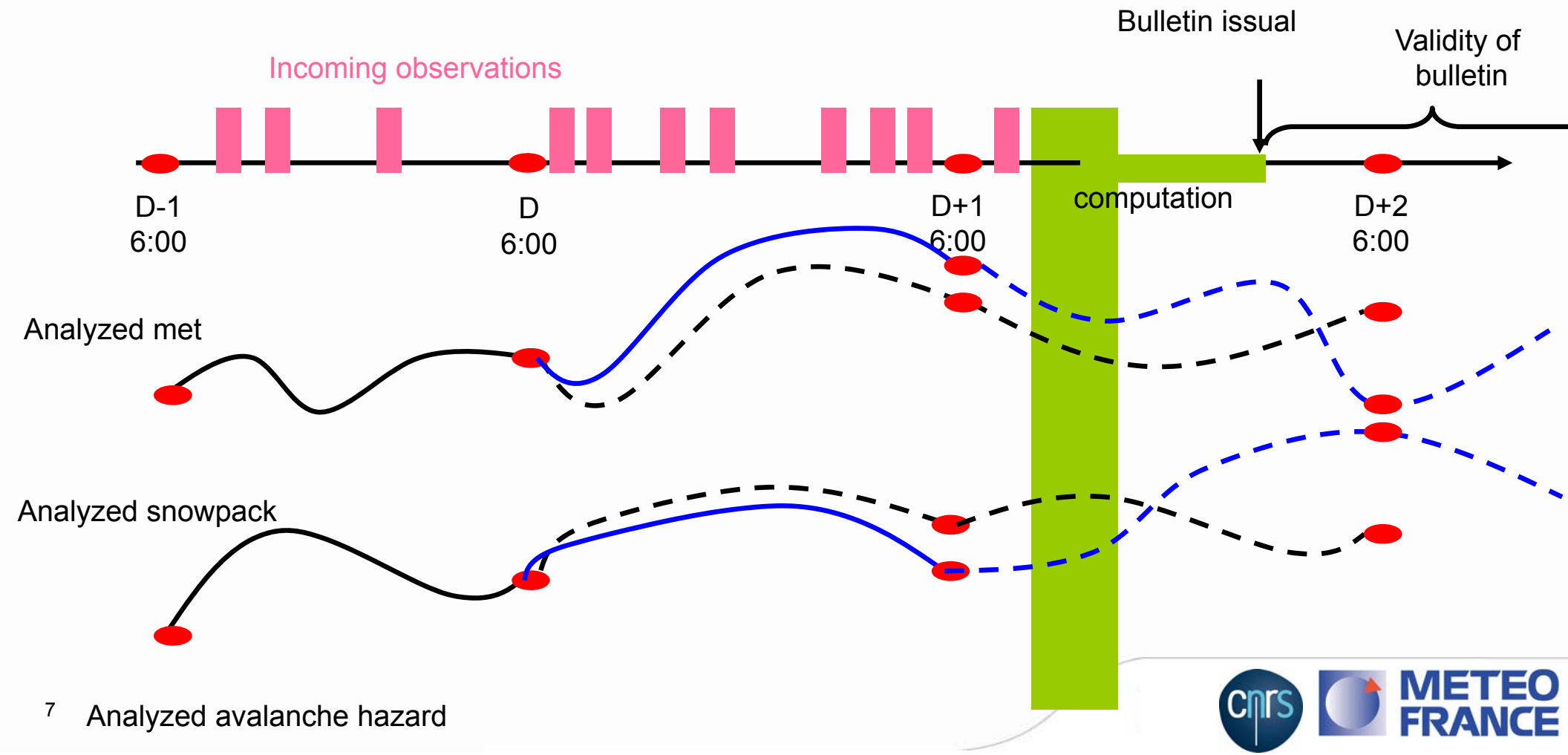
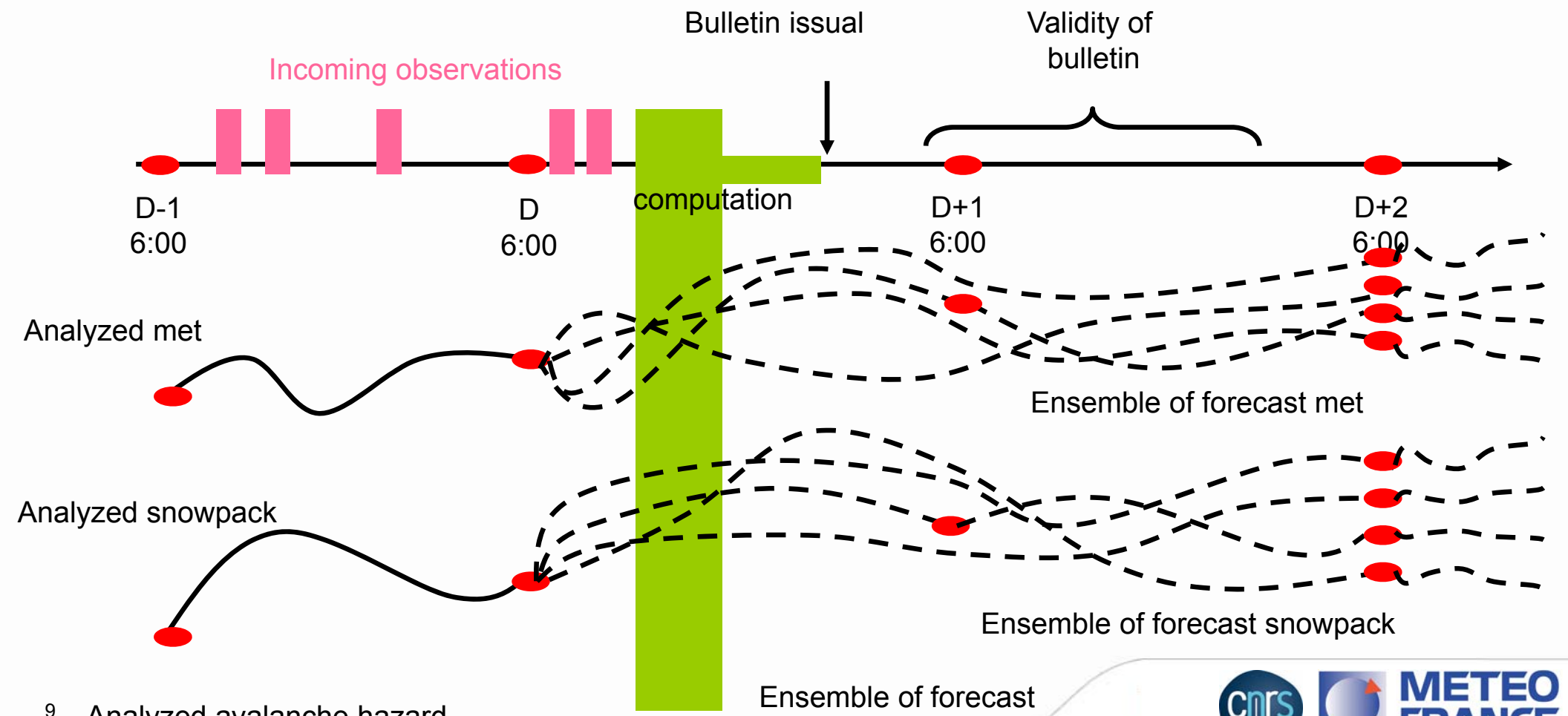


