June 20-22, 2023
Vienna, Austria

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SENS4ICE

SENSORS AND CERTIFIABLE HYBRID ARCHITECTURES
FOR SAFER AVIATION IN ICING ENVIRONMENT

A tool for remote detection and nowcasting of in-flight icing using satellite data

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International Conference on Icing of Aircraft, Engines, and Structures - SAE
June 20 - 22, 2023 - Vienna, Austria

This project has received funding from European Union's Horizon 2020 research and innovation programme under grant agreement n° 824253

Outline

Introduction

Aircraft **in-flight icing** is a major weather hazard to aviation: the accretion of ice on airplane's surfaces adversely affects the flight since it reduces aircraft performance, stability and controllability. The remote detection of meteorological conditions leading to icing is a very aspired goal for the scientific community.

In-flight icing occurs when supercooled water droplets strike the airframe and freeze on impact; it is determined by many factors, both meteorological and not.

The Meteorology Laboratory of CIRA is working on the goal to characterize in-flight icing using satellite data since 2017. A first algorithm for in-flight icing detection has been developed in collaboration with Meteorological Service of Italian Air Force (ITAF) and with the support of the internal experimental knowledge on icing thanks to the CIRA Icing Wind Tunnel facility. This product has been implemented into ITAF operational chain and is usable in meteorological surveillance functions for aviation safety.

SENS4ICE
SENSORS AND CERTIFIABLE HYBRID ARCHITECTURES FOR SAFER AVIATION IN ICING ENVIRONMENT

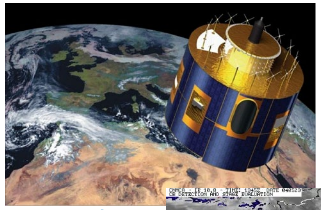
Currently, in the framework of the H2020 EU project **SENS4ICE** (SENSors and certifiable hybrid architectures for safer aviation in ICing Environment), a further maturation of the previously developed algorithm has been achieved, in order to consider also Supercooled Large Drop (SLD) Icing Conditions.

Icing detection tool: input

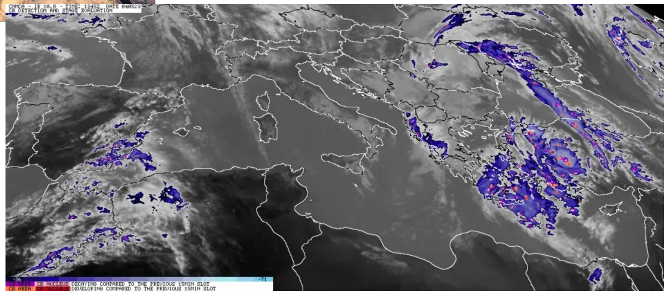
The algorithm relies on knowledge or inference from satellite data of the main meteorological factors determining icing condition: *Temperature*, *Droplet size* and *Cloud type*.

ALGORITHM INPUT:

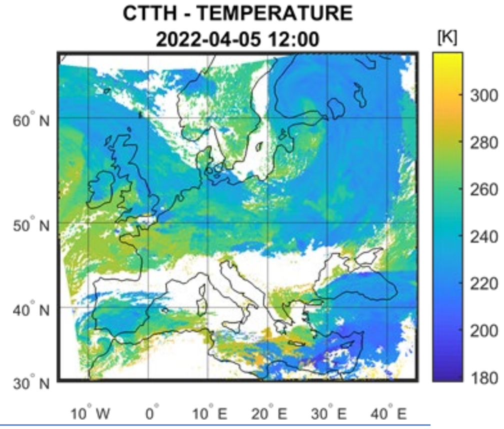
- satellite products, based on Meteosat Second Generation (MSG) data:
  - **NEFODINA** and **NEFODINA2** products, provided by ITAF, to detect convective areas;
  - Cloud Top Temperature and height (GEO-**CTTH**), NWCSAF product, to evaluate cloud properties;
  - Optimal Cloud Analysis (**OCA**) product, distributed by EUMETSAT, to retrieve cloud microphysical properties (effective radius).
- A set of experimental curves, representing the **icing reference certification rules** (**Appendix C** and **Appendix O** of FAA 14 CFR Part 25 / EASA CS-25)



EUMETSAT



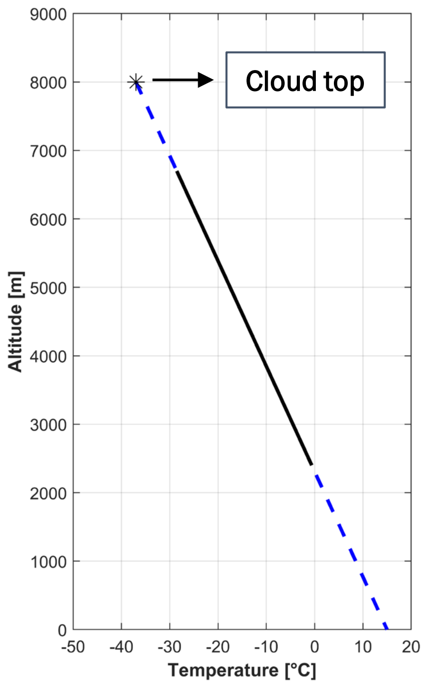
www.meteoam.it

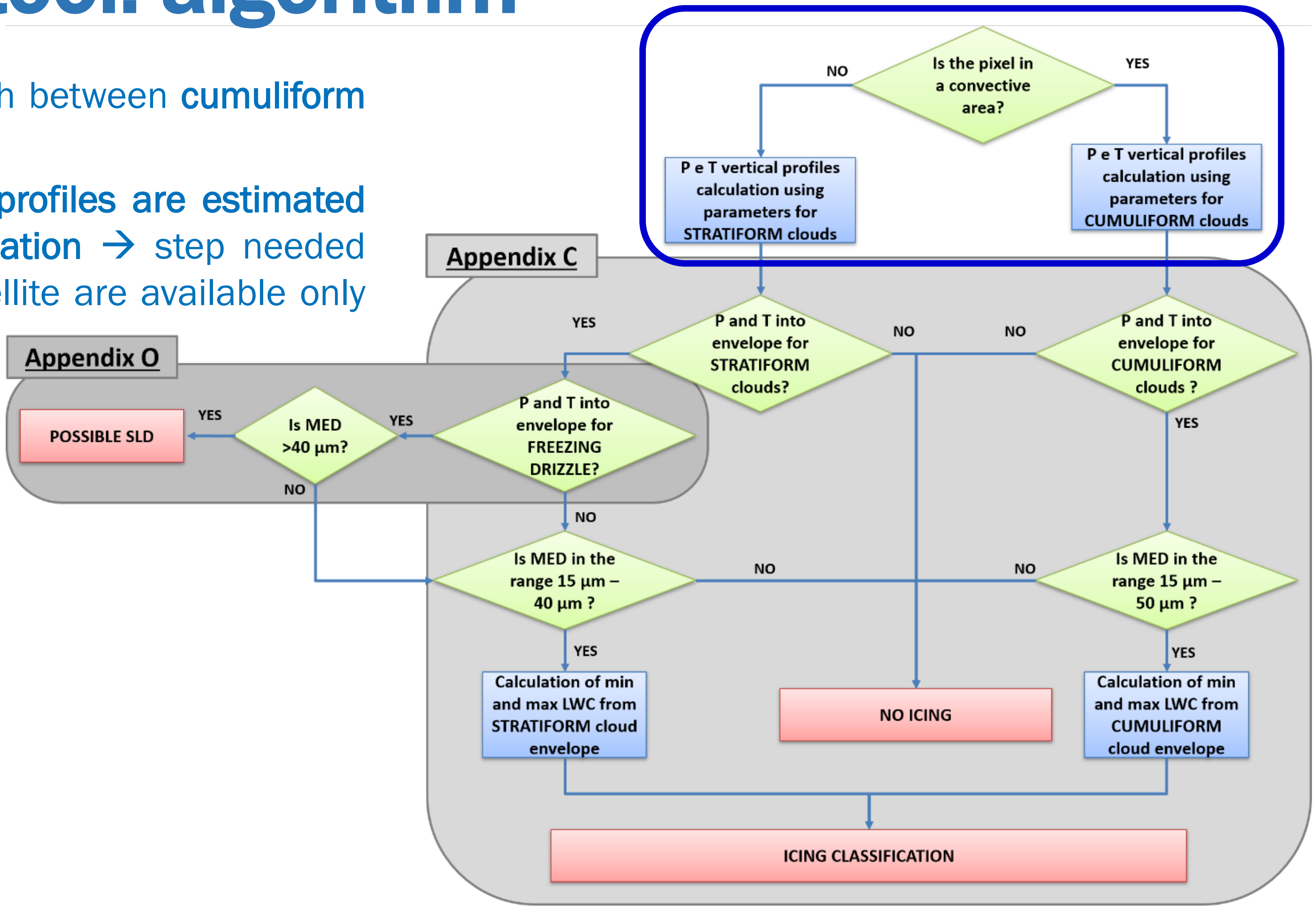


Icing detection tool: algorithm

First step: data pre-screening to distinguish between **cumuliform** and **stratiform** clouds.

