June 20-22, 2023
Vienna, Austria

SAE INTERNATIONAL

International Conference on Icing

of Aircraft, Engines, and Structures

sae.org/icing

SENS4ICE

SENSORS AND CERTIFIABLE HYBRID ARCHITECTURES FOR SAFER AVIATION IN ICING ENVIRONMENT

Overview of cloud microphysical measurements during the SENS4ICE airborne test campaigns: contrasting icing frequencies from climatological data to first results from airborne observations

SAE International Conference on Icing

Tina Jurkat-Witschas (DLR)
ET AL

20-22 June 2023

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

ET AL – „no (wo)man is an island“

… Johannes Lucke, Carsten Schwarz, Christoph Deiler, Falk Sachs, Deniz Menekay, Simon Kirschler, Johanna Mayer, Christiane Voigt - Deutsches Zentrum für Luft- und Raumfahrt

Alessandra Zollo - CIRA

Frank Kalinka – Deutscher Wetterdienst

Emilia Sanchez, Christian Pagé - CERFACS

Olivier Jaron and Benoit Vie – Météo France

Aurelien Bourdon and the SAFIRE crew- SAFIRE

Ben Bernstein – Leading Edge Atmosphere

Daniel Da Silva Martin, Luiz Antonio Algodoal Vieira, Carlos Roberta Hardt Lucia Silveira, Rogerio Pereira De Lima - EMB

Lyle Lilie and Dan Bouley - Science Engineering Associates SEA

and the SENS4ICE team

Overview

- Motivation
- Assessment of Climatological Means of Icing Conditions for targeted time and altitude of the SENS4ICE campaigns
- Overview on microphysical reference instrumentation
- First preliminary data of icing conditions during the SENS4ICE US campaign and the SENS4ICE EU Campaign

Motivation

- **Validation of new sensor technologies** tested in real icing conditions on aircraft require robust characterization of **LWC, MVD, particle size, number and phase -> measurements with well known, established “reference sensors”**

- Generally **data on atmospheric conditions** that allow the formation of SLD **sampled in Europe** are still rare

- Atmospheric conditions that lead to **aircraft icing at higher altitudes** are rare

- **Numerical weather prediction models** and icing forecasts need defined, high resolution measurements to **validated** their products

- **Icing climatologies (based on NWP or measurement data)** help to assess the best location for aircraft campaigns to test sensors in relevant conditions

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SENSORS AND CERTIFIABLE HYBRID ARCHITECTURES FOR SAFER AVIATION IN ICING ENVIRONMENT

Assessment of Climatological Means of Icing Conditions for targeted time and altitude of the SENS4ICE measurements

Deutscher Wetterdienst
Wetter und Klima aus einer Hand
DWD

CERFACS
CENTRE EUROPÉEN DE RECHERCHE ET DE FORMATION AVANCÉE EN CALCUL SCIENTIFIQUE

METEO FRANCE

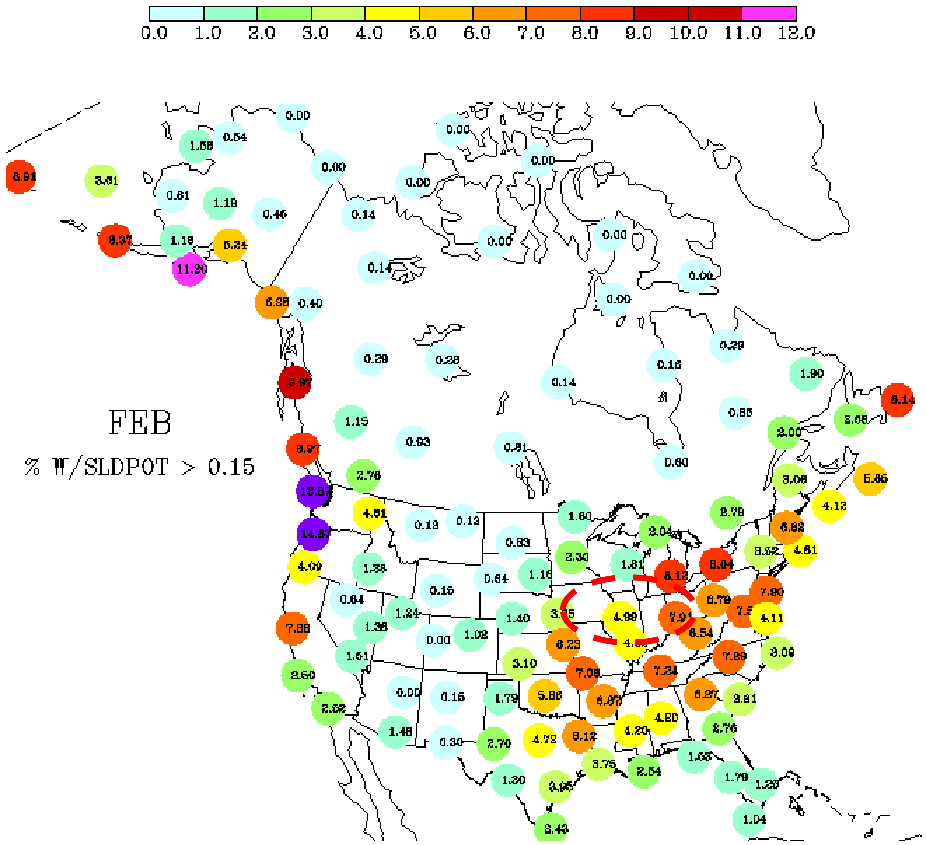
cnrs
www.cnrs.fr

CIRA
Italian Aerospace Research Centre

METEO FRANCE

LEA
Leading Edge Atmospherics

Climatology of icing (SLD) in the US



From study by Bernstein et al., 2007

- Product for SLD icing potential derived from 15 years of data (1997-2001) using CIP-sonde icing algorithm, combining coincident profiles of
  + weather balloons
  + surface observations
- SLD potential was derived from counting sounding with values above 0.15, indicating that there is a small chance of SLD
- Here shown full column for the month of February
  → months of the campaign
- Regions with enhanced SLD are the Northwestern coastal region and from the South Central U.S. through the Southern Great Lakes and Mid-Atlantic
- Further requirements: areas of flat terrain and low air traffic choose the operations base for the Phenom 300

Climatology of icing (incl. SLD) in Europe

- Complimentary data sets were used to assess **the question on the best location for stationing SAFIRE'S ATR-42 in April in Europe.**
- Three more recent data sets:

1.) ADWICE –ICON (Deutscher Wetterdienst)
2.) ICEP – ERA5 (CERFACS)
3.) MSG Satellite retrieval (CIRA)

Important safety requirements for SLD encounters (severe icing) of the aircraft had to be considered
- 8000ft of min. altitude
- warm air layer (T> 0°C) below
- no air traffic or complex terrain below

in order to allow the aircraft to deice before continuation of the flight.

These requirements were included in the climatological assessment.

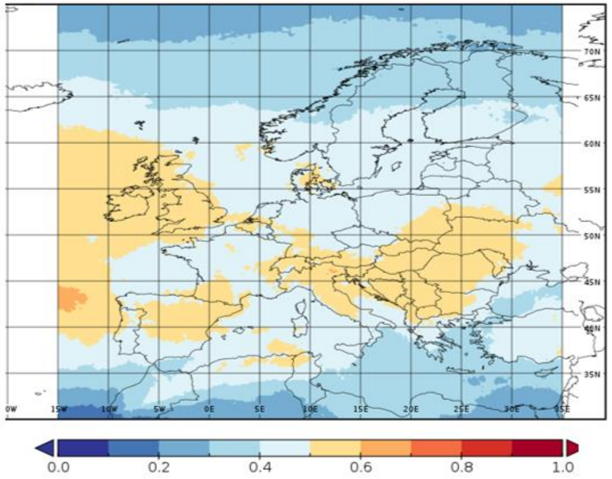
Icing frequencies from ADWICE (DWD)

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

Provided by Frank Kalinka

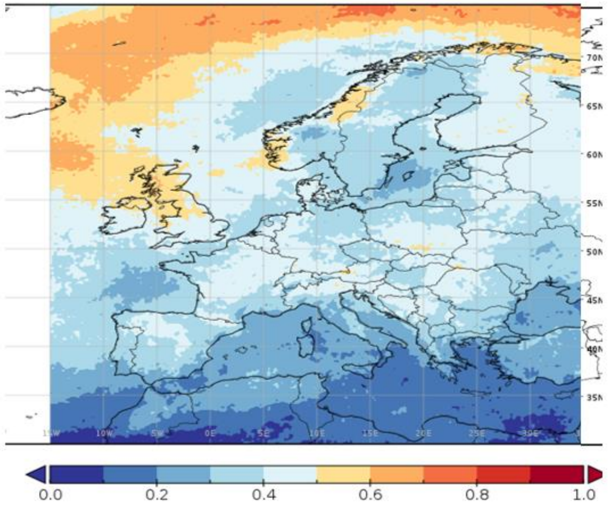
Above 750 hPa

All icing conditions



All altitudes

Moderate and severe conditions



- ADWICE (**Advanced Diagnosis and Warning System for Aircraft Icing Environments**) reforecasts from 2015 till 2020
- ICON model with a resolution of 0.25° x 0.25°
- total of 16950 h of data
- hourly resolution, 4 times daily revised on 32 pressure levels

