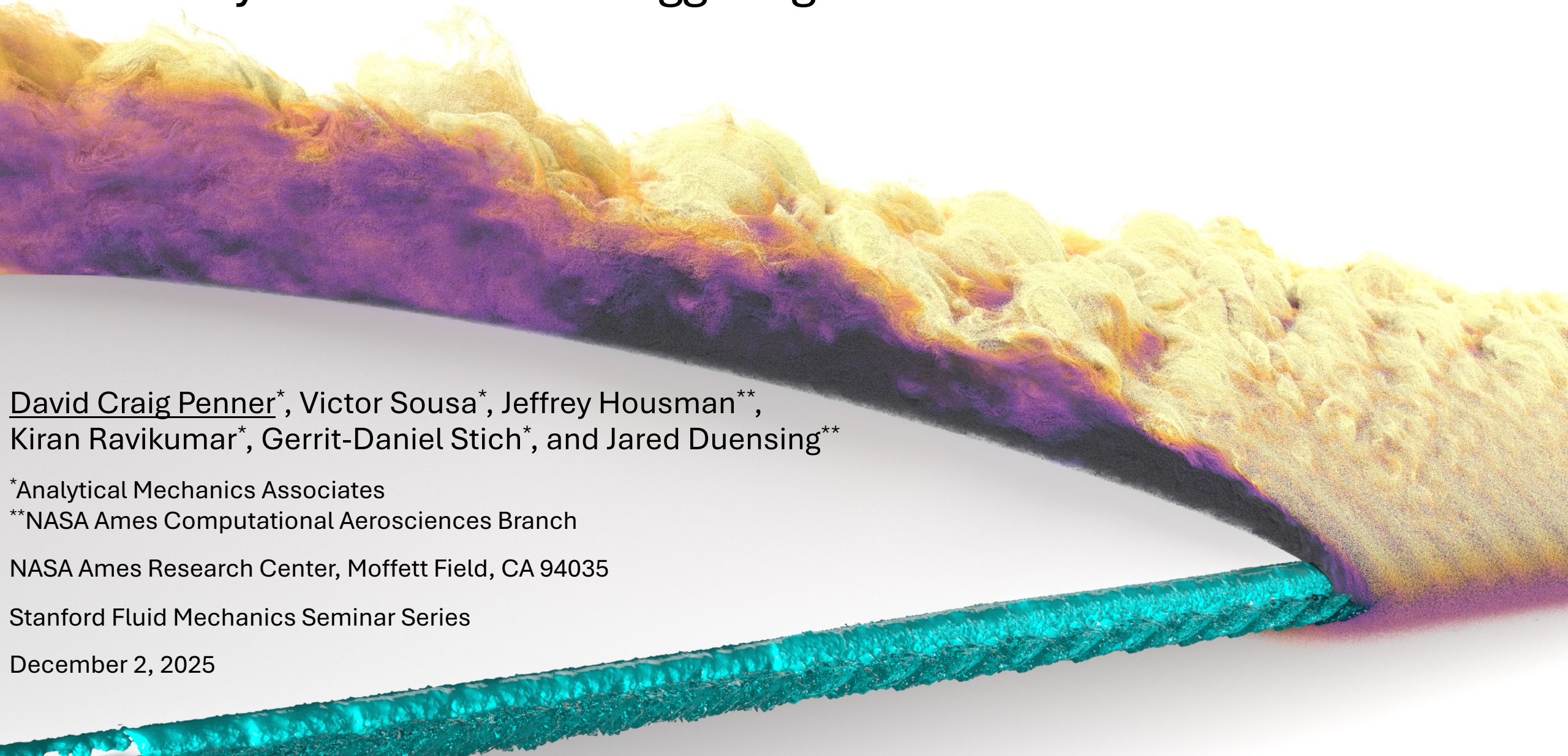
Large-Eddy Simulation of an Iced Swept Wing: A Perspective on the Aerodynamic Effect of Triggering Resolved Turbulence



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Kiran Ravikumar[*], Gerrit-Daniel Stich[*], and Jared Duensing[**]

[*]Analytical Mechanics Associates
[**]NASA Ames Computational Aerosciences Branch

NASA Ames Research Center, Moffett Field, CA 94035

Stanford Fluid Mechanics Seminar Series

December 2, 2025

Outline

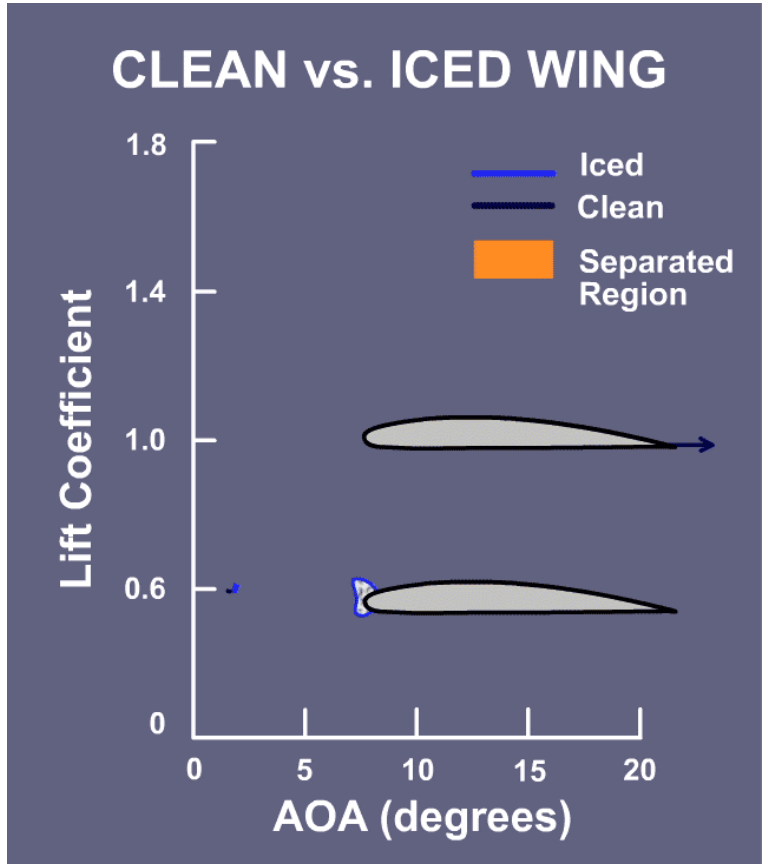
- ❑ **Why** do we study aircraft icing?
- ❑ **What** are the challenges for iced aerodynamics predictions with WMLES?
- ❑ **How** do we solve these challenges?
  - ❑ Aerodynamics predictions of an iced swept wing with LAVA
- ❑ **Summary** and **future** work

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Aircraft icing can have a large detrimental effect

- Aircraft icing is the buildup of ice on an aircraft when flying through supercooled water droplets
- Ice buildup can significantly reduce aircraft performance and controllability
- Understanding aircraft icing is critical for flight safety and certification



https://aircrafticing.grc.nasa.gov/media/img/1_1_3_3/1_1_3_3a_wingstall.gif

Example of leading-edge ice on a wing



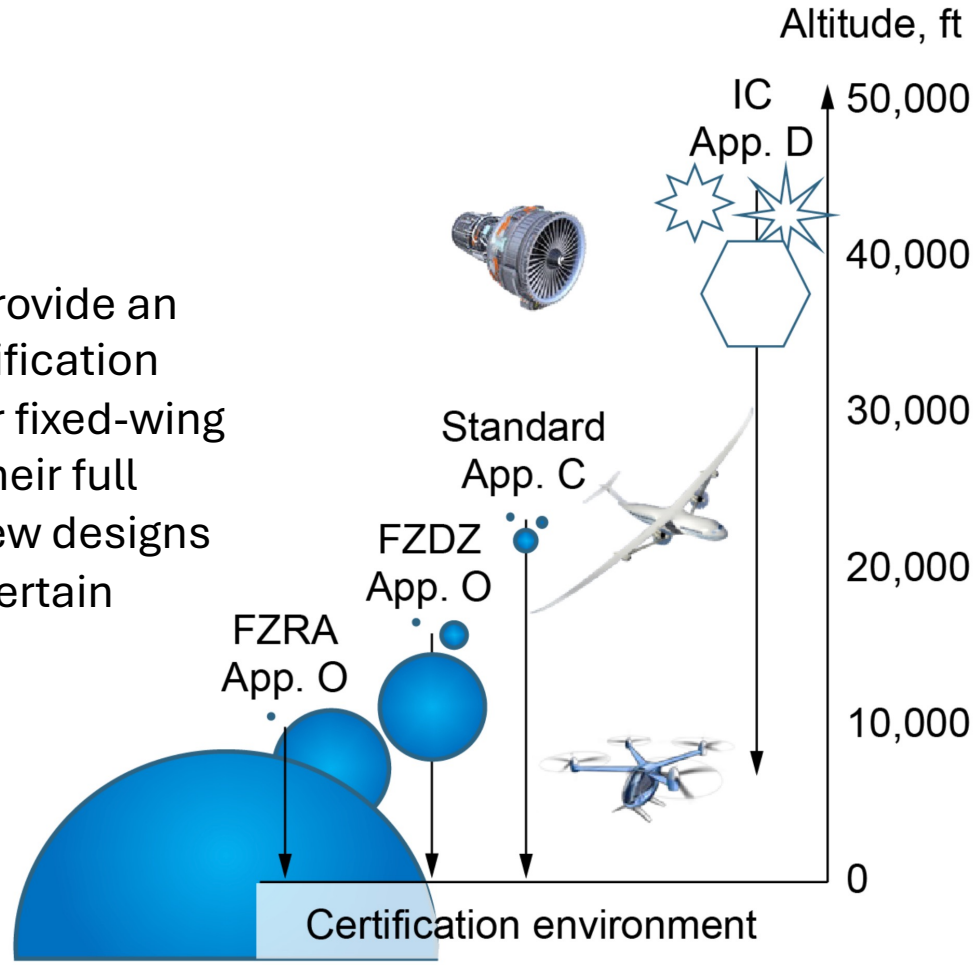
https://aircrafticing.grc.nasa.gov/1_1_2_1.html

The Federal Aviation Administration (FAA) has several regulations that govern aircraft icing

Three different icing environments covered in FAA rules that govern aviation within the United States

- **Appendix C:** Standard icing conditions with smaller supercooled droplets (15-50 μm)
- **Appendix O:** Supercooled large droplets (up to > 500 μm) in the context of freezing drizzle (FZDZ) and freezing rain (FZRA)
- **Appendix D:** High-altitude ice crystal (IC) conditions (50-200 μm) can cause turbine power loss

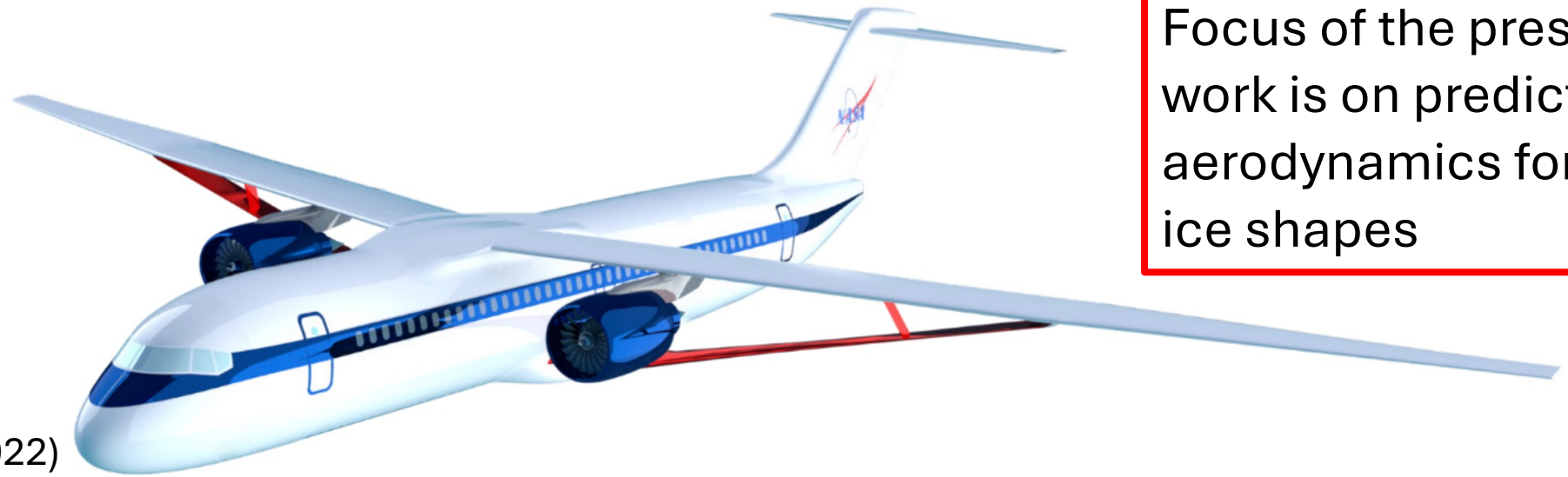
2015 rules provide an ongoing certification challenge for fixed-wing aircraft, as their full impact on new designs remains uncertain



Struk et al. (2022)
"NASA Analysis of Alternatives Study for Icing Research"

New FAA regulations have a significant impact on early aircraft design and certification

- Need to incorporate icing early to avoid penalties related to aircraft performance, efficiency, and emissions
- Relying on similarities to existing designs and heuristics for certification can limit research and development through conservative design choices, reductions in operational performance, and increased costs
- Validated predictive tools are needed to reduce risk through design exploration prior to flight testing, spreading out certification effort over the entire project lifecycle

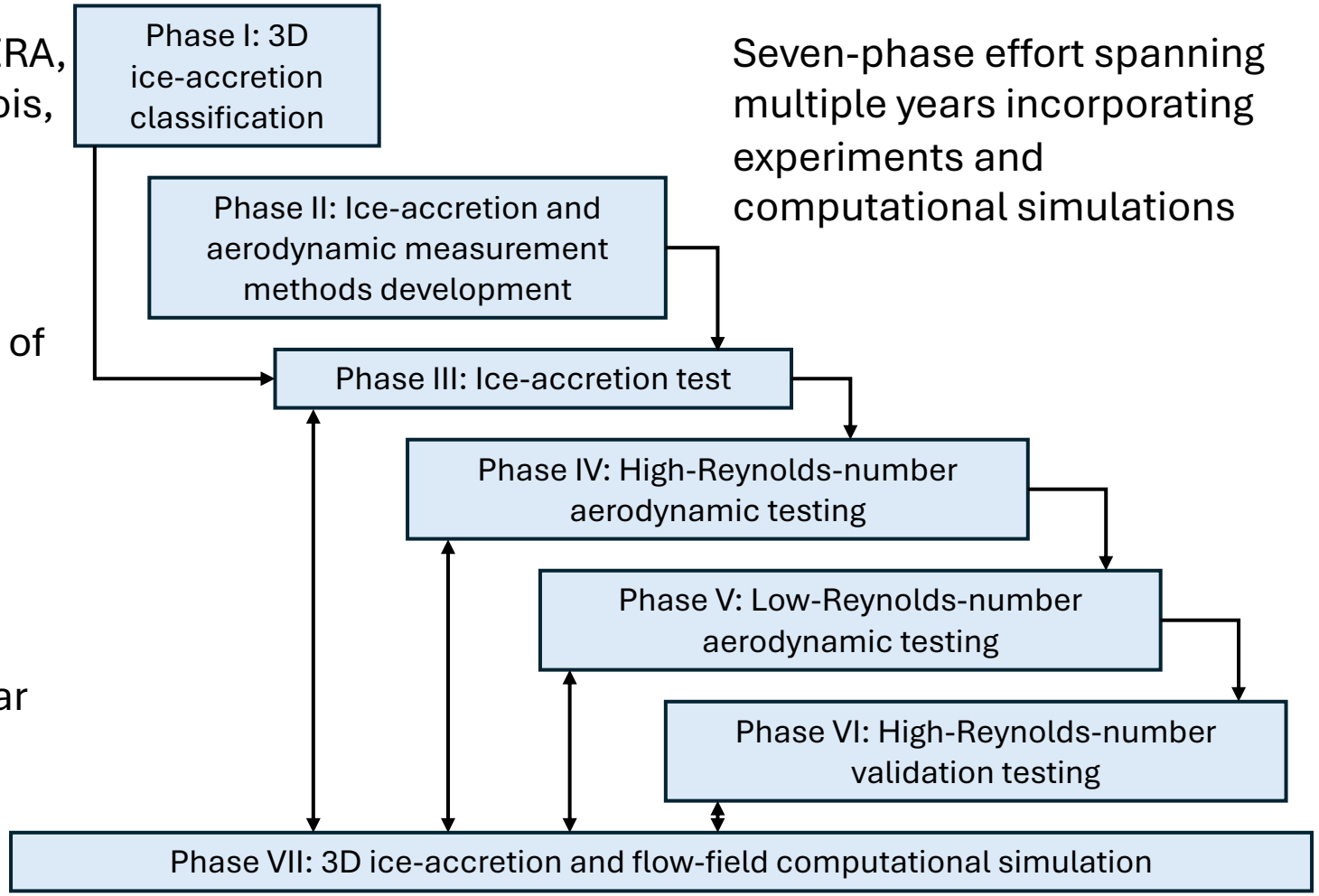


Focus of the present work is on predicting aerodynamics for fixed ice shapes

Struk et al. (2022)
"NASA Analysis of Alternatives Study for Icing Research"

NASA's Swept-Wing Icing Project (SWIP) or StUdies oN Scaling EffecTs due to ice (SUNSET) II

- Joint project sponsored by NASA, FAA, ONERA, and supported by Boeing, University of Illinois, University of Virginia, and University of Washington
- Project objectives
  1. **Produce** large experimental database of 3D ice accretion geometries
  2. **Develop** understanding of iced swept wing aerodynamics
  3. **Determine** effect of 3D ice shape geometric fidelity on aerodynamics
- Follows SUNSET I, which investigated similar topics for airfoils and straight wings

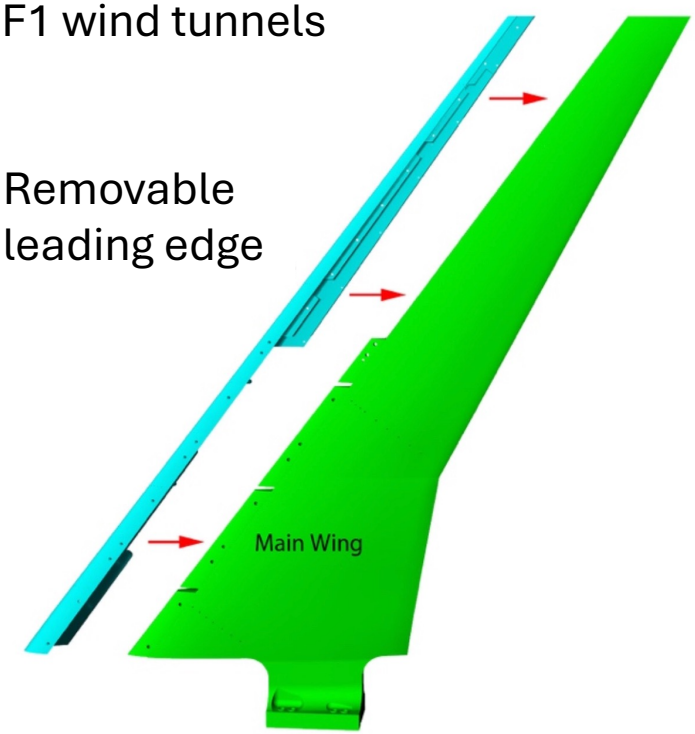


Seven-phase effort spanning multiple years incorporating experiments and computational simulations

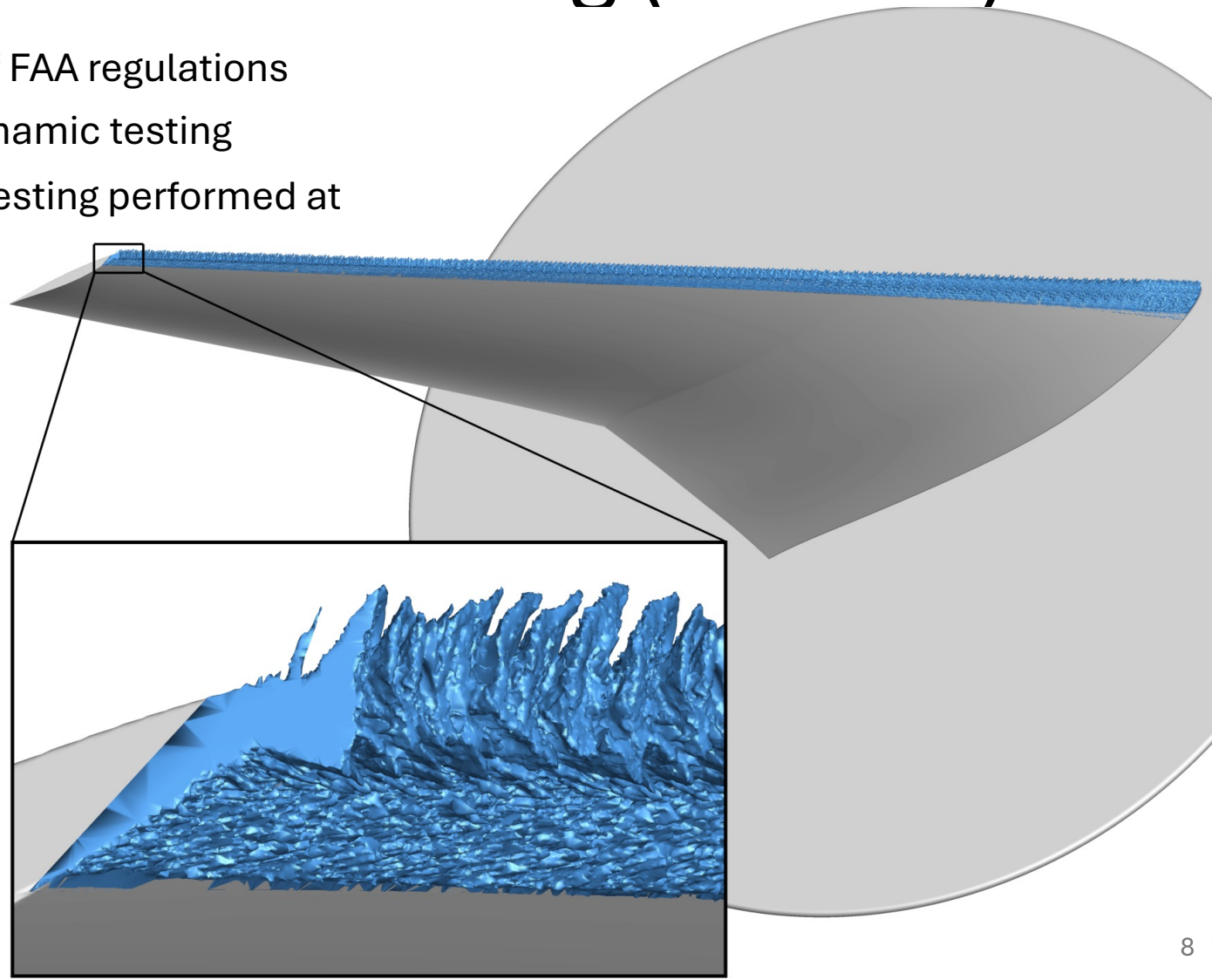
Broeren et al. (2022)
"Experimental and Computational Icing Simulation for Large Swept Wings"

