

Predictive LES of aircraft icing aerodynamics

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Stanford University

Advanced Modeling & Simulation (AMS) Seminar Series

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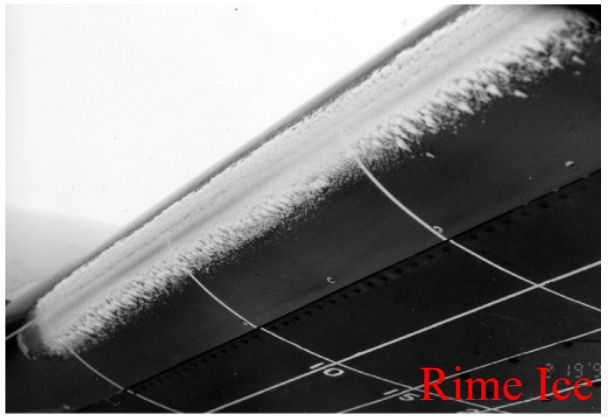
Introduction to aircraft icing

- Aircraft icing impacts airplane performance and is a consideration for certification and safety analysis.
- **Two FAA Rule Changes (App. C, D, and O):**
  - **2007** – Explicit requirements for handling/performance in both icing and non-icing conditions.
  - **2014** – Extended certification envelope for supercooled large droplets (SLD)
- **Ice on wings introduces challenges for simulations:**
  - Complex geometries for body-fitted meshes
  - Additional scales due to rough surfaces
  - Ice accretion modeling (droplet splashing, runback, freezing)

We need validated modeling tools to predict ice accretion and the resulting aerodynamic degradation!



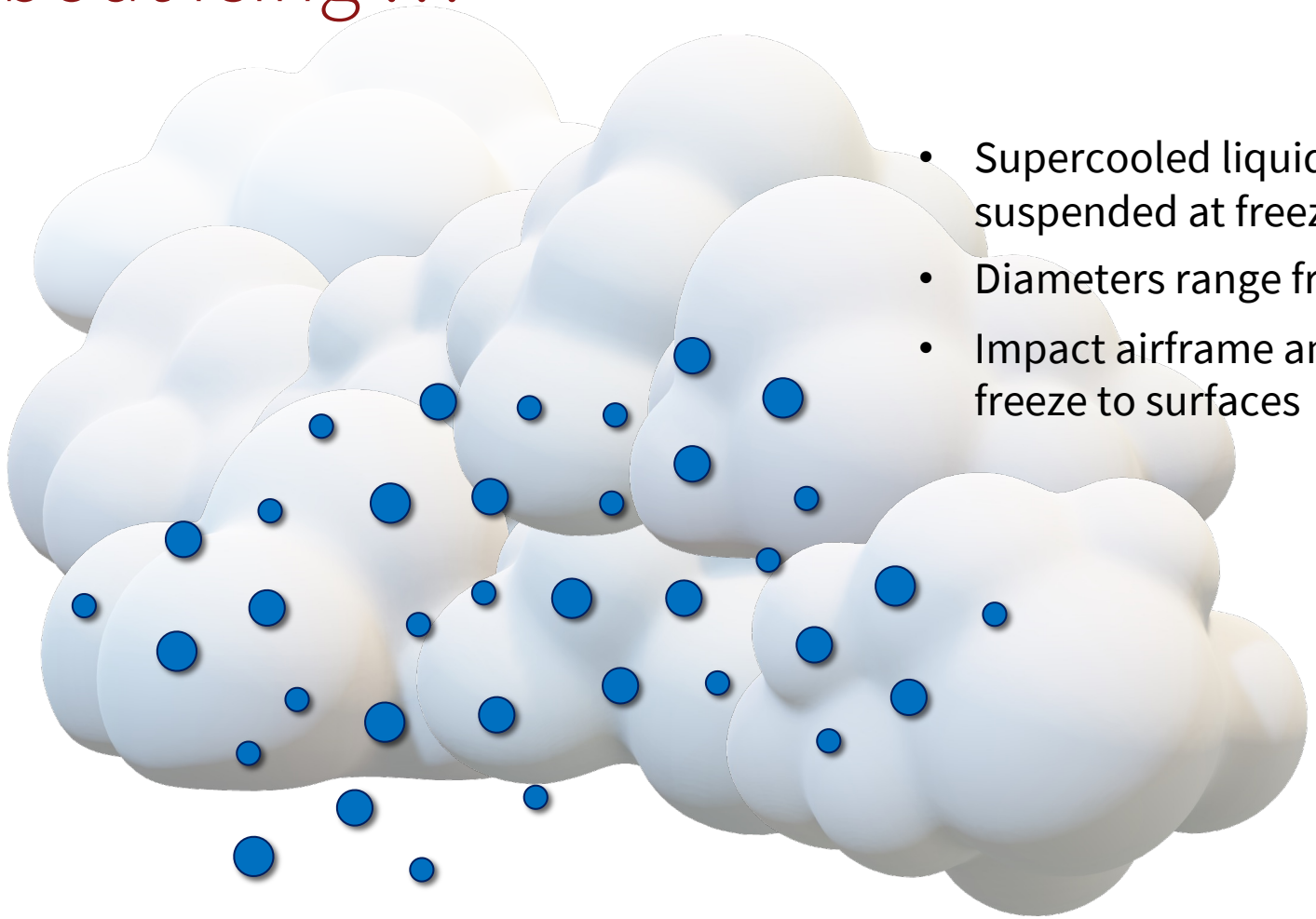
NASA Glenn Research Center
Twin Otter





Let’s talk about icing …





- Supercooled liquid water droplets suspended at freezing conditions
- Diameters range from $10 - 100\ \mu m$
- Impact airframe and fully or partially freeze to surfaces

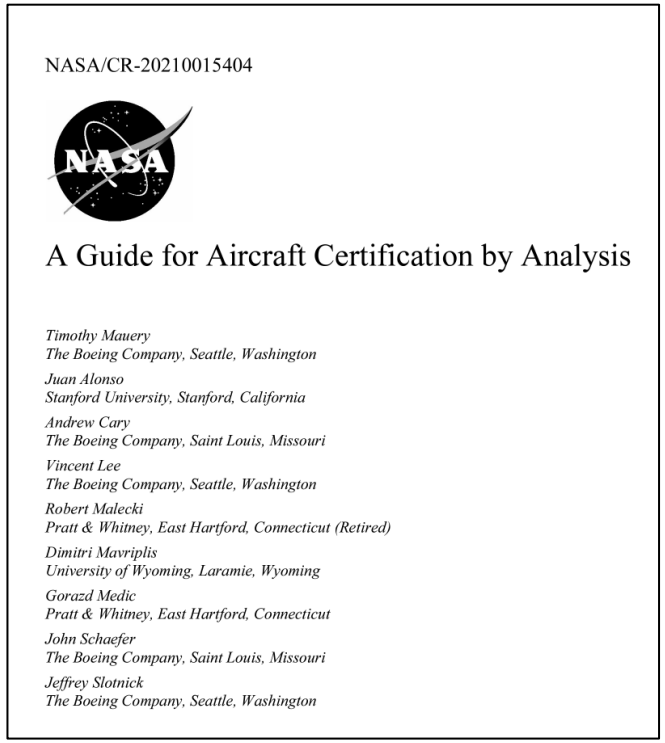
Let's talk about icing …



- Supercooled liquid water droplets suspended at freezing conditions
- Diameters range from $10 - 100\ \mu m$
- Impact airframe and fully or partially freeze to surfaces

- Ice builds up on various surfaces and can alter the shape of the airplane's OML
- Leads to performance degradation (can be catastrophic)
- Ice-protection systems designed to mitigate these issues.

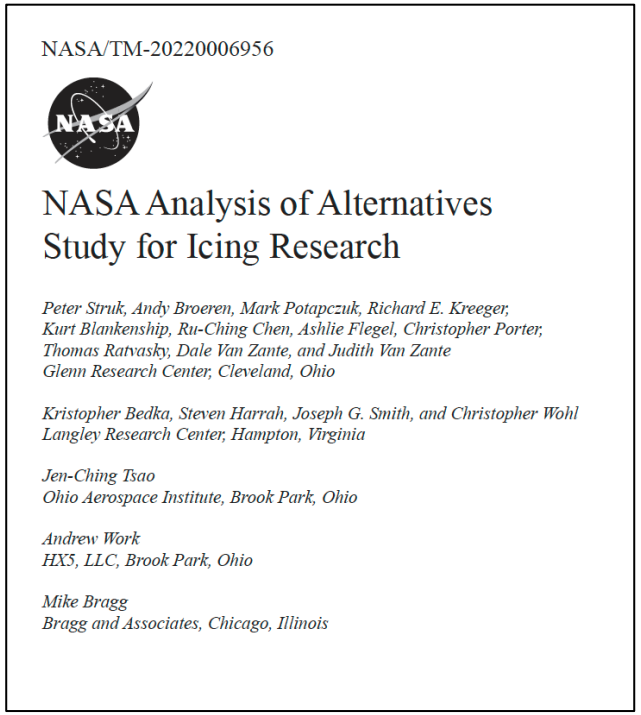
Introduction



NASA/CR-20210015404

A Guide for Aircraft Certification by Analysis

Timothy Mauery
The Boeing Company, Seattle, Washington
Juan Alonso
Stanford University, Stanford, California
Andrew Cary
The Boeing Company, Saint Louis, Missouri
Vincent Lee
The Boeing Company, Seattle, Washington
Robert Malecki
Pratt & Whitney, East Hartford, Connecticut (Retired)
Dimitri Mavriplis
University of Wyoming, Laramie, Wyoming
Gorazd Medic
Pratt & Whitney, East Hartford, Connecticut
John Schaefer
The Boeing Company, Saint Louis, Missouri
Jeffrey Slotnick
The Boeing Company, Seattle, Washington



NASA/TM-20220006956

NASA Analysis of Alternatives Study for Icing Research

Peter Struk, Andy Broeren, Mark Potapczuk, Richard E. Kreeger, Kurt Blankenship, Ru-Ching Chen, Ashlie Flegel, Christopher Porter, Thomas Ratvasky, Dale Van Zante, and Judith Van Zante
Glenn Research Center, Cleveland, Ohio

Kristopher Bedka, Steven Harrah, Joseph G. Smith, and Christopher Wohl
Langley Research Center, Hampton, Virginia

Jen-Ching Tsao
Ohio Aerospace Institute, Brook Park, Ohio

Andrew Work
HX5, LLC, Brook Park, Ohio

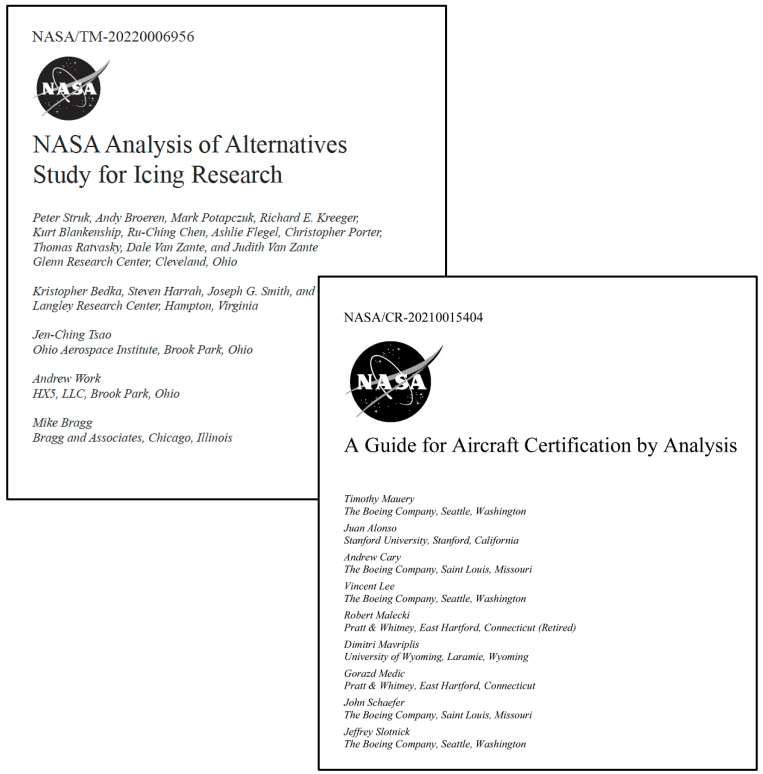
Mike Bragg
Bragg and Associates, Chicago, Illinois

Airplane Stalls Methodology Gaps:

"Accurate prediction of the effects of predefined ice shapes on aerodynamic performance"

"The current situation relative to new regulations is that manufacturers greatly rely on similarity to existing designs, fleet history, and experience. The new regulations could limit research and development toward new and different designs." (i.e. TTBW)

Introduction


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A Guide for Aircraft Certification by Analysis

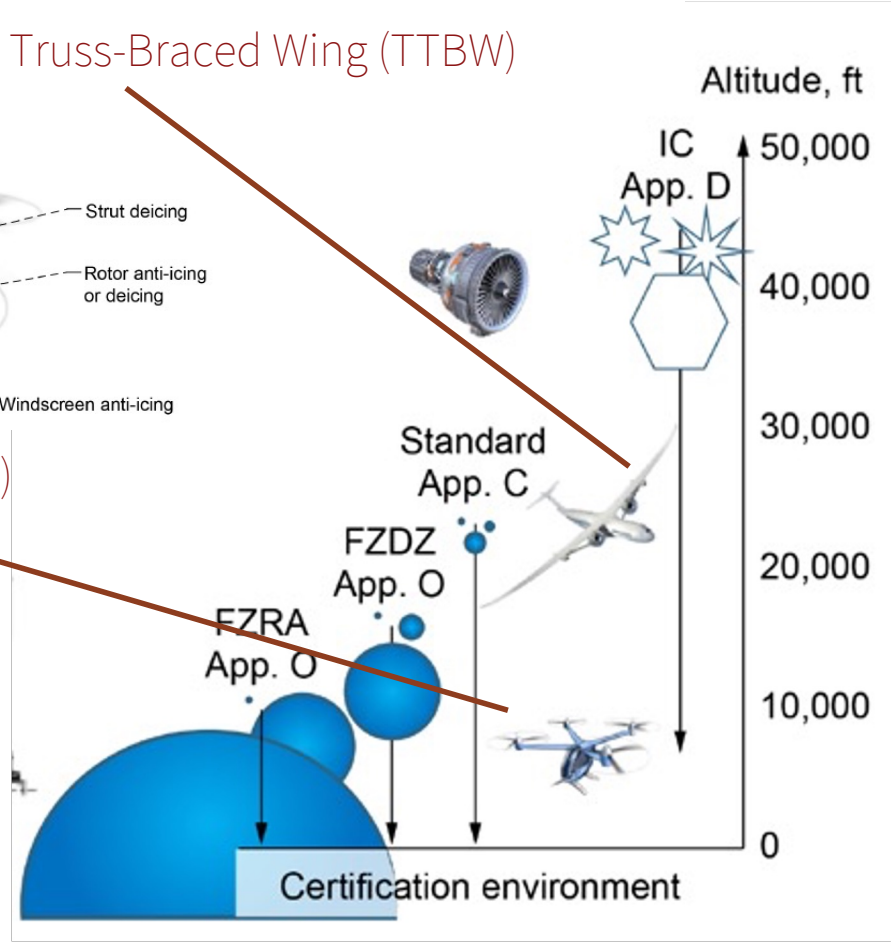
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Transonic Truss-Braced Wing (TTBW)



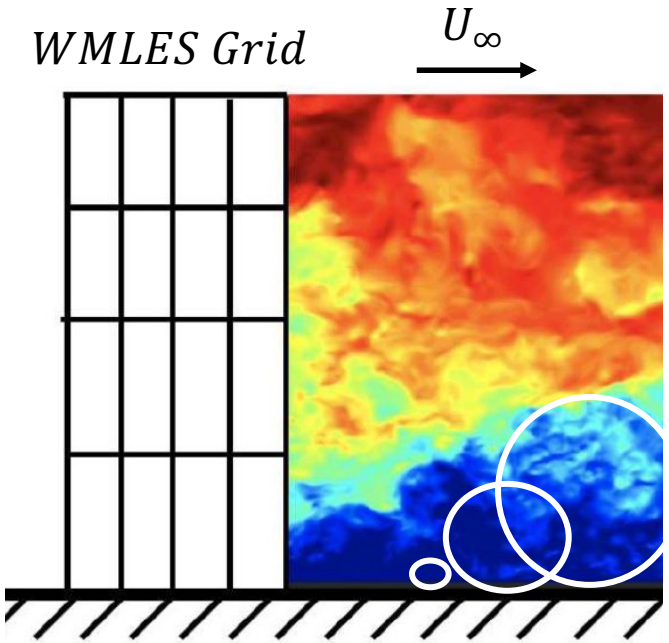
Advanced Air Mobility (AAM)



We need to mature and validate computational tools to enable CbA in icing conditions.

Large Eddy Simulation Equations

LES is a computational paradigm in which the impact of energy-containing flow structures (large eddies) is directly computed while dissipative small eddies (sub-grid eddies) are modeled.



Turbulent Boundary Layer Simulation

Compressible Navier-Stokes Equations

Modeled terms using DSM[1]

Continuity
$$\frac{\partial \bar{\rho}}{\partial t} + \frac{\partial \widetilde{u}_i \bar{\rho}}{\partial x_i} = 0$$

Momentum
$$\frac{\partial \bar{\rho}\widetilde{u}_i}{\partial t} + \frac{\partial \bar{\rho}\widetilde{u}_i\widetilde{u}_j}{\partial x_j} = -\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial \widetilde{\tau}_{ij}}{\partial x_j} - \frac{\partial \tau_{ij}^{sgs}}{\partial x_j}$$

Energy
$$\frac{\partial \bar{E}}{\partial t} + \frac{\partial \widetilde{u}_i \bar{E}}{\partial x_i} + \frac{\partial \widetilde{u}_i \bar{p}}{\partial x_i} = \frac{\partial \widetilde{\tau}_{ij}\widetilde{u}_i}{\partial x_j} - \frac{\partial \tau_{ij}^{sgs}\widetilde{u}_i}{\partial x_j} + \frac{\partial}{\partial x_i}\left(\lambda \frac{\partial \bar{T}}{\partial x_i}\right) - \frac{\partial Q_i^{sgs}}{\partial x_i}$$

$\bar{(\cdot)}$ = low-pass filtered $\widetilde{(\cdot)}$ = Favre filtered

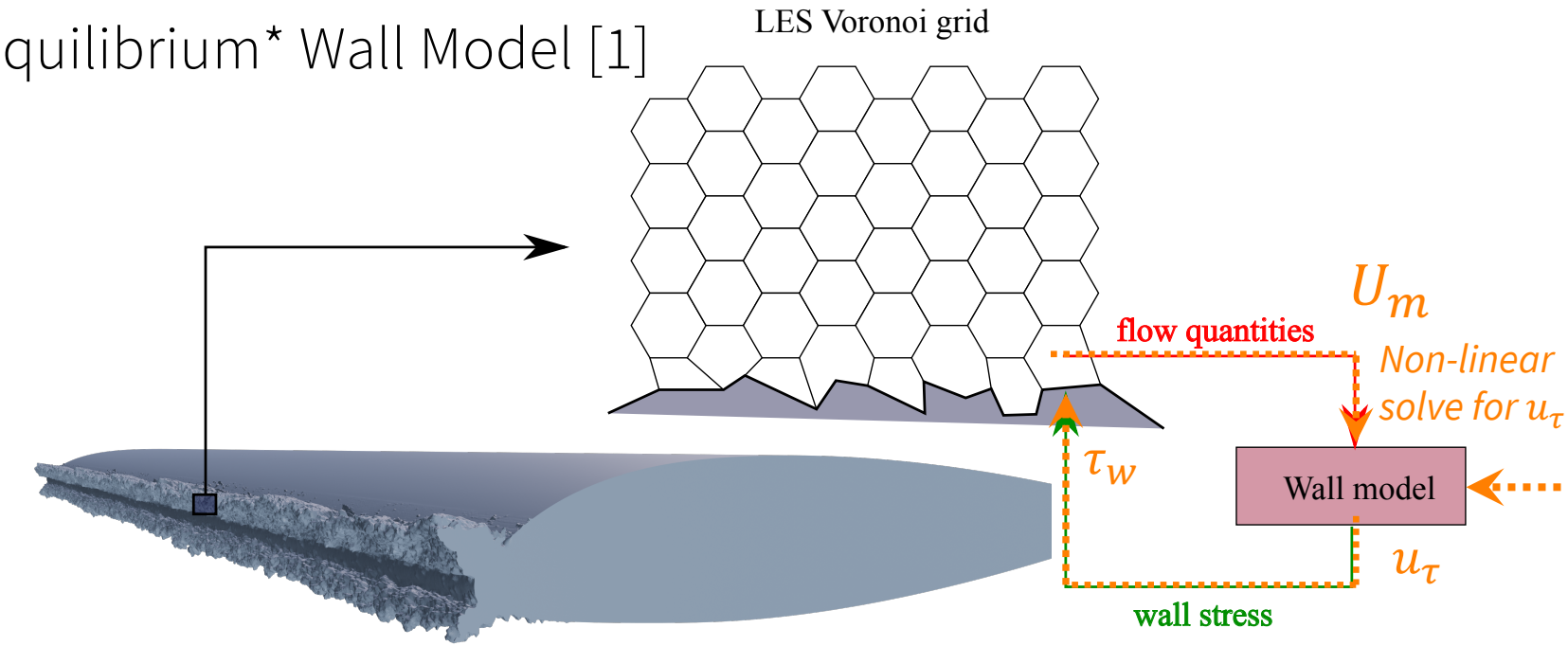
We Need Two Models:

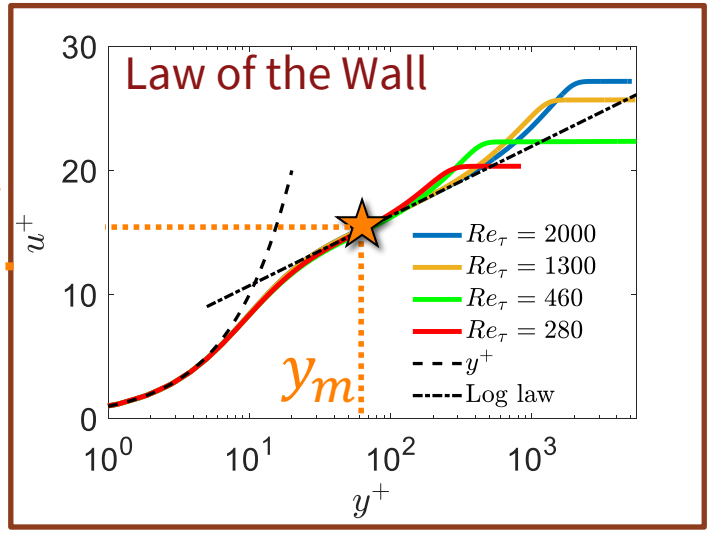
- Sub-grid scale turbulence in the bulk flow
  - Dynamic Smagorinsky[1]
- Near-wall turbulence model

[1] Moin, Parviz, et al. *Physics of Fluids* (1991)

Wall Modeling

Equilibrium* Wall Model [1]





Constant Stress Layer

$$\frac{d\tau}{d\eta} = \frac{d}{d\eta}\left(\mu\frac{dU}{d\eta} - \rho\overline{u'v'}\right) = 0$$

Assume the log law applies

$$u^+(y+) = \begin{cases} y^+ + a_1(y^+)^2 & \text{for } y^+ < 23, \\ \frac{1}{\kappa}\ln y^+ + B & \text{otherwise,} \end{cases}$$

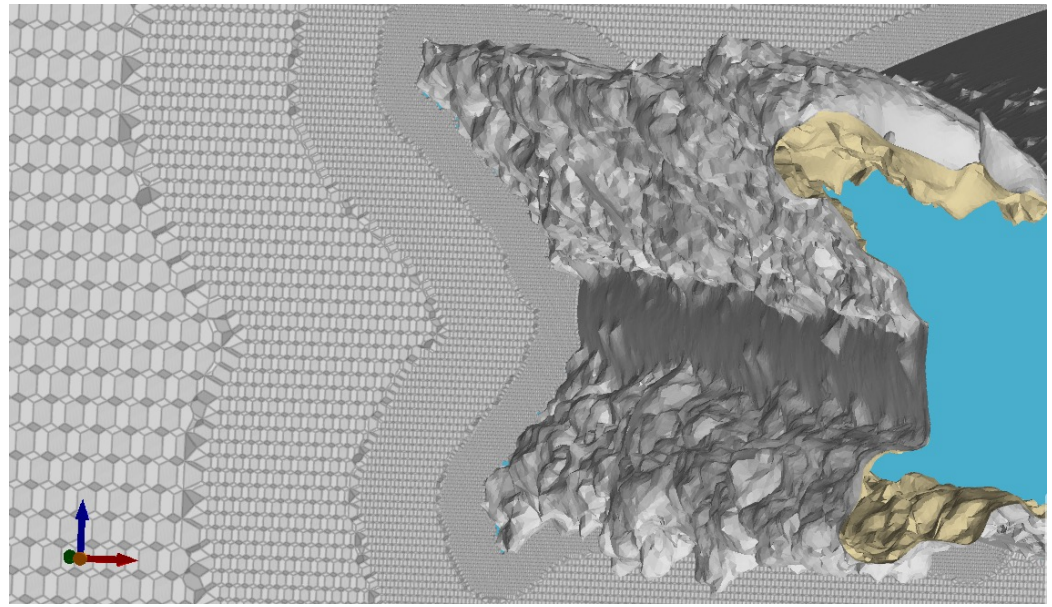
where $u^+ = \frac{U}{u_\tau}$, $y^+ = \frac{yu_\tau}{\upsilon}$, $\tau_w = \rho u_\tau^2$

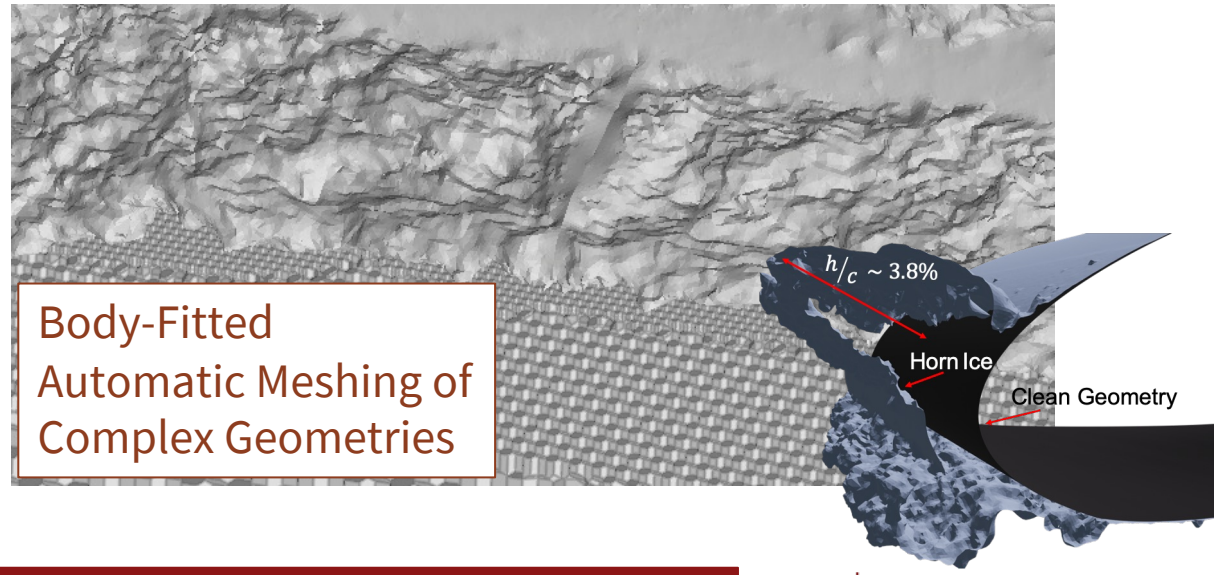
[1] Bose, S. and Park, G., *Annual Review of Fluid Mechanics, 2018*

*Equilibrium in this context means the pressure gradient balances advective term

Methodology and Grids

- Compressible Flow Solver: **charLES**
  - Developed by Cascade Tech.
  - Low-dissipation numerics
  - 2nd order finite-volume method
  - Kinetic Energy and Entropy Preserving (KEEP)
  - Explicit RK time integration
  - GPU Accelerated
- Wall Modeled:
  - Algebraic equilibrium wall model
- Subgrid-Scale Model:
  - Dynamic Smagorinsky model
- Grid Generation: stitch™
  - Custom grid generator for charLES
  - Voronoi grids of hexagonal close-packed topology





Body-Fitted
Automatic Meshing of
Complex Geometries

Outline

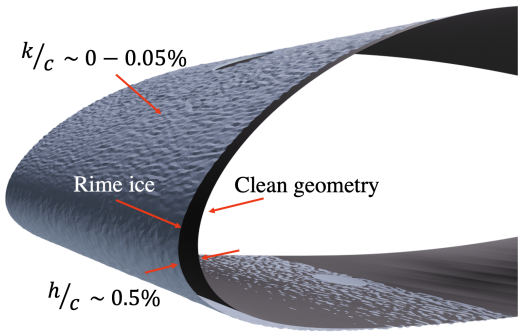
- Background
  - Intro to aircraft icing
  - Certification under new FAA rules
  - LES/Wall Modeling
- Evaluation of WMLES of Airfoils under various icing conditions
- Near-wall modeling for LES of turbulent flows with rough walls
  - Velocity transformation for rough-wall bounded turbulent flows
  - *A posteriori* testing of a new roughness wall model
- On the use of artificial ice shapes in icing

