Forecasting and modelling ice layer formation on the snowpack due to freezing precipitation in the Pyrenees

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Freezing precipitation on the snowpack

- **Supercooled precipitation** forming a **pure ice layer** on the snowpack
- Reported at least once every winter in the Pyrenees

Major event: 5 January 2012 in the Pyrenees

- A thick ice layer, locally >5 cm
- Widespread in most of the massifs
- On surface during more than 2 weeks
- 9 fatalities, numerous accidents

Current operational sytems used by mountain forecasters are unable to predict it

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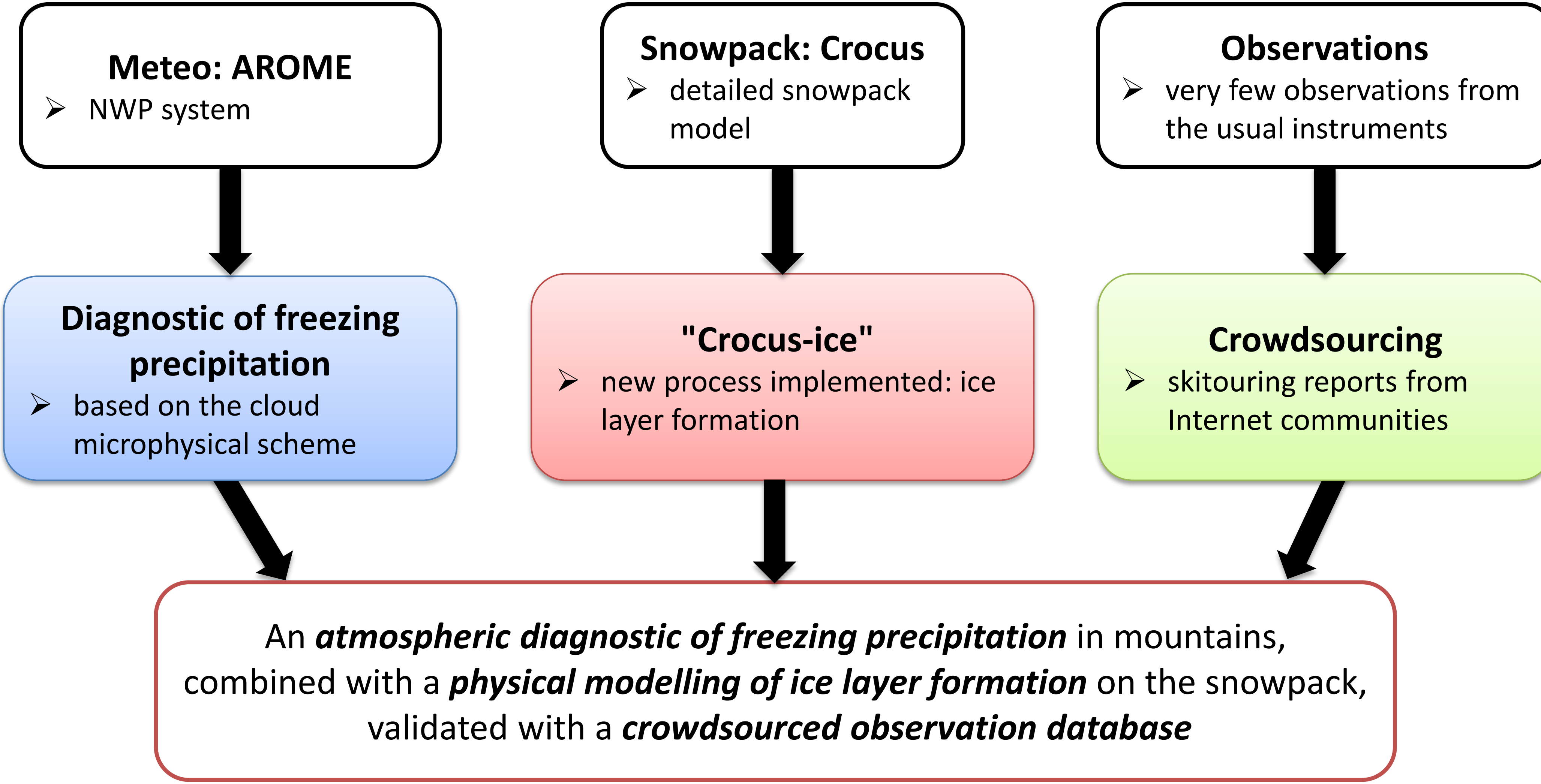
How to forecast and model ice layer formation due to freezing precipitation?



VISIT PICO A.12 !

2-min introduction

Contact

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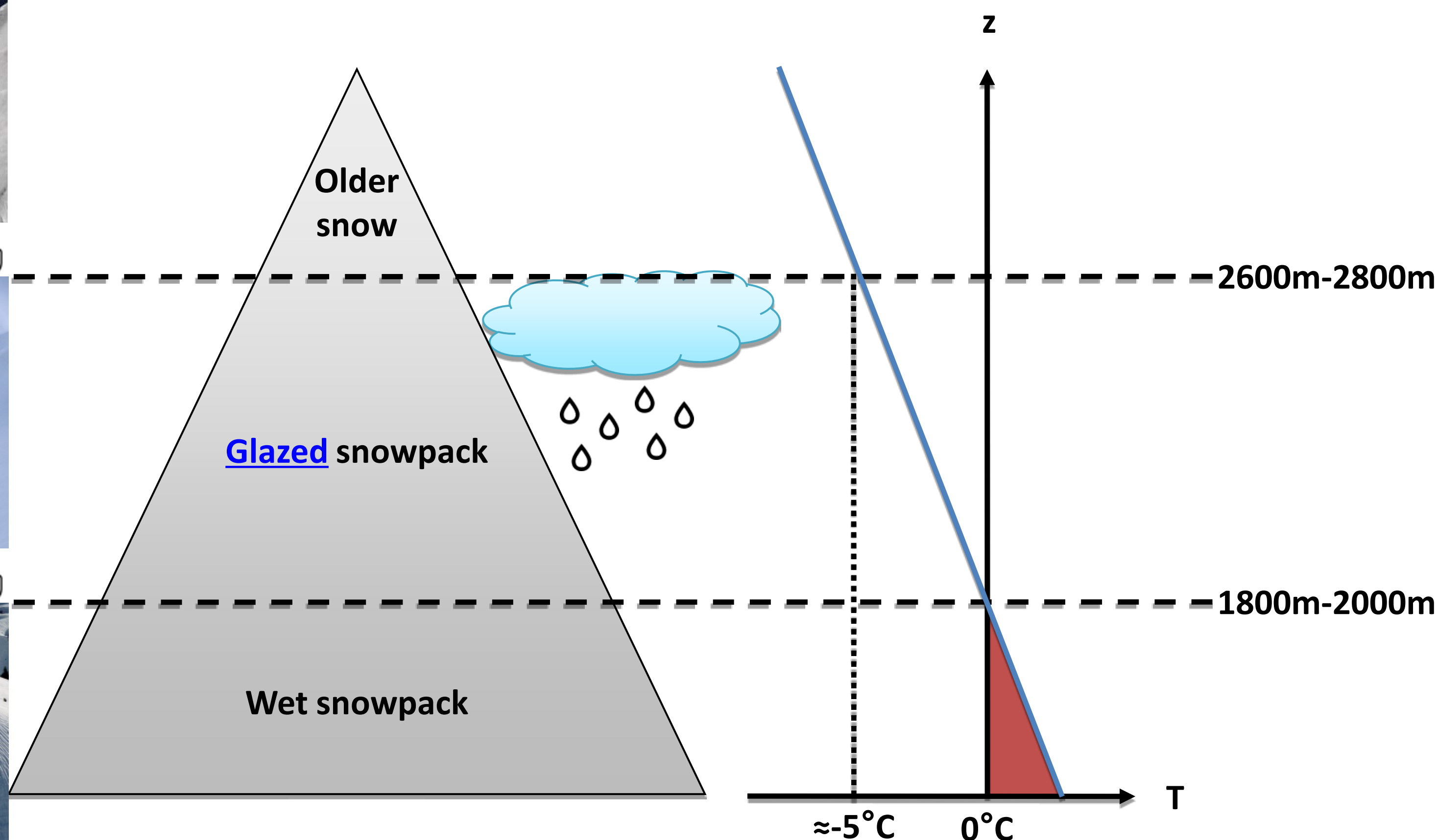
1. A poorly predicted phenomenon with high impacts