SUNSET II focused on 65% scale model of NASA Common Research Model wing (CRM65)

- Icing conditions defined based on Appendix C of FAA regulations
- 3D-printed ice shapes affixed to wing for aerodynamic testing
- Low- and High-Reynolds number aerodynamic testing performed at Wichita State University Walter H. Beech and ONERA F1 wind tunnels

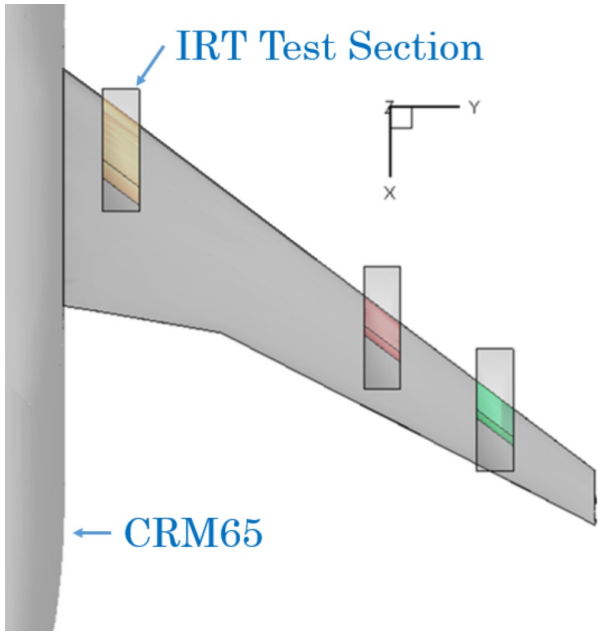


Camello et al. (2016)



Ice shapes for CRM65 developed at NASA Glenn Icing Research Tunnel (IRT)

Define hybrid models for use within IRT



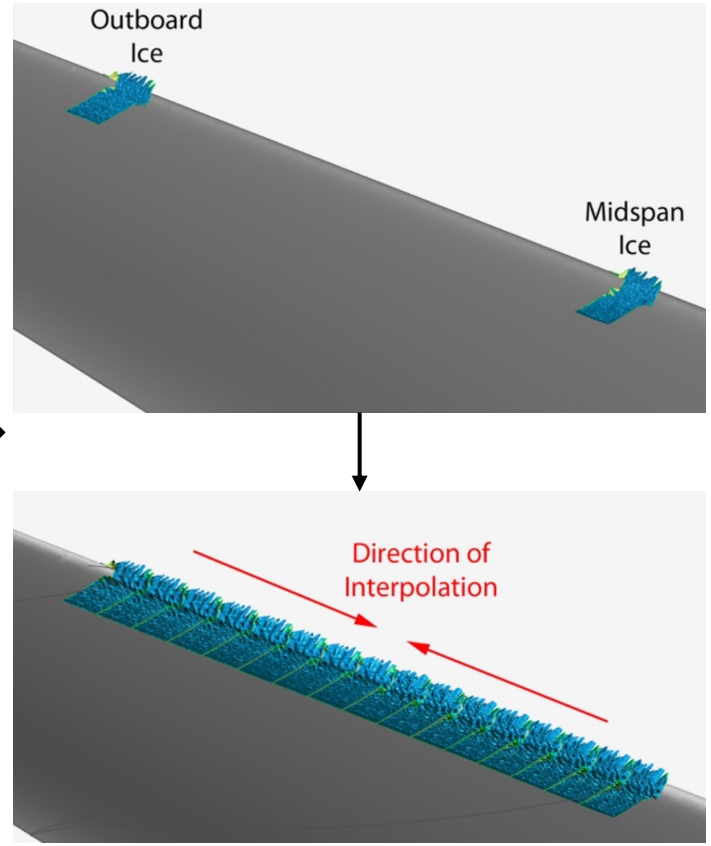
Camello et al. (2016)

Accrete ice within IRT and digitize via 3D electronic scanning



https://www.nasa.gov/directorates/armd/aetc/icing-research-tunnel/

Combine truncated sections into full spanwise shape



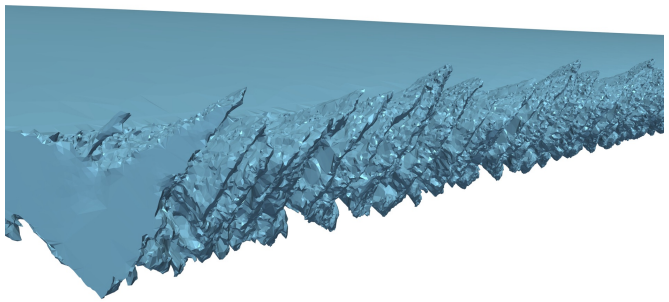
Camello et al. (2016)

Two shapes focused on by subsequent computational studies: high-fidelity and smooth

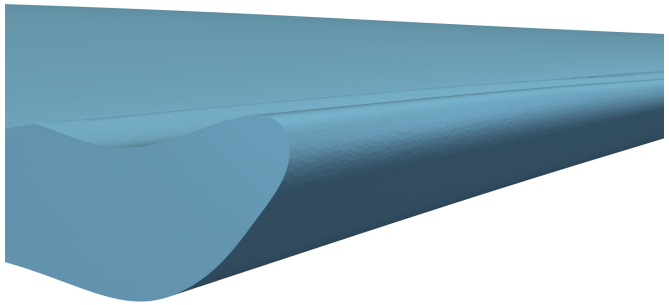
- Smooth ice shape created by lofting the maximum cross sections of the high-fidelity shape across the span
- Geometry simplification leads to non-conservative performance degradation

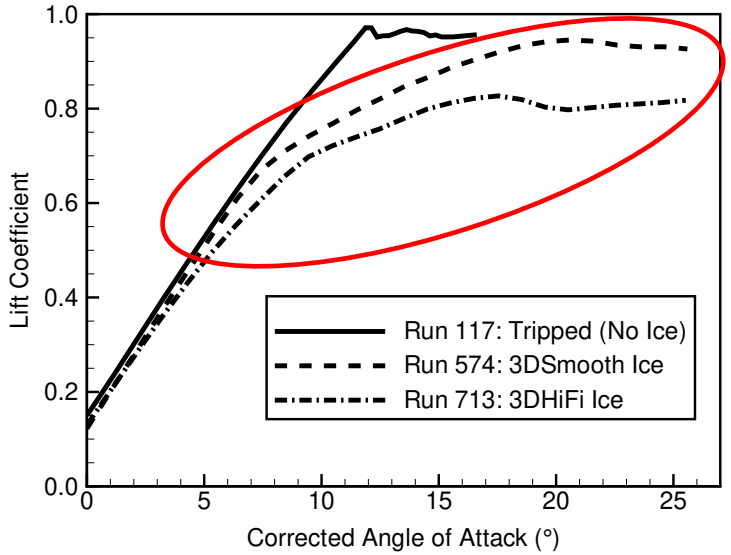
$$Re_{MAC} = 1.6 \times 10^6$$
$$Mach = 0.18$$

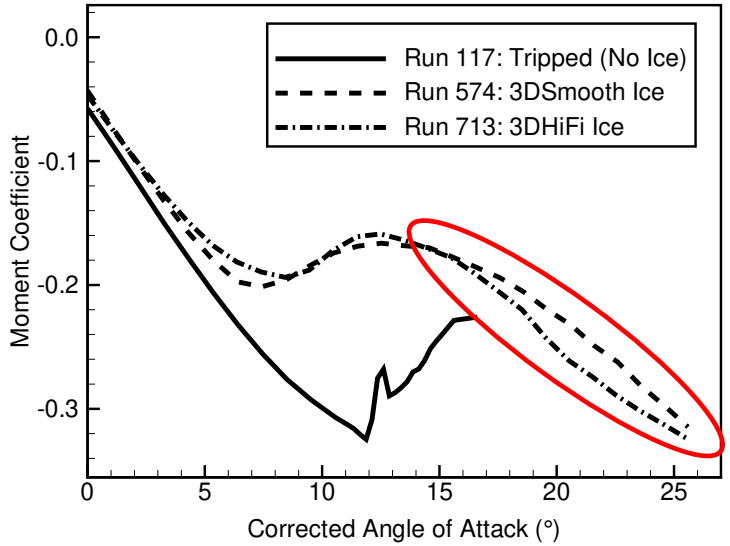
High-fidelity ice shape

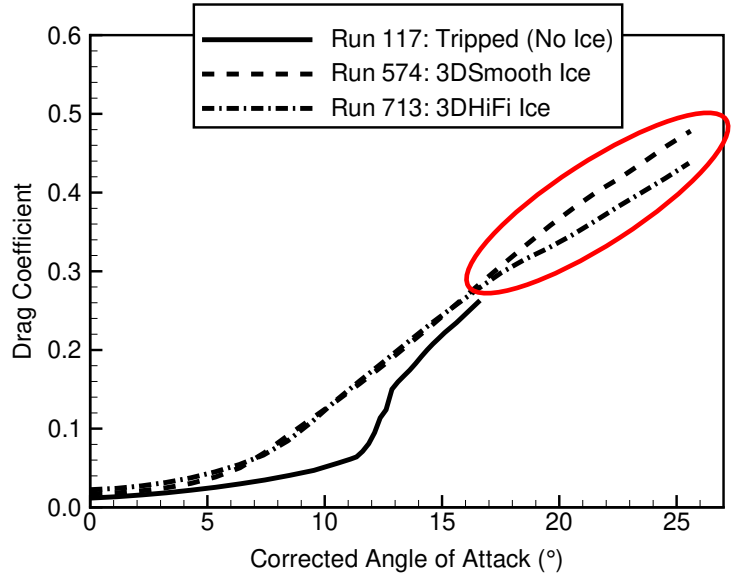


Smooth ice shape



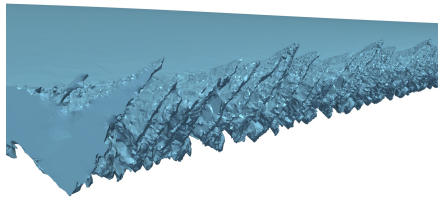


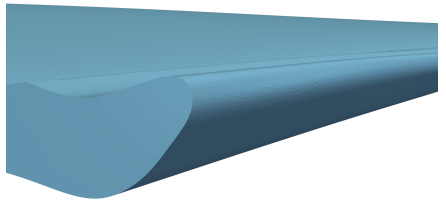




Performance differences between high-fidelity and smooth ice due to distinct flow fields

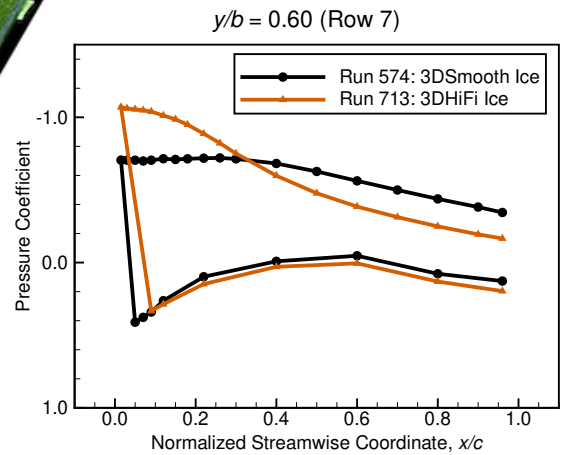
$\alpha = 8°$





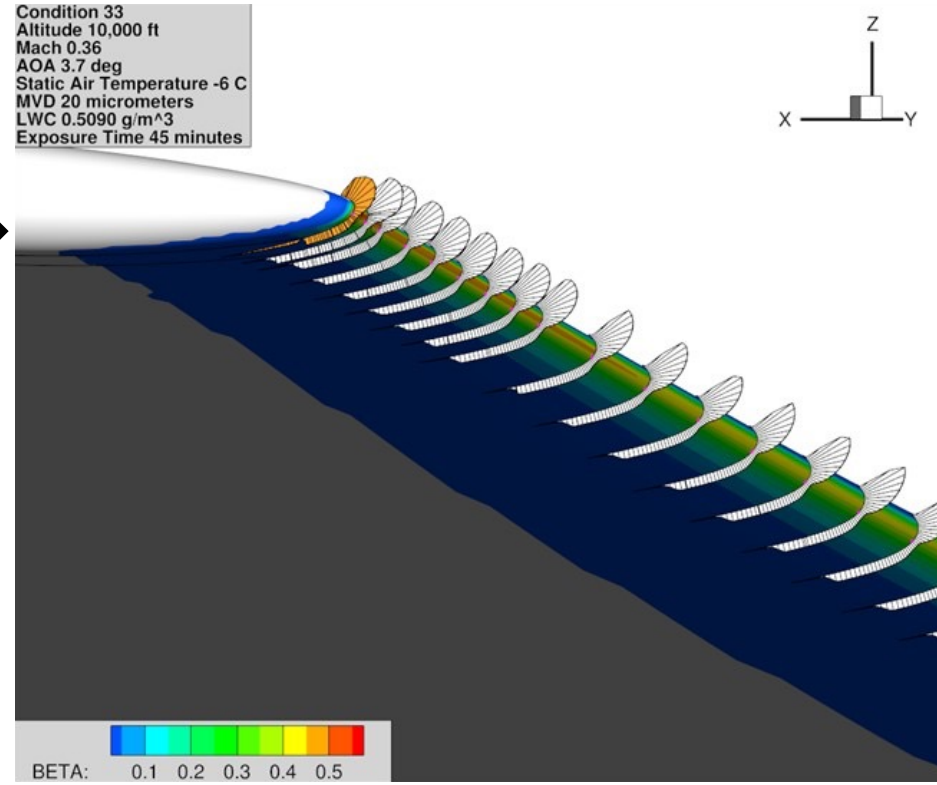
Leading-edge vortex suppressed by spanwise vorticity

Primary leading-edge vortex



Motivation for smooth ice due to limitations of computational ice accretion tools

- SUNSET II utilized two ice accretion codes: LEWICE3D (NASA) and IGLOO3D (ONERA)
  - **LEWICE3D:** uses 3D droplet trajectories on 2D user-specified cut planes
    Fujiwara et al. (2020)
  - **IGLOO3D:** uses predictor-corrector approach that is unable to capture highly 3D features (multi-shot expected to help)
    Radenac et al. (2024)
- **GlennICE** (NASA) is being developed as a fully 3D ice accretion code https://ntrs.nasa.gov/citations/20240008077
  - Can predict ice growth in highly 3D regions; however, the shapes produced will always look more like the “smooth” shape instead of the “high-fidelity” shape

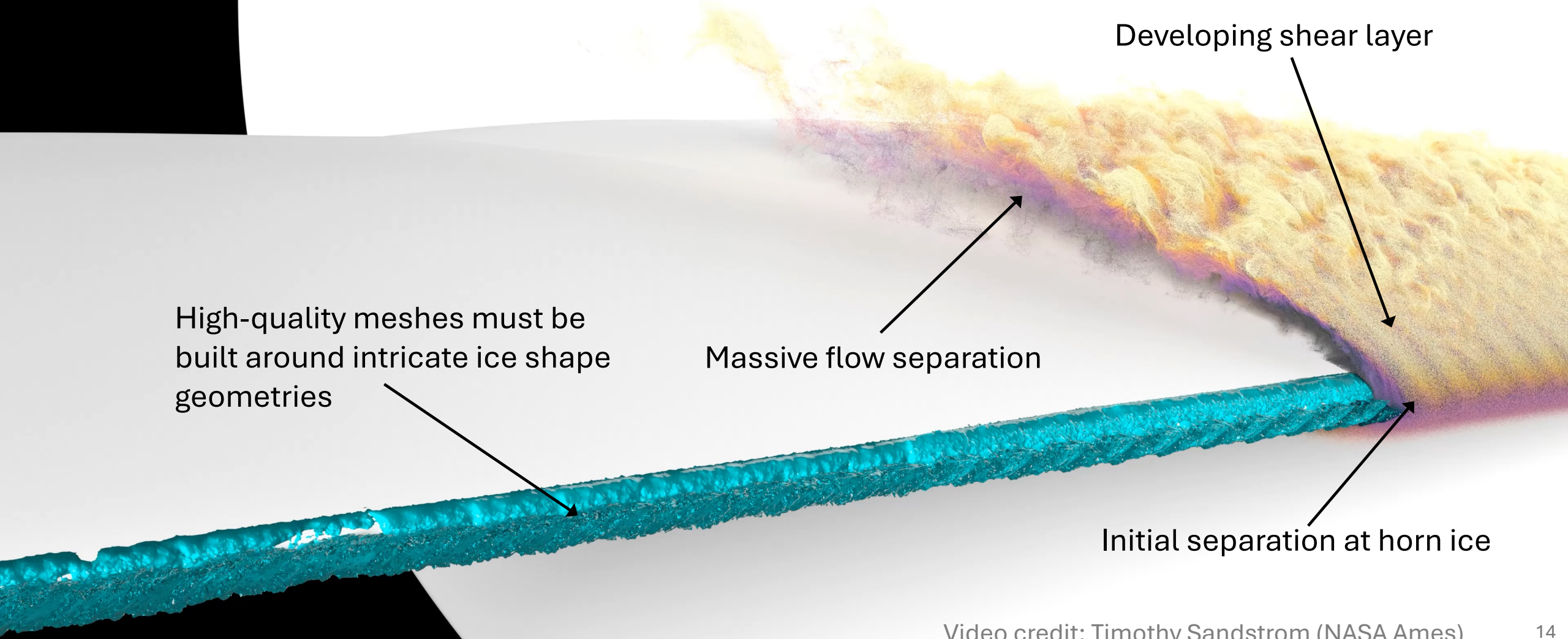


https://www1.grc.nasa.gov/wp-content/uploads/LEWICE3D.jpg

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Computational challenges introduced by iced swept wing aerodynamics



Video credit: Timothy Sandstrom (NASA Ames)

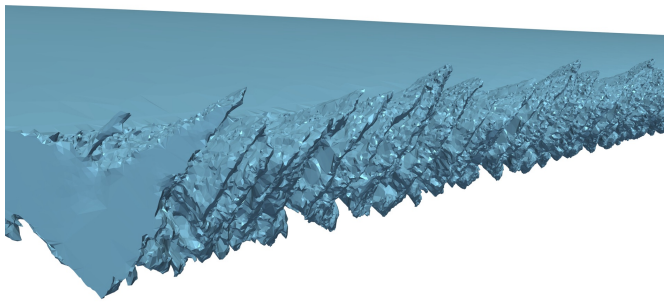
Smooth ice can present specific challenges for WMLES

Bornhoft et al. (2025) “On the Use of Artificial Ice Shapes for Large-Eddy Simulations in Aircraft Icing”

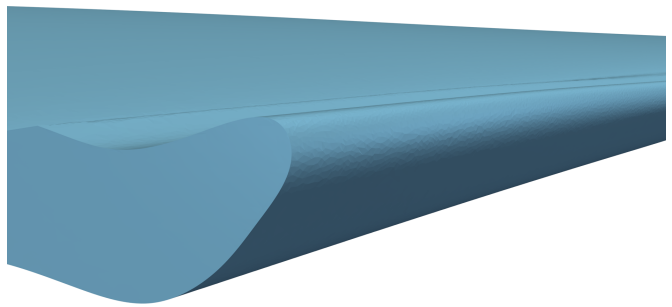
- Same grid resolutions used for high-fidelity ice shape were unable to simulate smooth ice accurately
- Improved results obtained by decreasing near wall spacing by a factor of 4, which substantially increased computational cost due to increased control volume count (320 million to 1.2 billion) and decreased time step
- Boundary condition placement informed by experimental oil-flow visualizations for improved results

“While we obtain improved results, we note that it is at the cost of significant computational overhead and the need to use experiments to select where to place boundary conditions.” Bornhoft et al. (2025)

High-fidelity ice shape



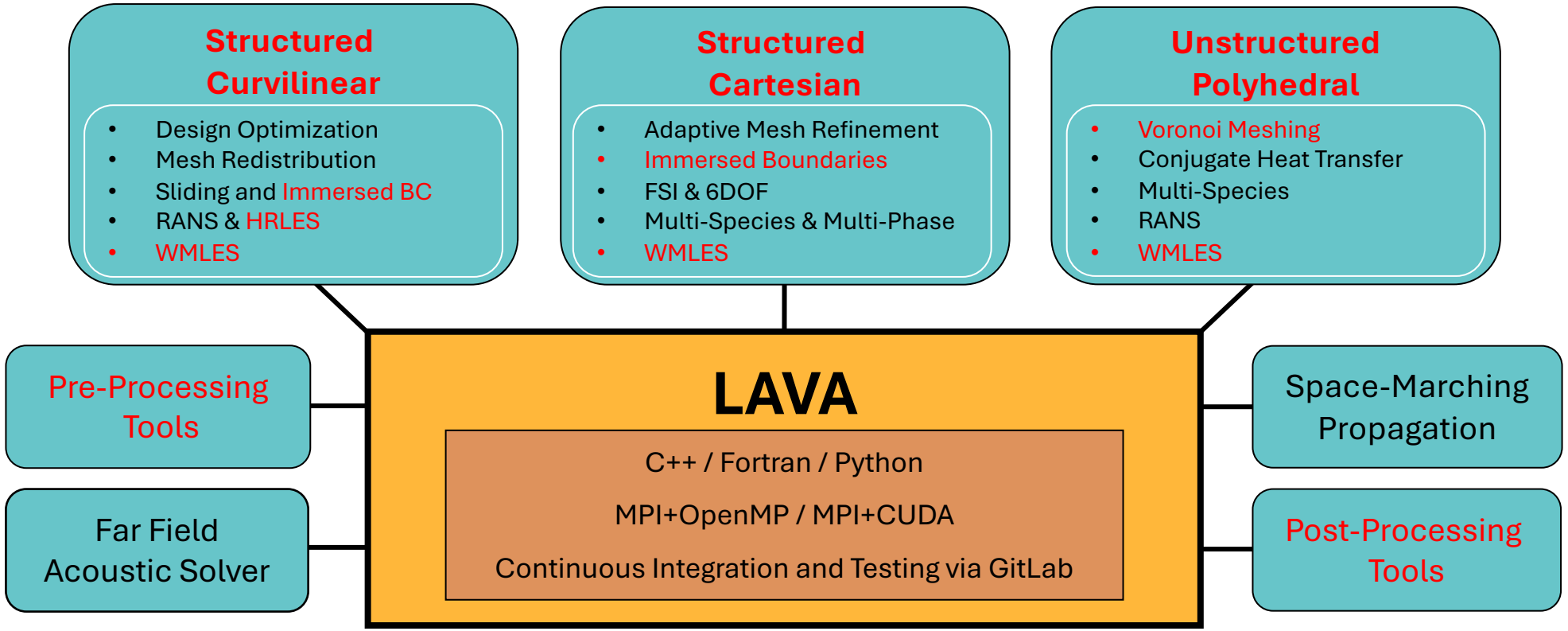
Smooth ice shape



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Launch, Ascent, and Vehicle Aerodynamics framework is a comprehensive computational tool