Current operations : deterministic meterological forecast

- The analysis system avoids the accumulation of forecast errors through the snow season
- Using one single deterministic meteorological forecast is a problem because:
  - Synoptic scale **forecast errors** occur and cannot be accounted for
  - Strong **non-linearities** of snowpack evolution weaken the robustness of the forecast system (rain/snow limit, precipitation amounts thresholds etc.)
  - It has limited the forecast lead time to about **2 days** hitherto

Principles of ensemble forecast



Implementation of ensemble forecast with S2M

Need a synoptic scale ensemble forecast:

ARPEGE Ensemble Prediction (PEARP from Météo-France, *Descamps et al, 2014*)

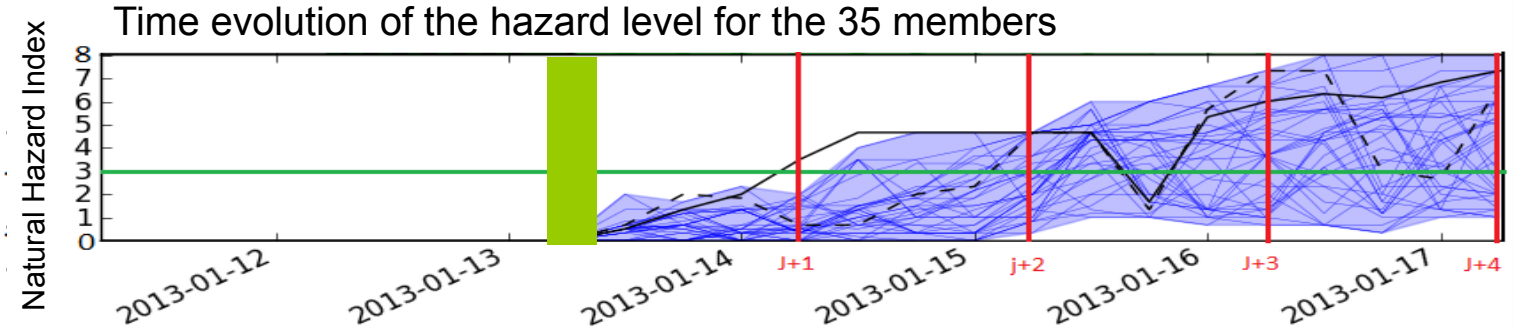
→ Synoptic scale uncertainty