1.1 Description of the phenomenon



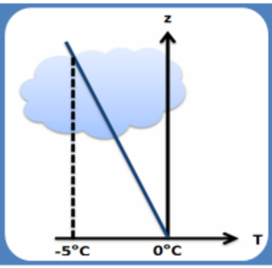
Example of the vertical profile of 5 January 2012

« Warm rain » process, different from the usual freezing rain profile

1.2 Meteorological context

Warm front

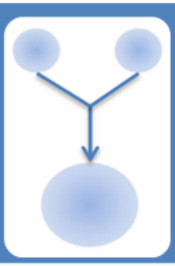
In N/NW flux with orographic blocking



Top of cloud temperature between **-5°C and -10°C**

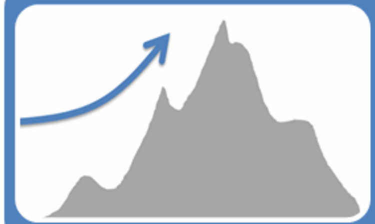
Negative temperature profile

- Water droplets stay supercooled



Few freezing nuclei

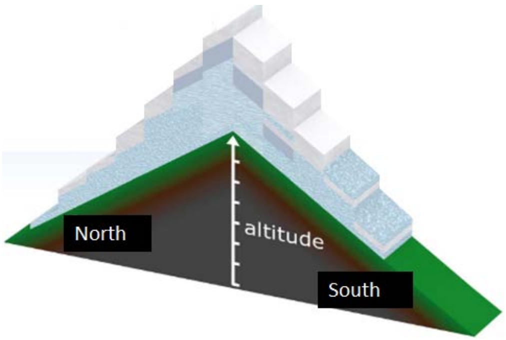
- Oceanic origin of the air in the Pyrenees ?
- Collision-coalescence process



Strong winds

- Significant precipitations

1.3 Limitations of the current operational systems

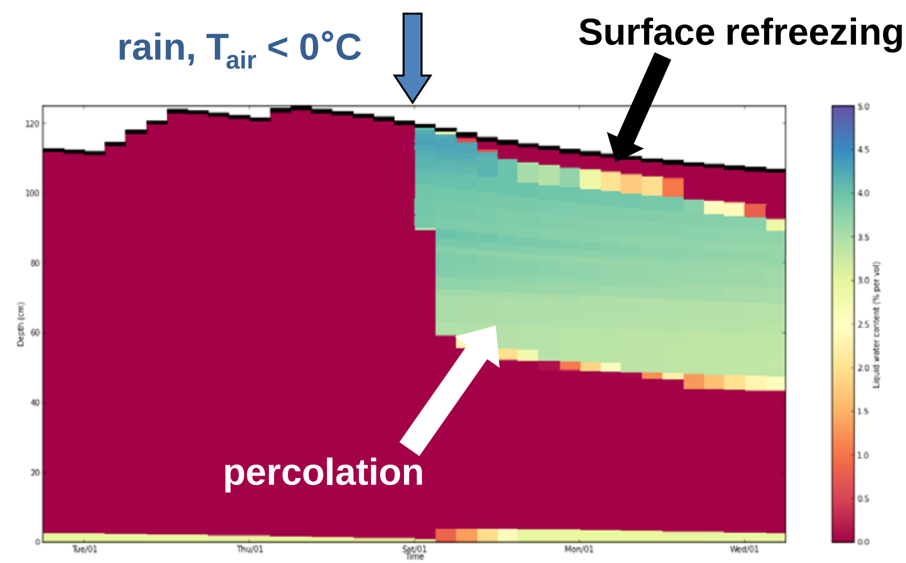


Meteorological analysis system : **SAFRAN**
[Durand et al., 1993]

Detailed snowpack model **Crocus**
[Vionnet et al., 2012]

- Threshold of **+1°C** for snow/rain limit
  - ➢ No freezing precipitation
- SAFRAN-Crocus analysis on 5 January 2012: ≈25cm of **dry snow** instead of the ice layer (Hte-Bigorre, 2400m)

- Does not handle supercooled precipitation
- Water percolation in the snowpack



Liquid water content, Crocus simulation

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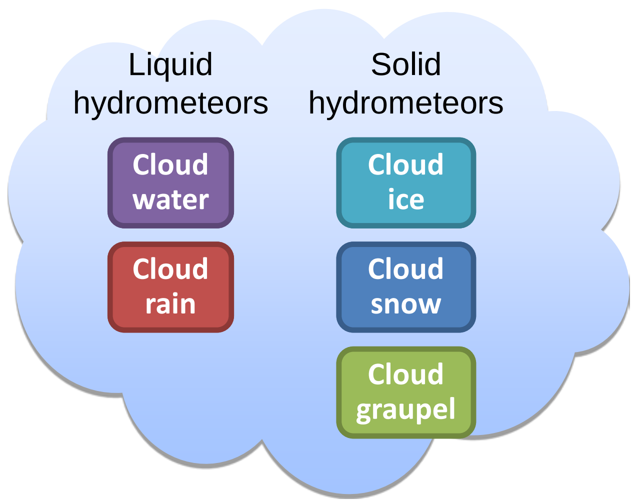
2. Data and models

2.1 NWP system AROME and Crocus snowpack model

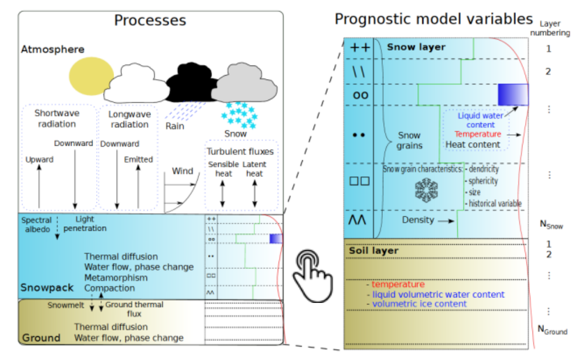
AROME: Météo-France NWP system

- Grid spacing: 2.5 km (1.3 km since 2015)
- Benefits for snowpack modelling:
  - Intra-massif variability
  - Finer meteorological forcing
  - (Quéno et al., TC, 2016), (Vionnet et al., JHM, 2016)

- Information from AROME cloud microphysics sheme: hydrometeors mixing ratio



Crocus:
detailed snowpack model
(Vionnet et al., 2012)



What possible benefits of using AROME associated with Crocus to forecast such events ?

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2.2 Observation database built on crowdsourcing

- No observation from usual instruments (except anemometers jammed by accreting ice)
- Human observations in ski resorts are generally at lower altitudes
- **Crowdsourcing**: a lot of information in skitouring and mountaineering reports

« giant ice rink »

« mirror »

« glazed snow »

« crampons are necessary »

« the mountain looks shiny »

Author: regis65, licence CC-by-nc-nd
www.camptocamp.org/outings/315614/fr/puig-de-lanos-depuis-le-col-du-puymorens

Pictures in reports help to confirm

- A new ice layer observation database built up, based on **skitouring reports** from the Camptocamp community website (www.camptocamp.org)
- Selection with **key words** (ice/icy/glaze/glassy in French)
- Wide spatial and altitudinal coverage
- **Limitations**: subjective reports, not exhaustive

3. New methods developped

3.1 Freezing precipitation diagnostic with AROME

Test case: 5 January 2012

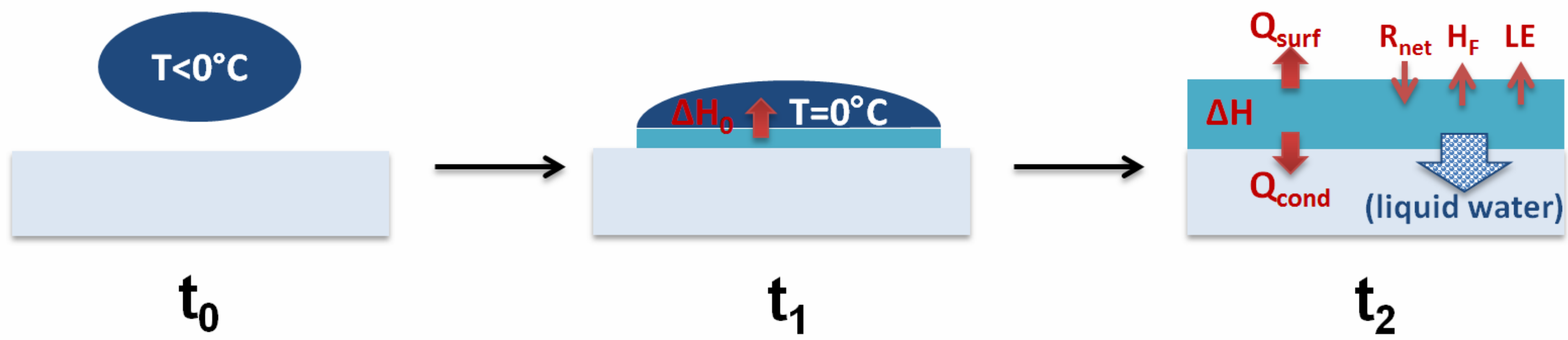
No freezing precipitation forecast

A signal of high cloud water content

Hence, a diagnostic based on the cloud microphysics:

- [Rasmussen et al., J. Atm. Sci., 2002] : cloud water threshold of 0.35 g/kg for freezing drizzle onset
- A **simple diagnostic** of freezing precipitation
  - Liquid hydrometeors content (cloud water + cloud rain) at 100m > 0.4 g/kg
  - $T_{2m} < 0°C$
- To be compared with the **spatial distribution of observations of 5 January 2012**

3.2 Ice layer formation in Crocus-ice



t_1: metastable state broken at impact

- All the drop at 0°C
- Latent heat flux $\mathbf{\Delta H_0}$: instantaneous (<20ms) solidification of a proportion $\boldsymbol{\phi_s}$ (1,3% per « negative degree »)

t_2: remaining liquid water has time to spread (no air bubbles entrapped)

- Solving the energy budget $$\Delta H + (R_{net} - H_F - LE) - Q_{cond} = 0$$
- Freezing of the water
- Total or partial if « energy sinks » insufficient
- Percolation of unfrozen water

Implementation in "Crocus-ice"

- New ice layer
  - Density = 917 kg/m^3
  - Temperature = 0°C
  - Melt forms, max. diameter and sphericity
- Energy budget solved

4. Results

4.1 Evaluation of the diagnostic

Test case: 5 January 2012 with the simple diagnostic

Major event alert evaluated over 5 winters

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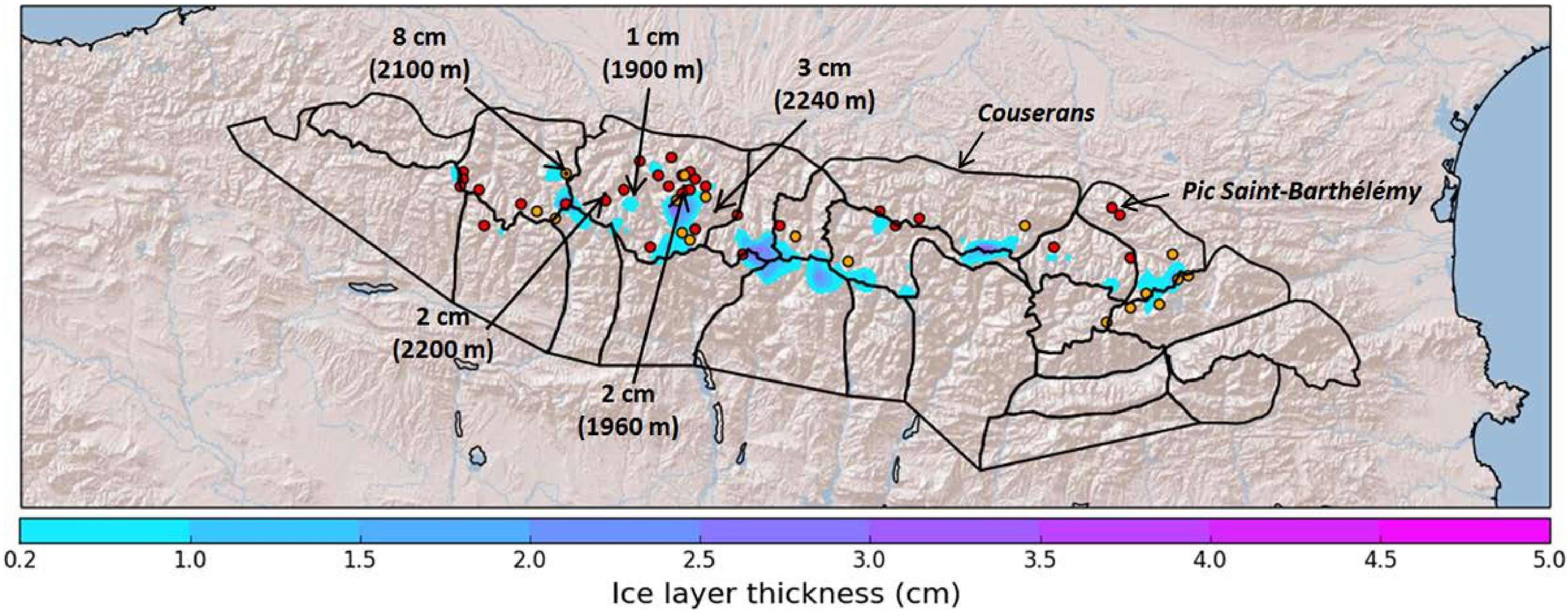
4.1 Evaluation of the diagnostic

Test case: 5 January 2012

- **Simple diagnostic**, with precipitation converted into equivalent ice thickness
- **Good agreement** of the predicted **spatial and altitudinal distribution** of ice to the observations (accidents in red, skitouring reports in orange)
- Ice thickness **underestimated**

altitude	
min	1825m
moy-std	2044m
moy	2237m
moy+std	2429m
max	2666m



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4.1 Evaluation of the diagnostic

Major event alert evaluated over five winters

- All diagnostics may not form an ice layer (low precipitation, surface energy budget…)
- Observation database: only major events
- When compared to the observation database, almost 4 times too many diagnostics with 0.4 g/kg threshold.
- Need for an **alert of major events** in the whole Pyrenees:
  - Liquid hydrometeors content at 100m **> 0.6 g/kg**
  - $T_{2m} < 0°C$
  - During at least 2 hours, on at least 6 points

(Thresholds validated through a sensitivity study)

	FORECAST	NOT FORECAST
OBSERVED	17	4
NOT OBSERVED	5	1035

Probability Of Detection = **81%**
False Alarm Ratio = **23%**

- In average 4 events/year
- Variable magnitude
- Satisfying scores for operational forecast