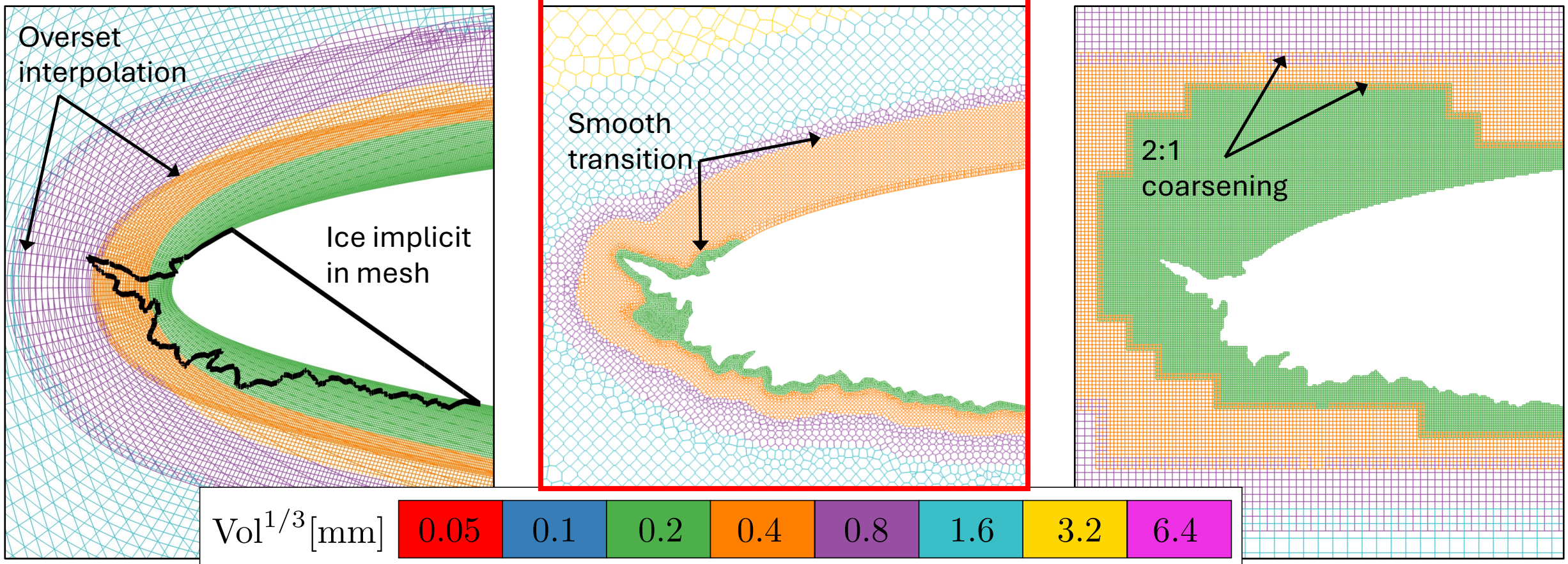


Primary difference between methods is treatment of ice triangulation

Curvilinear
source-term IB

Voronoi
body-fitted

Cartesian
ghost-cell IB



IB = immersed boundary

LAVA unstructured solver options

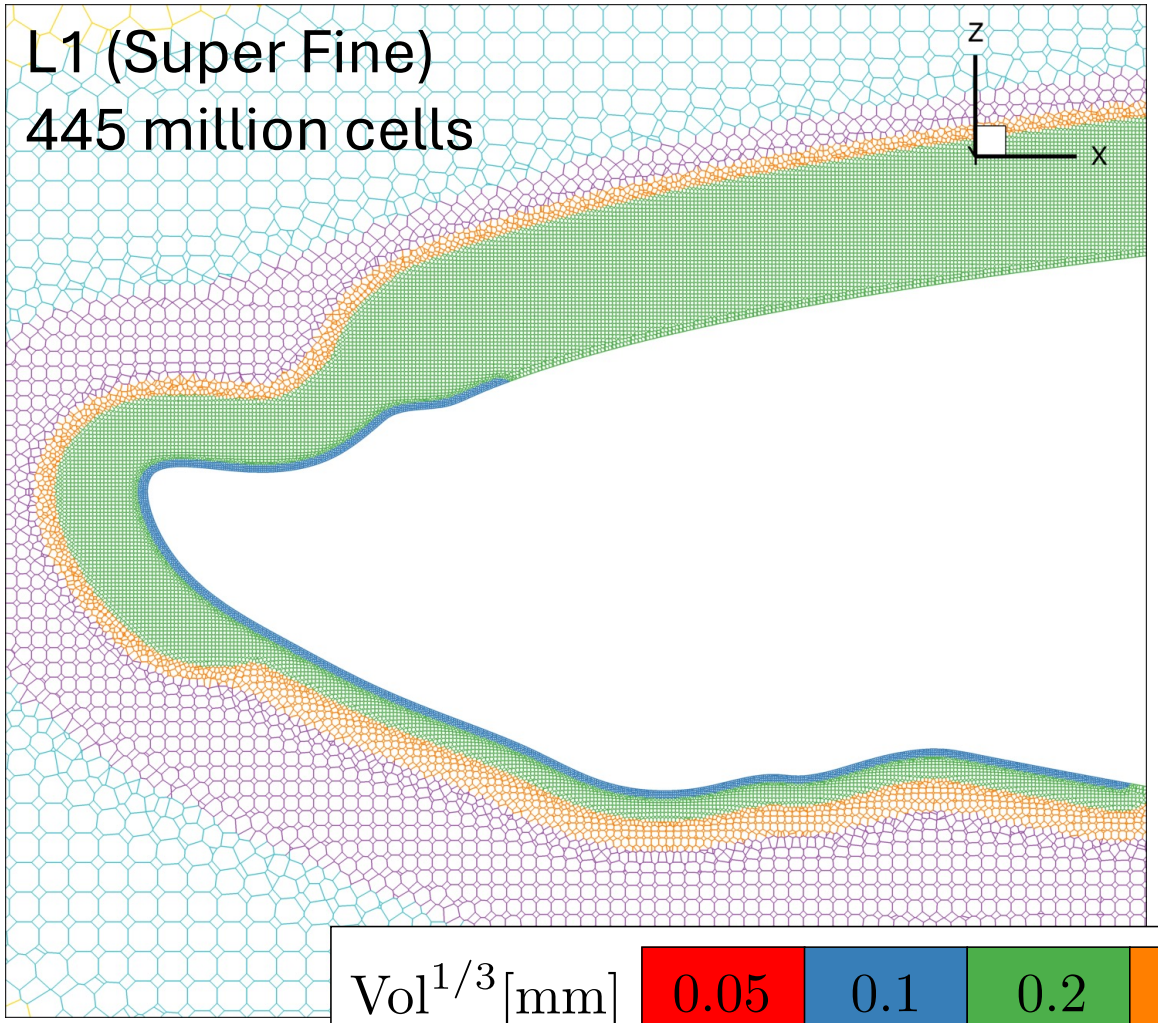
- GPU-accelerated second-order accurate finite-volume solver
- Flow conditions: $\mathrm{Re}_{\mathrm{MAC}} = 1.6 \times 10^6$ and $\mathrm{Mach} = 0.18$
- Low-dissipation numerical scheme based on asymptotically entropy-consistent and kinetic-energy preserving numerical flux flux function
- Time-marching performed using explicit third-order Runge-Kutta
- Wall-modeled large-eddy simulation employed
  - Vreman subgrid-scale model with fixed coefficient of 0.08
  - Default algebraic equilibrium wall-model based on Musker's law (1979)
  - Wall model exchange location is first cell centroid off the wall
- Voronoi meshes used
  Sousa et al. (2024)
  "LAVA Voronoi Mesher for Wall-Modeled Large-Eddy Simulations"

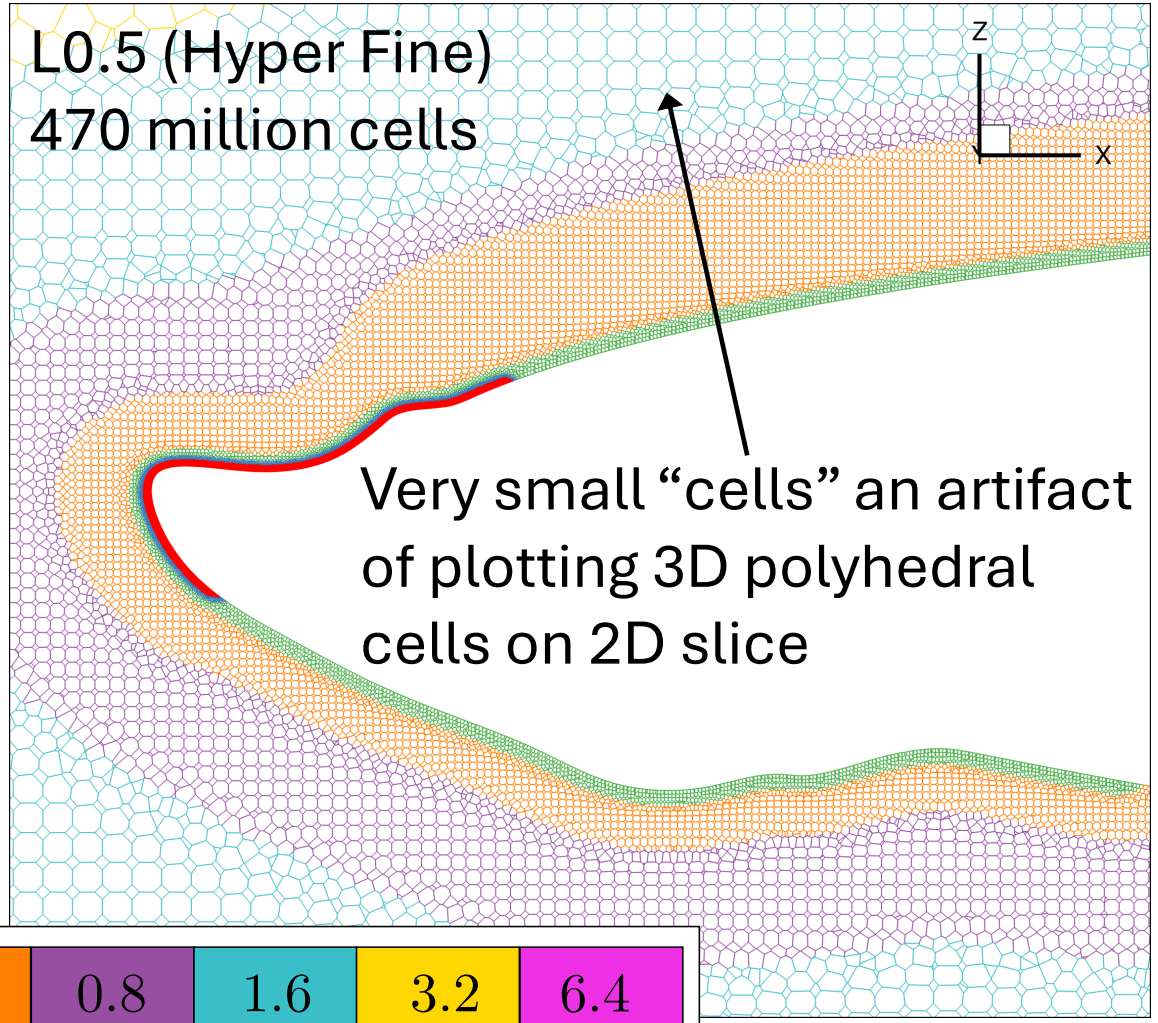
Voronoi mesh details

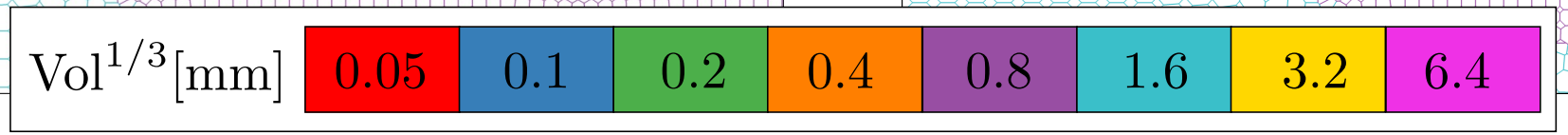
Configuration	Name	Descriptor	Minimum dx (mm)	Cells (million)
3DHiFi Ice	L8	Coarse	0.8	6
	L4	Medium	0.4	22
	L2	Fine	0.2	97
3DSmooth Ice	L8	Coarse	0.8	6
	L4	Medium	0.4	21
	L2	Fine	0.2	90
	L1	Super Fine	0.1	445
	L0.5	Hyper Fine	0.05	470
Tripped (No Ice)	L8	Coarse	0.8	13
	L4	Medium	0.4	47
	L2	Fine	0.2	181

Mean aerodynamic chord = 423 mm, Max. scallop length (Ozcer et al. 2023) = 5 mm

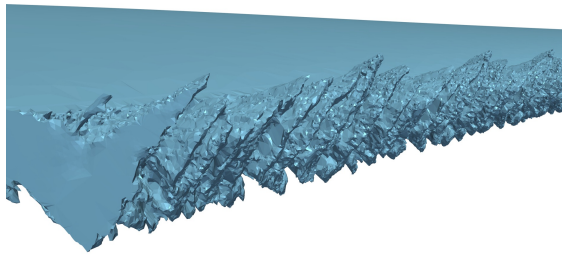
L0.5 (Hyper Fine) mesh not an in-family mesh to save mesh cells

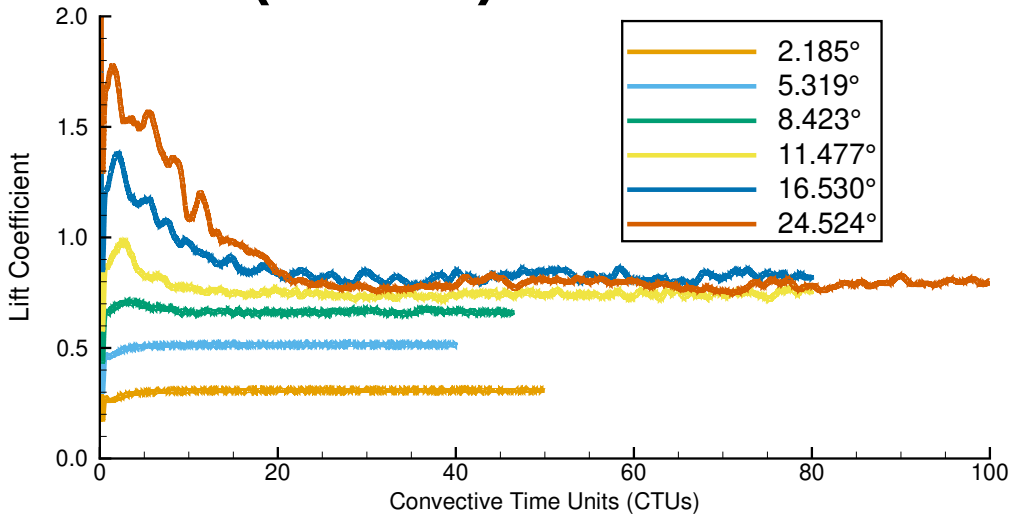


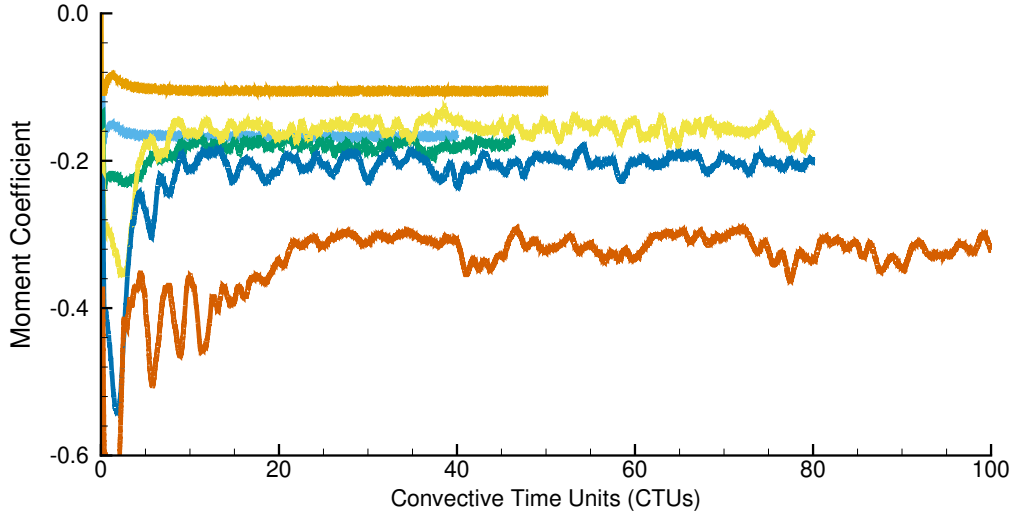


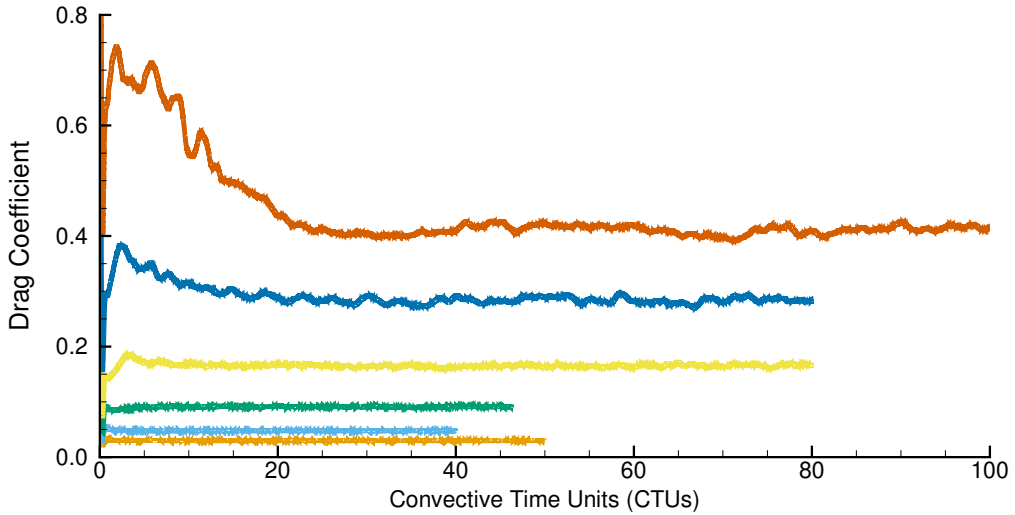


3DHiFi Ice: Time histories of loads on L2 (Fine) mesh



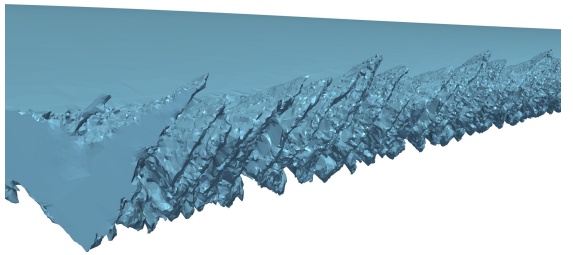


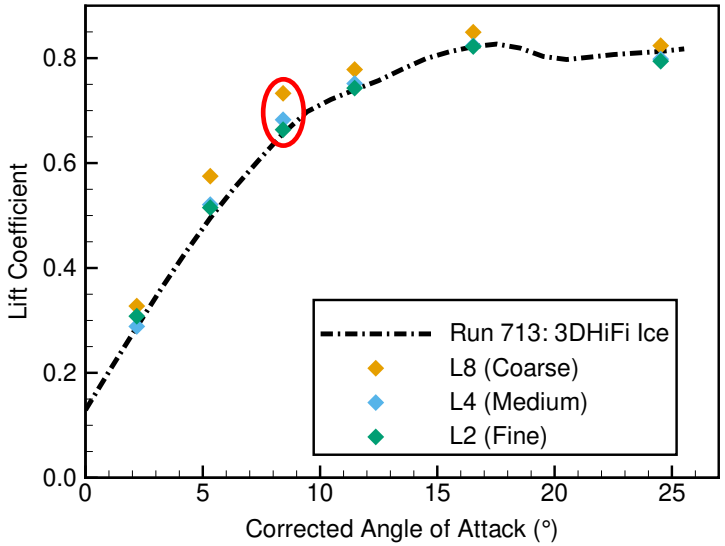


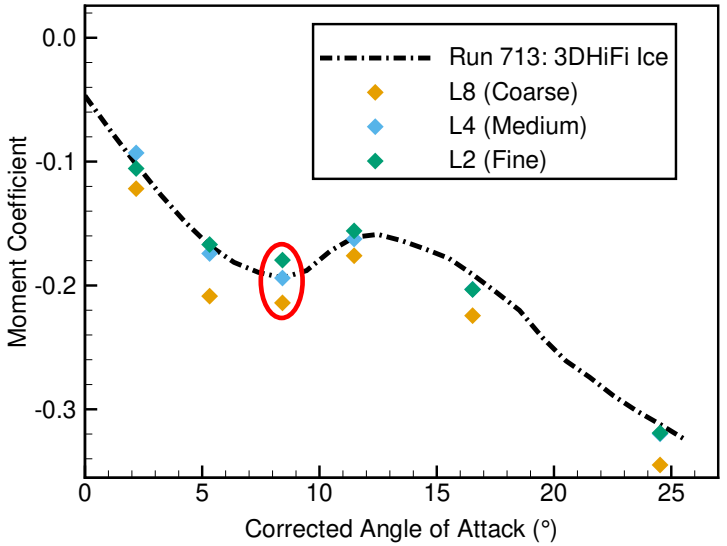


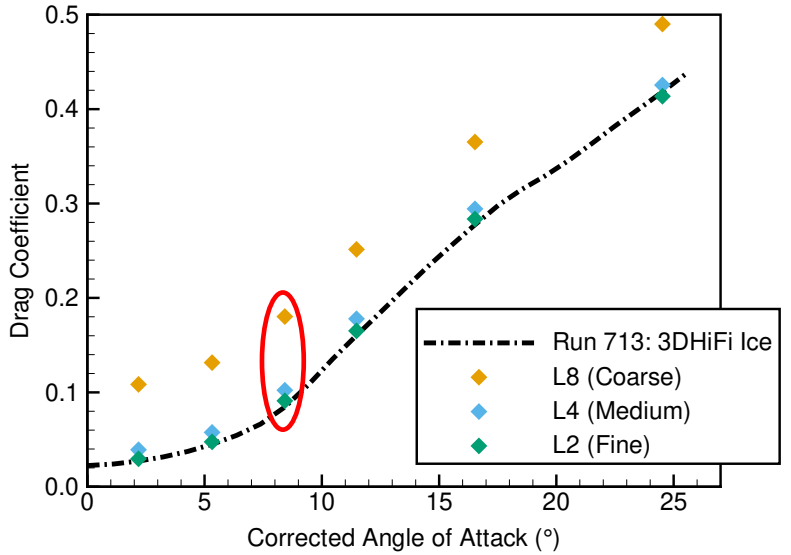
- 1 CTU = mean aerodynamic chord / freestream velocity magnitude
- 40-100 CTUs simulated depending on angle of attack
- Time-averaging performed starting at 20 or 30 CTUs depending on angle of attack