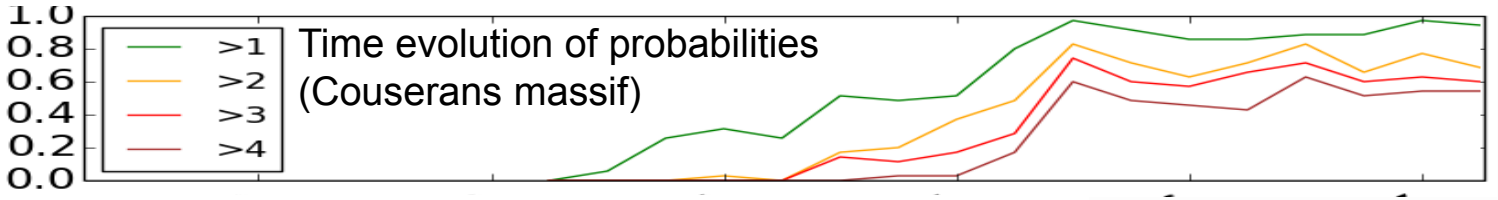
→ **35 runs** from 35 initial states + 10 physical configurations of ARPEGE

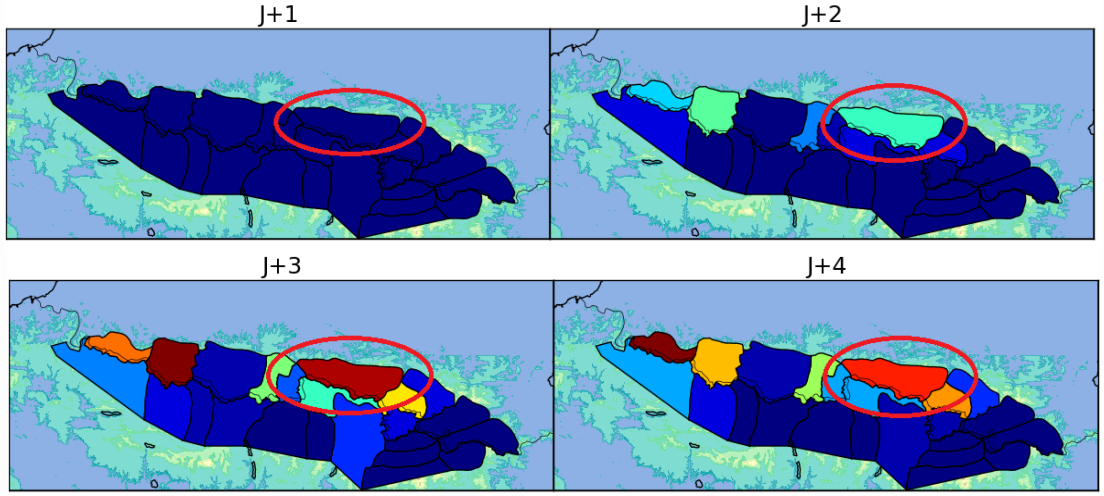
→ Extension of forecast lead-time to **4 days**

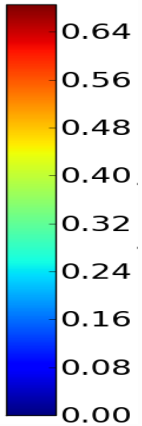
ARPEGE – SAFRAN – SURFEX/ISBA-Crocus – MEPRA	Deterministic
PEARP – SAFRAN – SURFEX/ISBA-Crocus - MEPRA	Ensemble

What do we get ? Examples from the Pyrenees









Analysis

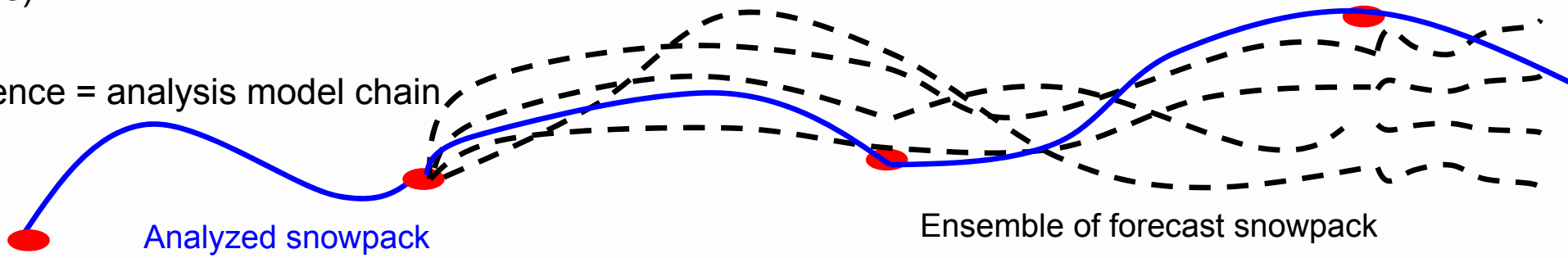
Deterministic forecast

Forecast initialized on 13 January 2013 6:00 for the next four days

Probability to exceed a threshold of 3 on a scale from 1 to 8

Evaluation method : overview

- Time period : from 1st november 2013 to 28 February 2014 (2760 forecasts spanning all Alpine massifs)
- Reference = analysis model chain