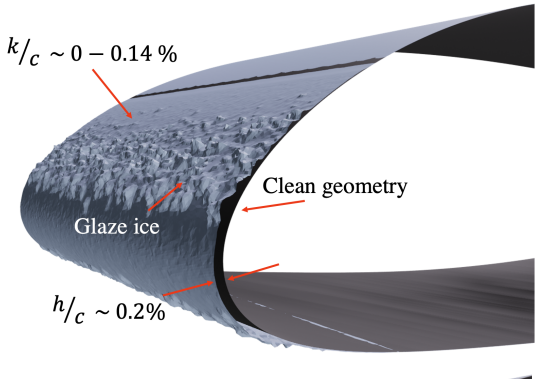
Evaluation of WMLES of Airfoils under various icing conditions

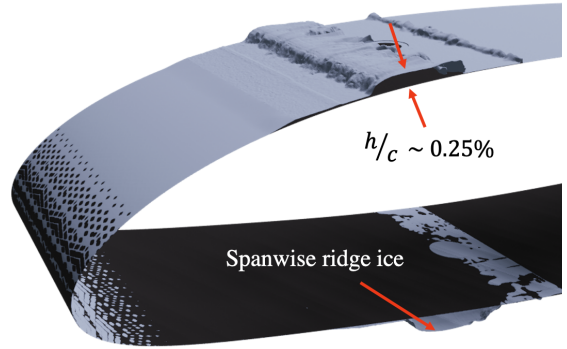
Laser-Scanned Iced NACA23012 Airfoil

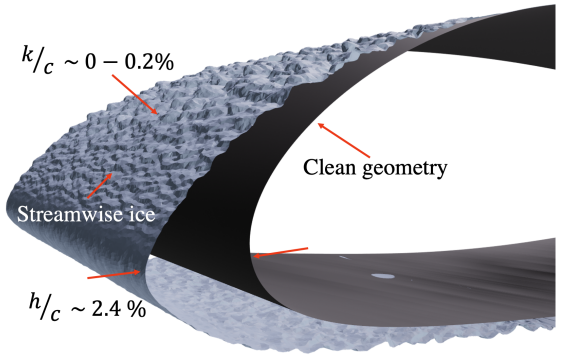


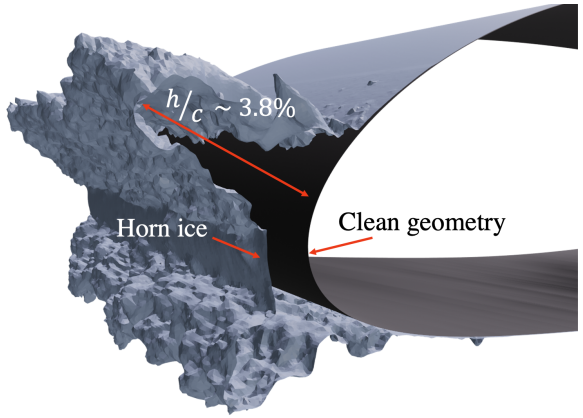










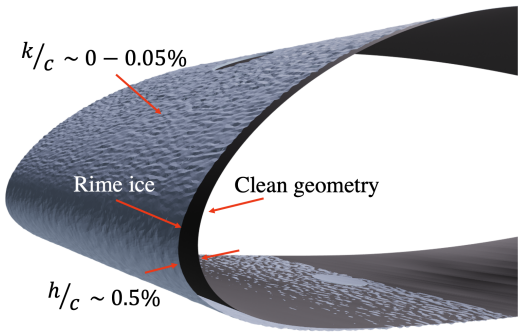


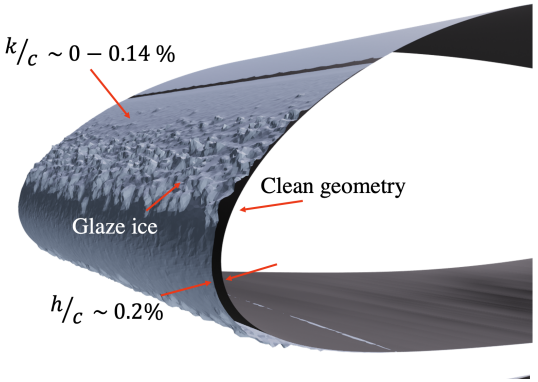
[1] Broeren et al., Journal of Aircraft, 2018

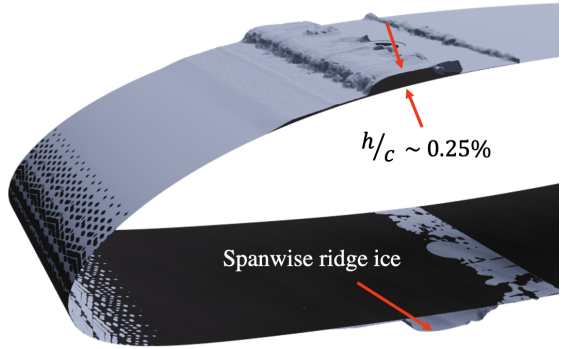
Laser-Scanned Iced NACA23012 Airfoil

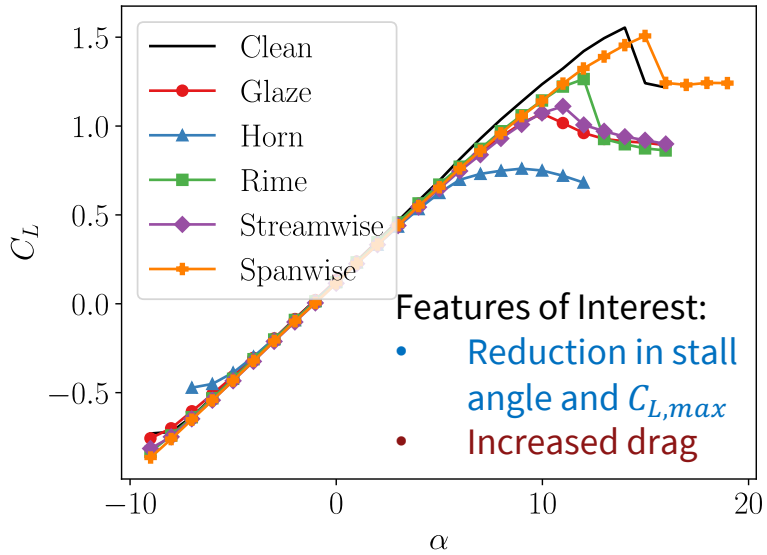


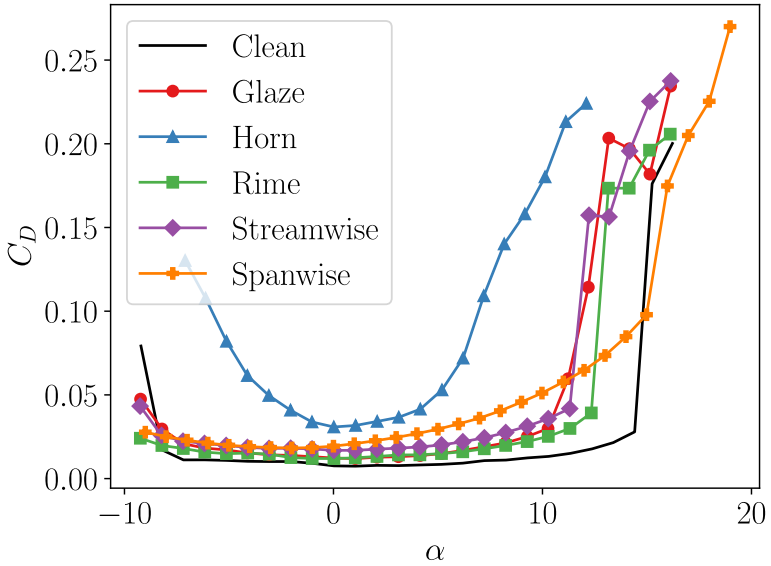












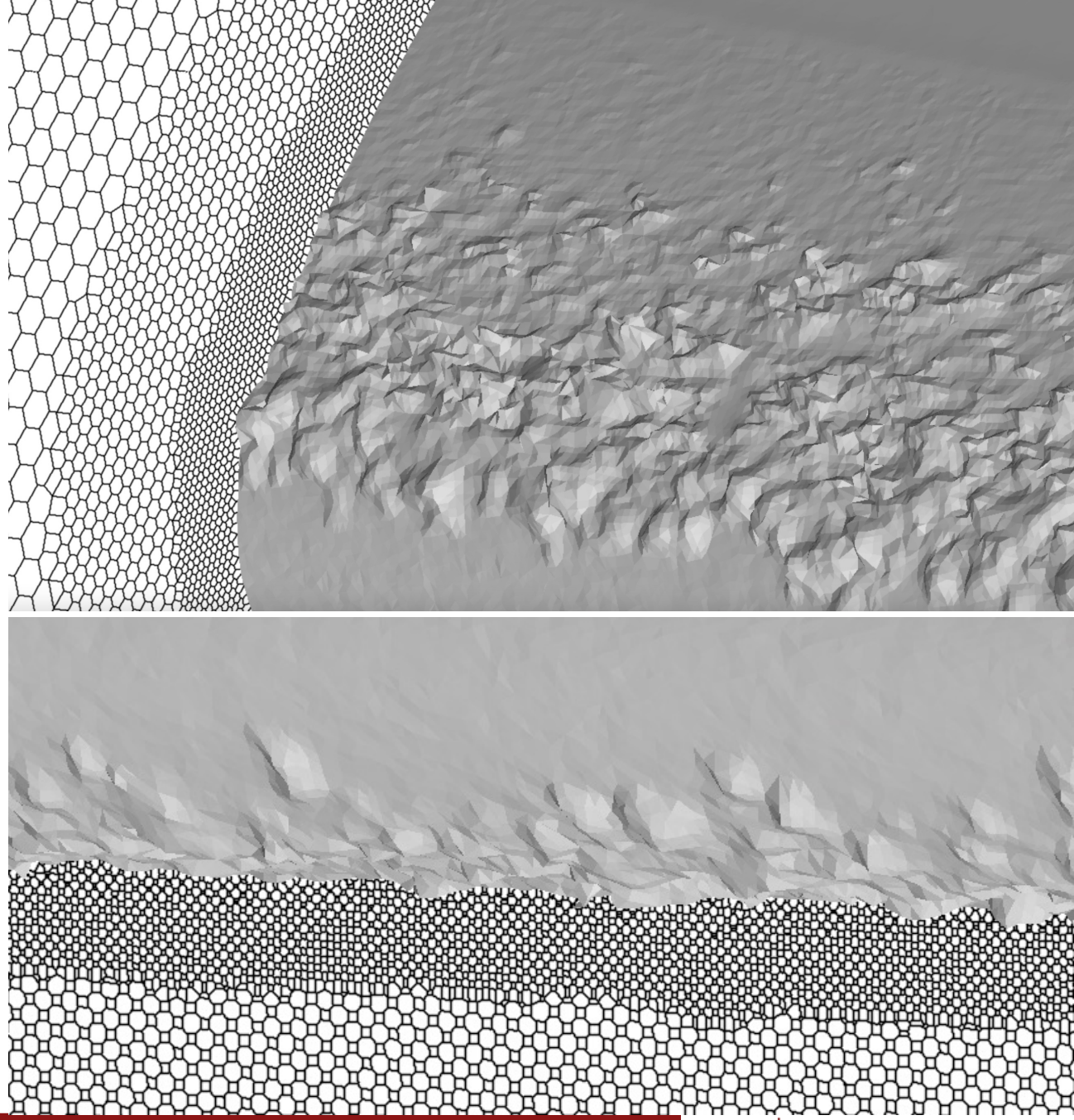
Objective: To evaluate WMLES using laser-scanned ice shapes, create best practices, and identify modeling gaps.

[1] Broeren et al., Journal of Aircraft, 2018

Methodology and Grids

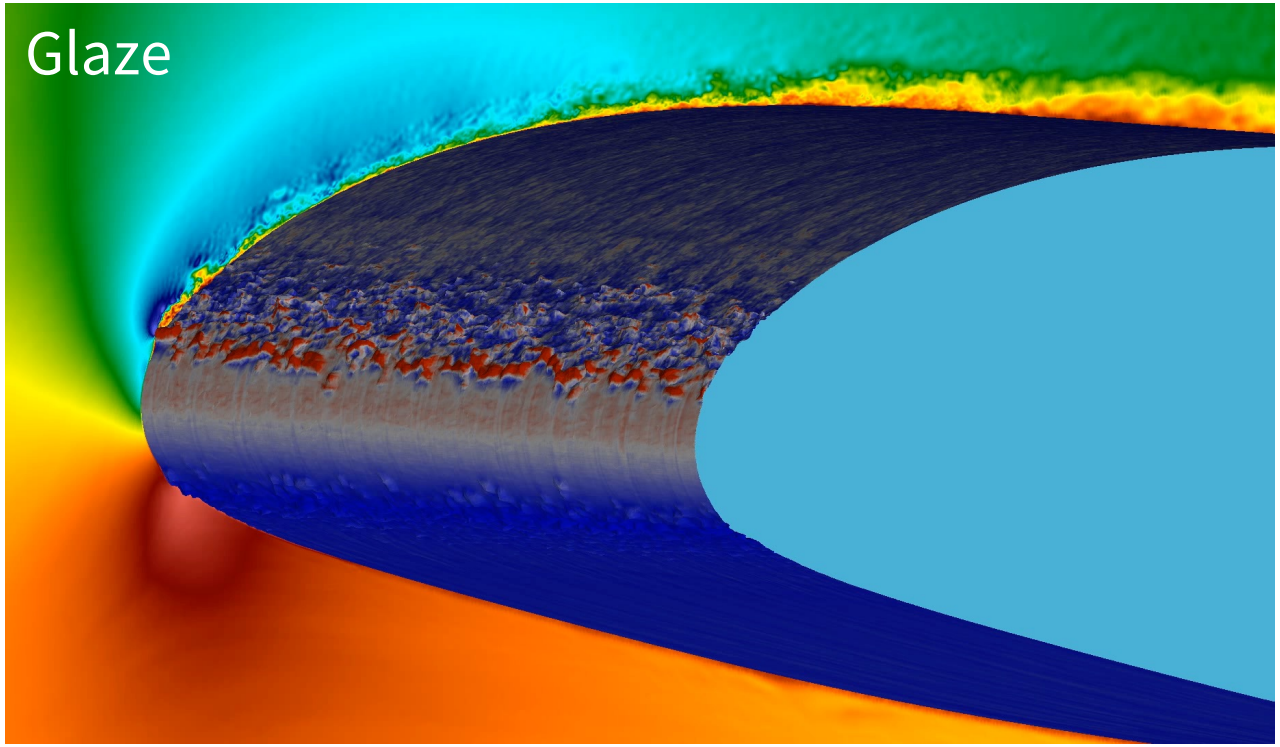
- Grid Refinements*:
  - $\delta/\Delta \sim 25$ (equivalent to 1.5Bcv for CRM-HL, denoted as “Fine”)
  - $\delta/\Delta \sim 40$ (denoted as “XFine”)

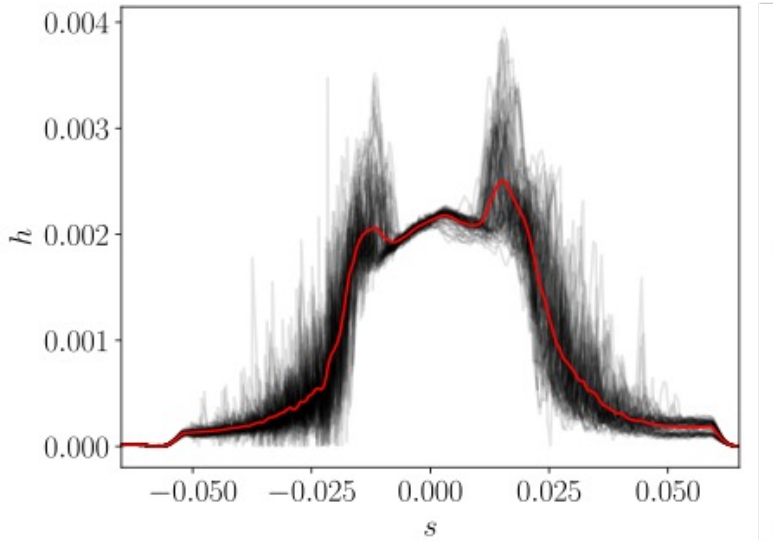
- Simulation Setup:
  - Span-wise periodic (forced through mirroring)
  - $\boldsymbol{M = 0.18, Re_c = 1.8\,M}$

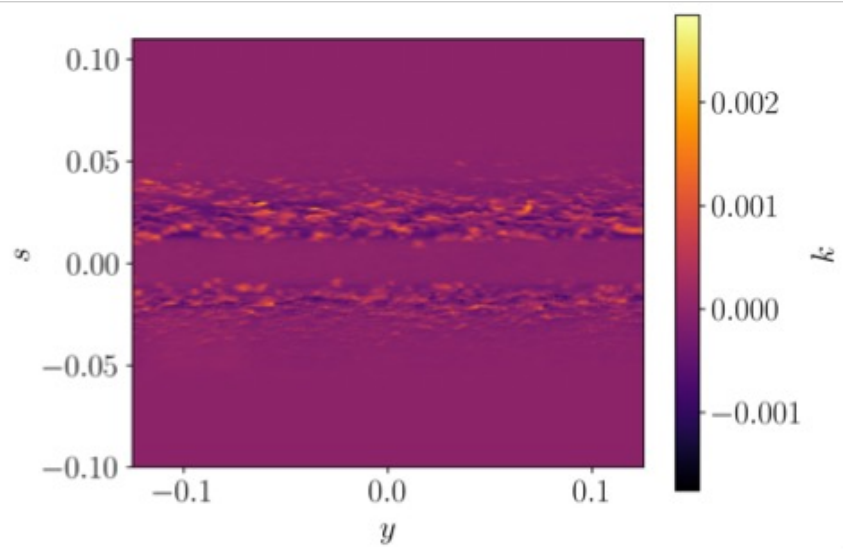


*δ/Δ is the number of points per boundary layer thickness at trailing edge of the airfoil. For all cases, we use the clean geometry for reference boundary layer heights.

Glaze Ice Geometry

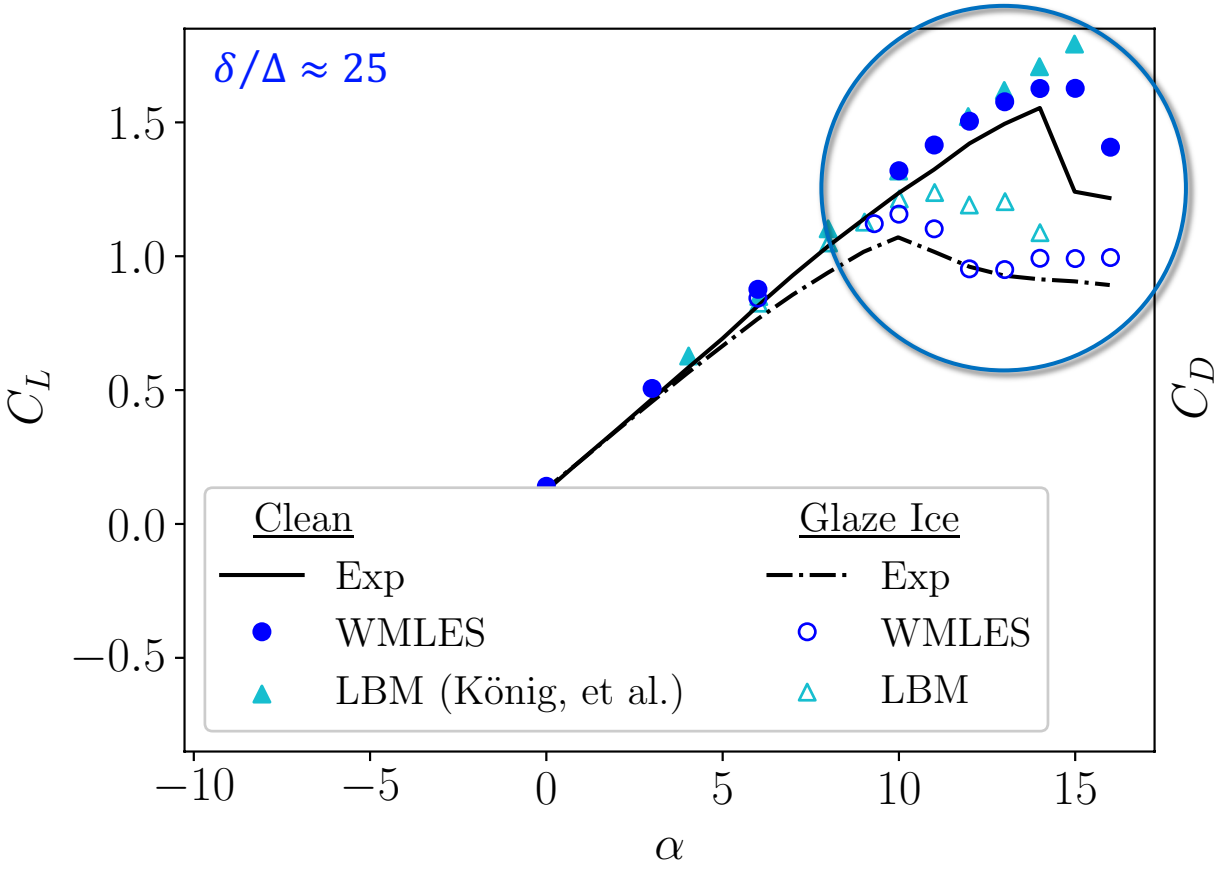


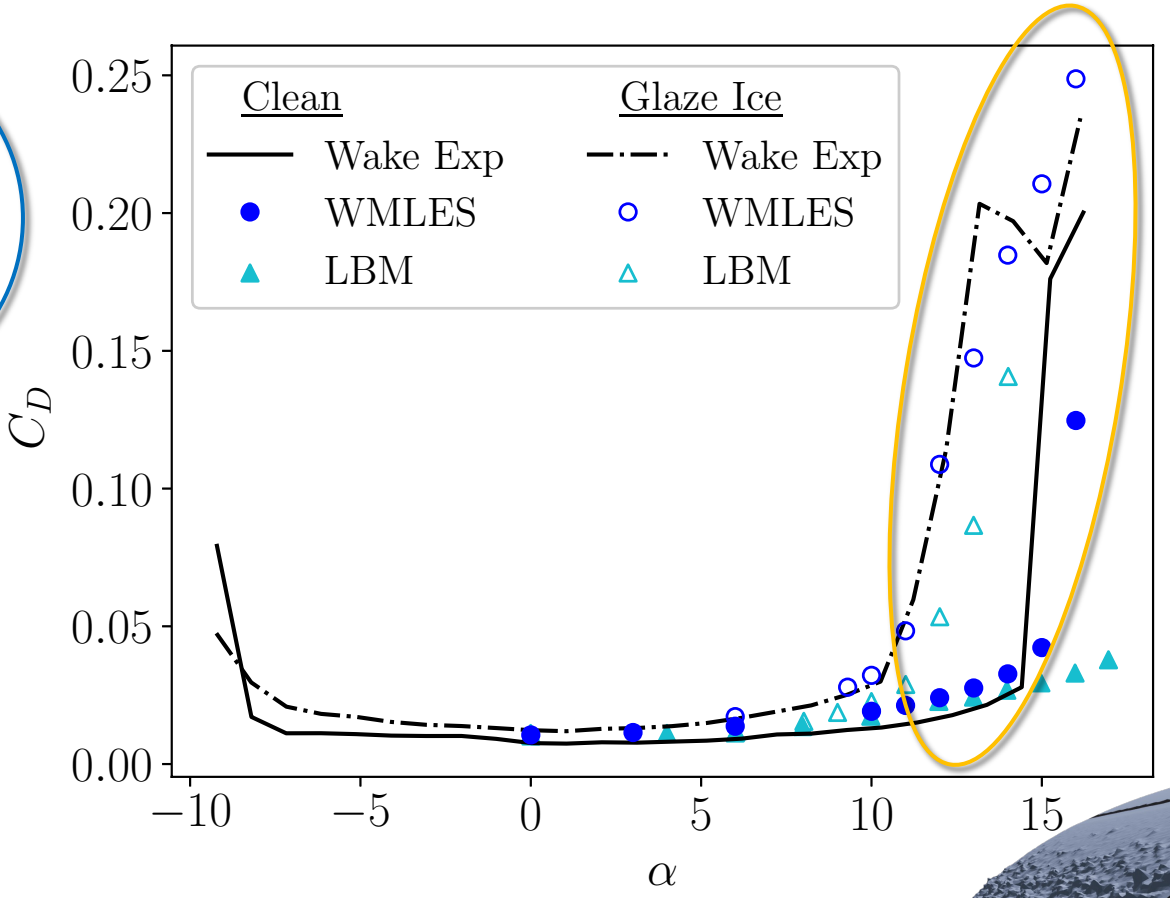


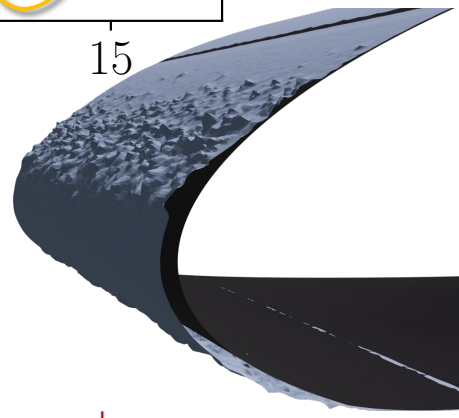


- $k_{avg}/c \sim 0.04\%$ → ~2 CVs per k_{avg}
- $k_{max}/c \sim 0.12\%$ → ~7 CVs per k_{max}
- The resolved roughness dominates transition to turbulence