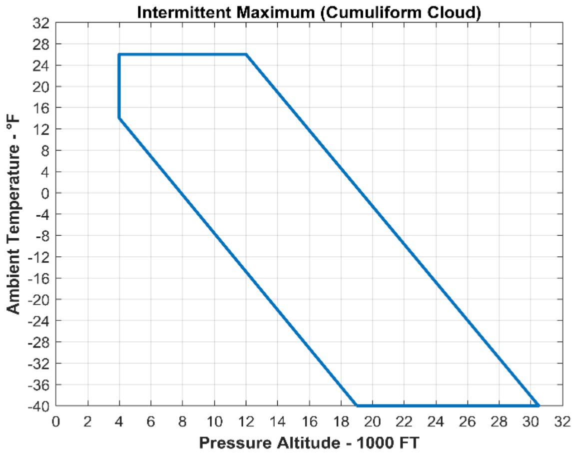
Then, temperature and pressure **vertical profiles are estimated** using the **standard atmosphere approximation** → step needed since temperature and pressure from satellite are available only at the cloud top.



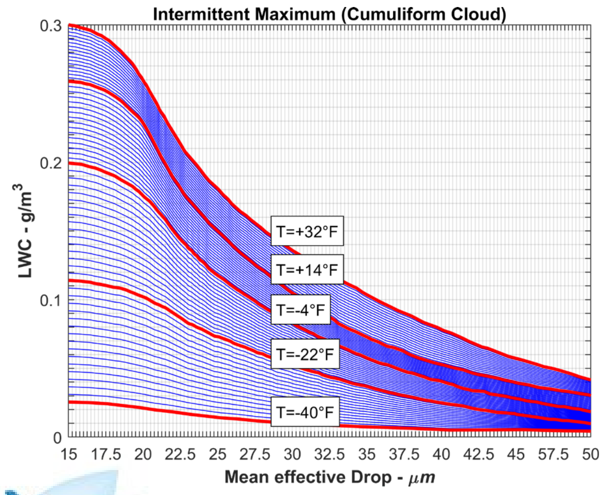


Icing detection tool: cumuliform clouds

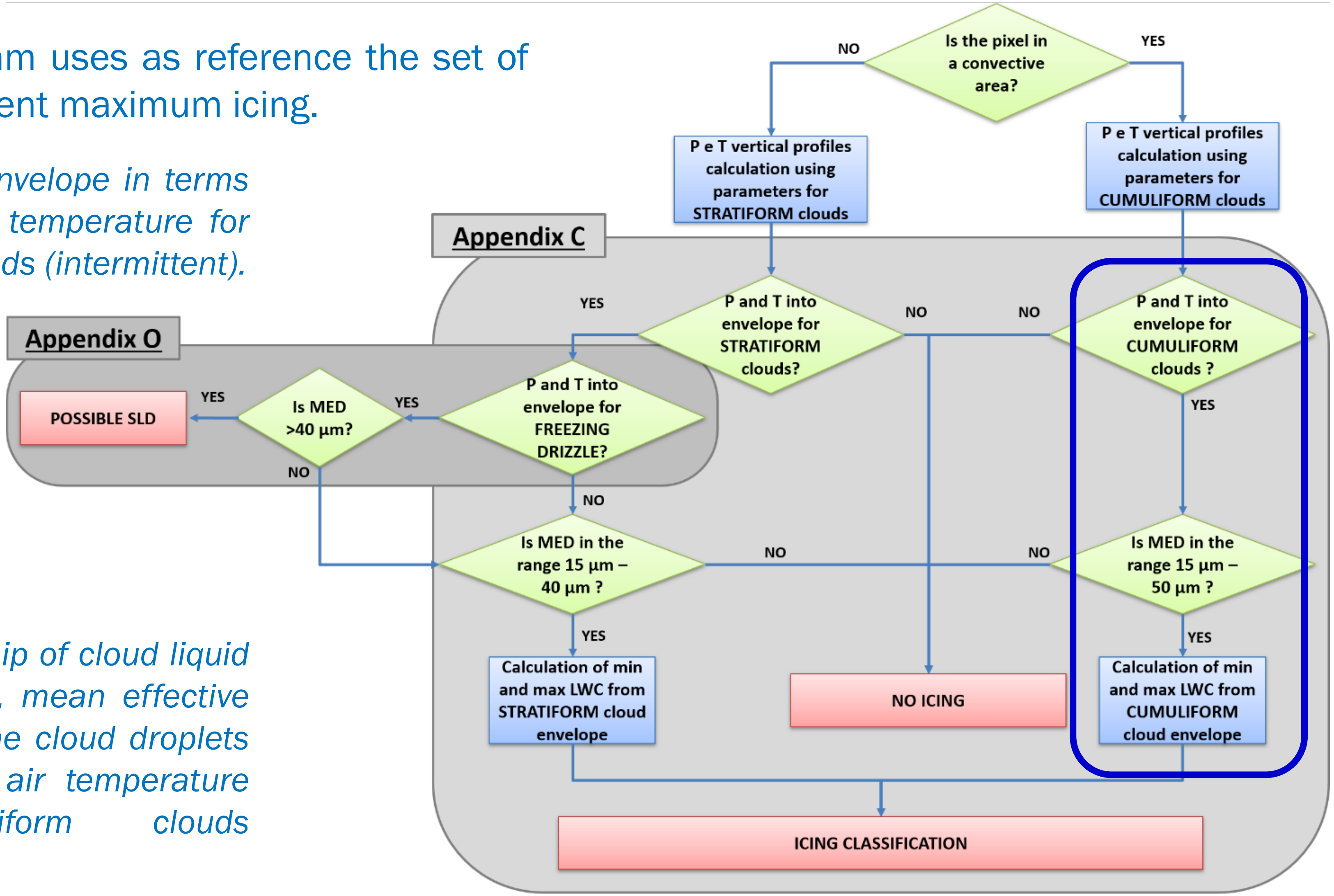
In case of **cumuliform** clouds, the algorithm uses as reference the set of experimental curves of **App. C** for intermittent maximum icing.



Limiting icing envelope in terms of altitude and temperature for cumuliform clouds (intermittent).

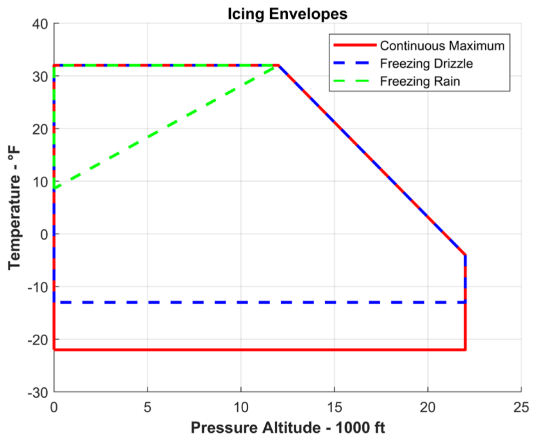


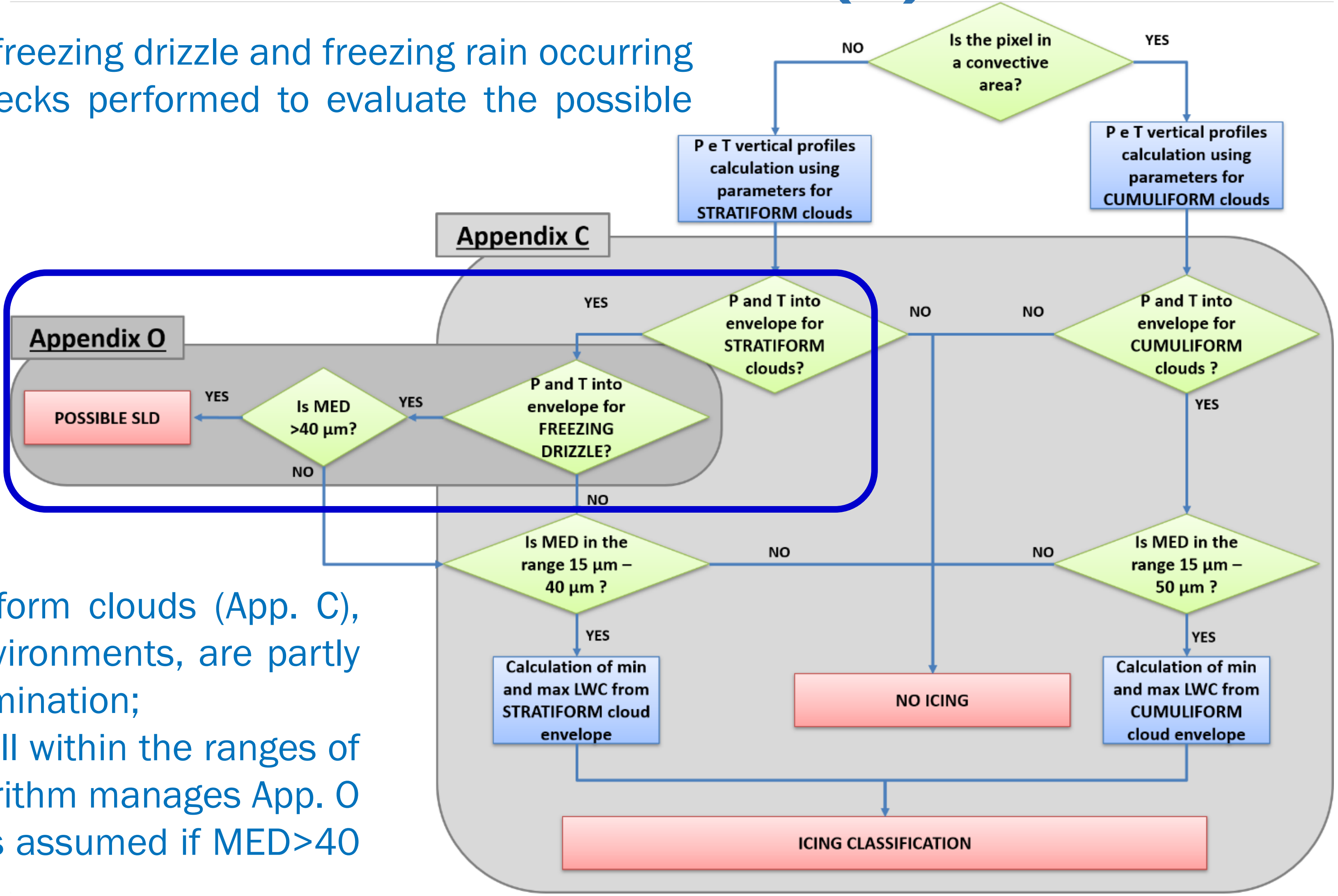
Interrelationship of cloud liquid water content, mean effective diameter of the cloud droplets and ambient air temperature for cumuliform clouds (intermittent).



