Additional Results of Glaze Icing Scaling in SLD Conditions

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Outline

- Background
  - Progress on scaling method development
- Test Objective
- Test Description
- Ice Shape Comparisons
- Conclusion

Modified Ruff Method

- Current recommended method for size scaling
  - In App-C & SLD

Modified Ruff Method

- Current recommended method for size scaling
  - In App-C & SLD
  - Match modified inertia parameter K_0 for scale MVD_S

$$K_0 = \frac{1}{8} + \frac{\lambda}{\lambda_{Stokes}}\left(K - \frac{1}{8}\right)$$

Modified Ruff Method

- Current recommended method for size scaling
  - In App-C & SLD
  - Match modified inertia parameter K_0 for scale MVD_S
  - Match stagnation-point freezing fraction n_0, with a scale LWC_S at user's choice, to find scale $t_{tot,S}$

$$n_0 = \frac{c_{p,ws}}{\Lambda_f}\left(\varphi + \frac{\theta_0}{b_0}\right)$$

Modified Ruff Method

- Current recommended method for size scaling
  - In App-C & SLD
  - Match modified inertia parameter for scale MVD_S
  - Match stagnation-point freezing fraction n_0, with a scale LWC_S at user's choice, to find scale $t_{tot,S}$
  - Match accumulation parameter A_c for scale τ_S

$$A_c = \frac{LWC\, V\, \tau}{d\, \rho_i}$$

Modified Ruff Method

- Current recommended method for size scaling
  - In App-C & SLD
  - Match modified inertia parameter for scale MVD_S
  - Match stagnation-point freezing fraction, with a scale LWC_S at user's choice, to find scale $t_{tot,S}$
  - Match accumulation parameter for A_c for scale τ_S
  - Match Weber Number We_L (= $\rho_w V^2 d / \sigma_{w/a}$) for scale V_S

$$We_L = c, \Rightarrow V_S = V_R \left(\frac{d_R}{d_S} \right)^{1/2}$$

Potential Method for SLD Glaze Icing

- Feo (2007) proposed a slightly different approach
  - Match film Weber Number for scale V_S

$$We_f = \rho_w V_f^2 h_f / \sigma_{w/a}$$

$$We_f = c, \Rightarrow V_S = V_R \left(\frac{d_R}{d_S} \right)^{2/3}$$

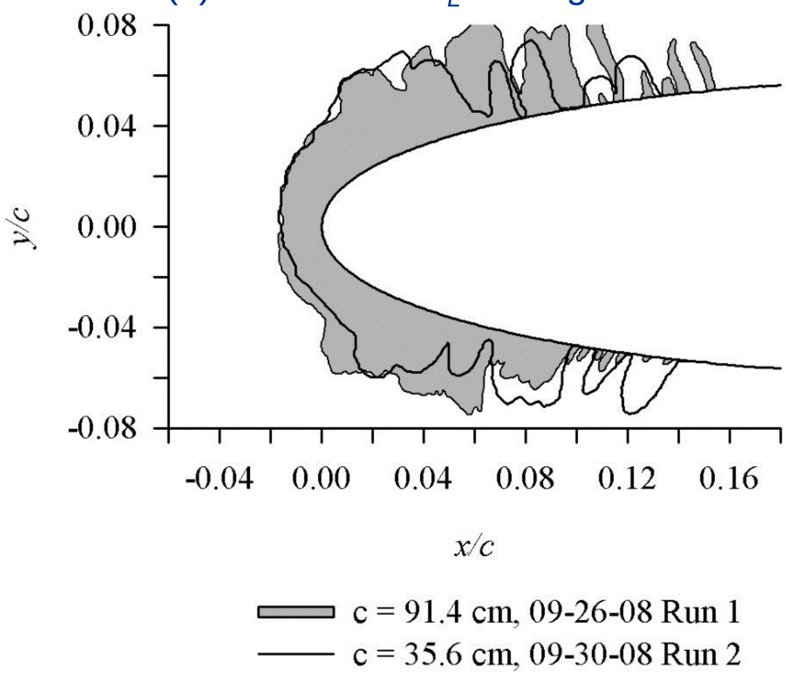
  - Match SLD film thickness correlation for scale LWC_S

$$\frac{h_f}{d} = c, \Rightarrow LWC_S = LWC_R \left(\frac{d_R}{d_S} \right)^{-0.7}$$

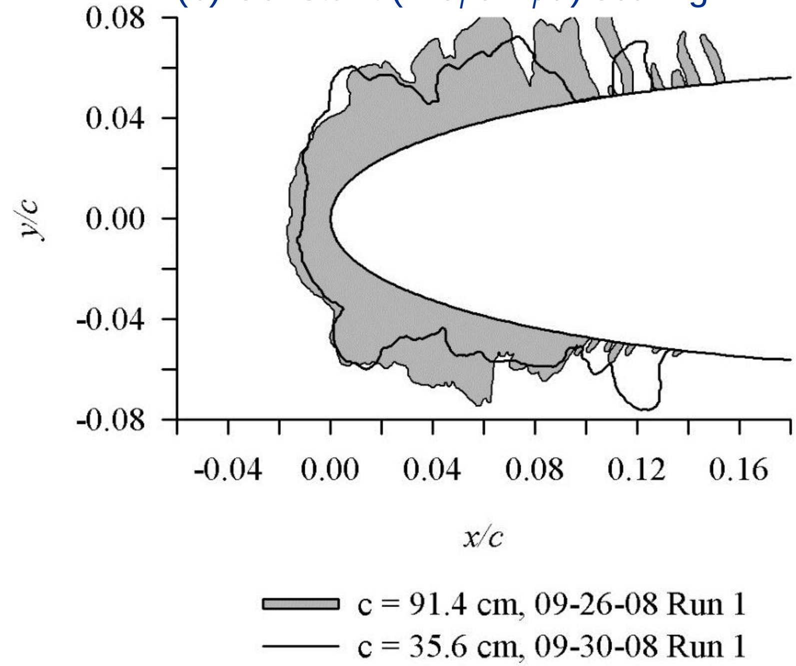
Typical Scaling Results

V_R=100kt, MVD_R=195μm, n_0=0.3

(a) Constant We_L scaling.



