

GlennICE Contributions to the 3rd Ice Prediction Workshop

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GlennICE Contributions to the 3rd Ice Prediction Workshop

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Outline

- NACA 0012 Bulk Property Convergence
- NACA 0012 Ice Shape Convergence
- NACA 0012 Temperature Sweep Analysis
- NACA 0012 Lower Horn Investigation
- NACA 0012 Ice Density Evaluation
- ONERAM6 Bulk Property Convergence
- ONERAM6 Ice Shape Convergence
- ONERAM6 Temperature Sweep Roughness Analysis
- Conclusion



Cases Investigated and Provided

Case 1: NACA 0012

- Analyzed both the AE3932 and AE3933 Cases
 - Performed 1, 3, 7, and 15-Bin analyses for all four grid levels
 - Performed surface restarts to analyze temperature change for AE3933

Case 2: ONERAM6

- Performed 1, 3, 7, and 15-Bin analyses for 1 [mm] roughness baseline
 - Performed for all four grid levels
- Performed 7-Bin analyses for all four grid levels
 - 0.5 [mm] roughness
 - 1.5 [mm] roughness
 - Variable roughness
- Solutions Analyzed
 - 50 CFD Solutions
 - 406 Icing Solutions
 - An additional 93 Icing Solutions were analyzed for the presentation



GlennICE Description

- CFD post-processing ice accretion solver being developed at NASA Glenn
- Currently solves for a fully 3D ice accretion in a single shot
- Lagrangian trajectory routine utilizing a provided CFD velocity field
- Leverages the Dormand-Prince method to solve the ODEs with an adaptive time stepping scheme ^[1]
- Impingement computed from a streamtube based per trajectory finite area approach with automatic impingement refinement
- Utilizes the Messinger model to calculate the amount of frozen water on the surface per discrete cell
- Migration of unfrozen water between surface cells occurs based upon surface shear vectors
- After the per element ice shape is solved for, an extrusion of the ice shape is conducted to generate a 3D computational ice shape



Numerical Methodology

Model / Method	NACA0012	ONERAM6
CFD Model	FUN3D v14.3 RANS – Stabilized Finite Element	FUN3D v14.3 RANS – Finite Volume
Turbulence Model	SA-neg-QCR2000	SA-neg-rough
HTC Method	Smooth: Two Isothermal Wall Temperature Rough: Tanh Roughness Enhancement	Smooth: Two Isothermal Wall Temperature Rough: None, Tanh Roughness Enhancement
Droplet Formulation	Lagrangian	Lagrangian
Droplet Drag Model	Salman & Verba (1988) - Sphere	Salman & Verba (1988) - Sphere
SLD Effects	No Splashing Used	No Splashing used
Thermodynamic Model	Messinger	Messinger
Ice Density Model	Variable Freezing Fraction LEWICE Model	680 kg/m ³
Roughness Height	Variable – McClain Model	Constant (0.5, 1, 1.5 [mm]), Variable McClain Model
Geometry Evolution	Prismatoid Extrusion	Prismatoid Extrusion
Ice Accretion Steps	Single-shot with Unsteady Freezing Fraction and Enhancement	Single-shot, Single-shot Unsteady Freezing Fraction and Enhancement



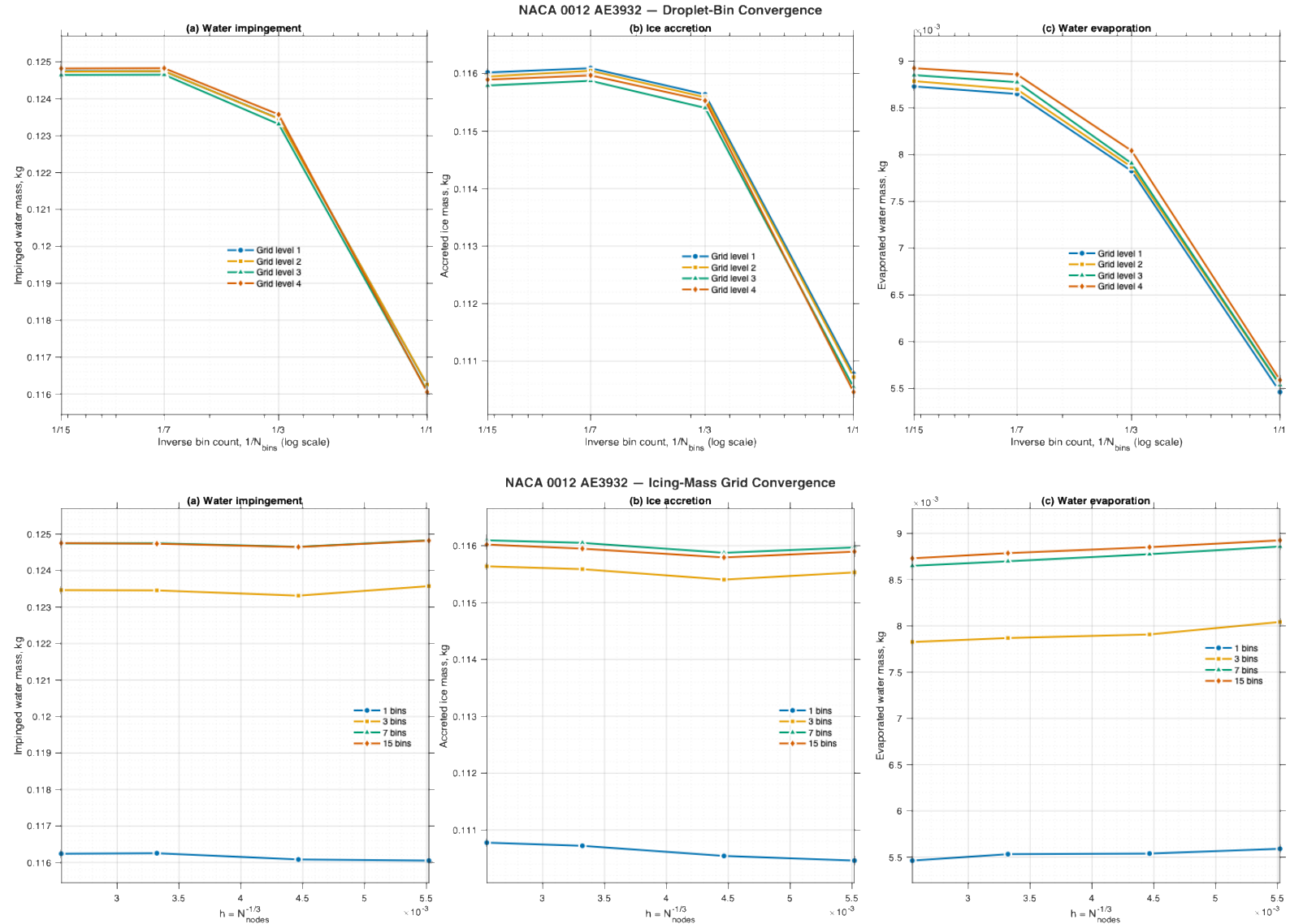
CASE 1: NACA 0012

AE3933, $N_0 = 0.3$ / AE3932, $N_0 = 0.5$



AE3932 Integrated Property Solution Convergence

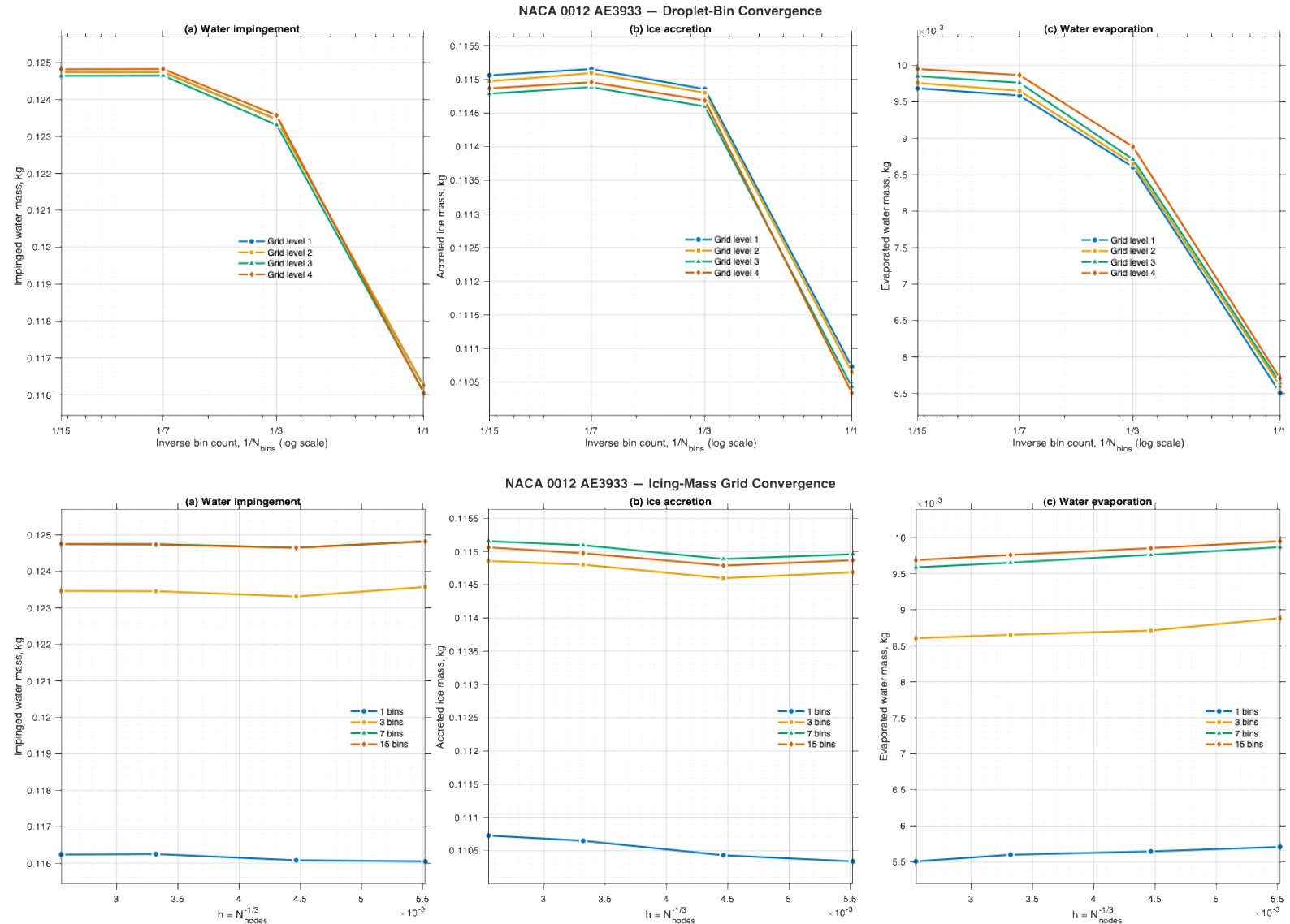
- Integrated impingement converged by L2 solution
- Impingement differences 7-bins and 15-bins are negligible
- Drop in accreted mass between 7-bins and 15-bins
- L4 solution is set apart from expected convergence trends
- Accreted ice trends across grid levels are nonmonotonic while evaporation and impingement are





