

AIAA Ice Prediction Workshop 3: ONERA's Simulations with IGLOO3D

Emmanuel Radenac, Adèle Veilleux

ONERA

Presented 23 September 2026

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THE FRENCH AEROSPACE LAB

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September 23, 2026

Outline

- Presentation of the numerical tools
- NACA0012 Test Case
 - Computations performed
 - Aerodynamics
 - Droplets
 - Ice
- ONERA M6 Test Case
 - Computations performed
 - Aerodynamics
 - Droplets
 - Ice

PRESENTATION OF THE NUMERICAL TOOLS

Presentation of the numerical tools

Emmanuel Radenac, Ghislain Blanchard, Thomas Renaud, and Quentin Duchayne. 2023. Workflow for predictor–corrector simulations of in-flight ice accretion, with applications on swept wings. Eng. with Comput. 40, 4 (Aug 2024), 2307–2330. <https://doi.org/10.1007/s00366-023-01910-y>

Aerodynamics
(Navier-Stokes, RANS solution)

CEDRE / CHARME



Trajectorygraphy
(Eulerian)

CEDRE / SPIREE



Ice Accretion

IGLOO3D / MESSINGER3D

IGLOO3D:

Modular approach:

- Coupling through CGNS files

- Other codes could be used

Unstructured codes used, based on CEDRE

Eulerian approach most often used for the droplet trajectories → CEDRE/SPIREE

Presentation of the numerical tools

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Aerodynamics

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Ice Accretion

IGLOO3D / MESSINGER3D

Airflow:

HLLC scheme, 2nd order accuracy in space

Dynamic air viscosity: Sutherland's law for air

RANS turbulence model: k- ω SST model (fully-turbulent)

Heat transfer Coefficient on rough-wall:

Aupoix-Grigson-Colebrook model (2015)

1 simulation used + assumption on recovery temperature

$$h_{tc} = \frac{\phi_{wa}}{T_{wa} - T_r}, \quad T_r = T_e \left(1 + r_{rec} \frac{\gamma - 1}{2} M_e^2 \right), \quad r_{rec} = \text{Pr}^{1/3}$$

Presentation of the numerical tools

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Aerodynamics

(Navier-Stokes, RANS solution)

CEDRE / CHARME



Trajectorygraphy

(Eulerian)

CEDRE / SPIREE



Ice Accretion

IGLOO3D / MESSINGER3D

Droplets:

Eulerian method

Godunov scheme, 2nd order accuracy in space

Drag model: Schiller-Naumann model

“Splashing” model: not activated (no SLD cases addressed), full deposition

Solving only the dynamics

Ice:

Iterative Messenger

Predictor method (1-step)

Ice density model: Makkonen, Stallabras (1984)

Presentation of the numerical tools: summary

Model / Method	NACA0012	ONERA M6
CFD Model	RANS	
Turbulence Model	k- ω SST Menter + Aupoix's rough-wall model	
HTC Method	One Solution + Recovery Temperature assumption	
Droplet Formulation	Eulerian	
Droplet Drag Model	Sphere (Schiller-Naumann)	
SLD Effects	None	
Thermodynamic Model	Iterative Messinger	
Ice Density Model	Variable	680 kg/m ³
Roughness Height	Constant: 0.53mm	Constant: 0.5mm,1mm,1.5mm
Geometry Evolution	Algebraic	
Ice Accretion Steps	Single-shot	

IGLOO2D simulations for the NACA0012 test-case

Pierre Trontin, Ghislain Blanchard, Alexandros Kontogiannis, and Philippe Villedieu. 2017. Description and assessment of the new ONERA 2D icing suite IGLOO2D. AIAA 2017-3417, 9th AIAA Atmospheric and Space Environments Conference. <https://doi.org/10.2514/6.2017-3417>

Default setting used:

- Structured mesh
- Euler simulation coupled with simplified integral method (EULER2D, SIM2D)
- Lagrangian computation for trajectories (TRAJL2D)
- Messinger approach (MESSINGER2D).
- Far-field conditions (using the reference conditions provided by the IPW committee)
- Roughness height=chord / 1000

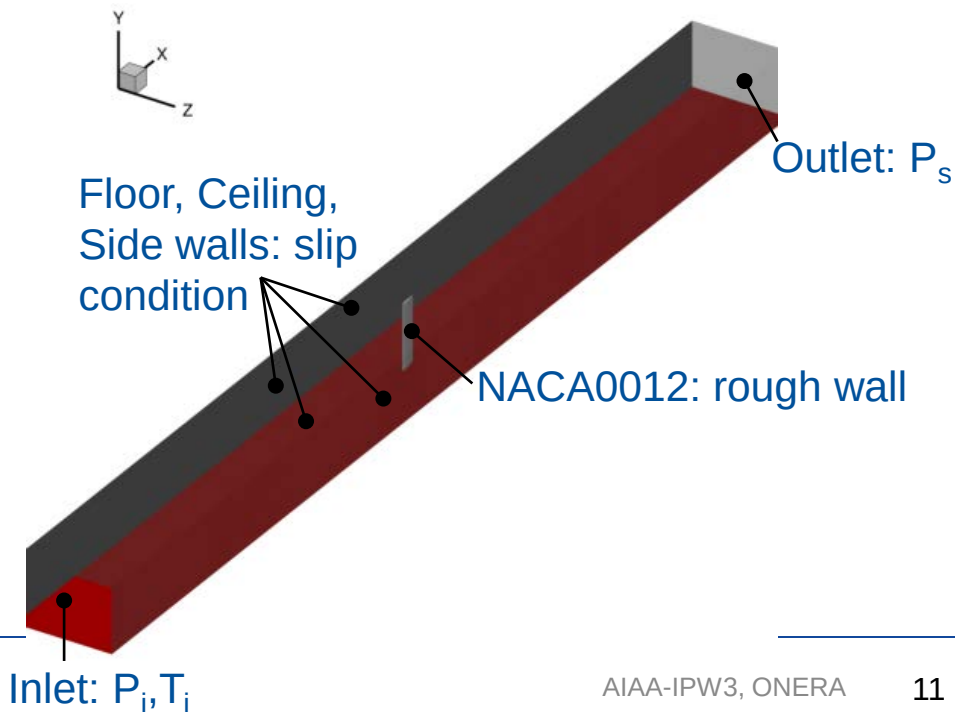
1-step simulations (predictor approach)