(b) Constant (We_f & h_f/d) scaling

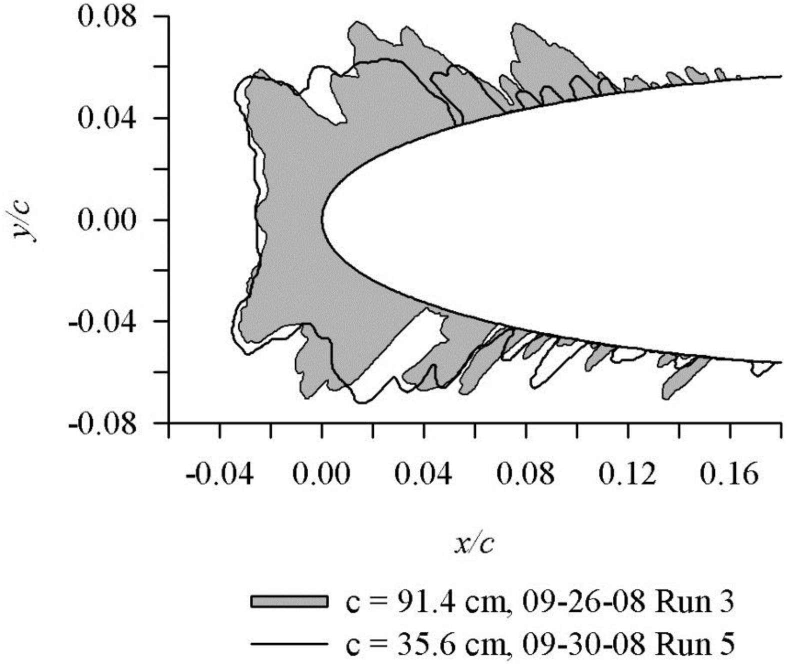


	t_{tot}, °C	V, kt	MVD, μm	LWC, g/m³	τ, min	β_0, %	$\beta_0 A_c$,	n_0,	We_L, 10^6	We_f, 10^{-16}	h_f/d 10^{-9}
Ref	-7.8	100	198	1.08	14.0	96.3	1.69	0.31	1.17	0.74	0.82
(a)	-2.9	159	87	0.57	6.6	96.2	1.73	0.31	1.16	0.86	1.04
(b)	-2.7	185	86	0.54	5.7	96.4	1.63	0.32	1.56	0.72	0.84

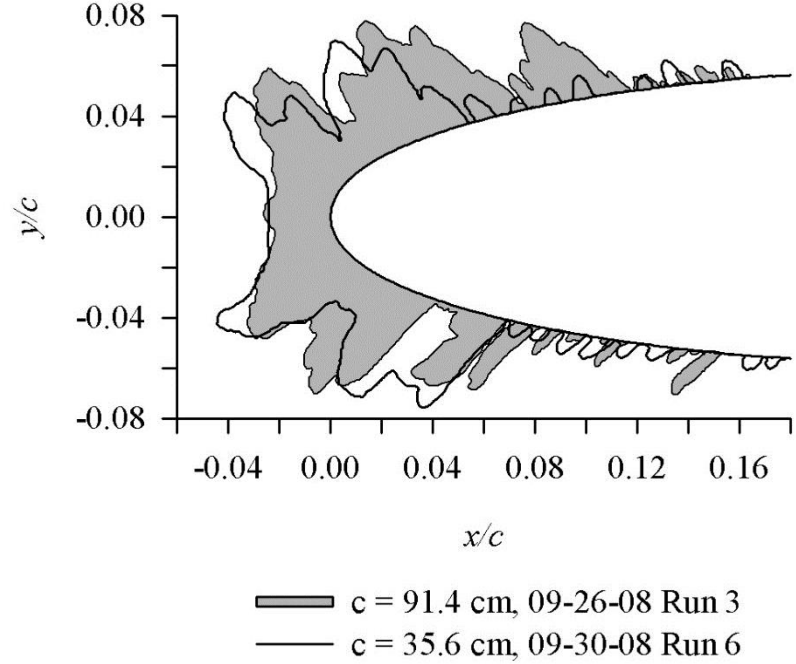
Typical Scaling Results

V_R=100kt, MVD_R=195μm, n_0=0.5

(a) Constant We_L scaling.



