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The State of Scale-Resolving Simulations for Aircraft High-Lift Applications: Summary of the Closing Discussion of the 2025 NASA High-Fidelity CFD Workshop

Gary Coleman, Mujeeb Malik, Chris Rumsey
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Boeing Commerical Airplanes, Retired

July 2025

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Acknowledgments

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Abstract

A thorough and robust discussion was held during the last session of the 2025 NASA Computational Fluid Dynamics (CFD) High-Fidelity Workshop, regarding the success of the current Revolutionary Computational Aerosciences (RCA) Technical Challenge (TC): to 'Develop and demonstrate computationally efficient, eddy-resolving modeling tools that predict the maximum lift coefficient for transport aircraft with the same accuracy as certification flight tests.' The consensus of the delegates was that significant progress towards achieving the TC has been demonstrated, particularly through the collaborative development and use of Wall-Modeled Large-Eddy Simulation (WMLES). The remaining tasks required to fully meet the TC were highlighted. No consensus was reached regarding possible topics for a new RCA TC. However, many opinions were expressed and captured, and key emerging technologies that will likely affect it were discussed.

Introduction

NASA's CFD Vision 2030 [1] and the subsequent Certification by Analysis 2040 [2] studies emphasize the need for development of advanced computational tools that are robust, efficient (cost effective) and accurate. For computational fluid dynamics (CFD) tools to provide accurate prediction near the edges of the flight envelope (e.g., in the high-lift regime), high-fidelity scale-resolving computational tools are needed. The Revolutionary Computational Aerosciences (RCA) program, under NASA's Transformational Tools and Technologies (TTT) project, has been engaged in sponsoring such tool development along with physical experiments to provide CFD-validation data. RCA has a technical challenge to develop and demonstrate computationally efficient, eddy-resolving modeling tools that predict maximum lift coefficient for transport aircraft with the same accuracy as certification flight tests. Here, for brevity, we will refer to this technical challenge as the 'CLmax TC.' The focus of the RCA research toward accomplishing this challenge, within NASA and the sponsored extramural research, has been primarily aimed at developing and demonstrating a Wall-Modeled Large-Eddy Simulation (WMLES) capability, sufficiently accurate to predict CLmax within 5%. Other scale-resolving methods, including hybrid RANS-LES methods like Delayed Detached-Eddy Simulation (DDES), are also viable, but have not been the main focus for this challenge. The primary objective of the NASA High-fidelity CFD Workshop, held 20-22 May 2025 in Suffolk VA, was to assess the progress made on the CLmax TC. The Appendix contains the full agenda of the three-day workshop, which was split into presentations and group activity. Presentations were made over the first $2\frac{1}{2}$ days, which were assessed by an independent program review panel, who later issued an internal, non-public evaluation to NASA management. The last half-day session of the workshop was dedicated to a group discussion of the present and future states of CFD as applied to applications of interest to NASA. The present document presents a summary of that discussion, which was organized around three questions, concerning: (1) progress on the CLmax TC, along with remaining gaps/issues, (2) next steps and identification of a potential new technical challenge, and (3) emerging technologies that need to be better understood and harnessed to achieve it. In preparation for the final discussion, the workshop attendees were randomly divided into three groups that met in three separate locations, for approximately one hour. Each of the three groups separately addressed all three questions, given in detail below. The groups were led by Chris Rumsey, Jeff Slotnick, and Gary Coleman, and responses were respectively recorded by Johan Larsson (University of Maryland), Dmitri Mavriplis (Scientific Simulations), and Neil Sandham (University of Southampton). The latter three then reported their summaries to the entire, reassembled group, which prompted further discussion.

Summary of responses

Below is a recapitulation of the summaries and discussion, with only minor editing. The raw comments have been preserved to capture the overall feedback from the participants. The summaries should make clear that a consensus was not reached, but the differing viewpoints indicate that future developments and applications of scale-resolving simulations (SRS) could be impactful in many different areas.

Question 1: What capabilities have been developed and established for accurately predicting aircraft CLmax, and what are the remaining gaps in our capabilities and understanding?