NACA0012 TEST CASE

NACA0012: computations performed

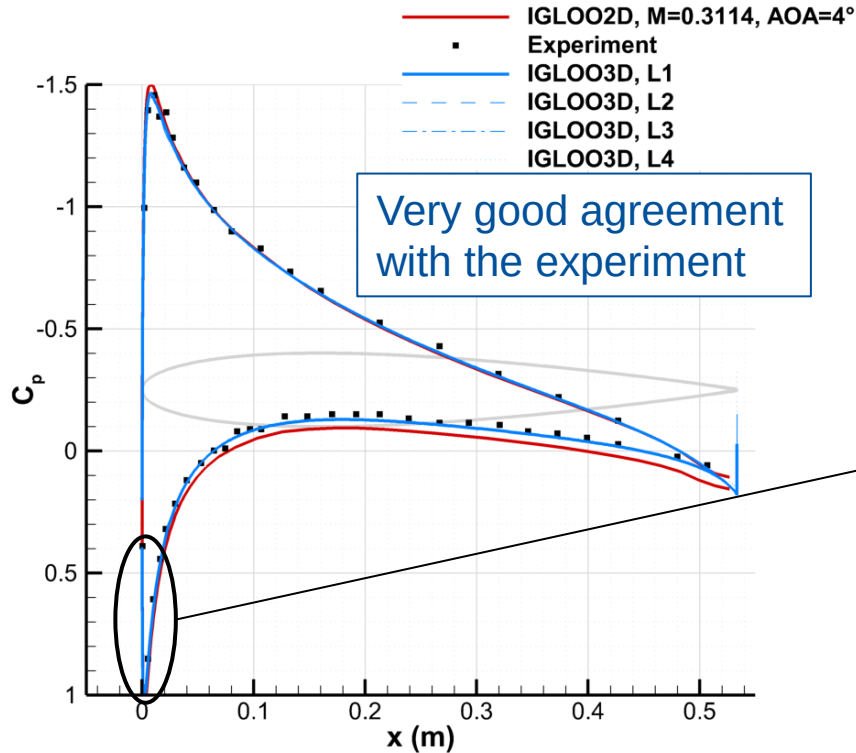
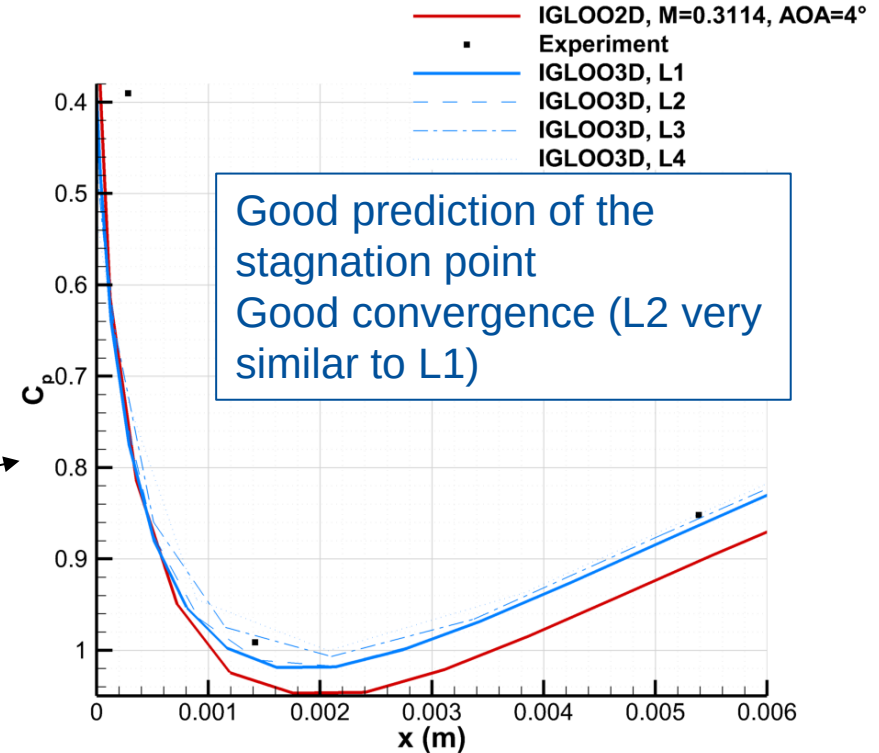
Cp conditions	L1	Air Smooth	→ C_p , C_L , C_D , C_M	
	L2	Air Smooth		
	L3	Air Smooth		
	L4	Air Smooth		
AE3932	L1	Air, Rough ($k=0.53$ mm)	Drops, 1 bin	Ice
			Drops, 3 bins	Ice
			Drops, 7 bins	Ice
			Drops, 15 bins	Ice
	L2	Air, Rough ($k=0.53$ mm)	Drops, 1 bin	Ice
			Drops, 3 bins	Ice
			Drops, 7 bins	Ice
			Drops, 15 bins	Ice
	L3	Air, Rough ($k=0.53$ mm)	Drops, 1 bin	Ice
			Drops, 3 bins	Ice
			Drops, 7 bins	Ice
			Drops, 15 bins	Ice
	L4	Air, Rough ($k=0.53$ mm)	Drops, 1 bin	Ice
			Drops, 3 bins	Ice
			Drops, 7 bins	Ice
			Drops, 15 bins	Ice
AE3933	L1	Air, Rough ($k=0.53$ mm)	Drops, 1 bin	Ice
			Drops, 3 bins	Ice
			Drops, 7 bins	Ice
			Drops, 15 bins	Ice
	L2	Air, Rough ($k=0.53$ mm)	Drops, 1 bin	Ice
			Drops, 3 bins	Ice
			Drops, 7 bins	Ice
			Drops, 15 bins	Ice
	L3	Air, Rough ($k=0.53$ mm)	Drops, 1 bin	Ice
			Drops, 3 bins	Ice
			Drops, 7 bins	Ice
			Drops, 15 bins	Ice
	L4	Air, Rough ($k=0.53$ mm)	Drops, 1 bin	Ice
			Drops, 3 bins	Ice
			Drops, 7 bins	Ice
			Drops, 15 bins	Ice

3 different airflow conditions → 3 airflow computations per mesh refinement level
Tunnel conditions setting done for L1



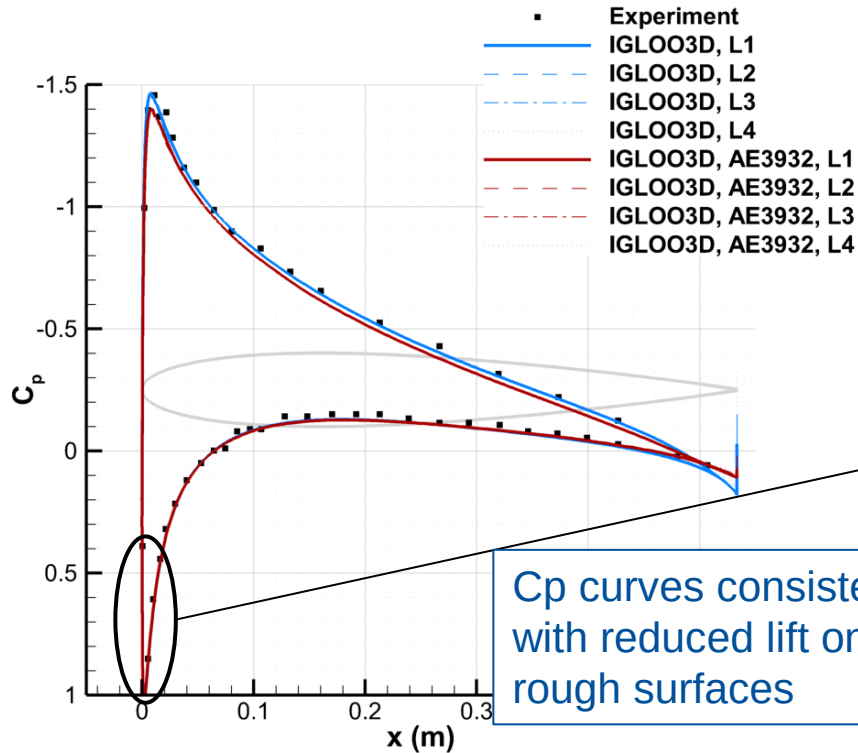
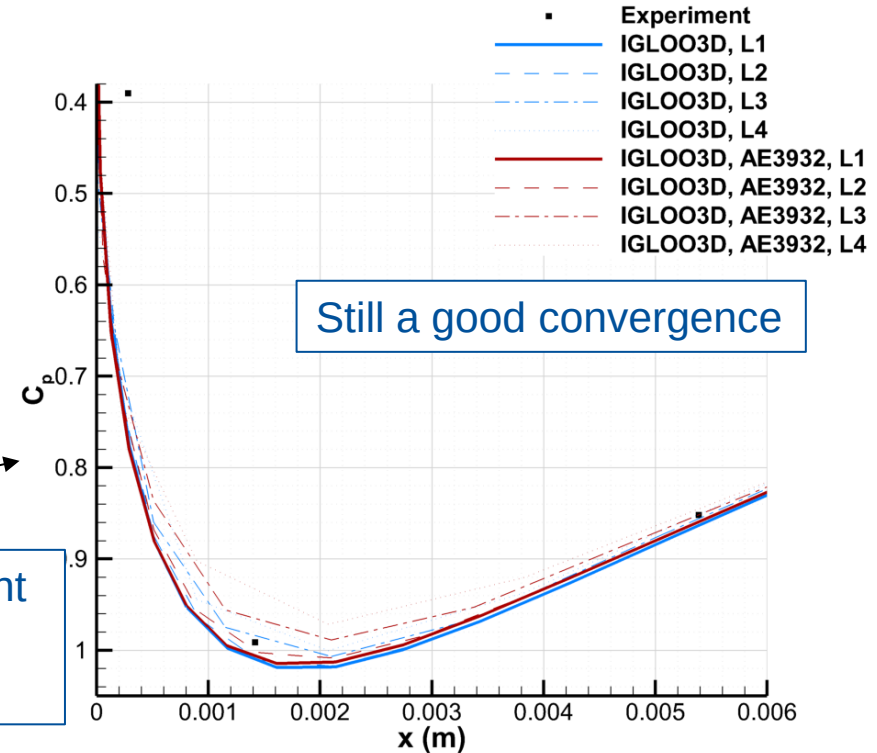
NACA0012 test-cases: aerodynamics

Pressure coefficient in « Cp conditions »