Temporal distribution of alerts and observations

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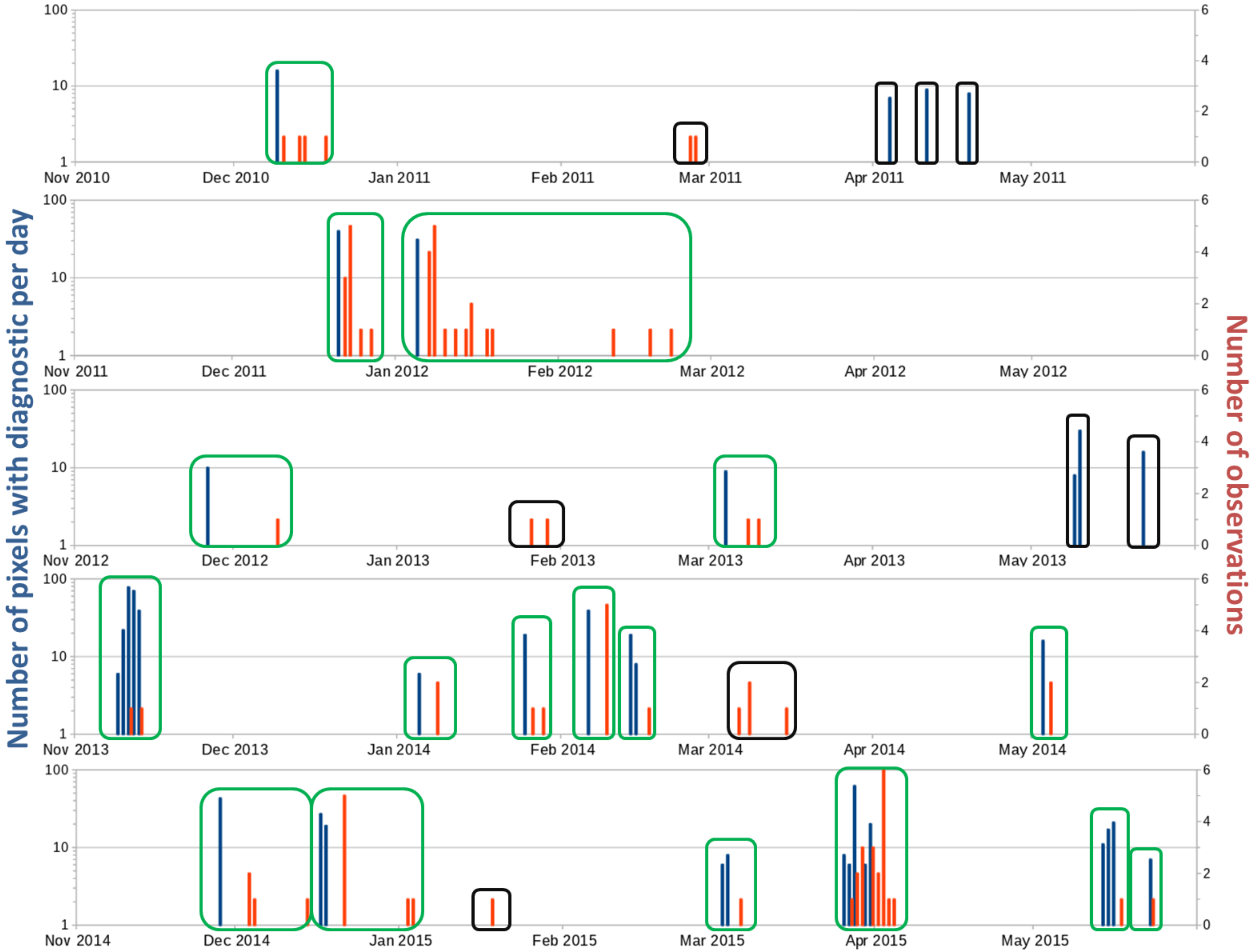
4.1 Evaluation of the diagnostic



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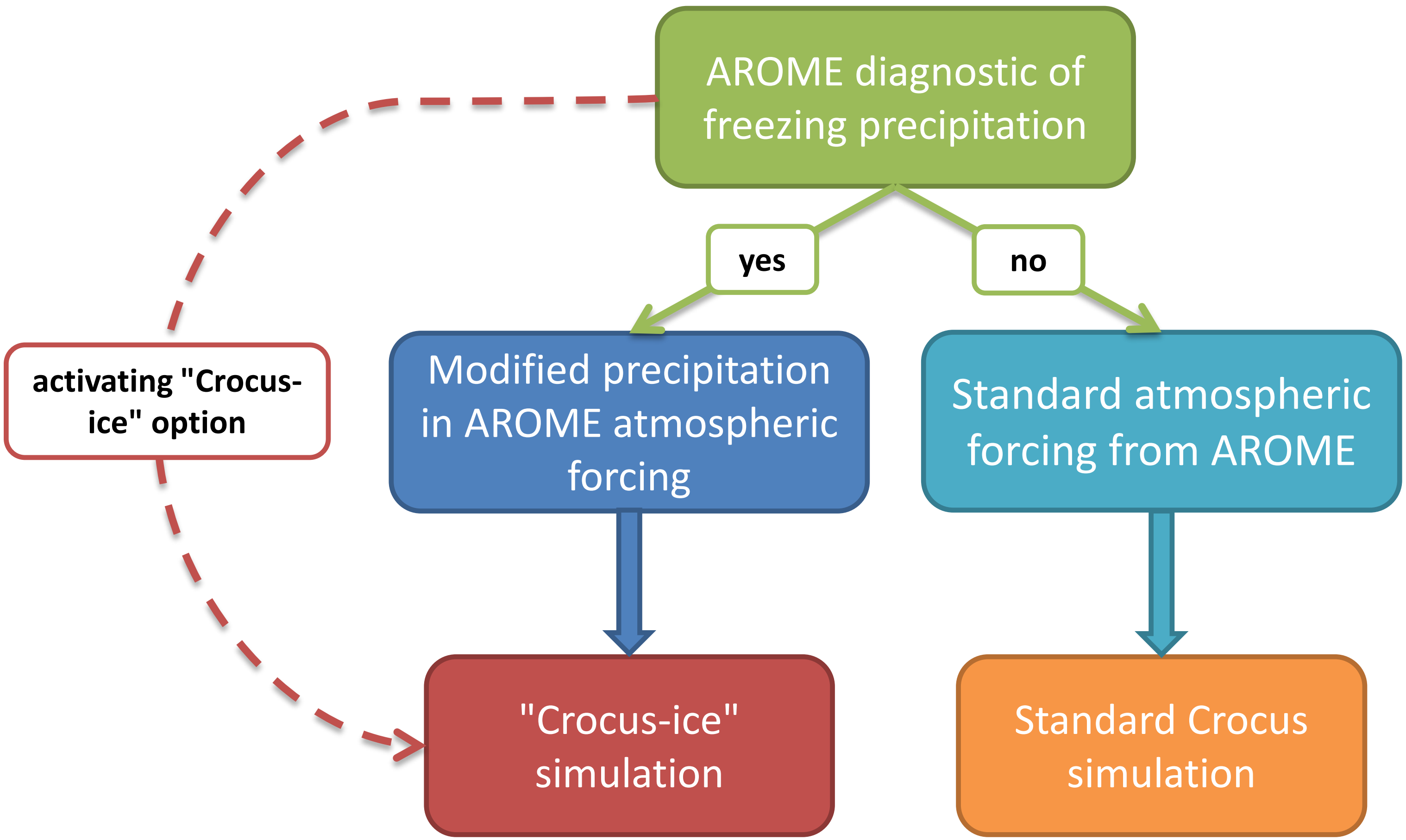
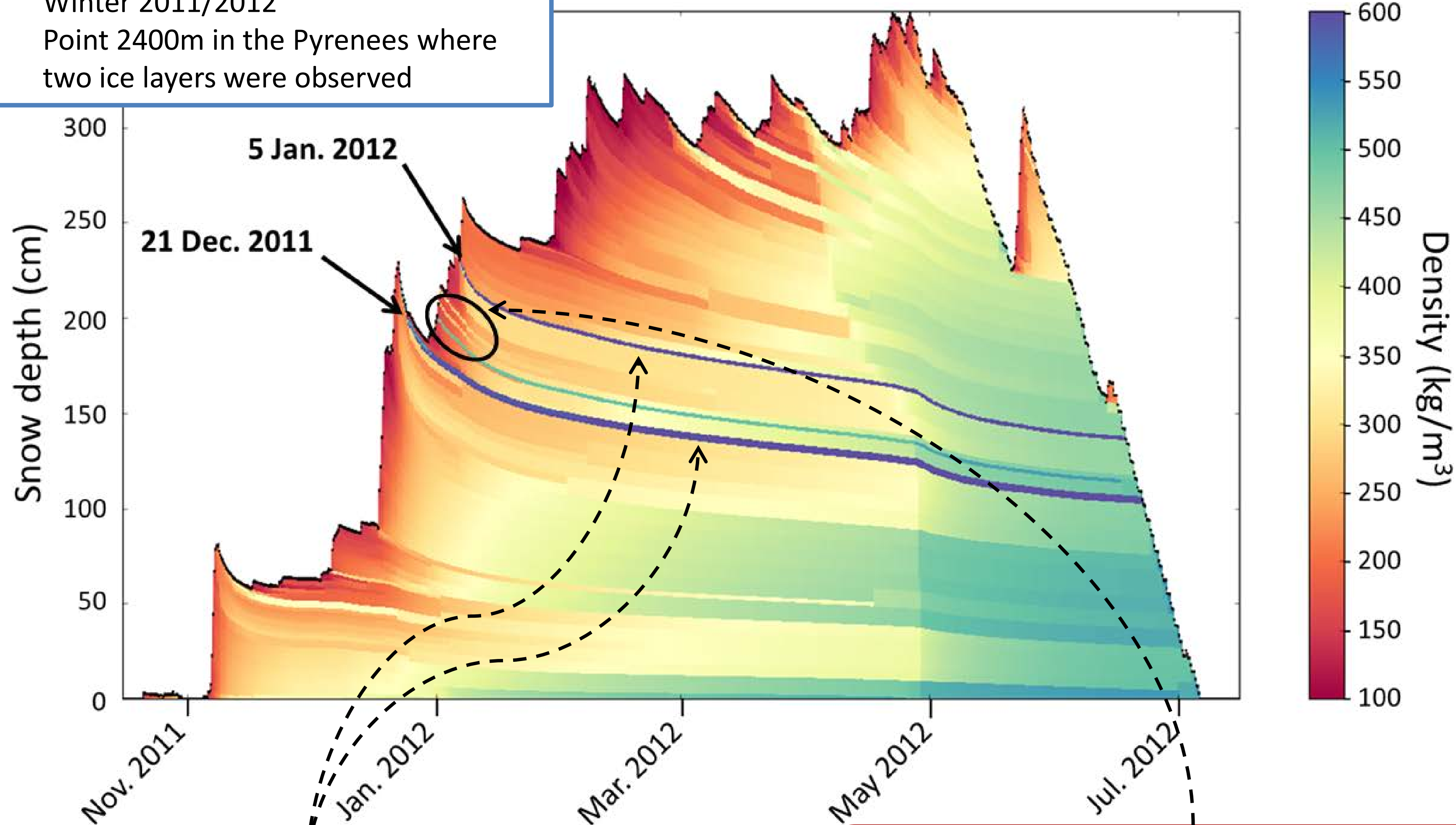
4.2 Study of the ice layer formation