1.1 *Assessment of capabilities*

- There has been substantial improvement in the capability of WMLES to predict CLmax for realistic, high-lift transport aircraft configurations. The concentrated effort over the course of the current TC has yielded positive results.

- Other scale-resolving methods such as DDES and wall-resolved LES may have advantages for certain classes of problems.

- RANS verification has improved significantly in recent years, leading to more confidence in the 'correctness' of RANS results (solving the turbulence model equations correctly, as intended). Even when these results are poor compared with experiments, they definitively demonstrate specific turbulence model weaknesses, which, once identified, could perhaps someday be rectified. This verification improvement includes the ability of many solvers to deeply converge, to machine precision, for problems of interest, including simplified CRM-HL configurations (e.g., without slat brackets) near CLmax. RANS verification has also benefited from recent improvements in Adaptive Mesh Refinement (AMR), which helps reduce discretization errors and speed up time-to-solution.

1.2 *Remaining gaps*

- Inadequate prediction of transition from laminar to turbulent states.

- Inadequate prediction of smooth-body separation on deployed wing flaps.
- Insufficient verification of WMLES methods (many codes use different implementations, which prevents repeatability from code to code, and thwarts verification of an implementation in a particular code).
- Modeling the wind-tunnel environment is more difficult than running in free air; the condition-setting procedures are not always the same as in the wind tunnel, and also tend to be inconsistent between CFD groups.
- WMLES often yields worse results than RANS for low angles-of-attack (away from CLmax, in the linear region of the lift-versus-angle-of-attack (AoA) curve).
- There is still much to explore regarding the mesh sensitivity of WMLES.
- A true predictive capability has not been demonstrated (thus far) using WMLES on a representative but different high-lift geometry, not previously utilized for CFD validation.
- Expert knowledge (particularly in gridding practices) is still required to run WMLES, although many best practices have been established over the course of the current TC.
- Incomplete understanding and usage of Uncertainty Quantification (UQ) in the general CFD community. Specific uncertainty in numerical modeling regarding complex, realistic geometry features, and the corresponding meshing requirements around them (e.g., regions adjacent to slats and slat brackets).
- Relatively little CFD-validation effort to date to account for aeroelastic effects for high-lift configurations, especially for SRS.
- Much uncertainty regarding the effect of surface (e.g., wing) roughness, both for transitional (see above) and fully turbulent cases.
- High costs of scale-resolving methods.

1.3 *General observations, opinions, further questions*

- The High-Lift Common Research Model (CRM-HL) configuration when simulated or tested at subsonic speed is characterized by a pressure-driven flow field, which is far easier to predict than a flow with more significant viscous effects; even very simple configurations like the Boeing speed bump are more difficult to predict.
- In general, for current CFD-validation efforts, the community has focused on comparing integral values. Future validation efforts should include specific flow-field details, like off-body velocity and/or turbulence fields.

- In light of the critical role and uncertainty regarding turbulence-transition prediction, there is a pressing need to develop new transition models and/or schemes to couple them to WMLES, as well as new experimental/simulation benchmark data for their validation. (Somewhat mitigating this shortcoming was the observation that - while important for wind-tunnel conditions – at flight Reynolds numbers, the transition region will be much more limited and thus may not have a significant effect on certain quantities of interest.)

- AMR will likely be beneficial for helping to determine optimal/efficient mesh distribution in future LES development.

- CFD simulations should not rely solely on free-air runs, specifically for CFD validation purposes. High-lift simulations should also include model deformation and the wind-tunnel geometry, in order to capture wall and blockage effects in wind-tunnel experiments. (Three promising studies aimed at addressing wall and blockage effects, based on measurements in the NASA National Transonic Facility, were presented at the workshop.)

- The Technology Focus Group (TFG) concept, within the high-lift prediction workshop series, has been a huge boon. With researchers around the world working in tandem during the year prior to the workshop (rather than independently as was done in the past), progress/learning has been greatly accelerated. Also, applying many different tools to the same problem has been beneficial. However, collective results, then, have not been very independent or truly 'blind.'