- Evaluated variables :
  - Height of 24 hours new snow at 1800 m altitude on flat field: HN24
  - Massif-level natural hazard level : NHI
- Use of deterministic and probabilistic scores
  - Brier Score $BS = \frac{1}{N}\sum_{k=1}^{N}(y_k - o_k)^2$ (score about exceedance threshold event, mix **reliability** and **resolution**)
  - Brier Skill Score $BSS = 1 - \frac{BS}{BS_{ref}}$ Reference: deterministic system

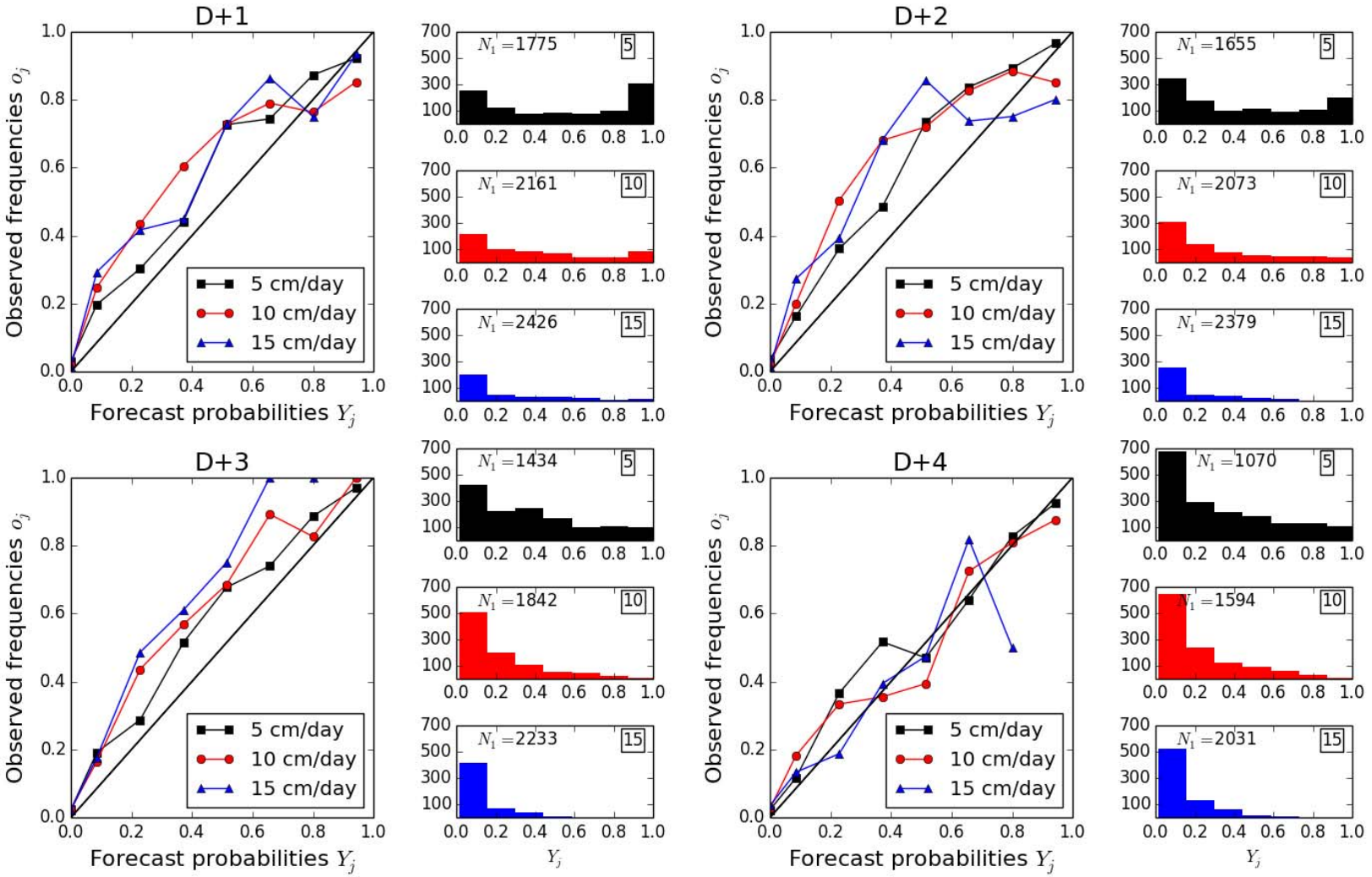
Overview of results

Scores for HN24 forecast for exceedance of 10 cm threshold over all French Alps

Scores	D+1	D+2	D+3	D+4
RMS (cm)	4.0	4.2	4.9	5.1
Dispersion (cm)	1.9	2.2	2.6	3.3
Brier Score	0.07	0.07	0.08	0.09
Reliability	0.01	0.01	0.01	0.01
Accuracy	0.06	0.06	0.04	0.03
Uncertainty	0.12	0.12	0.12	0.12
BSS	0.21	0.25	0.24	0.24

- Dispersion < RMS → Under dispersive system
- Low BS → Good intrinsic performance of the ensemble forecast system
- Low value for reliability : reliable forecast of probability of exceedance
- > 0 BSS (wrt deterministic system) : better than deterministic system