Icing detection tool: stratiform clouds (1)

App. O: supercooled large drop consist of freezing drizzle and freezing rain occurring in and/or below **stratiform** clouds → checks performed to evaluate the possible presence of **SLD** conditions.

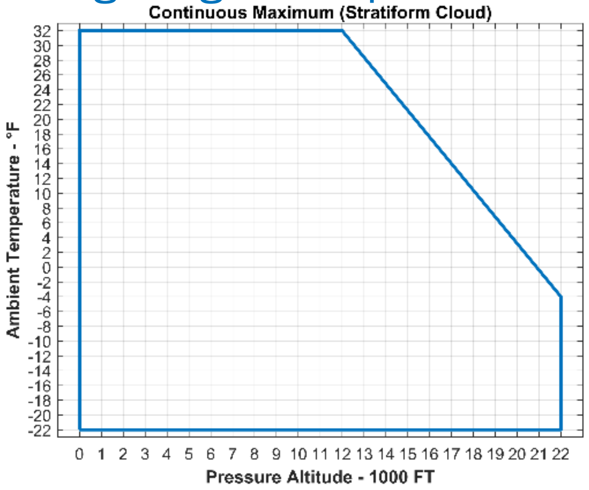




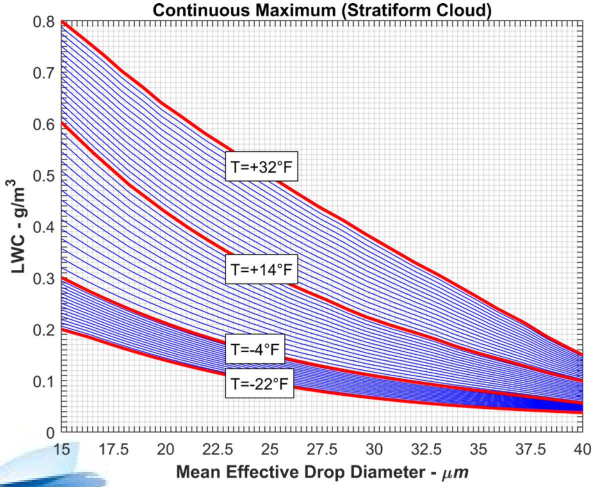
- The limiting icing envelopes for stratiform clouds (App. C), Freezing Drizzle and Freezing Rain environments, are partly overlapped → uncertainty in the discrimination;
- If temperature and pressure altitude fall within the ranges of freezing drizzle environments, the algorithm manages App. O conditions → possible SLD condition is assumed if MED>40 µm, omitting cases with MED<40 µm.

Icing detection tool: stratiform clouds (2)

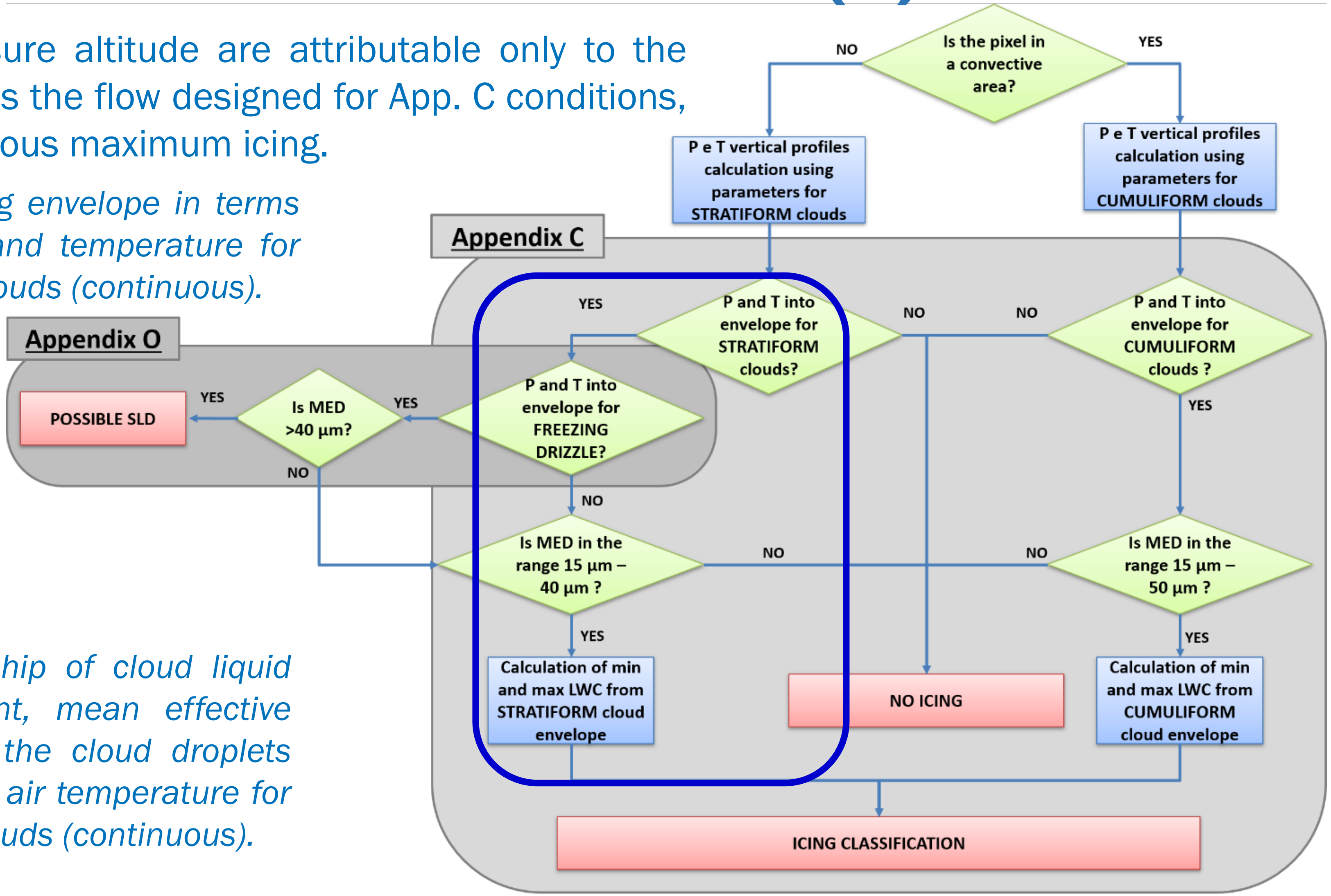
If the values of temperature and pressure altitude are attributable only to the conditions of **App. C**, the algorithm follows the flow designed for App. C conditions, using icing envelopes defined for continuous maximum icing.



Limiting icing envelope in terms of altitude and temperature for stratiform clouds (continuous).



Interrelationship of cloud liquid water content, mean effective diameter of the cloud droplets and ambient air temperature for stratiform clouds (continuous).