- While scale-resolving methods are not yet viable as general-purpose predictive/design tools for industry (for example, to quantify low-speed trends or predict flap separation, much less serve as the basis for Certification by Analysis (CbA) – which requires accurate CFD results for real aircraft under a wide range of realistic flight conditions), they nevertheless have been able to illuminate trends and answer specific questions regarding real flight issues. Industry is thus beginning to have more confidence in WMLES, and scale-resolving methods are beginning to yield a meaningful return on investment.

Question 2: What should be the target application for future CFD developments (the new NASA Revolutionary Computational Aerosciences Technical Challenge) to further advance computational capabilities and why?

2.1 *General comments, opinions, questions*

- An alternative critical question emerged during this discussion and became the primary focus of attention: Should the next TC be some sort of continuation of the current CLmax TC, or should it be brand new? Discussion points were made in favor of both sides of this issue.

- In one of the three subgroups, an informal poll was taken on this question, with the result that approximately 2/3 thought it best to maintain the current TC (or something along very similar lines), and 1/3 voted to move on to another completely new one.
- While a defined TC aids in storytelling, it does not guarantee funding. Nevertheless, it provides the opportunity to increase stakeholder awareness by demonstrating how research directly tackles industry challenges and creates meaningful impact.
- We need a new challenge to appeal to the stakeholders. Proposing to do more of the same would be problematic, as it would make it potentially more difficult to convince stakeholders of the impact of new investments for previously funded efforts.
- An advantage of the CLmax TC was its very tangible and relevant nature. It was easy to get a wide variety of researchers/organizations interested in trying to tackle it. Because it was pertinent to so many, we should not be afraid of keeping the spotlight on the current TC, but extend it in some way to incorporate additional challenges/physics by perhaps employing a related/tangential use case.
- We have years of CRM-HL ecosystem testing coming up. What will happen to it if the next TC switches to something completely different?
- The NASA TTT portfolio is always much broader than just what is specified in its TC.

- Regarding whether to maintain and refine the current CLmax TC or move to a new one:
  - On one hand:
    - Over the next five to seven years, with looming funding cuts, it is not feasible to pivot to a completely new TC; it would be wise to not squander advances realized under the current TC.
    - We could propose multiple emerging TCs to lead up to a future grand challenge.
  - On the other hand:
    - Continuation of the current TC risks being seen as focusing on the same problem for too long, which could be interpreted as no progress having been made.
    - Methods developed and applied to the current TC could also be used for a new TC.

2.2 *Comments/proposed topics*

- Suggested new topics ranged from Flow Physics to Aircraft Performance (such as CLmax research, oriented towards CbA) to Design Methodologies (i.e., to use for incremental or optimization studies).

- Some felt that we are still very far from CbA, particularly since industry has not yet eliminated aerodynamics-related flight-test surprises. Hence, continuing with an emphasis on CbA would be appropriate.
- If the focus remains on 'predictive high lift,' one could extend complexity with added effects:
  - Sideslip, engine-power on, engine out, icing, ground-plane effects, maneuvers.
  - Focus on the prediction of flap pressure (which is currently not well captured at all conditions).
- The next TC could be focused around a newly invented design challenge. The existing example of the Digital-Twin study by DLR (DLR-F25) was brought up. This is a new high-aspect-ratio research platform used throughout Europe by many research disciplines.
- Other/specific proposed topics:
  - Buffet onset and/or deep buffet: another element of predicting the 'edge of the envelope.'
  - Full maneuvering aircraft under conditions mentioned above (engine-out, side-slip conditions, with takeoff power included, or for other maneuvers). This may need to involve multi-timescale LES.
  - Propulsion/Airframe integration.
  - Other aircraft types: UAV/UAM (smaller scales, unsteady prop/wakes, flow separation), advanced air mobility.
  - Turbomachinery (has same basic flow physics and issues encountered on aircraft wings, although typically at lower Reynolds numbers – e.g., transition, Shock-Boundary Layer Interaction (SBLI), heat transfer, aeroelasticity).
  - Transition (particularly for WMLES of attached boundary layers).
  - Multi-disciplinary coupled/integrated effects (heat transfer, aeroelasticity).
  - Slat wakes.
  - Hypersonics.
  - Reduction of time to market.
  - A specific product-certification regulation (as a potential use case), towards CbA (with careful attention paid to definition of exit criterion). This may need to be realized in a completely virtual scenario.
  - Multi-disciplinary study of some previous, specific flight-test surprise.
  - Optimization/design (not currently possible with scale-resolving tools).
  - Addressing/improving an aircraft's operational envelope – e.g., increase cruise Mach number without loss of efficiency.