AE3932 Integrated Property Solution Convergence

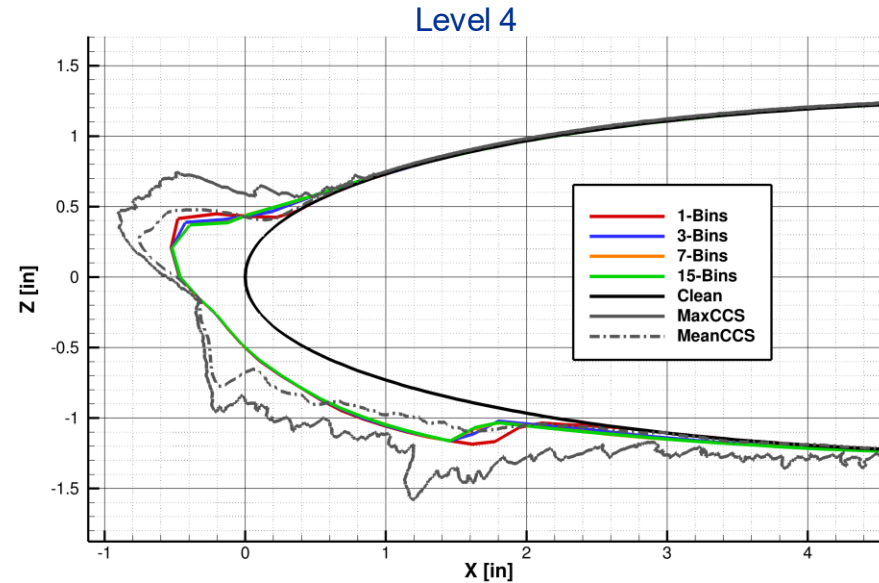
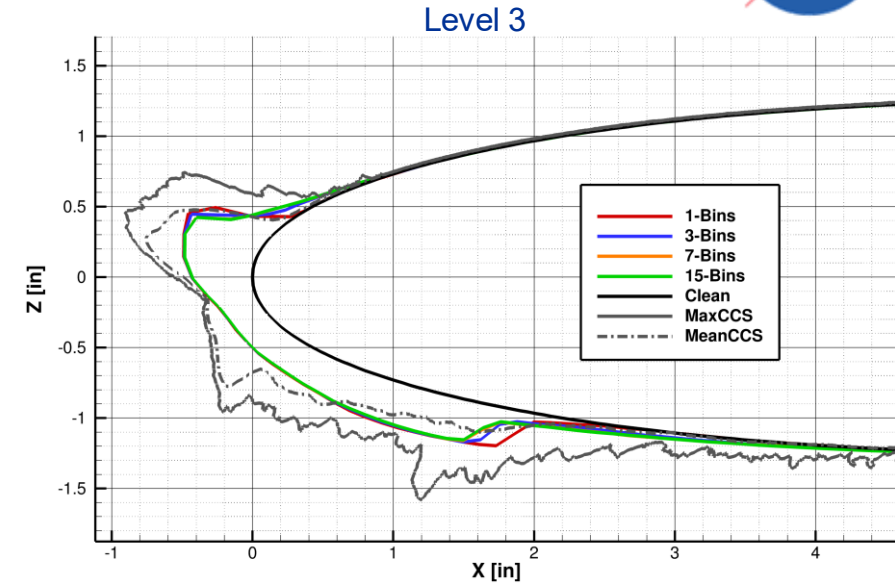
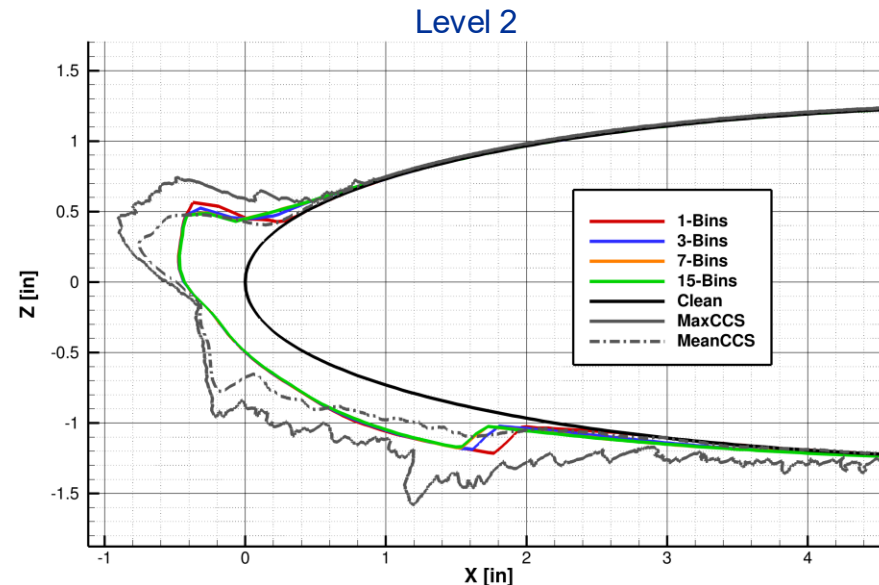
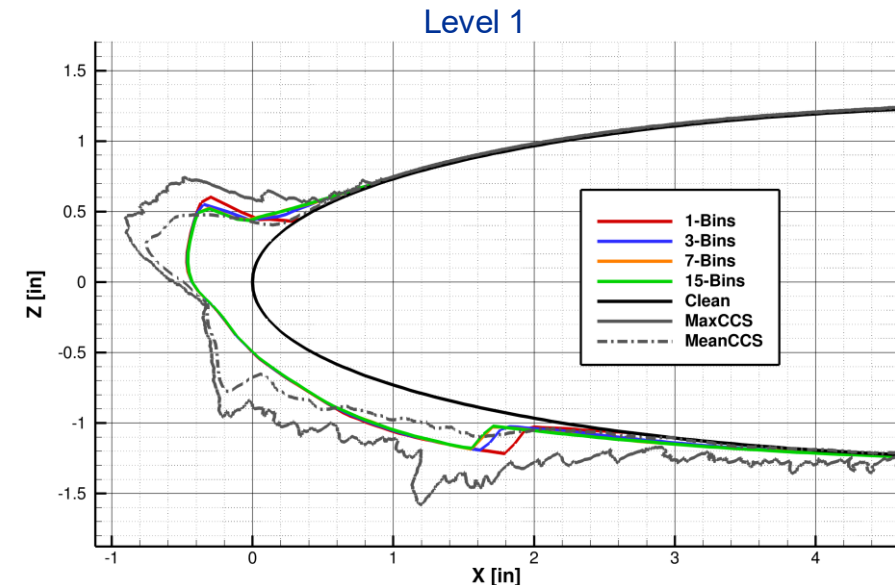
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Ice Shape Convergence for Drop Distributions: AE3932

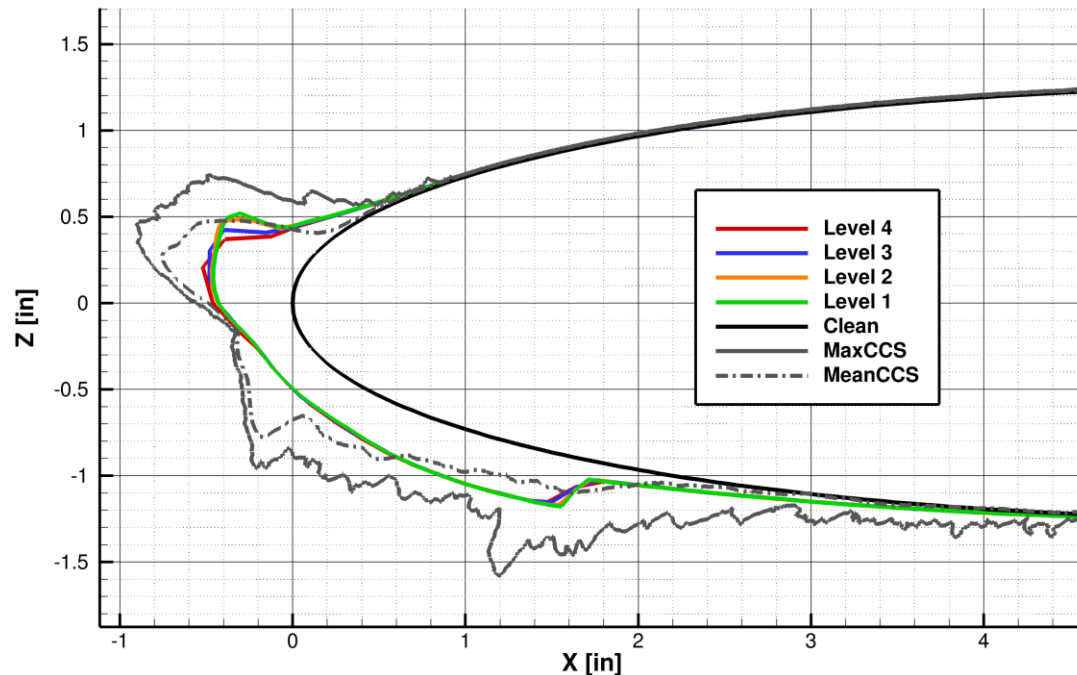
- General trend of agreeable upper-horn angle through results
- Convergence behavior of drop distributions are consistent across grid levels
- Lower horn not forming regardless of level or distribution
- Attachment line thickness is matched
- MeanCCS limits matched on lower surface through all grid levels



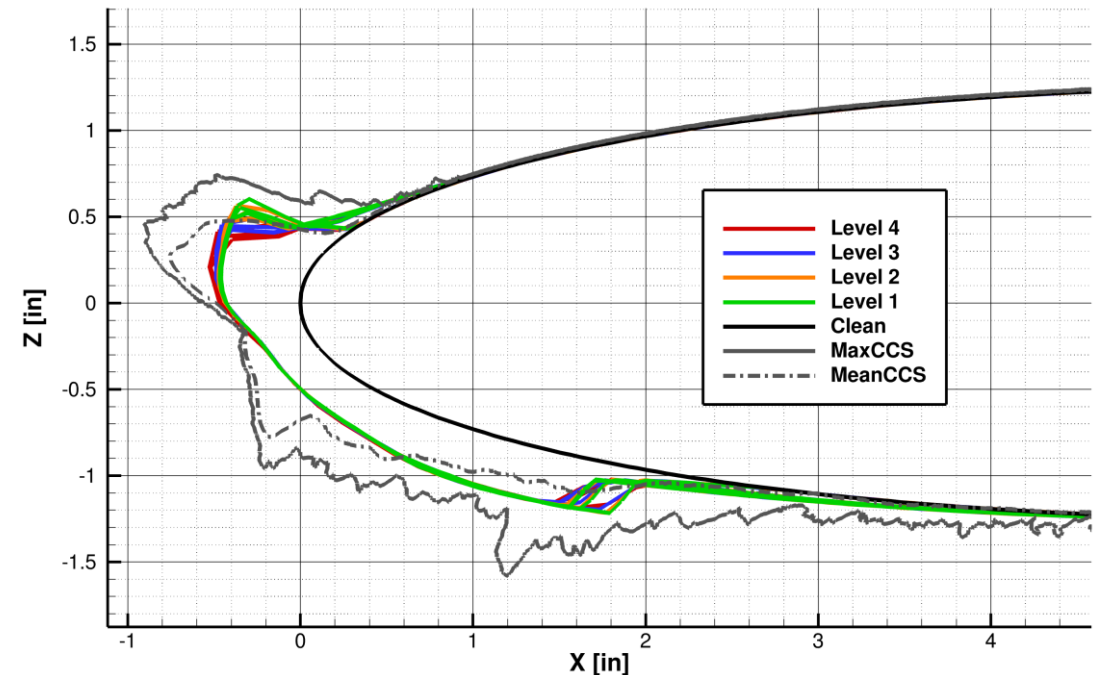


Ice Shape Grid Convergence: AE3932

- Upper horn angle has a general shift in positive s as grid refinement increases
- Lower surface ice shape impacted primarily by drop distribution not grid refinement
- Low complexity of the geometry results in reduced changes due to refinement and convergence
- Lower horn angle non-emergence not addressed through improvements in computed HTC