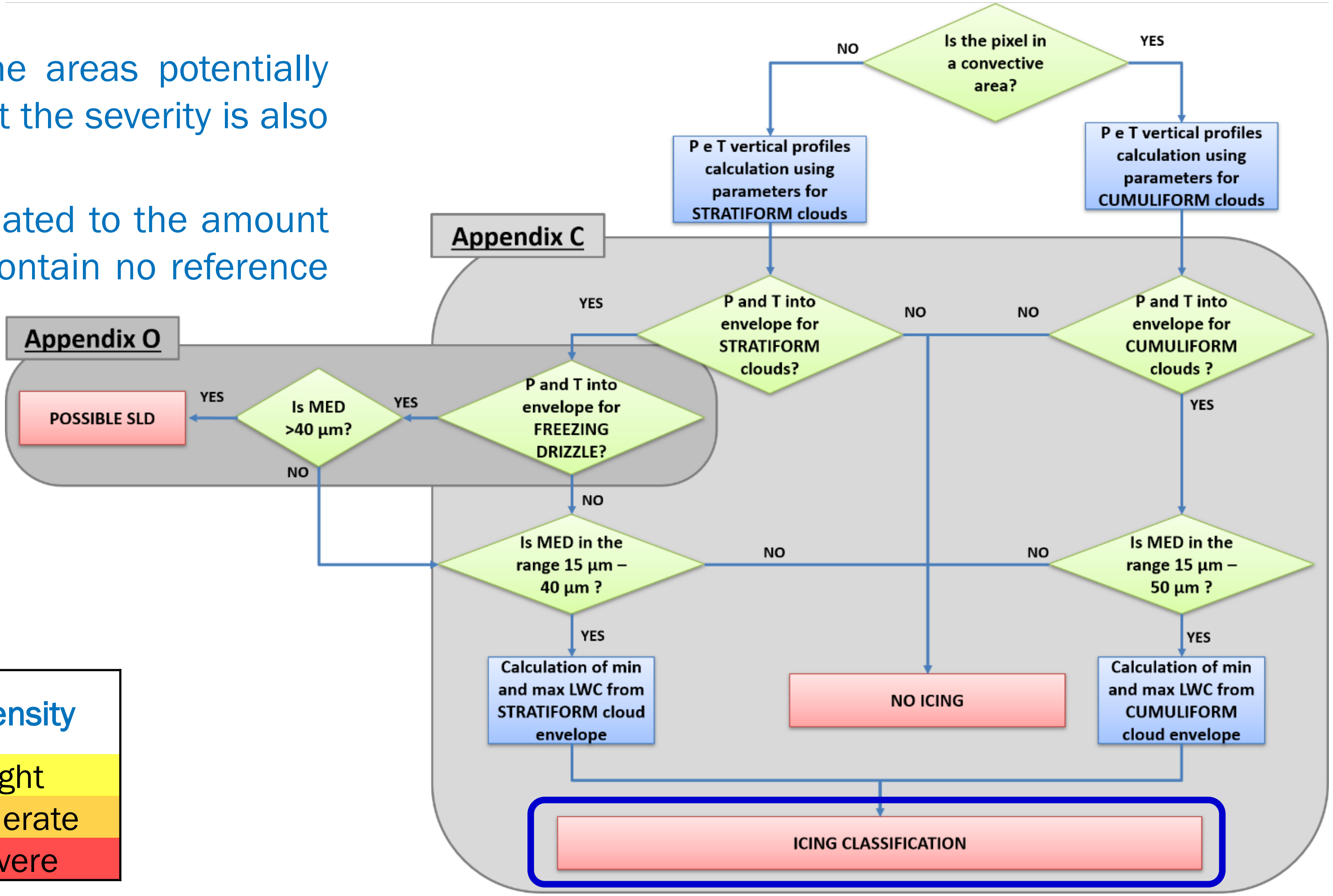


Icing detection tool: hazard classification

In case of Appendix C conditions, for the areas potentially affected by icing hazard, information about the severity is also provided: light, moderate or **severe.**

Accepted icing intensity definitions are related to the amount of the accreted ice on aircraft and they contain no reference to atmospheric variables.

In order to develop an icing product intended for general use, an alternate scale has been used, where ice accretion rates are replaced by cloud Liquid Water Content (LWC).



Supercooled Water Content (g/m^3)	Intensity
0.1-0.6	Light
0.6-1.2	Moderate
>1.2	Severe

DOT/FAA/AR-01/91

Icing detection tool: altitudes estimate

Temperature vertical profiles are estimated using the **standard atmosphere approximation**, starting from the temperature at the cloud top.

Due to the limitations of this approach, two alternatives have been investigated:

- temperature profiles retrieved from **satellite** (e.g. Radio Occultation Meteorology Satellite Application Facility - ROM SAF);
- temperature profiles obtained from Numerical Weather Prediction (**NWP**) models.

But...

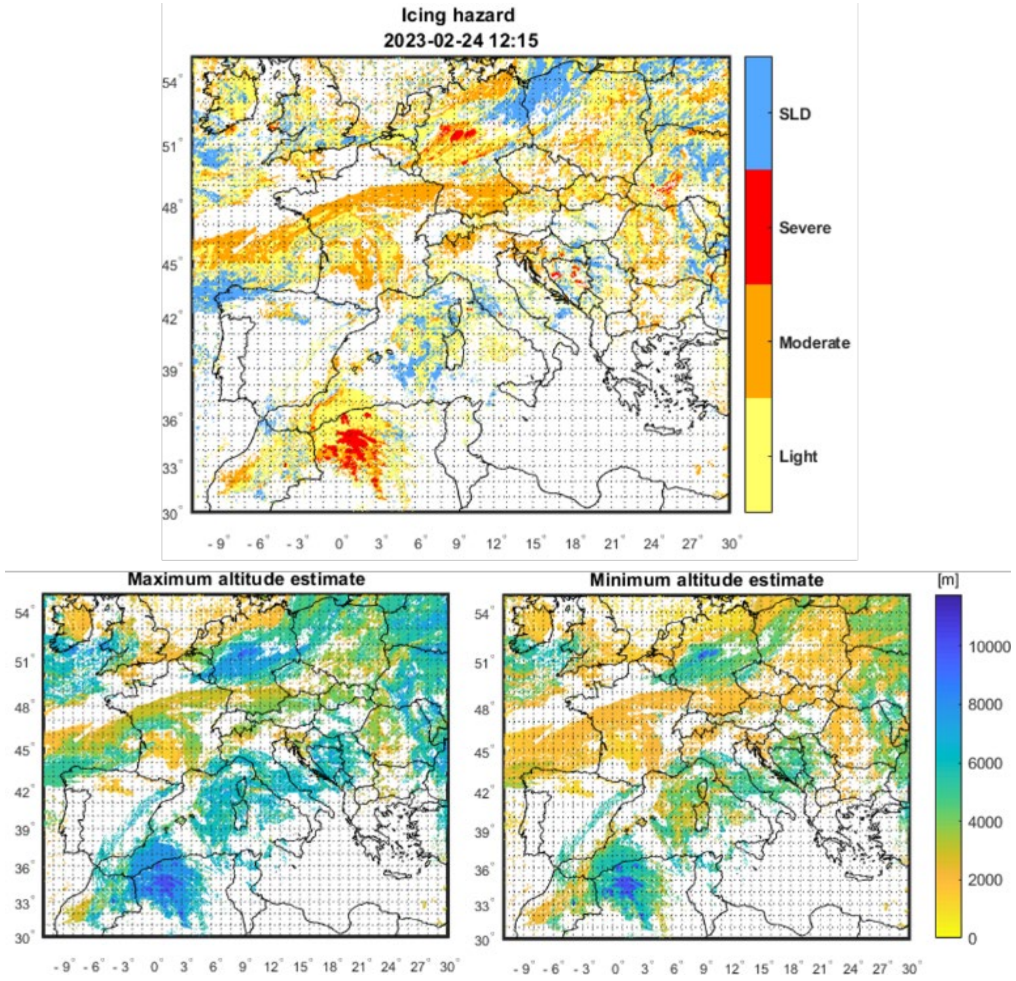
- satellite retrieved profiles from radio occultation are very discontinuous in time and space;
- the use of temperature profiles obtained from NWP would imply a very strong increase in the computational times and costs of the algorithm.

Furthermore, a preliminary comparison with respect to soundings data, has shown that, in terms of mean bias, the difference between the temperature profiles estimated using the standard atmosphere approximation and NWP profiles is not very significant.

For these reasons, at this stage, the usage of NWP data was not preferred.

Icing detection tool: output

- This tool is targeted to display the resulting information of the pixel-based analysis of the algorithm as a graphical representation of icing hazard.
- The spatial and temporal resolutions are respectively of about 3 km and 15 minutes.
- An estimate of the minimum and maximum altitudes affected by the icing hazard is also available for each pixel of the map.
- As for the evaluation of algorithm results:
  - a complete validation is a challenging task, due to the lack of suitable observations;
  - PIREPs (pilot reports) represent the only dataset for direct in-situ icing observation, but these data are difficult to be found and collected;
  - it is even more difficult to find observations on the presence of SLD.