Shown here: geographical distribution of the mean frequency of icing in April

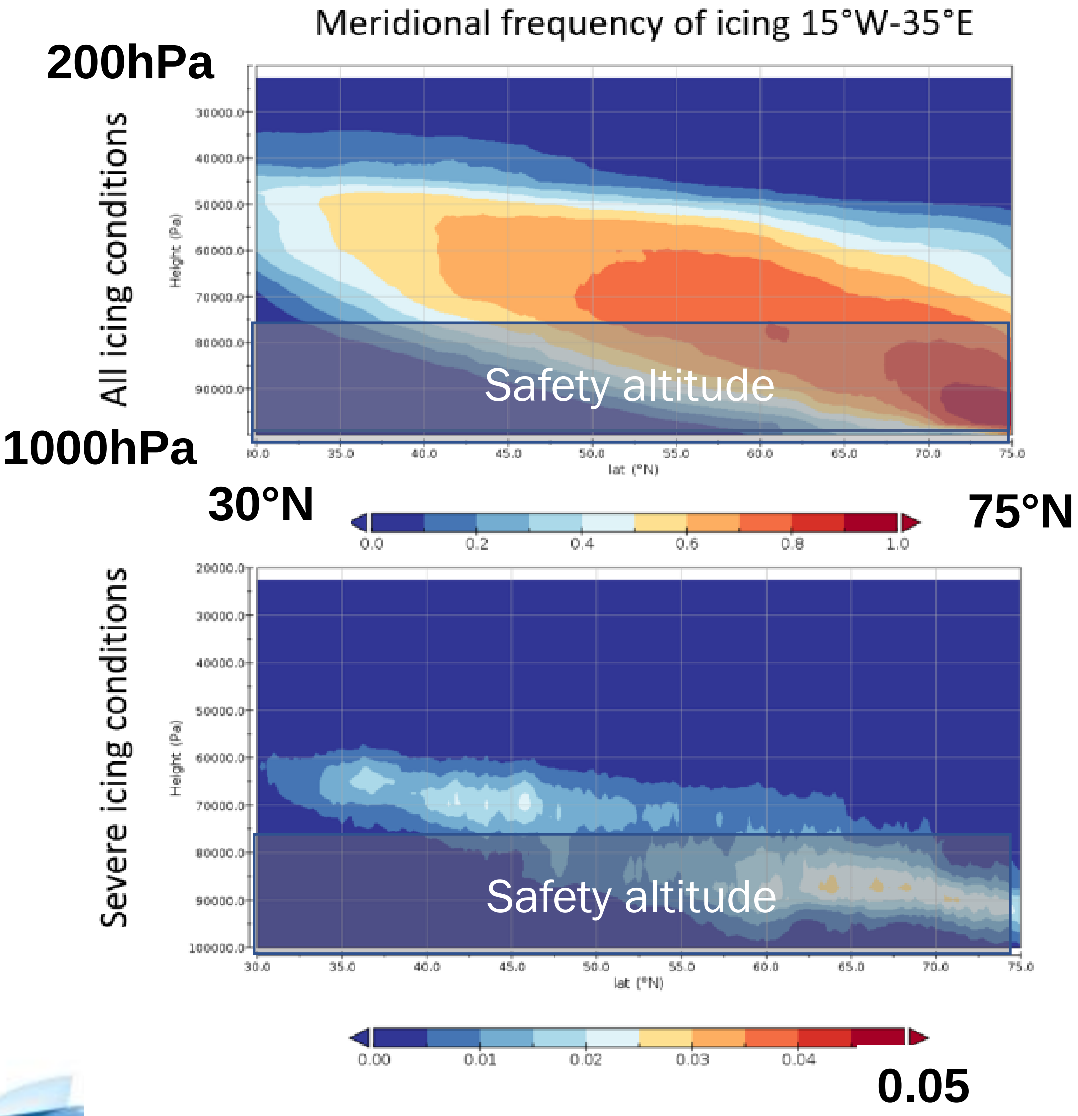
Moderate and severe icing is most frequently indicated above the North Atlantic (ground to 350hPa)

For the higher levels (750-350hPa), Southern European countries suggest higher frequencies of icing (Atlantic and Mediterranean Sea)

Icing frequencies from ADWICE (DWD)

DWD
Deutscher Wetterdienst
Wetter und Klima aus einer Hand

Provided by Frank Kalinka



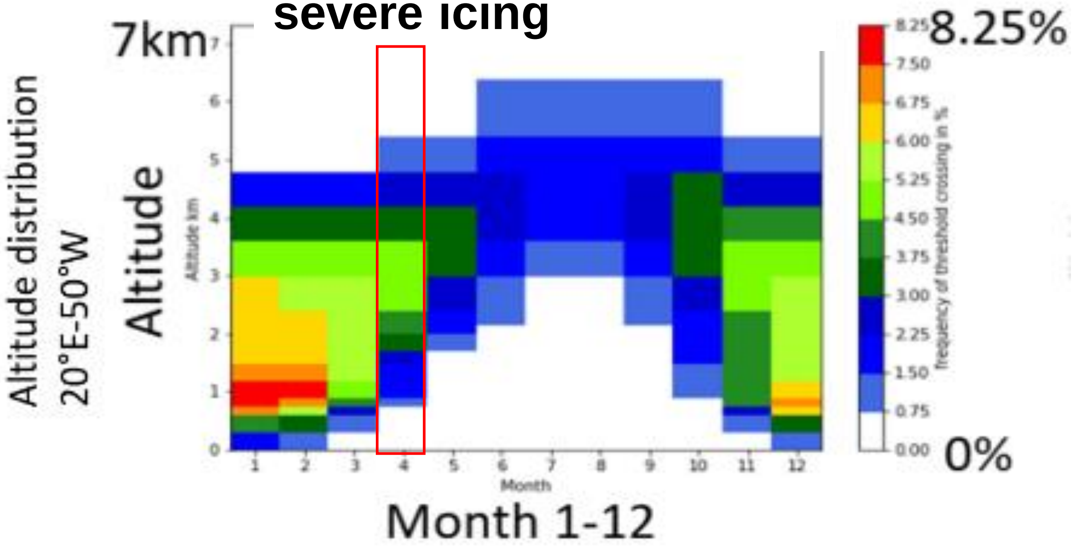
- Meridional cross sections of all icing conditions from long 15°W to 35°E for April
- Northern European countries experience icing at lower altitudes/higher pressures (up to 800hPa)
- Southern European countries show enhanced frequencies up to 400hPa (45-55%)

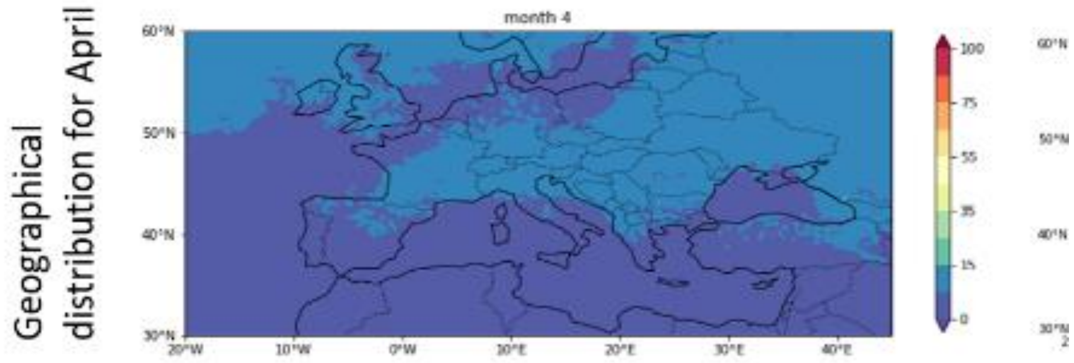
- Severe icing is just a subset of the all icing conditions with a rather low frequency (2%)
- ADWICE estimates these conditions up to 6000 hPa at southern European countries

Icing frequencies from ICEP (CERFACS)

Provided by Chistian Pagé

Indicated potential for severe icing



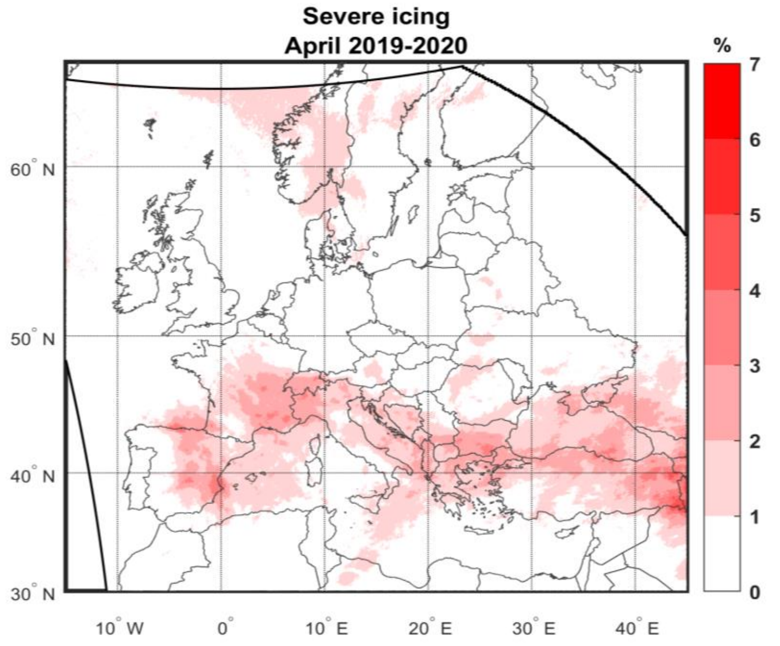


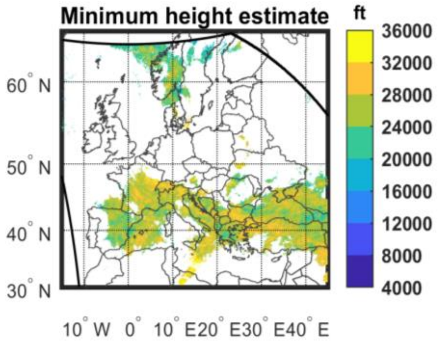
- Icing index from **Météo France's ICE Potential forecast index (ICEP**)
- computed from relative humidity (RHw) and temperature (T) on different atmospheric pressure levels.
- Degree of severity from 0 to 10
- A high icing index (> =8) has a greater potential of severe icing as indicated by ICEP
- In contrast to SIGMA, ICEP does not use satellite, radar or other observational data.
- The data set comprises more than 40 years of ERA-5 data with a resolution of 0.5° on 20 vertical levels
- Annual variability shows probability of icing on the order of ~5% between 2 and 4 km in April

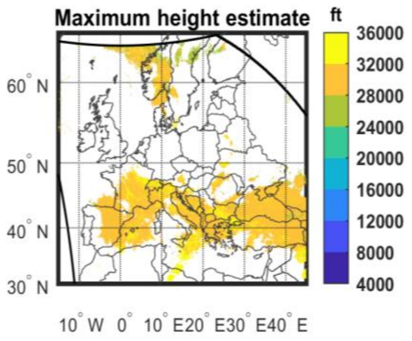
Icing frequencies from MSG retrieval (CIRA)