15-Bin Solutions Across Grid Levels

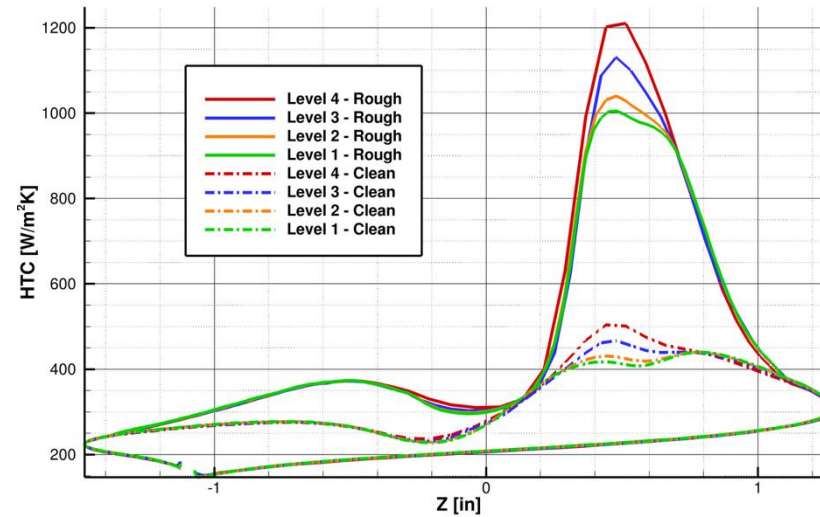


All Drop Size Distributions Across Grid Levels

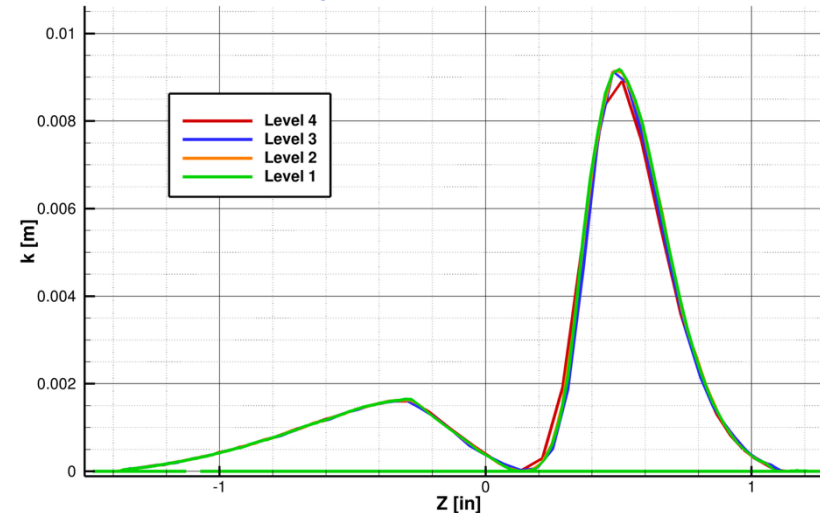


Evaluation of Heat Transfer: AE3932

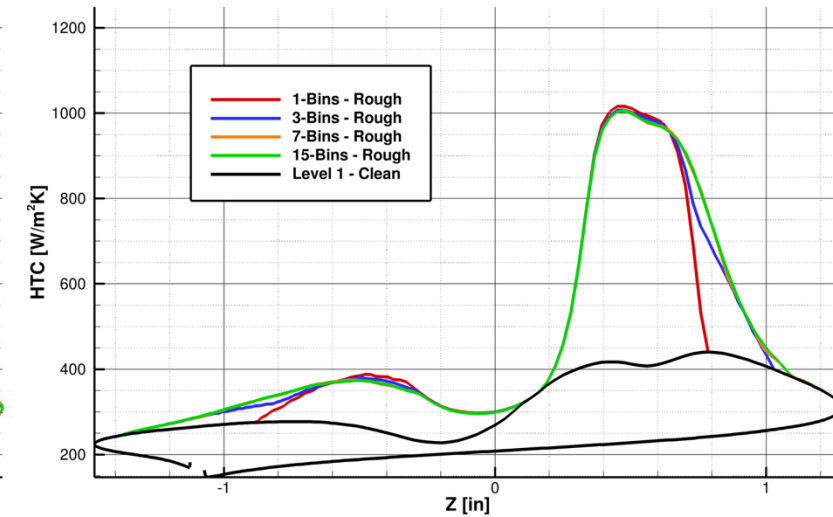
- Lower surface enhancement is not sufficient for horn formation
- Consistent roughness predictions explain ice shape agreement across grid levels
- Upper surface sees grid-based convergence of HTC while lower surface is converged at L4
- Global convergence of roughness curve for L1 over drop distribution



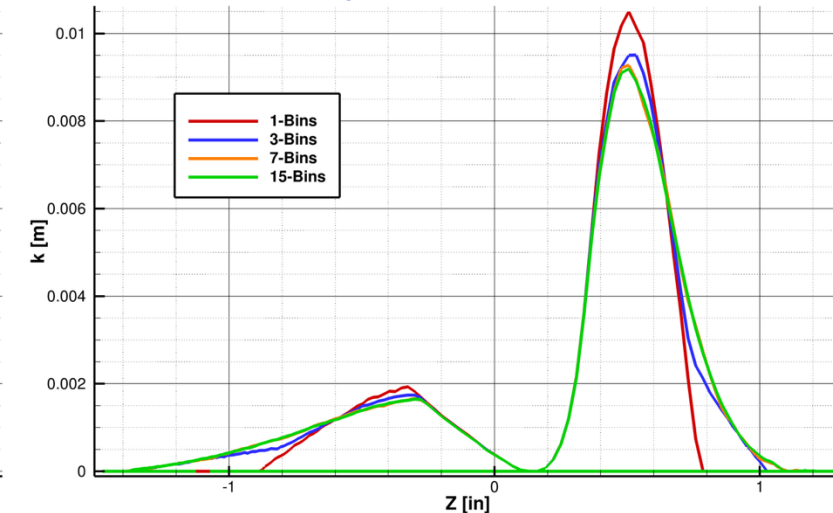
Smooth and Rough HTC for 15-Bins Across Grid Levels



Roughness Height for 15-Bins Across Grid Levels



Smooth and Rough HTC for L1 Across Distributions



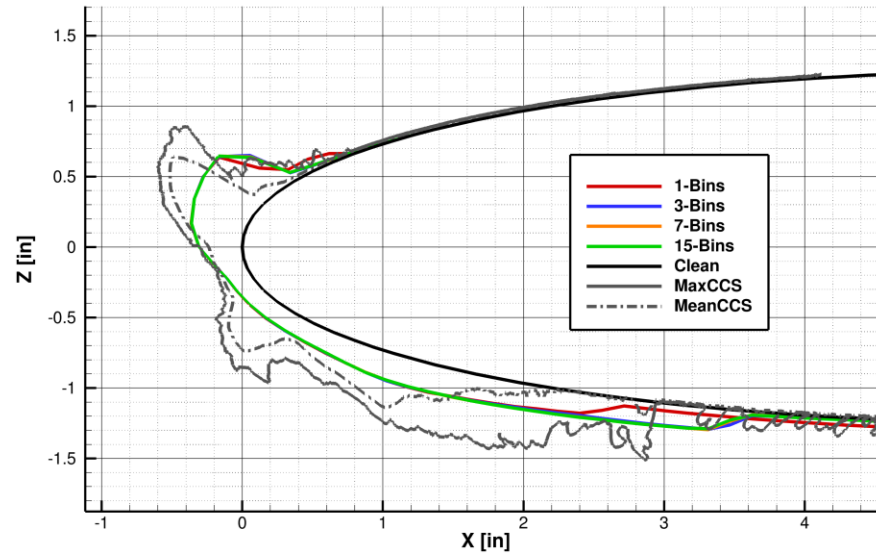
Roughness Height for L1 Across Distributions



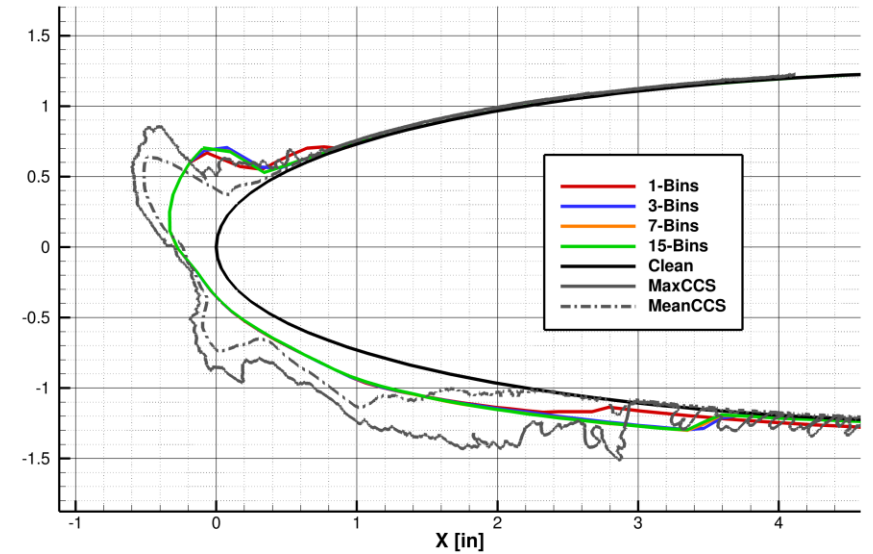
Ice Shape Convergence for Drop Distributions: AE3933

- Warmer condition seeing increase in associated runback
- MeanCCS alignment at extents no longer present
- Upper-horn angle agreement less clear
- Leading edge thickness matched again
- No lower surface horn formation
- Decrement in accreted mass is not properly observed
- Ice shapes converged by the 3-Bin distribution