(b) Constant (We_f & h_f/d) scaling



		t_{tot},	V,	MVD,	LWC,	τ,	β_0,	$\beta_0 A_c$,	n_0,	We_L,	We_f,	h_f/d
		°C	kt	μm	g/m³	min	%			10^6	10^{-16}	10^{-9}
(grey bar)	Ref	-14.1	100	198	1.07	14.0	96.3	1.69	0.52	1.18	0.74	0.81
(line)	(a)	-5.9	159	87	0.57	6.6	96.2	1.73	0.51	1.16	0.87	1.03
(line)	(b)	-6.0	186	86	0.54	5.7	96.4	1.64	0.53	1.58	0.72	0.83

Test Objective

- Data for larger model size and size ratio
- Expanded SLD conditions in IRT
- Strong glaze icing regime

Test Description

- NASA Glenn Icing Research Tunnel (IRT)
- 72-in and 21-in-Chord NACA 0012 (size ratio 3.4:1)
- AOA = 0°
- n_0 = 0.2, 0.3
- Reference MVD's – 85 μm and 170 μm
- Reference Velocities – 100 kt and 130 kt

NACA 0012 Test Models in IRT

reference model (72”)

scale model (21”)

Ice Shape Photographs

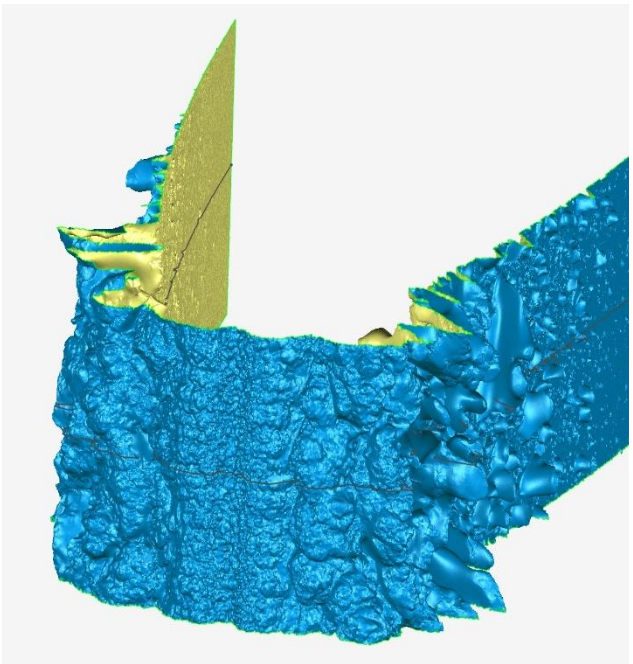
(a) reference

(b) scale

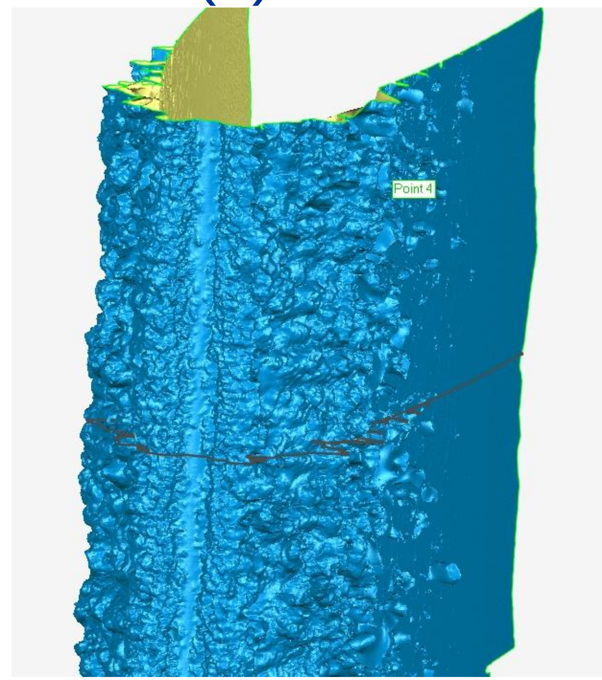
Date/Run	c in	t_{tot} ^{0}C	V kt	MVD μm	LWC g/m^3	t min	b_0 %	A_c	$b_0 A_c$	n_0	We_L 10^6
(a) 12-1-14/3	72	-6.0	99	84	1.2	23.2	82.9	1.61	1.33	0.20	2.30
(b) 1-19-16/6	21	-2.7	184	31	1.0	4.4	83.2	1.62	1.35	0.21	2.33

3-D Scanned Ice Shapes

(a) reference



(b) scale

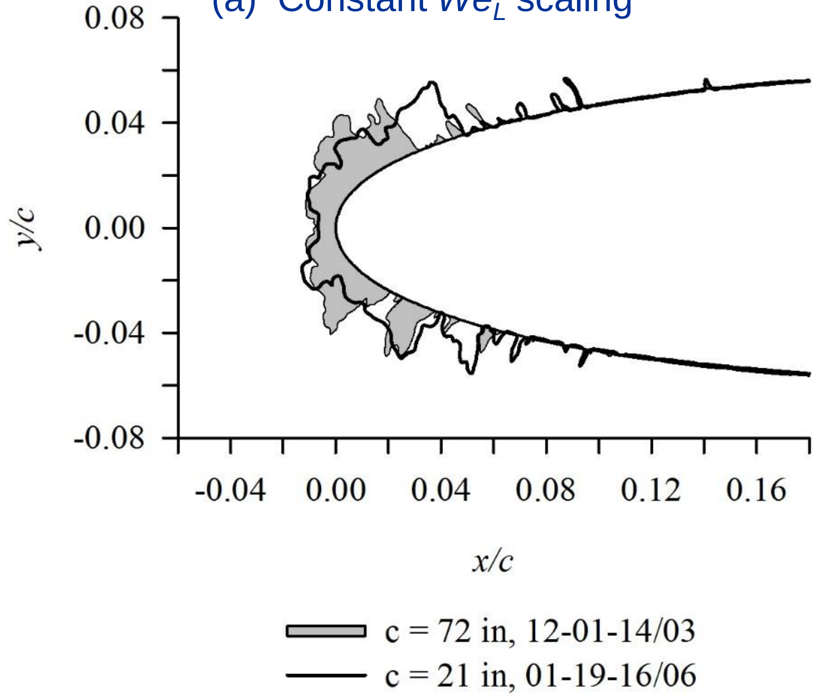


Date/Run	c in	t_{tot} ^{0}C	V kt	*MVD* μm	*LWC* g/m^3	t min	b_0 %	A_c	b_0A_c	n_0	We_L 10^6
(a) 12-1-14/3	72	-6.0	99	84	1.2	23.2	82.9	1.61	1.33	0.20	2.30
(b) 1-19-16/6	21	-2.7	184	31	1.0	4.4	83.2	1.62	1.35	0.21	2.33