See the resulting snowpack simulation

4.2 Study of the ice layer formation

- Winter 2011/2012
- Point 2400m in the Pyrenees where two ice layers were observed



- Good representation of the **two major ice layers** of the season

- Importance to take into account the surface energy budget in addition to the atmospheric diagnostic (formation of **lower density crusts**)

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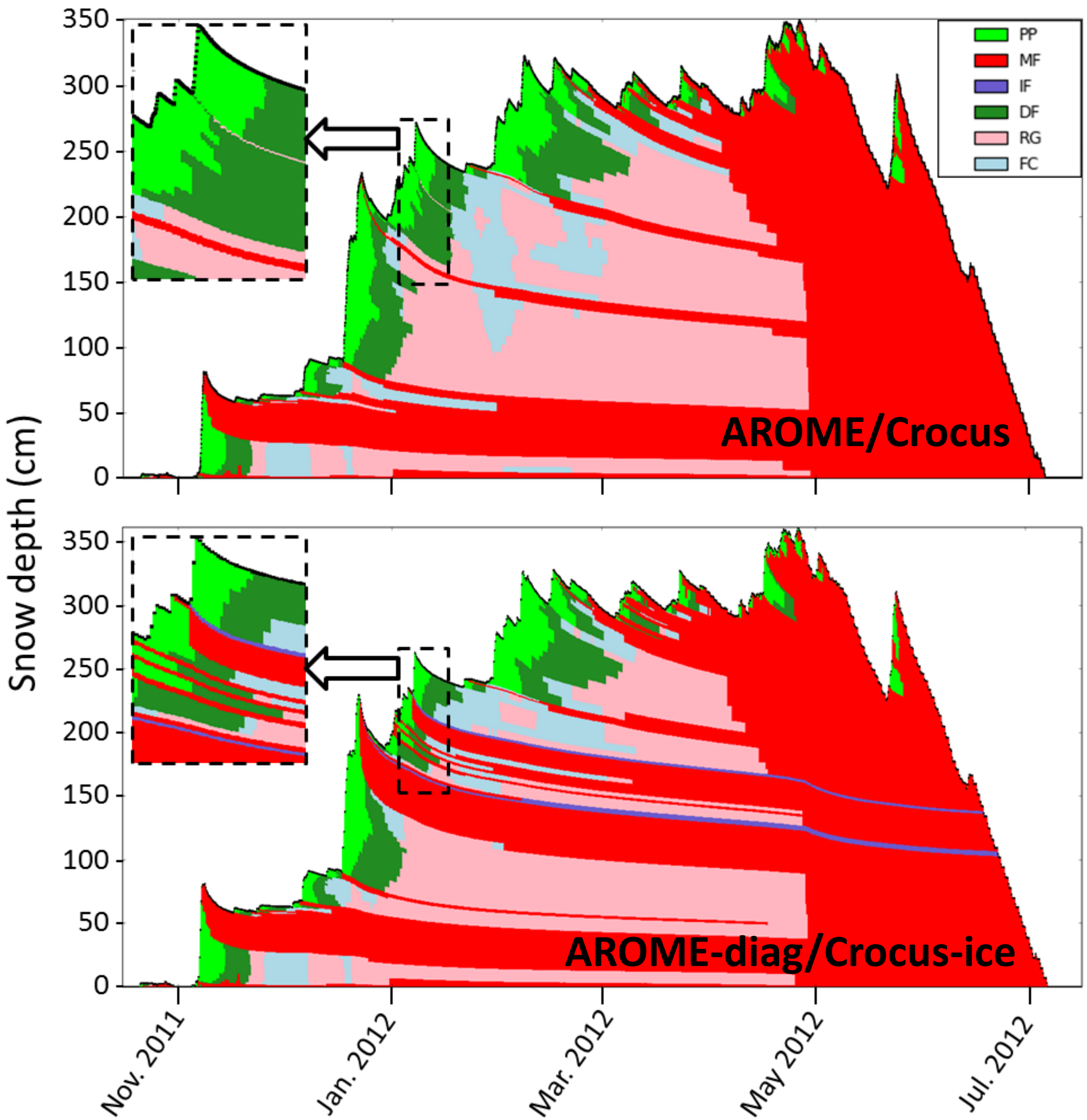
5. Open issues

5.1 Consequences on the snowpack stratigraphy

- 5 Jan. 2012: 5 cm of ice instead of fresh snow
  - Very different stability
  - Possible impact during the whole season

- Possible increased facetting close to the crust [Hammonds et al., 2015; Jamieson, 2006 ; …]
  - Weak layers of facetted grains/depth hoar
  - High thermal conductivity of ice: increased temperature gradient in the vicinity
  - Impermeability to vapour fluxes: forced condensation under the ice layer

- In Crocus-ice simulations:
  - Probably too much percolation under the ice
  - Increased facetting of grains close to the ice layer
  - Needs to be assessed with an extensive campaign of measurements



5.2 Limitations

AROME diagnostic

- Need for a higher threshold for major events detection
- Possible non-simultaneity of diagnostic and simulated precipitation
- Difficulty to estimate the freezing precipitation rate

Crocus-ice modelling

- Lack of in-situ observations of vertical snowpack profiles for validation

Crowdsourced observation database

- Spatial bias due to different massif attendance by skiers
- Subjectivity of reports

Conclusion

- **Freezing precipitation** forming an **ice layer** on the surface of the snowpack: an average of 4 events per year in the Pyrenees
- **Variable impact**, depending if ice is covered by snow quickly

- Simple **diagnostic** of freezing precipitation based on **AROME** cloud microphysical scheme (liquid water content threshold at 100m and $T_{2m}<0°C$)
- **Physical modelling of ice layer formation** due to impinging supercooled drops on the snowpack implemented in **Crocus**
- For validation: observation database using **crowdsourcing**

✓ Major events in the Pyrenees are detected with **satisfying scores** for mountain forecasters.

✓ **Added value of the ice formation modelling**: complements the atmospheric diagnostic with the surface energy budget.