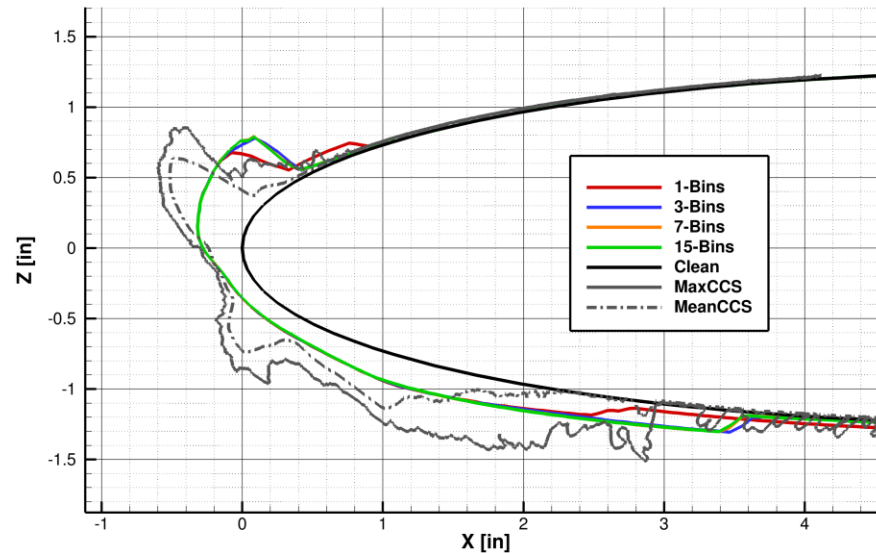
Level 4



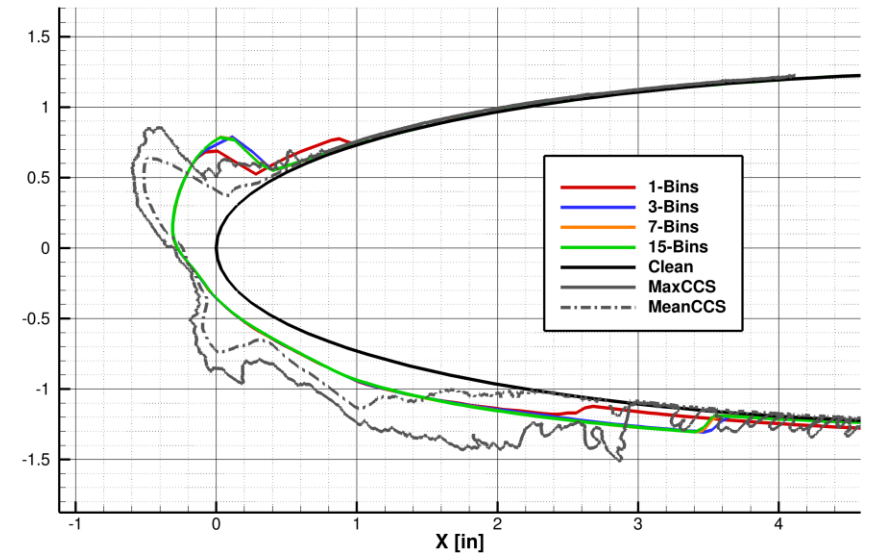
Level 3



Level 2



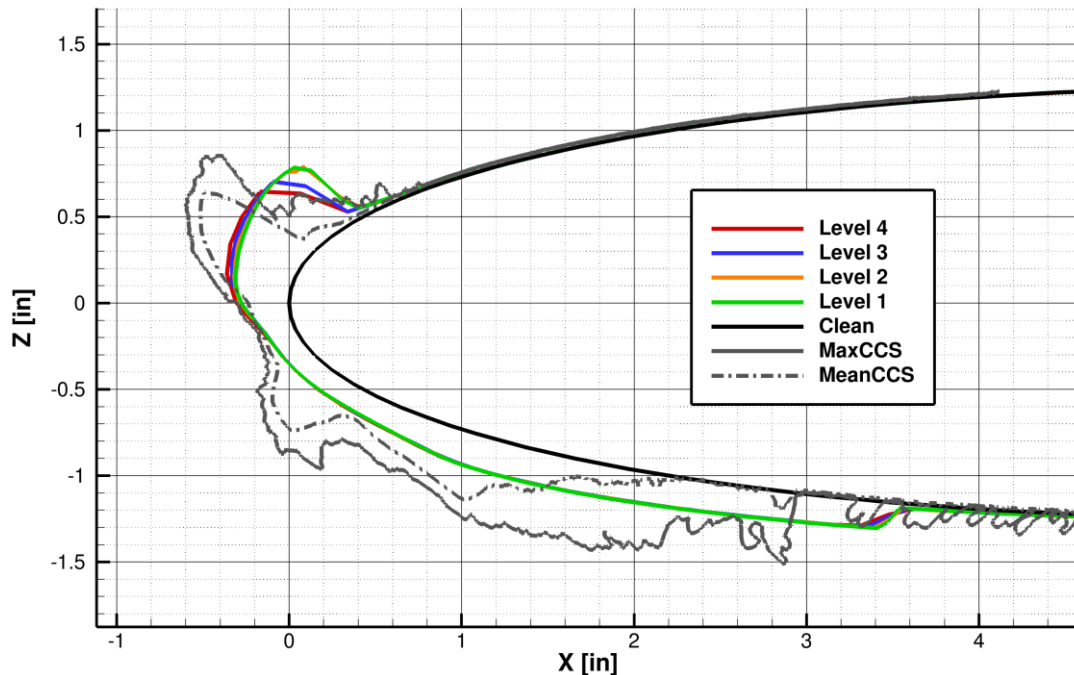
Level 1



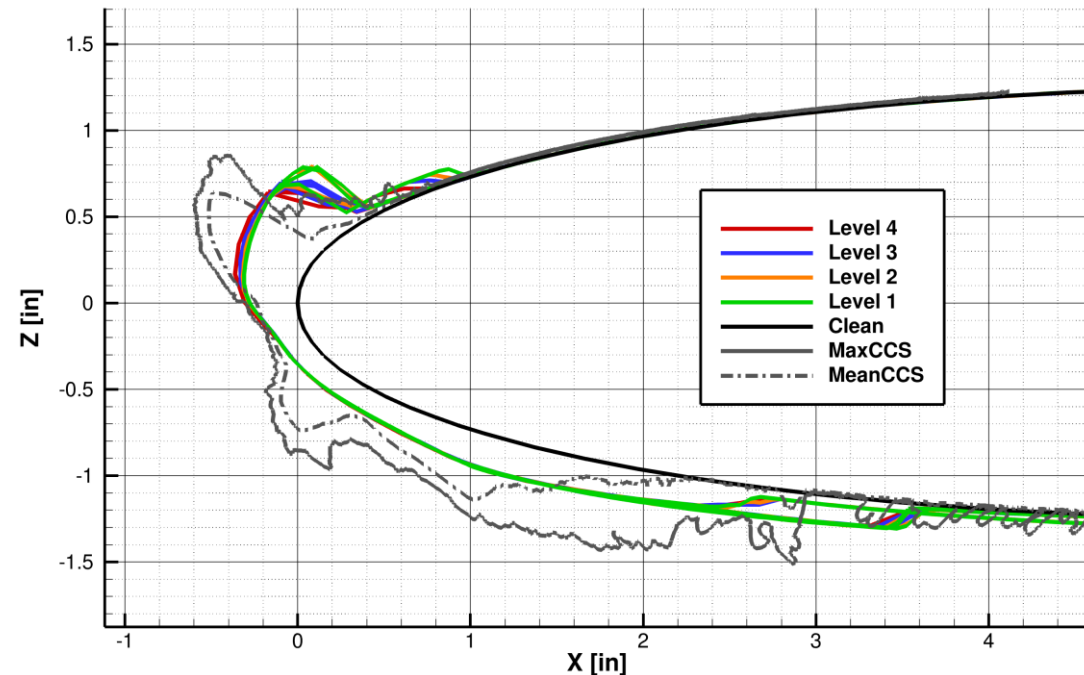


Ice Shape Grid Convergence: AE3933

- Upper-horn angle has a general shift in positive s as grid refinement increases
- Upper-surface ice shape not impacted by drop distribution beyond 3-Bins
- Lower-surface ice shape not impacted by drop distribution nor grid refinement
- The increase in temperature does retain favorable upper-surface horn behavior while producing a more glaze overall shape



15-Bin Solutions Across Grid Levels

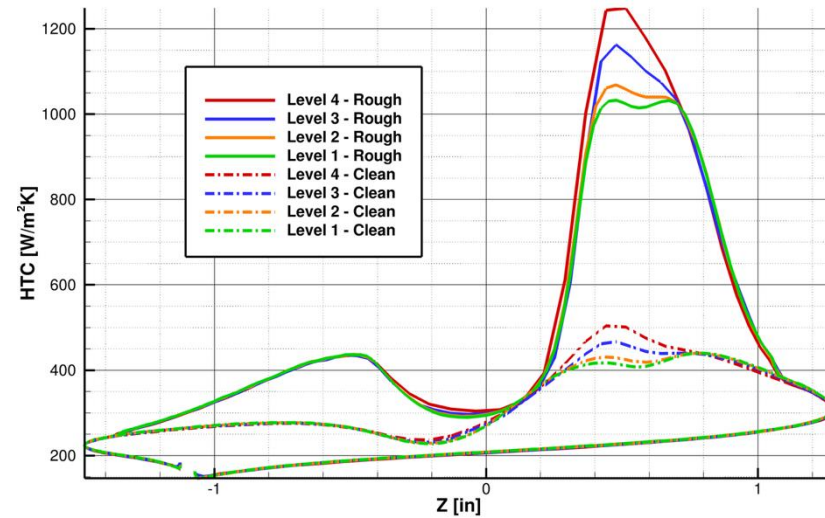


All Drop Size Distributions Across Grid Levels

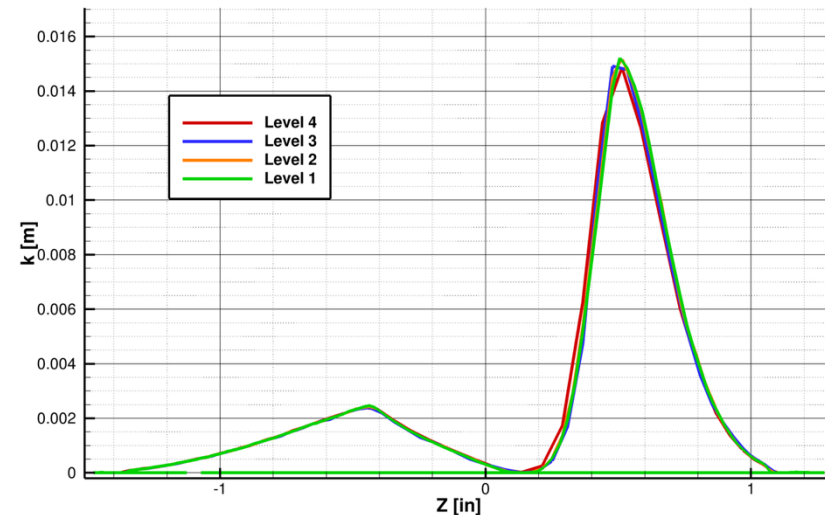


Evaluation of Heat Transfer: AE3933

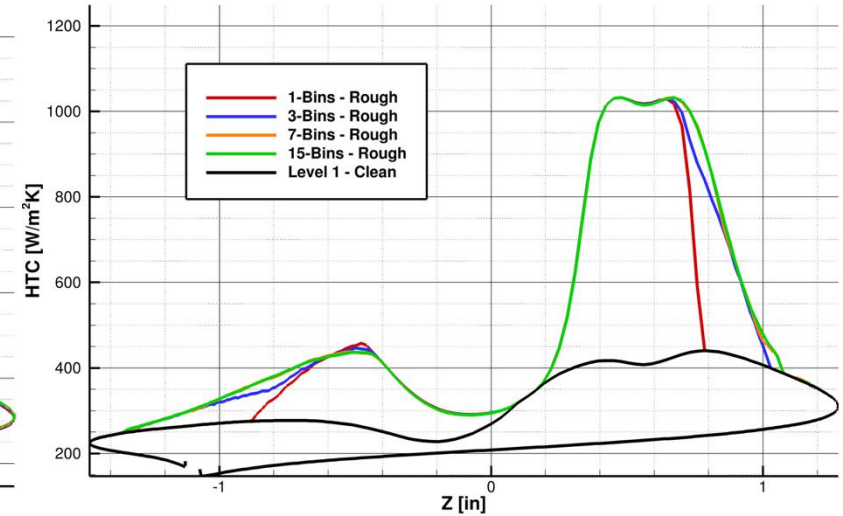
- A negative s shift is seen by the roughness between AE3933 and AE3932
- An increase in maximum roughness height is experienced on both the lower and upper surfaces
- Associated with an increase in the rough-HTC between cases
- Convergence of upper surface roughness is one sided and monotonic
- Roughness profiles are again resistant to grid refinement