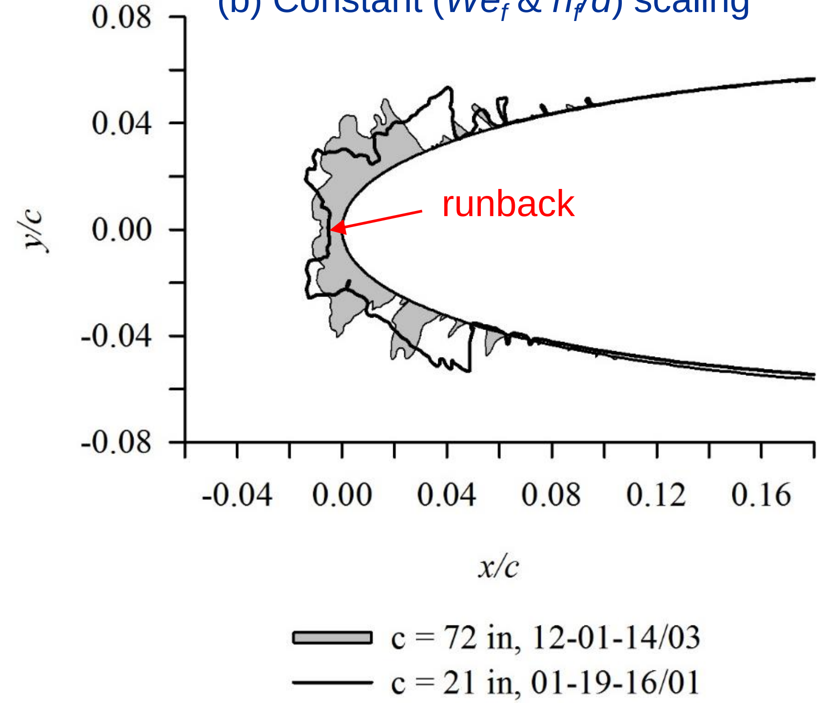
Ice Shapes Comparison (1)

V_R=100kt, MVD_R=85μm, n_0=0.2

(a) Constant We_L scaling



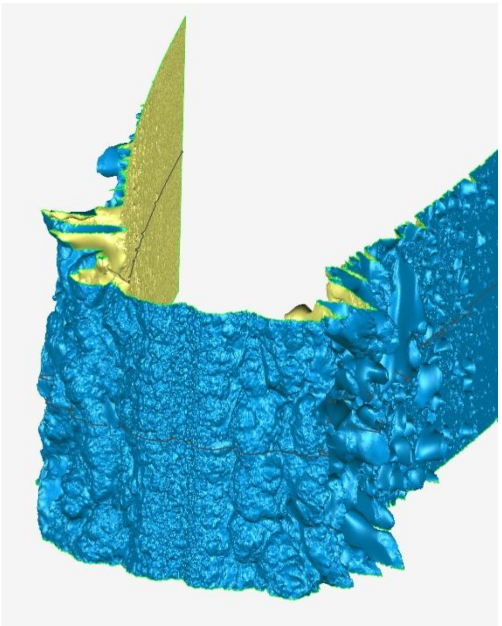
(b) Constant (We_f & h_f/d) scaling



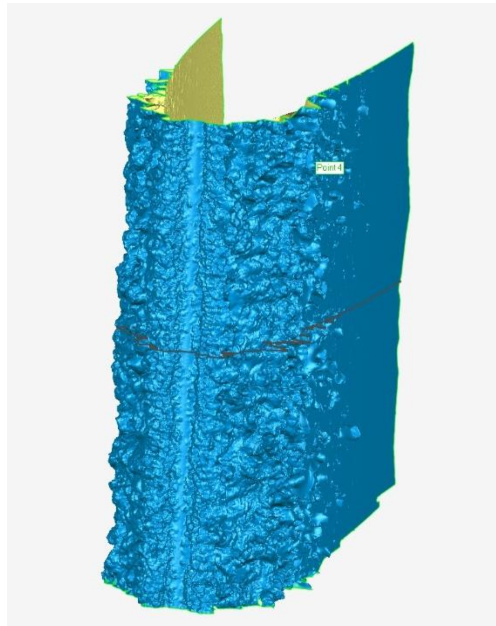
Date/Run	c in	t_{tot} ^{0}C	V kt	MVD μm	LWC g/m^3	t min	b_0 %	A_c	b_0A_c	n_0	We_L 10^6	We_f 10^{-16}	h_f/d, 10^{-9}
12-01-14/03	72	-6.0	99	84	1.2	23.2	82.9	1.61	1.33	0.20	2.30	2.68	0.80
01-19-16/06	21	-2.7	184	31	1.0	4.4	83.2	1.62	1.35	0.21	2.33	2.33	1.42
01-19-16/01	21	-0.2	225	28	0.54	6.3	83.2	1.66	1.38	0.20	3.55	2.81	0.83