◦ Icing.

Question 3: What are the key emerging technologies that will likely influence the success of the new Technical Challenge? How should the CFD community explore, develop, and deploy these technologies?

(Note: the organizers clarified that emerging technologies are some of the tools to be leveraged to solve tough problems that we have not been able to solve before. Mentioning these in a TC definition may help convince stakeholders that, with dedicated research efforts, a 'big bang for the buck' may be possible.)

3.1 *Quantum Computing (QC)*

- While QC is not expected to revolutionize scale-resolving simulations in the near future, it could be effectively applied to solve different types of problems besides Navier-Stokes solutions via CFD, such as optimization.
- As recommended by the CFD Vision 2030 study, it is important to follow developments in QC and exploit its potential where feasible.

3.2 *Artificial Intelligence/Machine Learning (AI/ML)*
(i.e., one aspect of the broader field of data science)

- The enthusiasm for use of AI/ML by our community is tempered somewhat by its lack of mathematical rigor, and general lack of critical expertise within the aerospace community.
- We were reminded that current HPC developments are not being driven – or even marginally affected – by the needs of CFD, but instead by AI/ML applications.
- With Graphics Processing Unit (GPU) development increasingly being driven by AI/ML applications, the CFD community needs to prepare for the possibility that future architectures/processors may not support efficient double-precision arithmetic, and will require development of mixed-precision codes/algorithms.
- Portable code bases are needed to take full advantage of emerging GPU-based, AI/ML-driven architectures. Some recent progress in this area, in the increasing use of portable programming languages, was noted.
- Use of AI/ML, and multi-fidelity data synthesis, to mine large solution databases generated by LES is recommended.
    - However, it was noted that ML typically needs data from many different configurations. To date, CFD of the CRM-HL has been for only a few configurations at a handful of different conditions (AoA and Re), with not a lot of variety.

- AI/ML could be tasked with setting up models, meshes, and methods – and perhaps combine existing technologies to tackle new problems.
- The AI/ML field is evolving rapidly; will we be able to keep up and leverage these advances effectively? Recommendations/reminders:
  - Need to expand to common frameworks.
  - Might be best to use AI/ML to develop best-practice guidelines.

3.3 *Other technologies expected to play a role*

- AMR, Wall-Resolved Large-Eddy Simulation (WRLES), transition prediction or simulation, error estimation, UQ, parallel space/time methods, multi-fidelity data, reduced-order modeling (including structure-resolving methods and tensor decomposition).

References

[1] J. Slotnick, A. Khodadoust, J. Alanso, D. Darmofal, W. Gropp, E. Lurie & D. Mavriplis 2014: CFD Vision 2030 Study – A Path to Revolutionary Computational Aerosciences. NASA CR 2014-218178. Available from NASA Technical Reports Server (https://ntrs.nasa.gov/citations/20140003093).

[2] T. Mauery, J. Alonso, A. Cary, V. Lee, R. Malecki, D. Mavriplis, G. Medic, J. Schaefer & J. Slotnick 2021: A Guide for Aircraft Certification by Analysis. NASA CR 20210015404. Available from NASA Technical Reports Server (https://ntrs.nasa.gov/citations/20210015404).