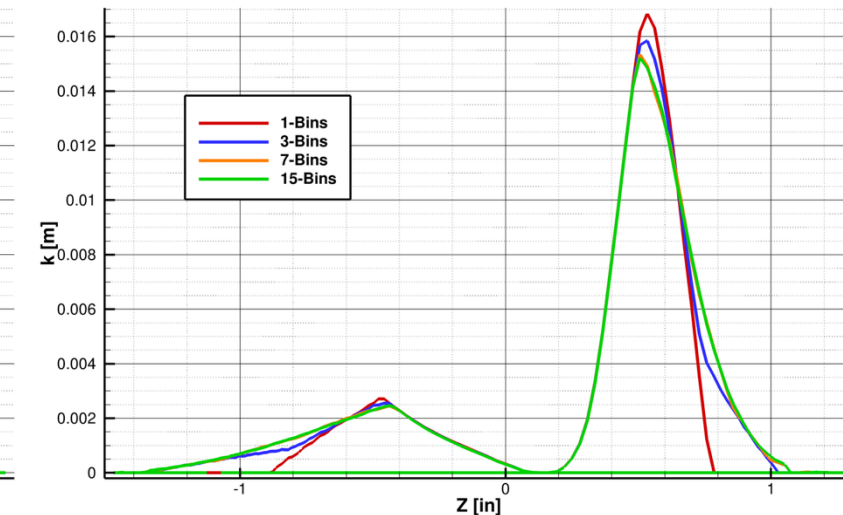
Smooth and Rough HTC for 15-Bins Across Grid Levels



Roughness Height for 15-Bins Across Grid Levels



Smooth and Rough HTC for L1 Across Distributions



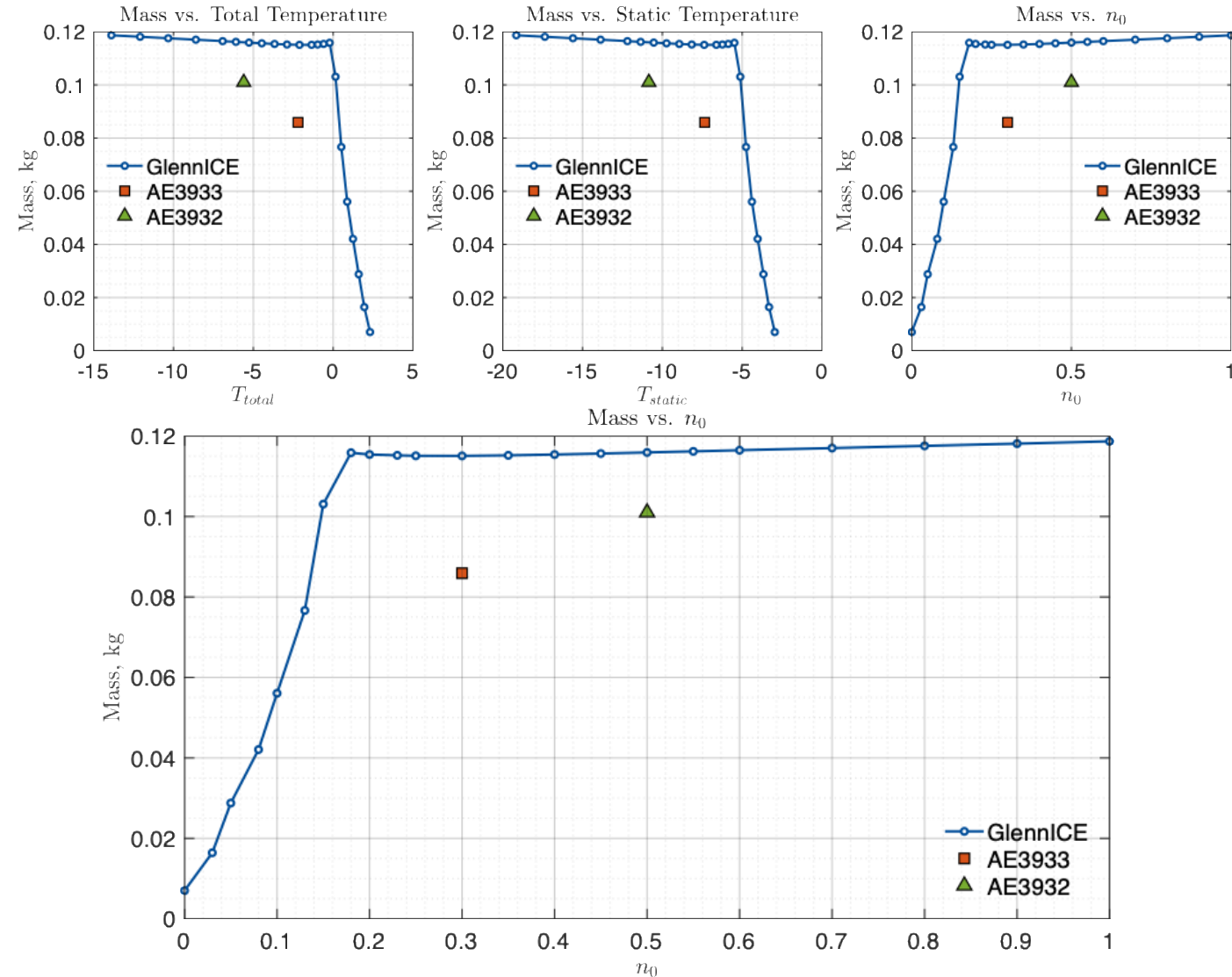
Roughness Height for L1 Across Distributions



Evaluation of Predicted Mass Trends Over Temperatures

- An evaluation was performed to analyze mass-based trends
- A general shift is seen between GlennICE and experiment
- Majority of mass loss transition is seen between $n_0 = 0.2$ and 0
- Increased enhancement moves the curve towards lower n_0
- More datapoints would provide valuable insights on general mass vs freezing fraction trends

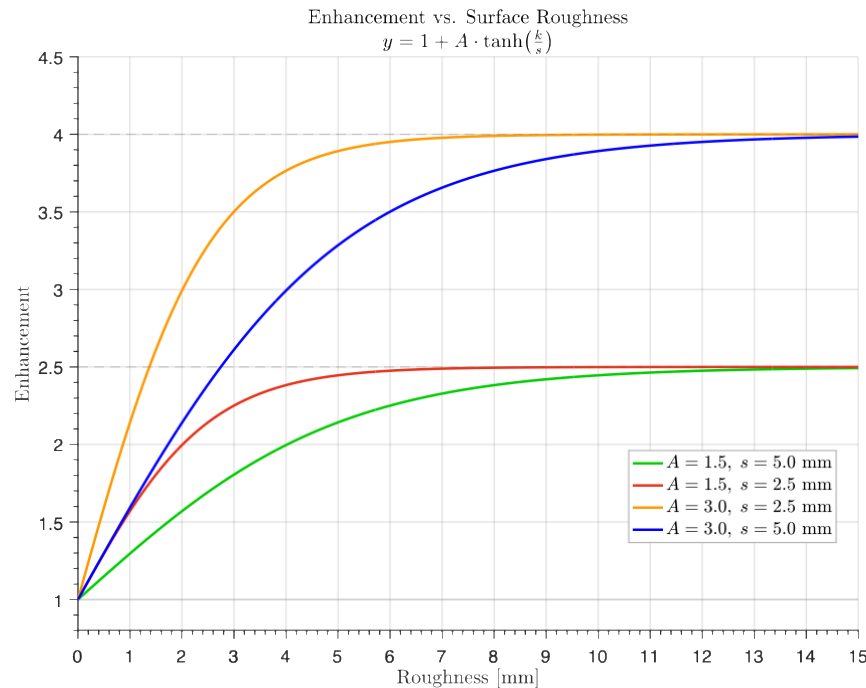
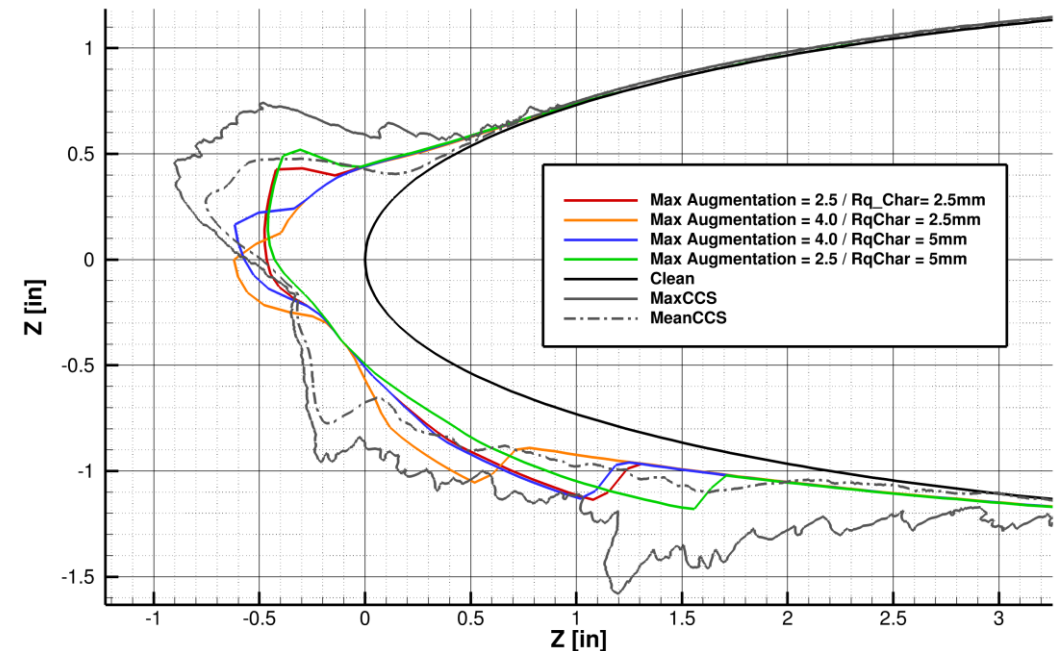
GlennICE Predicted Mass Compared with Experimental Data