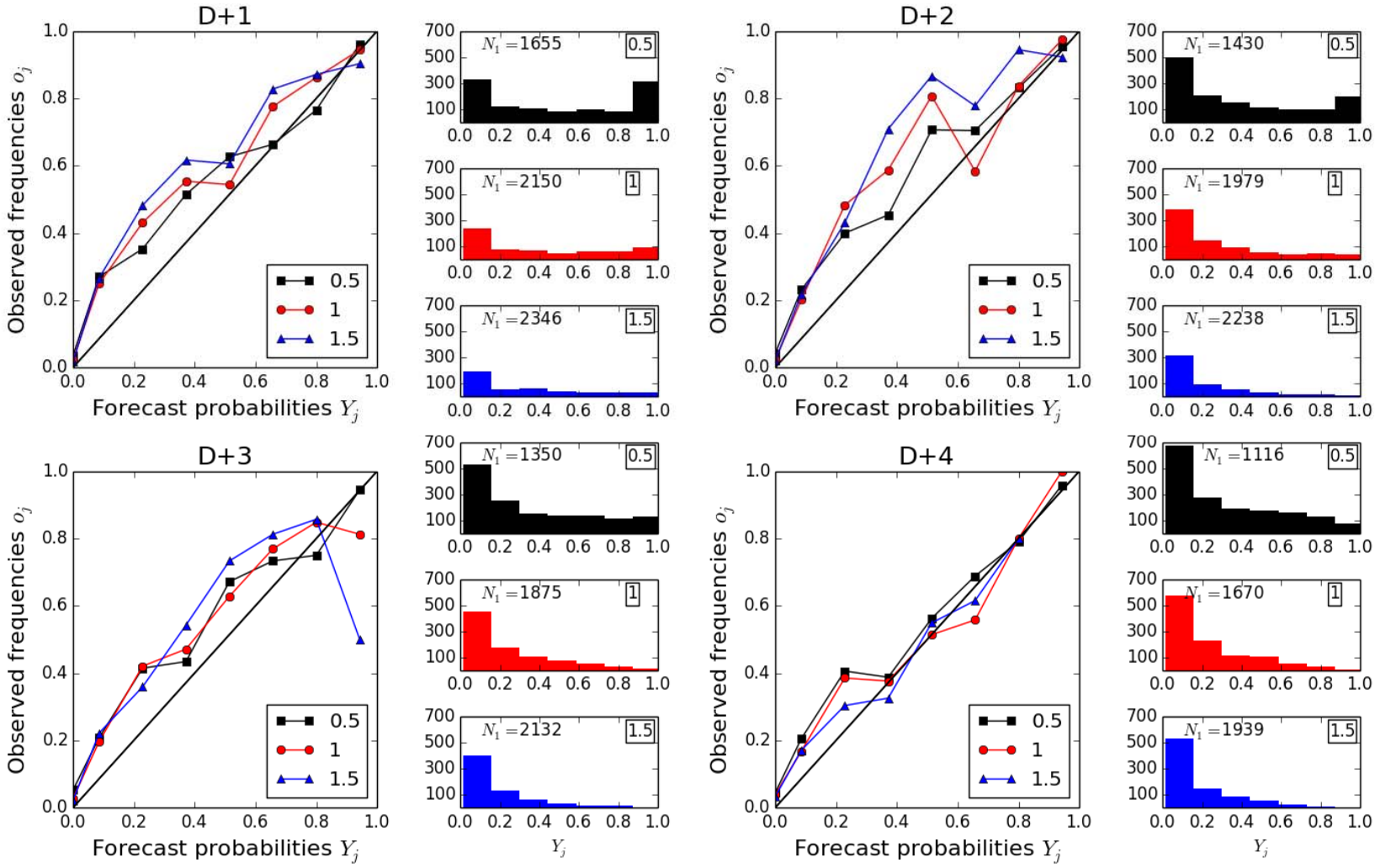
Results : reliability diagrams for HN24



Diagonal = perfect reliability

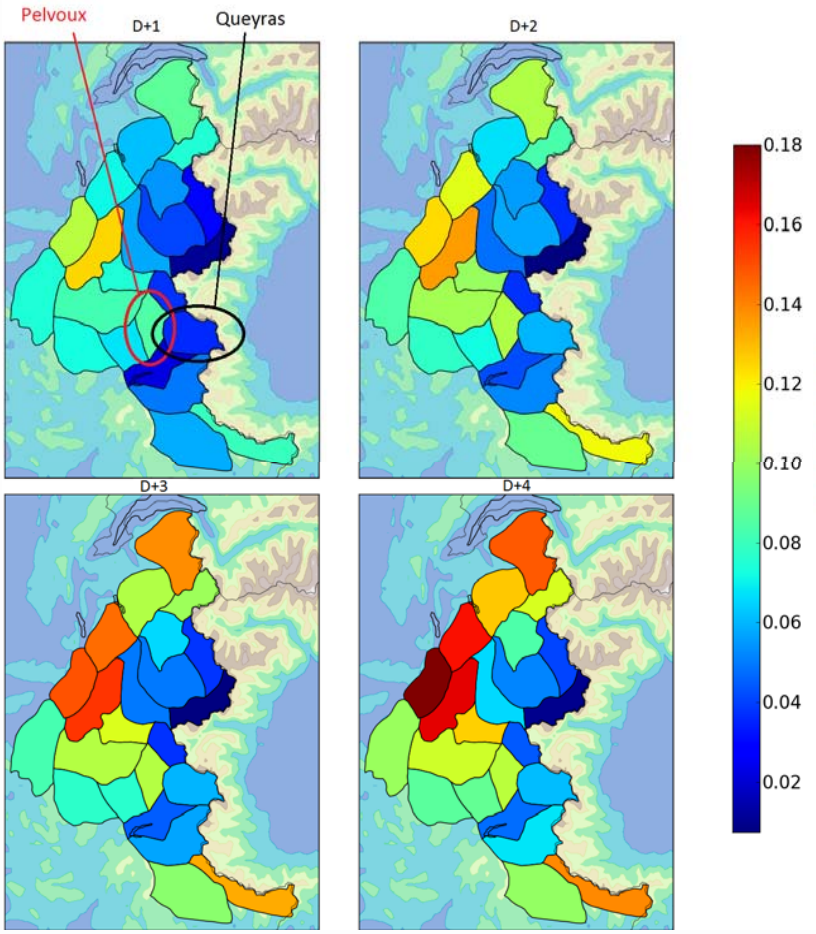
Reliability remains amazingly good even for 4 days lead time