Glaze Ice Geometry





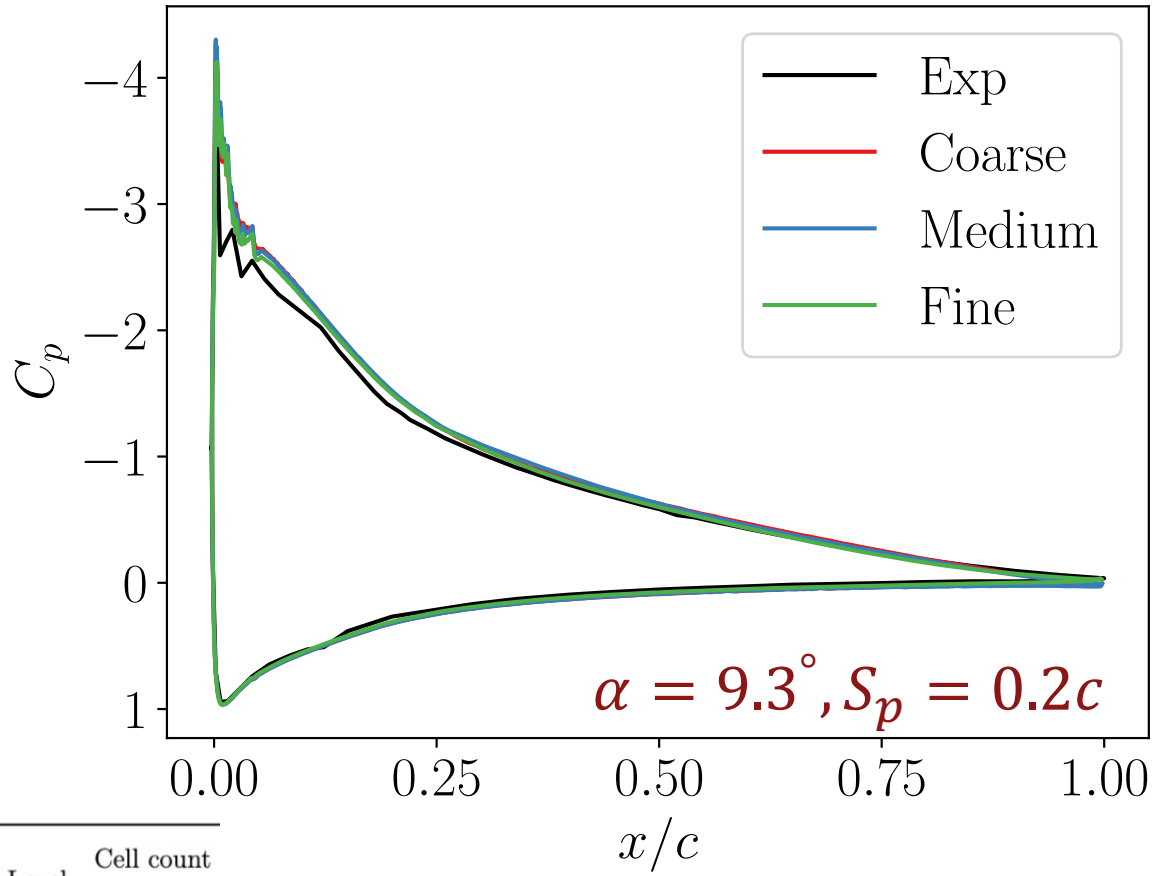


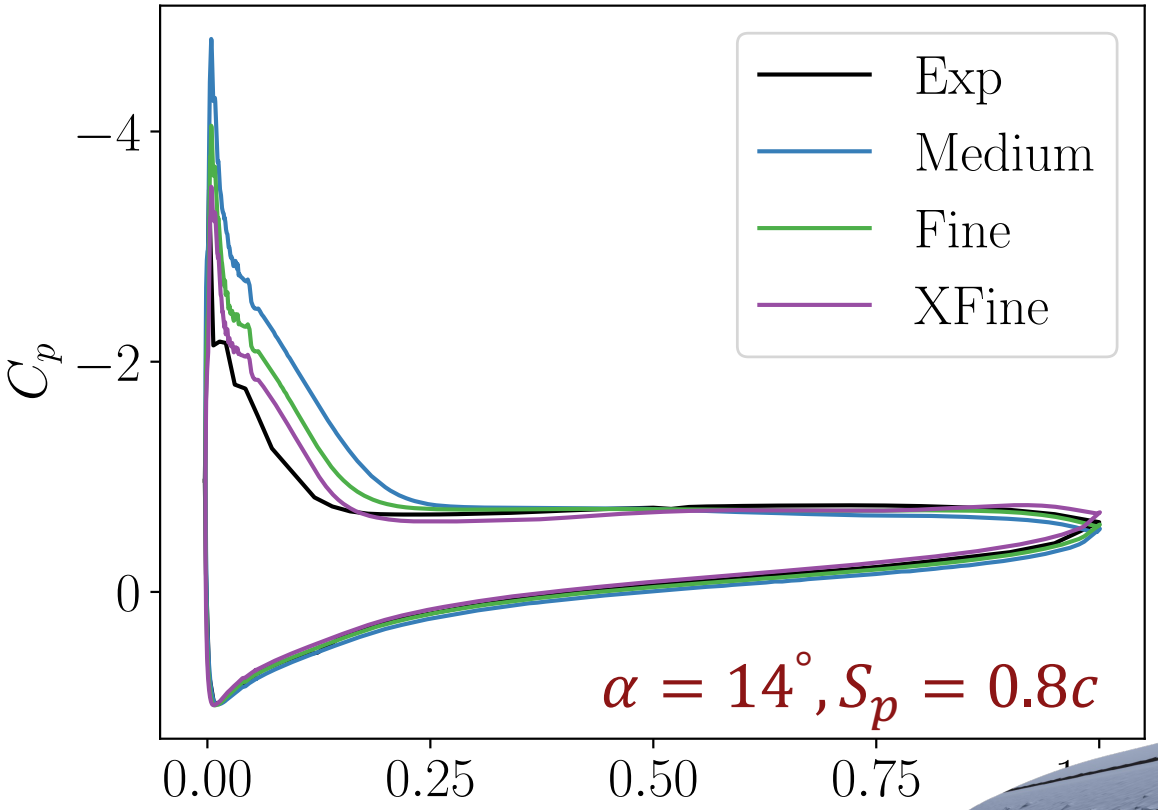
Clean – 14.25 Mcv
Glaze – 27 Mcv

Improved prediction, particularly for stalled cases

König et al., *SAE*, 2015

Glaze Ice Geometry

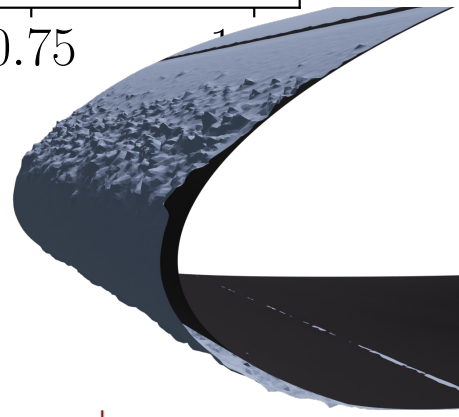




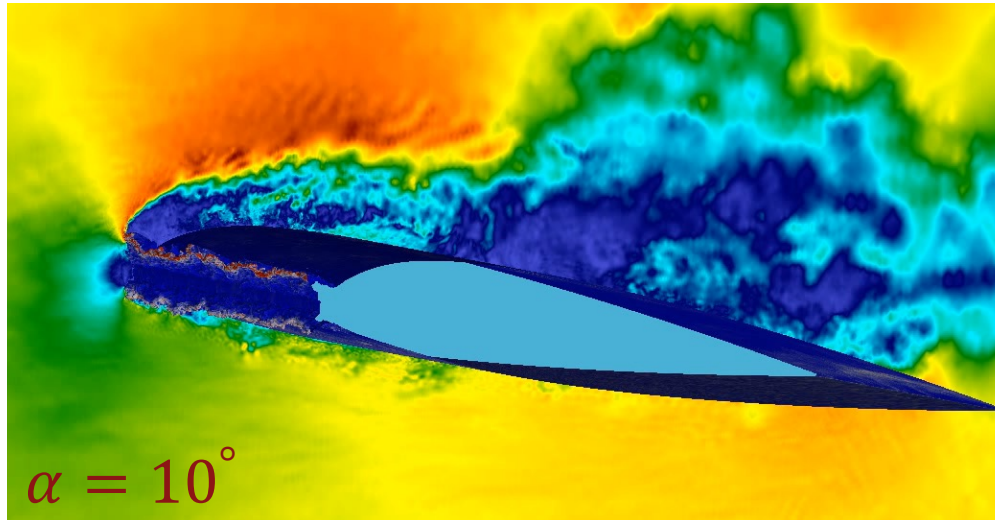
Ref. Level	Cell count (M CV)
Coarse	2
Medium	7.15
Fine	27

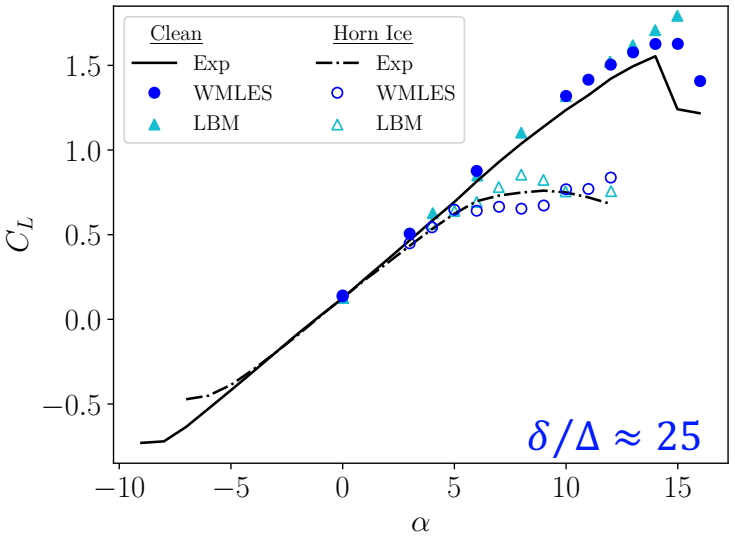
- Little sensitivity to grid resolution at pre-stall angles
- At post-stall, observing convergence to experimental result

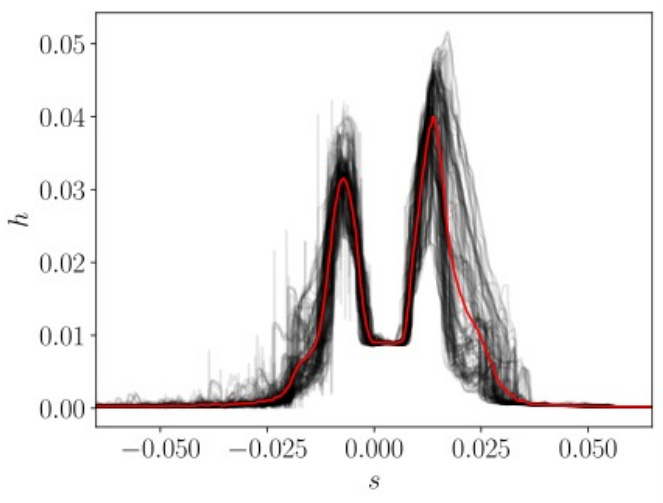
Ref. Level	Cell count (M CV)
Medium	21.23
Fine	85
Extra fine	310



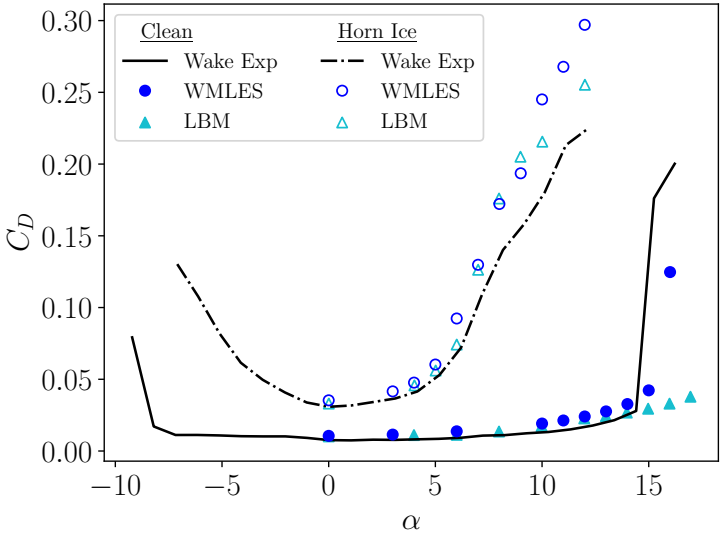
Horn Ice Geometry

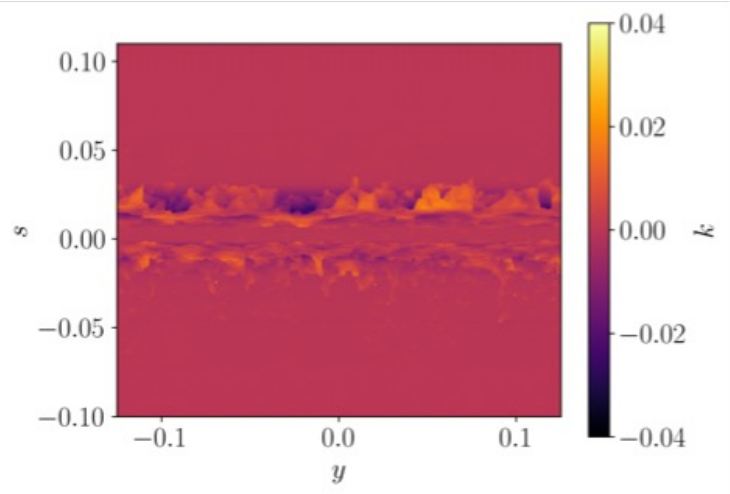




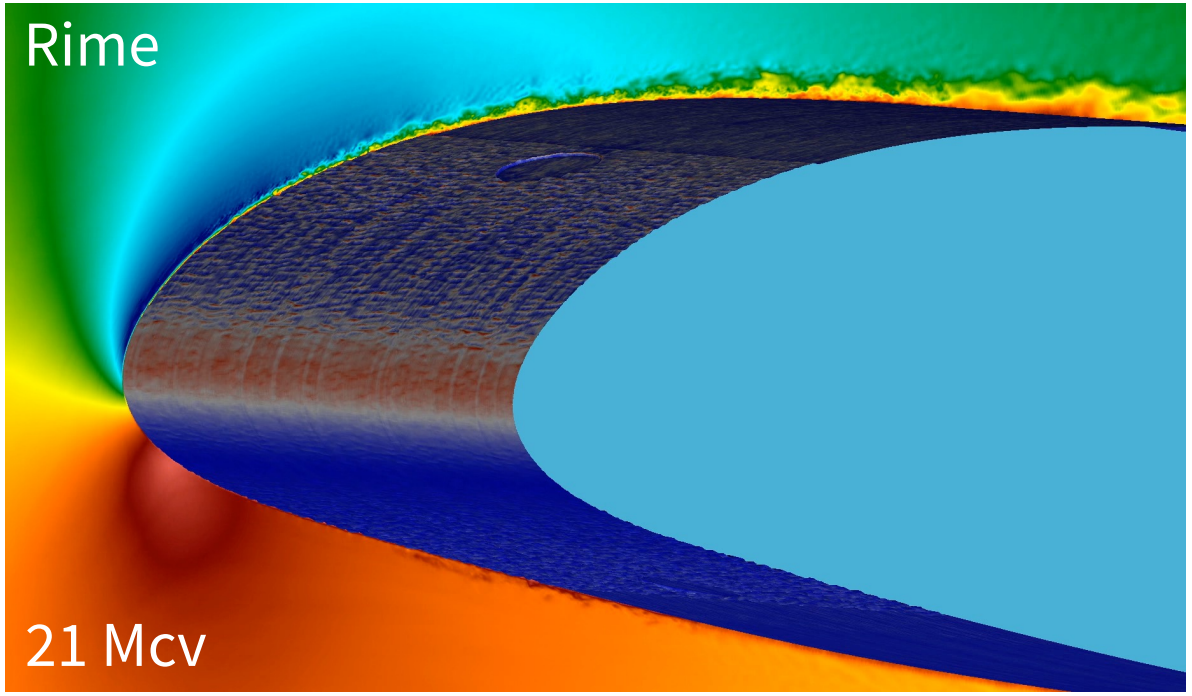


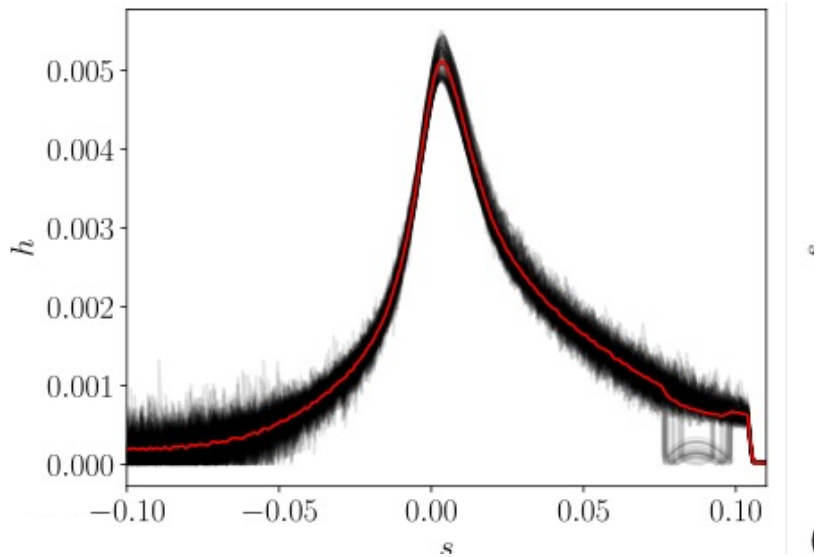
- Roughness and ice displacement concentrated on horns. Order of magnitude increase in horn size.
- Comparable prediction to LBM approach for the horn-ice case
  - Separation is dominated by geometric horn obstructions

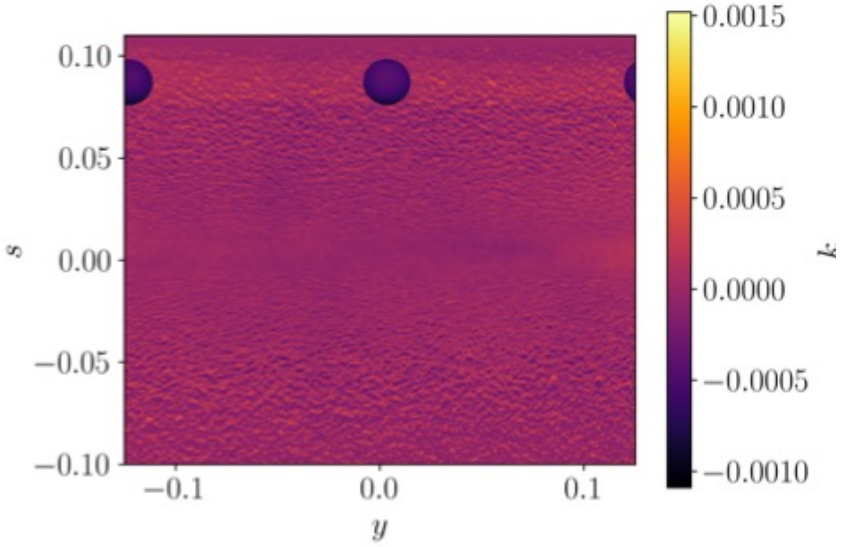




Rime Ice Geometry



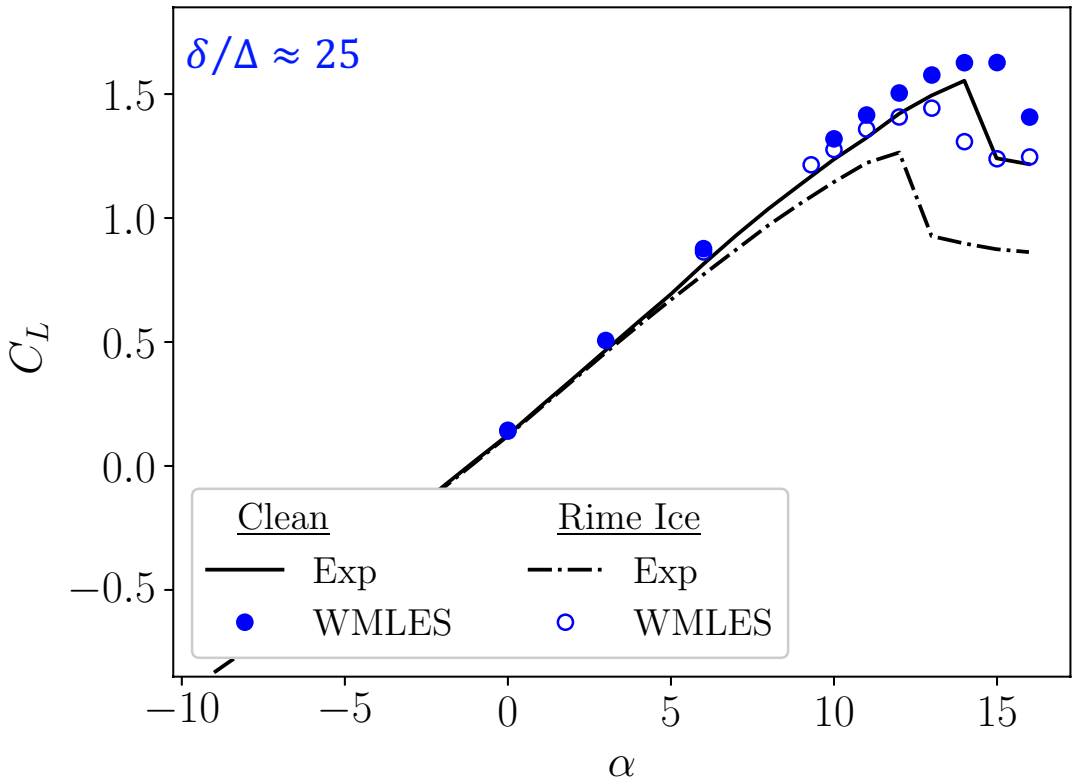


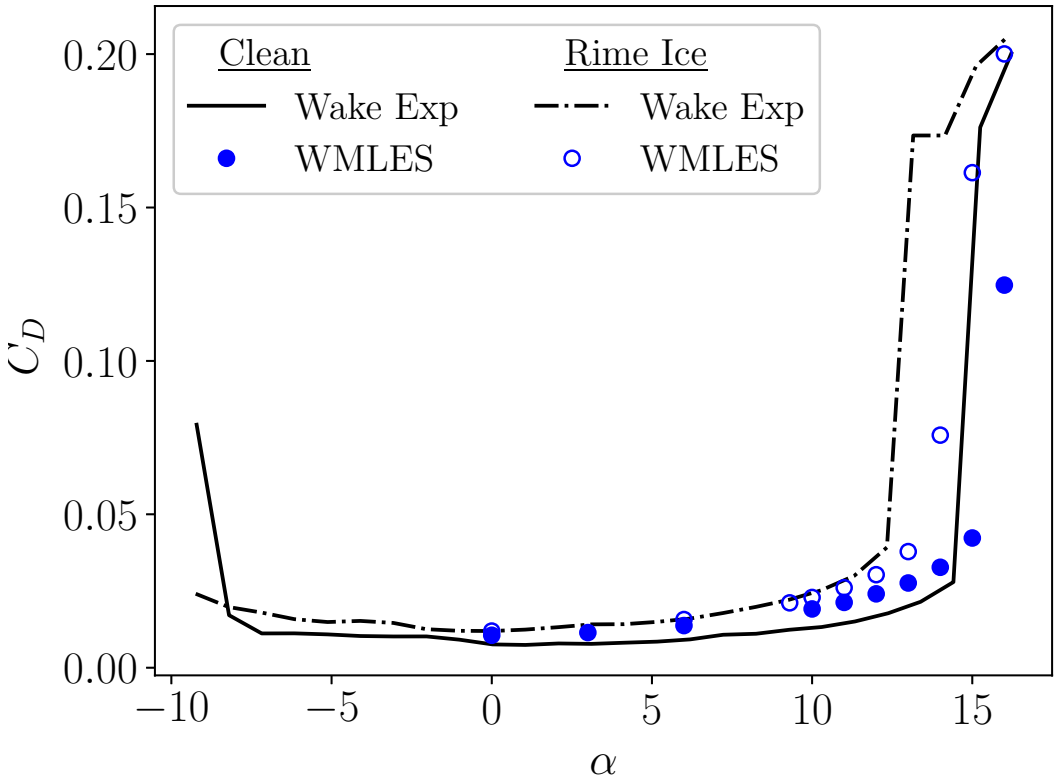


- $k_{avg}/c \sim 0.0125\%$ → < 1 CVs per k_{avg}
- $k_{max}/c \sim 0.03\%$ → ~1.5 CVs per k_{max}

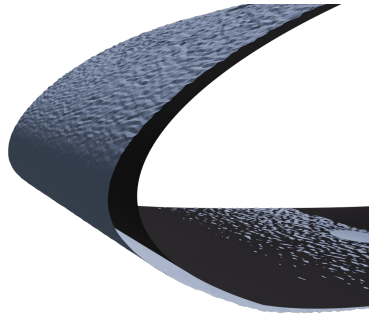
- Given our baseline resolution, the roughness elements are all sub-grid

Rime Ice Geometry

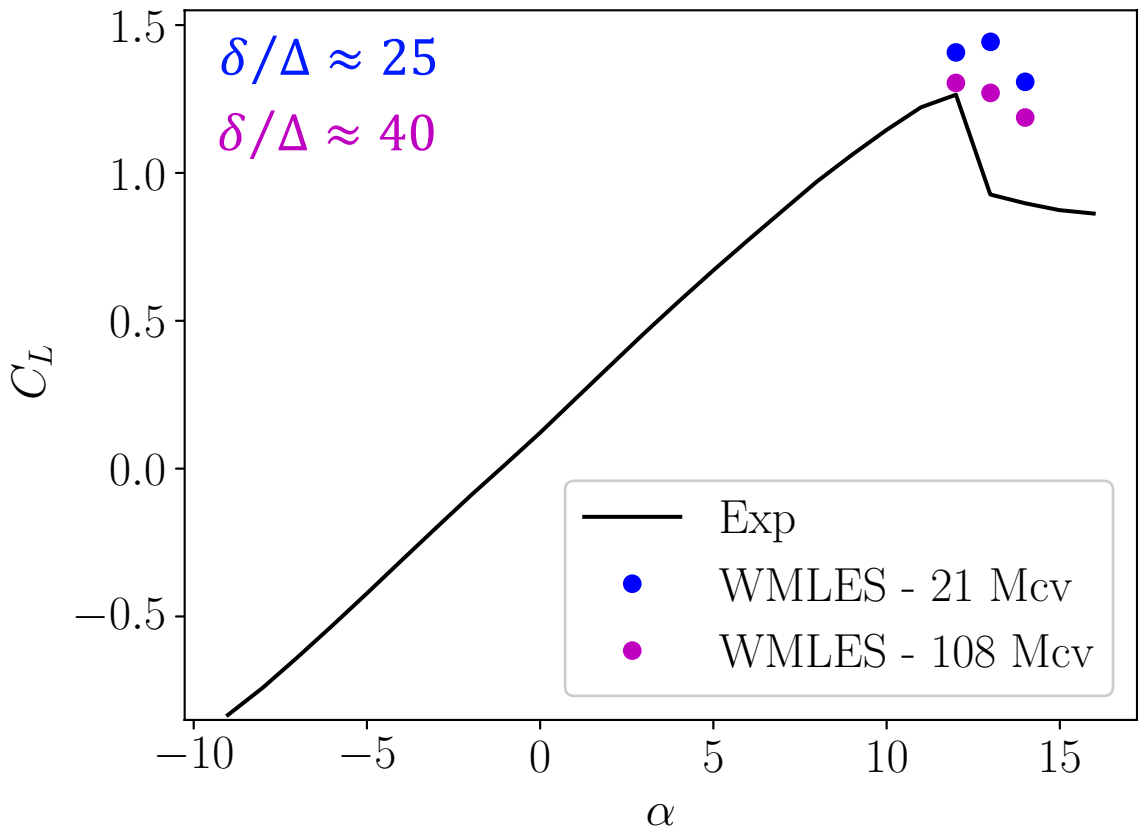


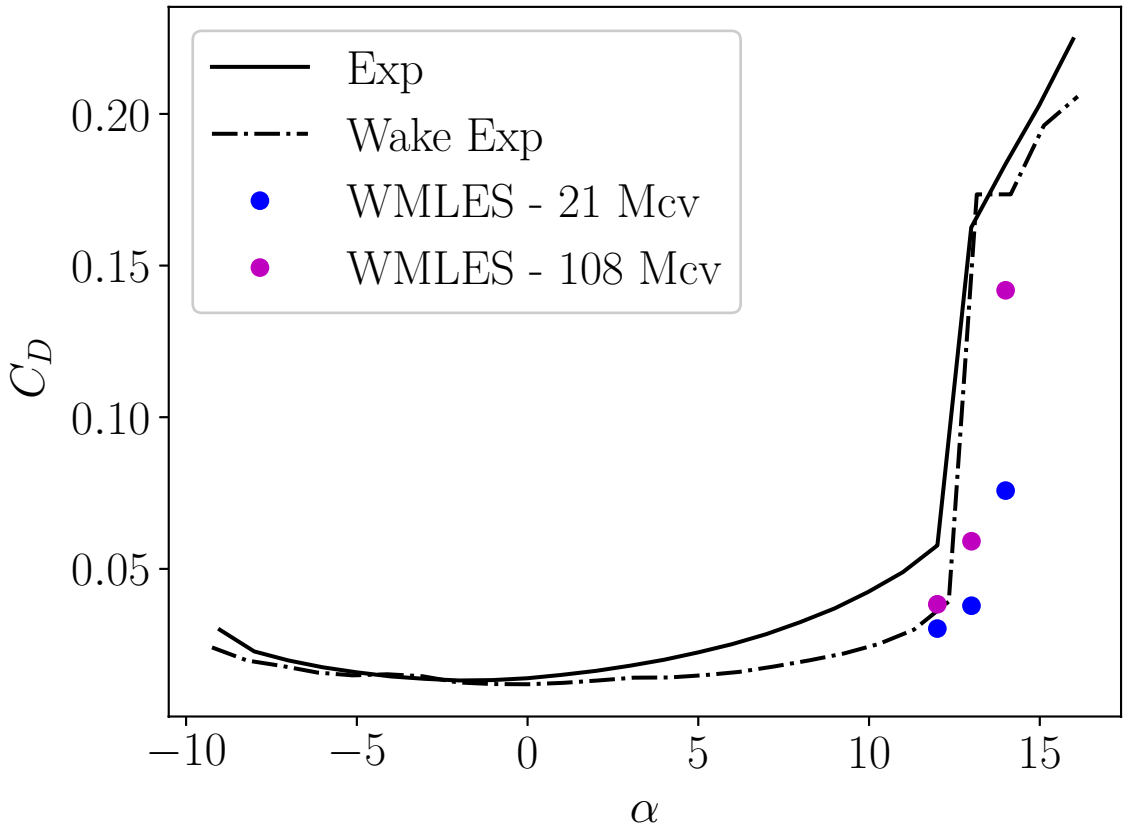


- Established practices shown to be lacking for rime ice
- Large over-prediction of lift coefficient