3-D Scanned Ice Shapes

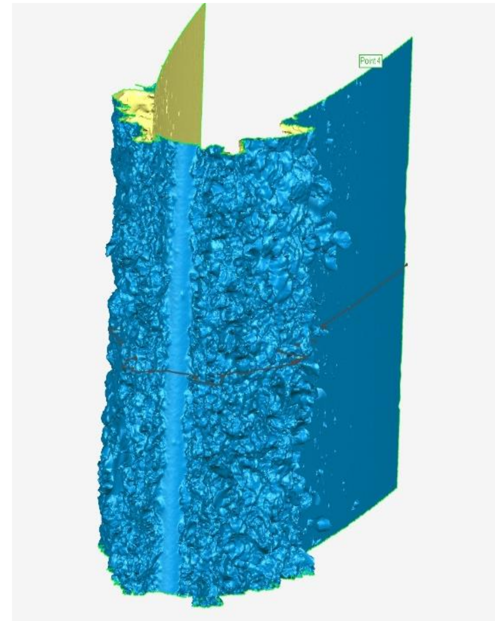
12-01-14/03



01-19-16/06



01-19-16/01

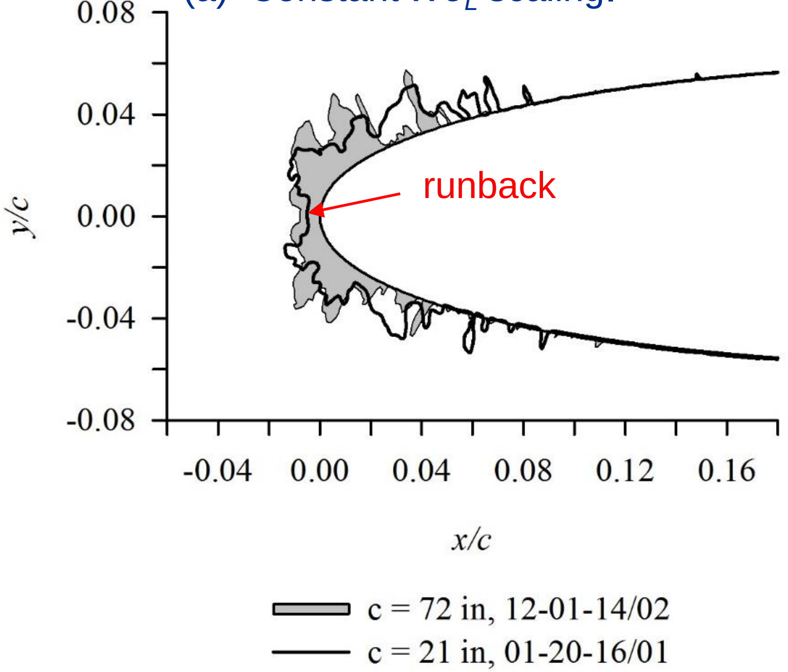


Date/Run	c in	t_{tot} ^{0}C	V kt	MVD μm	LWC g/m^3	t min	b_0 %	A_c	b_0A_c	n_0	We_L 10^6	We_f 10^{-16}	h_f/d, 10^{-9}
12-01-14/03	72	-6.0	99	84	1.2	23.2	82.9	1.61	1.33	0.20	2.30	2.68	0.80
01-19-16/06	21	-2.7	184	31	1.0	4.4	83.2	1.62	1.35	0.21	2.33	2.33	1.42
01-19-16/01	21	-0.2	225	28	0.54	6.3	83.2	1.66	1.38	0.20	3.55	2.81	0.83

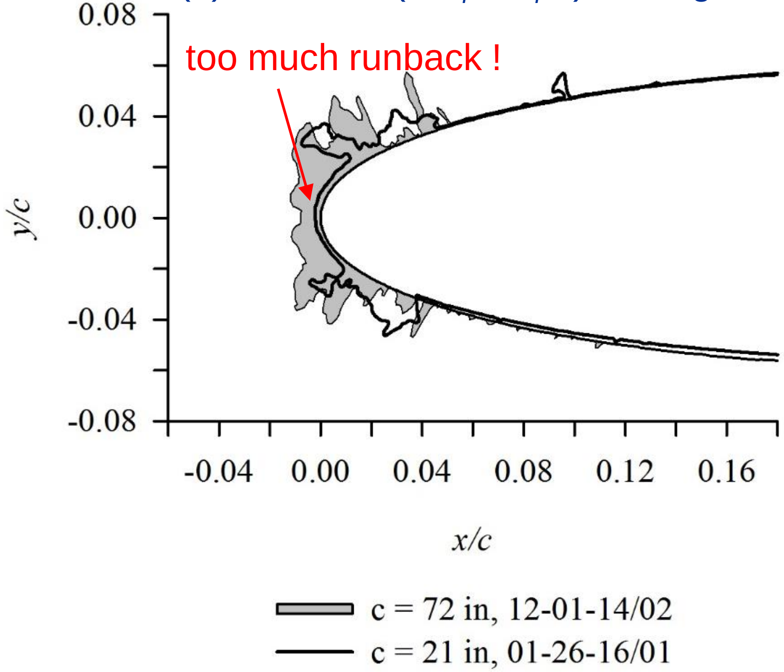
Ice Shapes Comparison (2)

V_R=130kt, MVD_R=85µm, n_0=0.2

(a) Constant We_L scaling.