Results : reliability diagrams for NHI

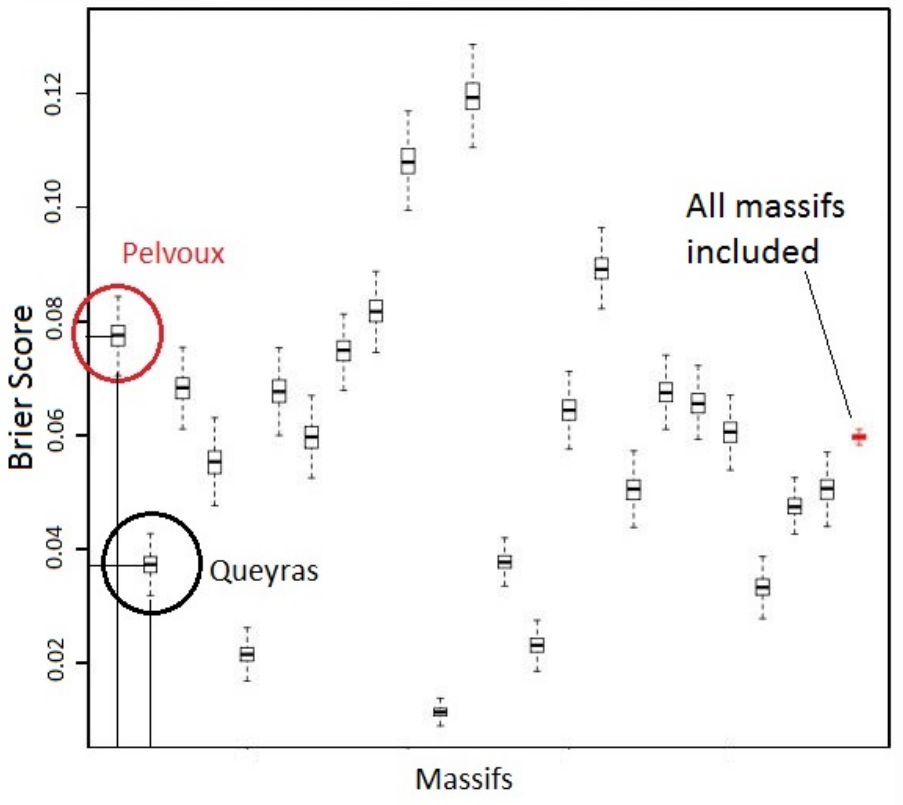


Similar results for Natural Hazard Index

Massif-scale evaluation



Brier Score for Natural Hazard Index (threshold 1)