Appendix

Agenda for TTT-RCA High-Fidelity CFD Workshop, May 20-22, 2025
Lockheed-Martin Center for Innovation (The Lighthouse)
8000 Harbourview Boulevard, Suffolk, VA 23435

RCA Technical Challenge Statement: Develop and demonstrate computationally efficient, eddy-resolving modeling tools that predict maximum lift coefficient for transport aircraft with the same accuracy as certification flight tests.

Date	Index	Time	Item	Presenter/Org	Time
20-May			**Day 1**		
		7.15am	**Registration**		
		8.00am	**Welcome: Jill Prince, Director, Research Directorate (NASA LaRC)**		
			Session 1: Chaired by Dr. David Lockard (NASA LaRC)		
	1	8.30am	Overview of RCA research portfolio: Progress toward the Technical Challenge	Mujeeb Malik/LaRC	45
	2	9.15am	Large-eddy simulation of high-lift common research model including grid-resolution and wind-tunnel effects	Parviz Moin/Stanford U	45
	3	10.00am	CRM high-lift simulations using FUN3D	Li Wang/LaRC	30
		10.30am	**Break**		**20**
	4	10.50am	CRM high-lift simulations using LAVA	Emre Sozer/ARC	30
	5	11.20am	Wall-modelled large eddy simulations of CRM-HL configuration in NTF	Cetin Kiris/Volcano Platforms, Inc.	30
	6	11.50am	CFD at the Edges of the Envelop (Invited)	Robert Gregg-III/Boeing	30
		12.20pm	**Group Photo + Lunch**		**70**
			Session 2: Chaired by Dr. Robert Baurle (AFRL)		
	7	1.30pm	Chasing the CFD Vision 2030 Exascale Milestone	Eric Nielsen/NASA LaRC	20
	8	1.50pm	Towards grid-adaptation in wall-modeled large-eddy simulations of realistic aerospace flows	Johan Larsson/U Maryland	20
	9	2.10pm	Scale-resolving turbulence simulations through adaptive high-order discretizations and data-enabled model refinements	Chris Fidkowski/U Michigan	20
	10	2.30pm	High-fidelity simulations in support of analysis and design of aircraft engines (Invited)	Stephan Priebe/GE	25
		2.55pm	**Break**		**20**
	11	3.15pm	Outlook for direct/wall-resolved numerical simulations of transitional transonic, supersonic and hypersonic flows (Invited)	Neil Sandham/U Southampton	25
	12	3.40pm	DNS and hybrid RANS/LES of canonical configurations	Ali Uzun/LaRC (AMA)	20
	13	4.00pm	WMLES of the Boeing speed bump	Prahladh Iyer/LaRC (AMA)	20
	14	4.20pm	Advances in subgrid-scale and wall modeling for large-eddy simulations of complex, separating flows	Rahul Agrawal/Stanford U	20
	15	4.40pm	Enabling industrially relevant high-fidelity CFD and AI surrogate models for external aerodynamics (Invited)	Neil Ashton/Nvidia	25
		5.05pm	**End of Day 1**		
		6.30 PM	**[no host] Group Dinner**		
21-May					
		7.30am	**Start of Day 2**		
			Session 3: Chaired by Professor Z J Wang (University of Kansas)		
	16	8.00am	For What the Bell Tolls: Computational efficiency through tuned approximation (Invited)	David Keyes/KAUST	30
	17	8.30am	Glenn flux reconstruction (GFR) development	Seth Spiegel/GRC	25
	18	8.55am	Stabilized finite-elements in FUN3D	Kyle Anderson/LaRC	25
	19	9.20am	Entropy-stable numerical schemes	Mark Carpenter/LaRC	25
	20	9.45am	Advancements in solver technology	Boris Diskin/LaRC	25
		10.10am	**Break**		**20**
	21	10.30am	Matrix and tensor reduced-order modeling for accelerating high-fidelity CFD simulations	Hessam Babaee/U Pittsburgh	30
	22	11.00am	Uncertainty quantification – QUEST	Marian Nemec/ARC	25
	23	11.25am	Advances in multi-fidelity uncertainty quantification to support certification by analysis in the separated-flow regime	Alex Gorodetsky/U Michigan	25
	24	11.50pm	Quantum-ready and quantum-inspired CFD	Peyman Givi/U Pittsburgh	25
		12.15pm	**Lunch**		**55**
			Session 4: Chaired by Dr. Cornelia Grabe (DLR)		
	25	1.10pm	Integrated boundary-layer transition prediction	Meelan Choudhari/LaRC	30