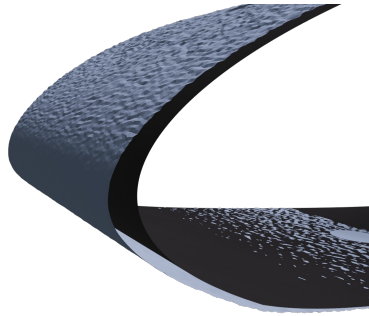


Rime Ice Geometry Refinement Study

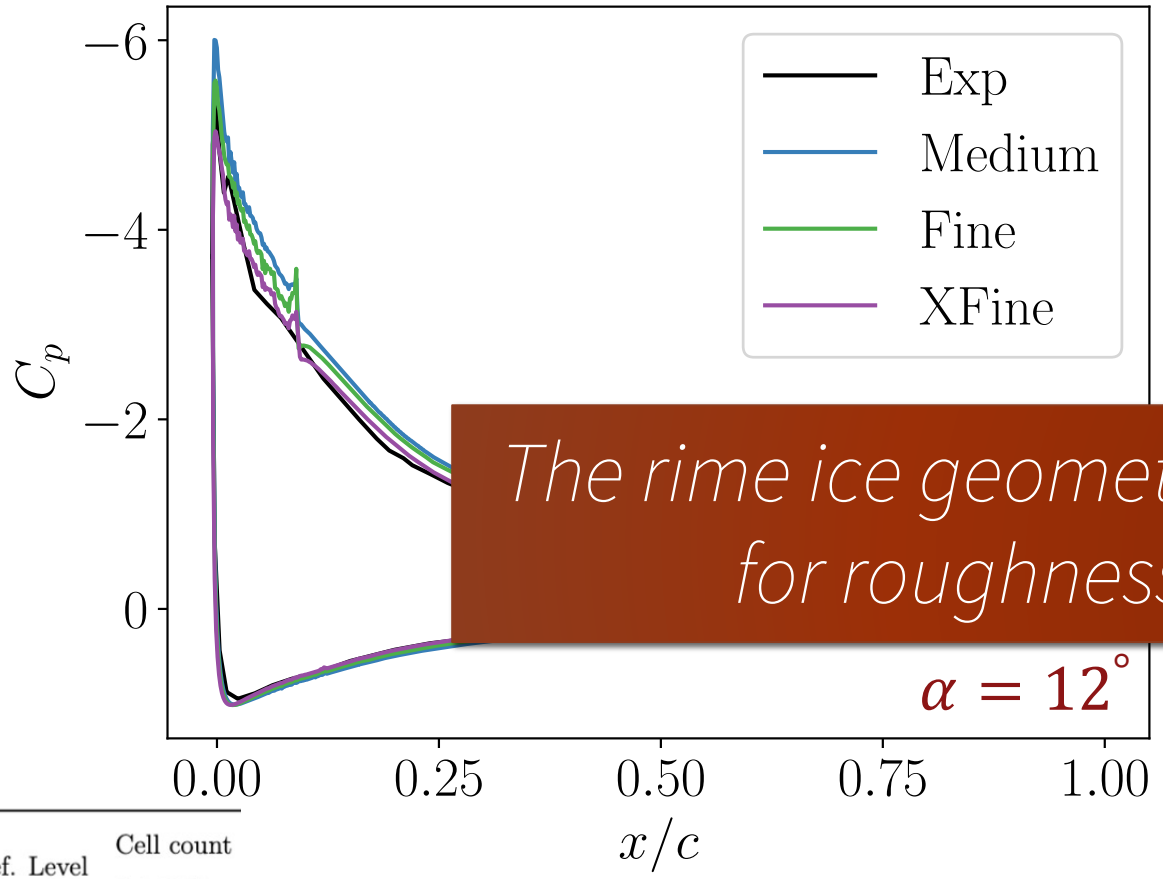


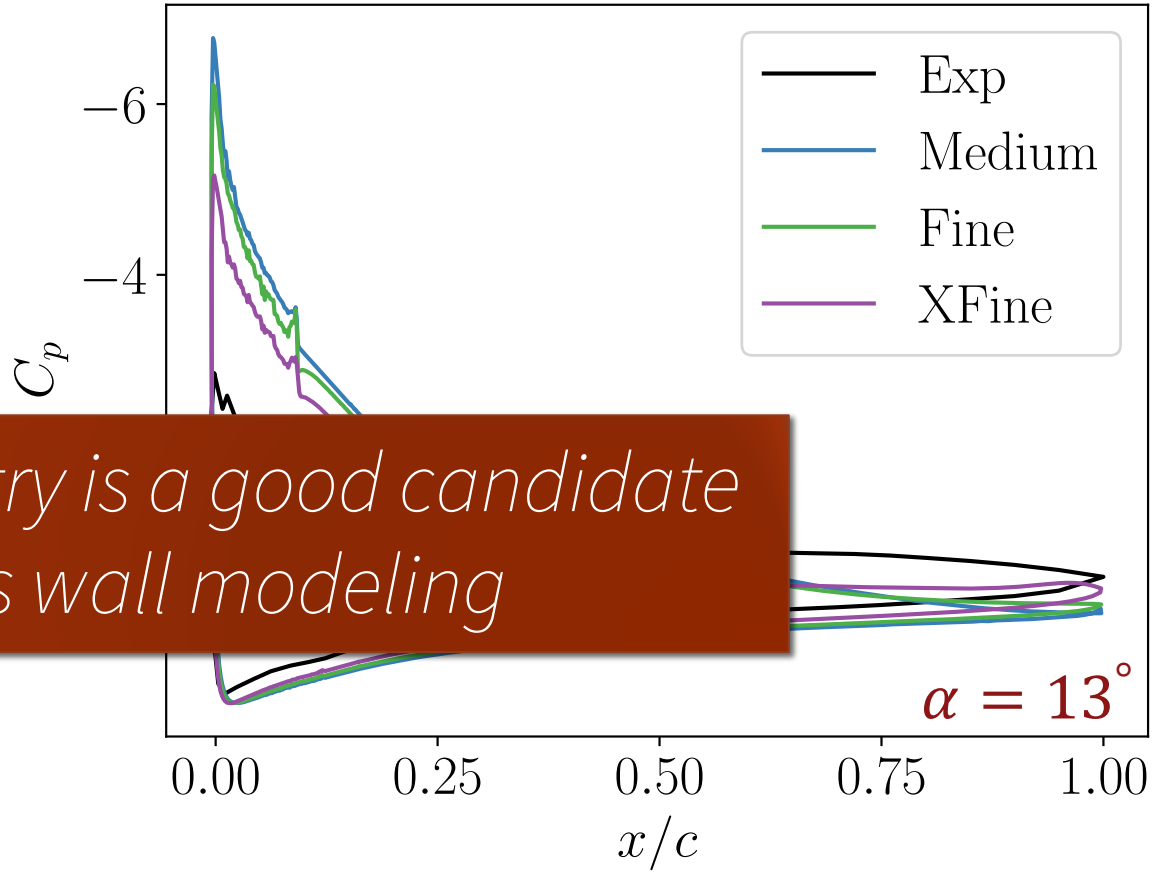


- Resolving additional roughness scales results in improved results, but still overpredicts the post-stall lift and underpredicts the drag.



Rime Ice Geometry Refinement Study





The rime ice geometry is a good candidate for roughness wall modeling

Ref. Level	Cell count (M CV)
Medium	4.1
Fine	21
Extra fine	109

- Little sensitivity to grid resolution at pre-stall angles
- At post-stall, the result still yields little to no stall and only minimally improves towards the experimental data

Conclusions

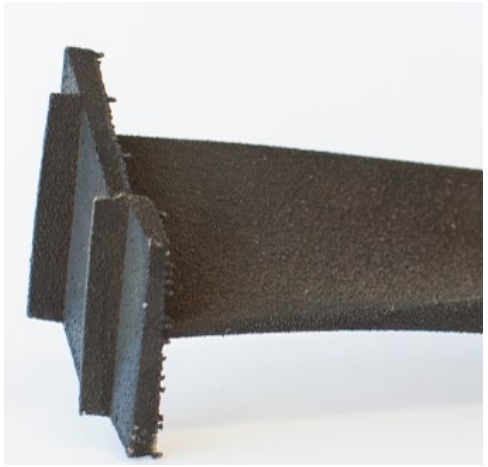
- Voronoi meshes provide the capability to simulate complex ice shapes from real ice accretion experiments
- WMLES of glaze and horn ice geometries correctly predicts critical $\alpha, C_{L,max}$, and other integrated quantities of interest
- Classical WMLES is adequate in simulating glaze ice conditions due to the large-scale resolved features that dominate the flow
  - Requires laser-scanned ice shapes
- We conducted first-ever WMLES of rime ice conditions
  - Overprediction of lift coefficient
  - **Motivates the need for modeling subgrid roughness due to small roughness scales**

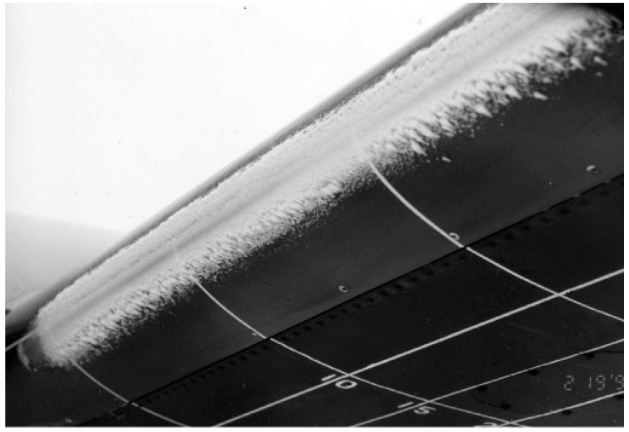
Details of this work are available in the following article

Bornhoft, B., Jain, S. S., Goc, K., Bose, S. T., and Moin, P., "Large-eddy simulations of the NACA23012 airfoil with laser-scanned ice shapes," Aerospace Science and Technology (2024): 108957.

Near-wall modeling for LES of turbulent flows with rough walls

Rough Surface Examples in Wall-Bounded Flows

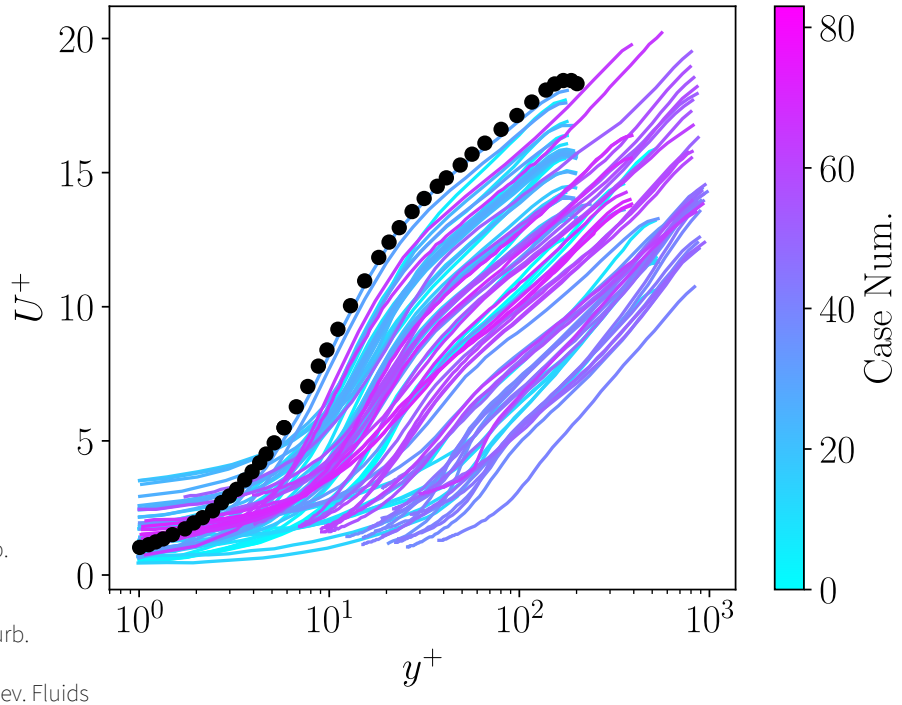



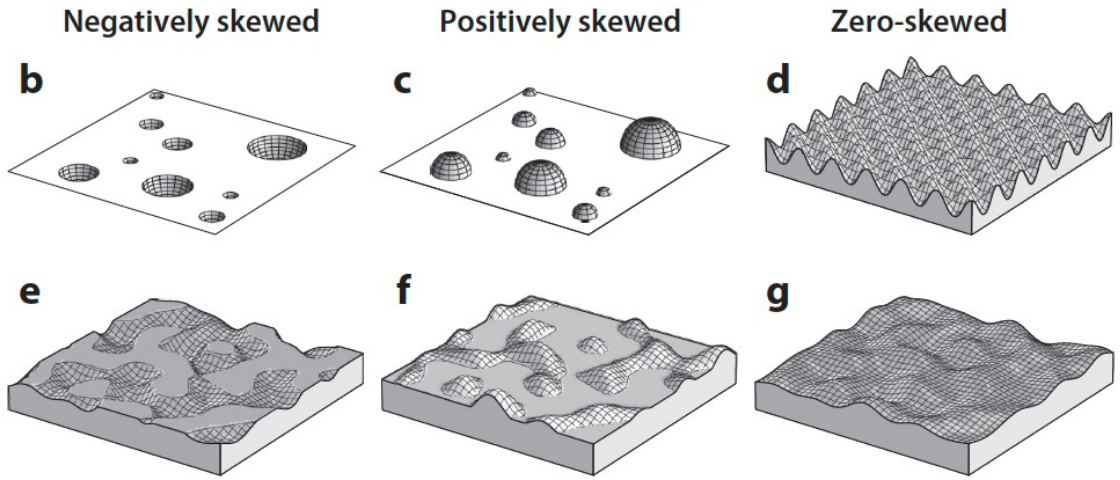




Motivation

- Multiple parameters influence rough-wall flows ($k_a, k_{rms,}\ ES, \Lambda, s_k, \dots$)
- Surfaces with same height can have different topographies and flow fields
- k_s^+ is used for modeling, which is inherently a hydrodynamic quantity and is not predictive.





Chung et al., 2021. Annu. Rev. Fluid Mech.

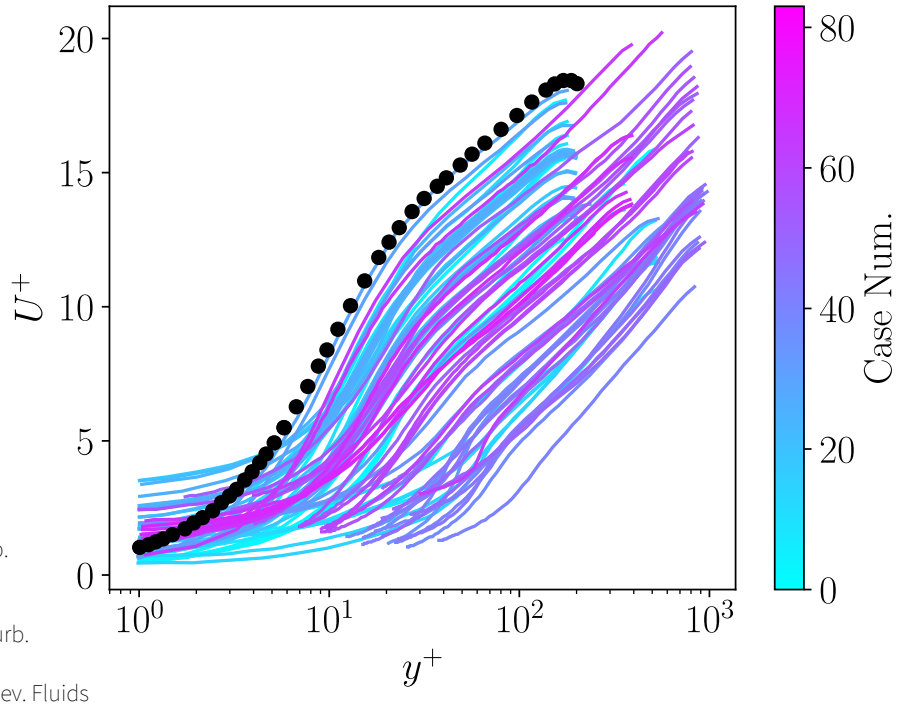
[1] Ma et al., 2020, JFM
[2] Jouybari et al., 2021, JFM
[3] Busse et al., 2023, J. of Turb.
[4] Chan et al., 2015, JFM
[5] Chan et al., 2018, JFM
[6] Thakkar et al., 2017, J. of Turb.
[7] Thakkar et al., 2018, JFM
[8] Chung et al., 2021 Annual Rev. Fluids

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Motivation

- Multiple parameters influence rough-wall flows ($k_a, k_{rms,}\ ES, \Lambda, s_k, \dots$)
- Surfaces with same height can have different topographies and flow fields
- k_s^+ is used for modeling, which is inherently a hydrodynamic quantity and is not predictive.

- Question: Given access to a roughness topography, what is the best approach to modeling roughness effects in both the roughness sublayer and log-layer in the context of WMLES?



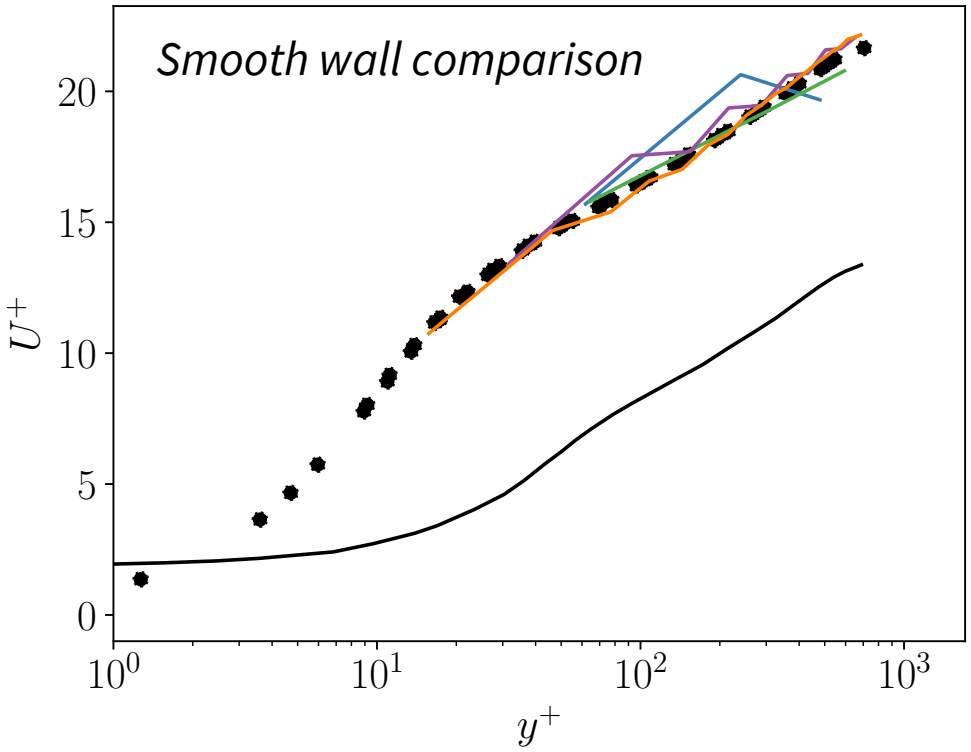
Prediction of Rough Surfaces Require at Least

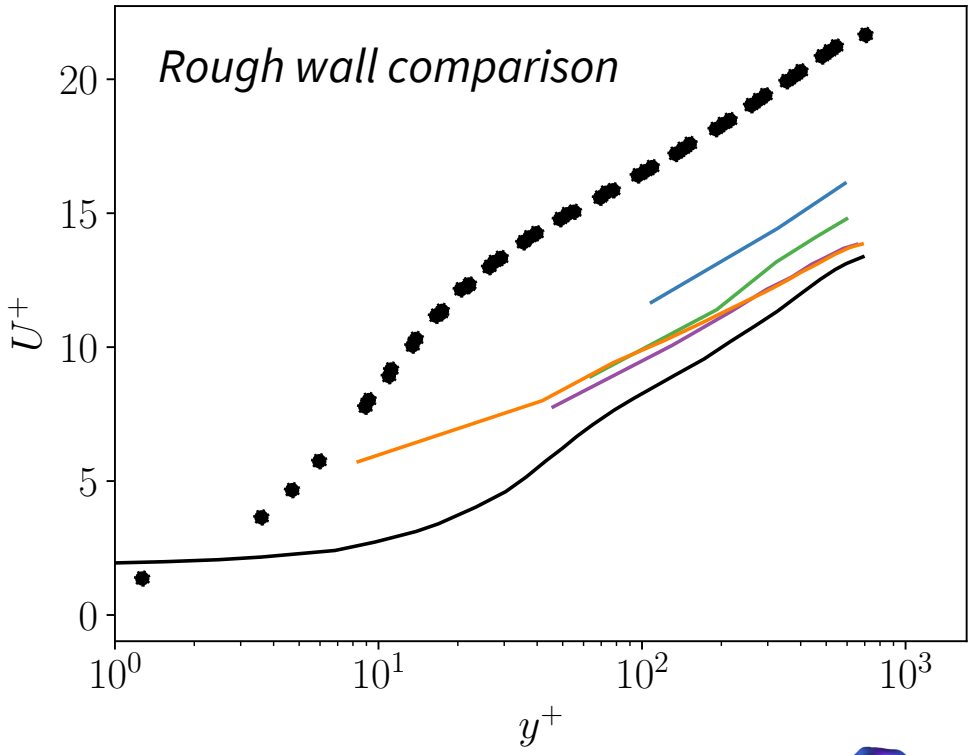
- Roughness height ($\mathbf{k_{rms}, k_a, k_t}$)
- Frontal area parameter ($\boldsymbol{\lambda_f}$, **ES**)
- Surface coverage parameter ($\boldsymbol{\lambda_p}$, $\mathbf{s_k}$)

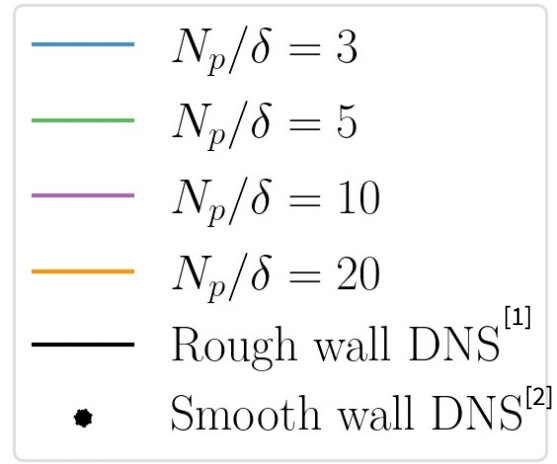
Chung et al., 2021. Annu. Rev. Fluid Mech.

[1] Ma et al., 2020, JFM
[2] Jouybari et al., 2021, JFM
[3] Busse et al., 2023, J. of Turb.
[4] Chan et al., 2015, JFM
[5] Chan et al., 2018, JFM
[6] Thakkar et al., 2017, J. of Turb.
[7] Thakkar et al., 2018, JFM
[8] Chung et al., 2021 Annual Rev. Fluids

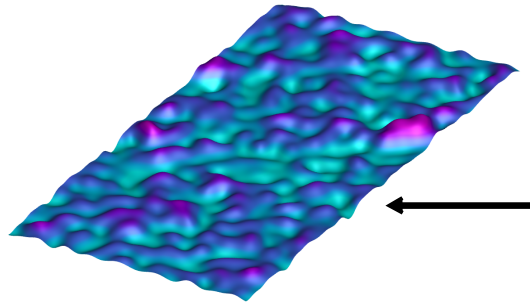
Motivation: EQWM Applied to Smooth and Rough Walls







Applying the EQWM to rough surfaces yields slower grid convergence as compared to the smooth wall case



$Re_\tau = 720$
$ES_x = 0.1162$
$s_k = 0.5964$
$k^+_{rms} = 19.8$

[1] Thakkar, et al. JFM, 2018.
[2] Hu, et al. AIAA J. 2006

KES Model ($k_{rms,}\ ES, s_k$)

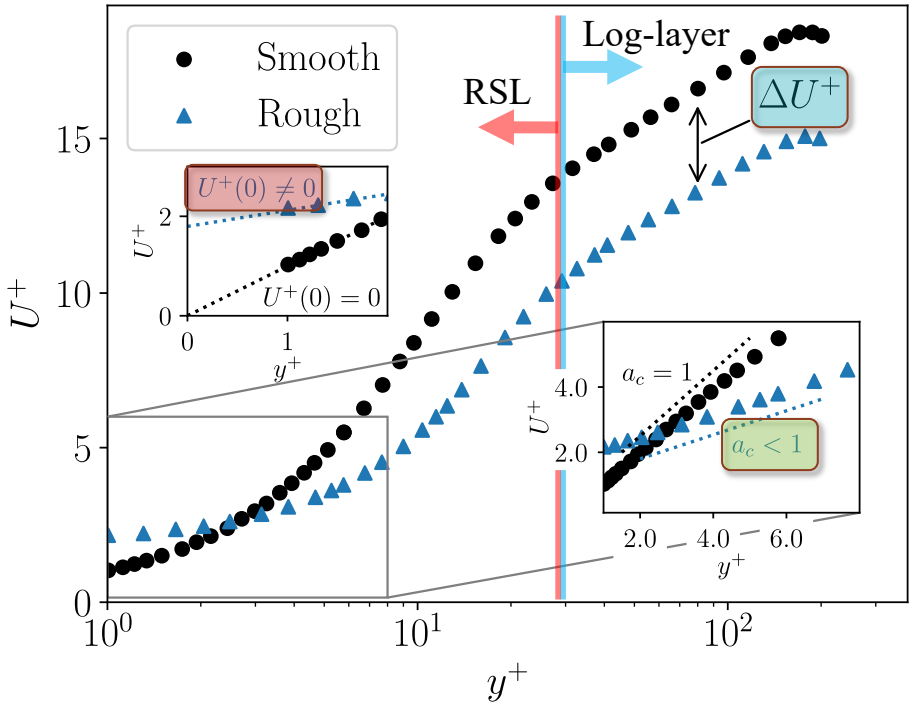
- We model our rough boundary layer using a two-layer approach

$$U^+ = \frac{1}{\kappa}\ln y^+ + B - \Delta U^+$$ } Log-layer

$$U^+ = a_c y^+ + \Delta U^+_{RSL}$$ } Roughness sublayer (RSL)

- We utilize the DNS database to inform empirical fits for each parameter

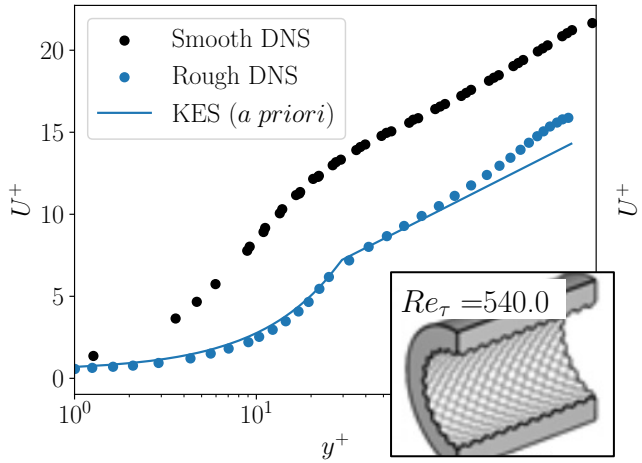
$$a_c = f(k^+_{rms}, ES_x, s_k)$$
$$\Delta U^+_{rsl} = f(k^+_{rms}, ES_x)$$
$$\Delta U^+ = f(k^+_{rms}, ES_x, s_k)$$



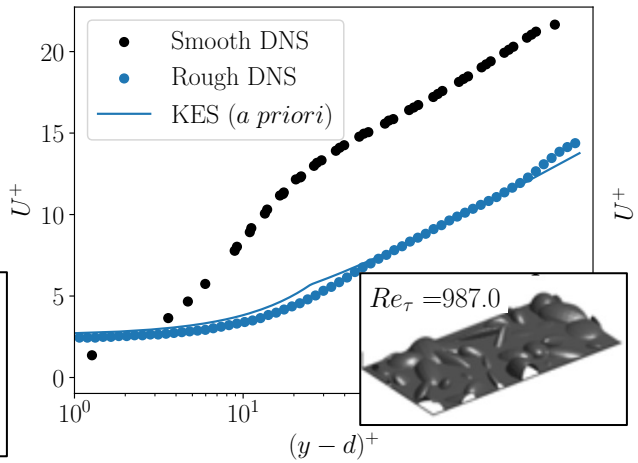
[1] Bornhoft et al. CTR Annual Brief, 2024