*Uncertainty of score assessed by a **Bootstrap** method*

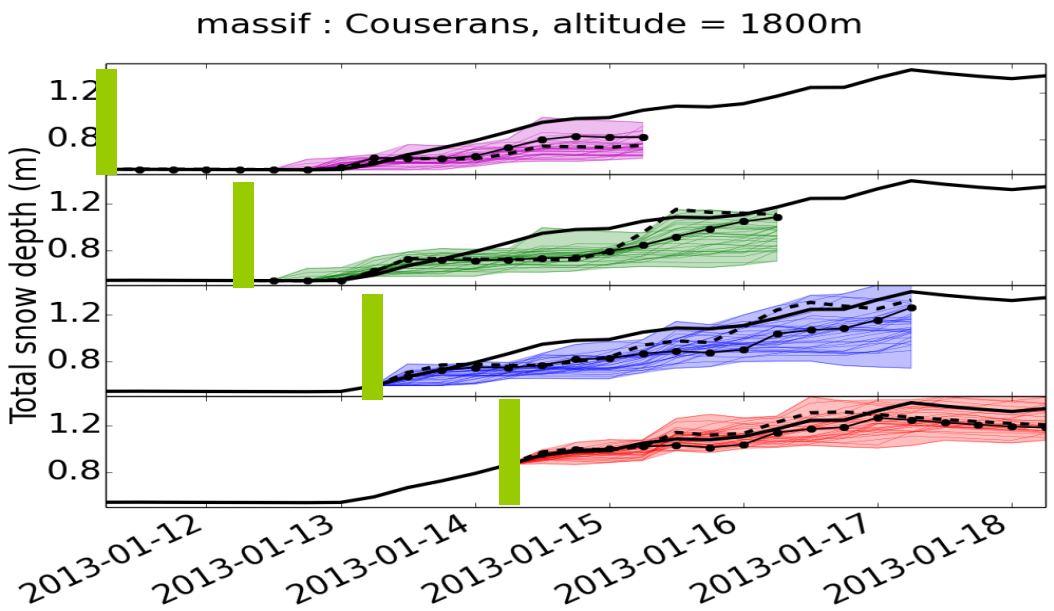
→ Scores less robust at the massif scale but the spatial pattern is significant.

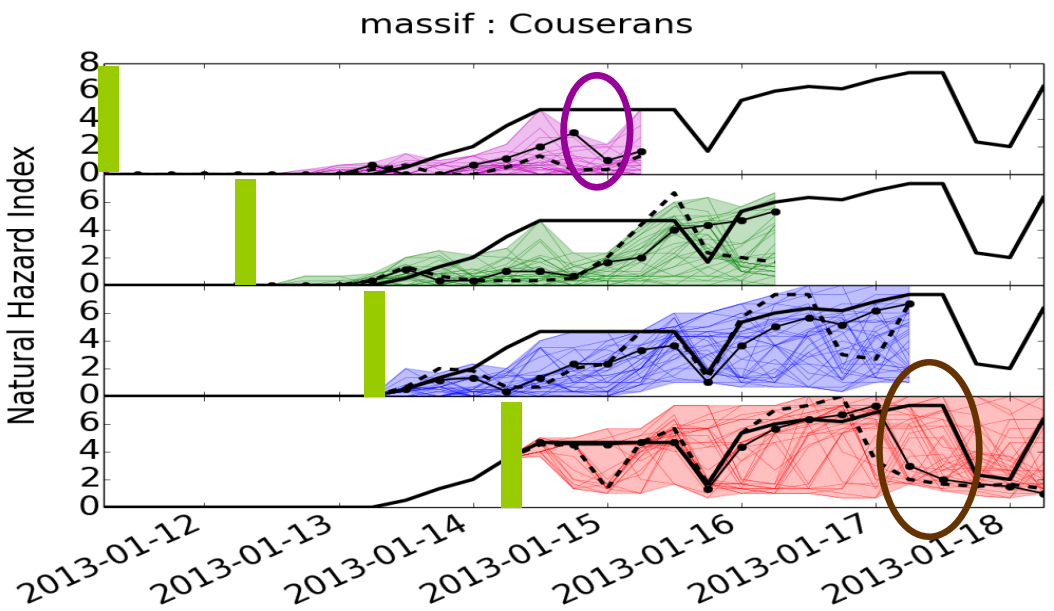
→ Linked to the specifities of the 2013-2014 season