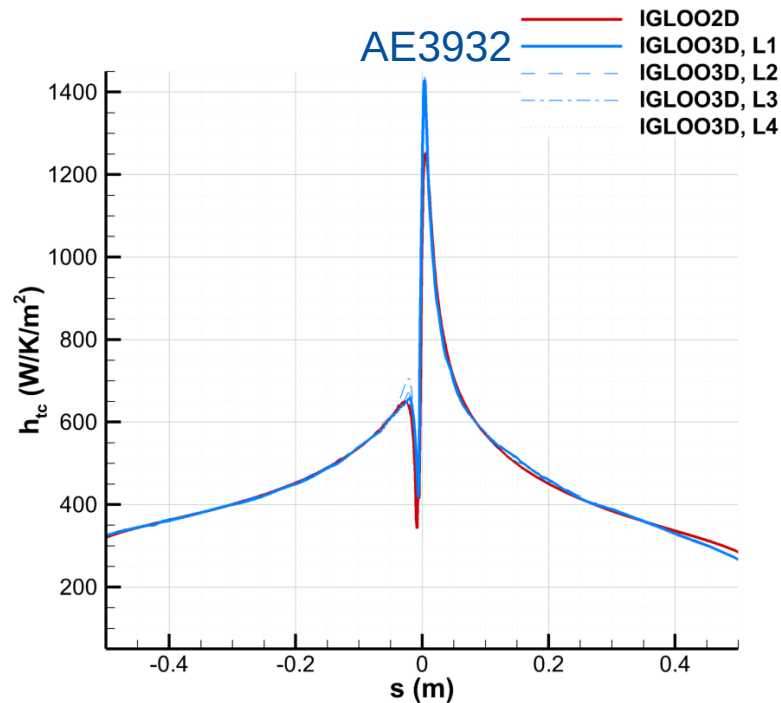
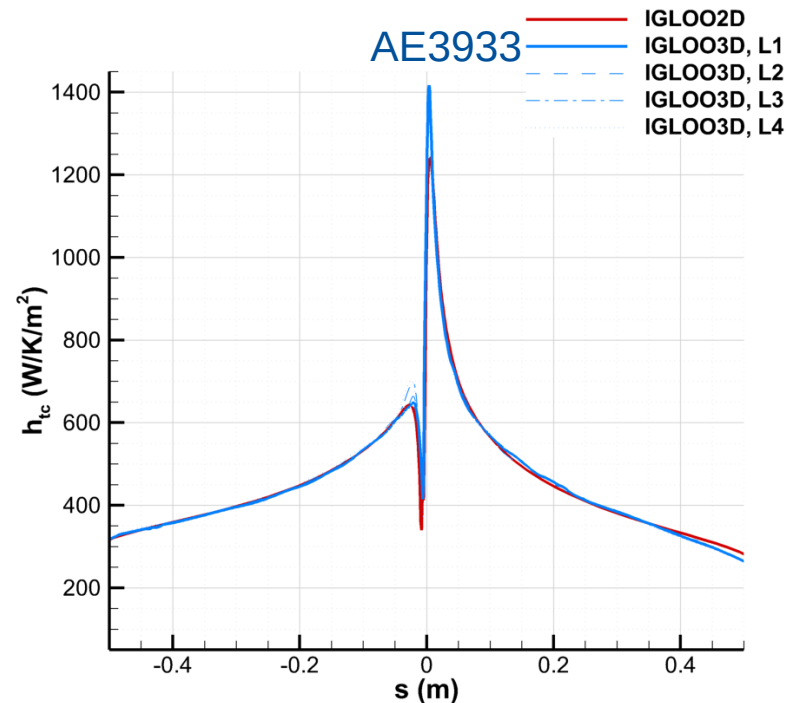
NACA0012 test-cases: aerodynamics

Pressure coefficient in « Cp conditions » (smooth) vs. AE3932 (rough)



NACA0012 test-cases: aerodynamics

Heat transfer coefficient



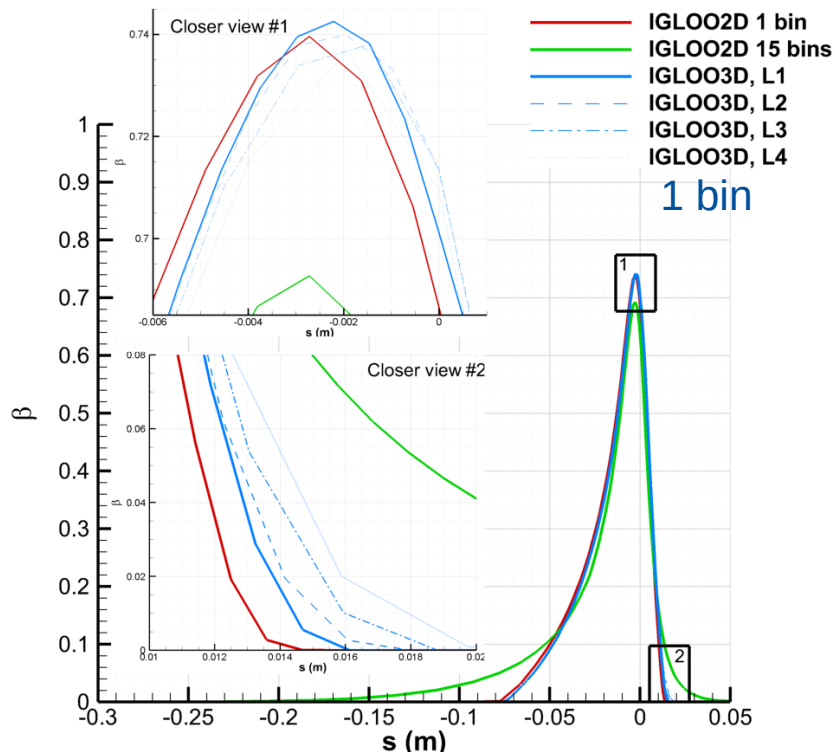
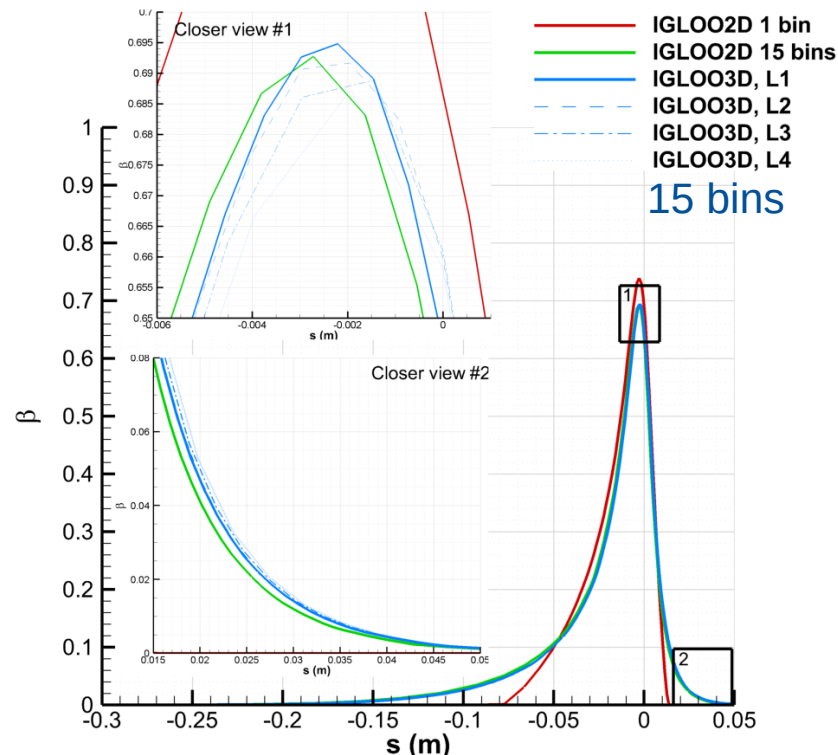
Very good mesh convergence

No significant effect of temperature on h_{tc}

IGLOO3D predicts slightly higher h_{tc} than IGLOO2D

NACA0012 test-cases: droplets

Collection efficiency, AE3932



Very good mesh convergence

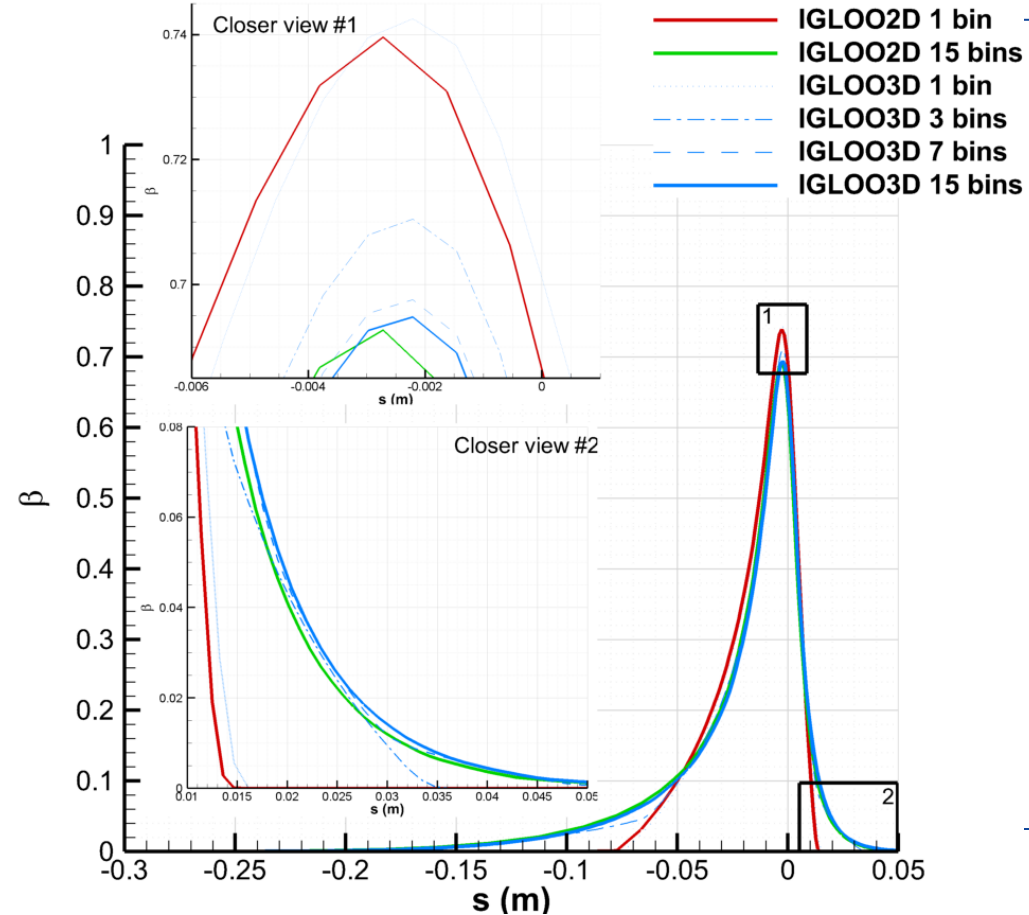
Good agreement between IGLOO2D and IGLOO3D