3DHiFi Ice: Aerodynamic loads



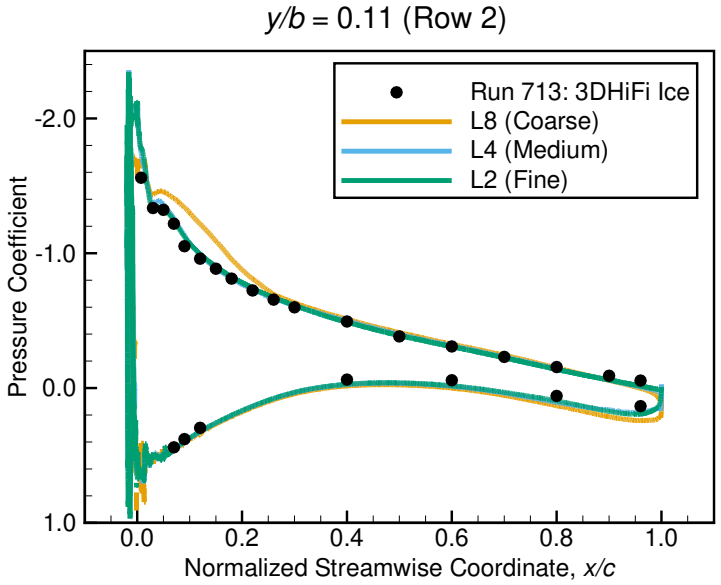


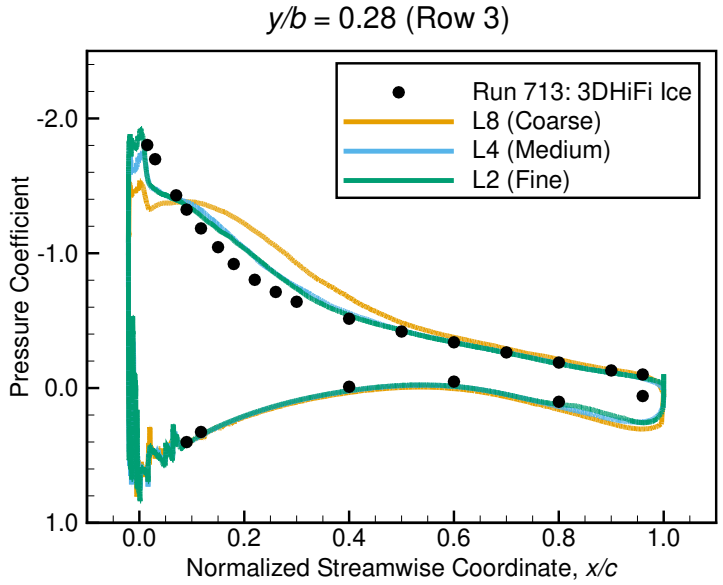


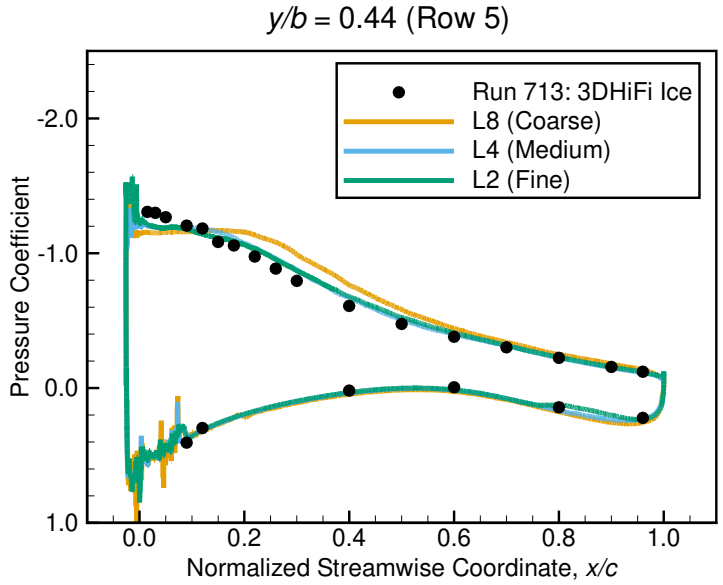


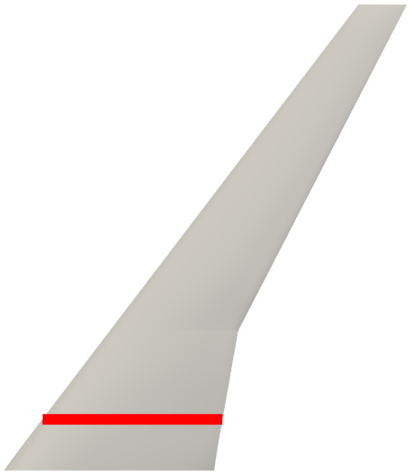
- Numerical predictions capture experimental trends and generally improve with refinement
- Persistent drag offset on L8 (Coarse) mesh removed with refinement
- On L2 (Fine) mesh, largest lift error, $\Delta C_L = 0.02$, occurs at $\alpha = 2.185°$

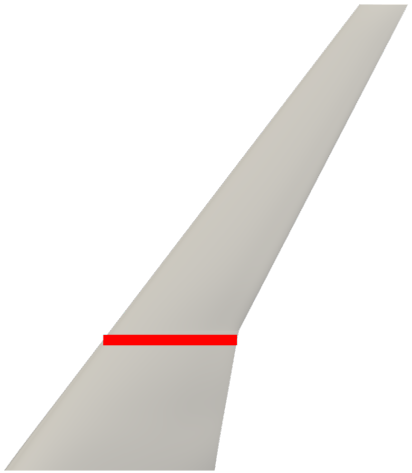
3DHiFi Ice: Pressure profiles compare reasonably well with experiment ($\alpha = 8.423°$)

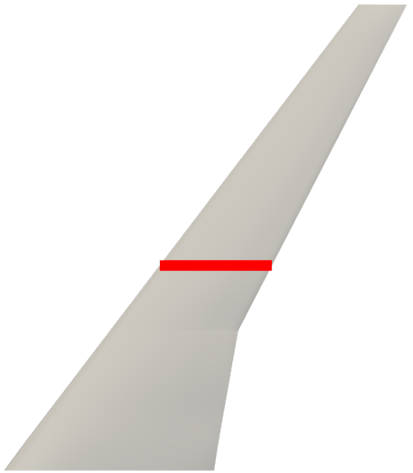




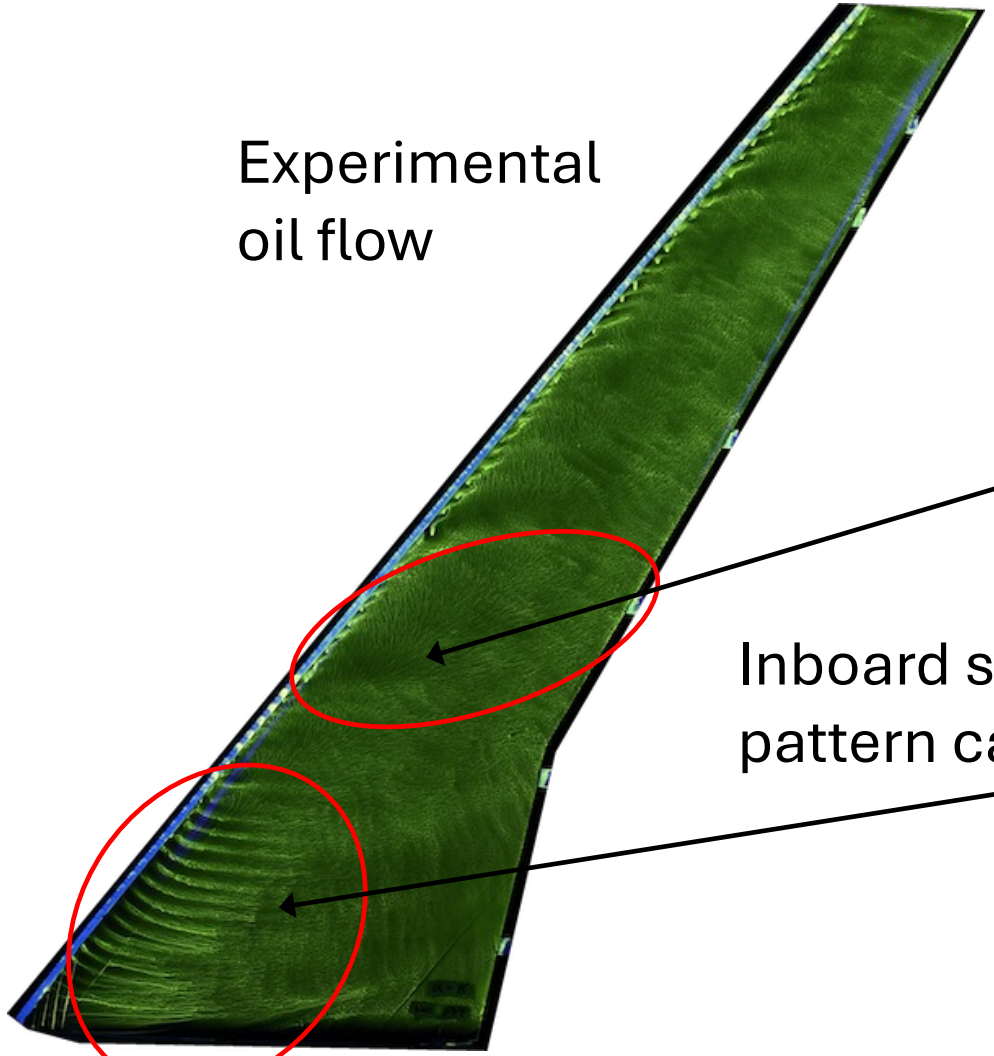








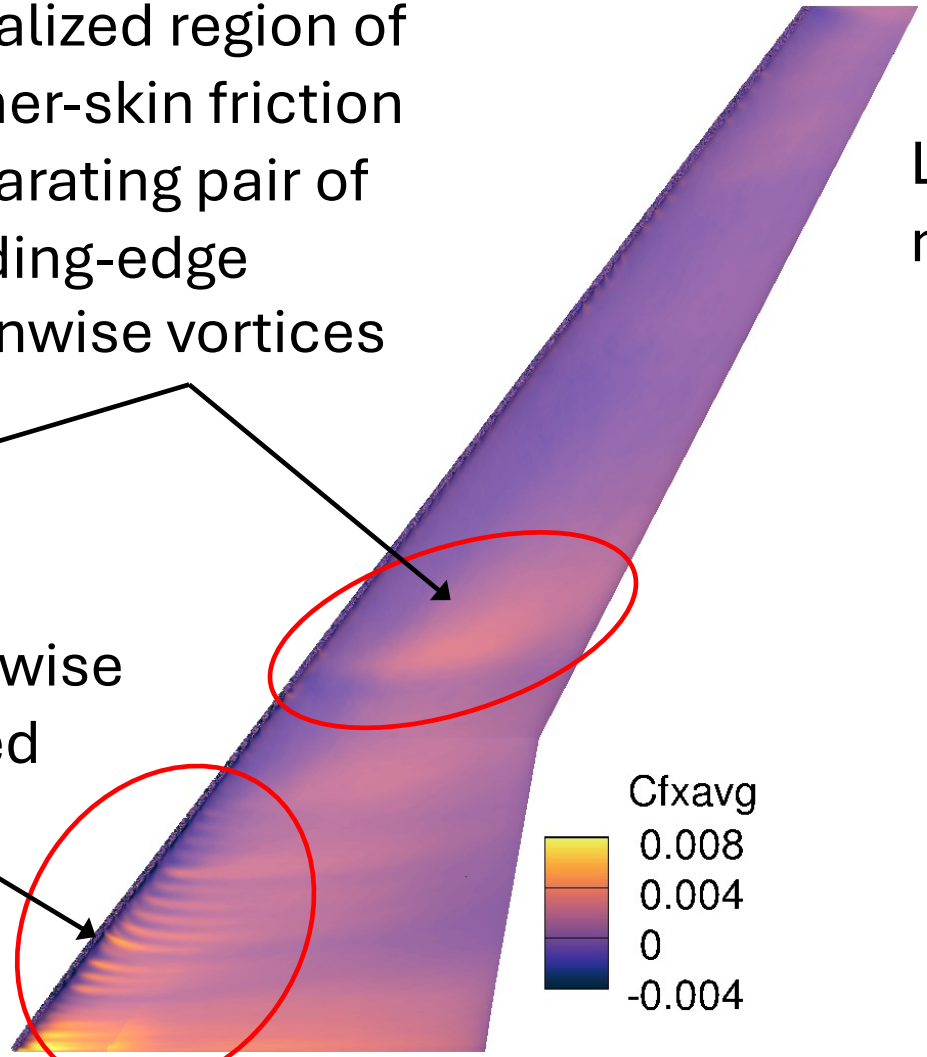
3DHiFi Ice: Time-averaged skin-friction contours consistent with experiment ($\alpha = 8.423°$)



Experimental oil flow

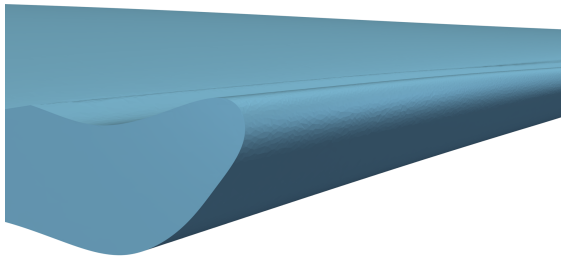
Localized region of higher-skin friction separating pair of leading-edge spanwise vortices

Inboard streamwise pattern captured



L2 (Fine) mesh

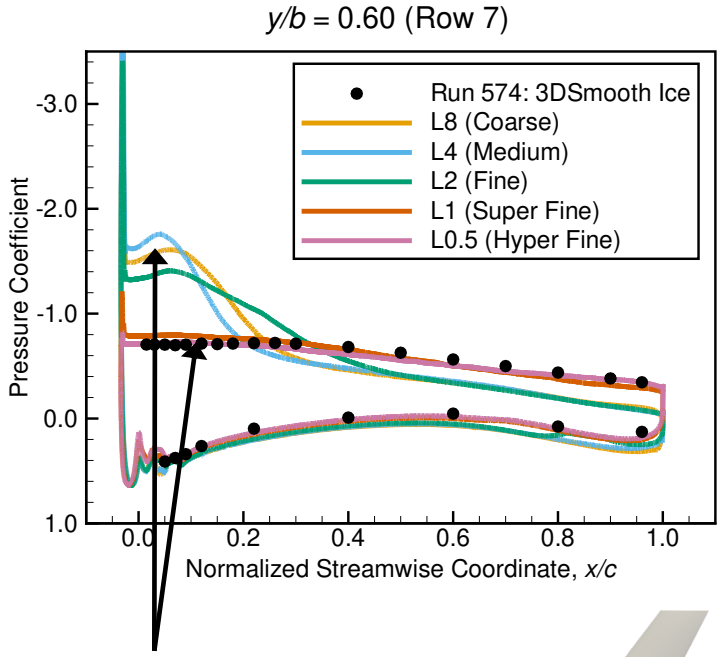
3DSmooth Ice: Aerodynamic loads ($\alpha = 8.458°$)

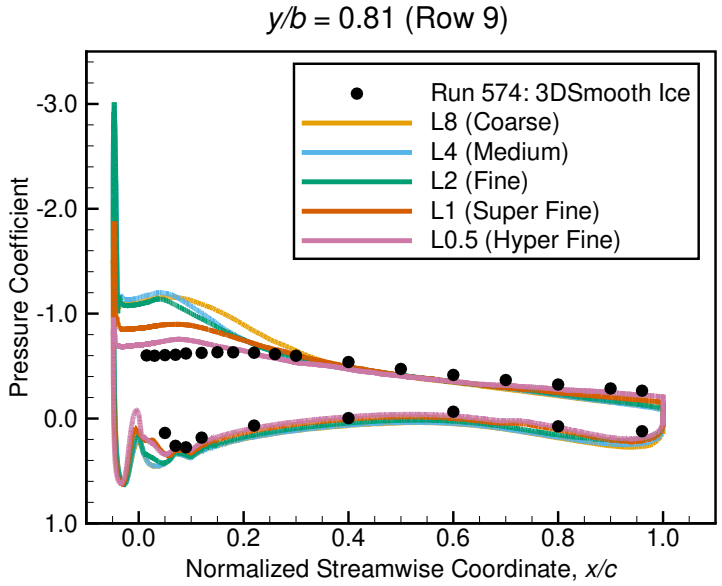


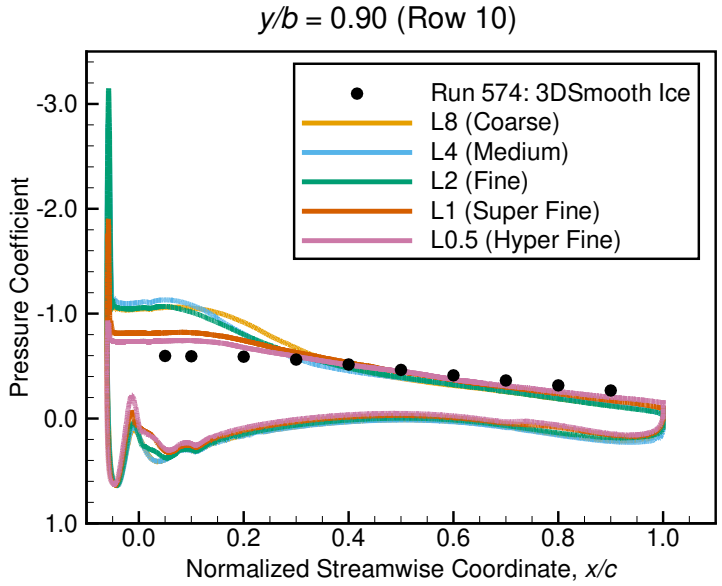
Configuration	Mesh	$\lvert\Delta C_L\rvert \times 10^{-2}$	$\lvert\Delta C_M\rvert \times 10^{-3}$	$\lvert\Delta C_D\rvert \times 10^{-4}$
3DHiFi Ice	L2 (Fine)	0.71	14.37	65.39
3DSmooth Ice	L2 (Fine)	3.35	27.85	255.73
	L1 (Super Fine)	2.87	13.95	86.13
	L0.5 (Hyper Fine)	1.72	0.02	27.11

- For smooth ice, error magnitudes of loads on L2 (Fine) mesh significantly larger than those on comparable L2 (Fine) mesh for high-fidelity ice
- Only on L0.5 (Hyper Fine) mesh are smooth ice error reduced below maximum errors observed for high-fidelity ice across all angles
- All these simulations used Musker-type wall model applied to wing and ice

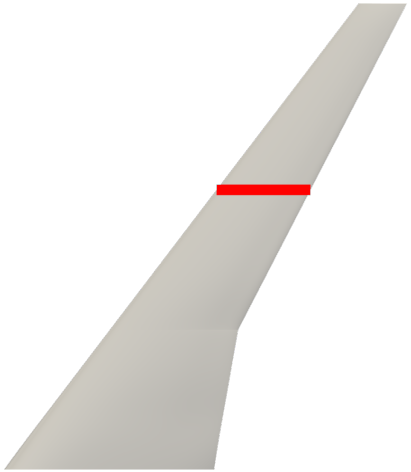
3DSmooth Ice: Pressure profiles require further refinement for similar accuracy ($\alpha = 8.458°$)