Example *a priori* Results on a Variety of Surfaces

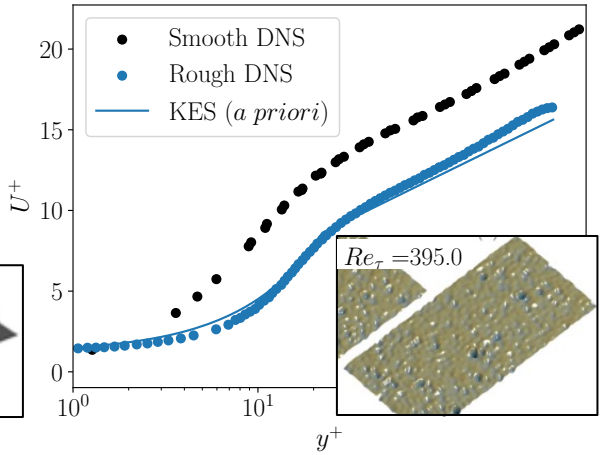
Sinusoidal Pipe Roughness



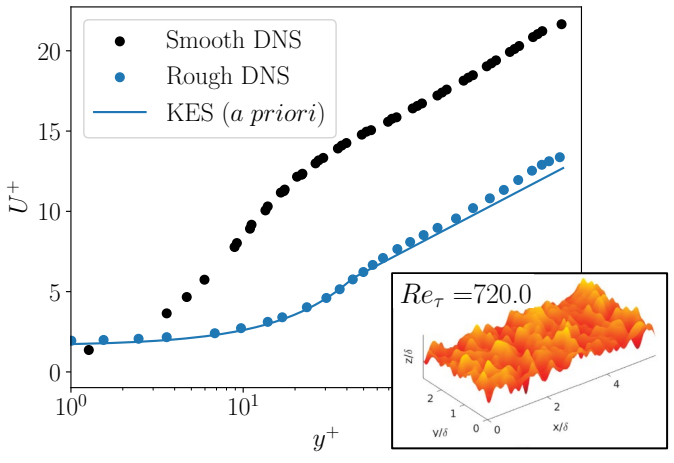
Irregular Ellipsoidal Roughness

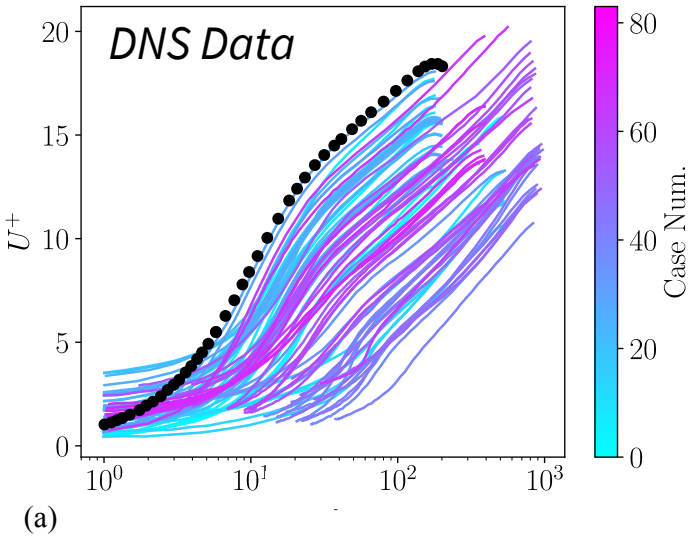


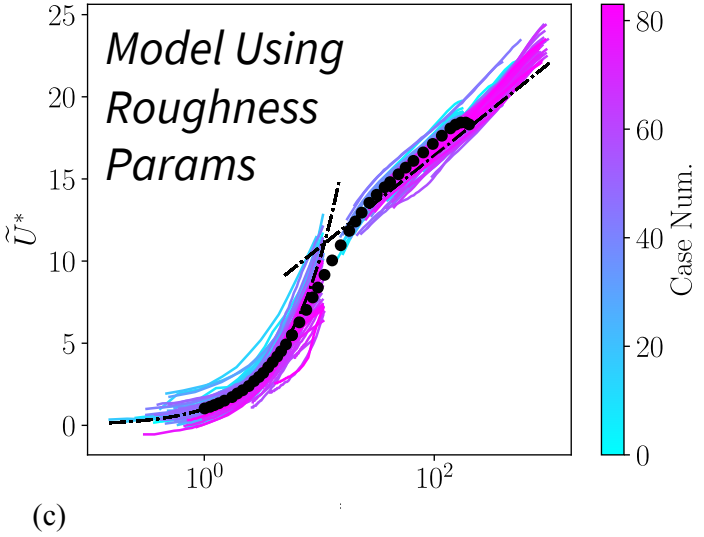
Highly-Skewed Gaussian Surface



Industrial Sand-Blasted Roughness







Reasonable collapse observed across all rough surfaces in the DNS database

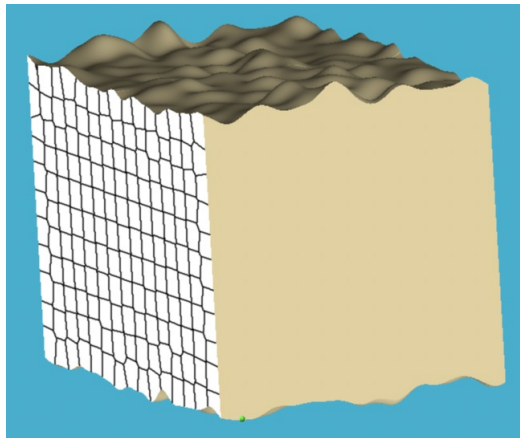
Model Summary

$a_c \rightarrow \mathrm{r}^2 = 93.3\%$

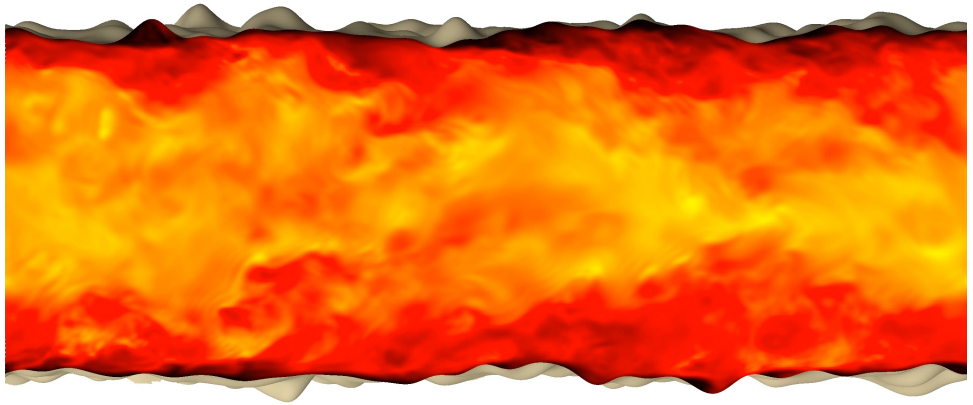
$\Delta U^+_{RSL} \rightarrow \mathrm{r}^2 = 81\%$

$\Delta U^+ \rightarrow \mathrm{r}^2 = 95.4\%$

Setup of *a posteriori* Results



$$Re_\tau = 720$$
$$ES_x = 0.2339$$
$$s_k = -0.519$$
$$k^+_{rms} = 25.78$$



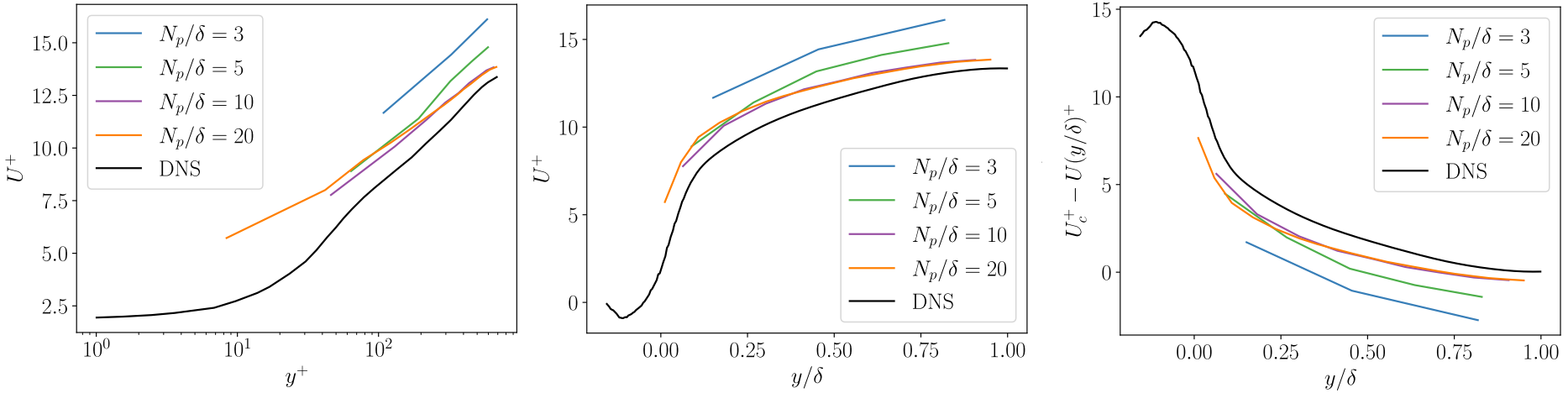
Grids: $N_p/\delta = 3, 5, 10, 20$

- Partially (marginally) resolve the surface roughness and apply KES model

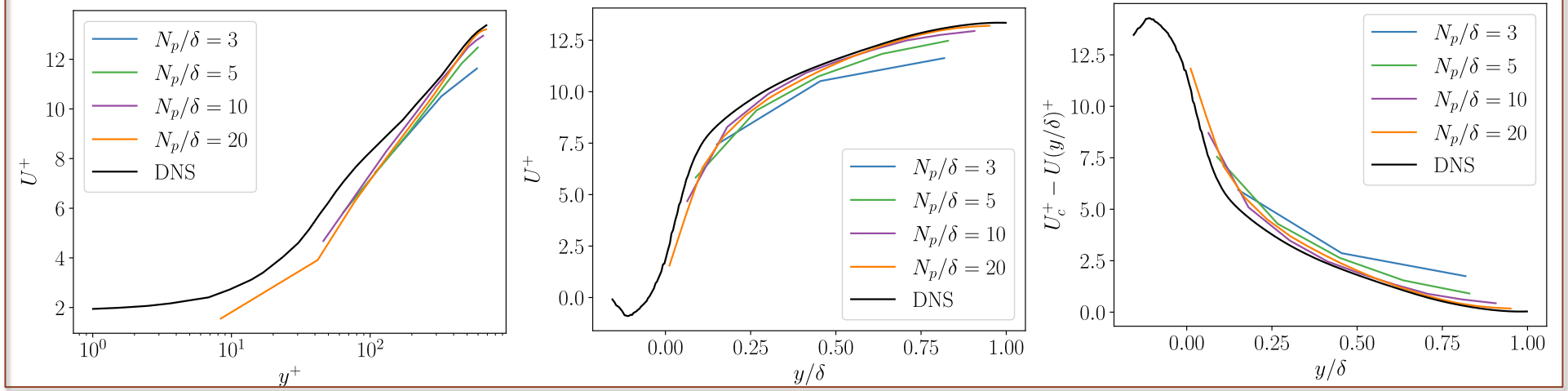
[1] Thakkar et al., 2018, JFM

Marginally resolved surface + KES model

EQWM



KES Model



Marginally resolving the surface with the KES model gives an improved result regardless of the mesh resolution

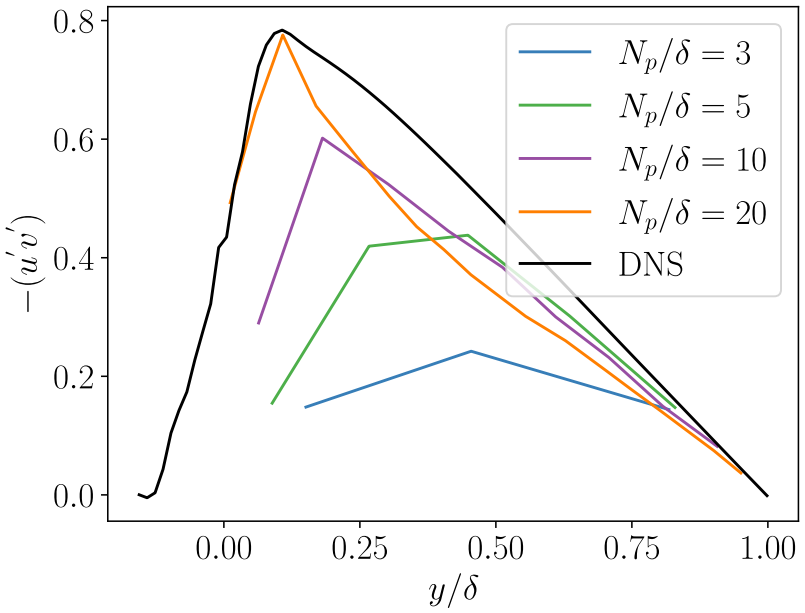
$Re_\tau = 720$
$ES_x = 0.2339$
$s_k = -0.519$
$k_{rms}^+ = 25.78$

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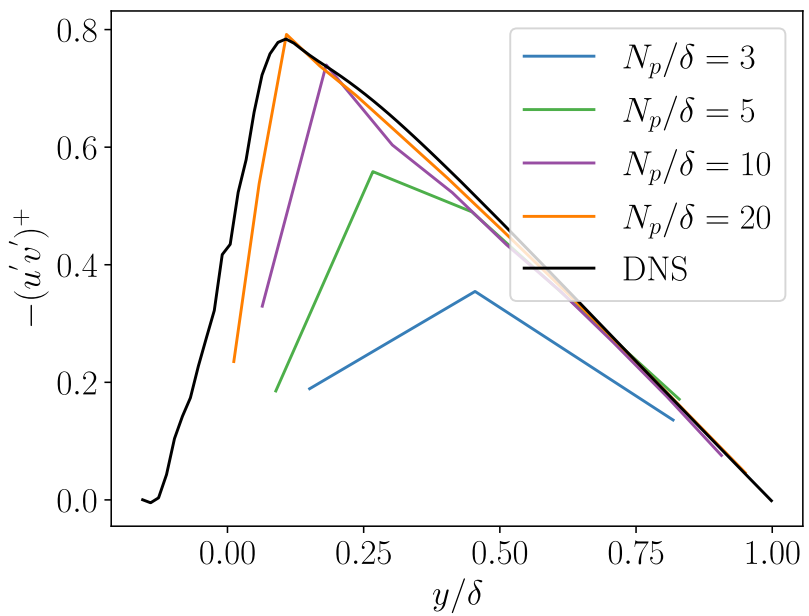
Marginally resolved surface + KES model

$N_p/\delta = 3,\ k_a/\Delta = 0.14$
$N_p/\delta = 5,\ k_a/\Delta = 0.28$
$N_p/\delta = 10,\ k_a/\Delta = 0.55$
$N_p/\delta = 20,\ k_a/\Delta = 1.1$

EQWM



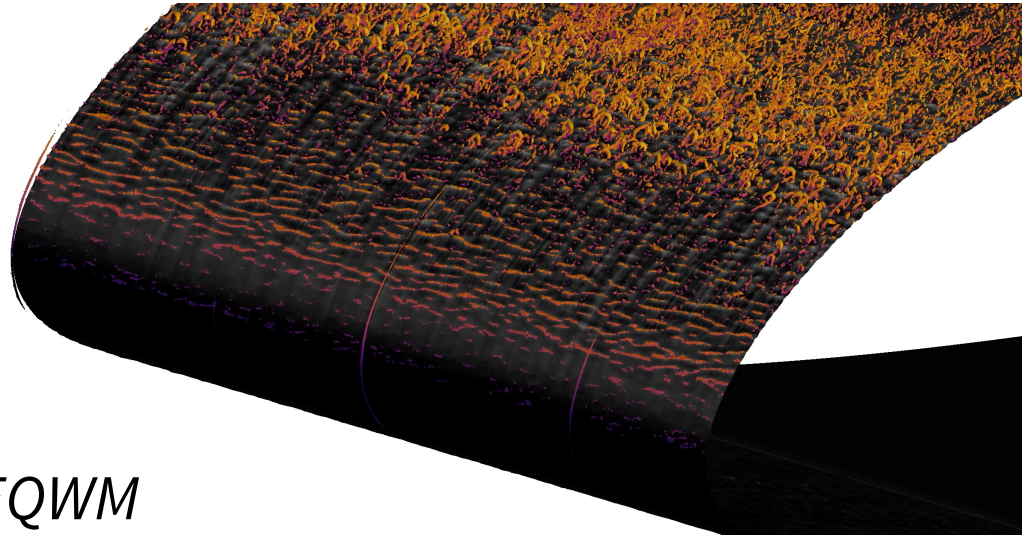
KES Model



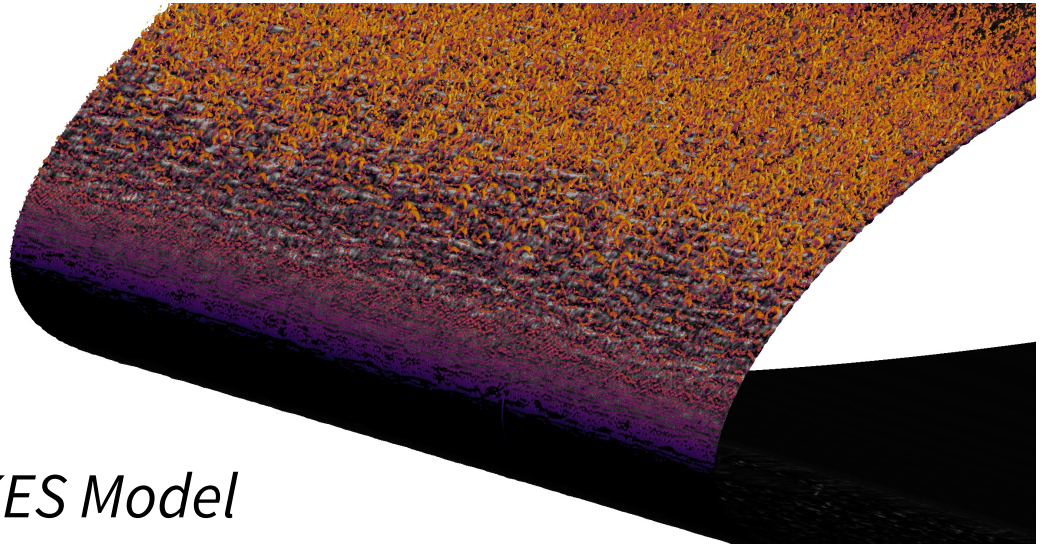
We observe large improvements with respect to an accurate prediction of the Reynolds stresses, especially in the outer region of the boundary layer

$Re_\tau = 720$
$ES_x = 0.2339$
$s_k = -0.519$
$k^+_{rms} = 25.78$

Revisiting the Rime Ice Geometry



EQWM



KES Model

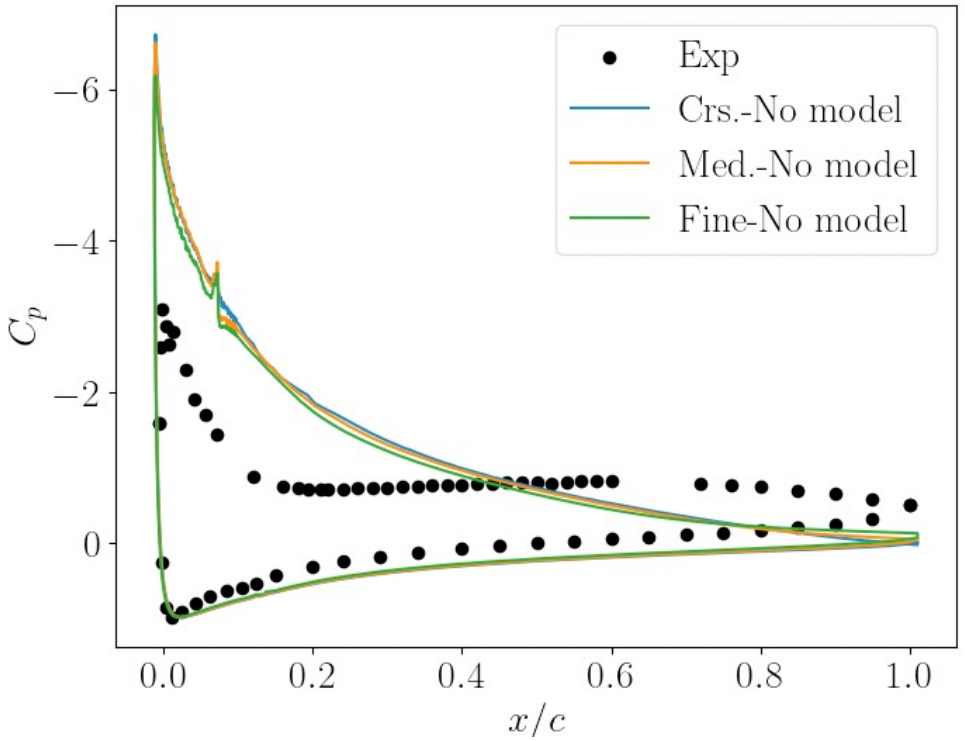
$\alpha = 8^{\circ}, S_p = 0.2c$

- Using averaged roughness properties, we apply the KES model to the rough surfaces
- We observe increased wall shear stress with the applied KES model
- This triggers a minor transition location change and increases the drag due to the rough surface

Revisiting the Rime Ice Geometry

Simulation using full span geometry ($S_p = 1.86c$) at $\alpha = 13^\circ$

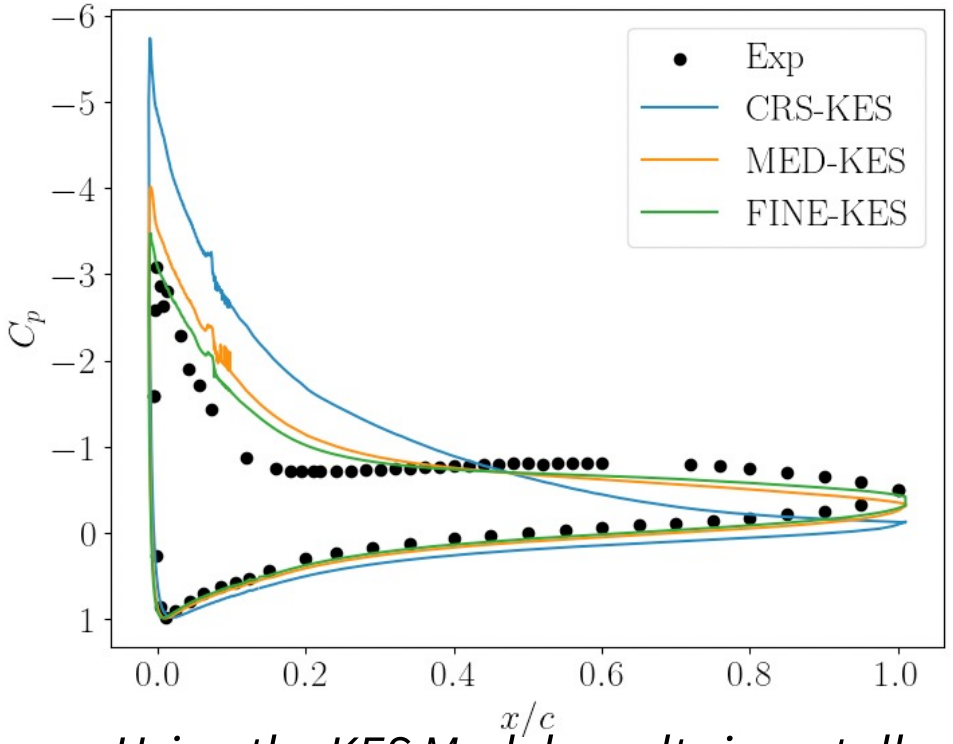
EQWM



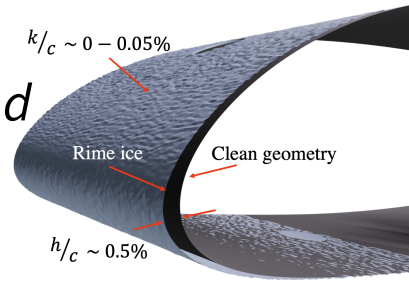
	Cells	k/Δ
Crs –	18.7M	0.16
Med –	69.9M.	0.32
Fine –	270M	0.63

Under the given resolutions, the EQWM does not predict a stall event at any tested resolution

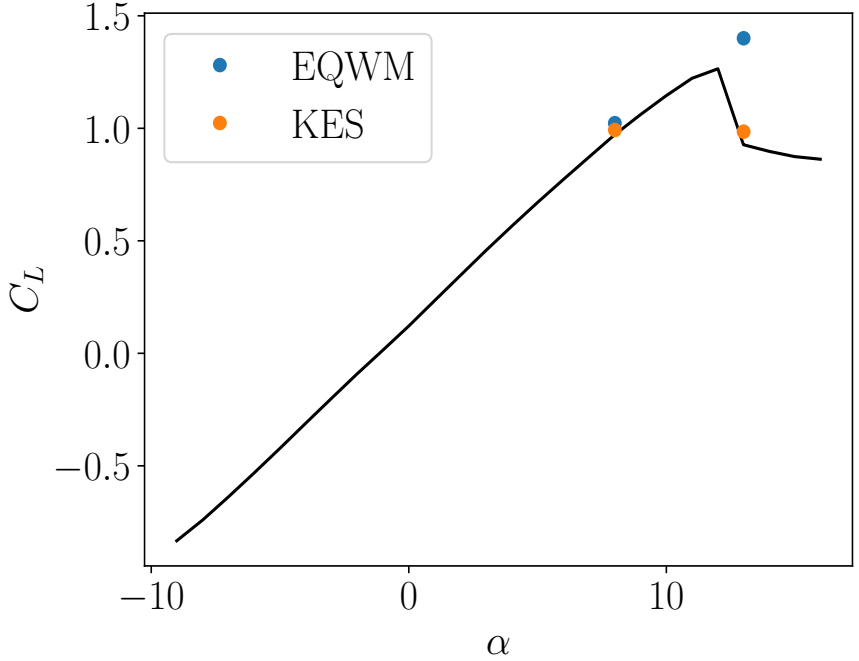
KES MODEL

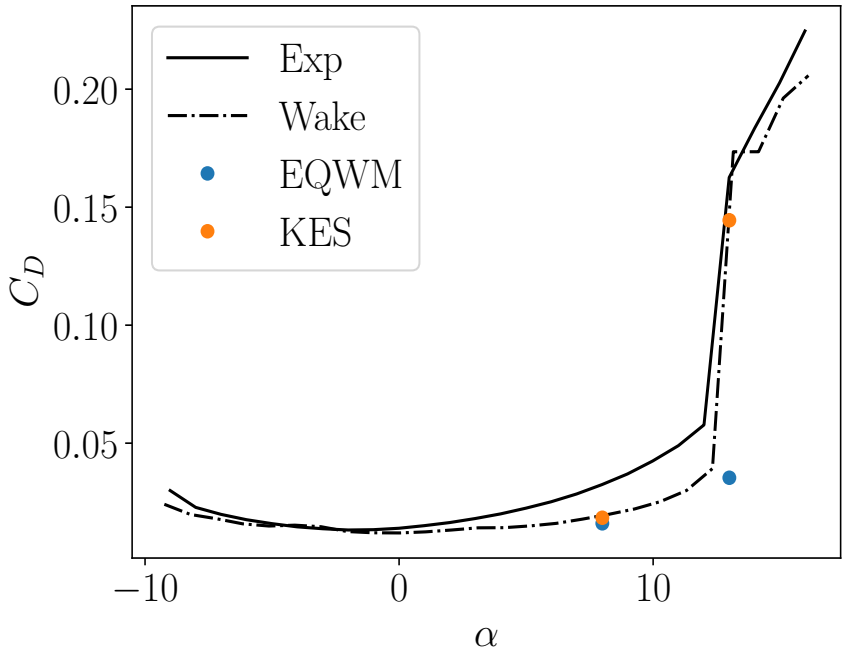


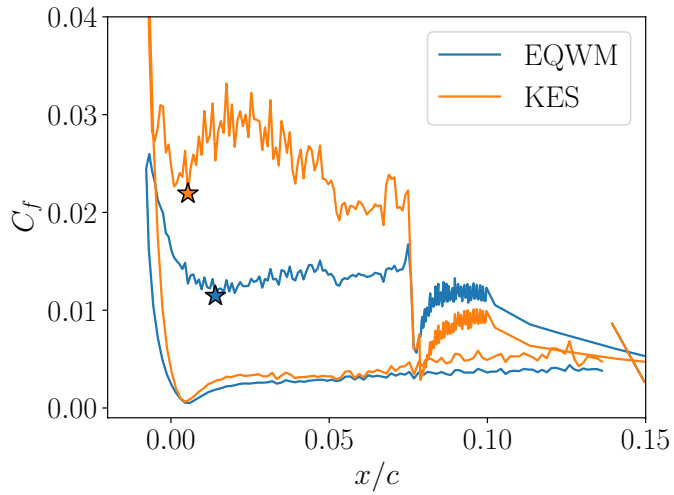
Using the KES Model results in a stall event even at the medium resolution and leads to a large improvement when compared to the experimental data

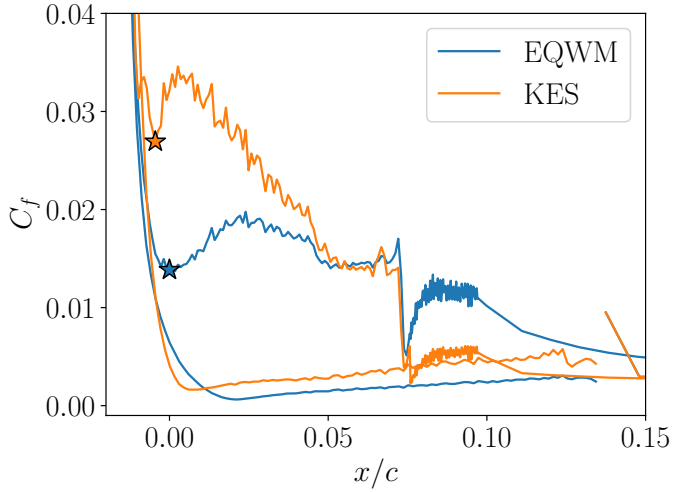


Revisiting the Rime Ice Geometry



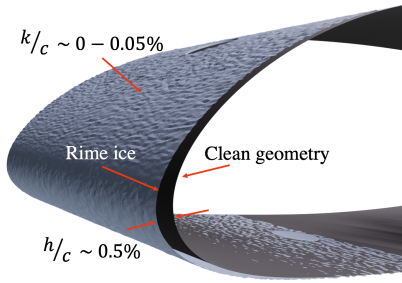






- We find a drastic improvement in the prediction of stall with the KES model
- The primary modification is the increase in shear stress in the iced region of the flow

α	Model	ΔC_L	$\epsilon_L(\%)$	ΔC_D	$\epsilon_D(\%)$
8°	EQWM	0.051	5.25	0.0038	19.21
	KES	0.021	2.12	0.0014	7.26
13°	EQWM	0.473	51.1	0.1381	79.63
	KES	0.042	4.56	0.0340	19.59



Conclusions

- We introduced a new velocity transformation for rough-wall bounded turbulent flows
  - First ever attempt to collapse the roughness sublayer region
  - Improved upon existing 2 and 3-term models for the roughness function
- The new KES model was used as a modification to the EQWM for marginally resolved surfaces
  - The marginal resolution of the channel surface + KES model gives reasonable results regardless of the grid resolution
  - The KES model resulted in improved results for the rime ice geometry where it specifically predicted the stall event, which was unable to be predicting from the use of the EQWM alone.