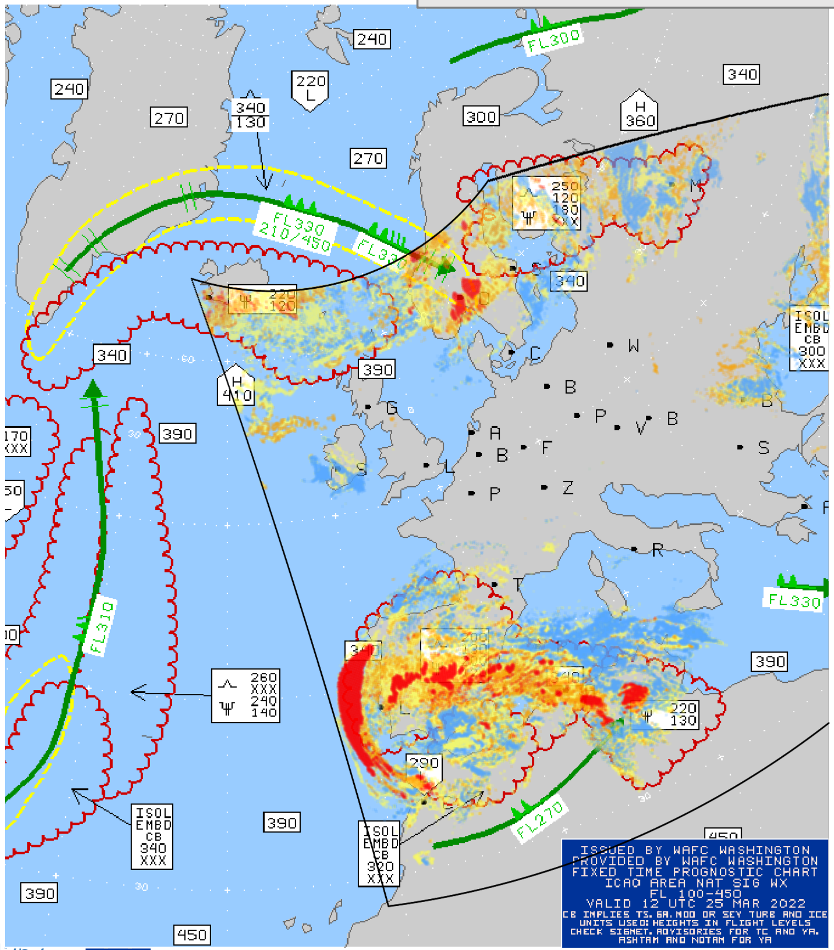


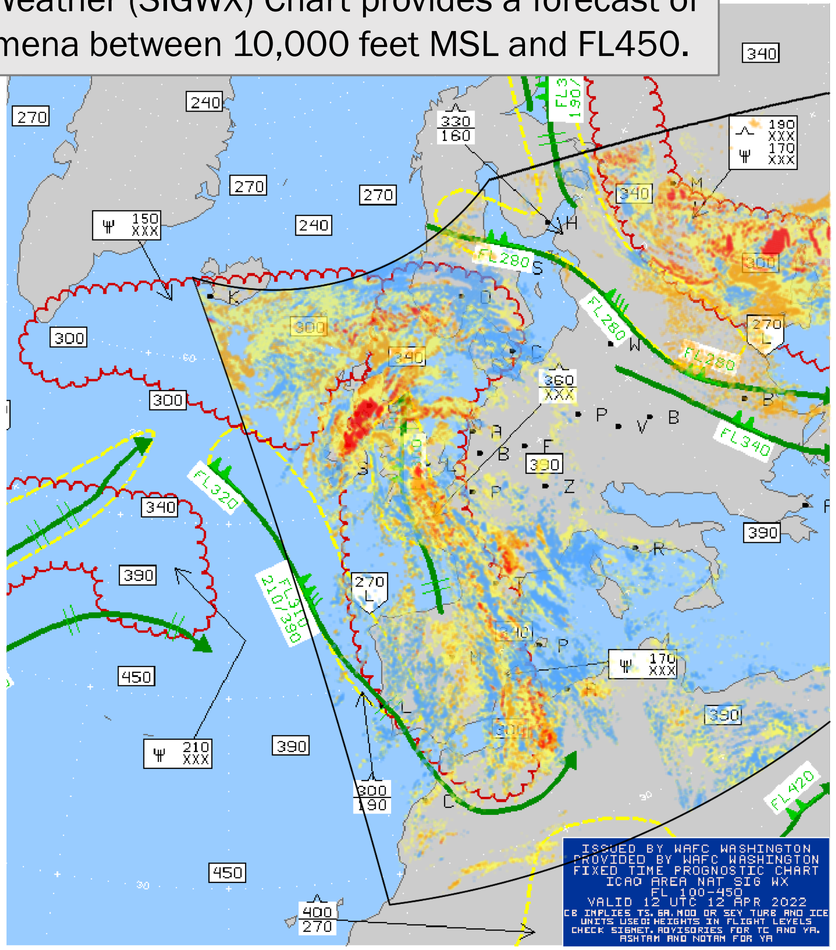
Icing detection tool: preliminary results

A qualitative comparison with Mid-Level Significant Weather (SIGWX) Chart has shown a quite good agreement in definition of regions affected by icing conditions.

The Mid-Level Significant Weather (SIGWX) Chart provides a forecast of significant weather phenomena between 10,000 feet MSL and FL450.

Such a comparison has been carried out for several hundreds of dates (starting from September 2020) with a general tendency of good agreement and a minority of cases with poor accordance.





Some examples of overlapping of the algorithm results on SIGWX charts.

https://www.aviationweather.gov/

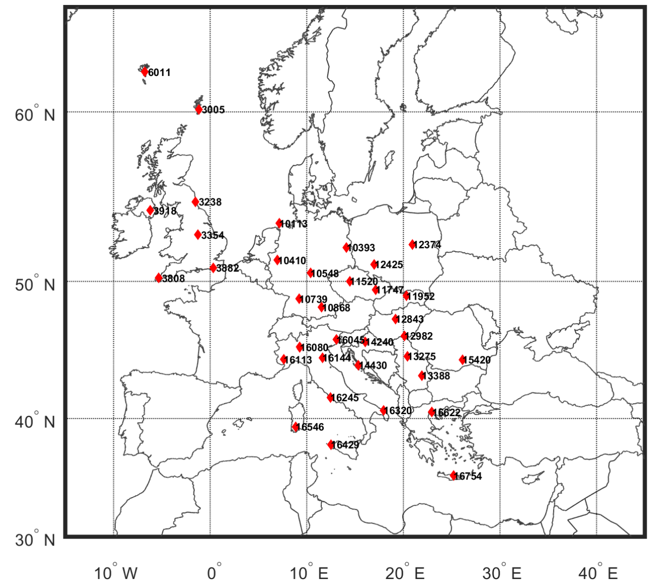
Icing detection tool: comparison with soundings

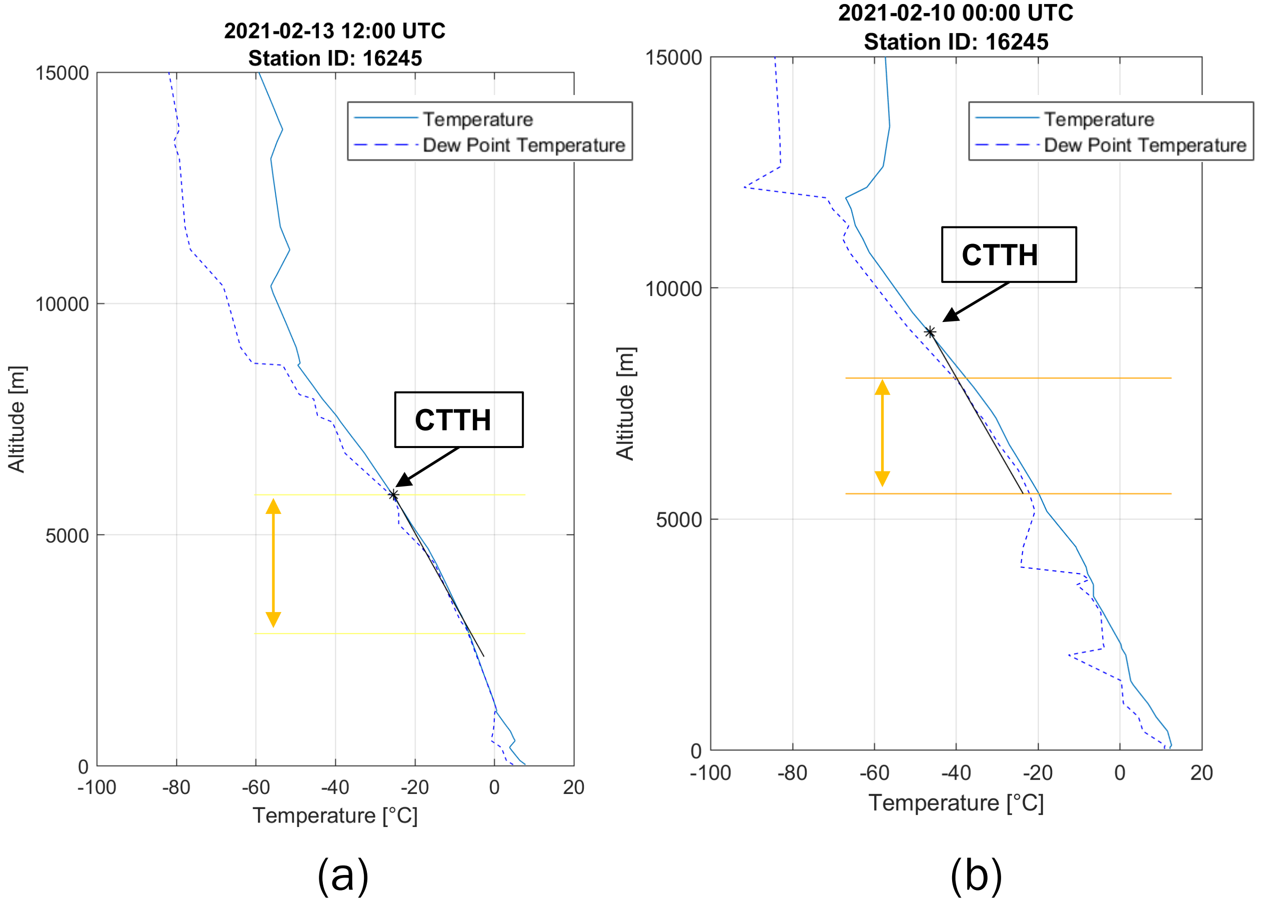
Another kind of validation is ongoing based on the comparison with soundings data.