NACA0012 test-cases: droplets

Collection efficiency, AE3932

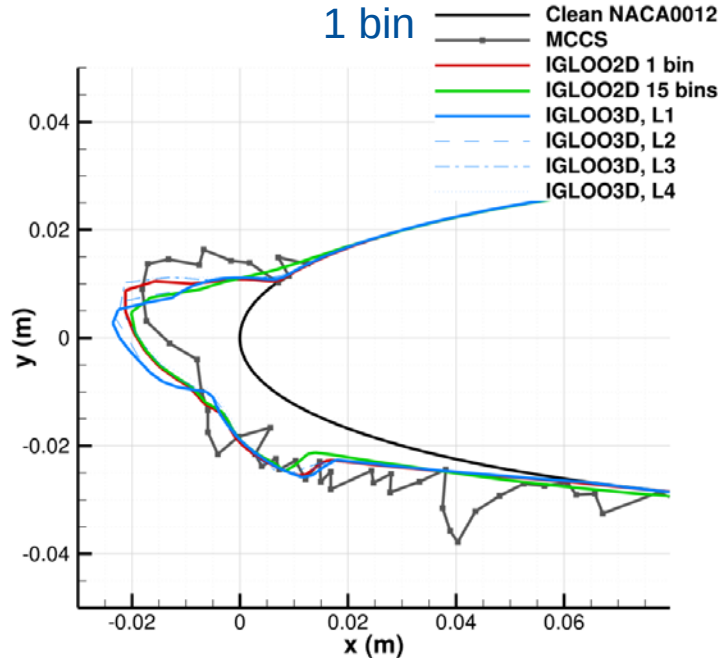
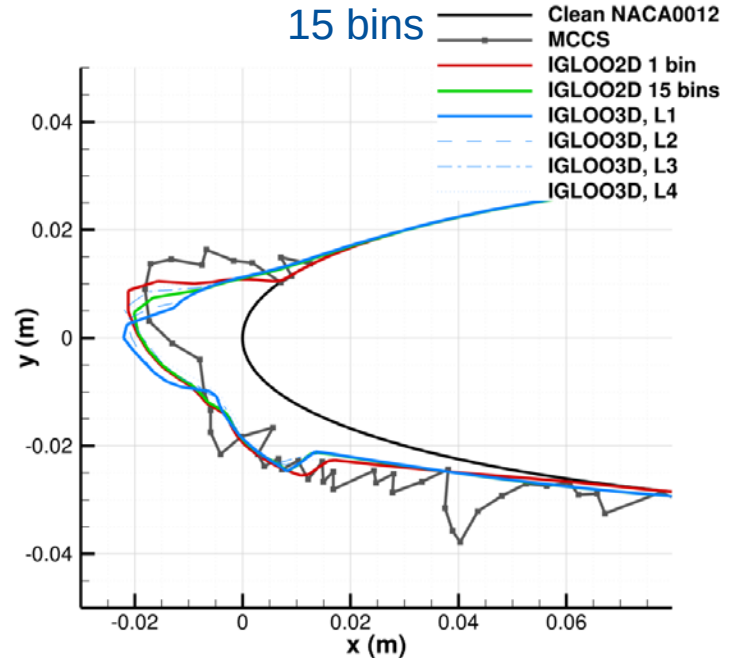
In addition:

- no significant effect of temperature on β (not shown)
- good convergence in number of bins



NACA0012 test-cases: ice

Ice Shapes, AE3932

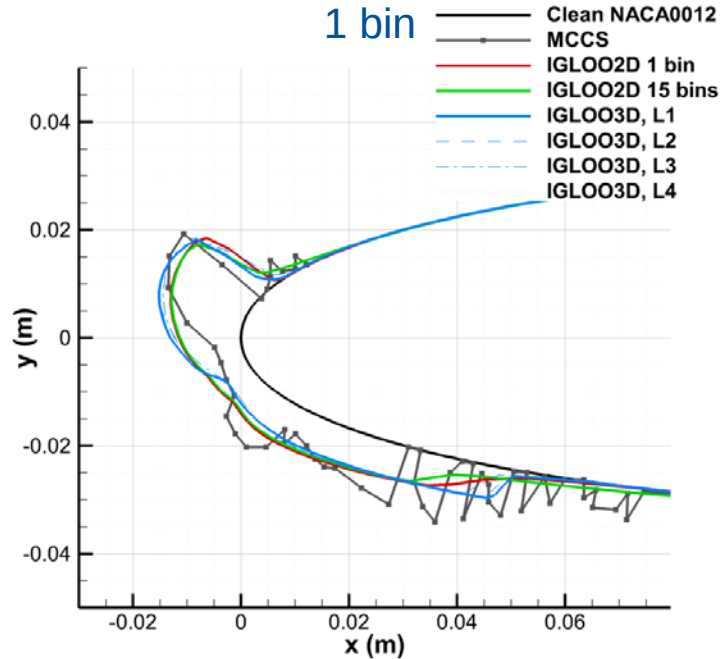
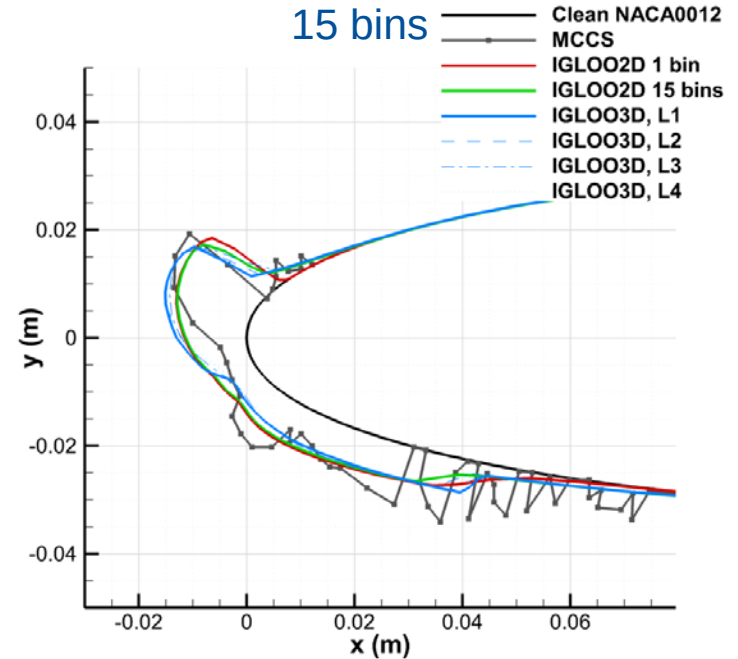


Glaze / Mixed ice shapes predicted

Slightly better ice shape predictions with IGLOO2D and with less bins!

NACA0012 test-cases: ice

Ice Shapes, AE3933



Glaze / Mixed ice shapes predicted

Trend in ice shape evolution with temperature well captured by the codes

NACA0012 test-cases: ice

Ice Mass

AE3932 Ice mass, kg				
	1 bin	3 bins	7 bins	15 bins
L1	0,1023	0,1069	0,1074	0,1073
L2	0,1026	0,1071	0,1076	0,1075
L3	0,1028	0,1075	0,1081	0,1080
L4	0,1031	0,1079	0,1086	0,1084

IGLOO3D ice mass / experimental ice mass				
L1	1,012	1,058	1,063	1,062
L2	1,016	1,060	1,066	1,064
L3	1,017	1,064	1,071	1,069
L4	1,021	1,068	1,075	1,074

AE3933 Ice mass, kg				
	1 bin	3 bins	7 bins	15 bins
L1	0,1006	0,1046	0,1051	0,1049
L2	0,1009	0,1048	0,1053	0,1052
L3	0,1008	0,1049	0,1054	0,1053
L4	0,1014	0,1056	0,1063	0,1061

IGLOO3D ice mass / experimental ice mass				
L1	1,171	1,218	1,224	1,221
L2	1,175	1,220	1,226	1,224
L3	1,173	1,221	1,228	1,226
L4	1,181	1,230	1,237	1,235

The ice mass is overestimated

Not inconsistent with the 1-step method
(after some IGLOO2D simulations)

Increasing the temperature from 262.3K (AE3932) to 265.8K (AE3933), the predicted ice mass becomes slightly lower, but the decrease observed experimentally is more significant