Details of the velocity transform are available in the following report

Bornhoft, B., Jain, S. S., and Moin, P., "A velocity transformation for rough-wall-bounded turbulent flow," Center for Turbulence Research Annual Briefs, 2024.

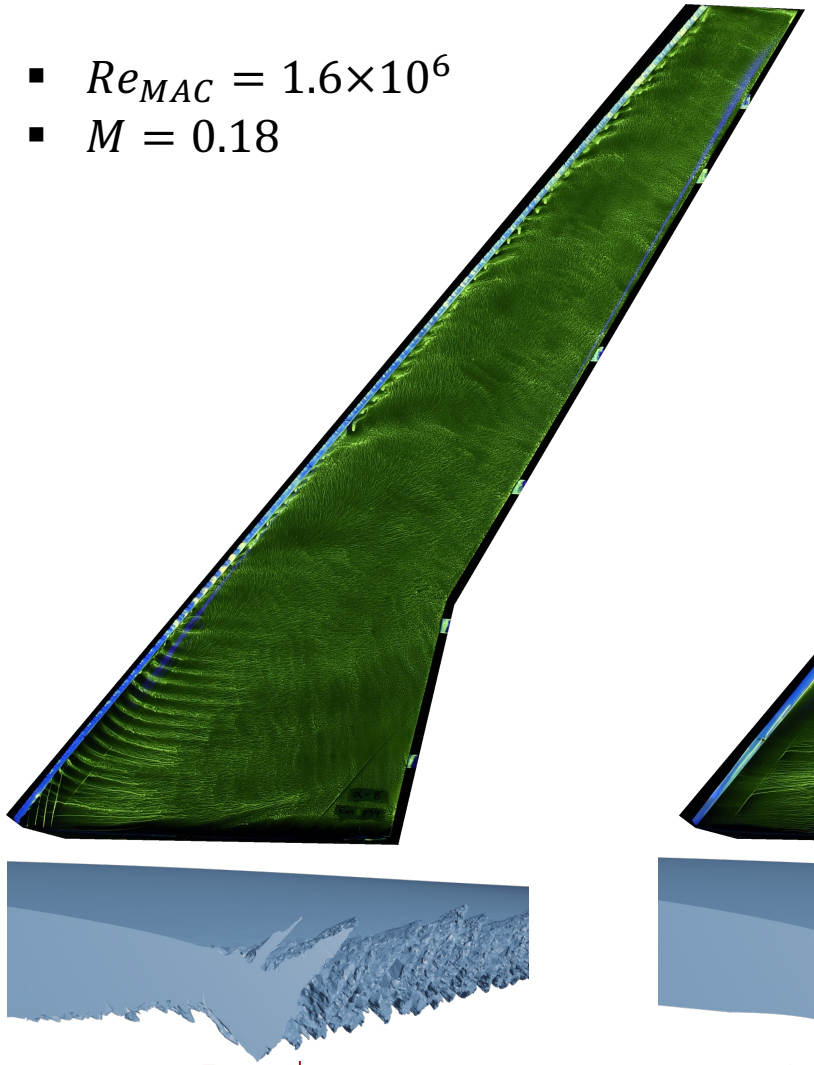
On the use of an artificial ice shape in icing

Laser-Scanned Iced CRM65 Swept Wing





- $Re_{MAC} = 1.6\times10^6$
- $M = 0.18$



Real Ice



Artificial Ice

[1] Broeren et al., NASA Technical Report 2023

Laser-Scanned Iced CRM65 Swept Wing

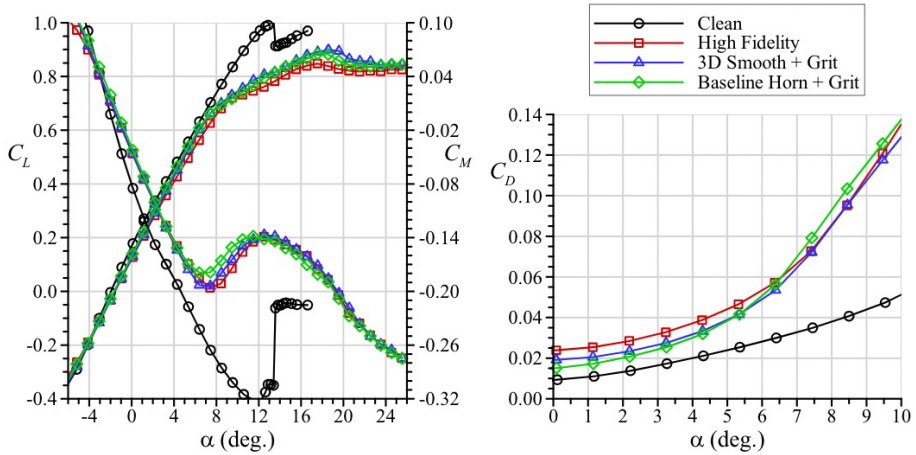


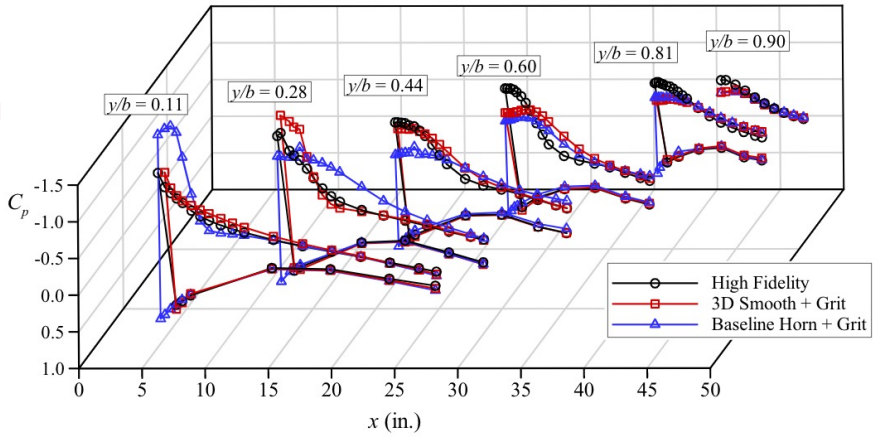


Artificial shapes are, in part, designed to validate simulations.

Data for validation:

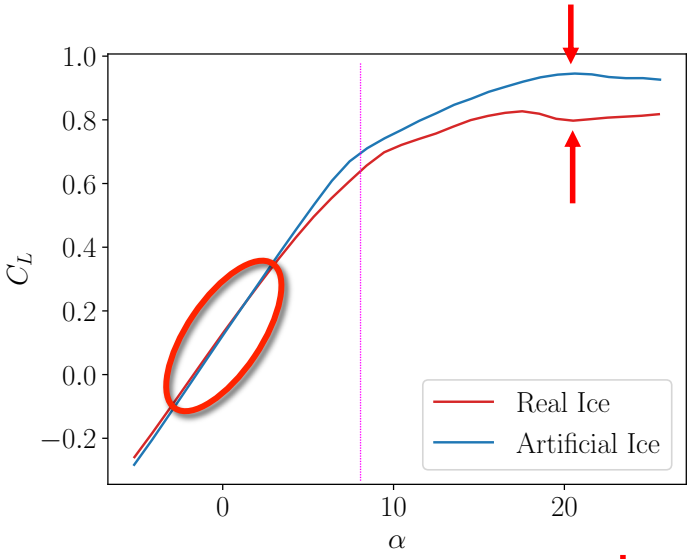
- Integrated forces
- Streamwise pressure profiles along wing-span
- Oil flow visualization

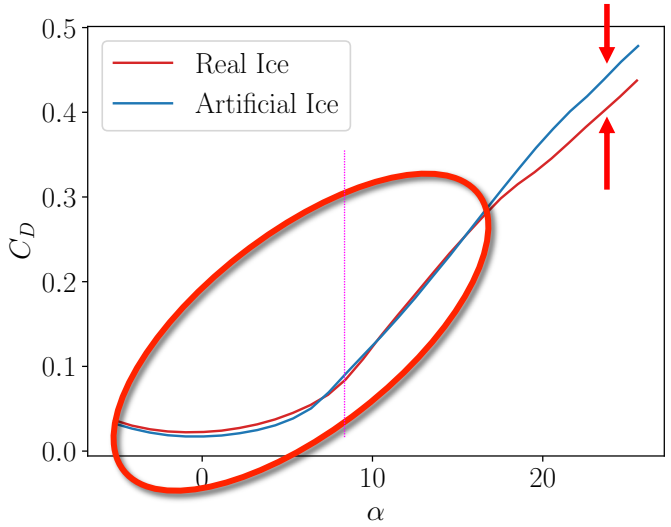


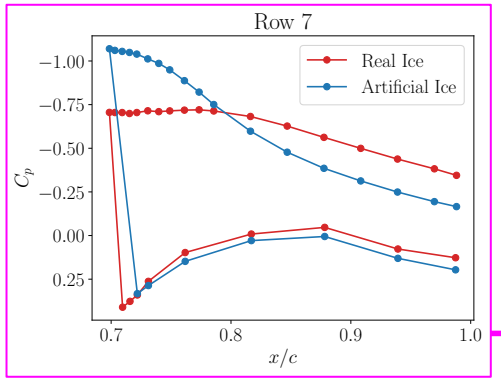


[1] Broeren et al., NASA Technical Report 2023

Real ice vs artificial ice oil flows ($\alpha = 8^\circ$)





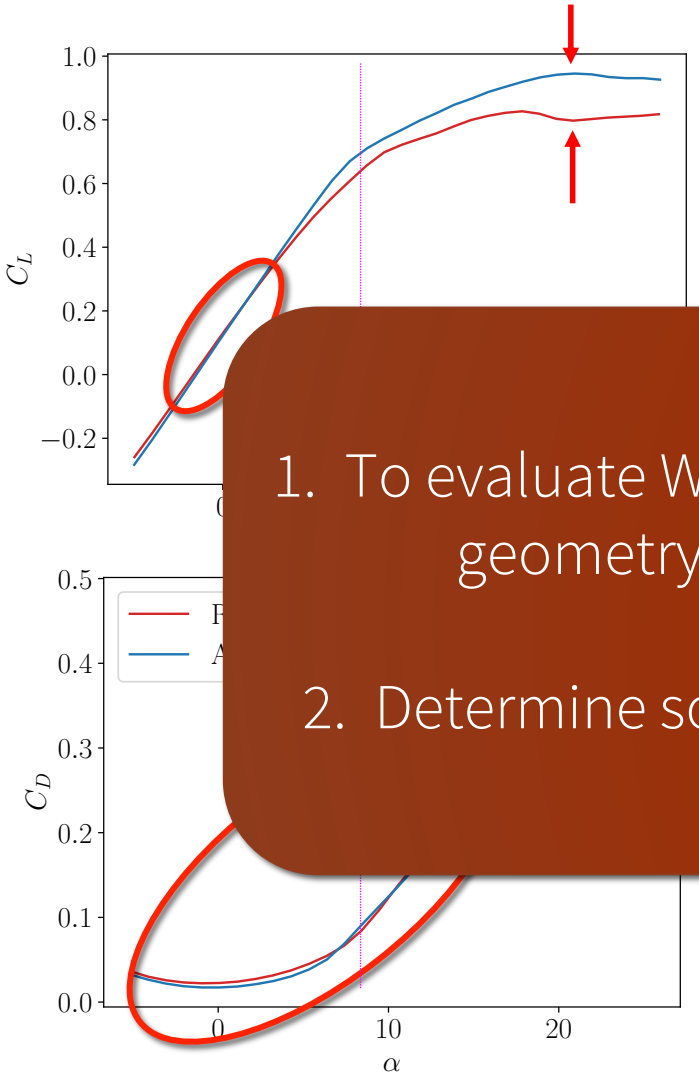


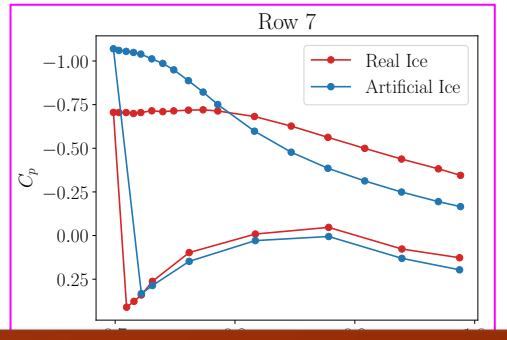
Real Ice

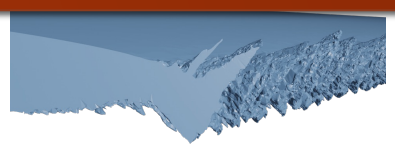
Artificial Ice

Note: We are specifically simulating the smooth artificial case. Many other shapes exist including with grit.

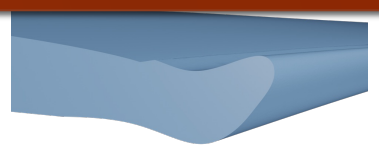
Real ice vs artificial ice oil flows ($\alpha = 8^{\circ}$)



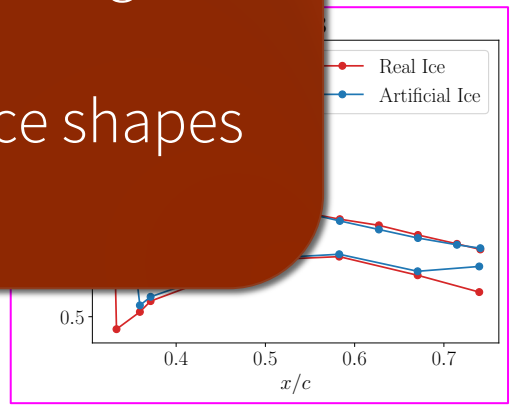




Real Ice



Artificial Ice



Objectives

1. To evaluate WMLES for both real and artificial ice shapes with a complex geometry and establish best practices for simulating iced wings

2. Determine some of the implications for simulating artificial ice shapes with LES approaches

Note: We are specifically simulating the smooth artificial case. Many other shapes exist including with grit.

Methodology and Grids

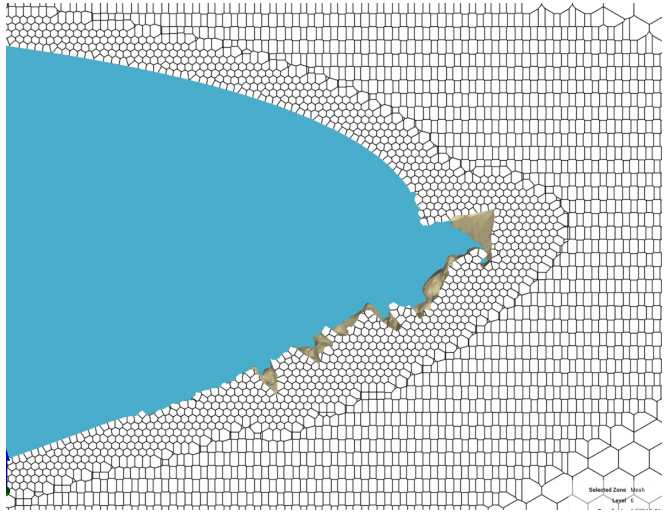
Ice shape	Grid name	Grid res. (M CVs)	Cells/MAC	Cells/ref. scallop length	Set of α
Real	Coarse	24	591	7	$\alpha = \{2°, 5°, 8°, 10°, 12°, 16°, 20°, 24°\}$
Real	Medium	85	1182	14	$\alpha = \{2°, 5°, 8°, 10°, 12°, 16°, 20°, 24°\}$
Real	Fine	320	2365	28	$\alpha = \{2°, 5°, 8°, 16°, 20°, 24°\}$
Artificial	Coarse	24	591	7	$\alpha = \{8°, 16°, 24°\}$
Artificial	Medium	85	1182	14	$\alpha = \{8°, 16°, 24°\}$
Artificial	Fine	320	2365	28	$\alpha = \{8°, 16°, 24°\}$
Artificial	XXFine	1200	3311	112	$\alpha = \{8°\}$

*Reference scallop height of 0.005 meters [25].

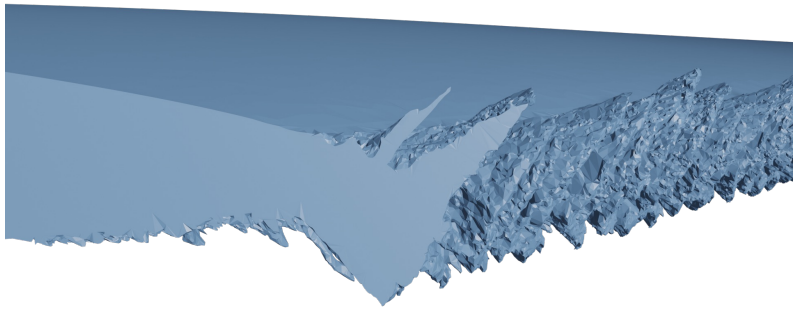
Wide set of AoA

Subset of Real Ice Cases

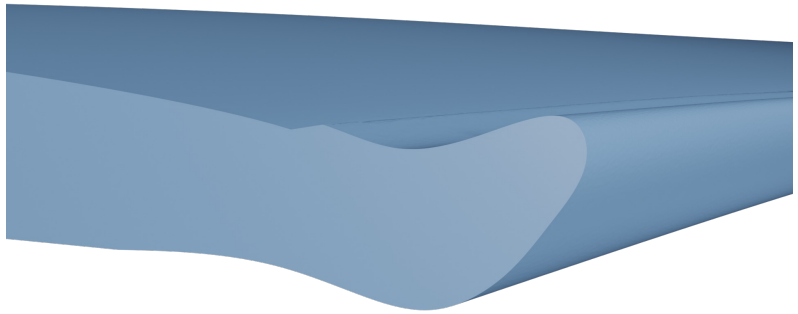
Single α at finest res.



Real Ice



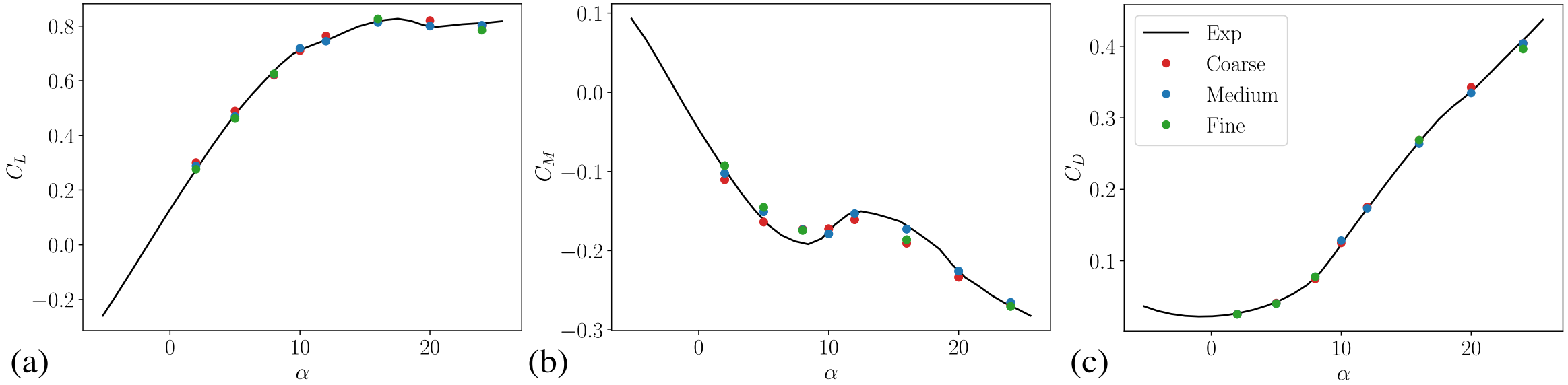
Artificial Ice



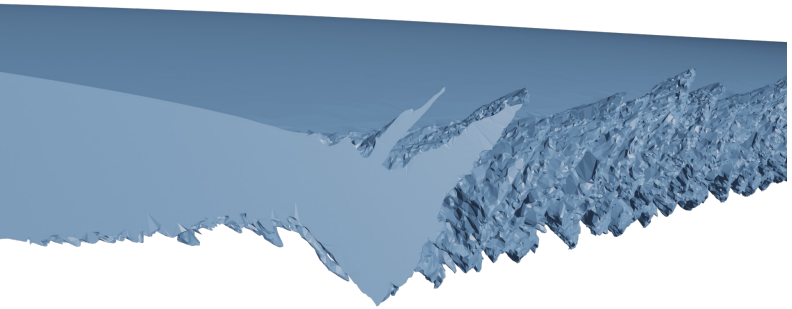
Comparison to corr. aero data of Broeren et al. with a 100 MAC hemisphere domain

$Re_{MAC} = 1.6\times10^6$ $M = 0.18$, 8.9% scaled model of CRM65

Real Ice Geometry Results

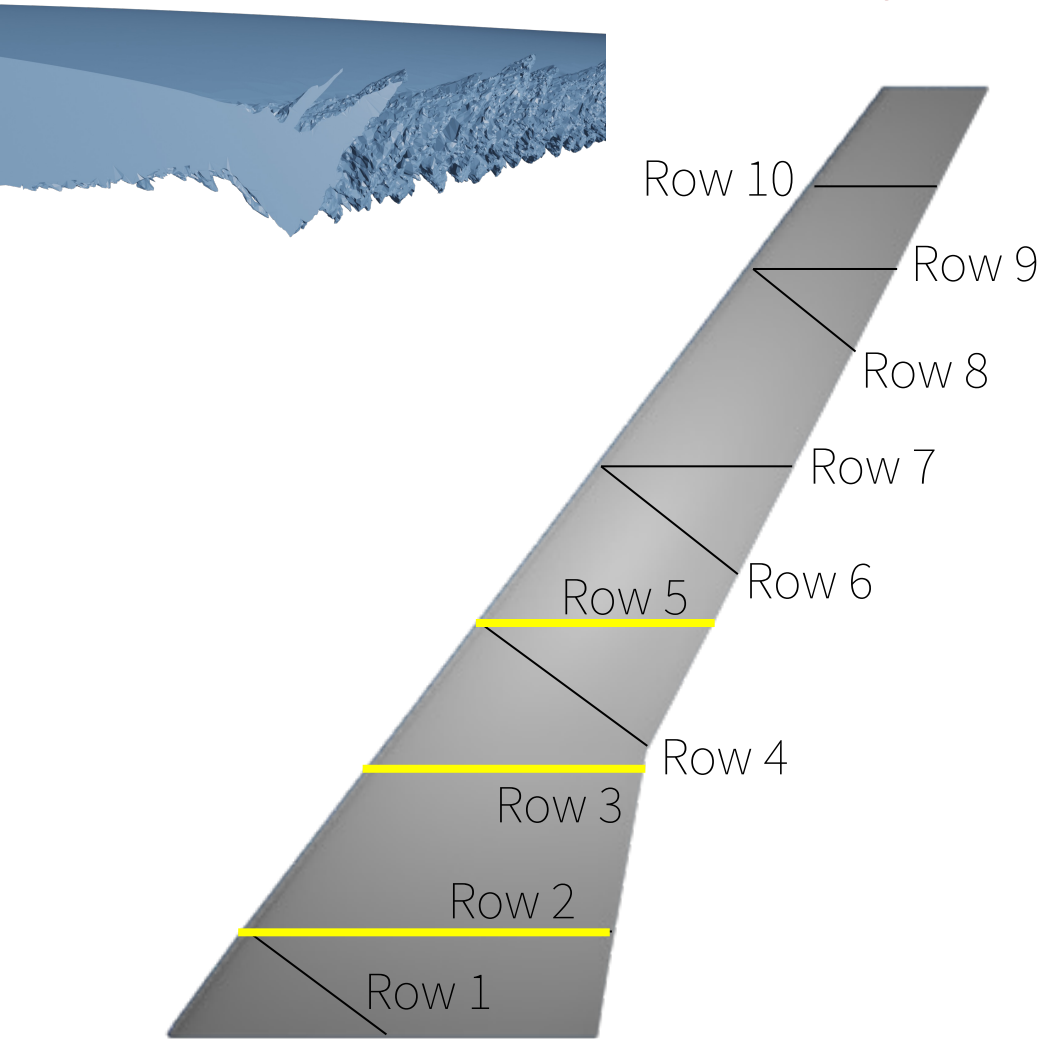


- All coefficients in good agreement with the experimental results.
  - Lift results across all cases are within three lift counts ($\Delta C_L < 0.03$)
  - Moments have some minor deviations; we look to Cp values as well

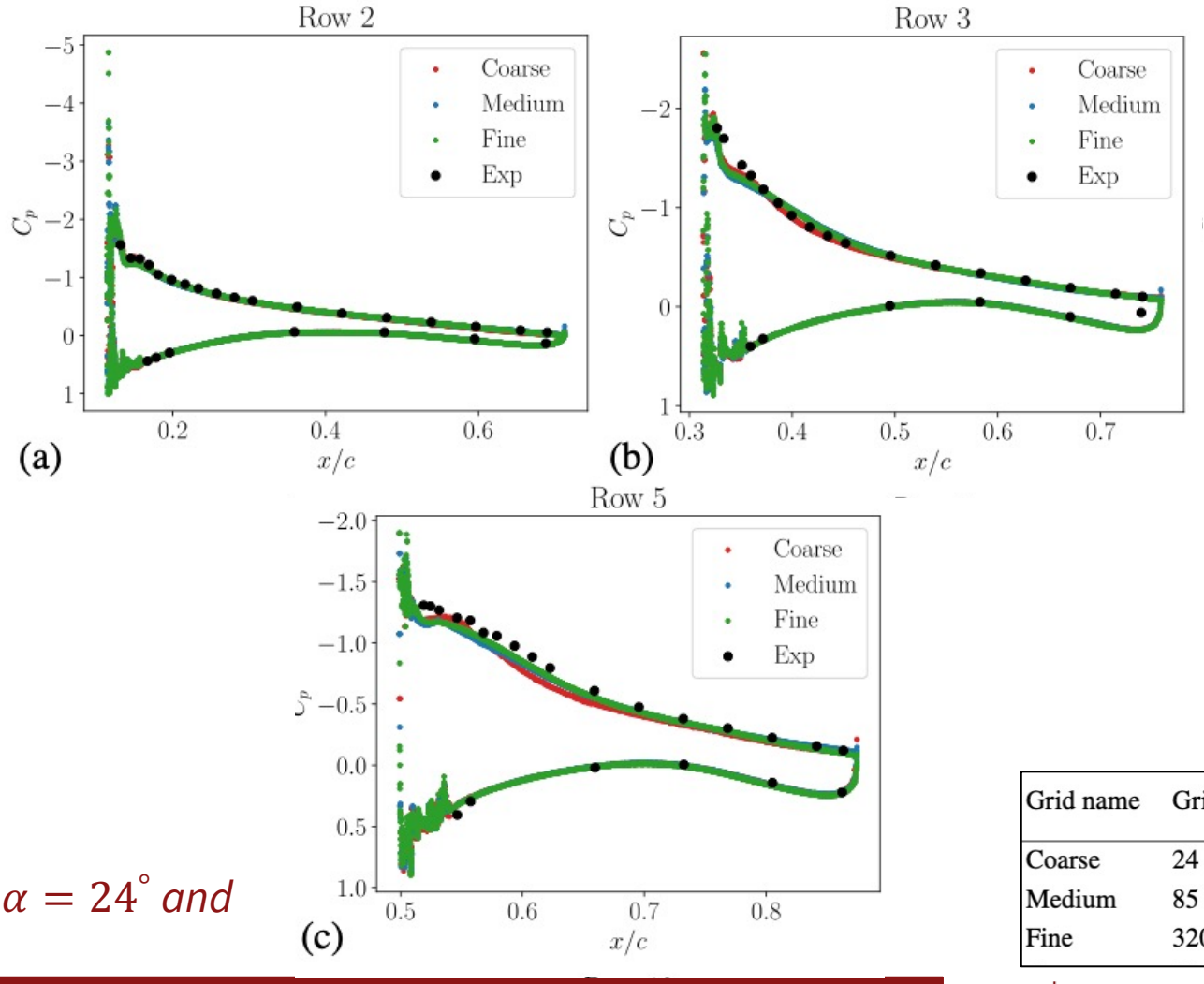


Grid name	Grid res. (M CVs)
Coarse	24
Medium	85
Fine	320

Real Ice Geometry Results



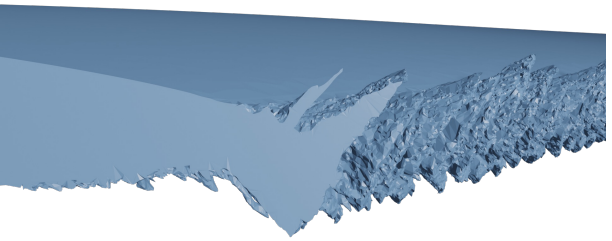
Selected inboard streamwise pressure coefficients at $\alpha = 8^{\circ}$