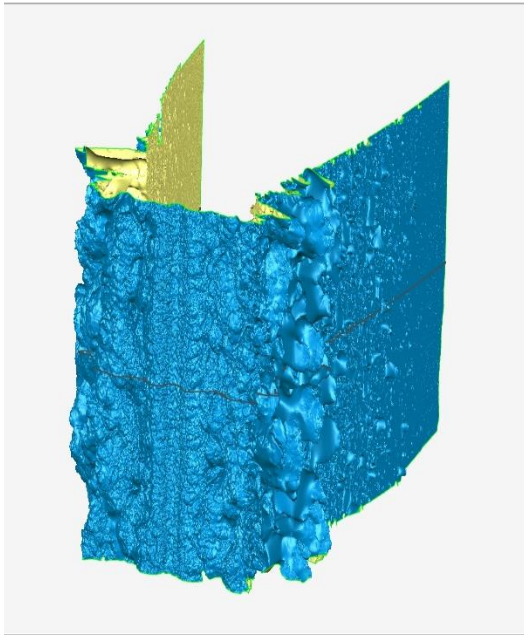
(b) Constant (We_f & h_f/d) scaling



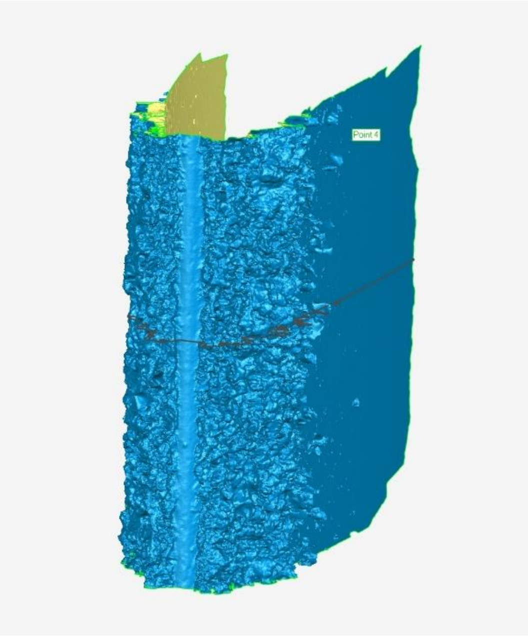
Date/Run	*c* in	t_{tot} °C	*V* kt	*MVD* µm	*LWC* g/m³	*t* min	b_0 %	A_c	b_0A_c	n_0	We_L 10^6	We_f 10^{-16}	h_f/d, 10^{-9}
12-01-14/02	72	-5.3	129	85	0.95	22.1	84.7	1.57	1.33	0.21	3.91	1.52	0.51
01-20-16/01	21	-0.4	239	30	0.60	5.5	84.8	1.59	1.34	0.20	3.93	3.06	0.81
01-26-16/01	21	1.7	296	28	0.42	6.7	84.9	1.67	1.41	0.20	6.00	1.71	0.55