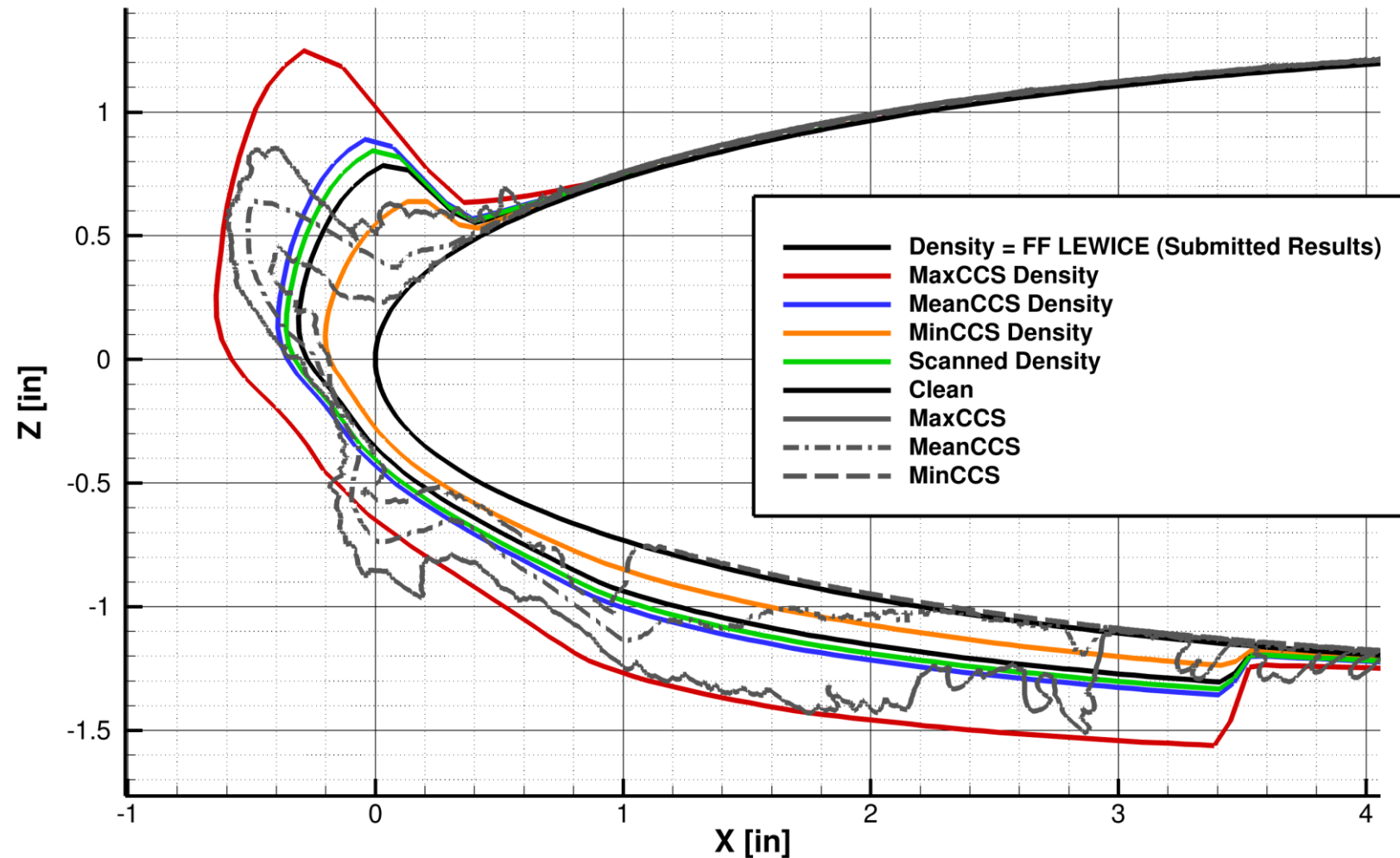
Enhancement Changes for AE3932

- Utilizing a tanh enhancement mechanism for evaluation (McClain 2026)
 - Changed rough-HTC routine from capping roughness to capping enhancement
- Can the lower surface horn be forced to appear
 - Increase in total allowable enhancement would increase HTC there more
 - Increasing allowable enhancement on lower surface at lower roughness heights
- The best scenario is an increase in lower surface enhancement while leaving the upper surface unchanged



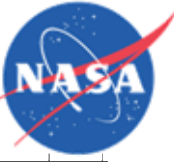


Density Impacts on AE3933 Ice Shape



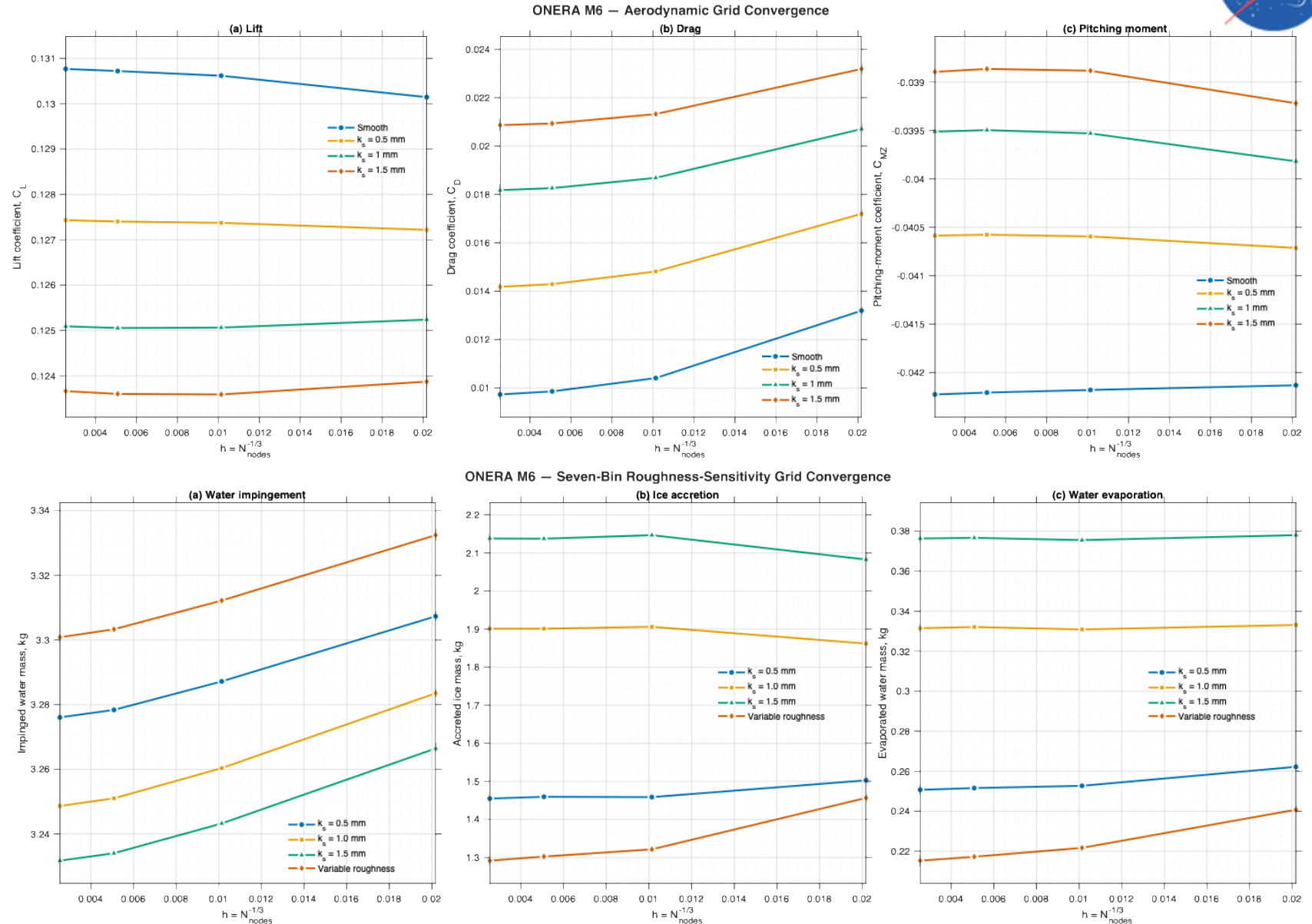


ONERAM6



Grid Based Integrated Properties Convergence

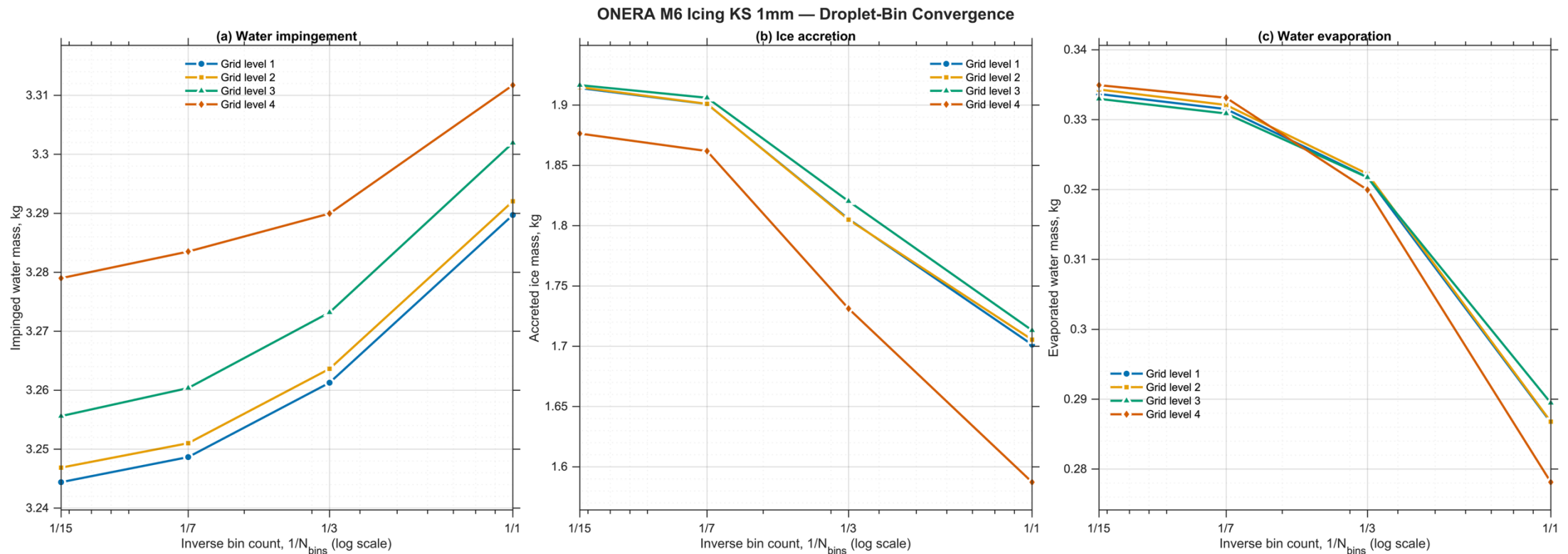
- Aerodynamic forces generally converge favorably
- Impingement converges well as grid resolution increases
- Evaporation appears robust to grid changes
- Increase in surface roughness results in decrease in impinging water
- Mass is largely converged by L3 solution
- The available enhancement to form ice is limited at this condition, grid-based over prediction of it does not imply further ice growth