Italian Aerospace Research Centre

Provided by Alessandra Zollo, CIRA

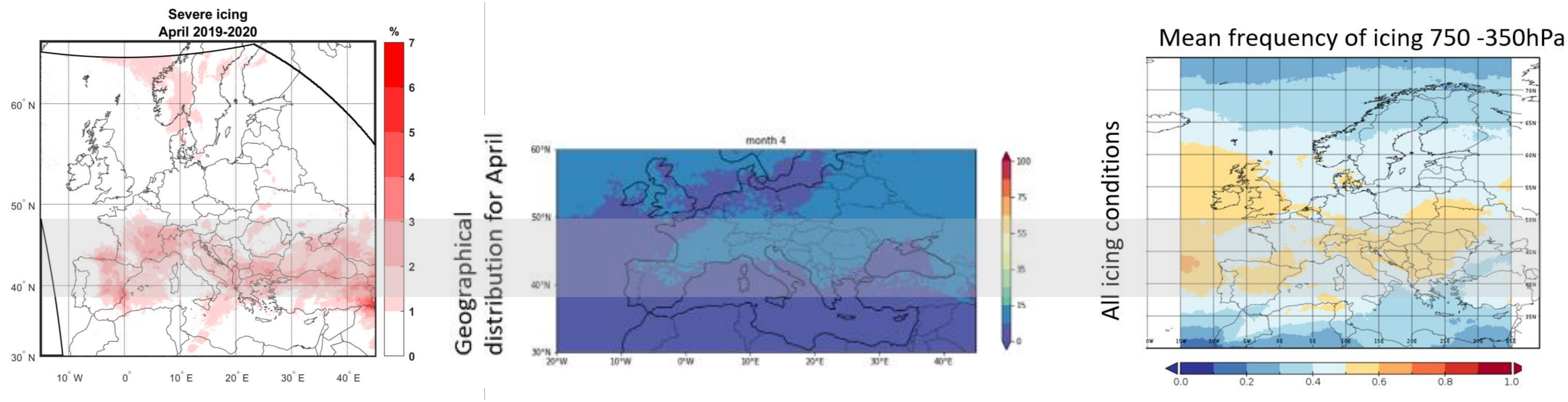






- Satellite images and microphysical properties derived from **Meteosat Second Generation (MSG)** were used to infer severe icing frequencies
- Algorithm developed by CIRA (Zollo et al., this session)
- Spatial and temporal resolution of 3 km and 15 min
- April data from two years 2019 and 2020 are here combined
- Minimum and maximum altitude estimate for indication of severe icing are shown
- Southern European Countries indicate enhanced frequencies (up to 7%)
- Icing may reach up to 30000ft

Summary on climatologies



- Although icing frequencies were based on different data and evaluation methods with a **large spread in their probability of occurrence**, the pattern in each analysis suggests enhanced indicated icing frequencies **in April in Southern France, Northern Spain and the Mediterranean Sea.**
- Toulouse was chosen as the base for operation combing occurrence frequencies and safety requirements in an optimal way

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FOR SAFER AVIATION IN ICING ENVIRONMENT

Overview on microphysical reference instrumentation

Overview SENS4ICE Flight Campaigns

- Total flight time: 75h
- SENS4ICE-US: North America, base Alton, Illinois
  - February/March 2023
  - Embraer Phenom 300 operated by Embraer
  - **15 flights**
  - **25 flight hours**

  Reference instruments operated by EMB and SEA

- **SENS4ICE-EU:** Europe, base Toulouse
  - April 2023
  - French ATR 42 environmental research aircraft of Safire
  - **15 flights**
  - **51.5 flight hours**

  Reference instruments operated by DLR and Safire

Embraer Phenom 300

Copyright © Embraer

SAFIRE ATR 42

Copyright © DLR

Reference instrumentation during SENS4ICE-US

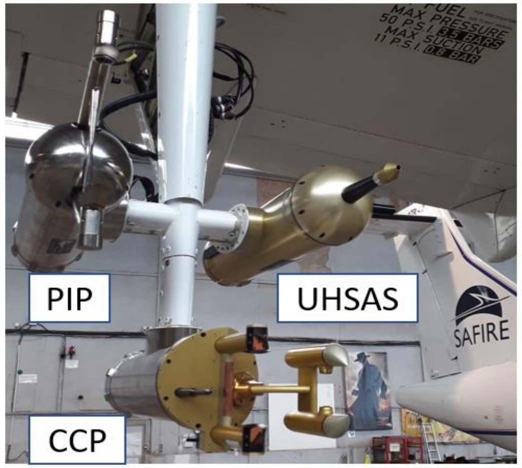

Picture courtesy Dan Bouley

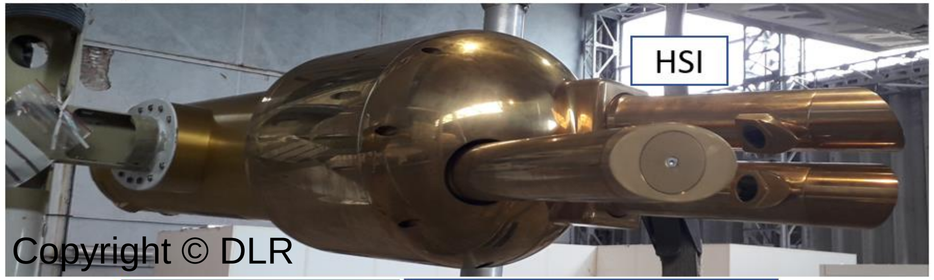
CCP and ice crystal detector on Phenom 300

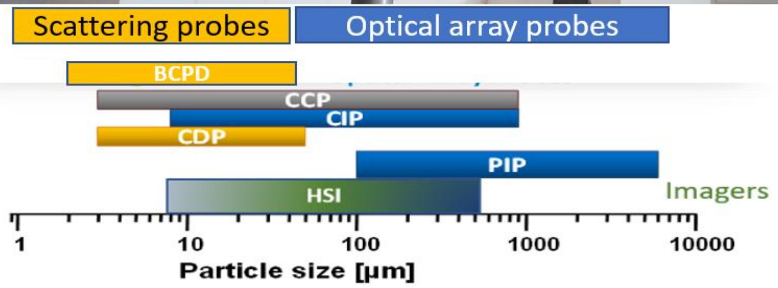
- CCP was used as reference instrument also for SENS4ICE wind tunnel tests (Lucke et al., 2022) to ensure consistent data evaluation

Instrument	Measured parameter	Range	Reference
Ice Crystal Detector	LWC and TWC	0.2 –5 g m^{-3}	Lilie, et al., 2021
Cloud Combination Probe (CCP)	Cloud droplet number and size	2 – 960 µm	See also Lucke et al., 2022, AMT

Reference instrumentation during SENS4ICE-EU



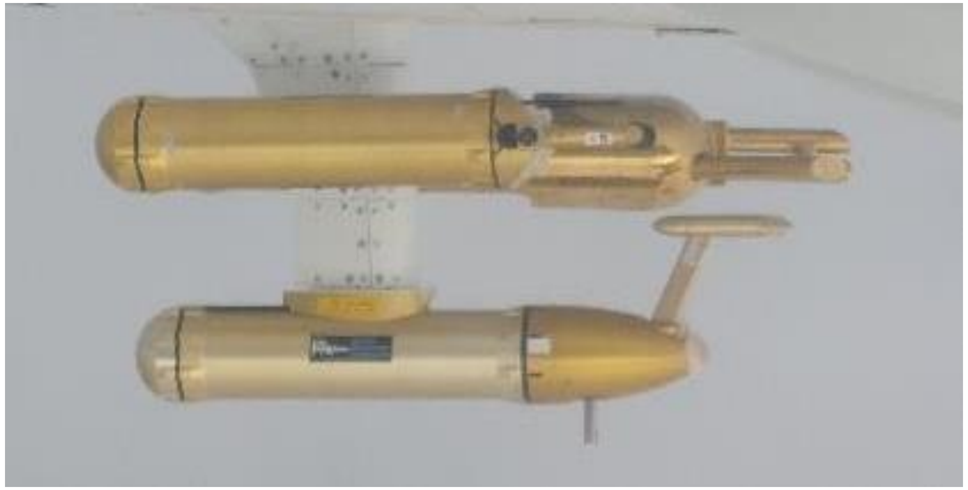




Instruments for measurements of microphysical properties comprise :

- Particle size distribution: CCP and PIP
  2 -6400 µm
- LWC, TWC : Nevzorov 0.03 -3 g m^{-3}
- Particle shape and information on phase :
  HSI (High Speed Imager) and BCPD (Backscatter cloud probe)
- Icing detection: Robust Probe (Safire)
- Aerosol number and size :UHSAS (Safire)

Reference instrumentation during SENS4ICE-EU



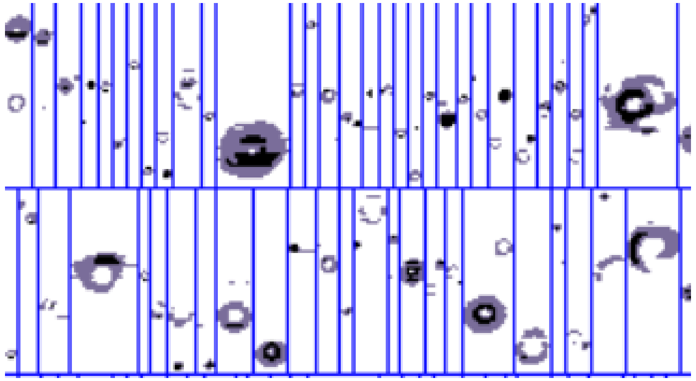
Ice accretion on reference sensors observed during test flight (© DLR)

Instrument	Measured parameter	Range	Reference
Cloud Combination Probe (CCP)	Cloud droplet number and size	2 – 960 µm	Lucke et al., 2022
Precipitation Imaging Probe (PIP)	Cloud droplet and ice crystal number number and size	100-6400 µm	De La Torre Castro, et al., 2023
High Speed Imager (HSI)	Droplet and Ice particle size and complexity	2-2000 µm	Esposito, et al., 2019
Nevzorov Probe	LWC and TWC	0.03 –3 g m^{-3}	Korolev, et al., 1998 Lucke, et al., 2022
Backscatter Cloud Probe with Polarization Detection	Droplet and ice crystal size and asphericity (phase)	2- 42 µm	Lucke et al., 2023