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Looking for a post-doc position

Appendices

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Snow on the highest ridges (>2600-2800m)

Author: M. Matveieff

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Glazed snowpack between 1800-2000m and 2600-2800m

Author: F. Cabot

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Wet snowpack under 1800-2000m

*Author: FMJ, licence CC-by-nc-nd
www.camptocamp.org/outings/315471/fr/col-d-aoube-collet-sans-nom-par-les-cabanes-d-aoube*

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Formation of glaze ice

- Precipitation of large supercooled drops (rain or drizzle)
  - Drops have time to spread to form pure ice
  - Transparent

- Different from rime
  - Projection of cloud droplets (<50µm)
  - Air bubbles entrapped
  - White

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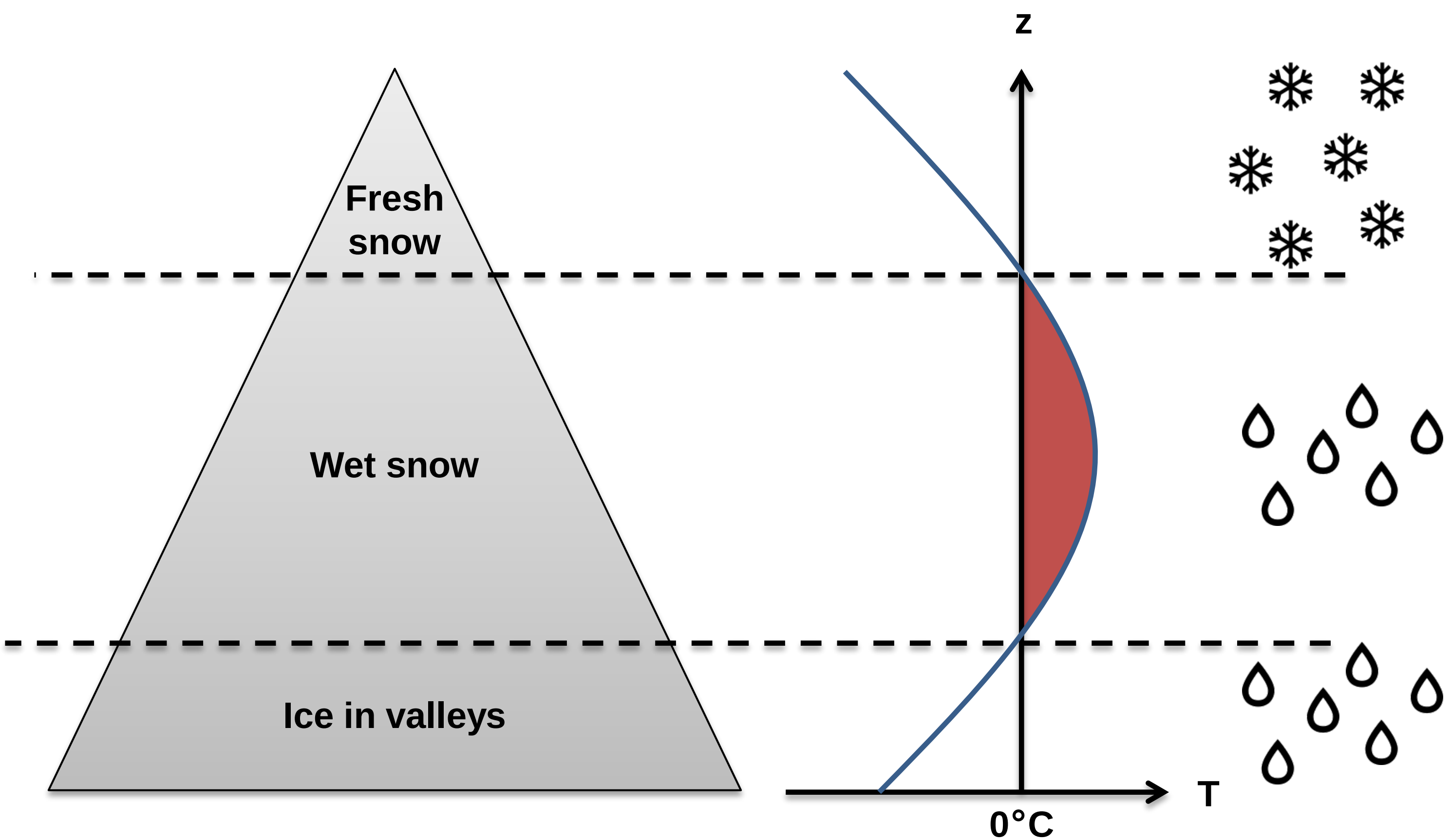
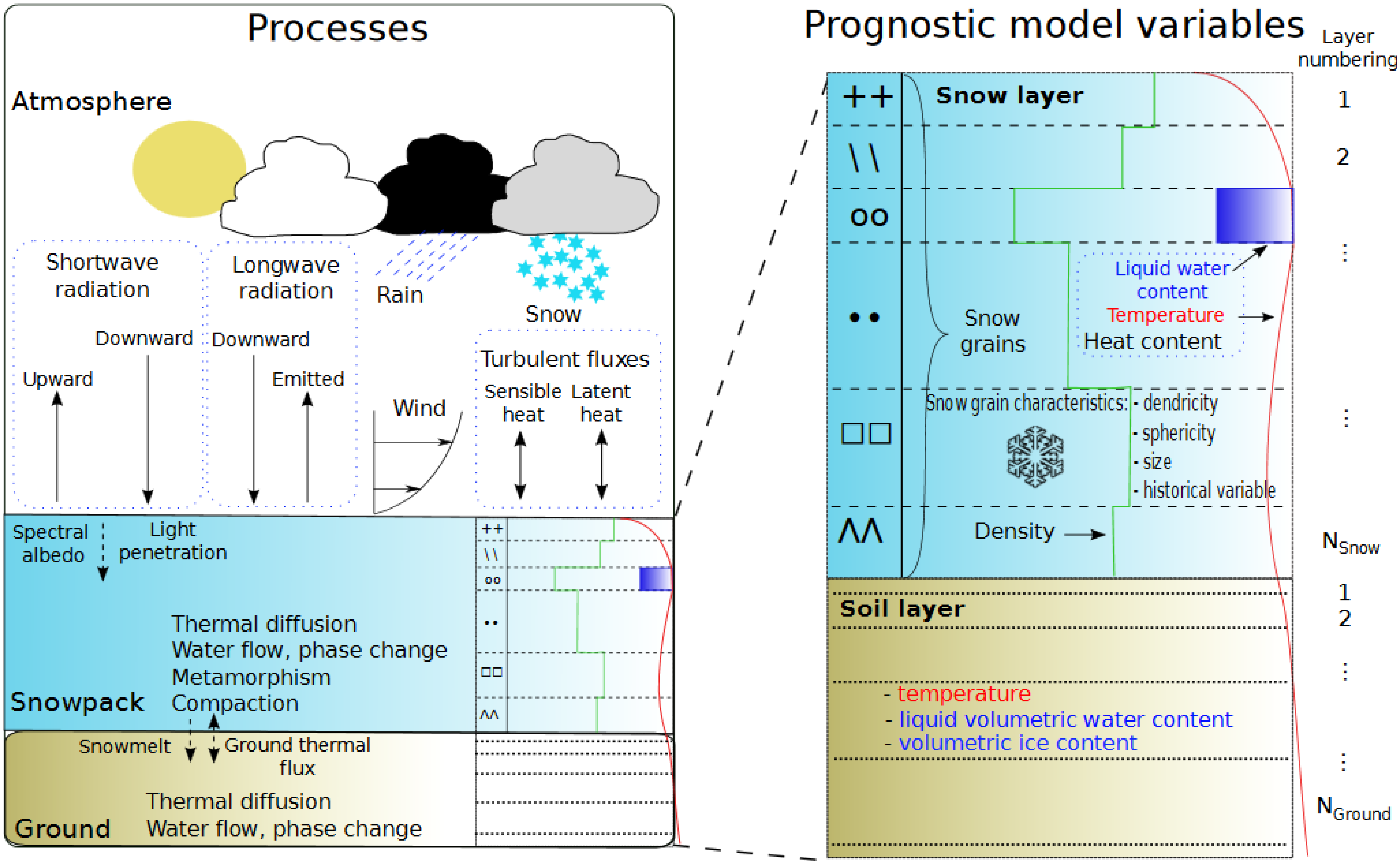
Usual freezing rain profile