The overestimation rises from 1–7% to 17–24%

Using a finer mesh (L1) systematically improves the prediction

However, using more bins systematically makes the predictions worse

ONERA M6 TEST CASE

ONERA M6: computations performed

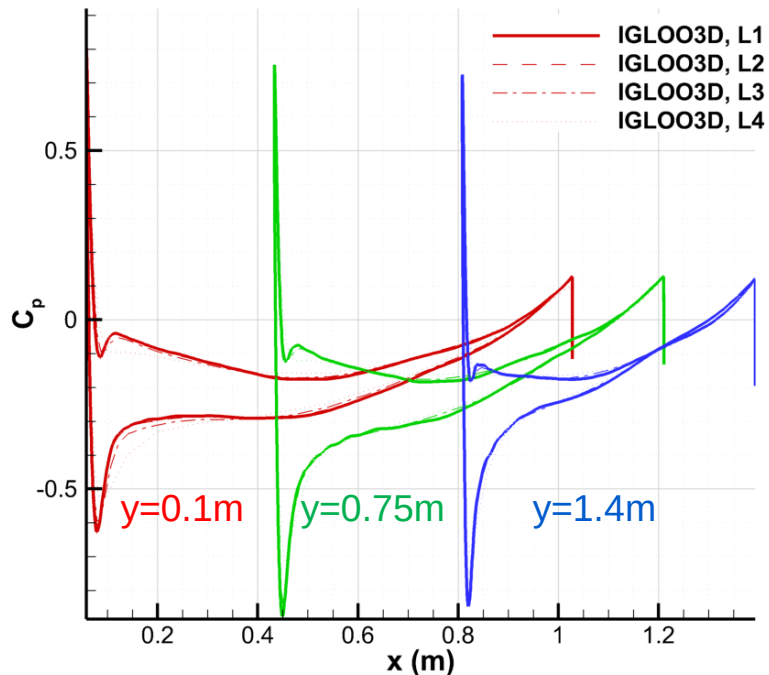
k=1mm	L1	Air, Rough	Drops, 1 bin	Ice
			Drops, 3 bins	Ice
			Drops, 7 bins	Ice
			Drops, 15 bins	Ice
	L2	Air, Rough	Drops, 1 bin	Ice
			Drops, 3 bins	Ice
			Drops, 7 bins	Ice
			Drops, 15 bins	Ice
	L3	Air, Rough	Drops, 1 bin	Ice
			Drops, 3 bins	Ice
			Drops, 7 bins	Ice
			Drops, 15 bins	Ice
	L4	Air, Rough	Drops, 1 bin	Ice
			Drops, 3 bins	Ice
			Drops, 7 bins	Ice
			Drops, 15 bins	Ice
k=0.5 mm	L1	Air, Rough	Drops, 7 bins	Ice
	L2	Air, Rough	Drops, 7 bins	Ice
	L3	Air, Rough	Drops, 7 bins	Ice
	L4	Air, Rough	Drops, 7 bins	Ice
k=1.5 mm	L1	Air, Rough	Drops, 7 bins	Ice
	L2	Air, Rough	Drops, 7 bins	Ice
	L3	Air, Rough	Drops, 7 bins	Ice
	L4	Air, Rough	Drops, 7 bins	Ice

C_p , C_L , C_D , C_M obtained in rough-wall conditions

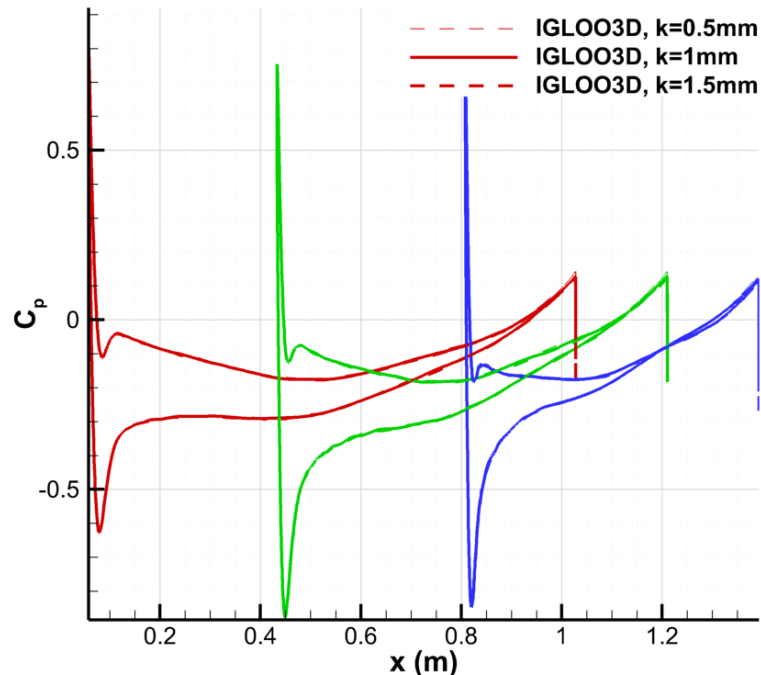
ONERA M6: aerodynamics

Pressure coefficient

Good mesh convergence, $k=1\text{mm}$



The roughness height value does not affect much the C_p (here for L1)



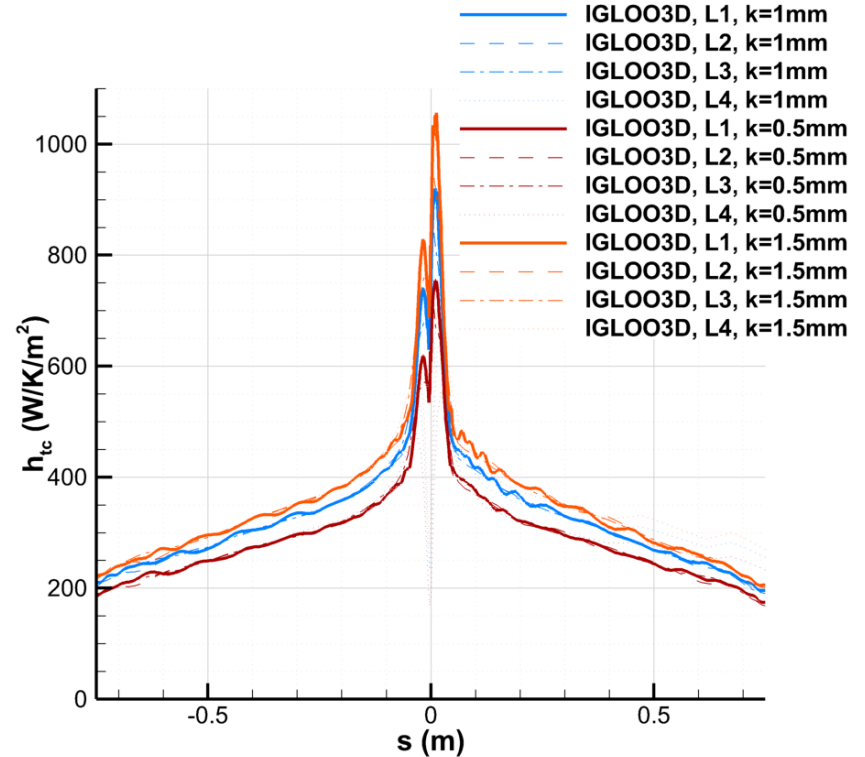
ONERA M6: aerodynamics

Heat transfer coefficient

Good mesh convergence, here in $y=0.75\text{m}$, for the 3 values of roughness height tested

As expected, the HTC is higher for higher roughness height

Small oscillations are observed in the rear part of the wing (where there is little to no ice). This may be due to the rather coarse meshes in this area