3-D Scanned Ice Shapes

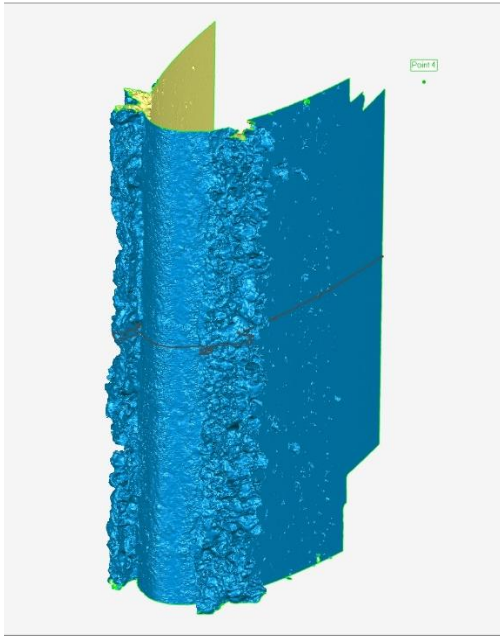
12-01-14/02



01-20-16/01



01-26-16/01

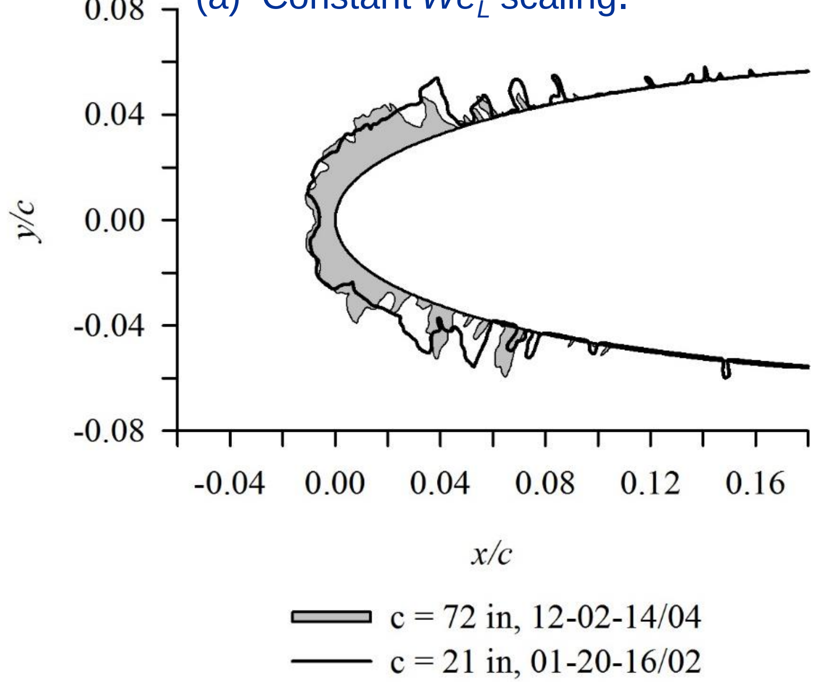


Date/Run	*c* in	t_{tot} ^{0}C	*V* kt	*MVD* *μm*	*LWC* g/m^3	*t* min	b_0 %	A_c	b_0A_c	n_0	We_L 10^6	We_f 10^{-16}	h_f/d, 10^{-9}
12-01-14/02	72	-5.3	129	85	0.95	22.1	84.7	1.57	1.33	0.21	3.91	1.52	0.51
01-20-16/01	21	-0.4	239	30	0.60	5.5	84.8	1.59	1.34	0.20	3.93	3.06	0.81
01-26-16/01	21	1.7	296	28	0.42	6.7	84.9	1.67	1.41	0.20	6.00	1.71	0.55

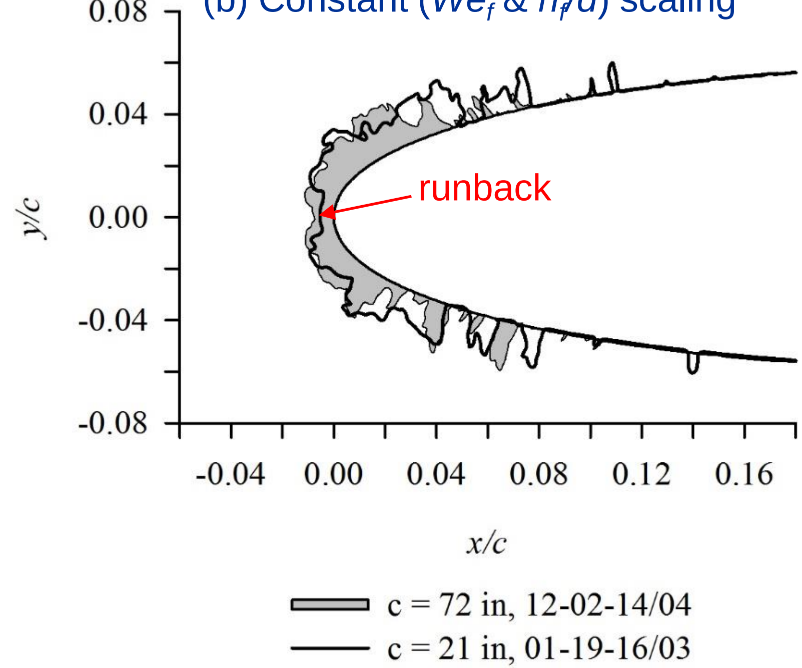
Ice Shapes Comparison (3)

V_R=100kt, MVD_R=170μm, n_0=0.2

(a) Constant We_L scaling.



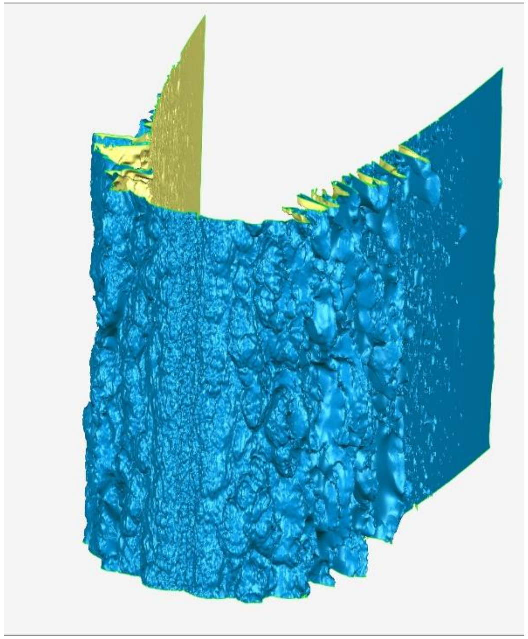
(b) Constant (We_f & h_f/d) scaling



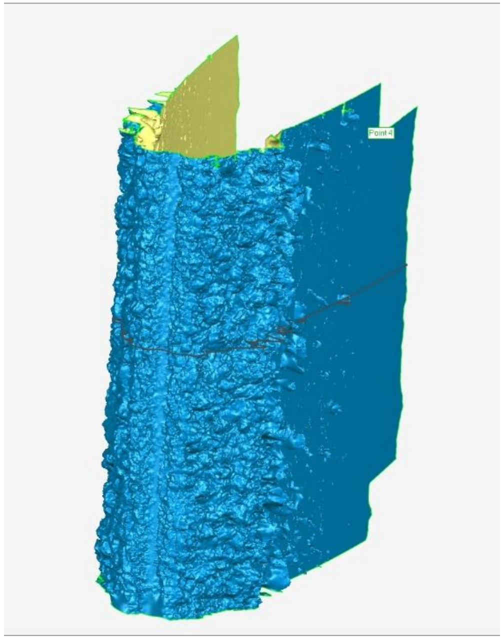
Date/Run	c in	t_{tot} ^{0}C	V kt	MVD μm	LWC g/m^3	t min	b_0 %	A_c	b_0A_c	n_0	We_L 10^6	We_f 10^{-16}	h_f/d, 10^{-9}
12-02-14/04	72	-6.9	99	171	1.35	18.6	92.3	1.45	1.34	0.20	2.30	1.10	0.60
01-20-16/02	21	-1.2	185	59	0.50	7.9	92.2	1.46	1.35	0.21	2.34	1.02	0.72
01-19-16/03	21	-0.8	226	58	0.56	5.7	92.6	1.44	1.33	0.20	3.52	1.08	0.60