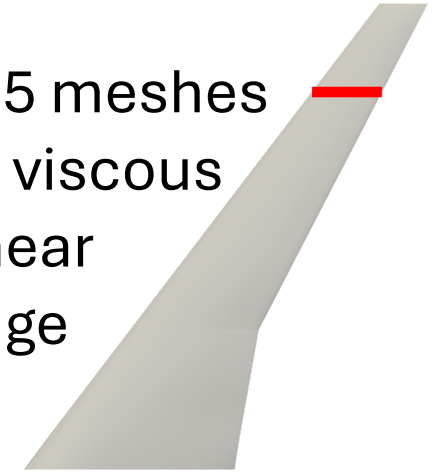


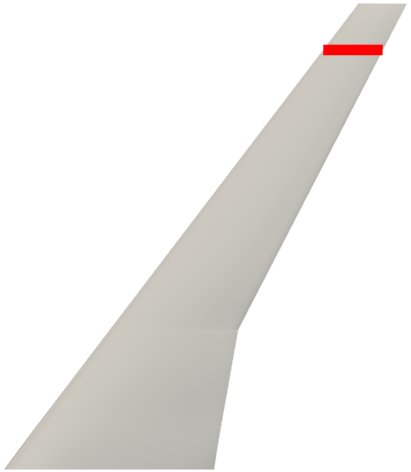


Family #1:
{L8, L4, L2}
Family #2:
{L1, L0.5}

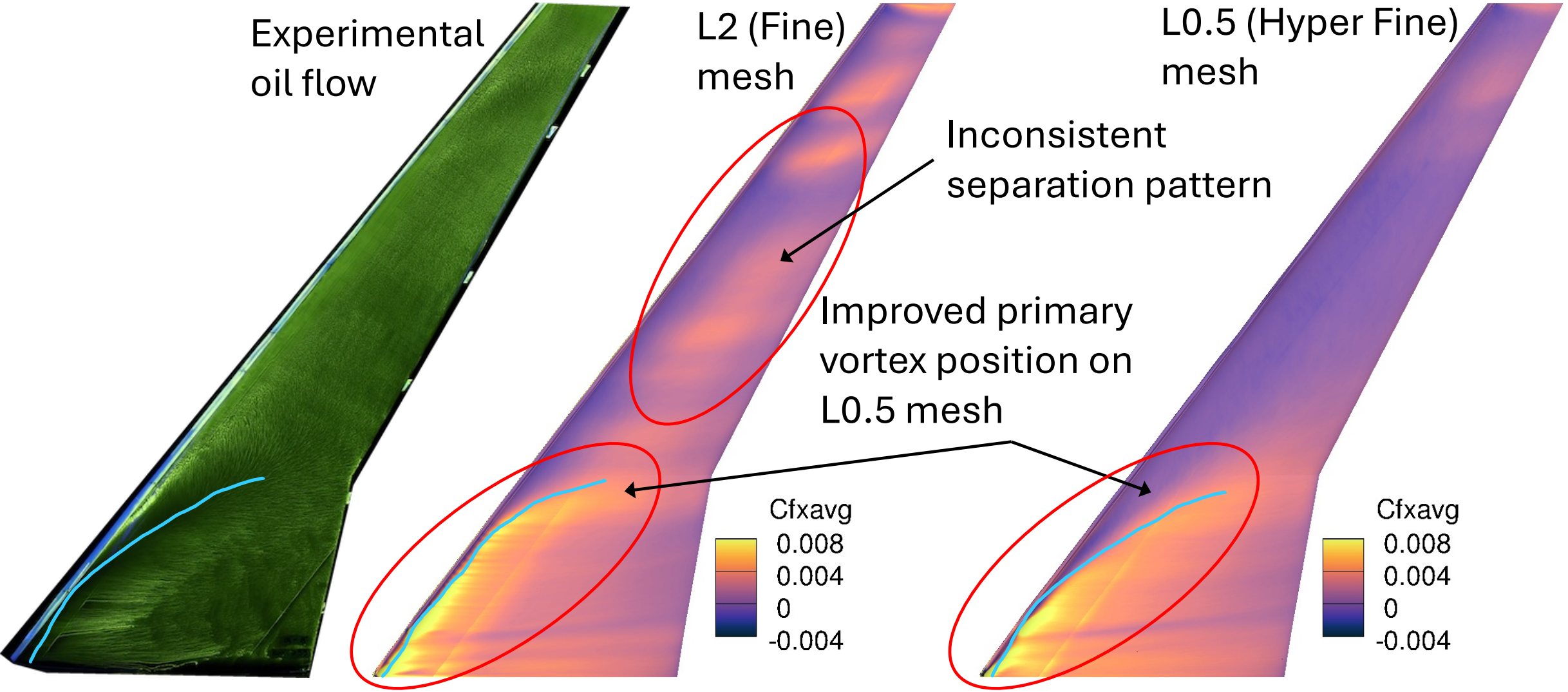


L1 and L0.5 meshes have y^+ in viscous sublayer near leading edge



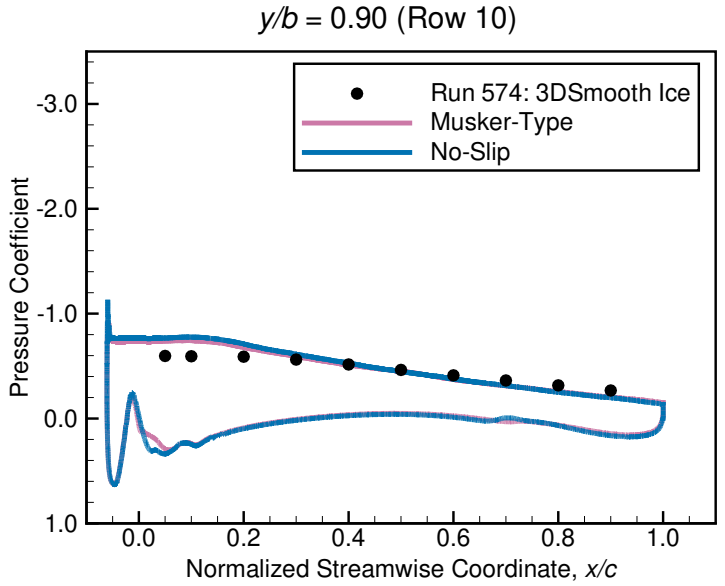


3DSmooth Ice: Time-averaged skin-friction contours ($\alpha = 8.458°$)

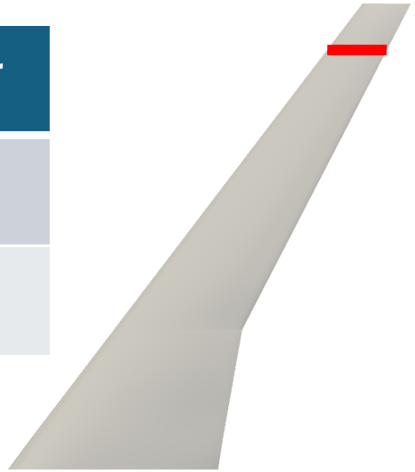


3DSmooth Ice: Similar performance between boundary conditions on L0.5 mesh ($\alpha = 8.458°$)

- Bornhoft et al. (2025) applied no-slip BC **to smooth ice and region aft of ice** based on oil flow on 1.2 billion control volume mesh
- Mimic strategy by applying no-slip BC **to smooth ice**
- Similar performance between BC types observed, likely because L0.5 y^+ values within viscous sublayer where Musker-type BC reduces to linear velocity profile

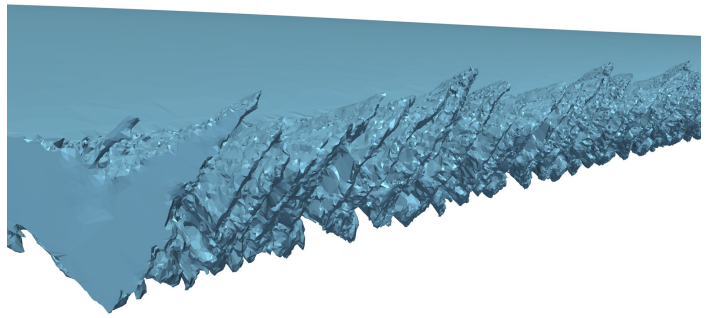


BC	$\lvert\Delta C_L\rvert \times 10^{-2}$	$\lvert\Delta C_M\rvert \times 10^{-3}$	$\lvert\Delta C_D\rvert \times 10^{-4}$
Musker-type	1.72	0.01	27.11
No-slip	2.32	7.23	44.69



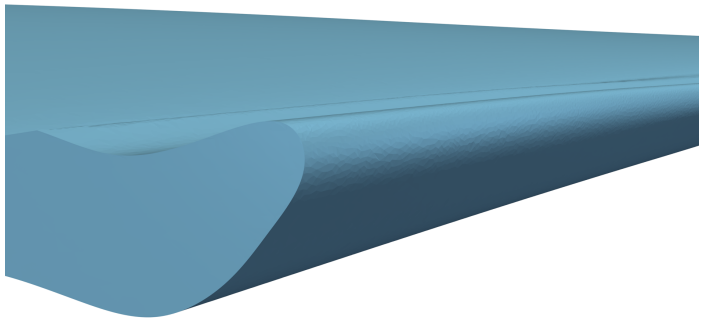
The smooth ice simulation paradox

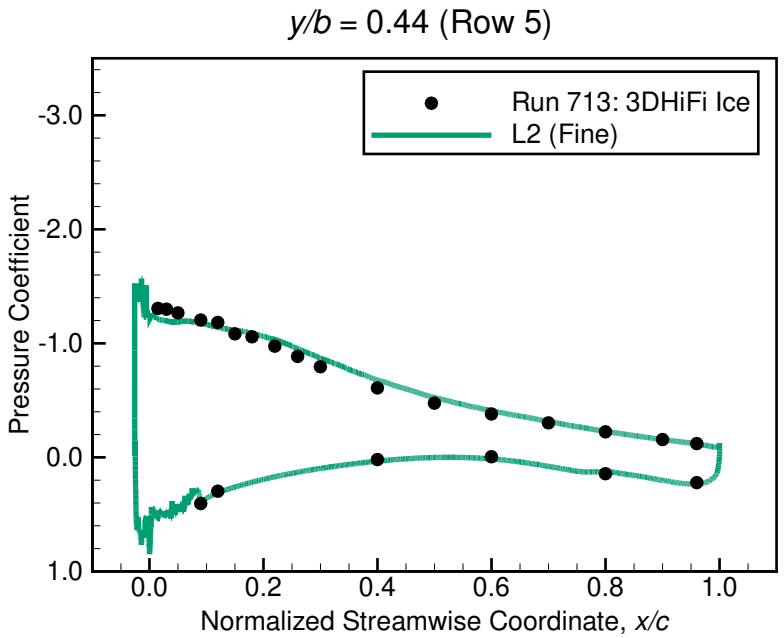
High-fidelity ice at 8.423°

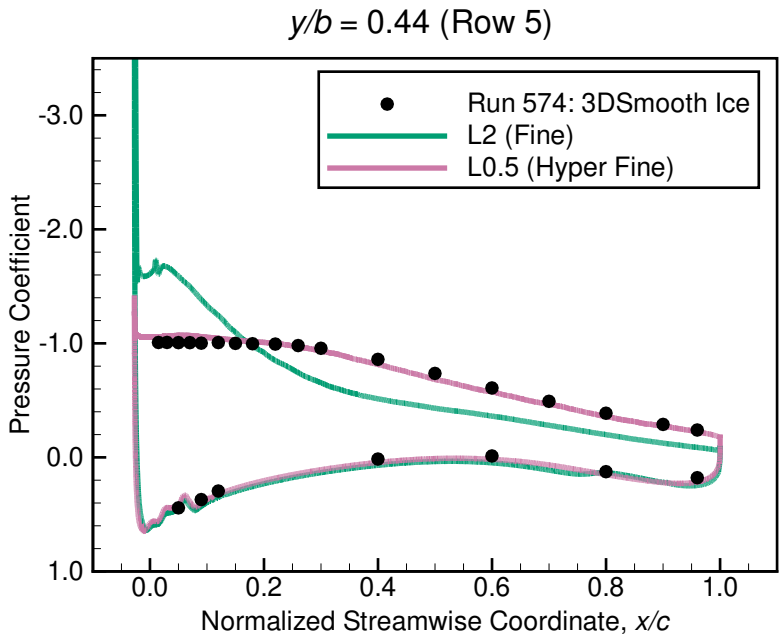


- Despite simpler geometry, smooth ice more challenging to simulate due to lack of resolved turbulence near the leading edge
- L2 mesh for high-fidelity ice gives similar accuracy compared to L0.5 mesh for smooth ice

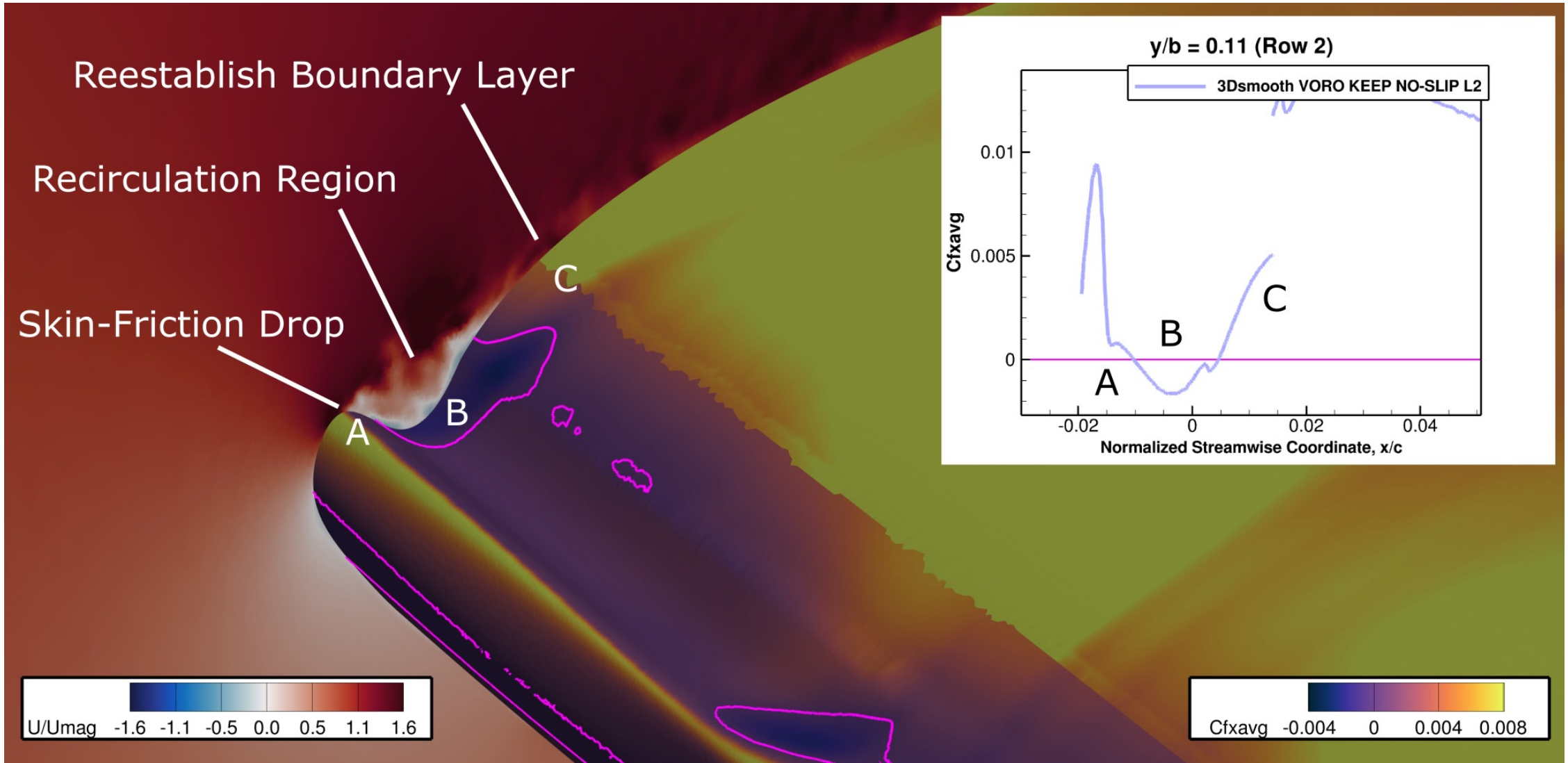
Smooth ice at 8.458°



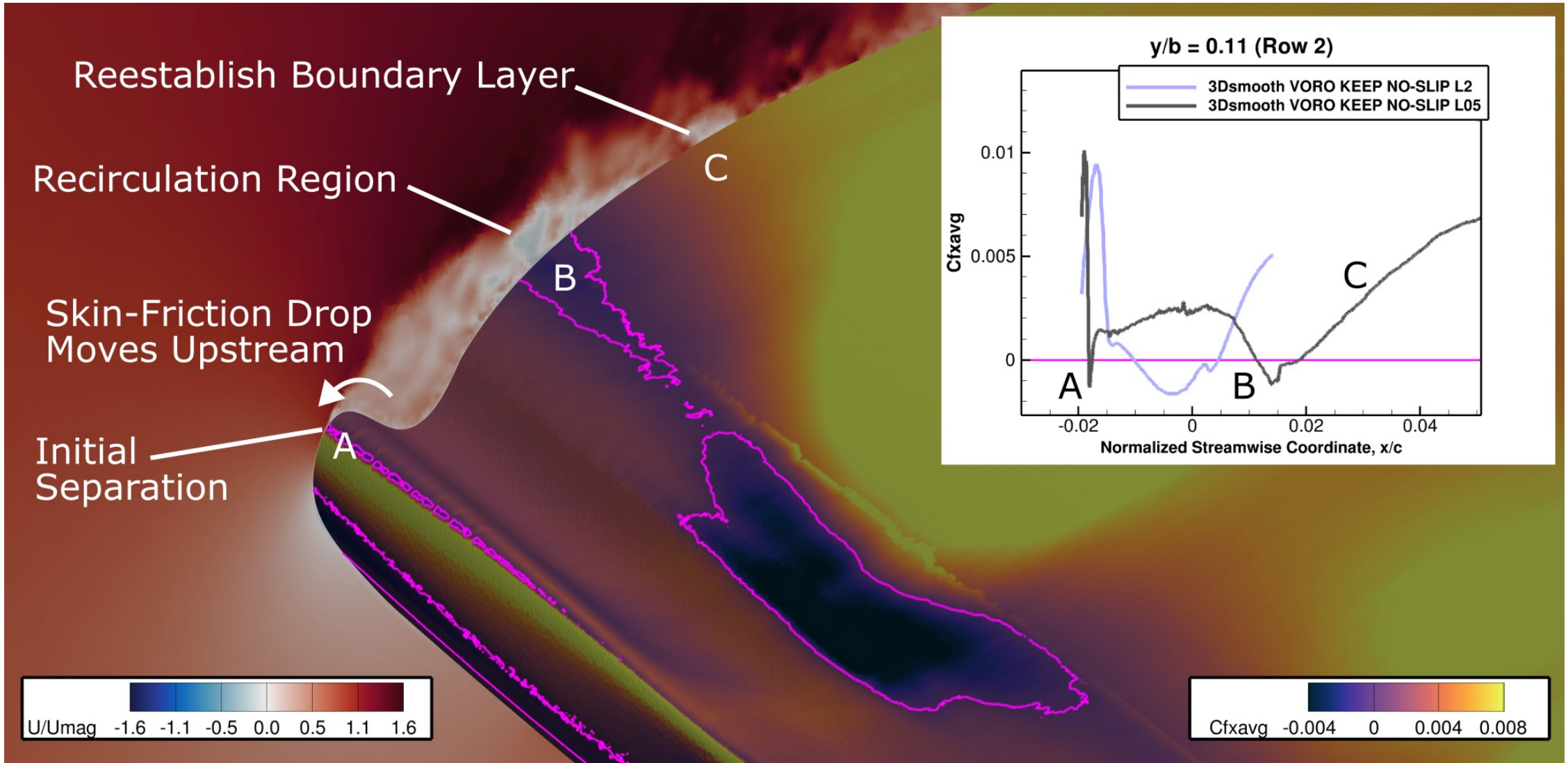




3DSmooth Ice: Flow topology near leading edge on L2 (Fine) mesh ($\alpha = 8.458°$)