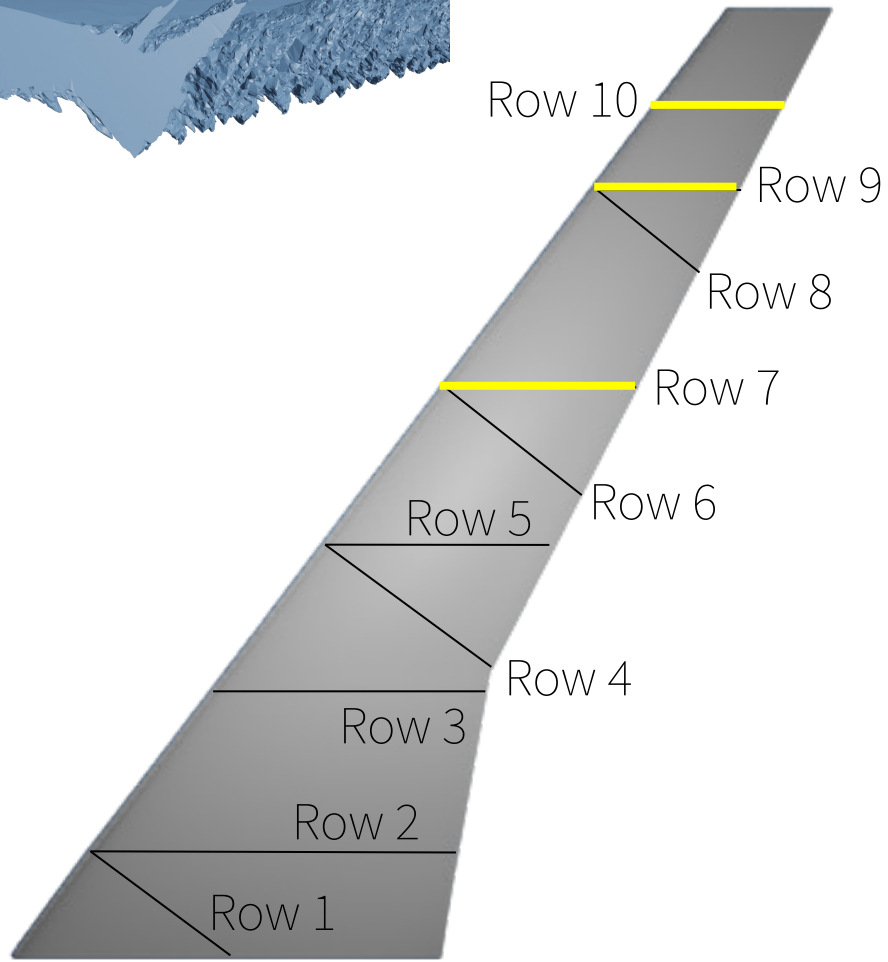


Note: Similar agreement are obtained for $\alpha = 16^{\circ}$ and $\alpha = 24^{\circ}$ and can be found in the accompanying manuscript

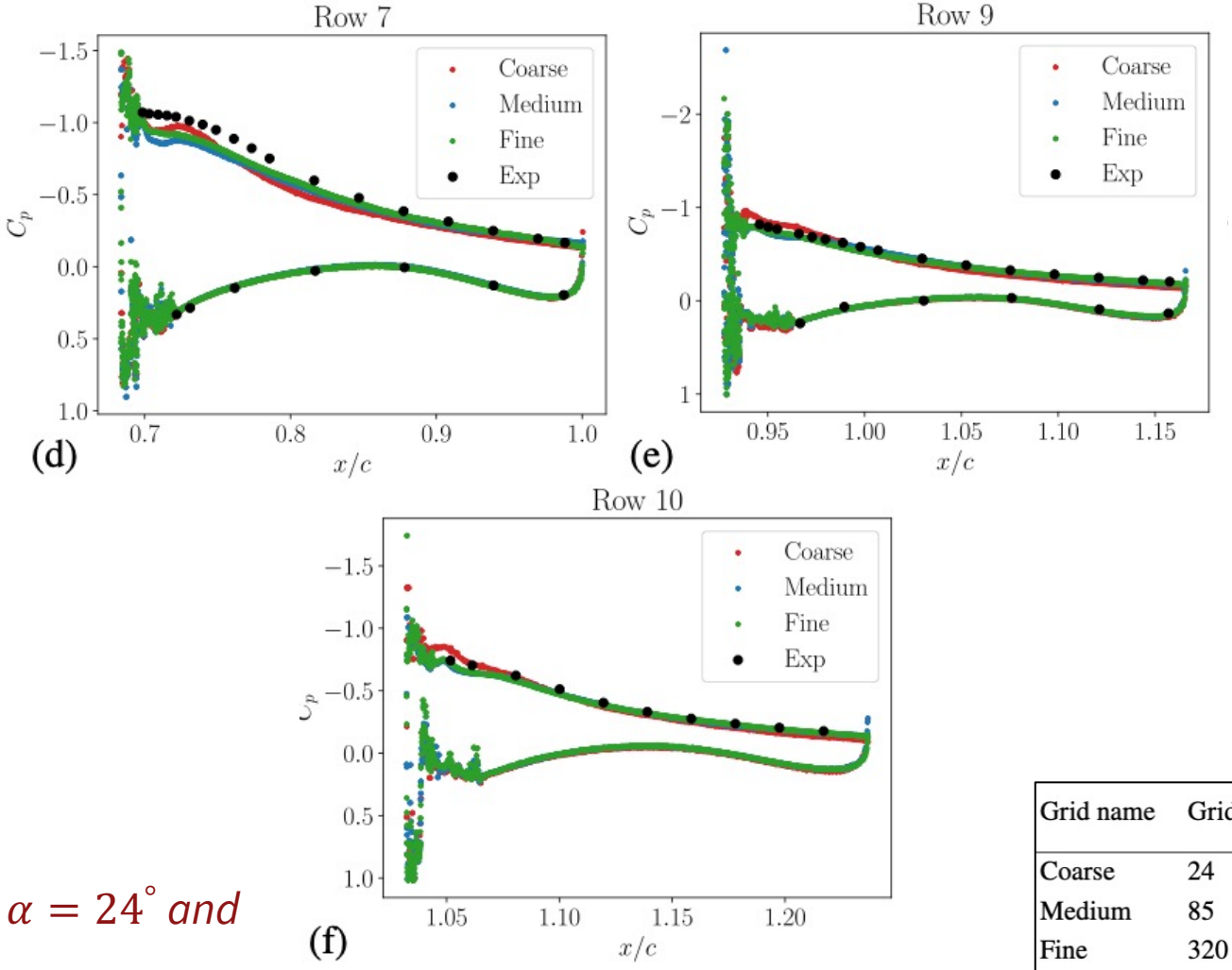
Grid name	Grid res. (M CVs)
Coarse	24
Medium	85
Fine	320

Real Ice Geometry Results





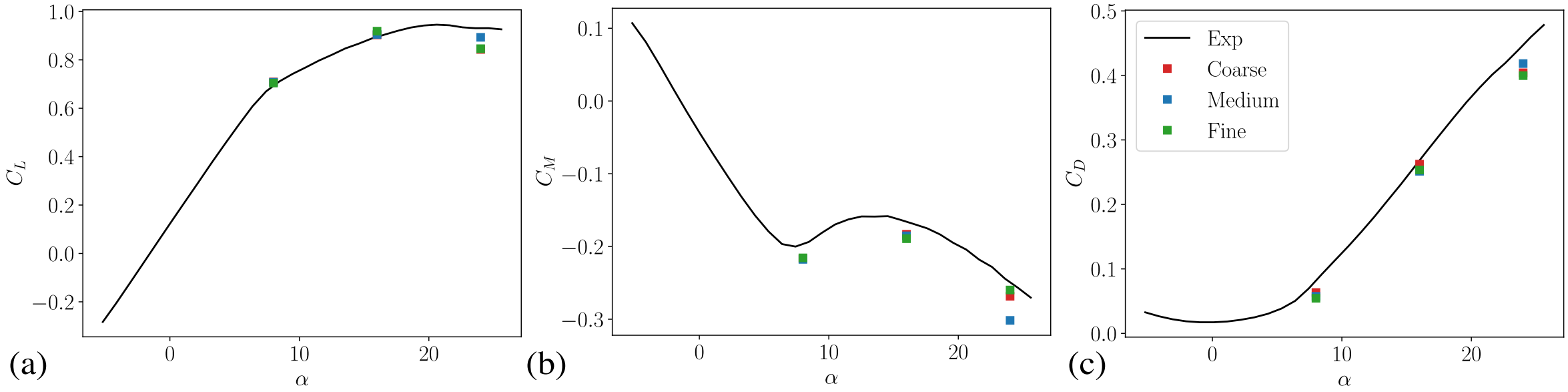
Selected inboard streamwise pressure coefficients at $\alpha = 8^{\circ}$



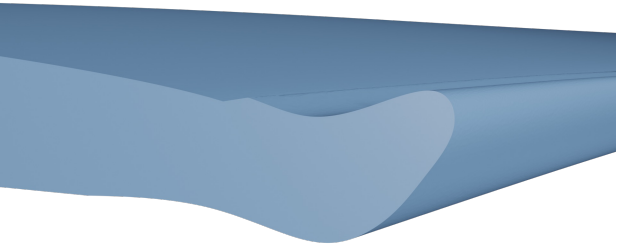
Note: Similar agreement are obtained for $\alpha = 16^{\circ}$ and $\alpha = 24^{\circ}$ and can be found in the accompanying manuscript

Grid name	Grid res. (M CVs)
Coarse	24
Medium	85
Fine	320

Artificial Ice Shape

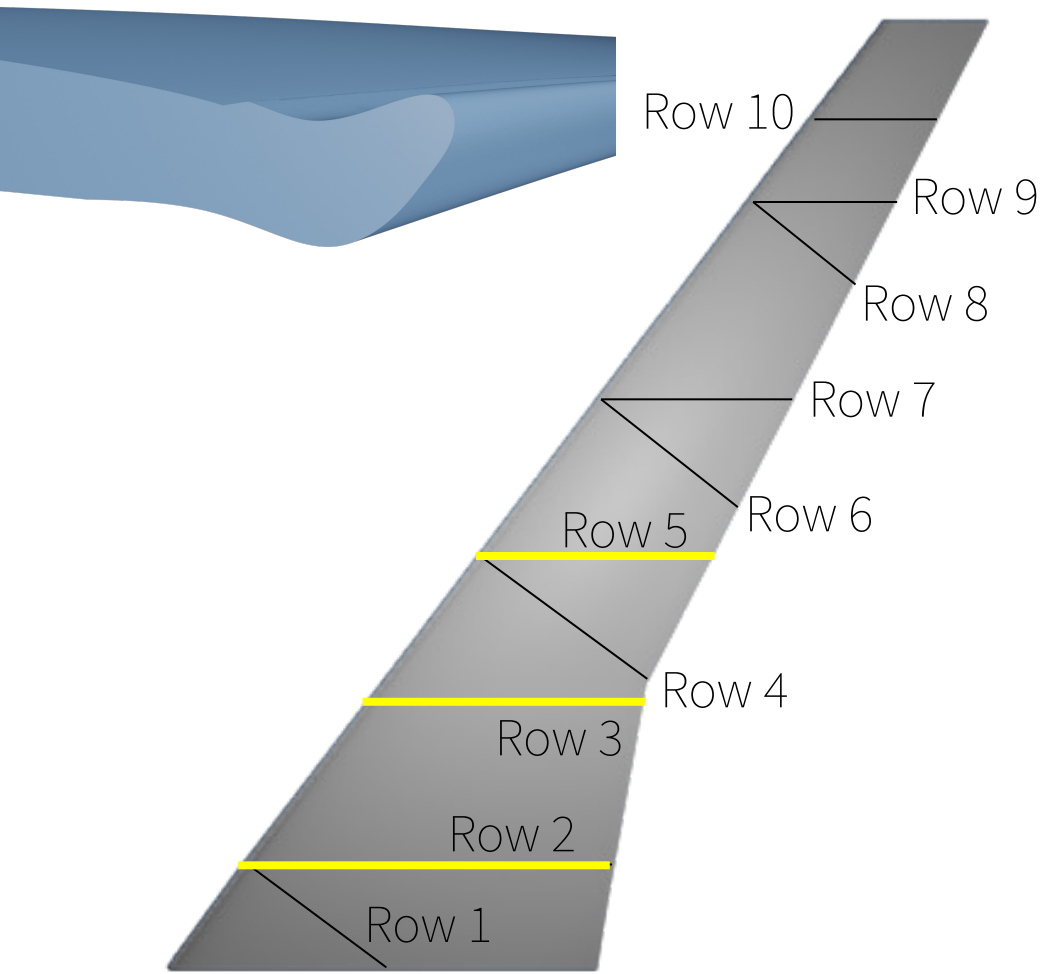


- We simulate a subset of the AoA for the artificial ice shape
- Good agreement is observed for C_L
- Under-prediction is observed for C_M and C_D
  - We look to C_P profiles to understand this discrepancy

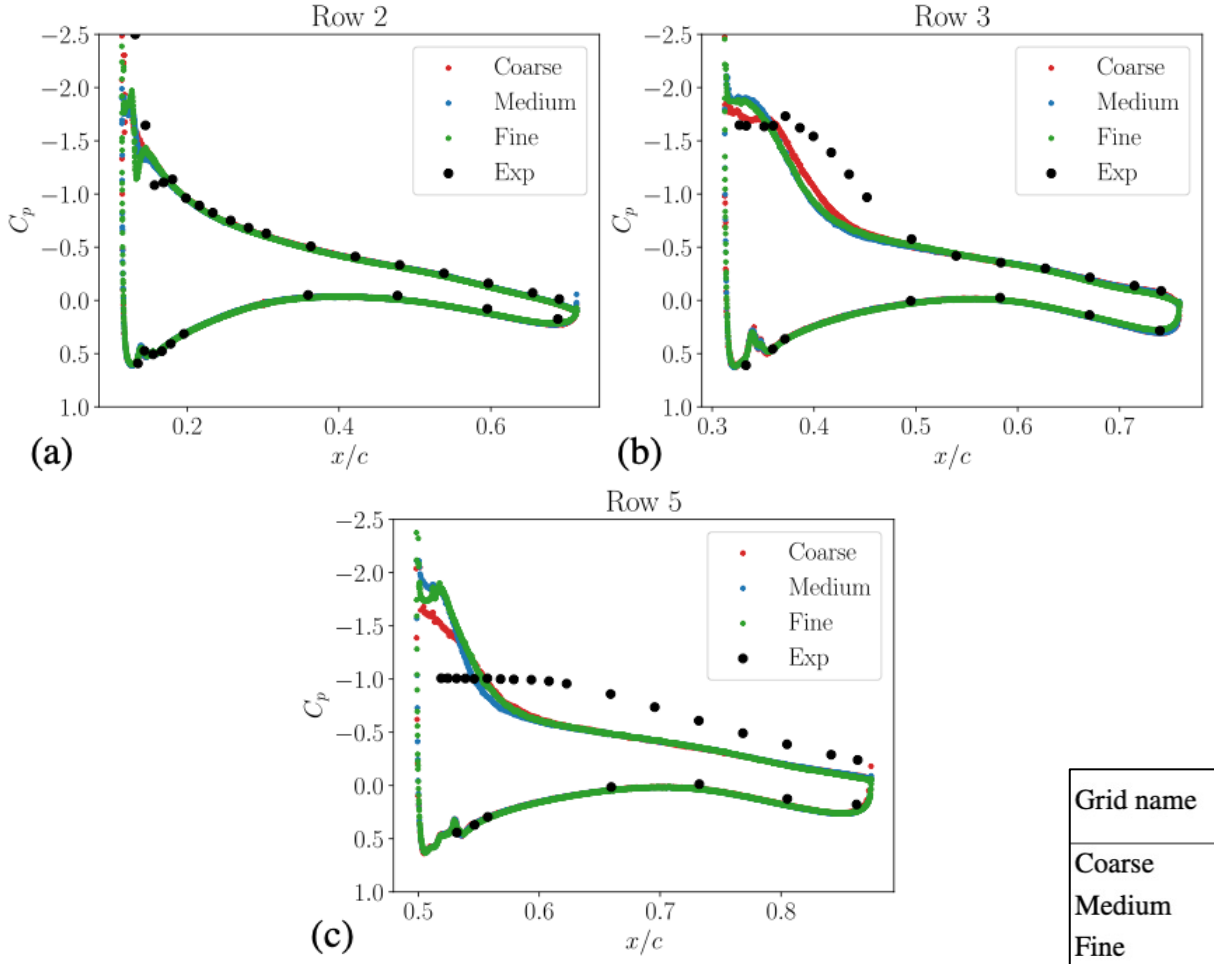


Grid name	Grid res. (M CVs)
Coarse	24
Medium	85
Fine	320

Artificial Ice Geometry Results

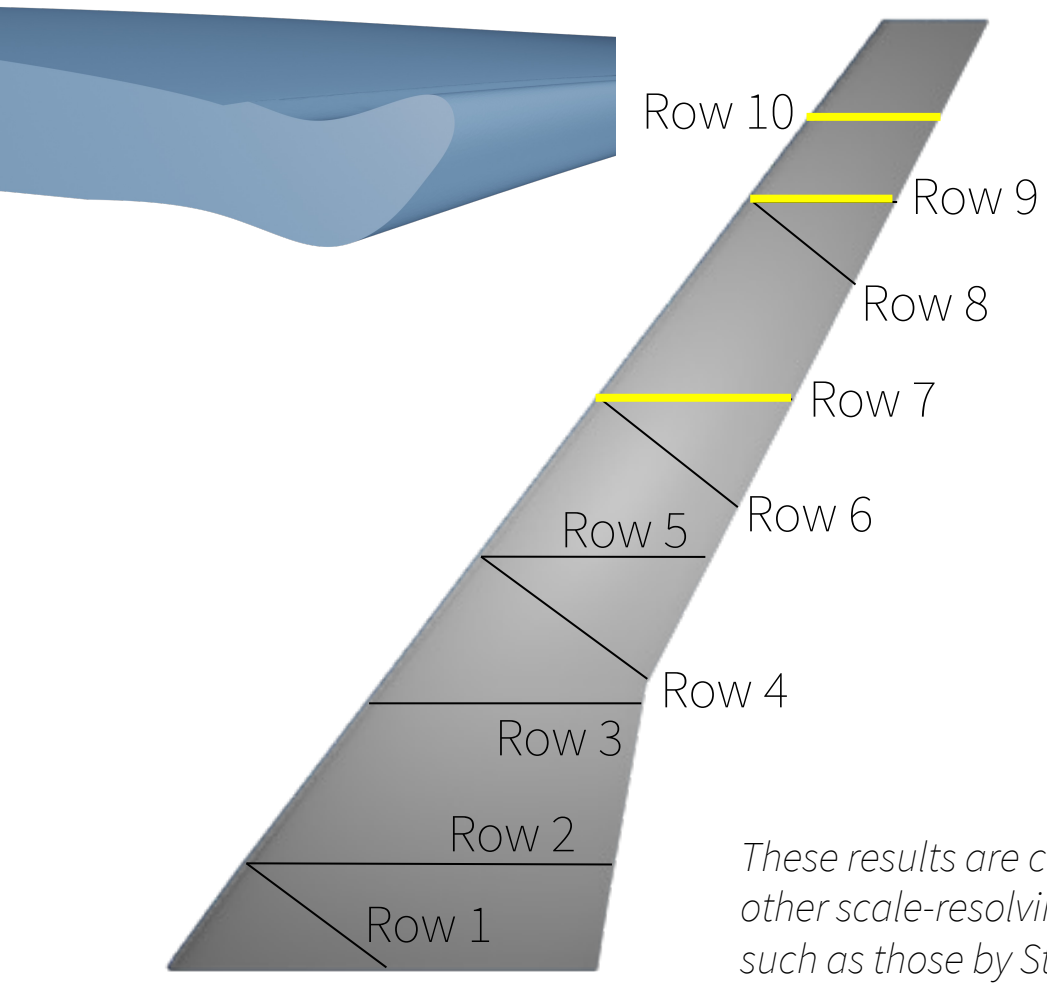


Selected inboard streamwise pressure coefficients at $\alpha = 8^{\circ}$

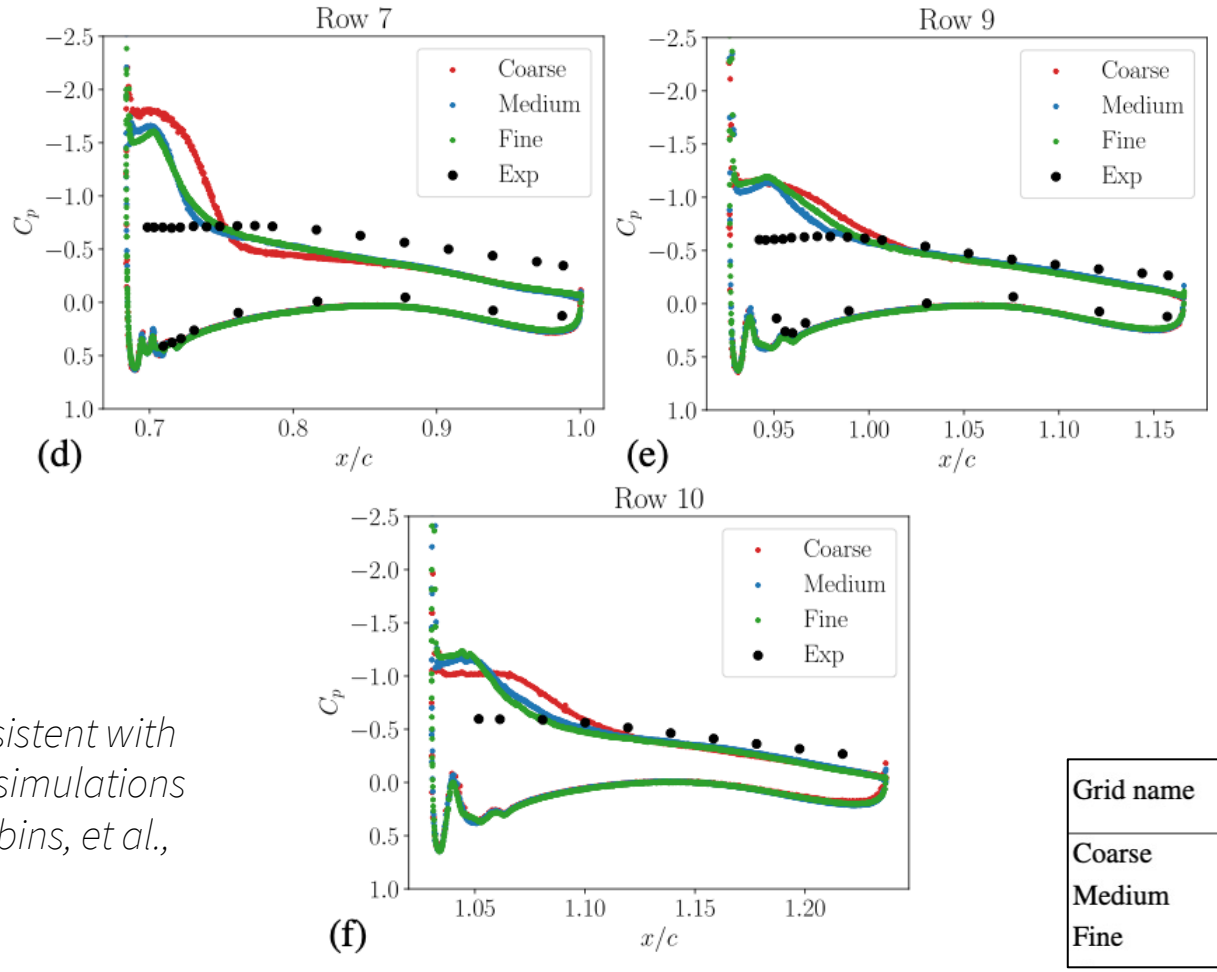


Grid name	Grid res. (M CVs)
Coarse	24
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Artificial Ice Geometry Results



Selected inboard streamwise pressure coefficients at $\alpha = 8^{\circ}$

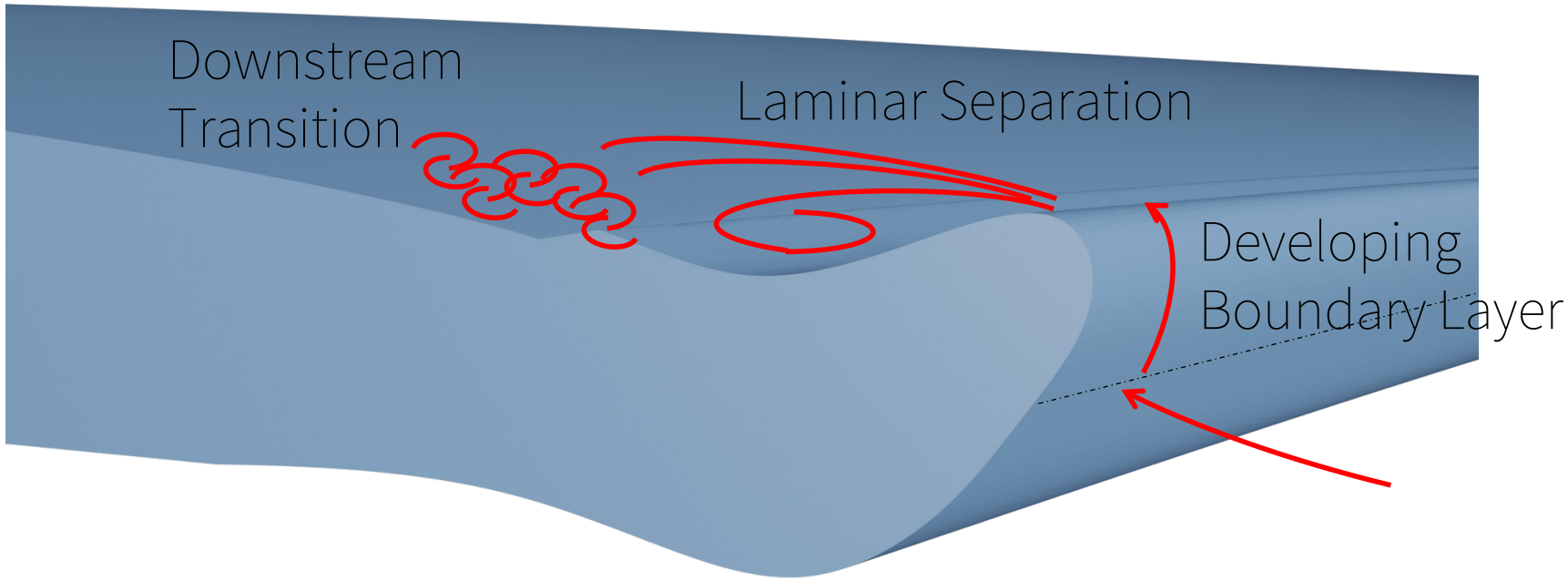


These results are consistent with other scale-resolving simulations such as those by Stebbins, et al., AIAA SciTech 2019

Grid name	Grid res. (M CVs)
Coarse	24
Medium	85
Fine	320

Artificial Ice Geometry

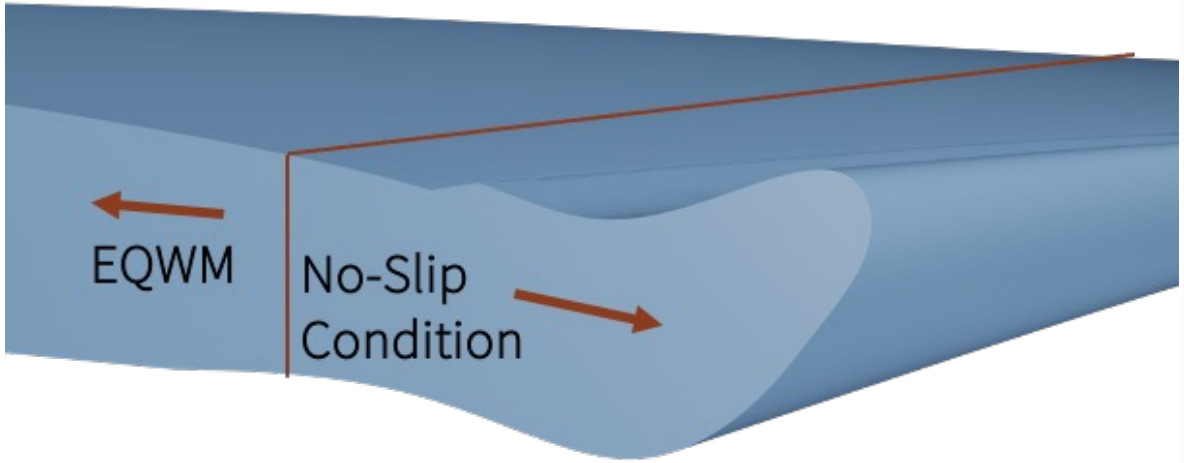
- Smooth surface can introduce additional physics including:
  - Laminar boundary layers
  - Laminar separation bubbles
  - Non-roughness induced transition
- These physics stress the assumptions of the equilibrium wall-model
- These physics are also not present in the real ice shape