Drop Distribution Based Integrated Properties Convergence

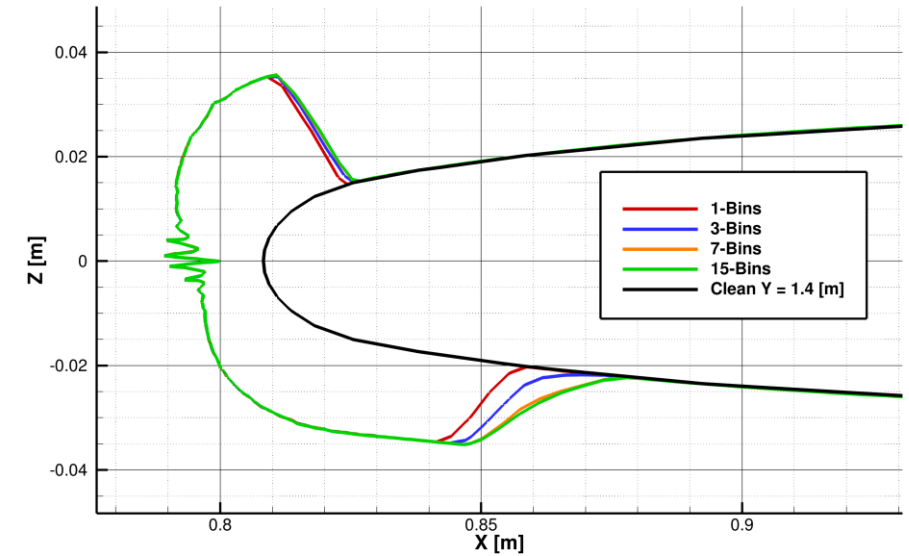
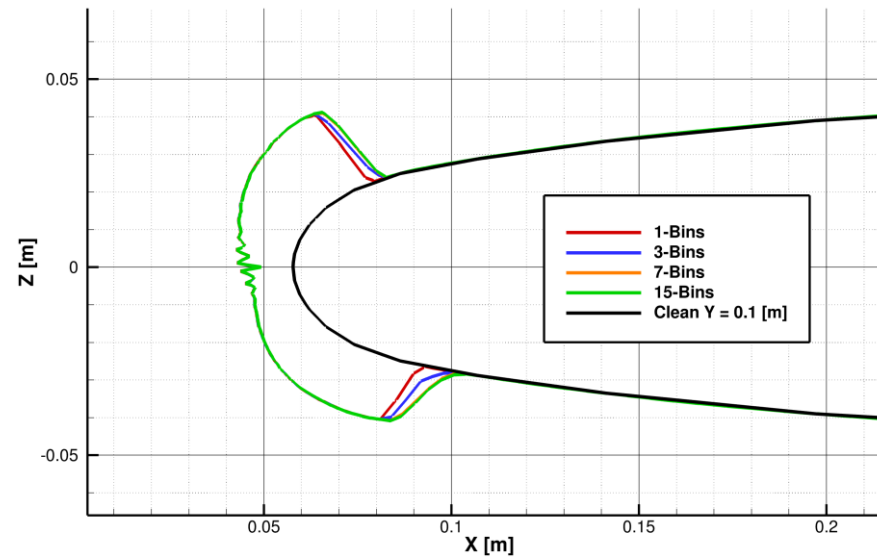
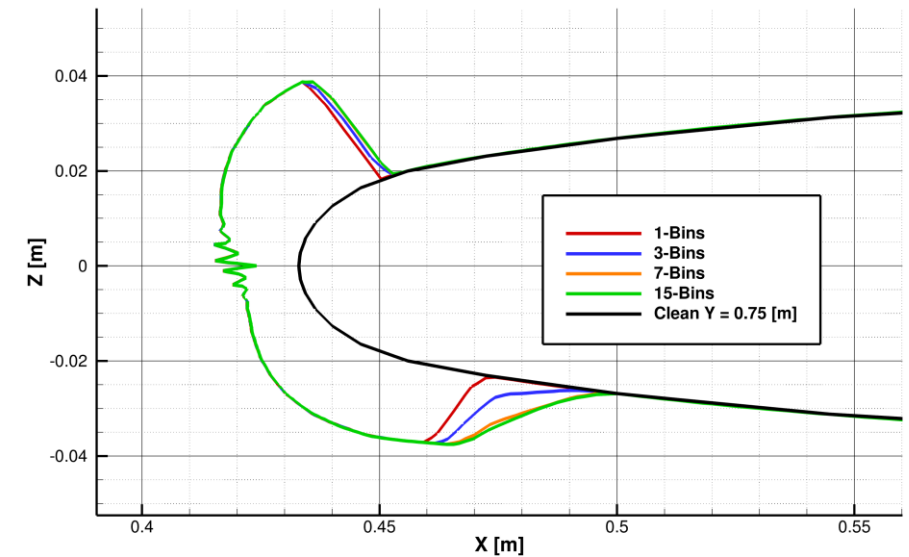
- Impingement convergence is favorable across both evaluation spaces
- Similar convergence behavior of ice mass provides increased confidence in NACA 0012 distribution method
- Evaporation is more dependent on drop size distribution than grid size





ONERAM6 Grid Level 1 Drop Distribution for 1 [mm] Roughness

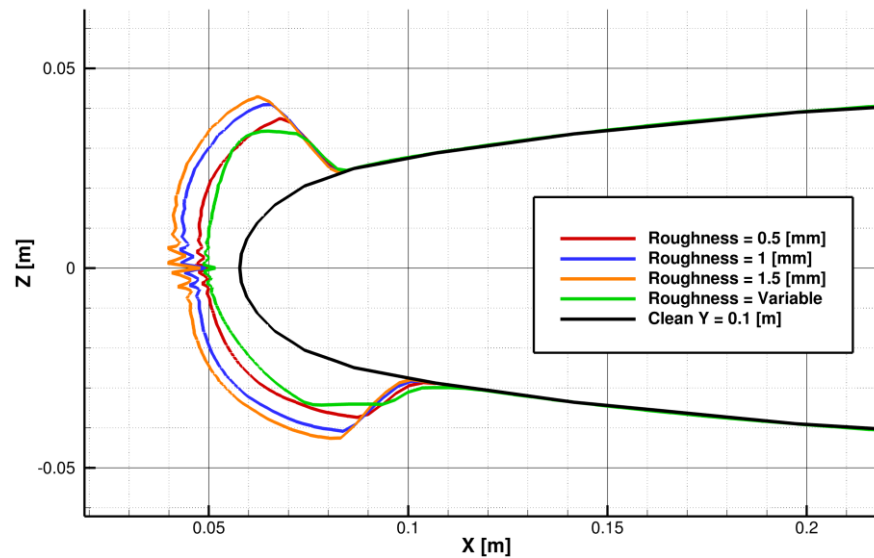
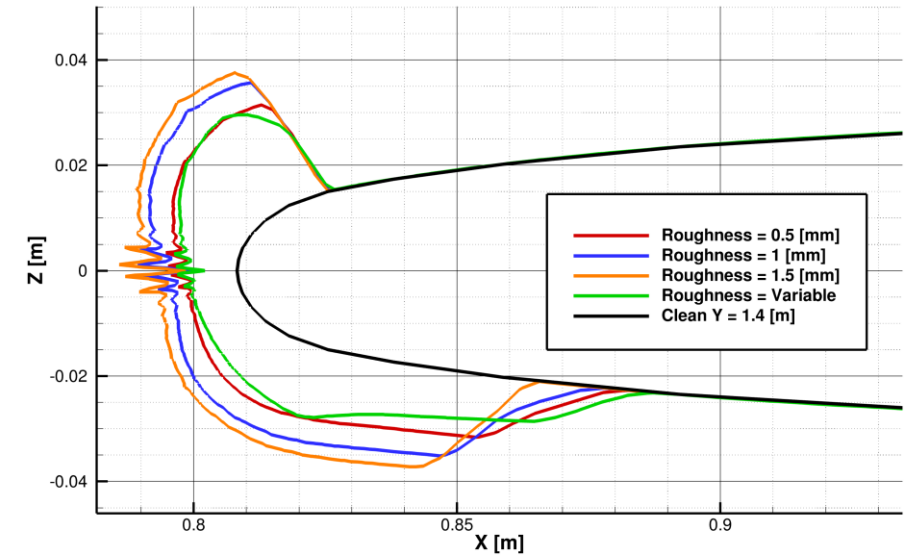
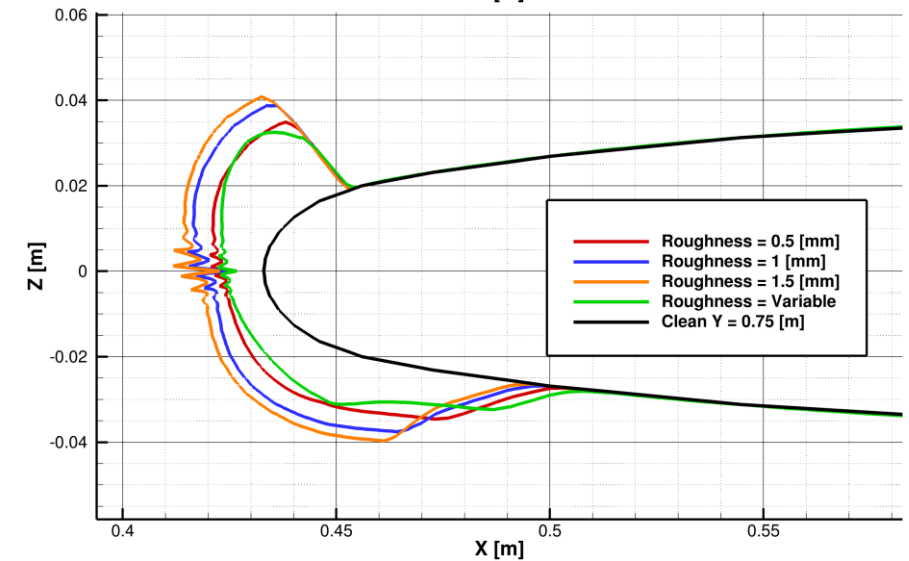
- Note leading edge wiggles are grid-quality and extrusion based
- Upper surface horn is largely impervious to drop size distribution changes
- Lower surface converged by 7-bins
- Moving outboard to inboard pushes lower surface accretion back while horn angle changes slightly