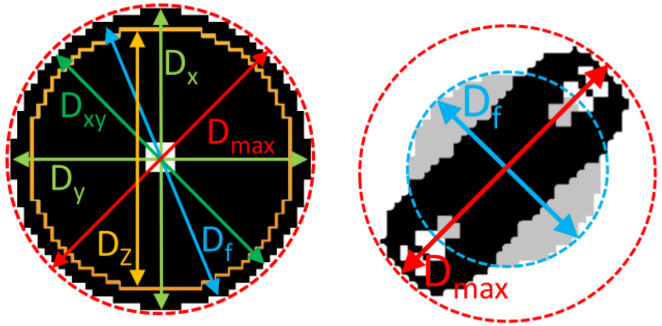
Data evaluation

provided by Johannes Lucke and Deniz Menekay

- Optical array probe measurements from the CIP are used to provide
  - particle size distribution (in combination with CDP)
  - shape analysis (differentiate ice particles from droplets)
- Filter for 3 kinds of particles: SLD, small droplets, ice crystals
- The filters are not perfect: Number of detected particles of each category tends to be underestimated → future work!
- Some ambiguities (especially between out-of-focus ice crystals and SLD) are possible
- Further corrections: Shattering correction, out-of-focus correction, all-in method, stuck-bit and air speed correction



CIP Grey scale images
15 µm resolution
75% greyscale level



Dissertation
S. Kirschler and E. De La Torre Castro

Classification of icing and SLD encounters

provided by Johannes Lucke and Deniz Menekay

SLD:

LWC > 0.025 g m^{-3}

Large ice crystal > 1 L^{-1} (Cober & Isaac 2012) → sample out ice crystals

The LWC SLD > 1% of total LWC (Cober & Isaac 2012)→ ensure significant fraction of LWC

SLD concentration >10 times ice particle concentration → avoid mixed phase

SLD concentration > 100 m^{-3} ~ 0.0001 L^{-1} → ensure good statistics

The Nevzorov LWC > 60% Nevzorov TWC measurement → consider size range of Hotwire probe

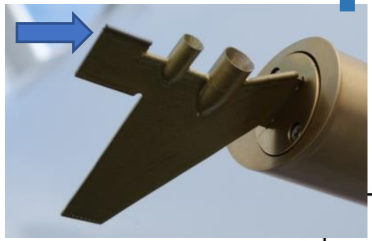
Ambient temperature (SAT) <0°C

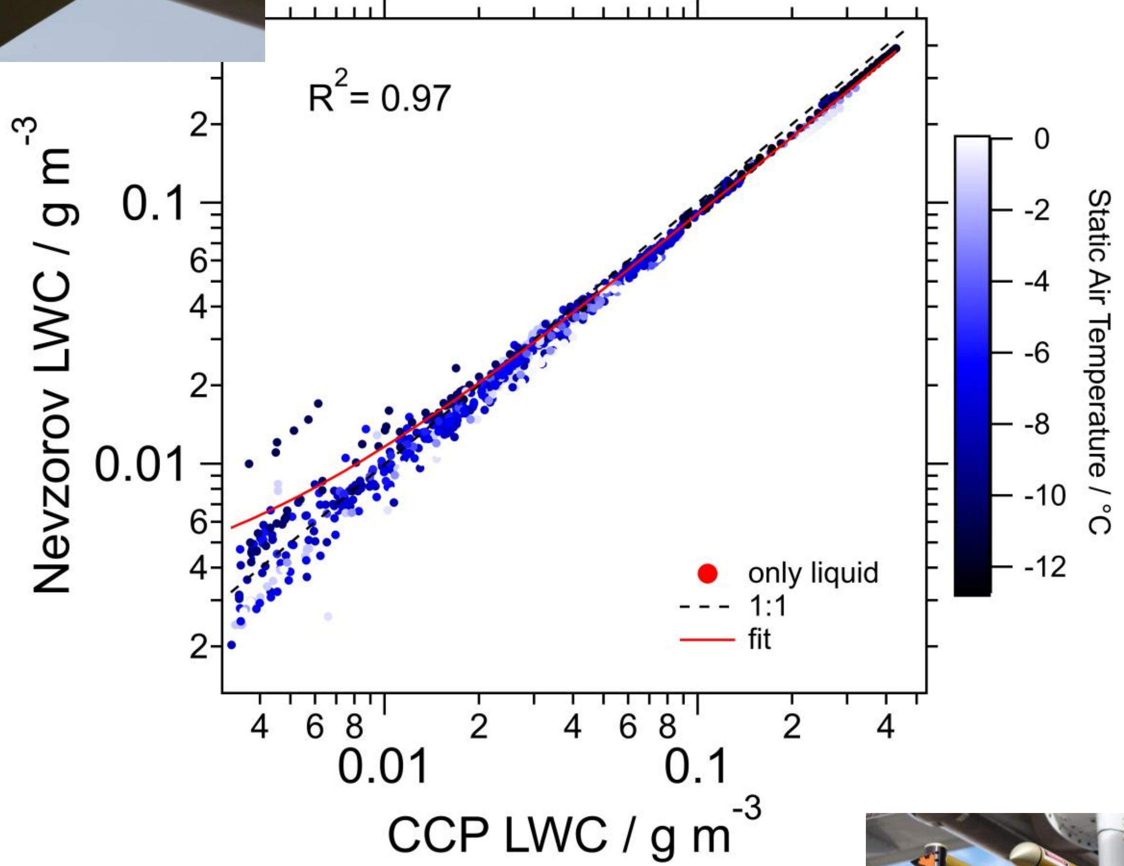
Icing:

LWC > 0.025 g m^{-3}

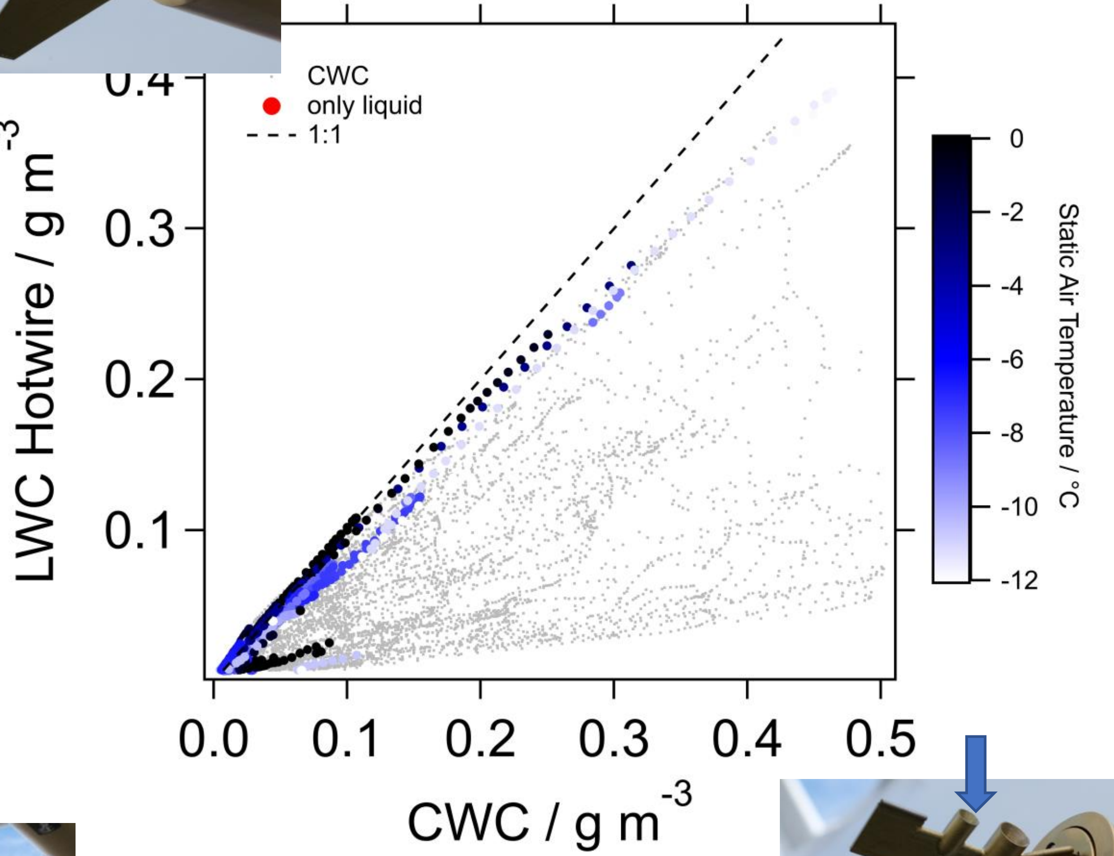
Ambient temperature (SAT) <0°C

Comparison of LWC from Nevzorov and CCP

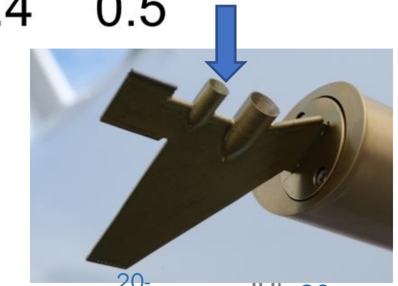




Preliminary data of OF13



- Filters (liquid-ice) seemed to be working good
- Sizing (volume) seems to be appropriate