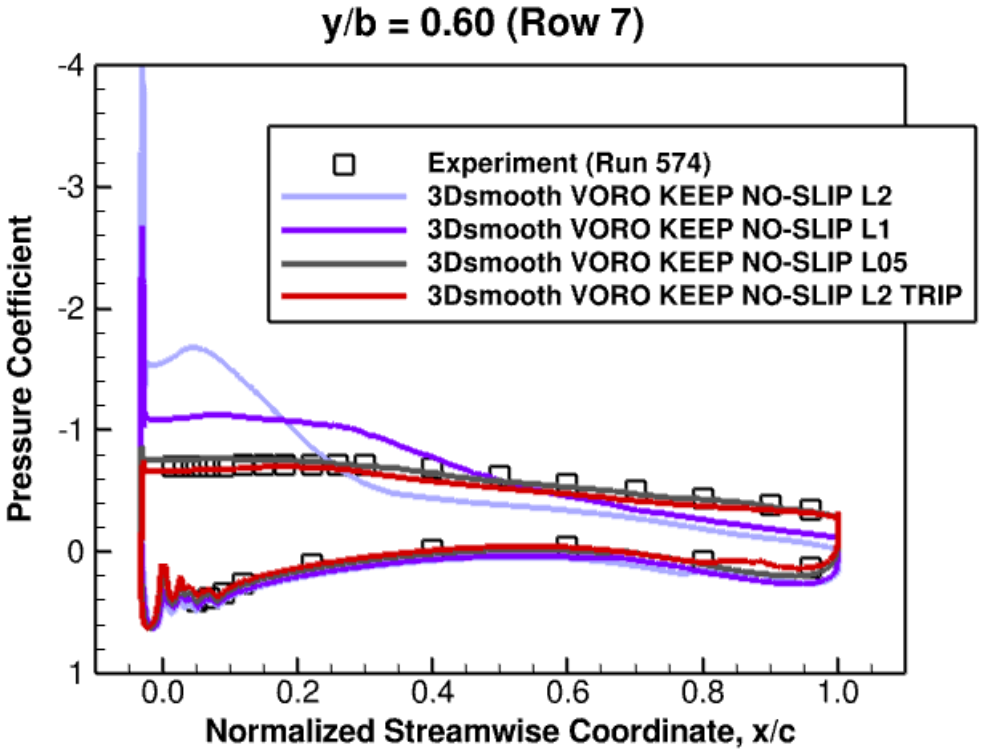


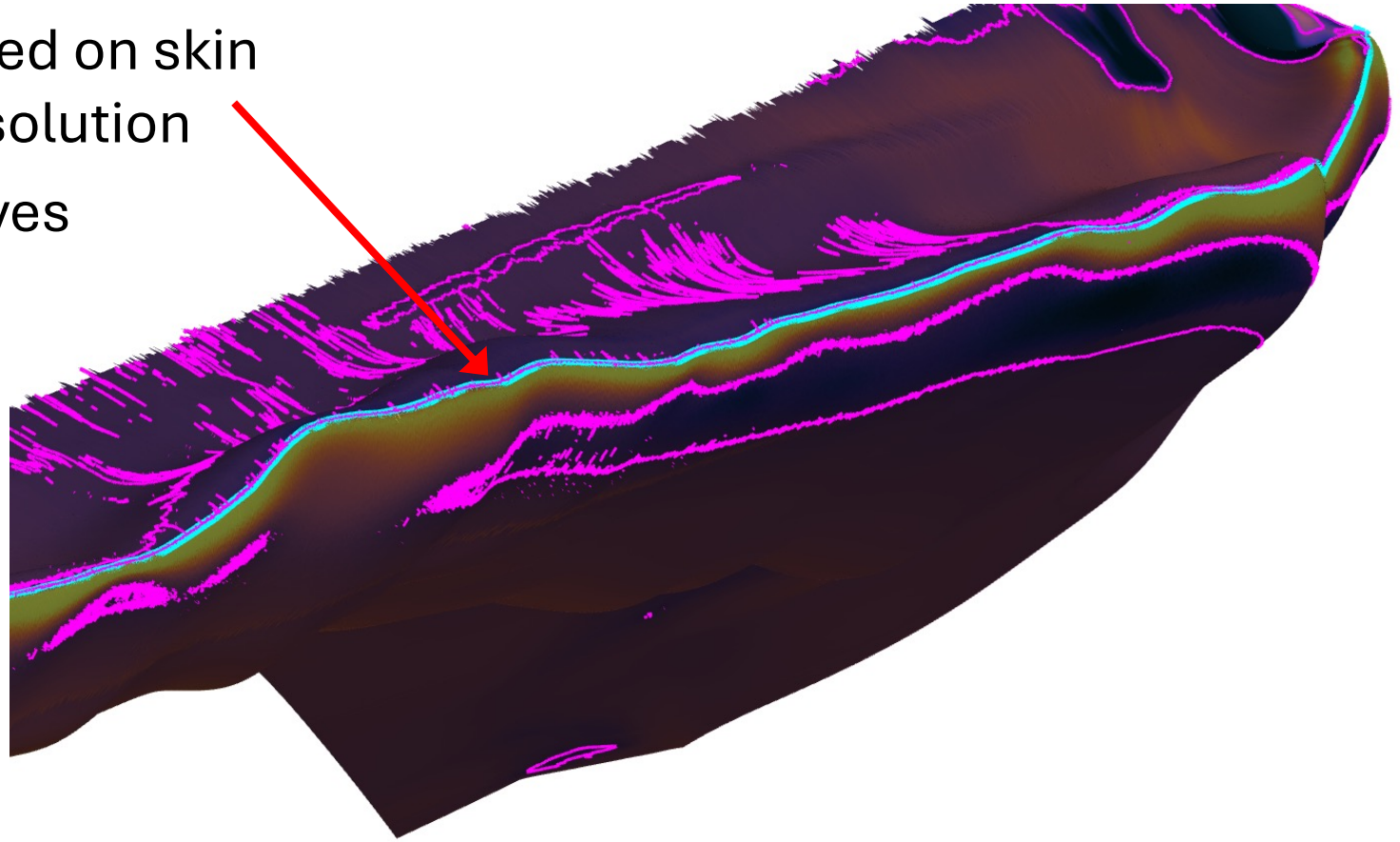
3DSmooth Ice: Flow topology near leading edge changes on L0.5 (Hyper Fine) mesh ($\alpha = 8.458°$)

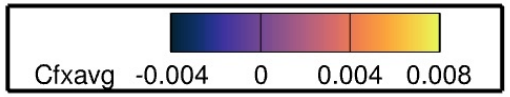


3DSmooth Ice: Use tripping to reproduce L0.5 flow on L2 mesh ($\alpha = 8.458°$)

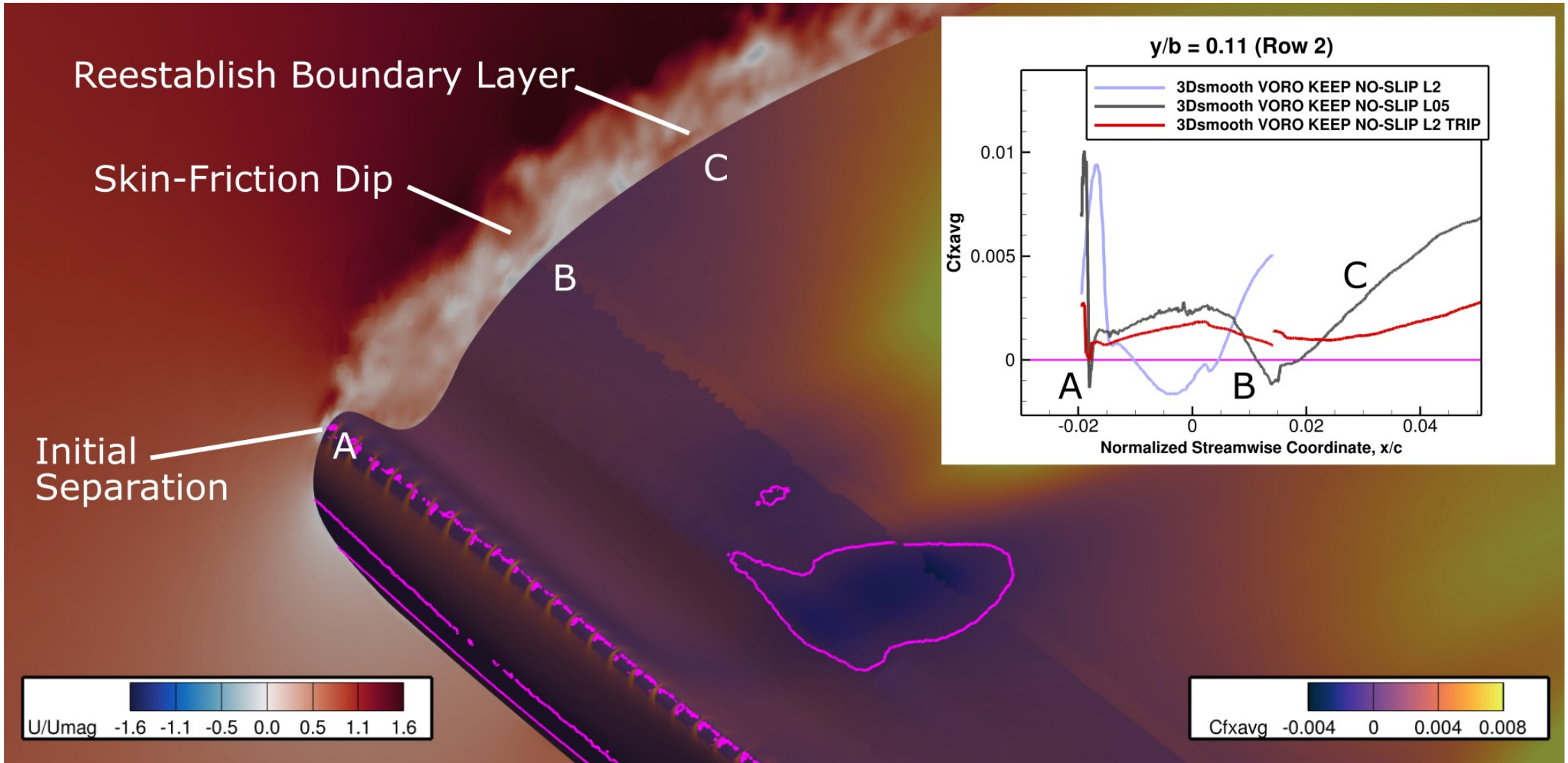
- Trip line shown in light blue based on skin friction contours of L0.5 mesh solution
- Flow solution drastically improves





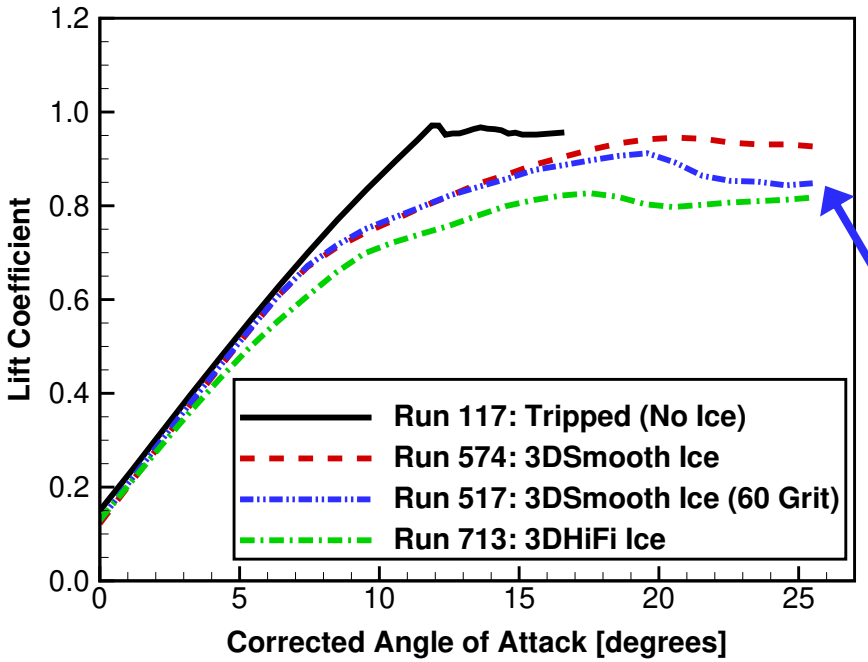


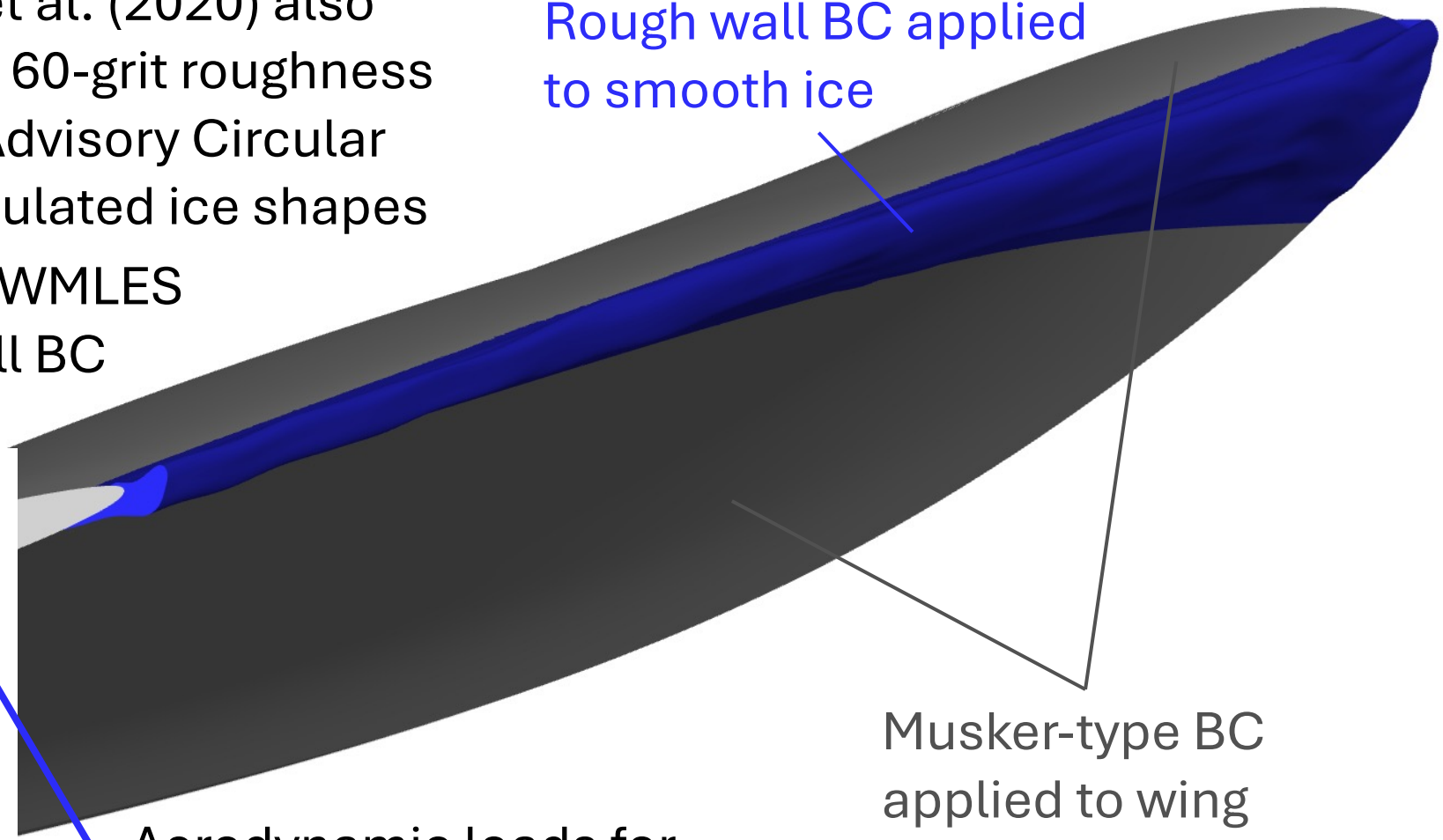
3DSmooth Ice: Flow topology on L2 with tripping comparable to L0.5 mesh ($\alpha = 8.458°$)



3DSmooth Ice with Grit: Rough wall BC

- Experiments by Broeren et al. (2020) also included smooth ice with 60-grit roughness results informed by FAA Advisory Circular 25-25A guidelines for simulated ice shapes
- Trigger turbulence within WMLES through simple rough-wall BC





Aerodynamic loads for smooth ice with grit closer to high-fidelity ice

3DSmooth Ice with Grit: Simple rough wall model to promote onset of turbulence

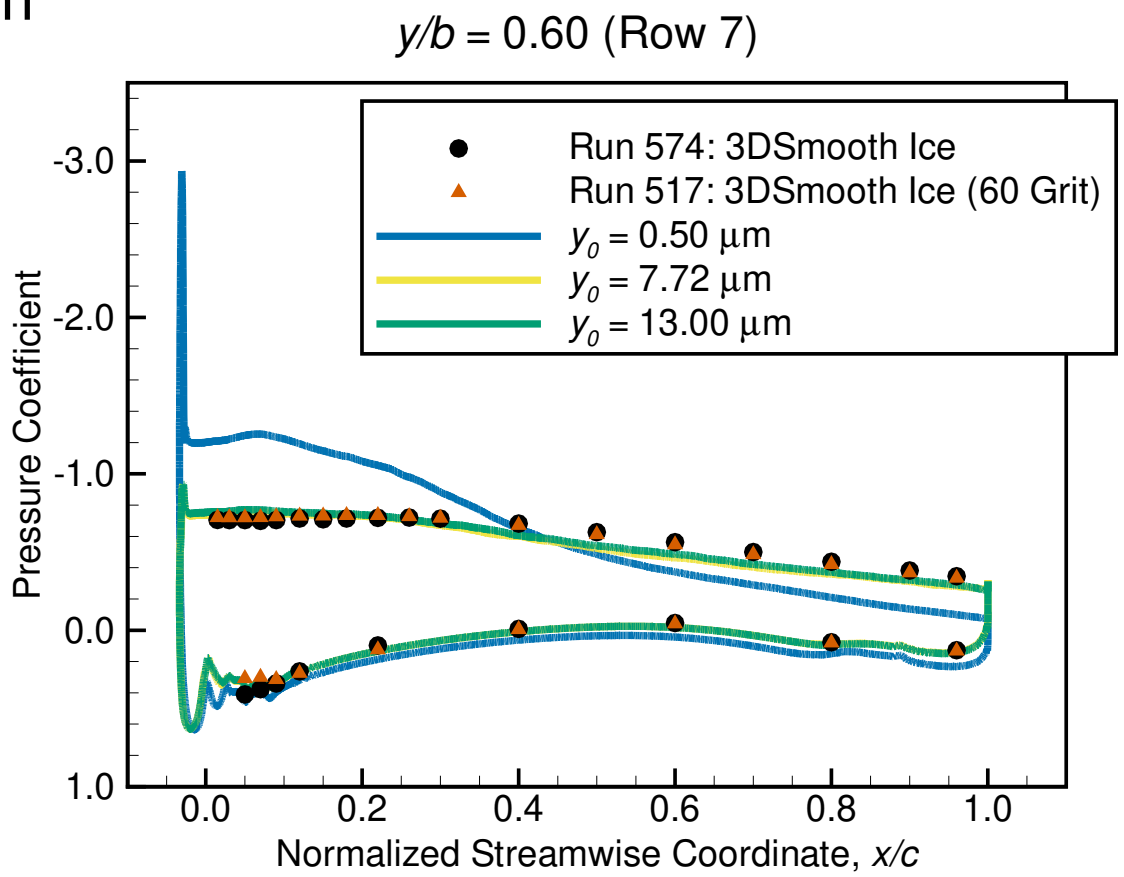
L2 (Fine) mesh

- For rough-wall BC, obtain wall shear stress from rough-wall law (Flack 2010):

$$u_\tau = 0.41 u_{||} \left[\ln \left(\frac{y_{\text{match}} - d}{y_0} \right) \right]^{-1}$$

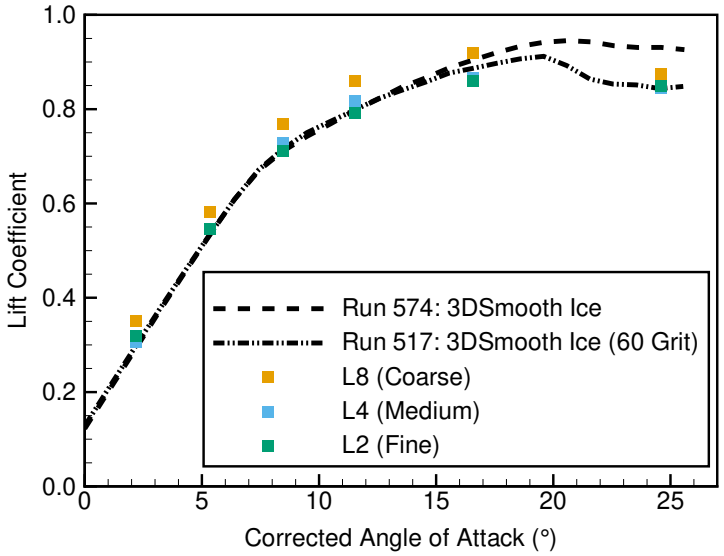
- Select equivalent sand-grain roughness using experimental 60-grit surface roughness and a simple geometric conversion (Adams 2012)
- Investigate three values of y_0:

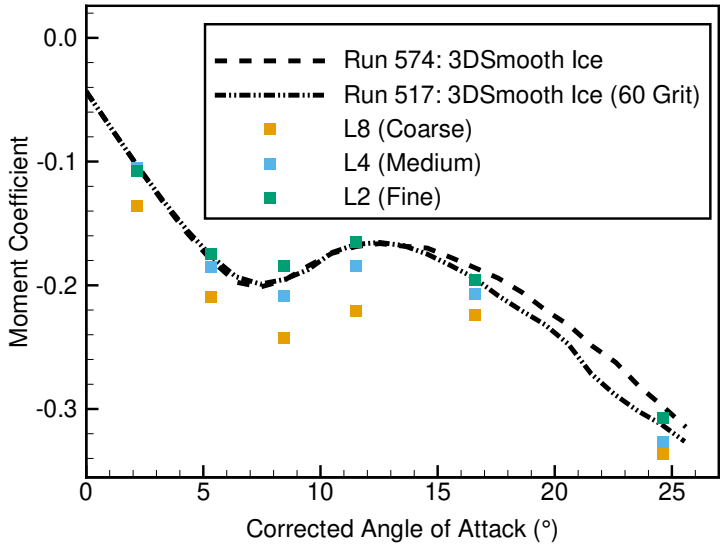
$$y_0 = 0.04 k_{s,\text{Ra}} \approx 0.5\ \mu\text{m}$$
$$y_0 = k_{s,\text{RMS}} = 7.72\ \mu\text{m}$$
$$y_0 = k_{s,\text{Ra}} = 13.00\ \mu\text{m}$$

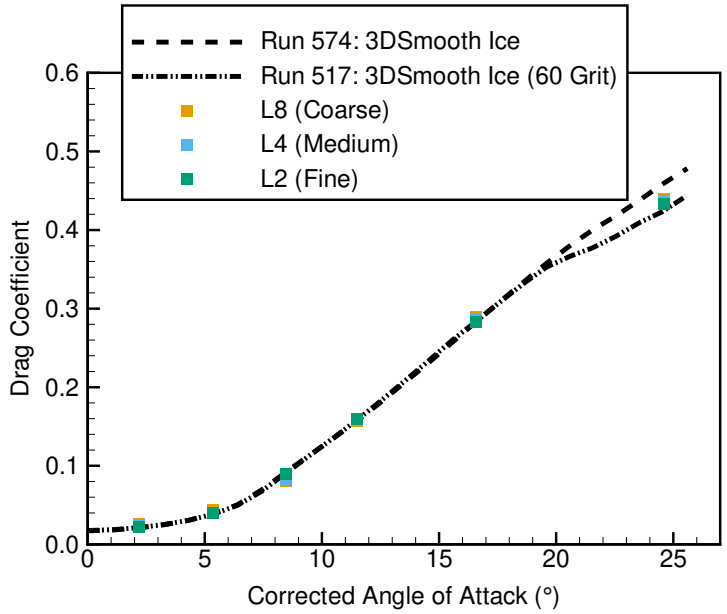


Choose $y_0 = 13.00\ \mu\text{m}$ to simulate additional angles and mesh resolutions