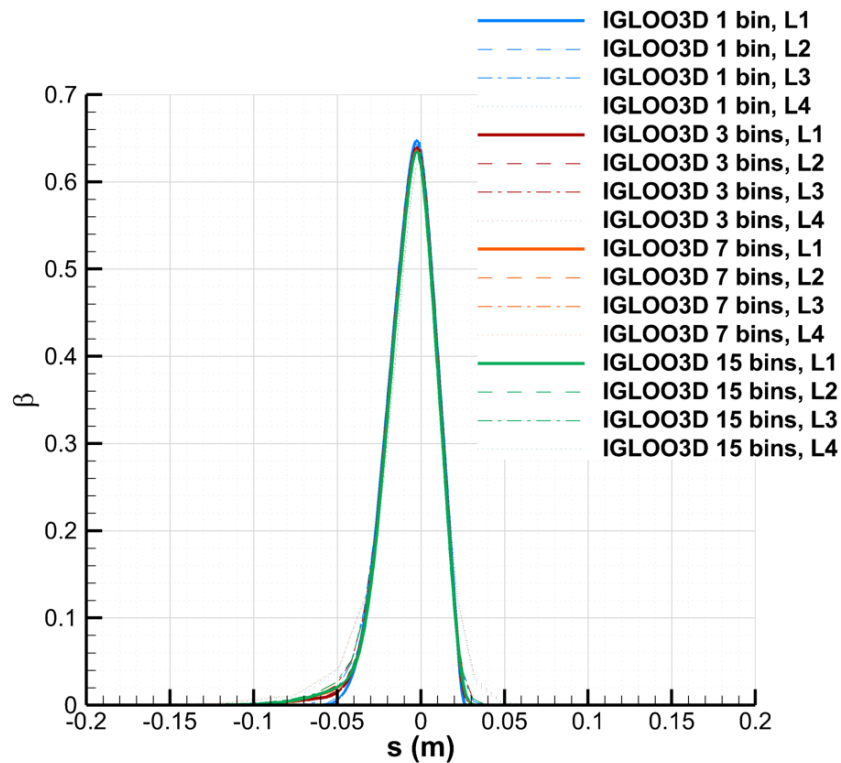


ONERA M6: droplets

Collection efficiency

Good mesh convergence,
here in $y=0.75\text{m}$, for 1 to 15
bins

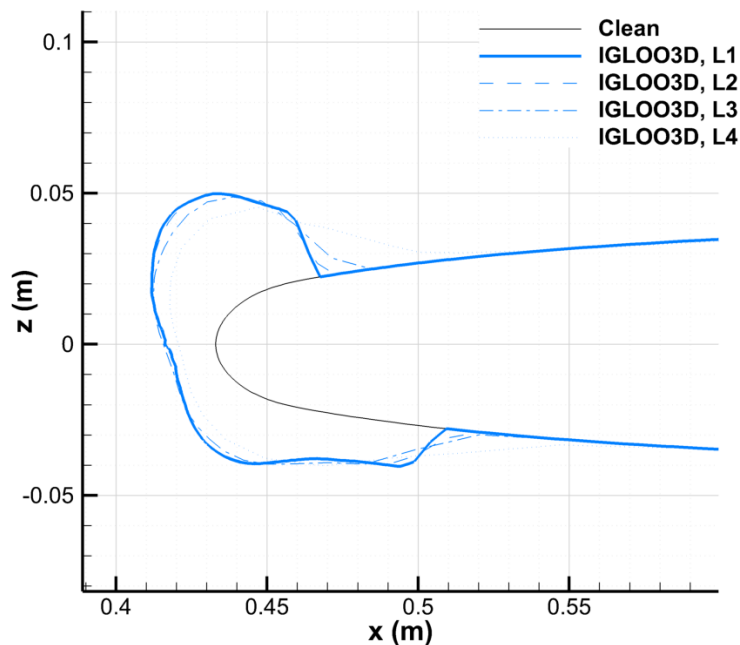
Only the 1-bin curve departs
'significantly' from the others



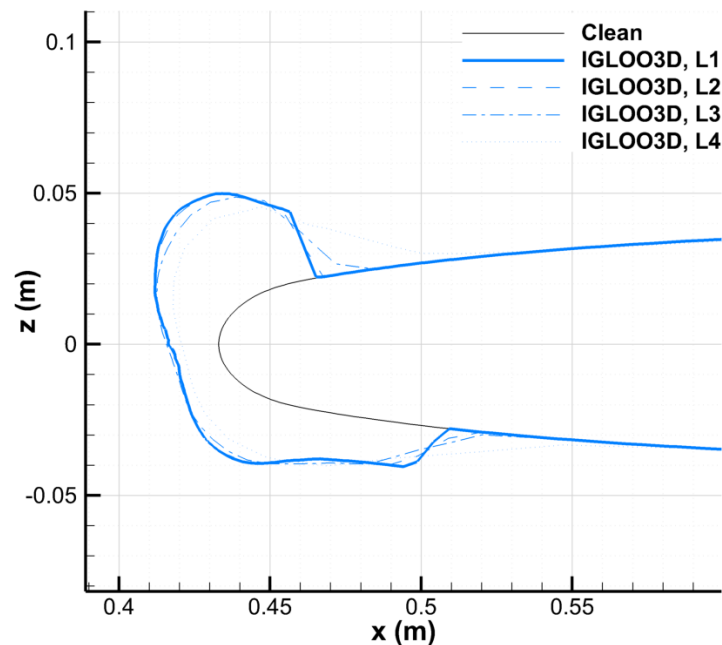
ONERA M6: ice shapes

Ice Cuts, $y=0.75\text{m}$, $k=1\text{mm}$

1 bin



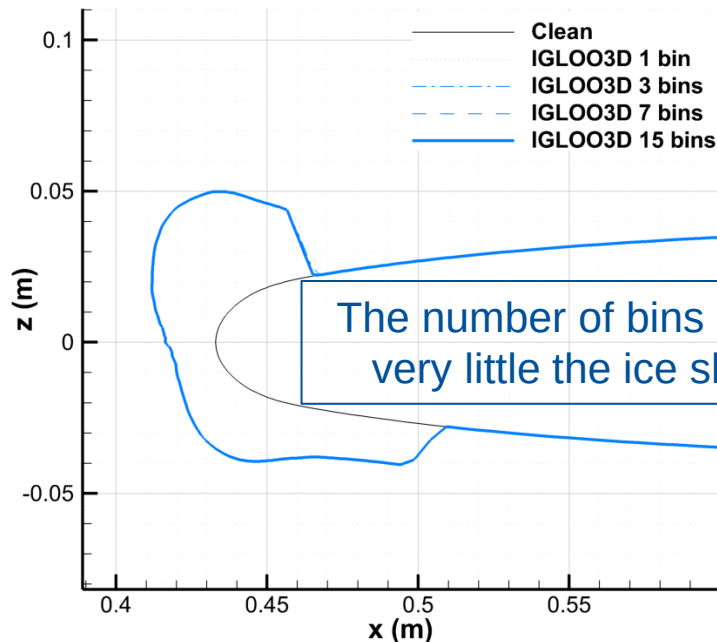
15 bins



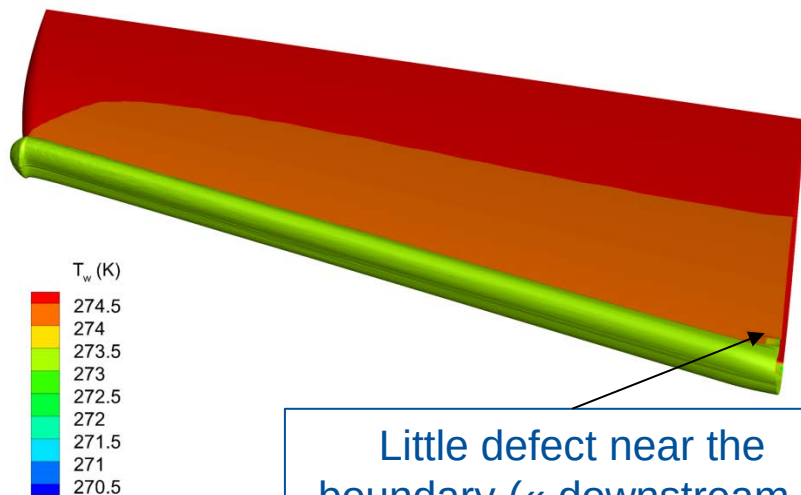
Very good mesh convergence

ONERA M6: ice shapes

Ice Cuts ($y=0.75\text{m}$) and Ice Shape, $k=1\text{mm}$, L1 mesh



15 bins
The ice shape is glaze

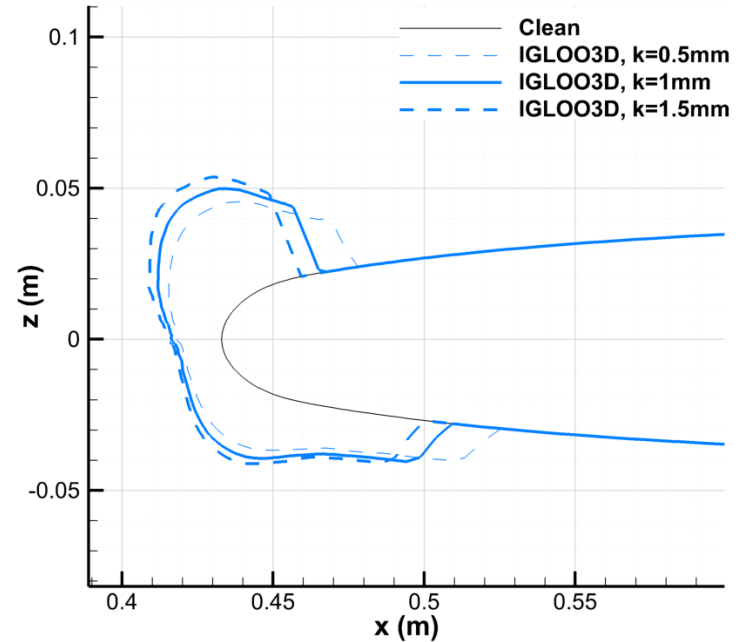


ONERA M6: ice shapes

Ice Cuts ($y=0.75\text{m}$), L1 mesh, 7 bins

As expected:

- A rougher ice shape produces less runback
- A smoother ice shape runs further downstream



THANK YOU FOR YOUR ATTENTION

APPENDIX

Appendix: NACA0012: computations performed

Tunnel conditions setting

Tunnel conditions setting done for L1, and then verified for L2, L3, L4

Targeted U_{ref}
102,15
102,31
102,19

	U at probe			
Condition	L1	L2	L3	L4
CFD	102,146	102,143	102,149	102,144
AE3932	102,299	102,295	102,301	102,297
AE3933	102,188	102,185	102,192	102,187

	$ U - U_{ref} $ at probe, expected < 0.5 (m/s)			
Condition	L1	L2	L3	L4
CFD	0,004	0,007	0,001	0,006
AE3932	0,011	0,015	0,009	0,013
AE3933	0,002	0,005	0,002	0,003