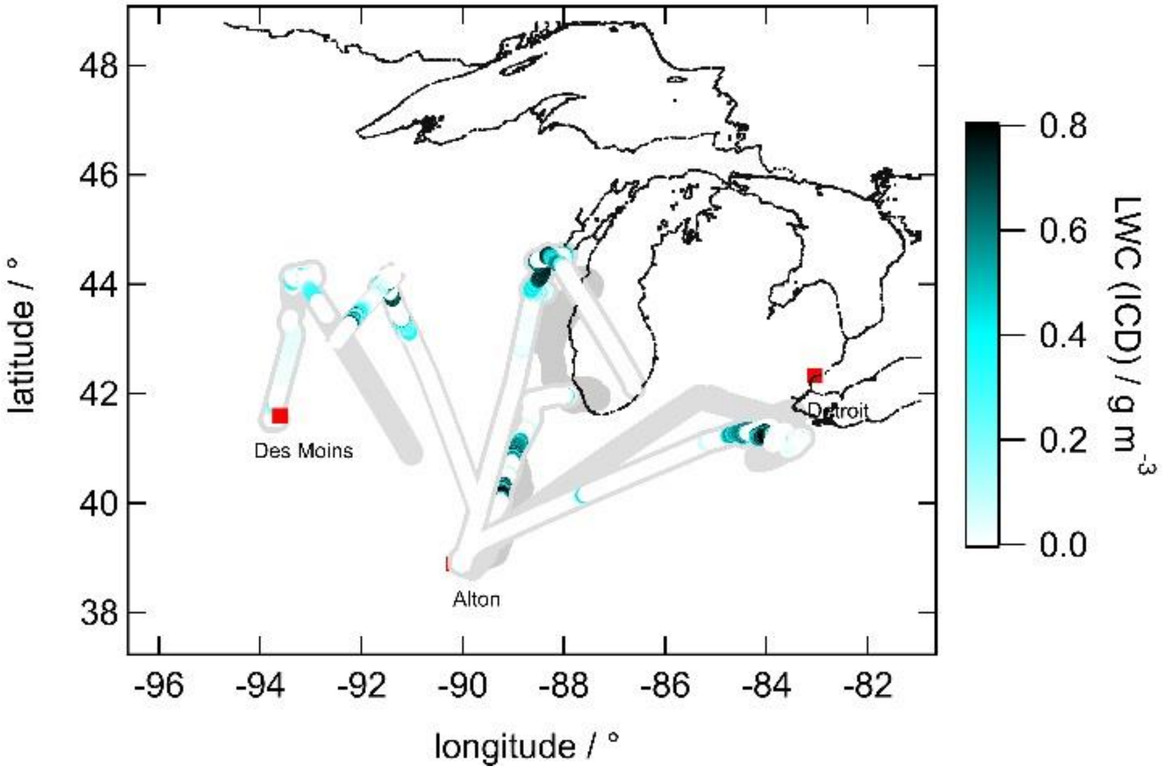


SENS4ICE

SENSORS AND CERTIFIABLE HYBRID ARCHITECTURES FOR SAFER AVIATION IN ICING ENVIRONMENT

First preliminary data of microphysical cloud properties during the SENS4ICE-US and the SENS4ICE-EU Campaigns

Overview of measurements during SENS4ICE-US

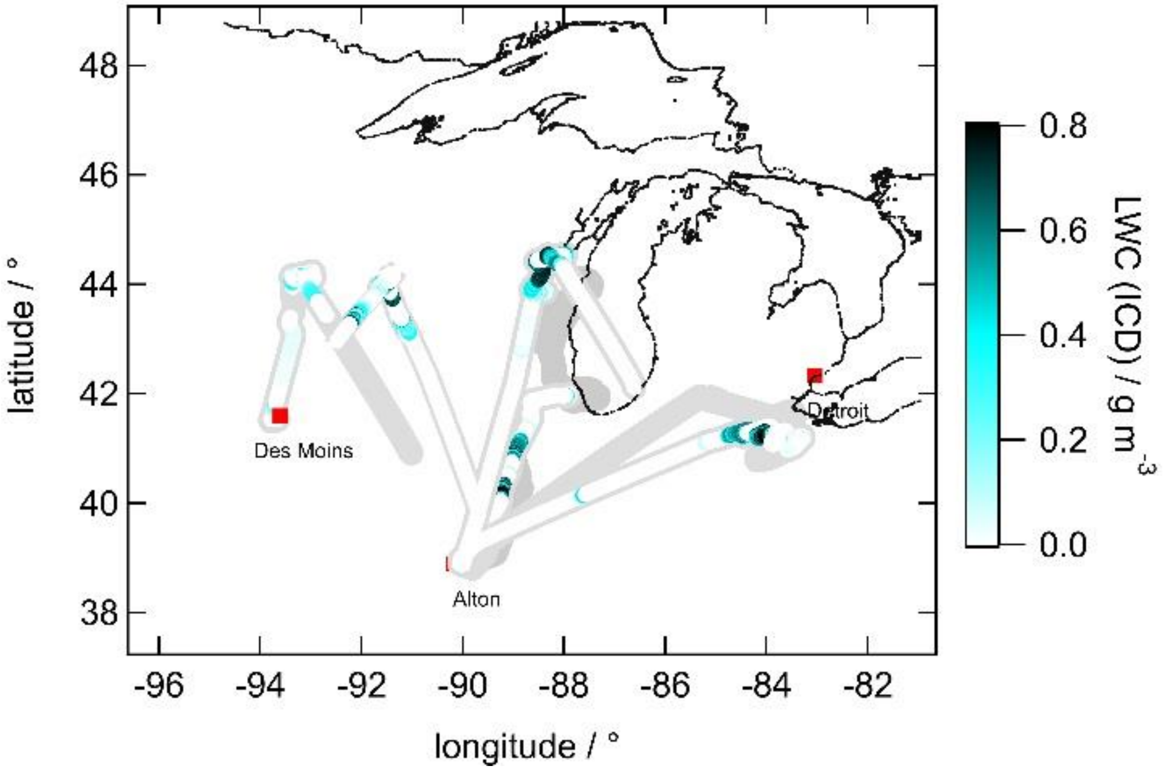


Geographic distribution of supercooled water encounters (grey areas== no clouds)

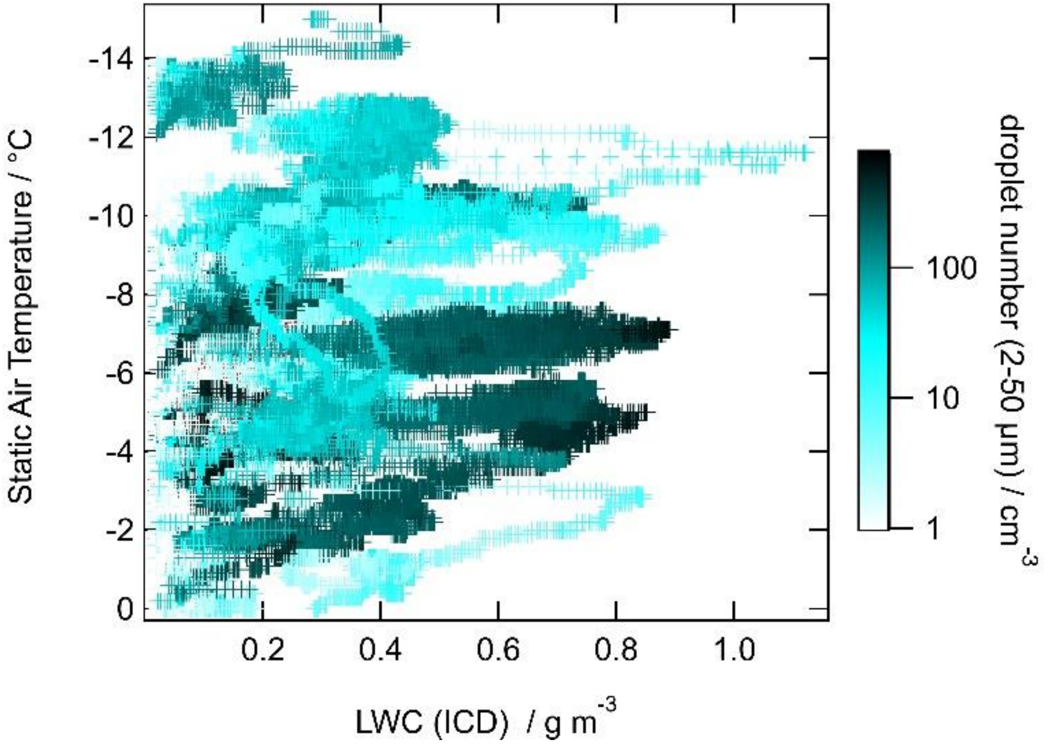
No	Date	Flight duration [hrs]	Comment
1	22 FEB	0:39	Check flight
2	23 FEB	2:45	Appendix O
3	23 FEB	1:12	Appendix C
4	25 FEB	2:03	Appendix O
5	25 F		Appendix C
6	01 MAR		Appendix O
7	01 MAR		dix O
8	06 MAR	1:07	endix C
9	06 MAR	-	y Air
10	08 MAR	2:21	Appendix O
11	08 MAR	0:40	Return to base
12	08 MAR	-	Check flight
13	09 MAR	1:23	Appendix C
14	10 MAR	2:15	Appendix O
15	10 MAR	1:08	Appendix C

Instruments worked during all flights!!

Overview of measurements during SENS4ICE-US



Geographic distribution of supercooled water encounters (grey areas== no clouds)