SURFEX-ISBA-Crocus



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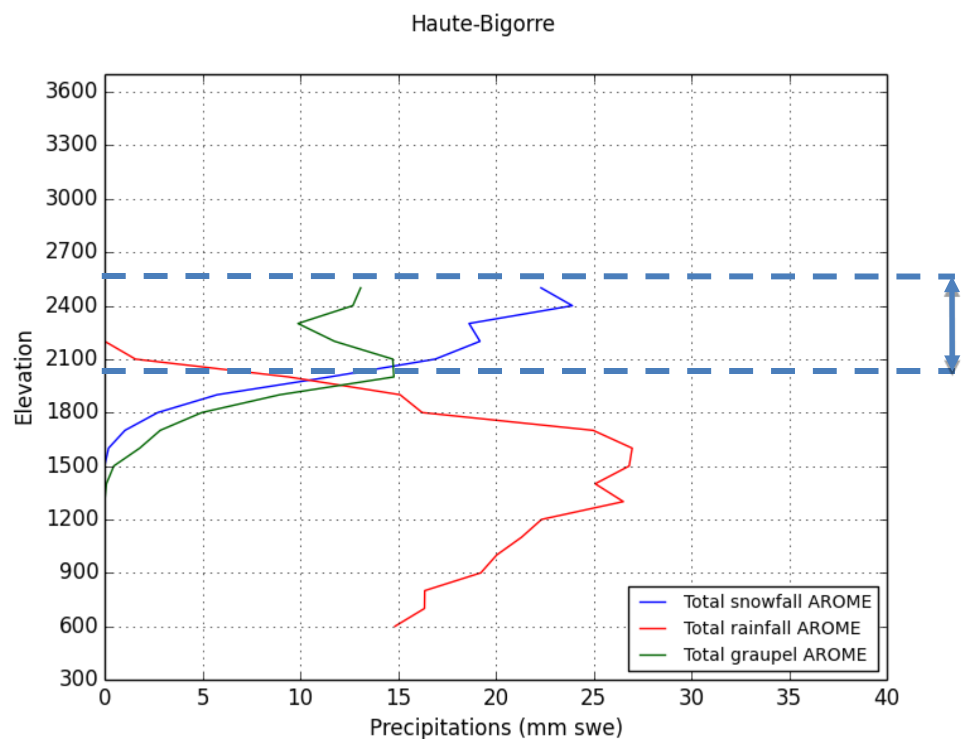
No freezing precipitation forecast

AROME does not forecast freezing precipitation between 2000m and 2600m on 5-6 January 2012



AROME, cumulated precipitation from 05/01/2012 18h UTC to 06/01/2012 6h UTC

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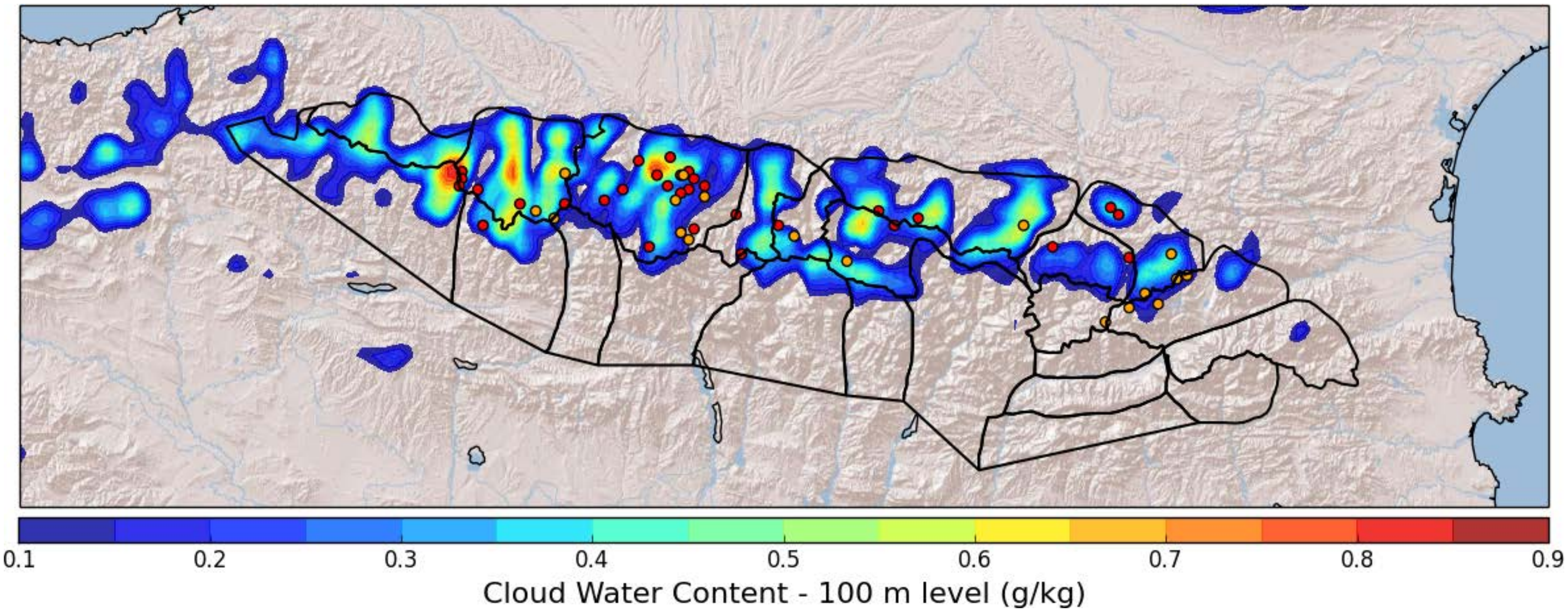
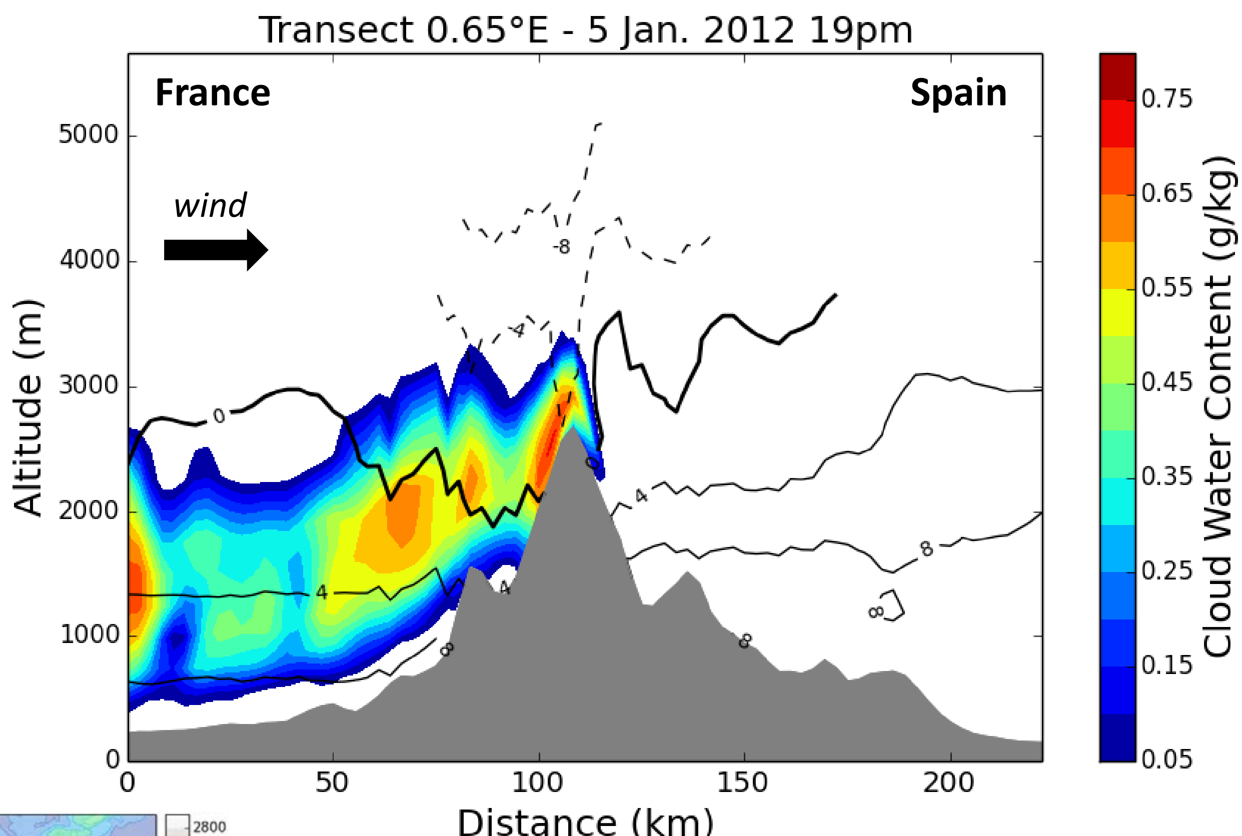
A signal of high cloud water content

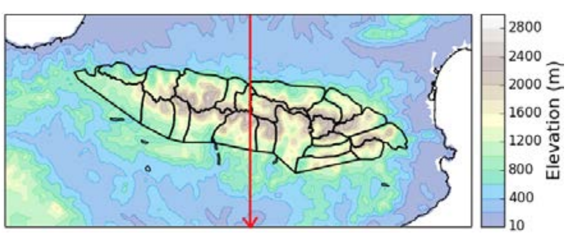


Average CWC at 100 m forecast by AROME between 5 January 2012, 14 UTC, and 6 January 2012, 6 UTC. Red dots: accident reports. Orange dots: mountaineers' observations.