A comparison between **the vertical temperature profiles estimated** by the algorithm with **soundings** temperature profile has been performed.

Several sites in Europe have been considered.

https://weather.uwyo.edu/upperair/sounding.html





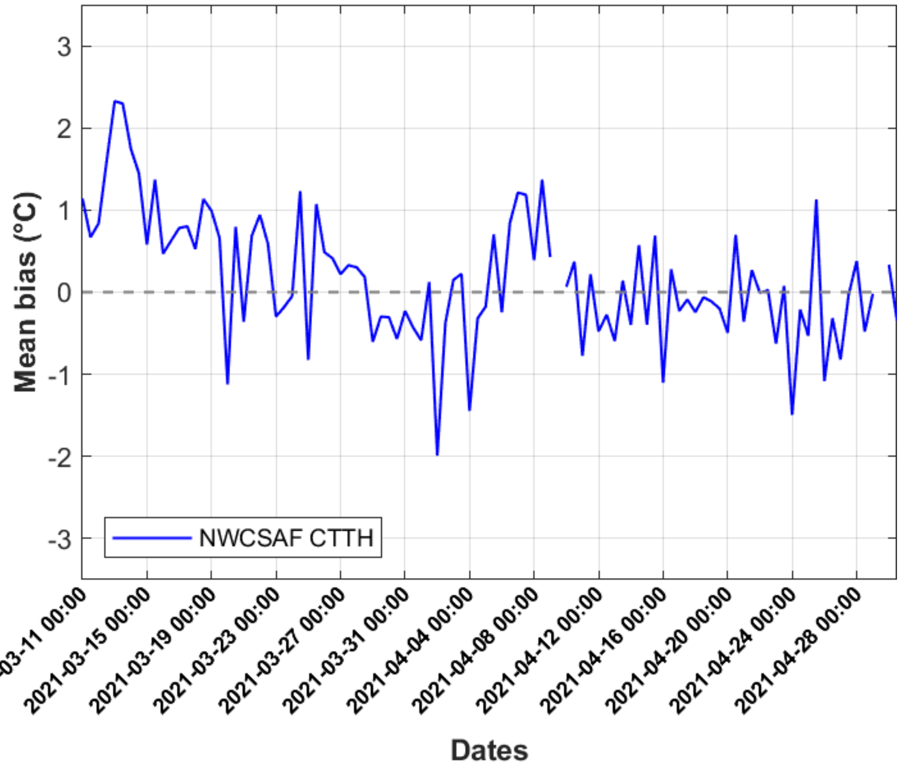
In some cases there is a good agreement while, in other cases, the two considered temperature profiles are more distant.

Icing detection tool: comparison with soundings

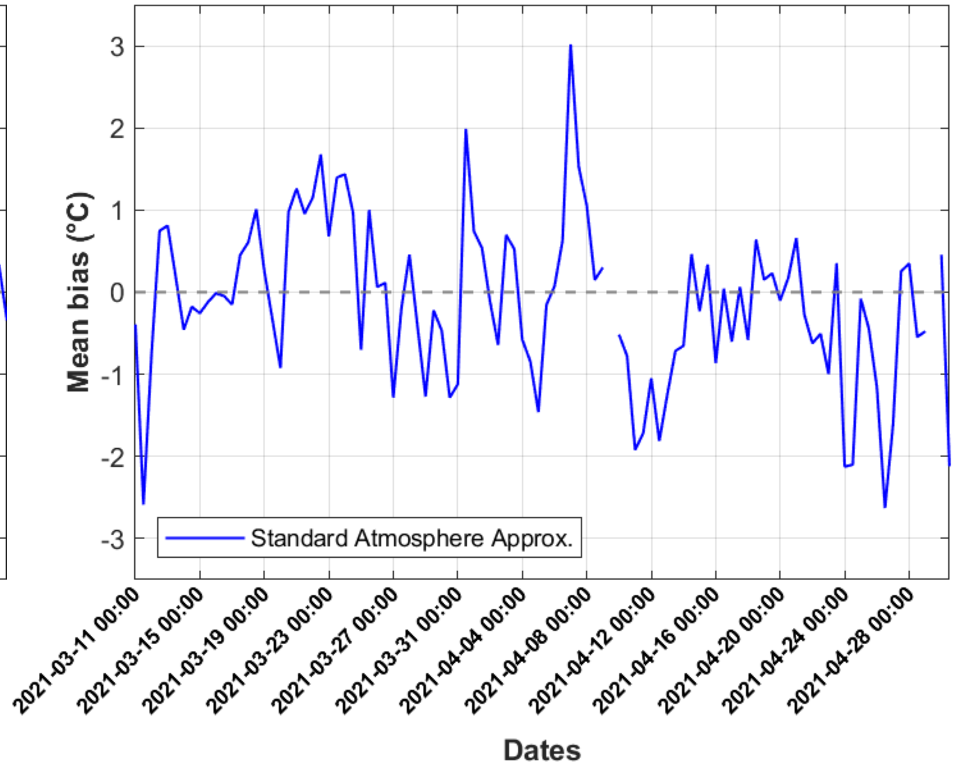
Spatial mean bias

Summary statistics: time series of the spatial mean bias (average of all soundings sites).

Temperature bias at the cloud top



Temperature bias averaged over the vertical profile



Comparison performed on data from 11-Mar-2021 to 30-Apr-2021

Icing detection tool: comparison with soundings

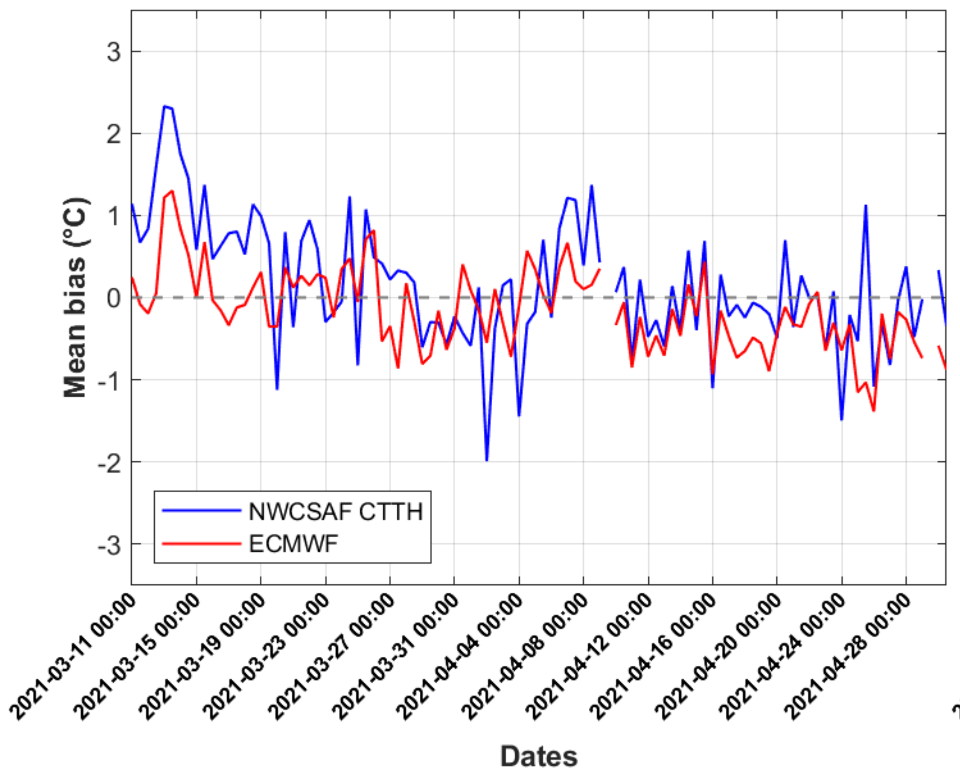
Spatial mean bias

Summary statistics: time series of the spatial mean bias (average of all soundings sites).