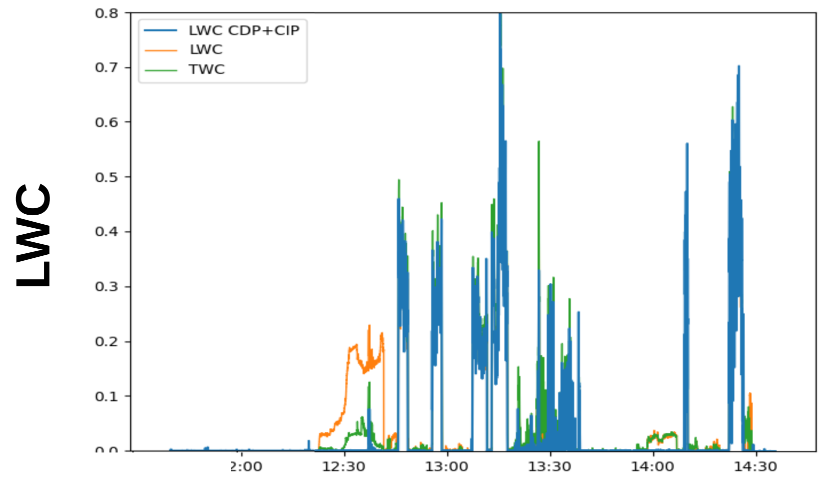


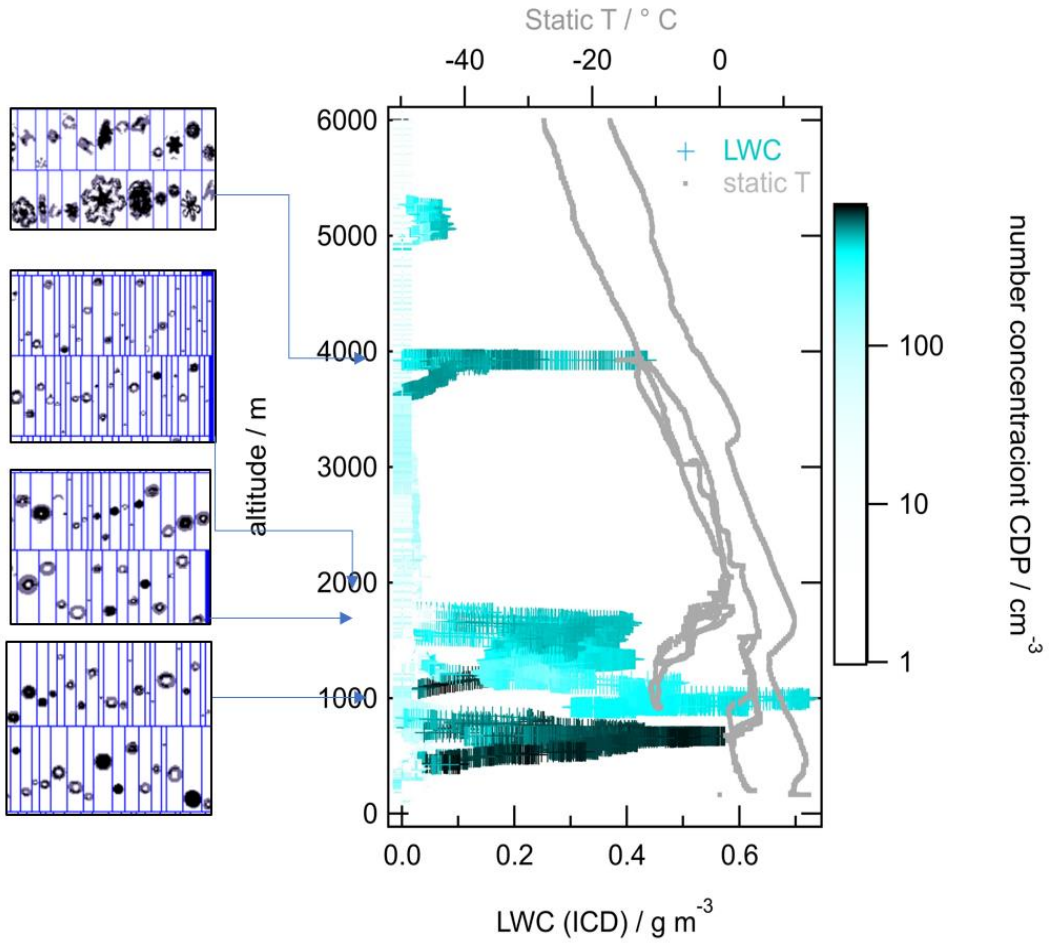
Temperature profile of LWC (ICD) of 8 flights during the SENS4ICE-US campaign

→ See also: Jaron, Bernstein et al., this session

Selected case from SENS4ICE-US

- Flight on 23 Feb 2023
- Good agreement of ICD and CCP+CIP LWC
  → gives confidence in the data
- SLD present (< 0.1 g m^{-3}) but small droplets prevalent
- found SLD MVD (D> 100 µm) reach up to 250 µm
- Further data evaluation needed



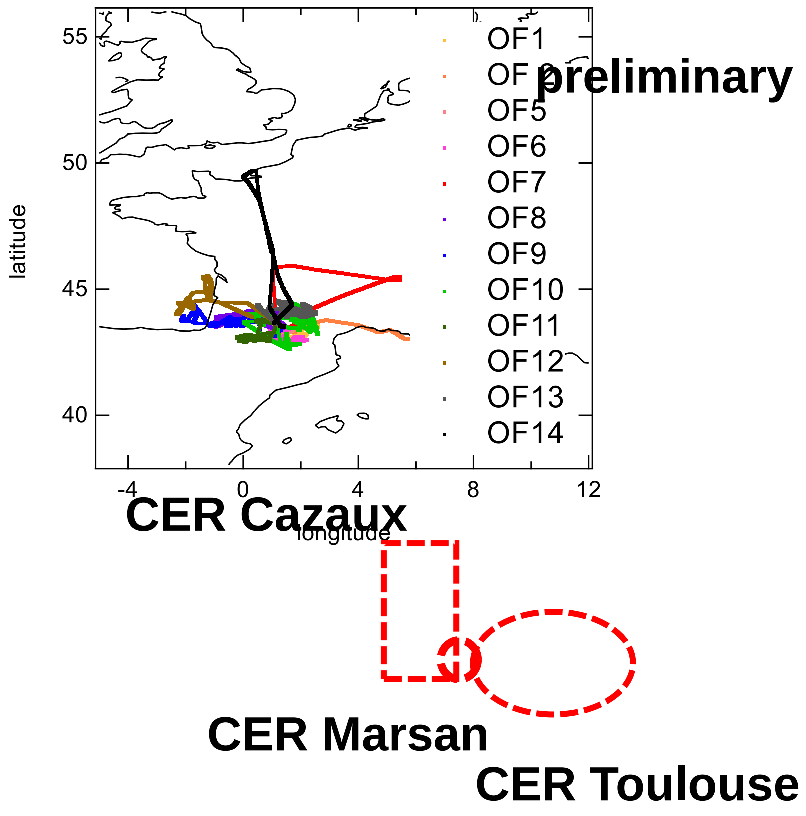


Layer 1: large droplets

Layer 2: small droplets

Preliminary data

Overview of measurements during SENS4ICE-EU



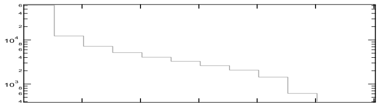
	No.	Date	Area
★	4 (OF1)	03.04	CER Toulouse
★	5 (OF2_1 & 2_2)	04.04	Airways (Toulon)
	6 (OF3)	[illegible]	Aborted (de-icing problem)
	7 (OF4)	[illegible]	CER Cazaux & Toulouse
★★★	8 (OF5)	[illegible]	CER Toulouse
	9 (OF6)	18.04	[illegible]se
	10 (OF7)	20.04	[illegible]Grenoble)
	11 (OF8)	22.04	CER [illegible] Marsan
★★★★	12 (OF9)	24.04	CER Cazaux & Marsan
★★★	13 (OF10)	25.04	CER Toulouse & Marsan
	14 (OF11)	26.04	CER Toulouse
★	15 (OF12)	26.04	CER Cazaux
★	16 (OF13)	27.04	CER Toulouse
★★	17 (OF14)	27.04	Airways (Le Havre)

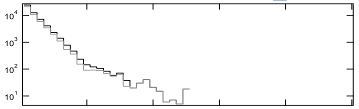
Instruments worked during all but one flight!!

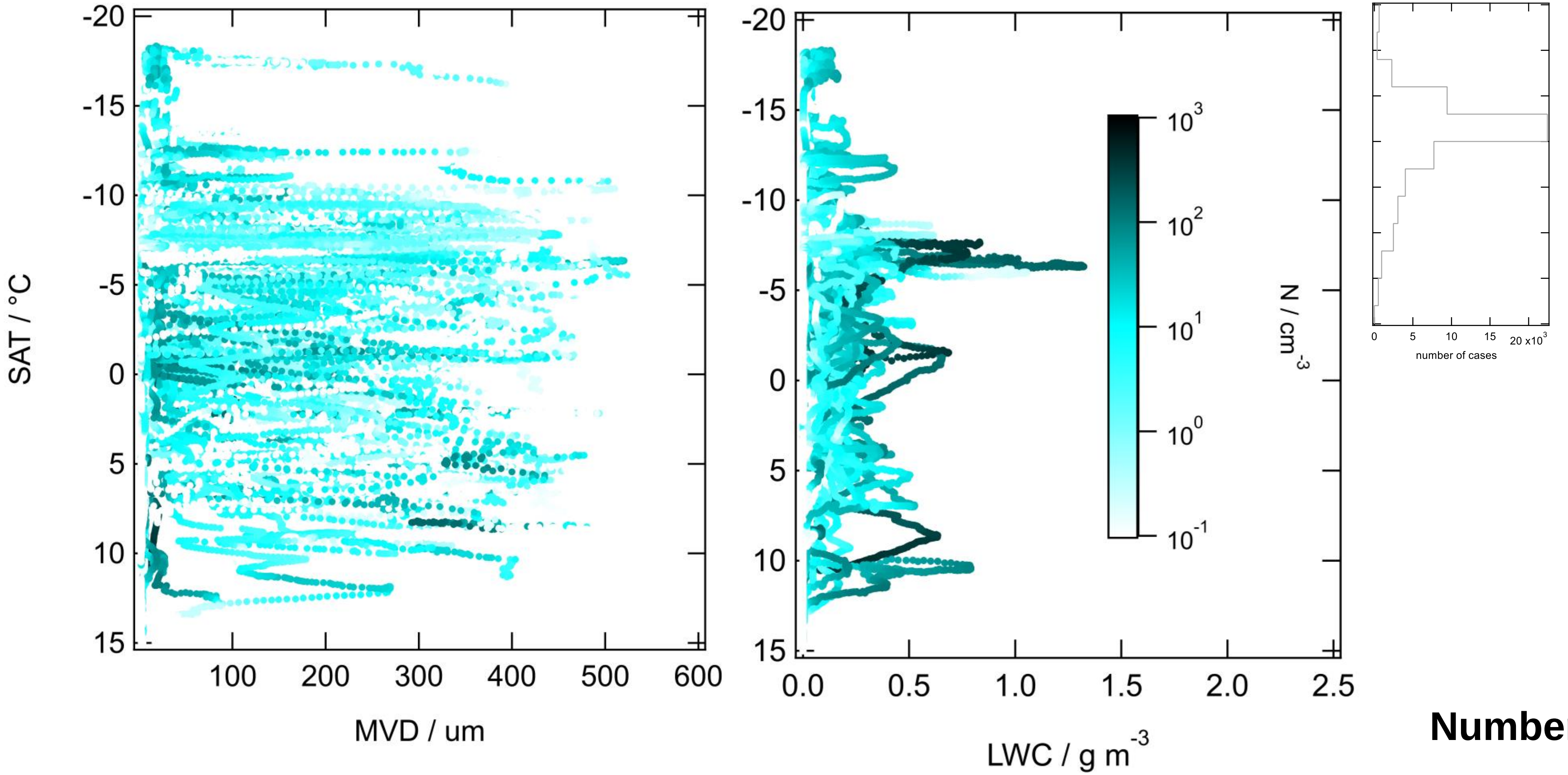
Track source : https://safireplus.aeris-data.fr/data-access