See the vertical transect

A signal of high cloud water content





High cloud water content but low cloud snow content

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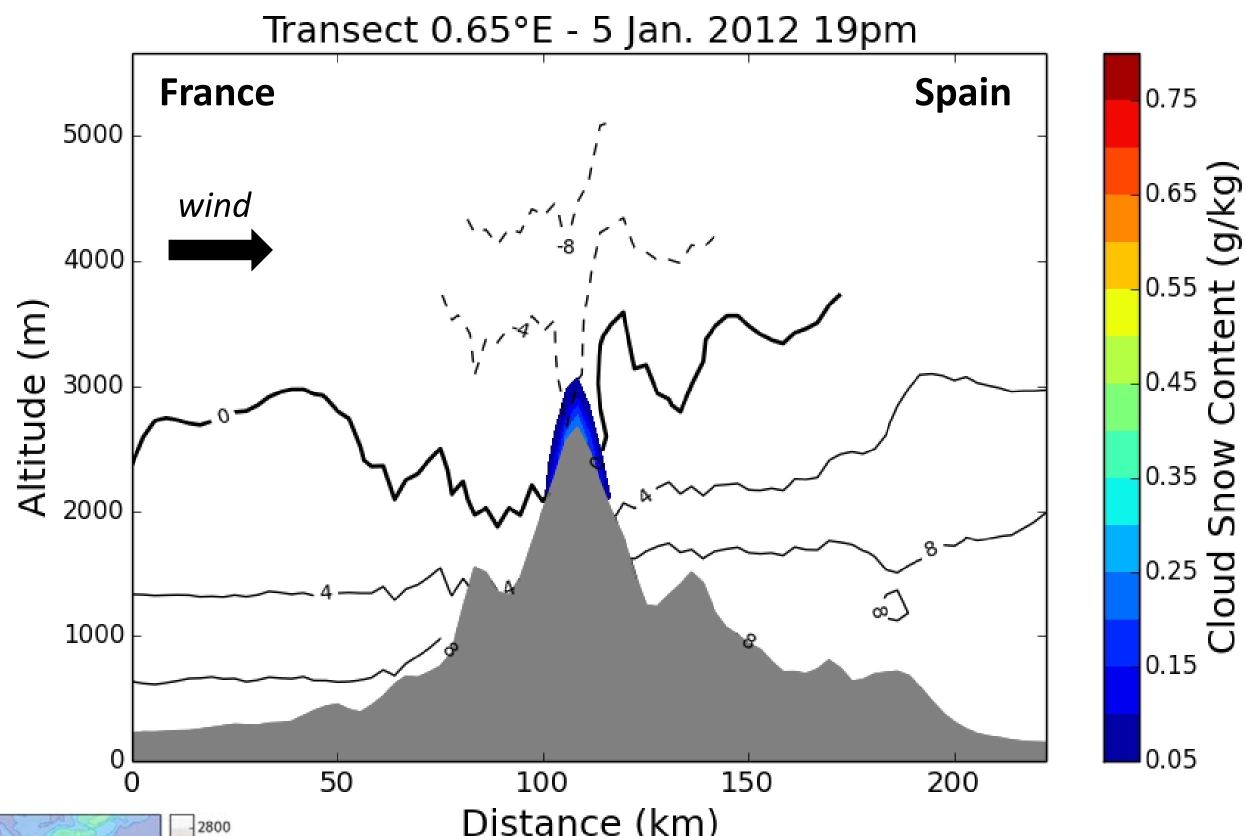
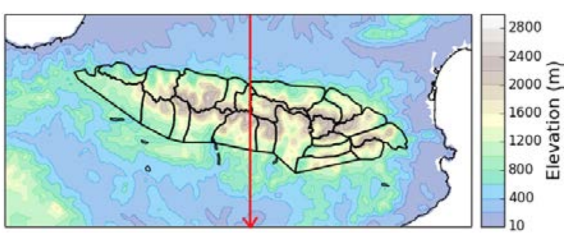
A signal of high cloud water content





High cloud water content but low cloud snow content

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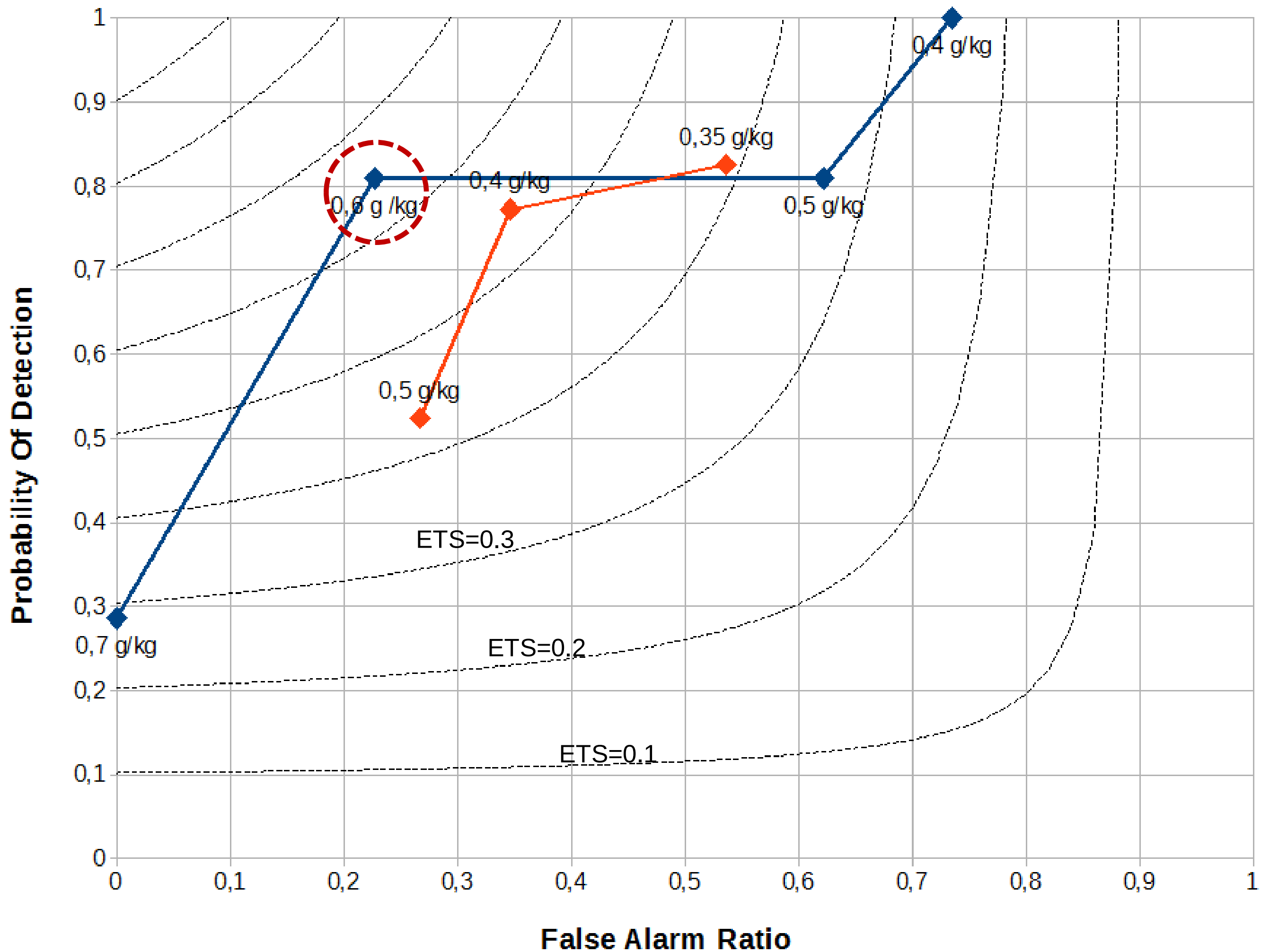
Threshold sensitivity study

Varying thresholds of liquid hydrometeors content at 100m



At least 6 pts over the threshold during 2 consecutive hours

At least 6 pts over the threshold during 2 consecutive hours, with at least 2mm of precipitation

Equitable Threat Scores

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