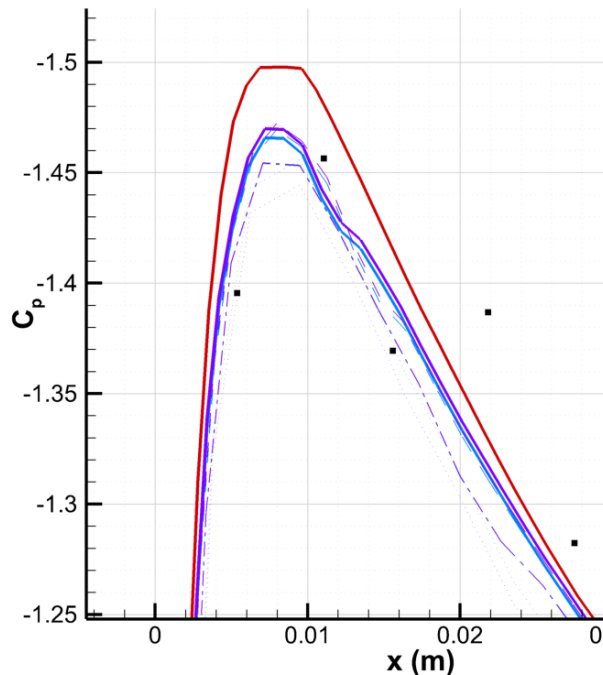
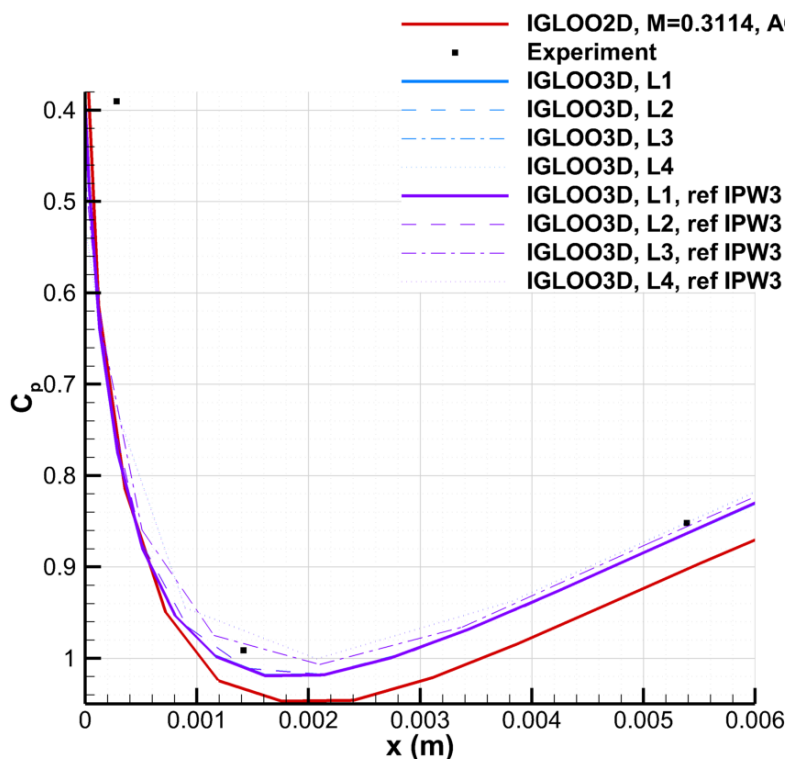
Targeted Ma_{ref}
0,3114
0,3151
0,3127

	Mach at probe			
Condition	L1	L2	L3	L4
CFD	0,3113	0,3113	0,3114	0,3113
AE3932	0,3150	0,3150	0,3150	0,3150
AE3933	0,3126	0,3126	0,3126	0,3126

	$ Ma - Ma_{ref} $ at probe, expected < 0.01			
Condition	L1	L2	L3	L4
CFD	0,00006	0,00007	0,00005	0,00006
AE3932	0,00007	0,00008	0,00006	0,00007
AE3933	0,00009	0,00010	0,00008	0,00009

Appendix: NACA0012 test-cases: aerodynamics

Pressure coefficient in « Cp conditions »



Note:

Purple lines: C_p sent to the IPW3 committee

assessed with the reference conditions provided by the committee

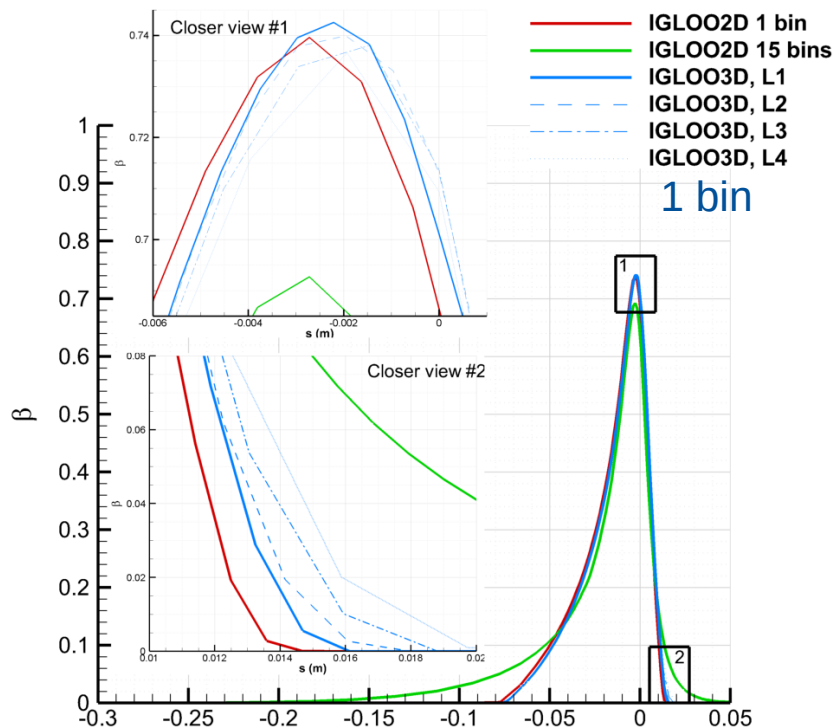
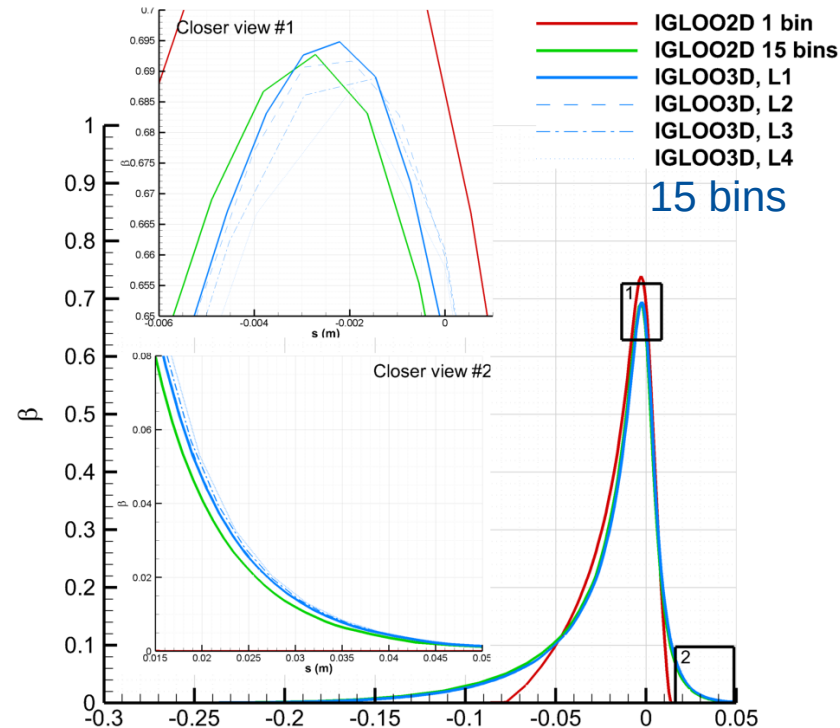
Blue lines:

assessed with the conditions measured in the computational results at the reference point $[(X, Y, Z) [in] = (-139, 45.58, 0)]$