Overview of SENS4ICE-EU microphysical measurements

Number of cases







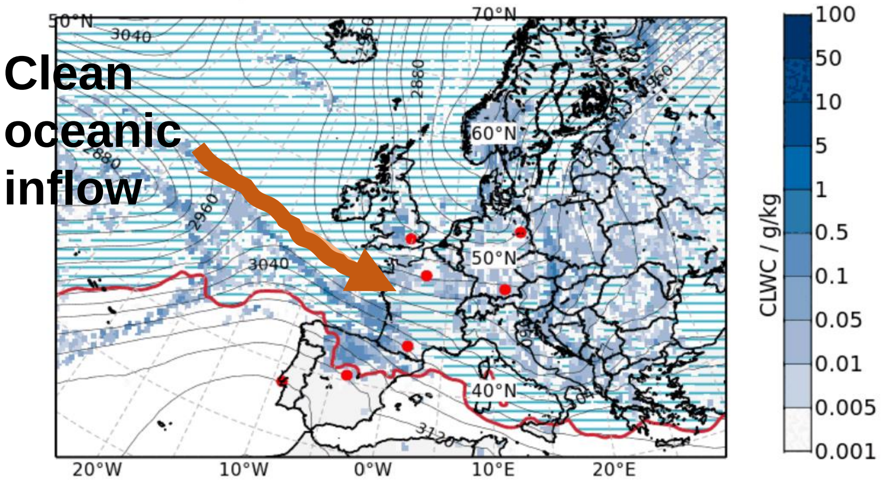
Number of cases

Preliminary data

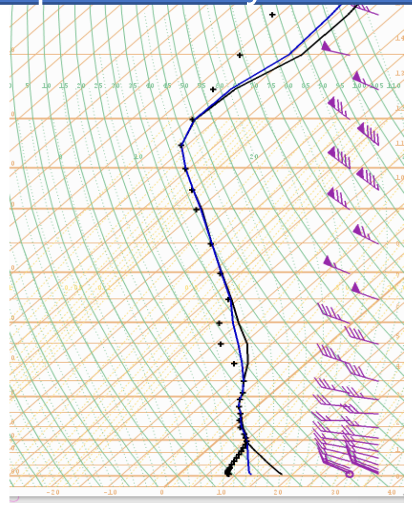
Selected case from SENS4ICE-EU: OF09

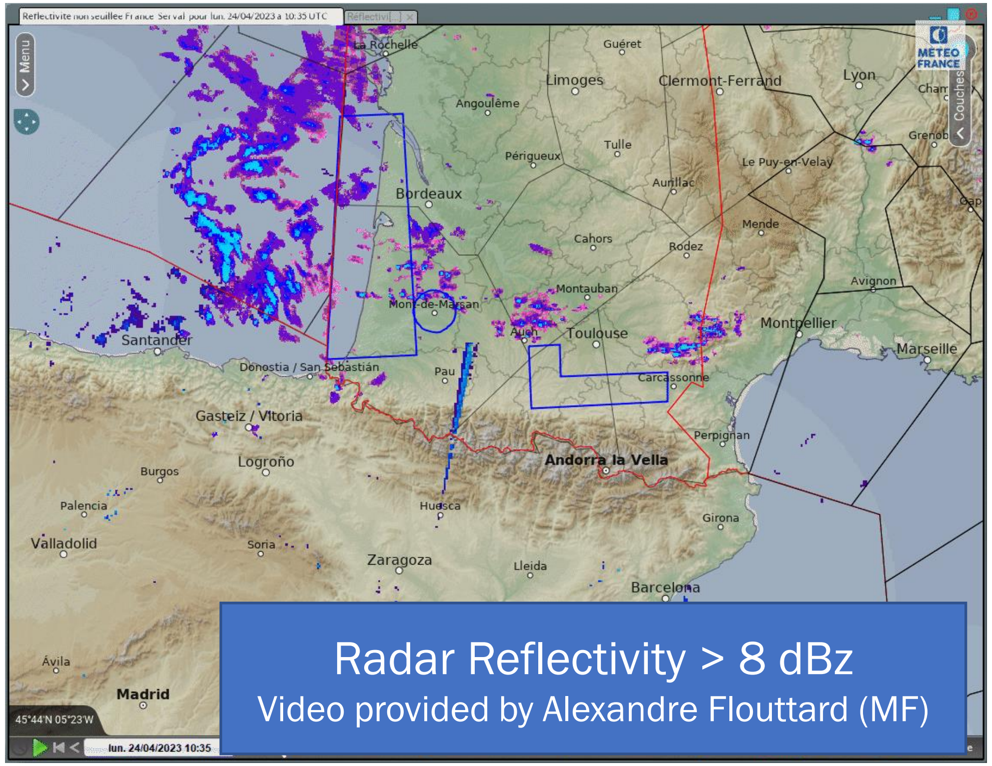
Master thesis
Deniz Menekay

ECMWF CLWC at 700hPa © DLR



Model: Scewed T-Diagram provided by MF



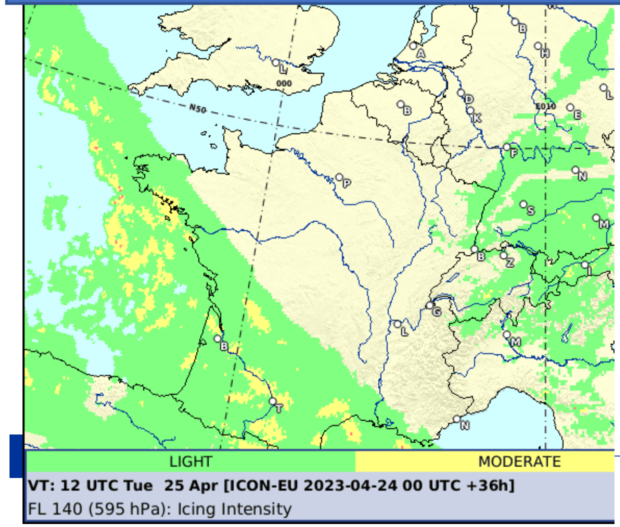


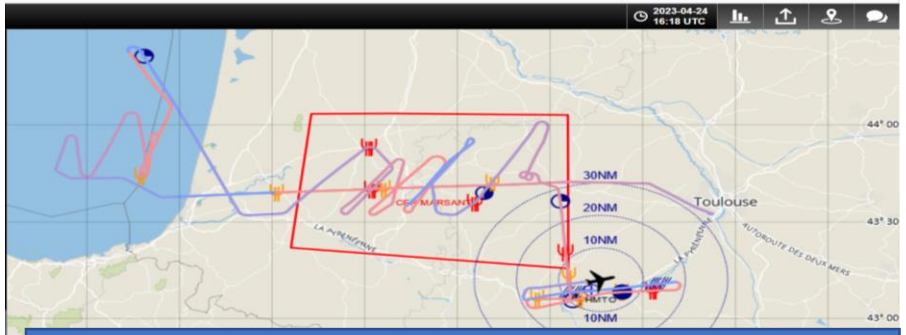
Radar Reflectivity > 8 dBz
Video provided by Alexandre Flouttard (MF)

Lagrangian tracking of a warm front with supercooled liquid water over 4 hours

High frequency of icing encounters thanks to excellent forecast and flight guidance!

ADWICE forecast © DWD





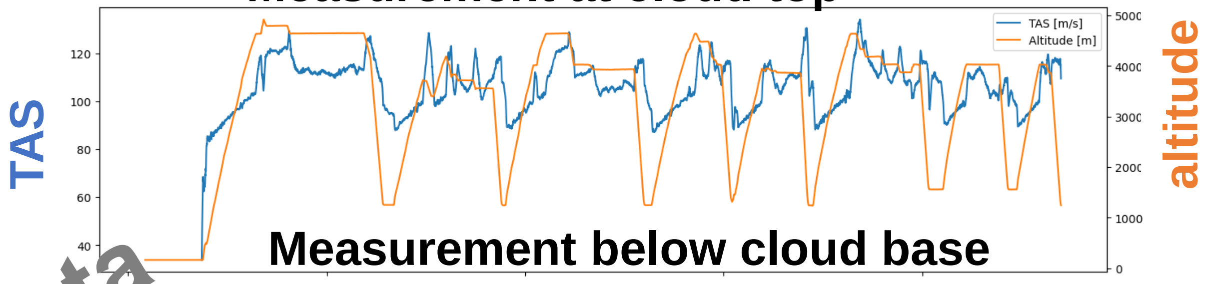
Planet with icing encounters © SAFIRE

Selected case from SENS4ICE-EU: OF09

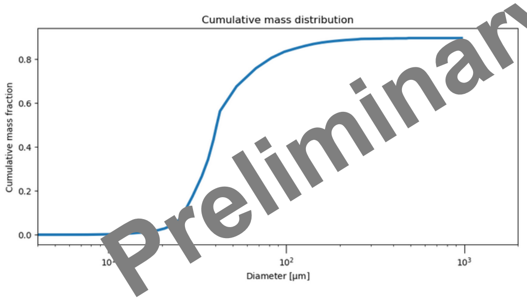
Master thesis
Deniz Menekay

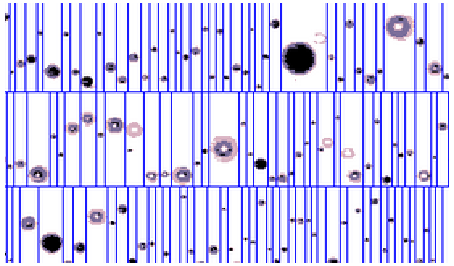
OF09 – 24 April 2023

- Lagrangian tracking of the cloud with SLW
- Total icing duration: 1:30:57
- SLD duration: 0:20:19
- 34 SLD encounters (10 s min. duration)