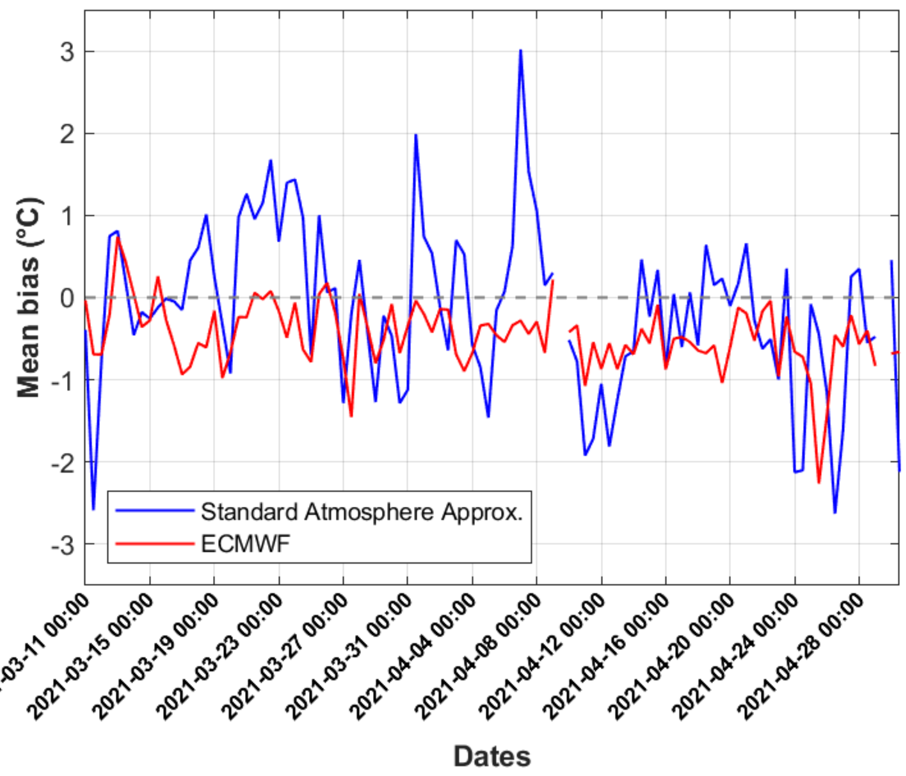
The same statistics have been calculated for the data of the ECMWF IFS numerical weather prediction model.

NWP data have better performance, but the difference between the two kinds of data is not very significant.

Temperature bias at the cloud top



Temperature bias averaged over the vertical profile



Comparison performed on data from 11-Mar-2021 to 30-Apr-2021

Icing nowcasting tool

CIRA has worked on nowcasting algorithms based on the extrapolation in time of the current weather conditions detected by satellite data (icing detection product). The idea is to use an estimate of the speed and direction of movement of the current icing conditions to perform a forecast over a short period ahead.

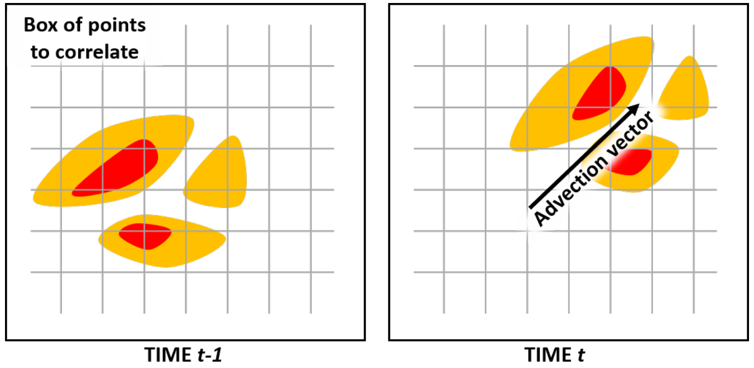
Two different nowcasting algorithms have been implemented:

- *uniform advection algorithm based on cross-correlation*

  To perform the extrapolation, it uses an estimate of the advection of the meteorological field, calculated by means of a cross correlation analysis of two consecutive satellite images.

- *pixel-to-pixel advection algorithm based on cross-correlation over sub-areas*

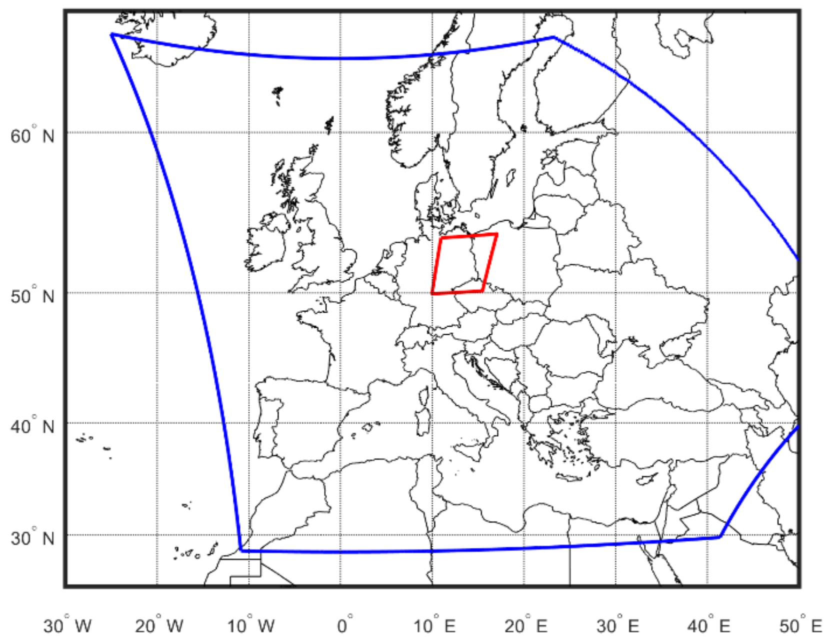
  It consists in dividing the region of interest in sub-areas and in repeating the correlation analysis for each of them: a set of displacement vectors is identified. This method allows a better estimate of the meteorological field velocity, but it is characterized by high computational time and cost.



Icing nowcasting tools: parameter and domain tuning

- The implementation of the pixel-to-pixel advection algorithm has requested an appropriate **tuning** of the size of the background sub-areas to be considered, chosen according to a proper compromise between the reliability of the calculated displacement vectors and the computational cost of the software.
- The sub-areas dimensioning has been carried out in an empirical way, by varying the cell size and calculating the value providing better results.

- The software implementation of the nowcasting tools, considering the whole domain of the detection product, leads to:
  - negligible computational times for the uniform advection algorithm;
  - very long computational times for the pixel-to-pixel advection algorithm → unacceptable for an early warning system
- A **domain reduction** has been implemented: the idea is to run the nowcasting tool focusing on a specific area of interest.



Icing nowcasting tool: results

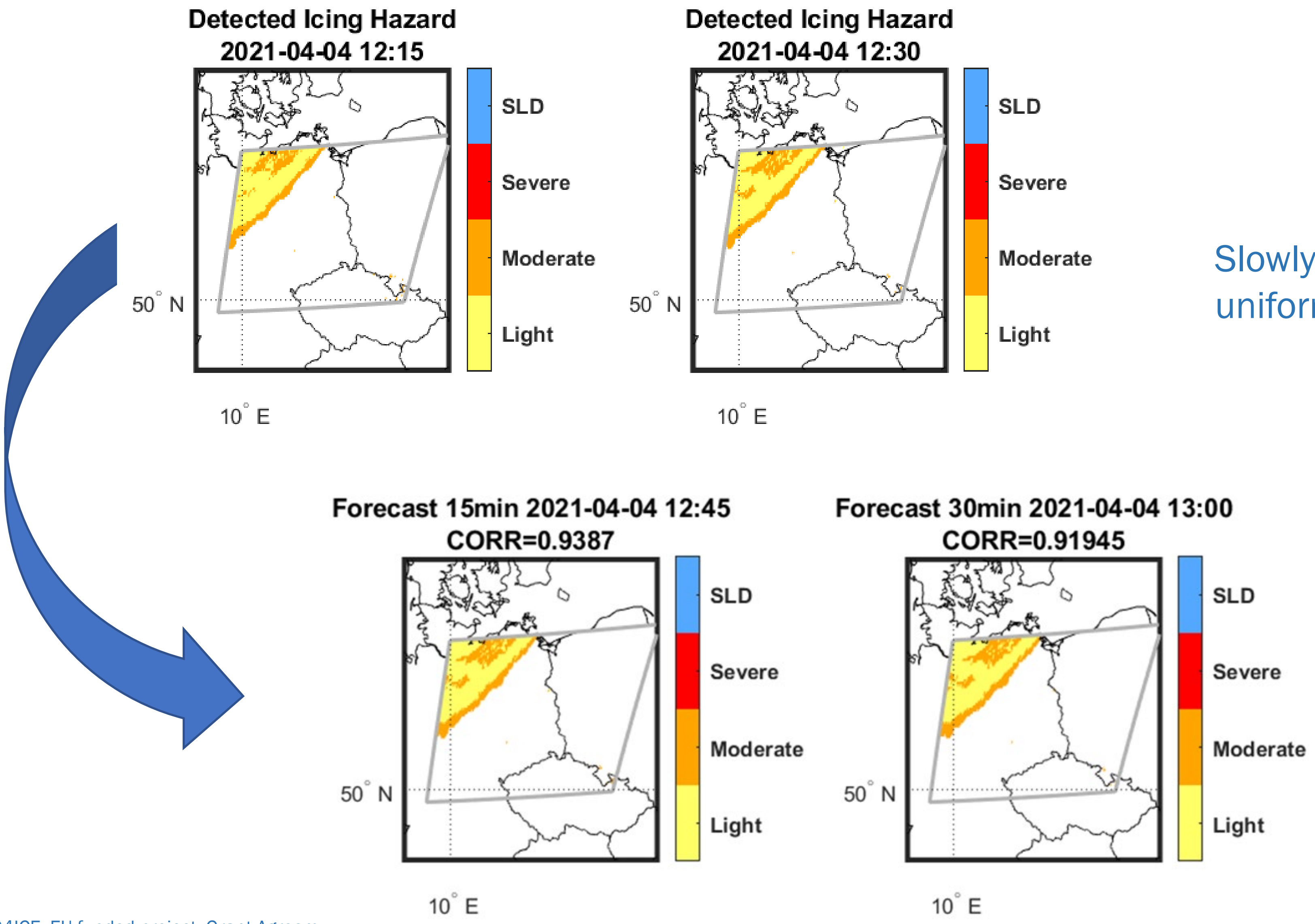
- A **comparison** between the two algorithms has been performed
- Four different lead times considered: 15 minutes, 30 minutes, 45 minutes and 1 hour.
- The nowcasting methods have been validated considering a set of data covering the month of April 2021.