Discrepancy <1%, worse case=L4

Appendix: NACA0012 test-cases: droplets

Collection efficiency, AE3932



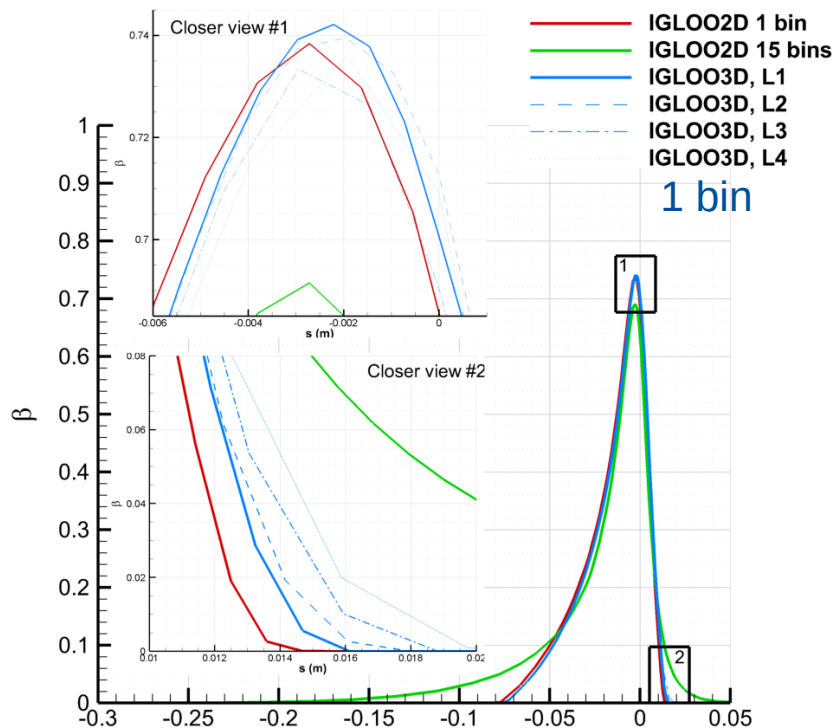
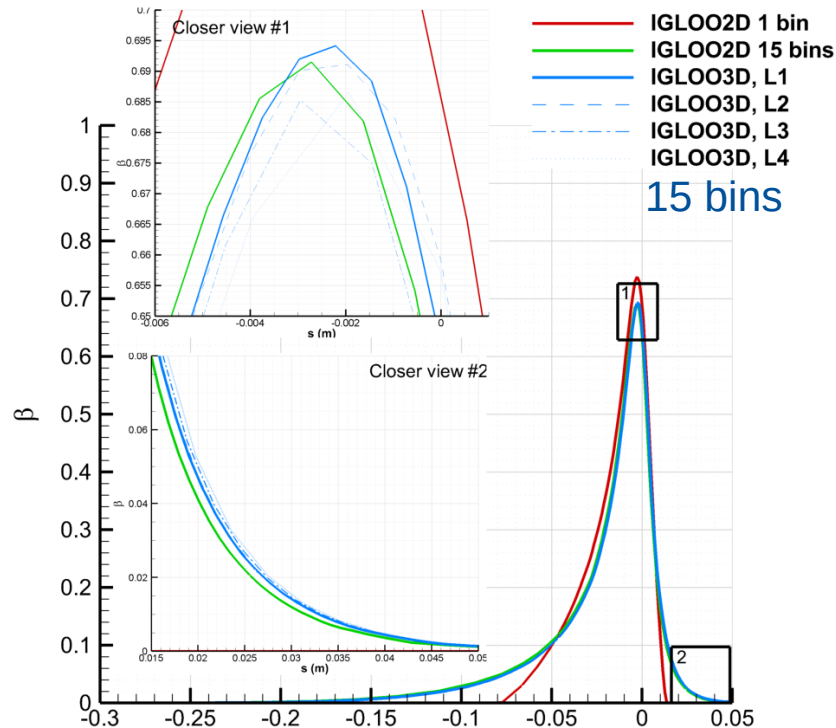
Very good mesh convergence

No significant effect of temperature on β (not shown)

Good agreement between IGLOO2D and IGLOO3D

Appendix: NACA0012 test-cases: droplets

Collection efficiency, AE3933



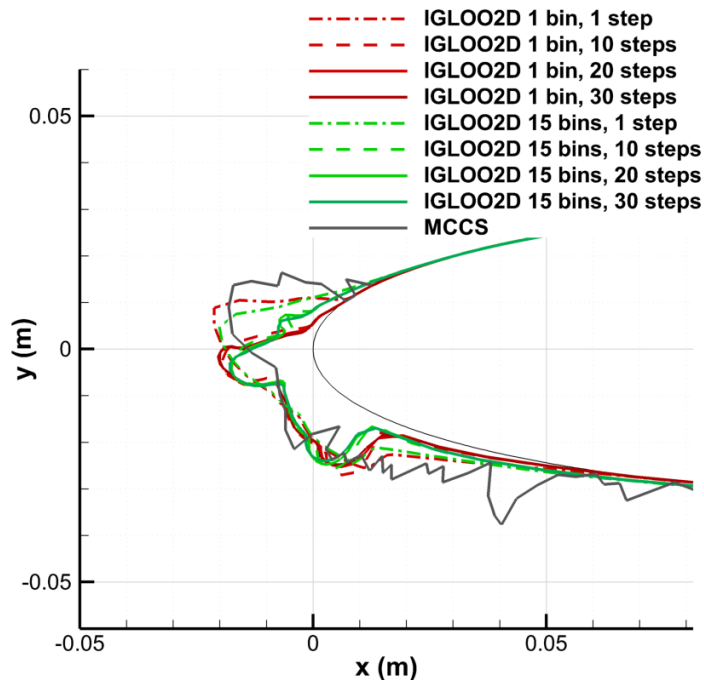
Very good mesh convergence

No significant effect of temperature on β (not shown)

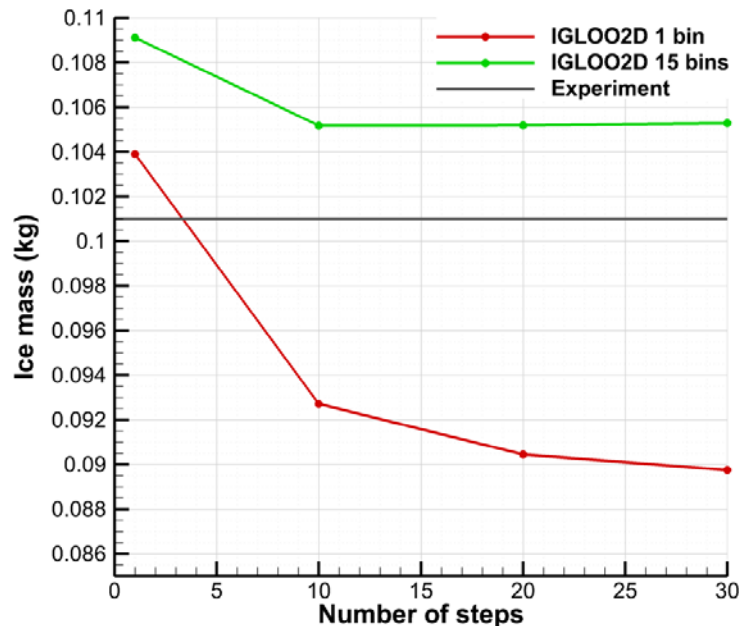
Good agreement between IGLOO2D and IGLOO3D

Appendix: NACA0012 test-cases: ice

IGLOO2D, effect of multi-stepping on the ice mass, AE3932



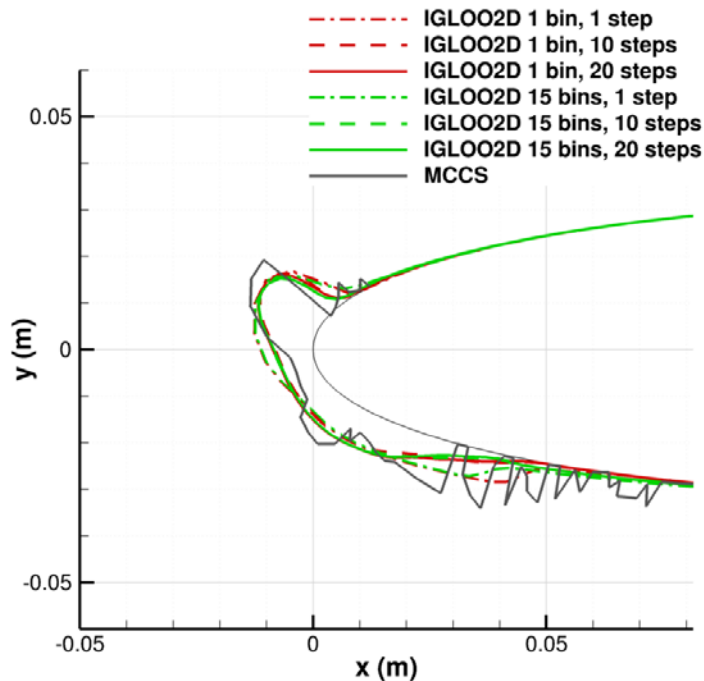
The ice shape prediction becomes worse with more steps



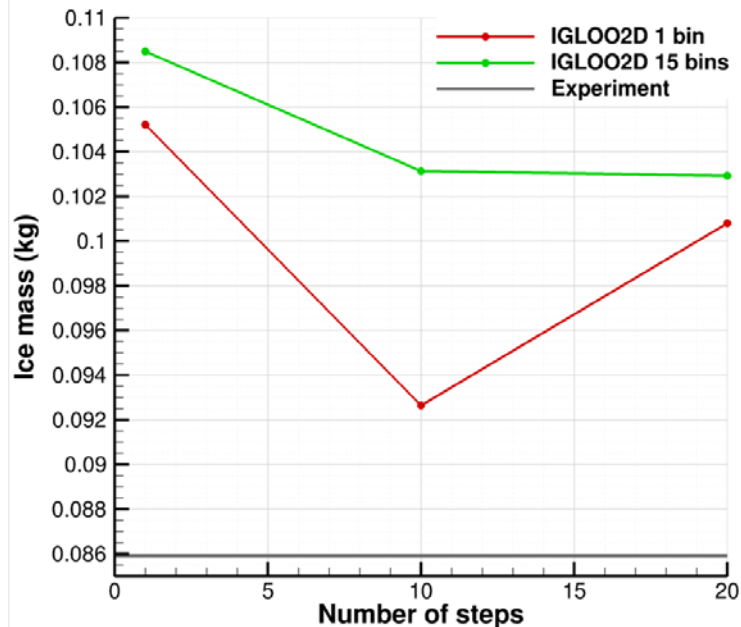
The ice mass decreases with more steps

Appendix: NACA0012 test-cases: ice

IGLOO2D, effect of multi-stepping on the ice mass, AE3933



The ice shape prediction becomes a bit better with more steps



The ice mass tends to decrease with more steps