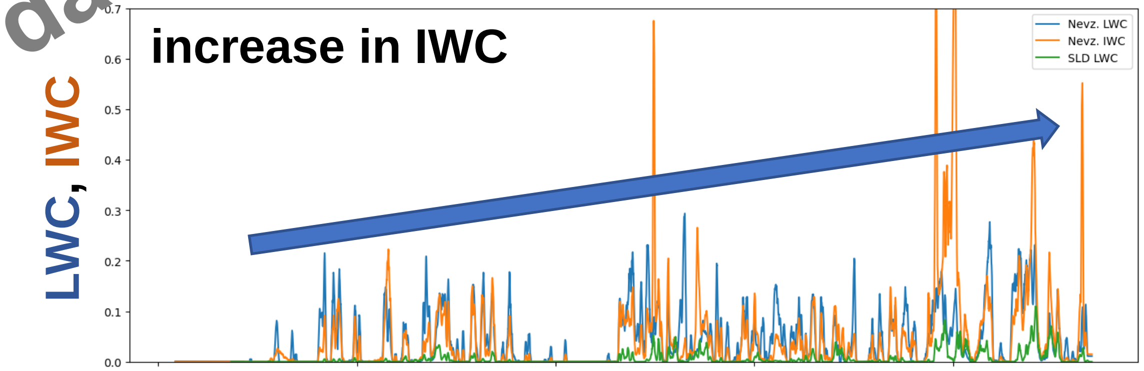


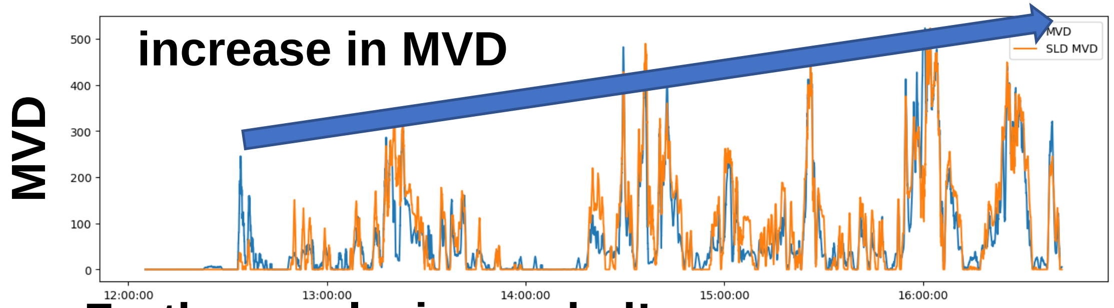
Preliminary data

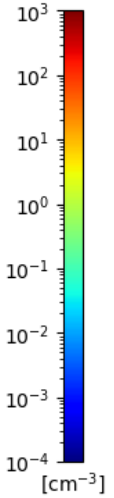


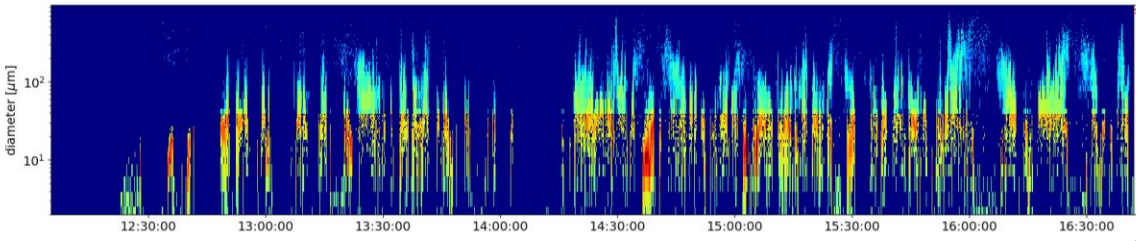


Images at 12:52 UT



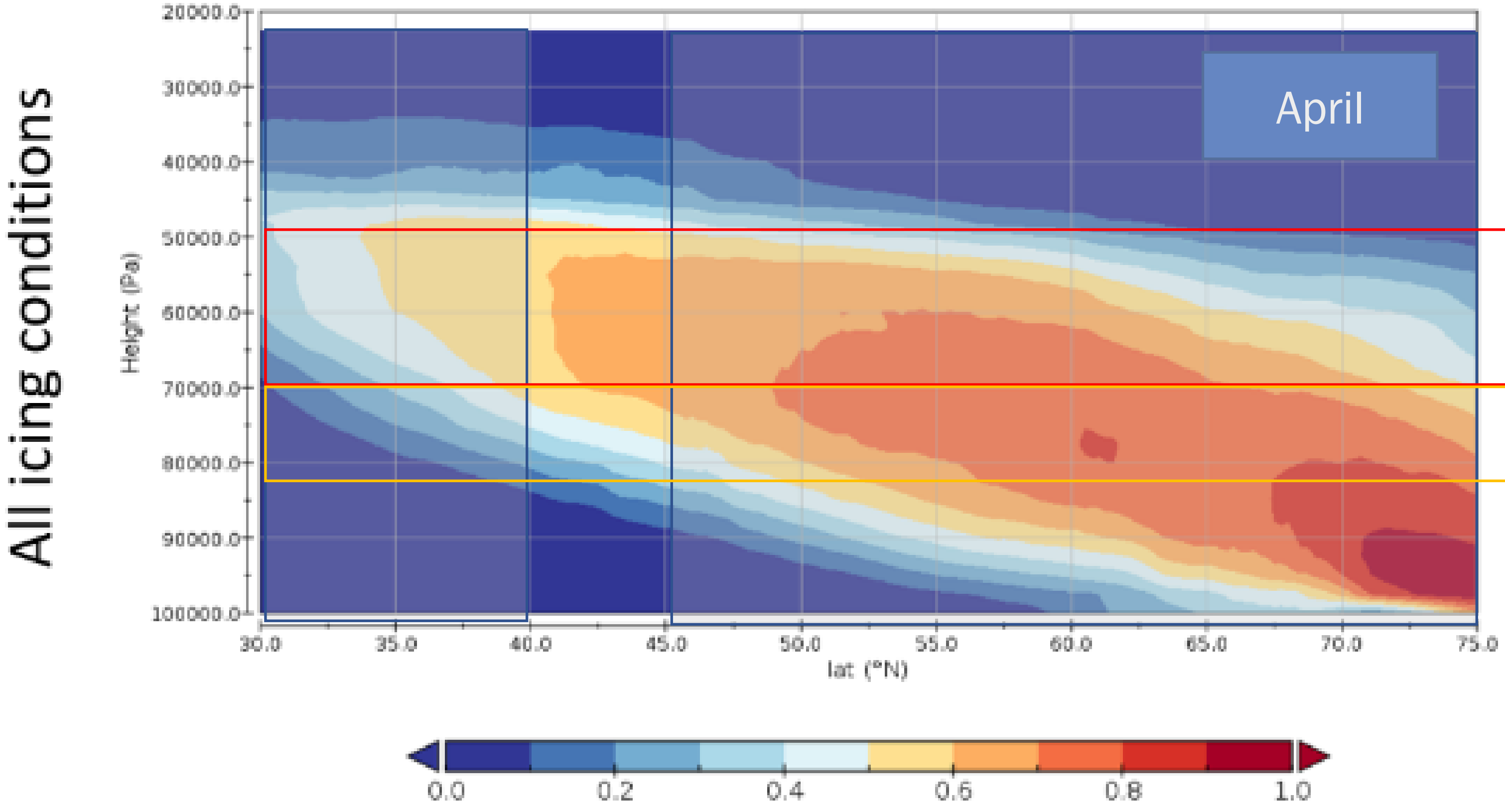




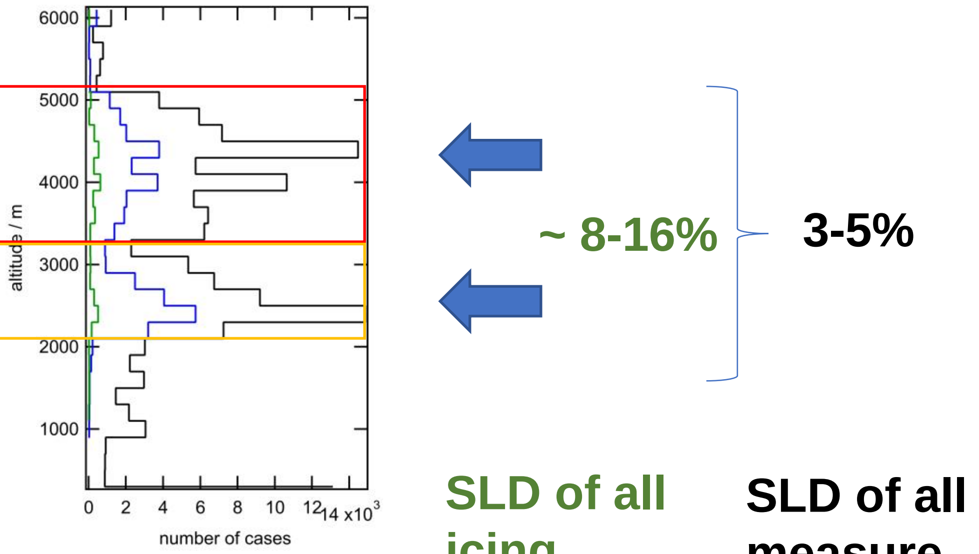


Further analysis needed!

Comparison of ADWICE climatological data to first results (altitude range) from airborne observations



Two layers:
~4500 m and ~2500 m



- Icing
- SLD
- All measurements

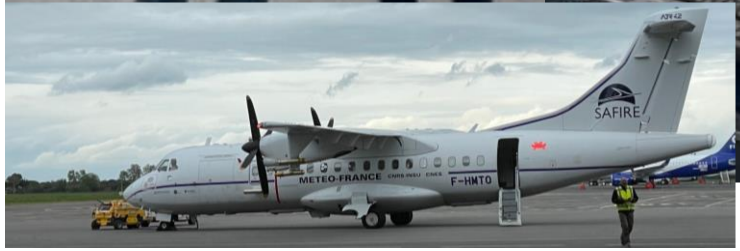
First preliminary (!) comparison of SENS4ICE-EU icing occurrence to meridional cross section from ADWICE climatology looks promising !! ☺

Summary

- Two successful campaigns were conducted with a large variability of icing conditions

→group effort of aircraft and instrument operators as well as forecast teams!

- Comprehensive microphysical data set was acquired
- NEW: icing conditions in altitude range between 2 and 5 km were sampled at high frequencies
- Will be made available for the community for model validation and improvement of satellite retrieval after further refined evaluation and sensitivity studies
- Data analysis is in an early stage and ongoing :
  - ice vs liquid classification needs sensitivity study
  - comparison of two aircraft campaigns: contrasting winter and spring 2023 (US and EU)
  - process study on cloud evolution
  - comparison to other data sets like ICICLE etc.



Thank you!!!

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

Airborne data was obtained using the aircraft managed by Safire, the French facility for airborne research, an infrastructure of the French National Center for Scientific Research (CNRS), Météo-France and the French National Center for Space Studies (CNES).

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SENS4ICE

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