Monthly mean performances evaluated in terms of correlation between forecast and observed images.

	Uniform Advection	Pixel-to-Pixel Advection
15 minutes	0.62	0.64
30 minutes	0.55	0.56
45 minutes	0.51	0.52
1 hour	0.49	0.49

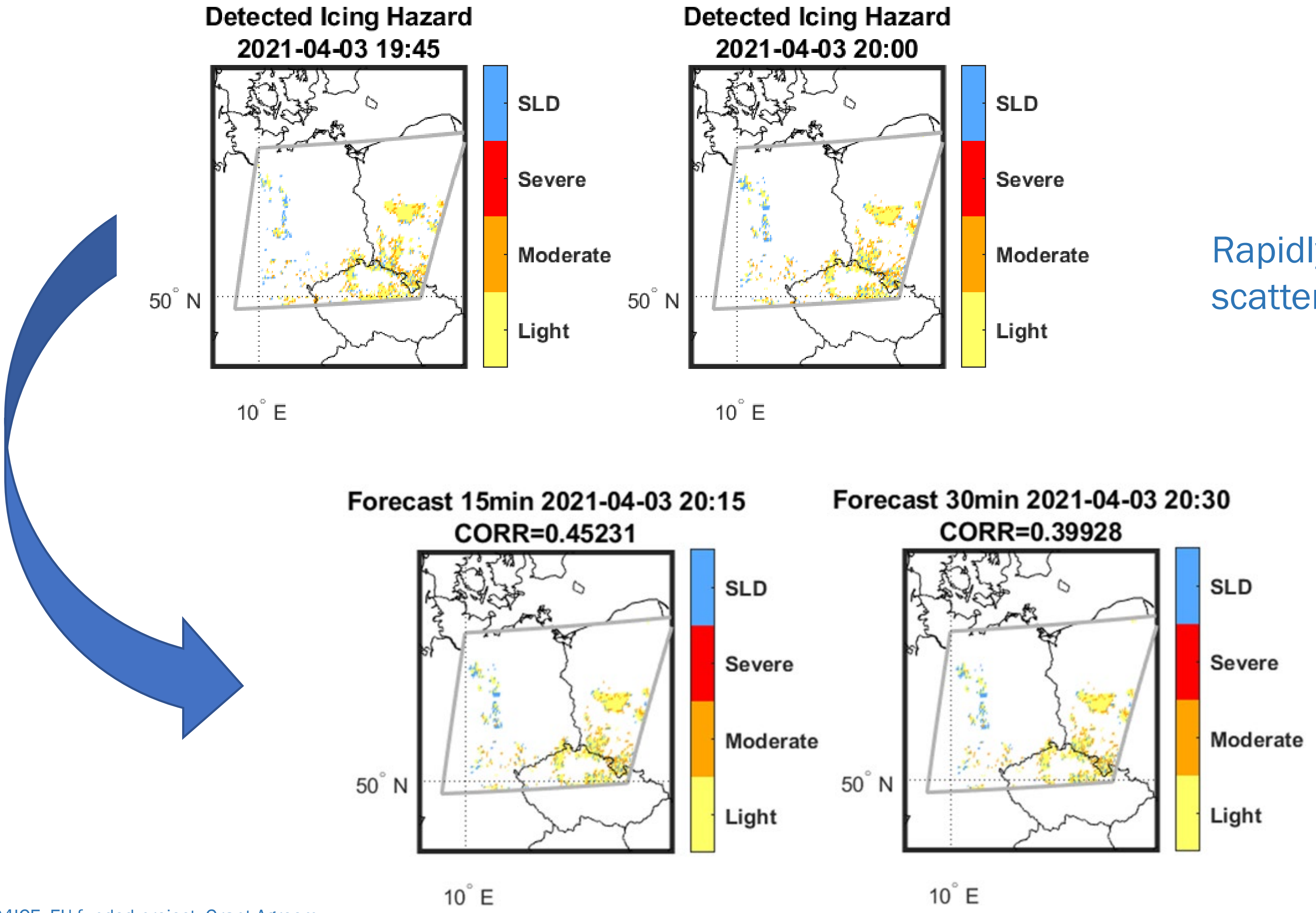
- It was found that the performances vary greatly from day to day: the forecast abilities of nowcasting methods depends on the nature of the event observed.
- Worst results obtained for frames with few icing pixels → these cases are less crucial (not intense events).

Icing nowcasting tool: example of good performances



Slowly changing and quite uniform icing hazard field

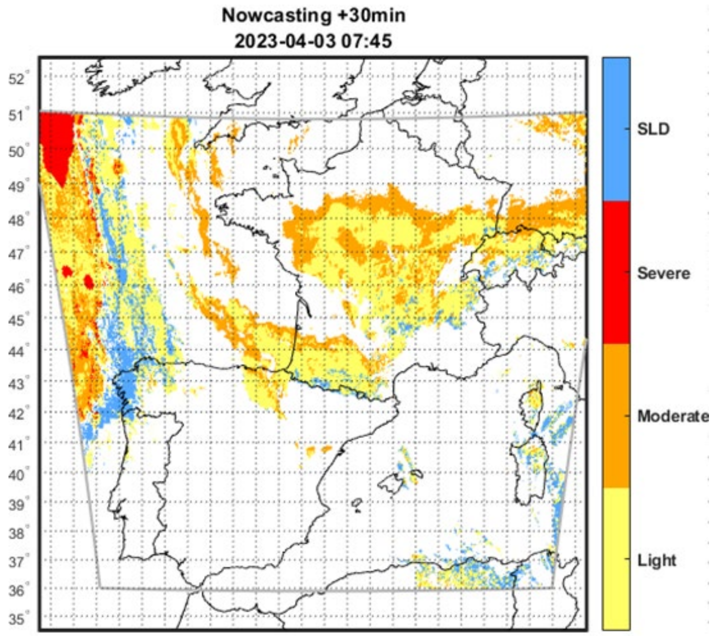
Icing nowcasting tool: example of poor performances



Rapidly changing and quite scattered icing hazard field

Ongoing and future work

- These tools have been used during the **SENS4ICE flight campaign** held in April 2023.
- During the flight test campaign, information on monitoring and nowcasting of icing conditions have been provided in the pre-flight phase and updated in near-real time.
- Considering the challenge of validating such a kind of product, the SENS4ICE flight campaign represents an important chance to evaluate the performance of the tool in environmental icing conditions.
- The analysis of post-flight data is ongoing with the aim to verify the level of probability of detection and false alarm rate of the tool.
- The results of this validation will be used to identify the strengths and weaknesses of the tools and the needed steps for their future maturation and exploitation.
- Further improvements can be expected in the near future thanks to innovative satellite products with enhanced cloud retrieval techniques.



Conclusions

- The early detection of regions affected by icing conditions is a challenging and desirable goal in order to increase aviation safety. In this framework, CIRA developed a tool based on satellite data for the remote detection of in-flight icing.

- The tool relies on satellite data, to remotely infer the properties of clouds, and a set of experimental curves and envelopes, as provided by aircraft certification specifications (FAA / EASA), defining the atmospheric icing conditions.

- This product has been utilized as base to develop a nowcasting algorithm based on the extrapolation in time of the current weather condition.

- This presentation has provided a preliminary analysis of the performance of the implemented tools.

- Further investigations are ongoing, regarding the evaluation of the tools in relevant icing conditions using the data of the SENS4ICE flight campaign.

This project has received funding from European Union’s Horizon 2020 research and innovation programme under grant agreement n° 824253.

Thank you

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