3DSmooth Ice with Grit: Aerodynamic loads

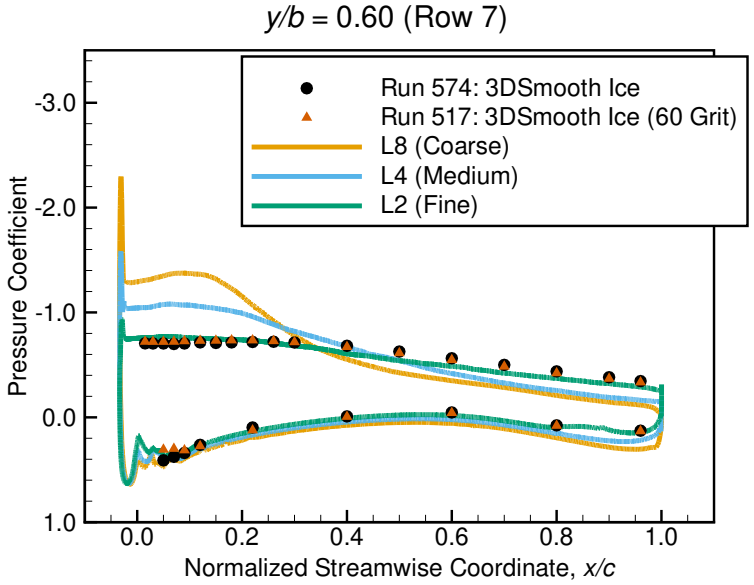


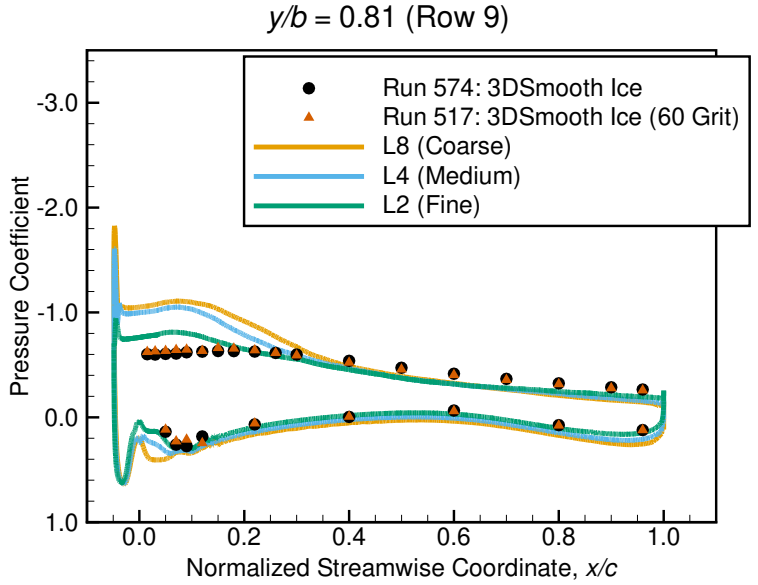


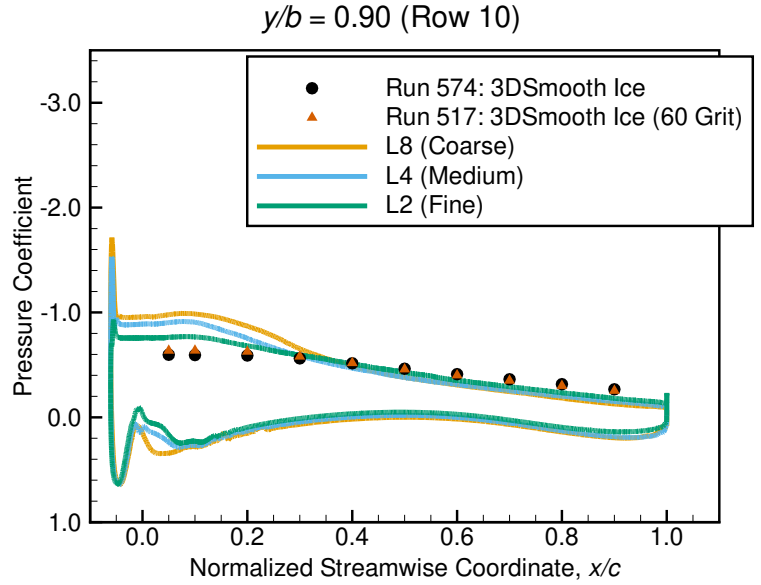


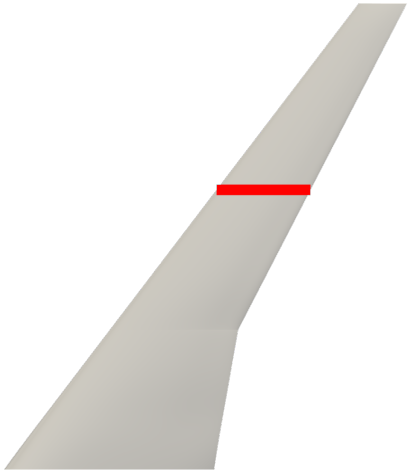
- At higher angles, numerical results converge toward experiment with grit roughness
- On L2 (Fine) mesh, errors in integrated coefficients comparable to high-fidelity ice on L2 (Fine) mesh
- Incorporating roughness for smooth ice achieves comparable accuracy relative to high-fidelity ice on similar mesh resolutions

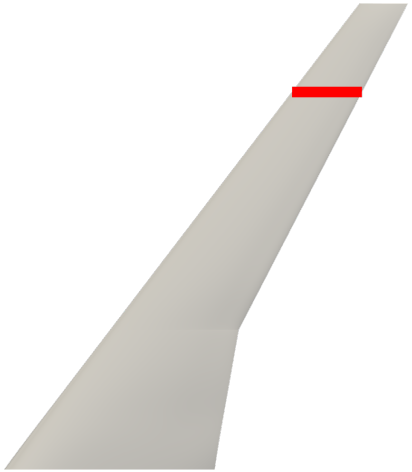
3DSmooth Ice with Grit: Pressure profiles converge toward experiment ($\alpha = 8.458°$)

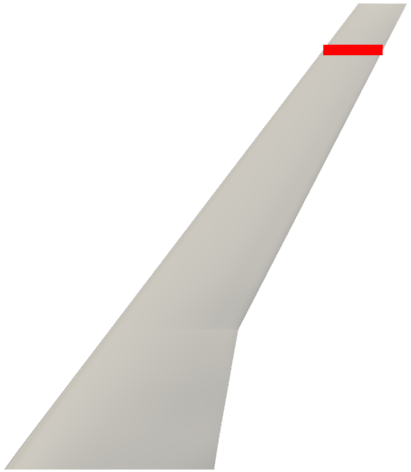




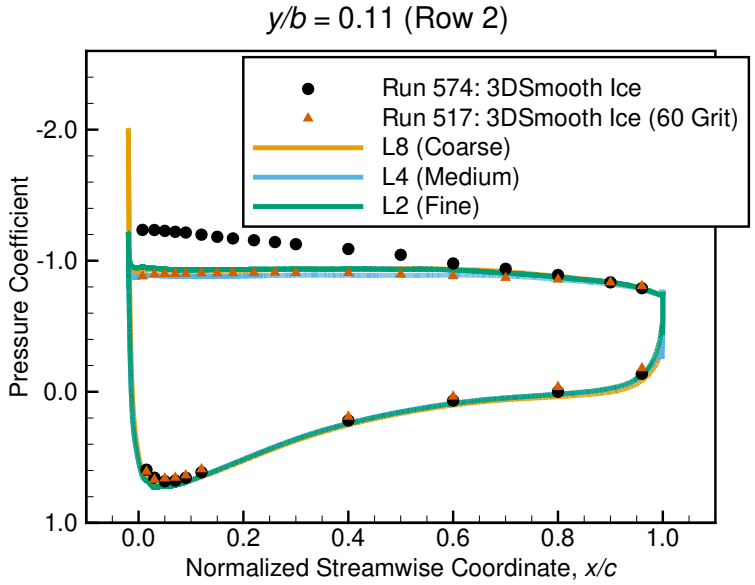


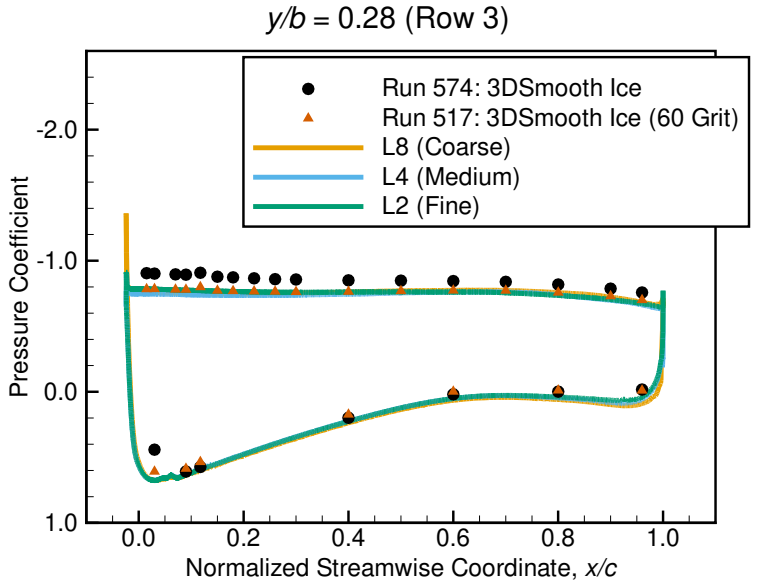


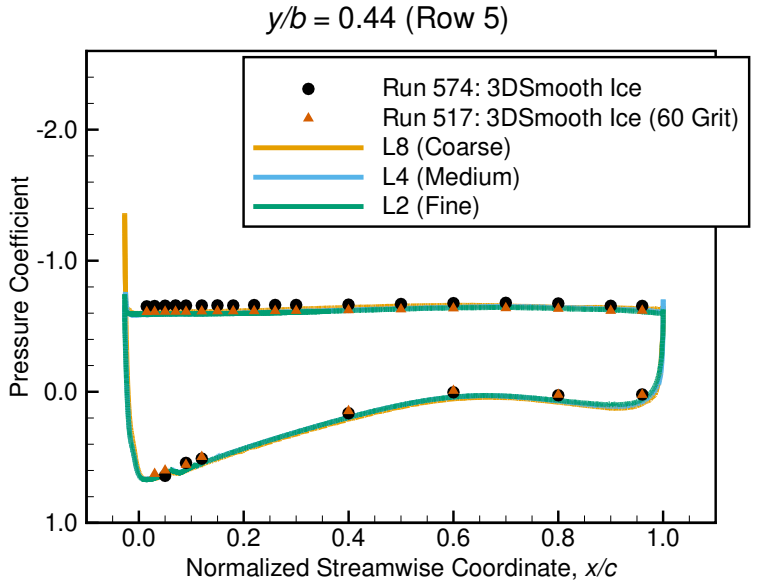


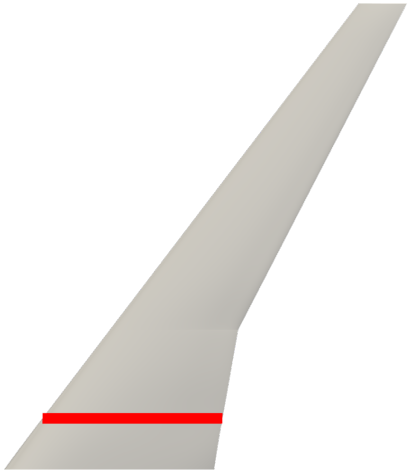


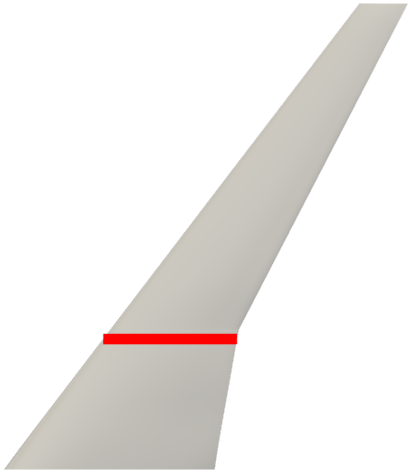
3DSmooth Ice with Grit: Pressures at higher angles converge toward grit results ($\alpha = 24.600°$)

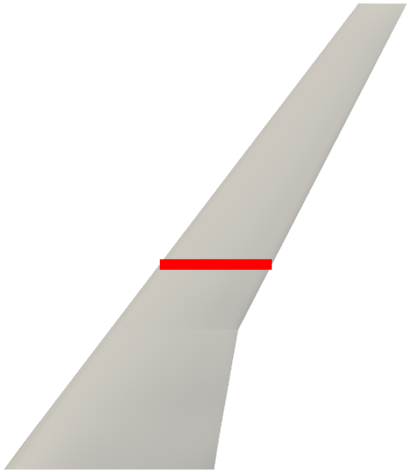




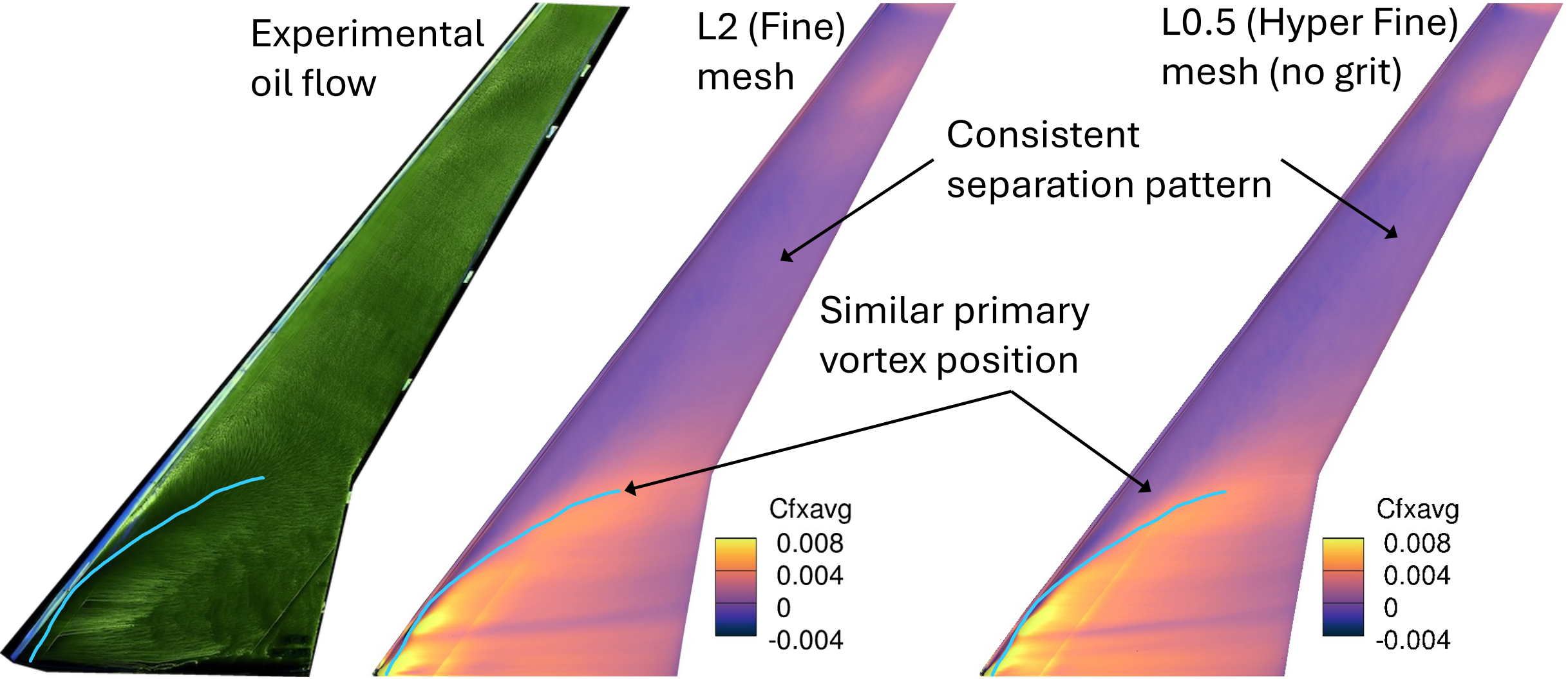








3DSmooth with Grit: Skin-friction flow topology with grit matches L0.5 ($\alpha = 8.458°$)



Clean wing simulations

- Simulate clean wing **without ice** as baseline to assess performance degradation due to icing
- Based on common practice for WMLES, along with experience with smooth ice, expected to require **boundary layer tripping** to achieve realistic turbulent flow

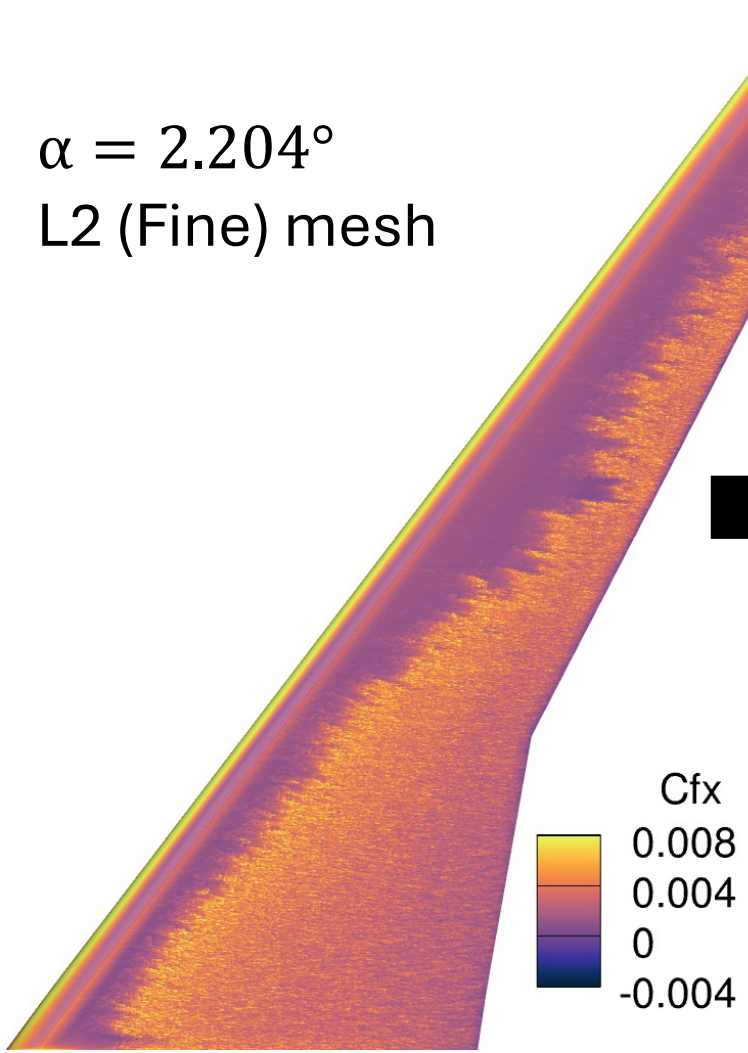
Tripped (No Ice): Tripping important for WMLES without ice

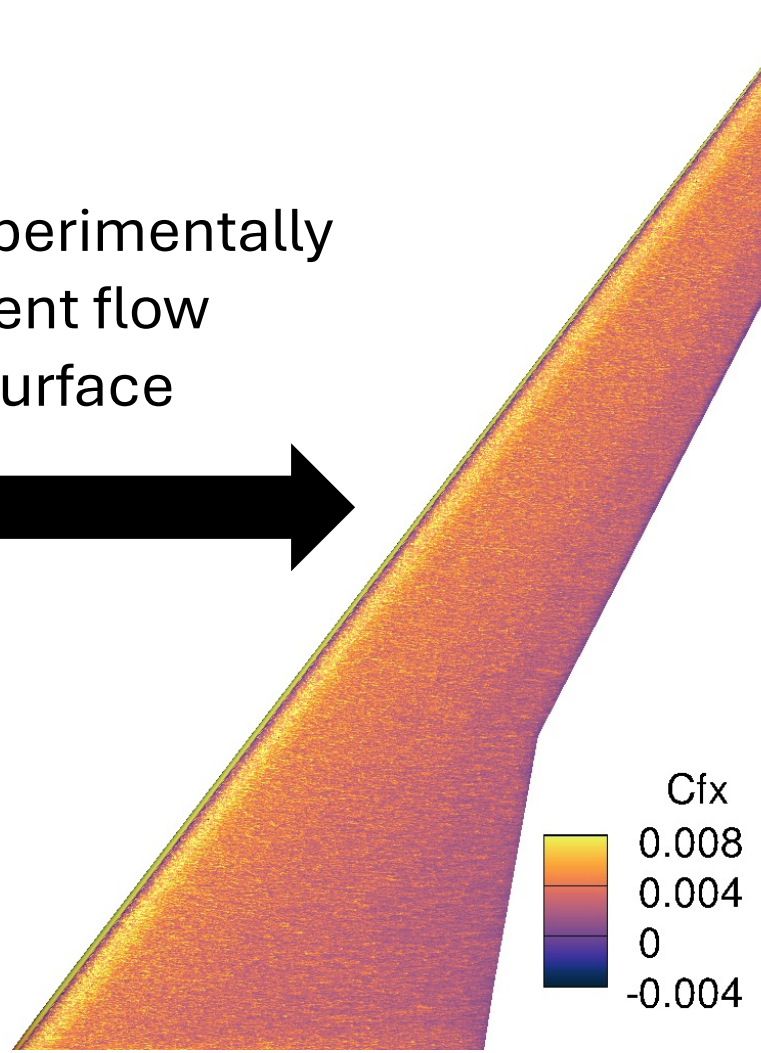
No tripping

Tripping

$\alpha = 2.204°$
L2 (Fine) mesh

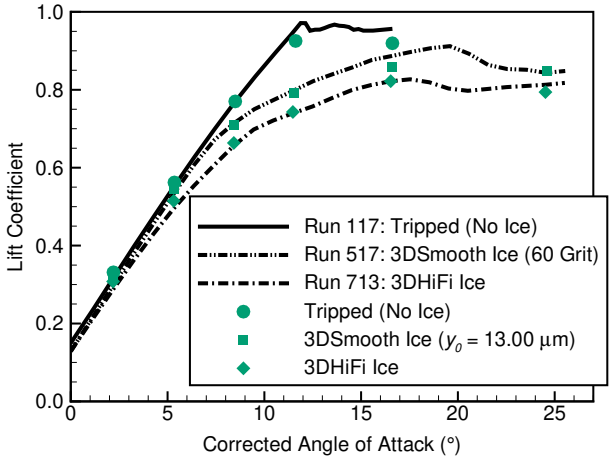
Tripping yields experimentally consistent turbulent flow over wing upper surface