ONERAM6 Roughness Variations for Level 1 15-Bins

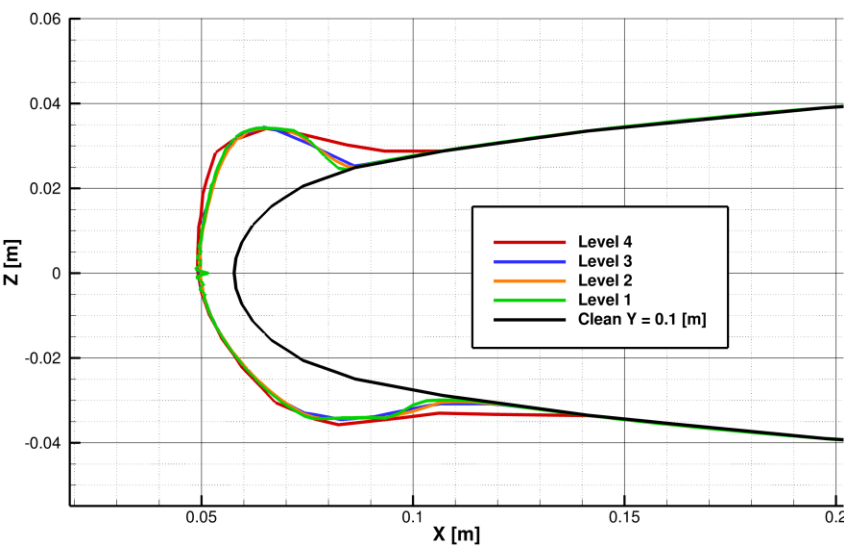
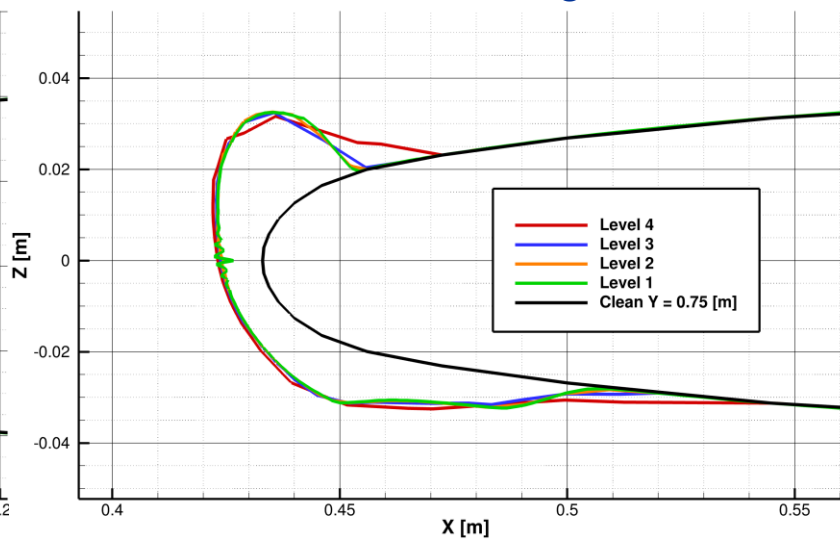
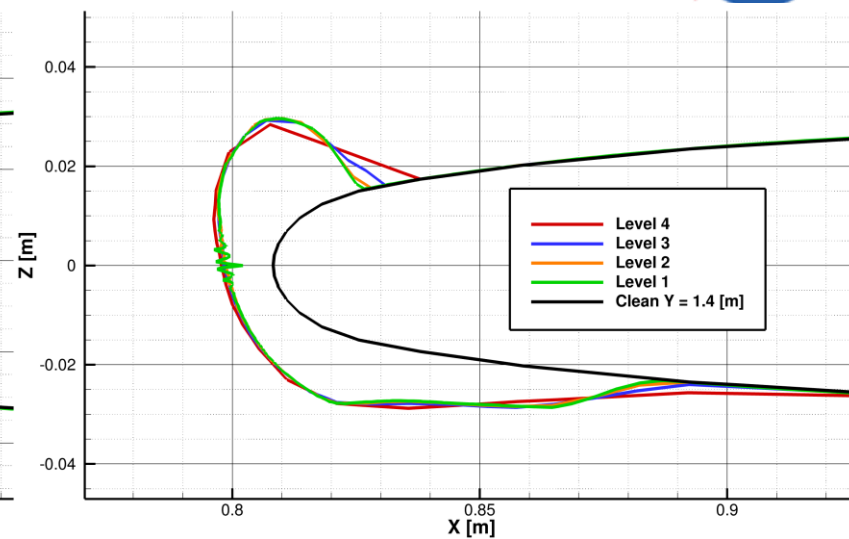
- Note leading edge wiggles are grid-quality and extrusion based
- Variable roughness enhancement on the order of 0.5 [mm] shape
- Horn angle is preserved across CFD roughness variations
- Variable roughness shape notably different than CFD roughness shapes
- Ice shape transitional behavior largely retained across the evaluation space



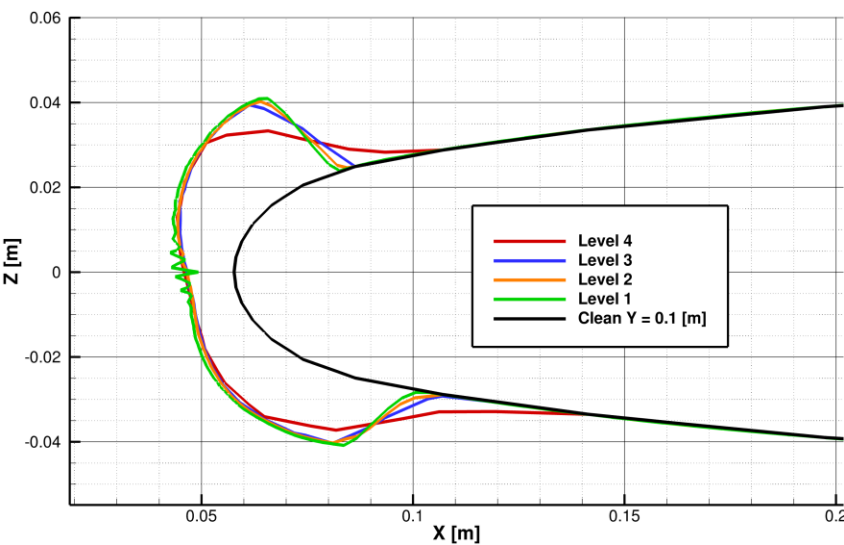
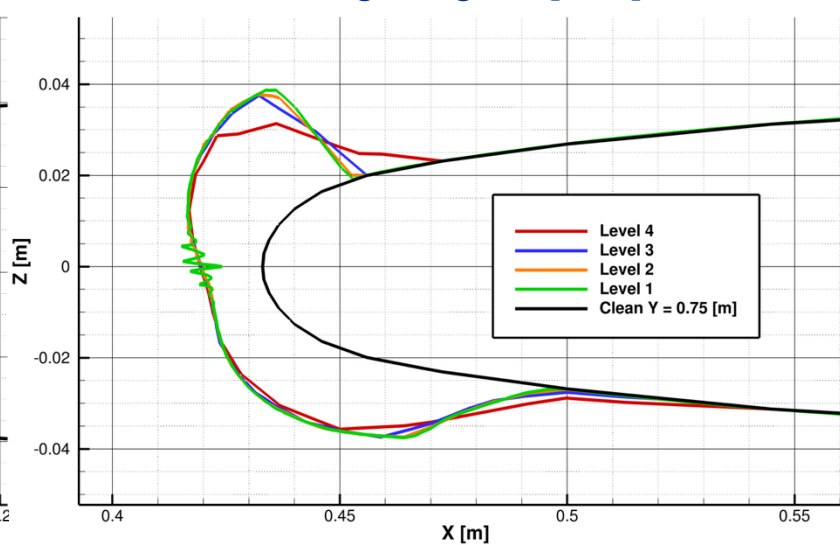
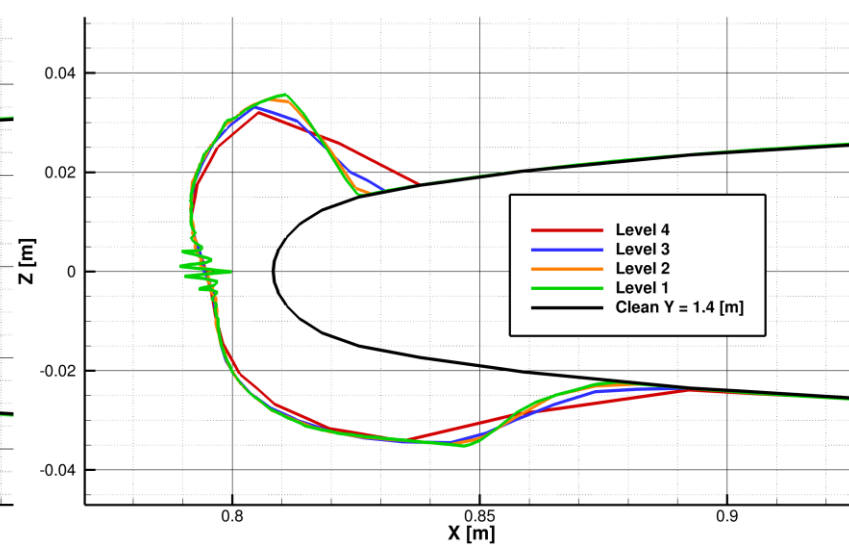
Grid Effects for 7-Bins with 1 mm and Variable Roughness



Variable Roughness



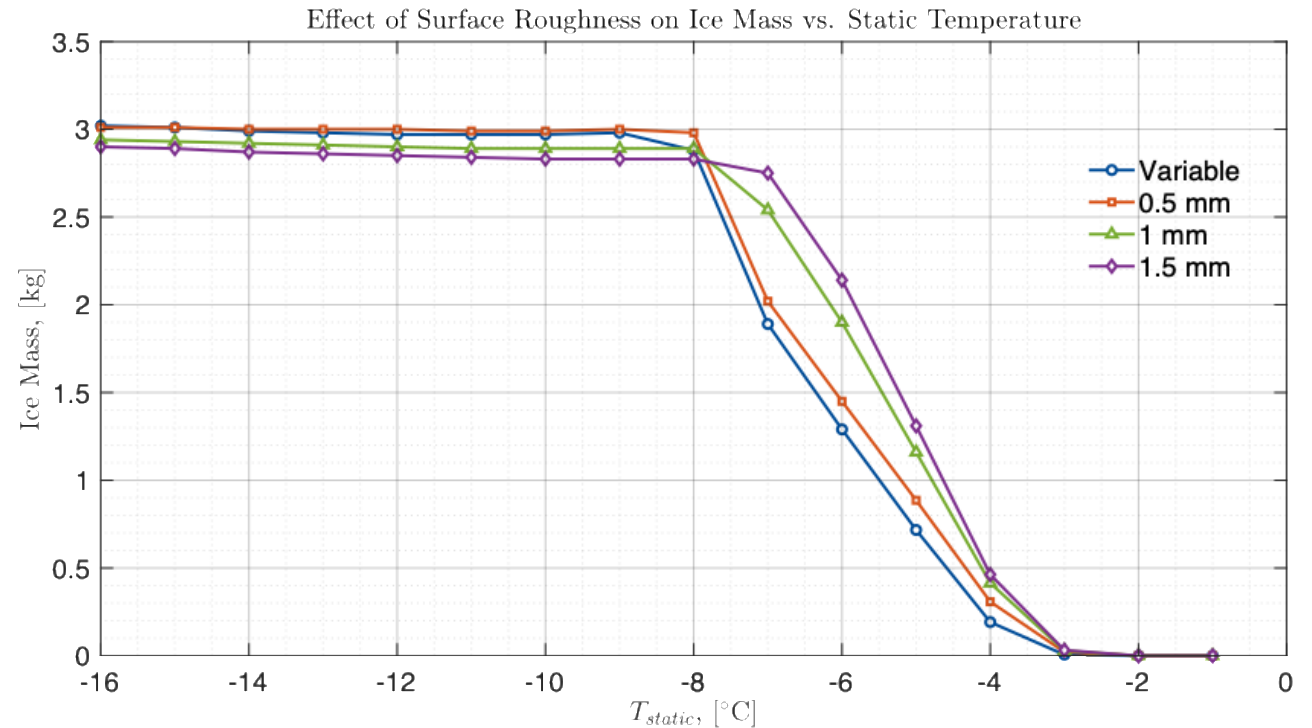
SA-neg-rough 1 [mm]





Temperature Sweep ONERAM6

- As was performed for the NACA 0012, an evaluation of transitional mass behavior was performed
- The workshop case was at $T_{static} = -6$ [°C]
- When ice begins forming is consistent across all models
- The range in which the accreted mass is changing is largely independent of roughness
- The mass is drastically different across the transition front





Conclusions Thoughts

- The NACA 0012 convergence was positive with limited grid effects
- Enhancement routine could benefit from an increased tanh slope on lower surface
- NACA 0012 Transitional mass behavior is right shifted when compared against freezing fraction
 - Is the experimental methodology representative of the evaluation method used
- Droplet distribution evaluation shows clear convergence for in-tunnel drop size distribution method when compared against clean distribution of ONERAM6
- Droplet distributions converged in a classical shape for these configurations
- Variable roughness model was less affected by grid-based HTC changes
- Transition behavior of roughness heights being aligned likely points to alternative avenues for evaluation of right shift behavior