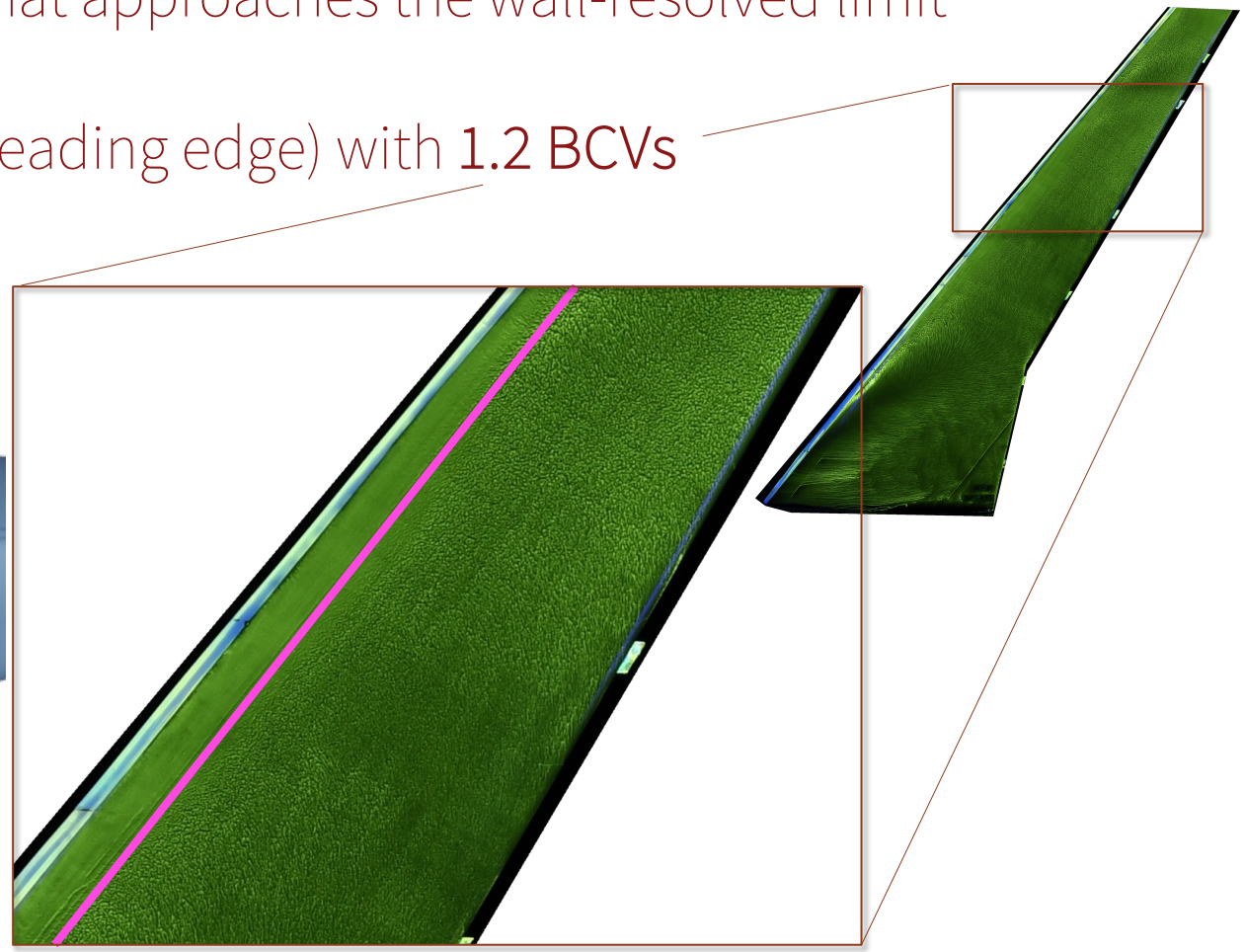


Artificial Ice Geometry (Modified Modeling Approach)

- Guided by the experimental oil flow visualizations, we model the horn shape with a no slip condition and refine it to a point that approaches the wall-resolved limit

- This yields a new mesh (denoted XXFine-leading edge) with 1.2 BCVs

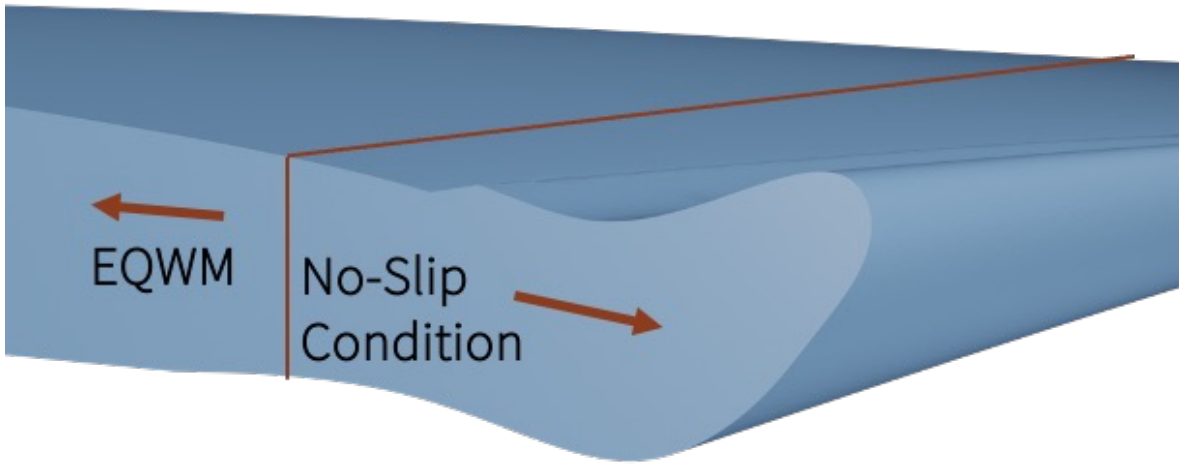


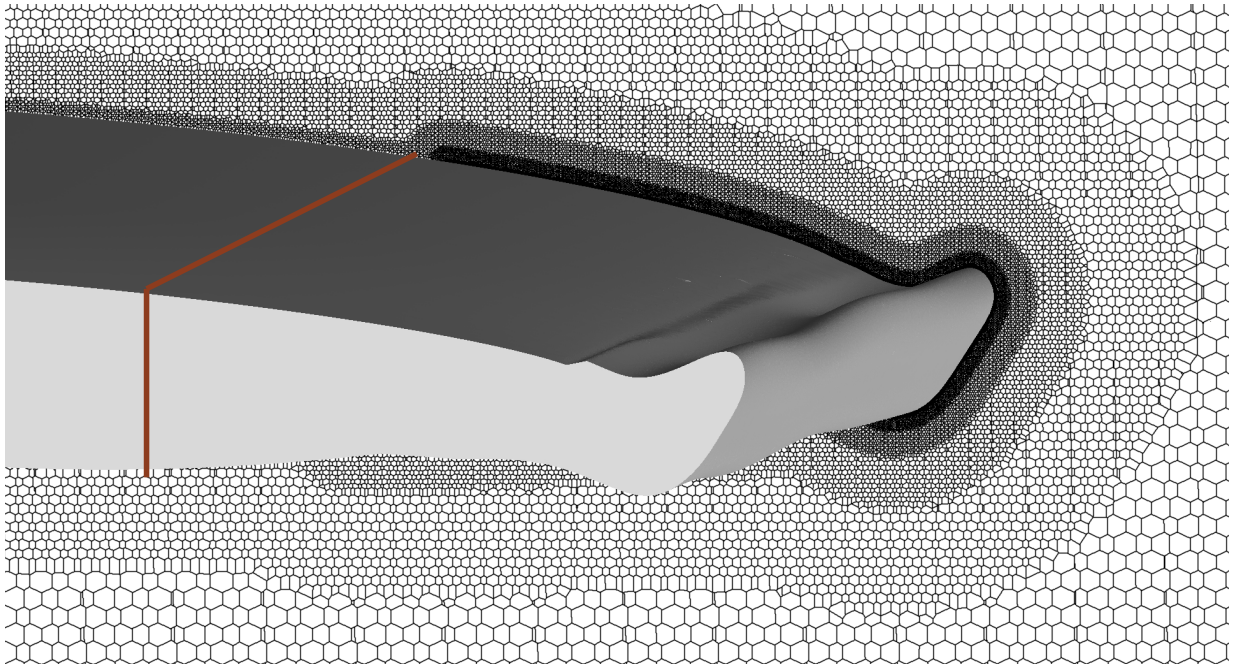


Artificial Ice Geometry (Modified Modeling Approach)

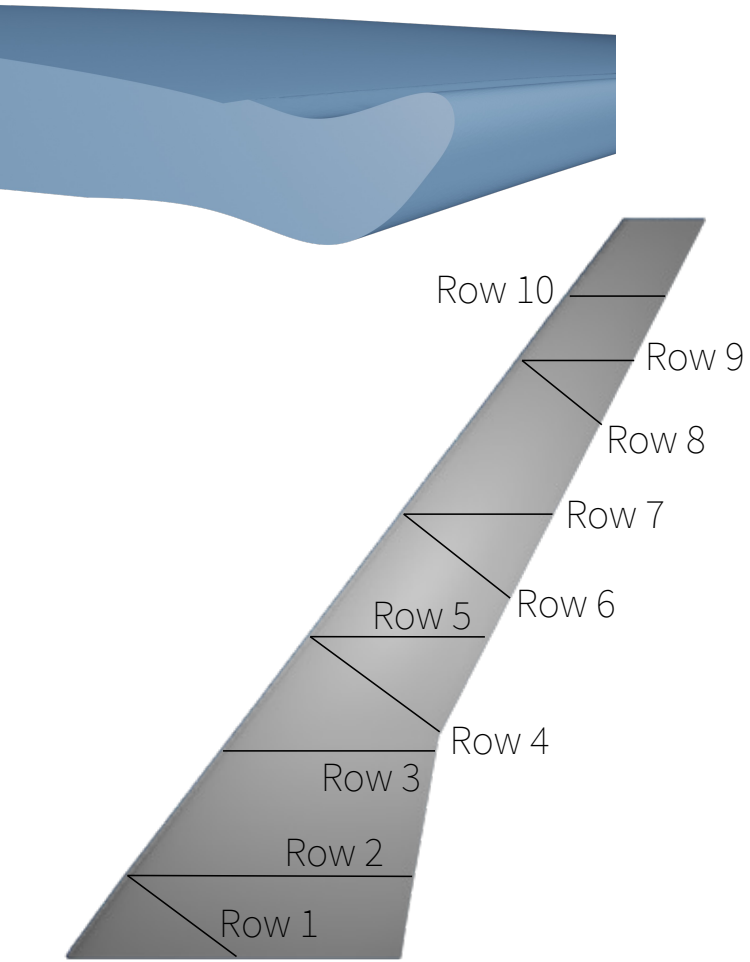
- Guided by the experimental oil flow visualizations, we model the horn shape with a no slip condition and refine it to a point that approaches the wall-resolved limit

- This yields a new mesh (denoted XXFine-leading edge) with **1.2 BCVs**

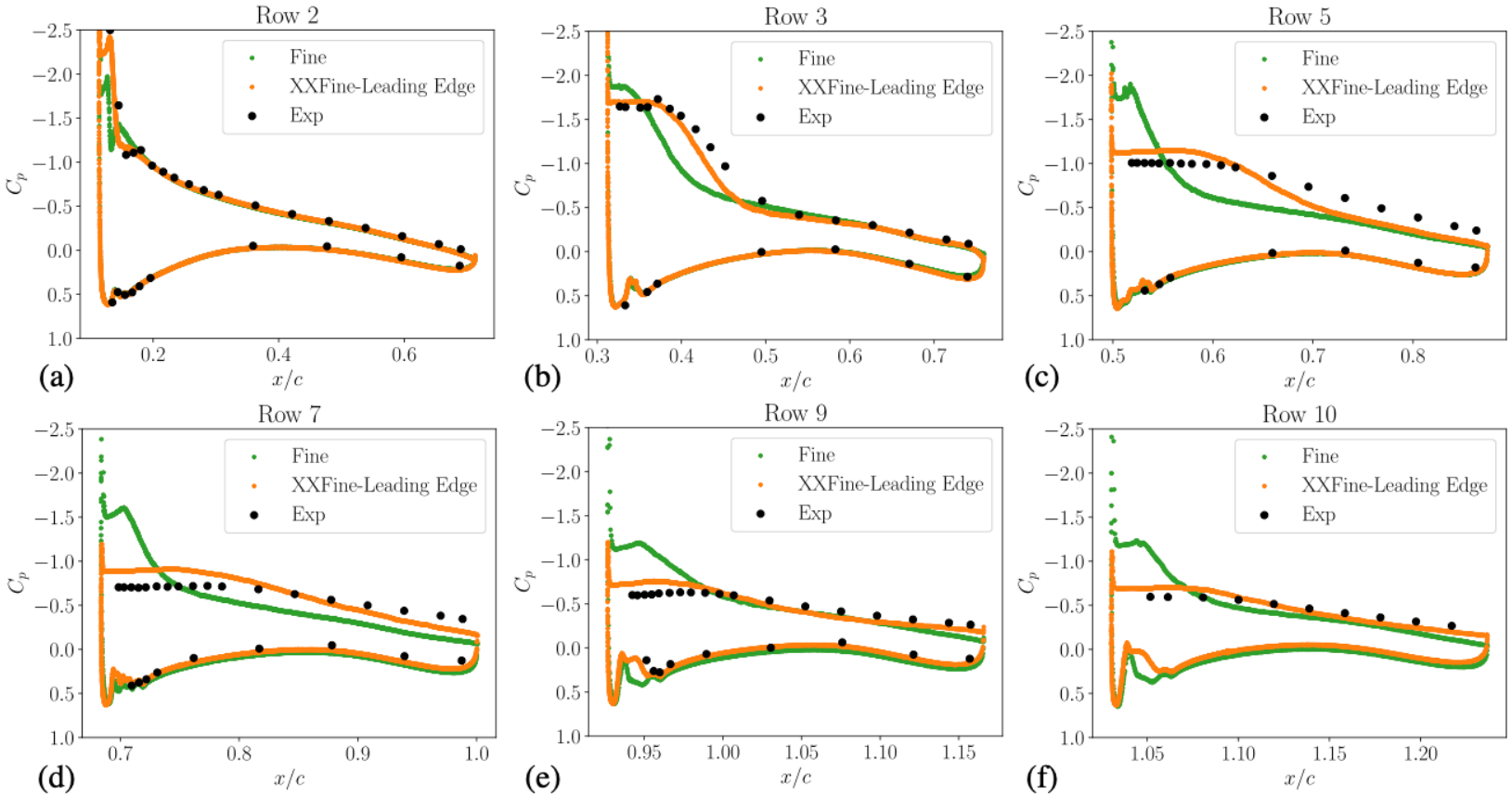




Artificial Ice Geometry

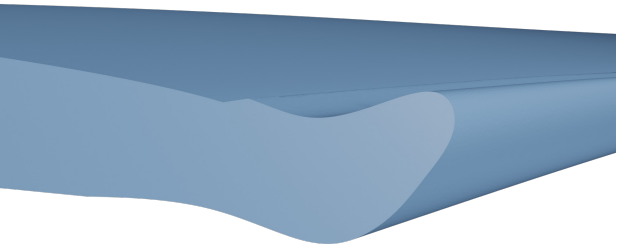


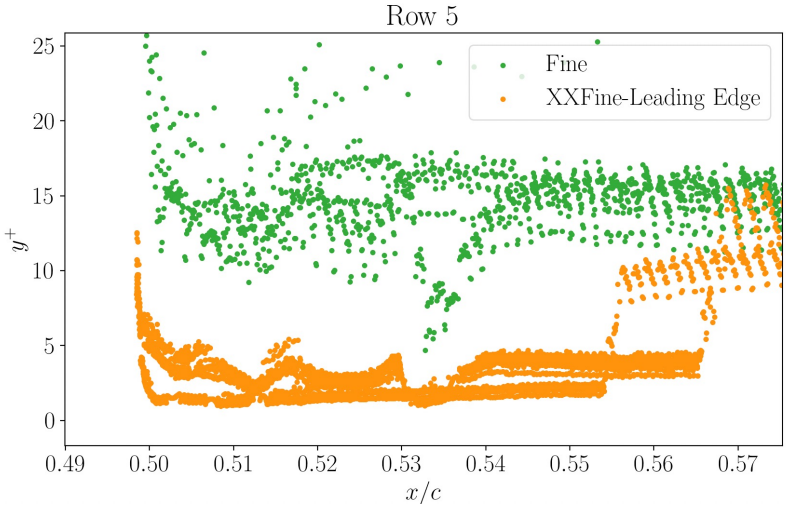
Streamwise pressure coefficients for $\alpha = 8^{\circ}$



- Increased grid resolution at the leading edge leads to drastically improved results

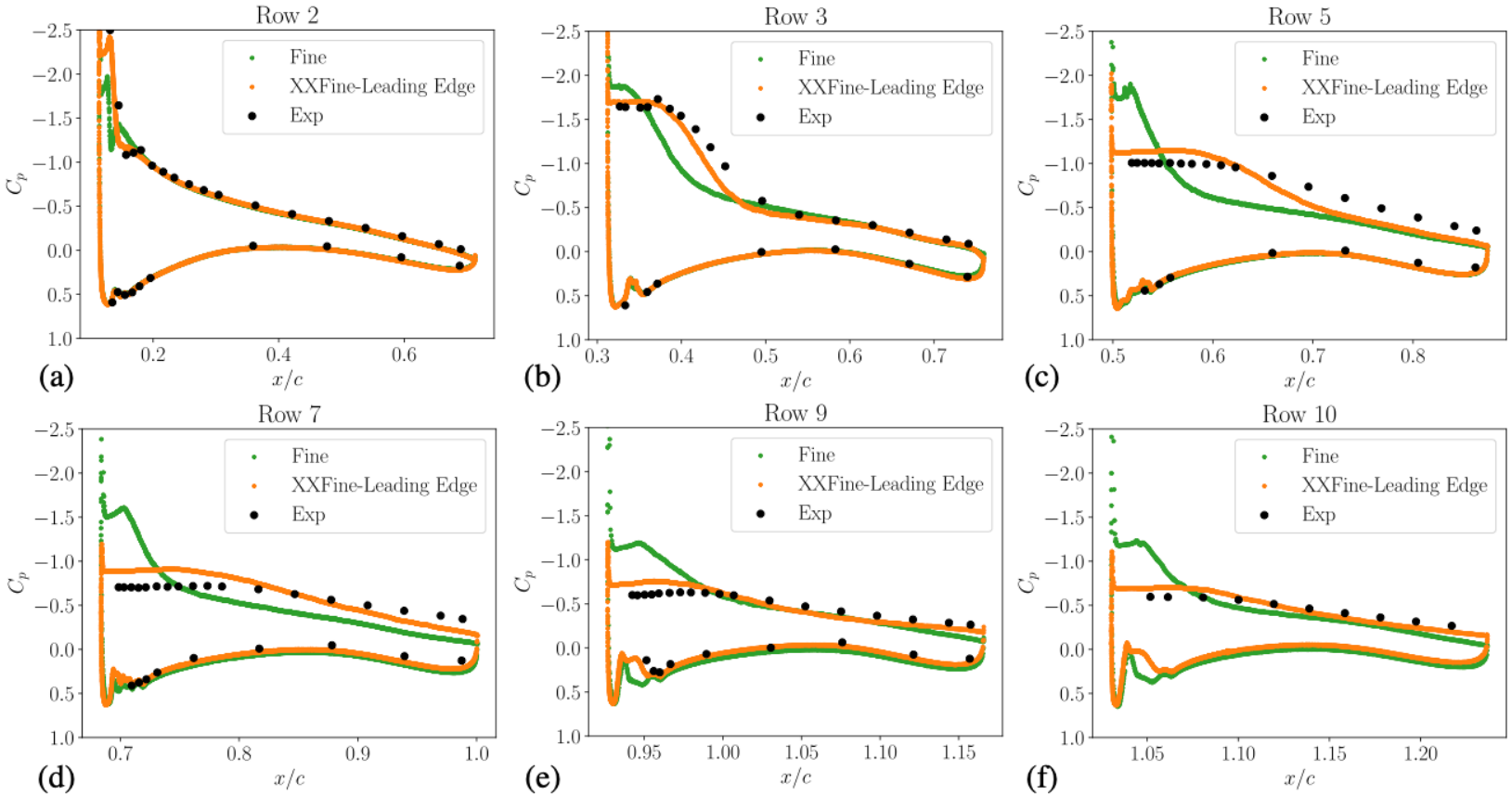
Artificial Ice Geometry





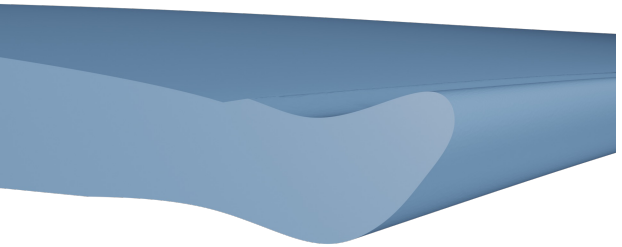
Leading edge y^+ approaching wall-resolved

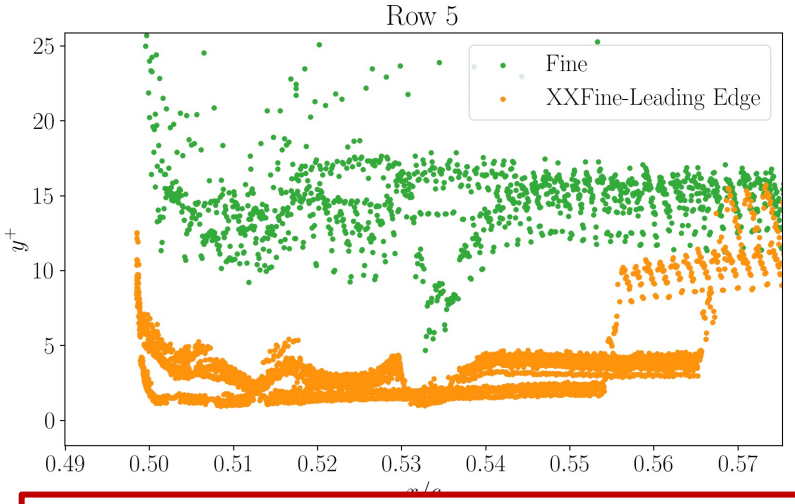
Streamwise pressure coefficients for $\alpha = 8^\circ$



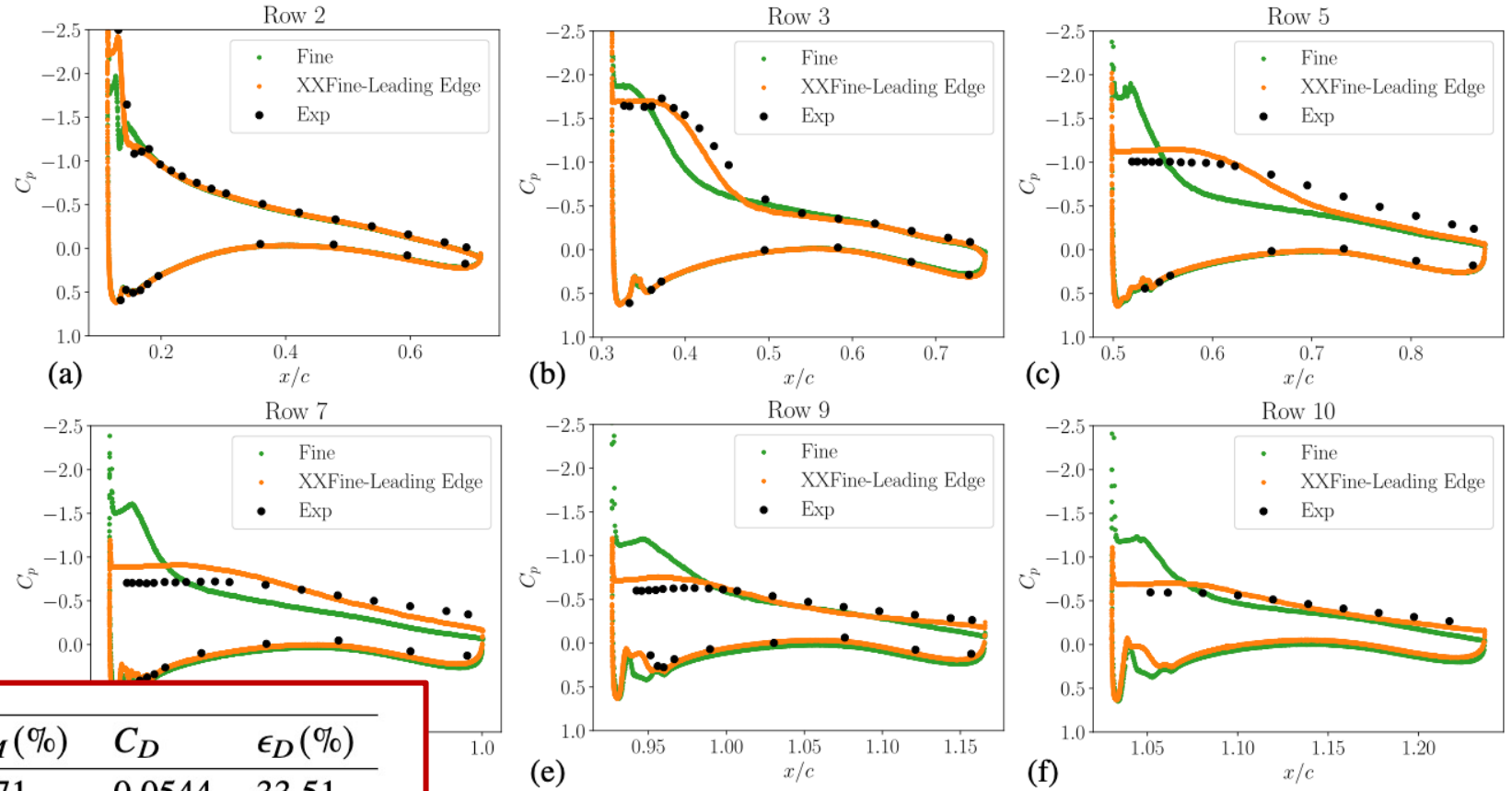
- Increased grid resolution at the leading edge leads to drastically improved results

Artificial Ice Geometry





Streamwise pressure coefficients for $\alpha = 8^\circ$



Resolution	C_L	ϵ_L(%)	C_M	ϵ_M(%)	C_D	ϵ_D(%)
Fine	0.7042	1.69	-0.216	9.71	0.0544	33.51
XXFine	0.7021	1.36	-0.194	1.17	0.0769	5.99

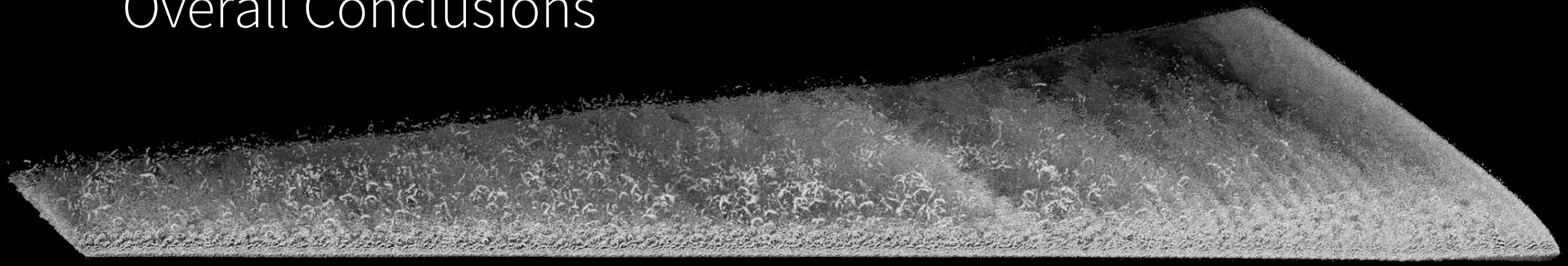
solution at the leading edge leads to drastically improved results

Conclusions

- Artificial ice shapes are, in part, created to make it possible for CFD tools to simulate the various geometries that attempt to mimic real ice shapes
- Issues with this approach:
  - Mimic QoI, but miss important flow behaviors
  - Intro of physics not present in real-ice stress state-of-the-art models
- Given a real ice shape, we can achieve good results for Cl, Cd, Cm, and Cp on moderately coarse grids using WMLES
- These artificial shapes should be designed to best mimic the real-ice, not be simplified for specific gridding practices

Bornhoft, B., Jain, S. S., Bose, S. T., and Moin, P., "Large-eddy simulations of the CRM65 swept wing under real and artificial icing conditions." AIAA SCITECH 2024 Forum. 2024.

Overall Conclusions



- Evaluation of WMLES for complex ice shapes showed good agreement with experimental results for both iced airfoils and wings for glaze ice conditions
- Identified rime conditions as a candidate for roughness wall modeling
- Developed a new roughness velocity transformation and applied it as a roughness wall model
  - Improved results for both rough channel and rime ice conditions
- Evaluated and showed the benefit of using real ice shapes vs artificial ice shapes in the context of WMLES

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CTR Stanford University
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