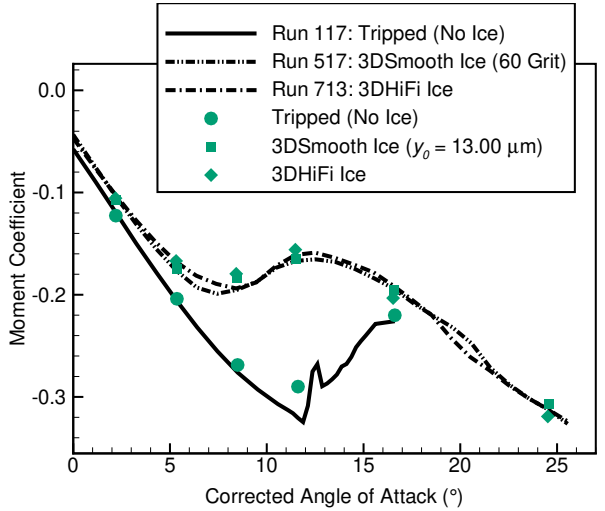


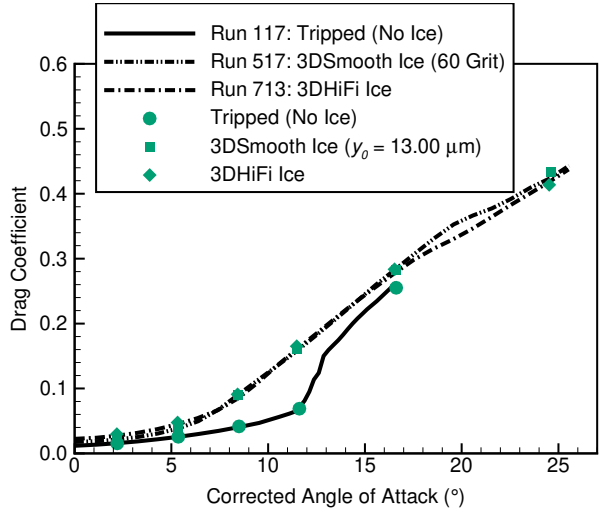


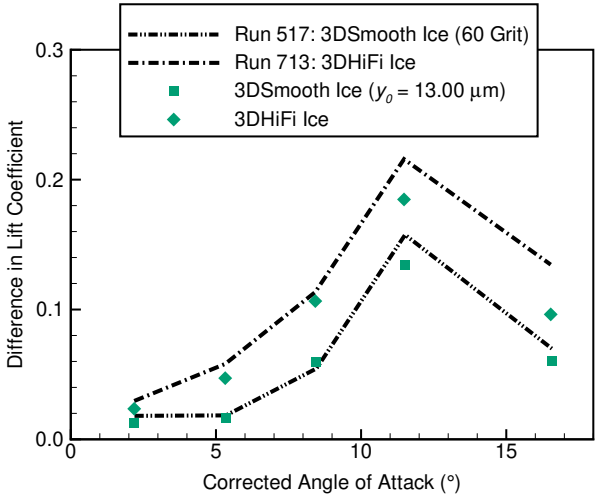
Tripped (No Ice): Loads and deltas

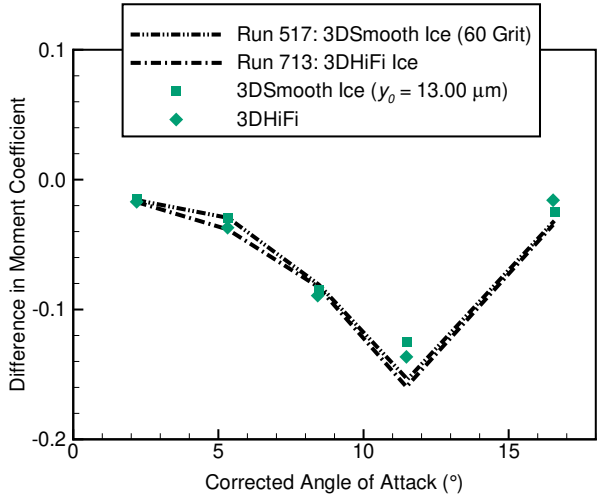
- Comparable accuracy achieved at similar L2 (Fine) mesh resolutions
- Performance deltas between tripped and iced wings capture experimental trends

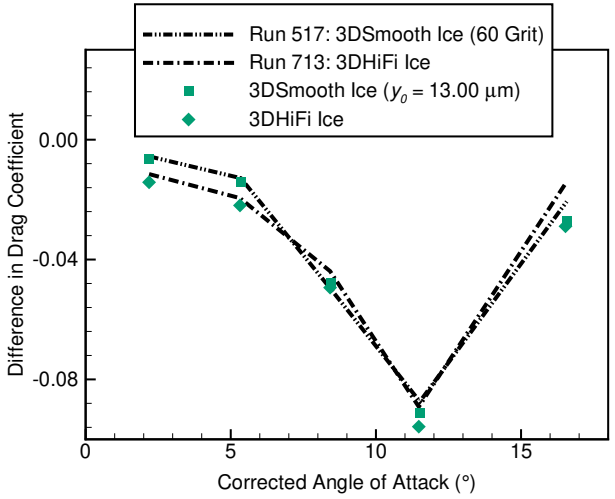












Computational cost

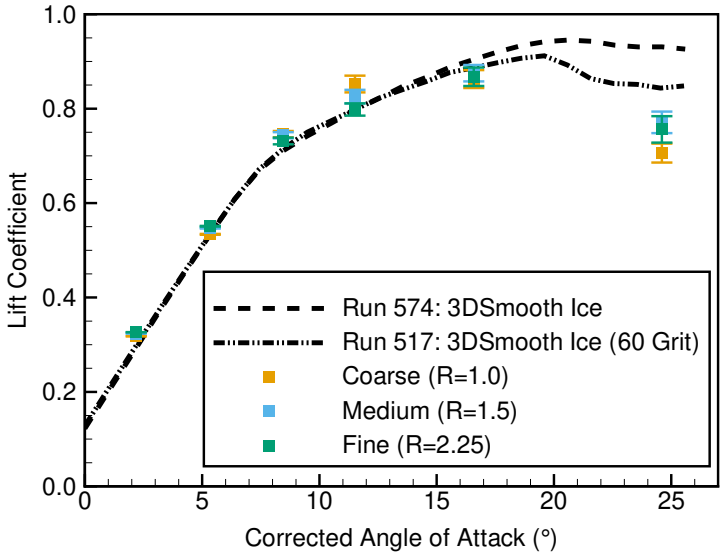
- Energy consumption across mesh levels increases by roughly a factor of 8 (cell count increases by factor of 4 and time step decreases by factor of 2)
- Smooth ice with roughness reduces computational cost by factor of 30 (estimated factor of 64 improvement if L0.5 were constructed as an in-family mesh)

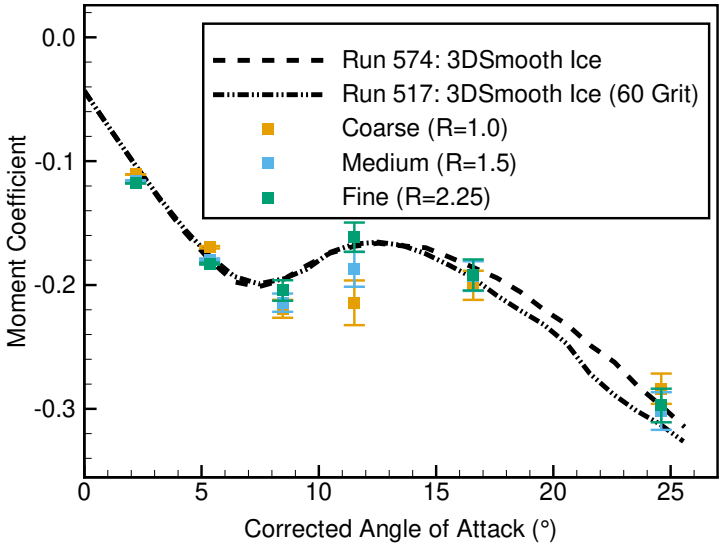
Configuration	Mesh	Cells (M)	Averaged Δt ($\times 10^{-7}$ s)	# GPUs	Wall-clock time per CTU (h)	Energy usage per CTU (MJ)
3DSmooth Ice	L8	6	7.36	1	0.16	0.57
	L4	21	3.54	4	0.28	4.08
	L2	90	1.67	20	0.54	38.89
	L1	445	0.87	50	2.24	403.53
	L0.5	470	0.35	50	5.78	1040.25
3DSmooth Ice with Grit	L8	6	7.60	1	0.15	0.54
	L4	21	3.70	4	0.29	4.16
	L2	90	1.85	20	0.49	35.19

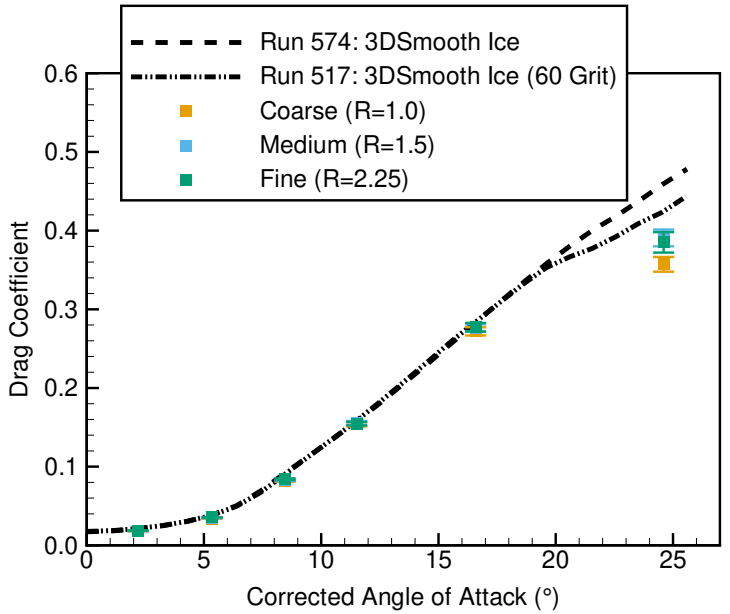
1 CTU = mean aerodynamic chord / freestream velocity magnitude

LAVA hybrid RANS-LES model applied to smooth ice and clean wing

- From WMLES, smooth ice simulations benefited from introduction of resolved turbulence
- Use LAVA HRLES model that assumes turbulent boundary layer avoids need to explicitly promote turbulence
- For smooth ice on best practice (Medium) mesh, LAVA HRLES takes **59.32 MJ Energy usage per CTU** (factor of **1.69** increase relative to rough-wall WMLES on L2)



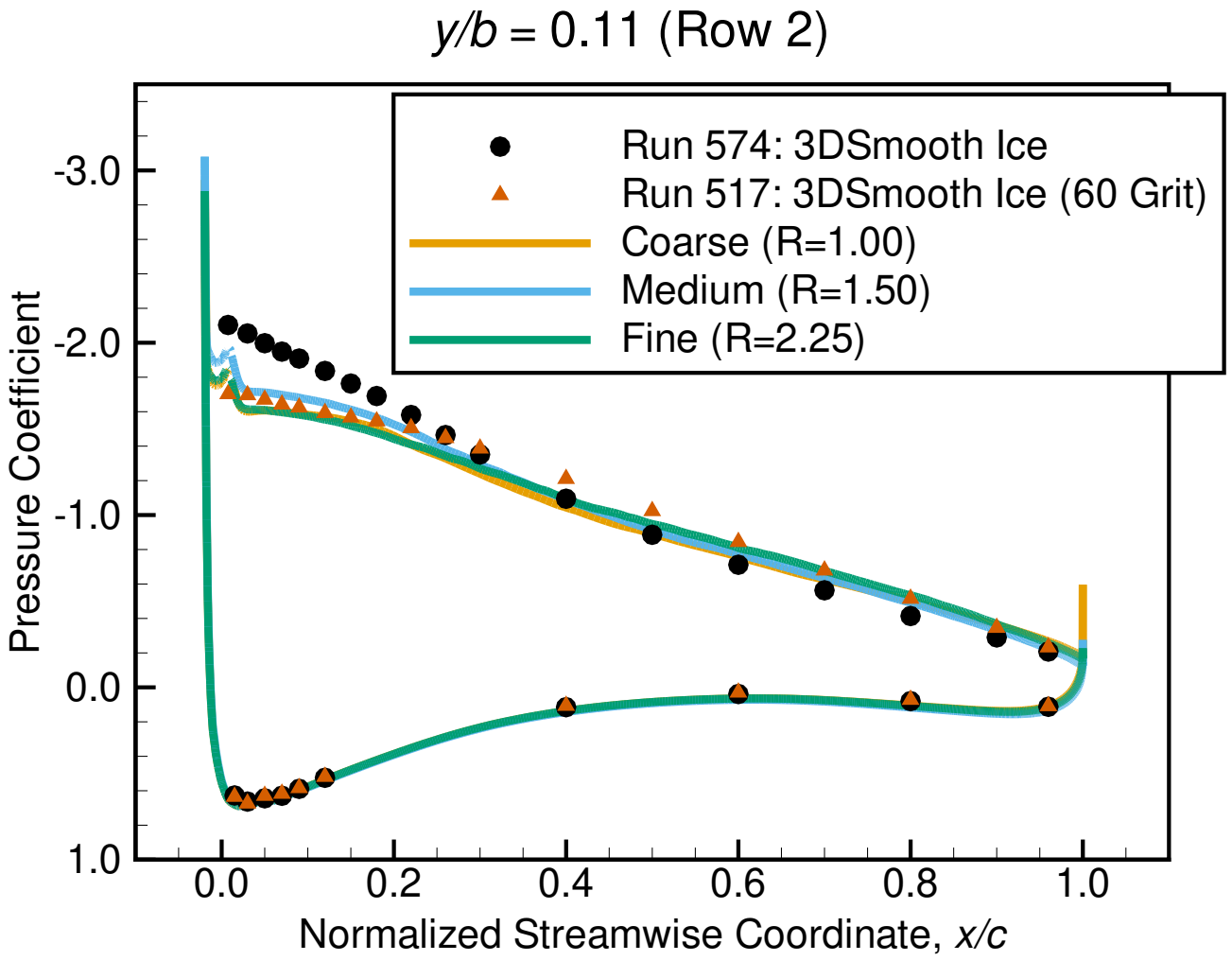




3DSmooth Ice with LAVA HRLES: Pressure profiles converge toward experiment with grit

$\alpha = 16.583°$

No special tripping or rough-wall boundary condition used for LAVA HRLES



Outline

- ❑ **Why** do we study aircraft icing?
- ❑ **What** are the challenges for iced aerodynamics predictions with WMLES?
- ❑ **How** do we solve these challenges?
  - ❑ Aerodynamics predictions of an iced swept wing with LAVA
- ❑ **Summary** and **future** work

Summary and future work

- High-fidelity ice, smooth ice, and clean wing cases simulated
- Adding roughness to smooth ice reduced WMLES cost by 30x while maintaining accuracy (estimate 64x improvement for in-family L0.5 mesh)
- LAVA HRLES model competitive with WMLES in cost and accuracy for smooth iced wing and clean wing

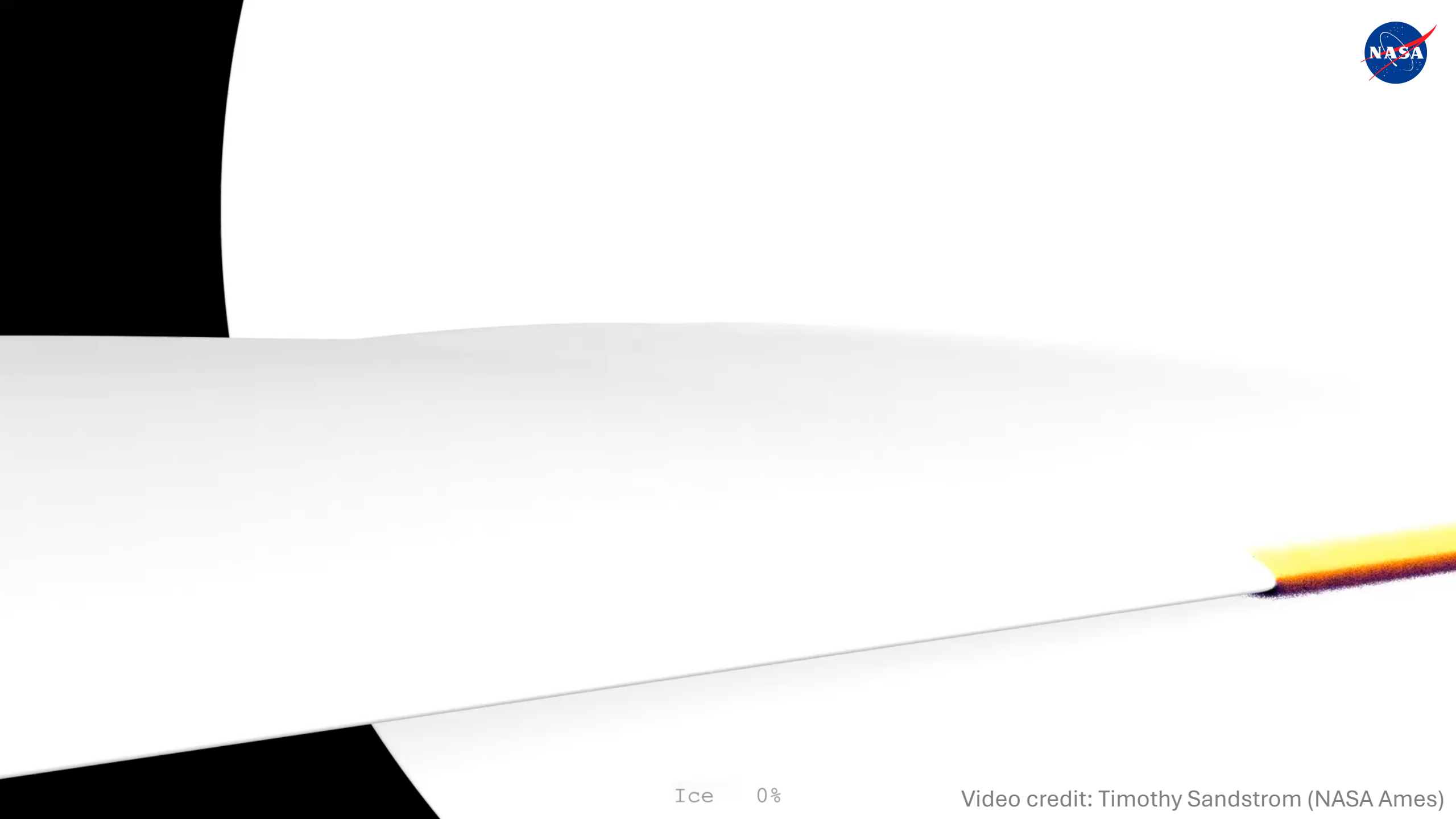
Keys to Successful Iced Aerodynamics Predictions

1) High-fidelity ice: standard mesh refinement gives accurate results at reasonable costs
2) Smooth ice: resolved turbulence near leading edge needed to get accurate results at comparable mesh resolutions and computational costs
3) Clean wing: similar introduction of turbulence needed to predict accurate performance deltas

Future work will examine iced high-lift CRM and transonic truss-braced wing designs

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Video credit: Timothy Sandstrom (NASA Ames)

Questions?

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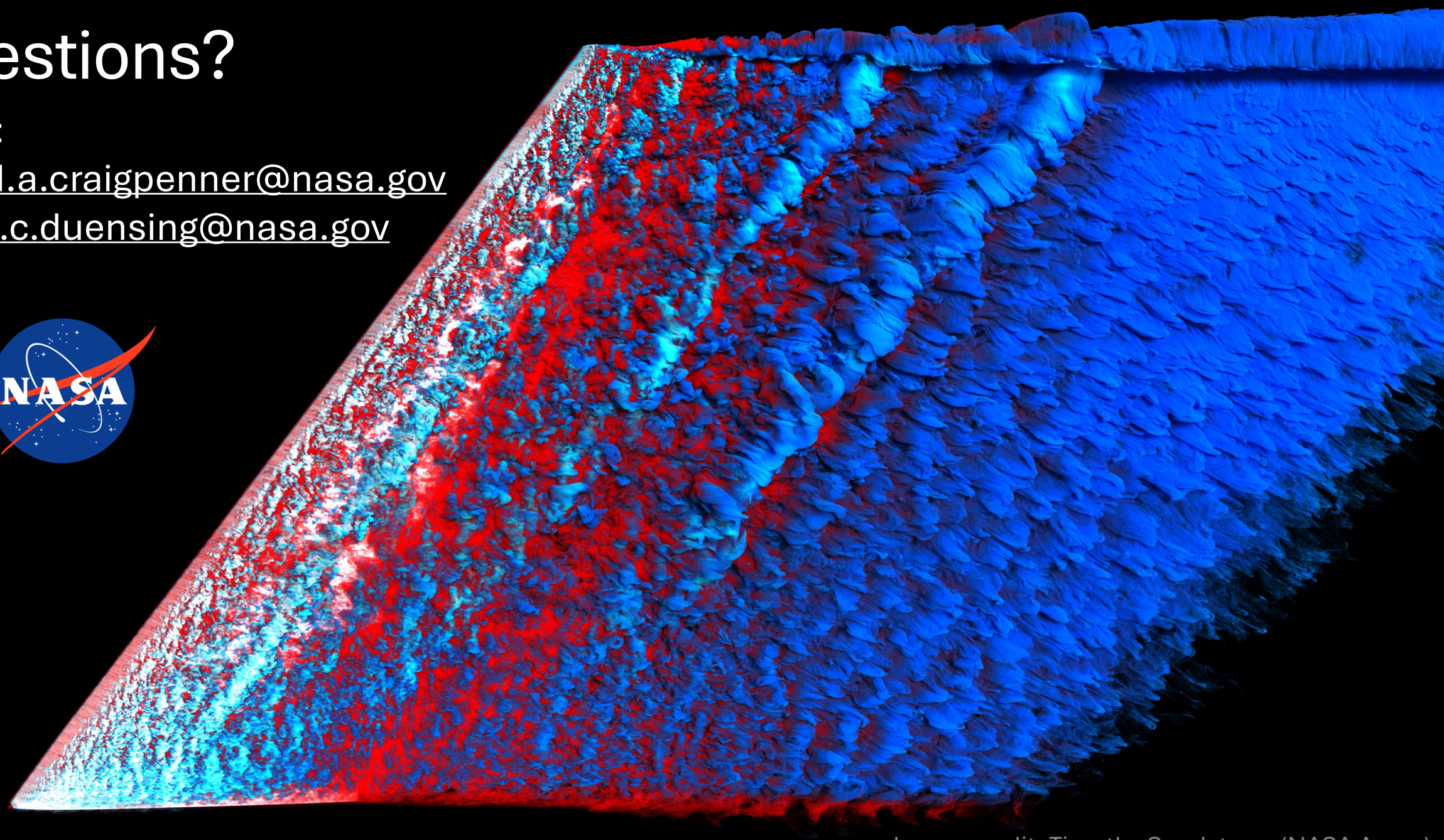


Image credit: Timothy Sandstrom (NASA Ames)