26	1.40pm	Building-block flow model: An ML-based general-purpose closure model for large-eddy simulation (Invited)	Adrian Lozano-Duran/CalTech	30
27	2.10pm	Toward a generalizable RANS model for separation using field inversion and machine learning	Gary Coleman/LaRC	20
28	2.30pm	An efficient data-driven approach for assessment and selection of Reynolds-stress-equation closure models	Ali Mani/Stanford U	20
	2.50pm	**Break**		**20**
29	3.10pm	Developments in automation of overset structured mesh generation	William Chan/ARC	20
30	3.30pm	Toward adaptive mixed-element unstructured grids for simulations of viscous flows	Gabe Nastac/LaRC	20
31	3.50am	Development of Voronoi grid capability for WMLES	Victor Sousa/ARC	20
32	4.10pm	Dynamic AMR for WMLES of complex configurations	Dimitri Mavriplis/Scientific Simulations	20
33	4.30pm	Fully automated large-eddy simulation of JAXA standard model and Mitsubishi SpaceJet high-lift configurations (Invited)	Soshi Kawaii/Tohoku U	20
34	4.50pm	JAXA's CFD and modeling efforts for off-design conditions (Invited)	Hiroyuki Abe/JAXA	20
	5.10pm	**End of Day 2**		

22-May

	7.30am	**Start of Day 3**		
		Session 5: Chaired by Professor Karthik Duraisamy (University of Michigan)		
35	8.00am	BeVERLI - The experiment, the challenge, and community engagement	Chris Roy/VA Tech	20
36	8.20am	CRM-HL Ecosystem	Adam Clark/Boeing	20
37	8.40am	NTF experiments on the CRM-HL configuration	Courtney Winski/LaRC	20
38	9.00am	High-lift flow physics experiment	Dan Neuhart/LaRC	20
39	9.20am	The THX experiments	Nick Georgiadis/GRC	20
40	9.40am	Shock/boundary-layer interaction experiments	Heath Reising/GRC	20
	10.00am	**Break**		**20**
41	10.20am	Transition experiments	Jenna Eppink/LaRC	20
42	10.40am	Aeroelastic analysis with FUN3D	Kevin Jacobson/LaRC	20
43	11.00am	Buffet onset prediction with FUN3D	Emmett Padaway/LaRC	20
44	11.20pm	Transonic buffet prediction in LAVA	Jared Duensing/ARC	20
45	11.40am	Towards GPU-enabled structural analysis tools for aeroelastic certification by analysis	Graeme Kennedy/GA Tech	20
	12.00pm	**Lunch**		**60**
	1.00pm	**Group Discussion: The discussion will be focused on three questions given below.**	Moderated by Jeff Slotnick and Chris Rumsey	
		1. What capabilities have been developed and established for accurately predicting aircraft CLmax, and what are the remaining gaps in our capabilities and understanding? **2. What should be the target application for future CFD developments (the new NASA Revolutionary Computational Aerosciences Technical Challenge) to further advance computational capabilities and why?** **3. What are the key emerging technologies that will likely influence the success of the new Technical Challenge? How should the CFD community explore, develop, and deploy these technologies?** **We will use the following process for the discussion:** **The attendees will be divided into three groups, led by Johan Larsson, Dmitri Mavriplis, and Neil Ashton, each of which will address the above three questions. After about an hour of discussion, and a short break, we will meet back as a single group, and each Leader will report out. One question will be addressed at a time, and we will try to reach broad consensus on each of the three questions.**		
	5.00pm	**End of Workshop**		