Case studies in the Pyrenees

- Critical avalanche situation in mi-January 2013 in the Pyrenees

S2M Analysis — Deterministic forecast ARPEGE-S2M — 35 members PEARP-S2M — control run



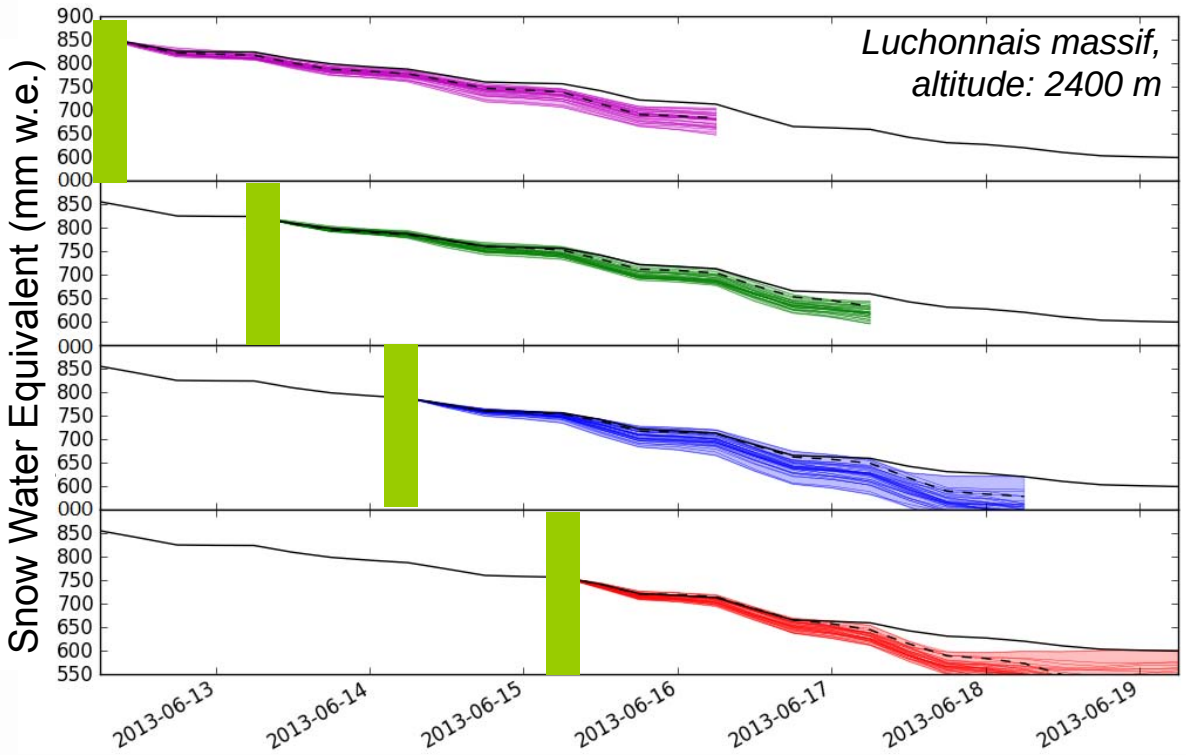


→ Analysis sometimes outside the ensemble (underdispersion)

→ Added-value of the ensemble system over the sole deterministic forecast

Case studies in the Pyrenees

- Critical snowmelt event in June 2013
- Forecast system not (yet) coupled to hydrological forecast system
- 4 days forecast of snow water equivalent ; low dispersion of ensemble



Conclusions

- For the height of 24h new snow and Natural Hazard Index, the ensemble system **objectively outperforms** the deterministic forecast system.
- System appears **reliable** with lead times of **4 days** (= correct probabilities)
- **Under-dispersion** (consequence of under-dispersion of several meteorological variables at this scale)
- Spatial pattern of scores but massif-scale evaluations limited by the number of data.
- Experimental chain **available in real-time** since February 2015 → to be fully used during next winter by forecasters

Future work

- Evaluations must be extended to longer time period :
  To reduce the influence of sampling ; to study high-impact thresholds ; to calibrate unbiasing methods
- Synthetic diagnostics for forecasters must be extended
- Other uncertainties should be accounted for:
  Snow model uncertainty (multi-physics) ; Meterological analysis uncertainty (ensemble analysis)
- Other ensemble methods can be considered :
  - High resolution ensemble modelling
- Application for hydrological forecasting

Vernay M, Lafaysse M, Mérindol L, Giraud G and Morin S, Ensemble forecasting of snowpack conditions and avalanche hazard, *Cold Reg Sci Technol* (2015), http://dx.doi.org/10.1016/j.coldregions.2015.04.010

Thank you for your attention !