3-D Scanned Ice Shapes

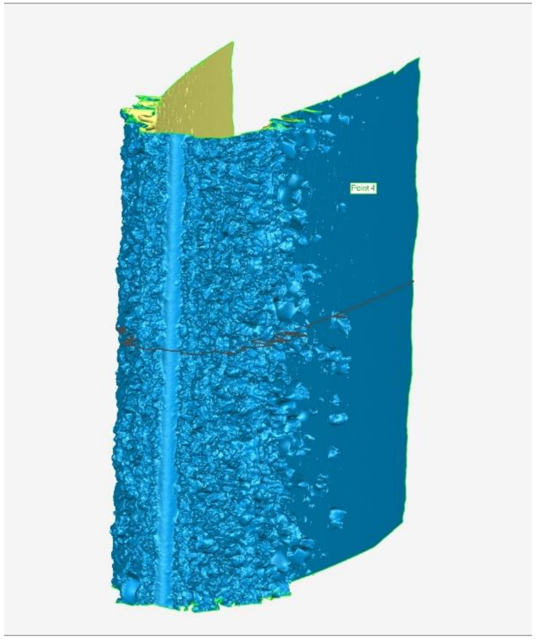
12-02-14/04



01-20-16/02



01-19-16/03

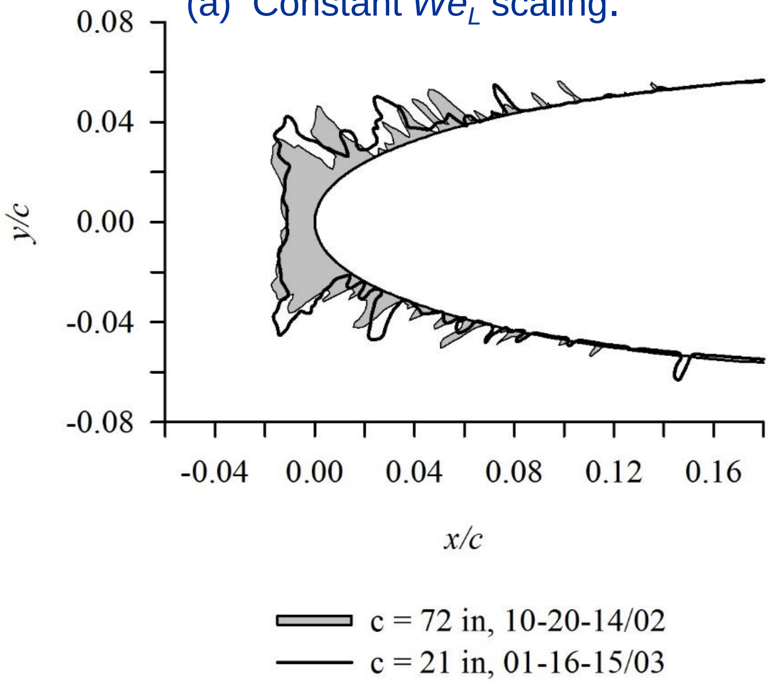


Date/Run	*c* in	t_{tot} ^{0}C	*V* kt	*MVD* *µm*	*LWC* g/m^3	*t* min	b_0 %	A_c	b_0A_c	n_0	We_L 10^6	We_f 10^{-16}	h_f/d, 10^{-9}
12-02-14/04	72	-6.9	99	171	1.35	18.6	92.3	1.45	1.34	0.20	2.30	1.10	0.60
01-20-16/02	21	-1.2	185	59	0.50	7.9	92.2	1.46	1.35	0.21	2.34	1.02	0.72
01-19-16/03	21	-0.8	226	58	0.56	5.7	92.6	1.44	1.33	0.20	3.52	1.08	0.60

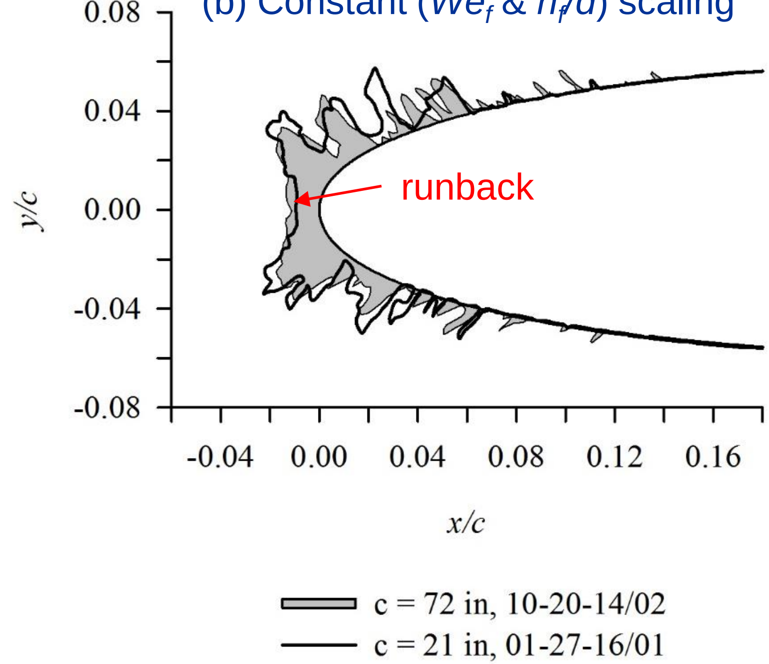
Ice Shapes Comparison (4)

V_R=100kt, MVD_R=170μm, n_0=0.3

(a) Constant We_L scaling.



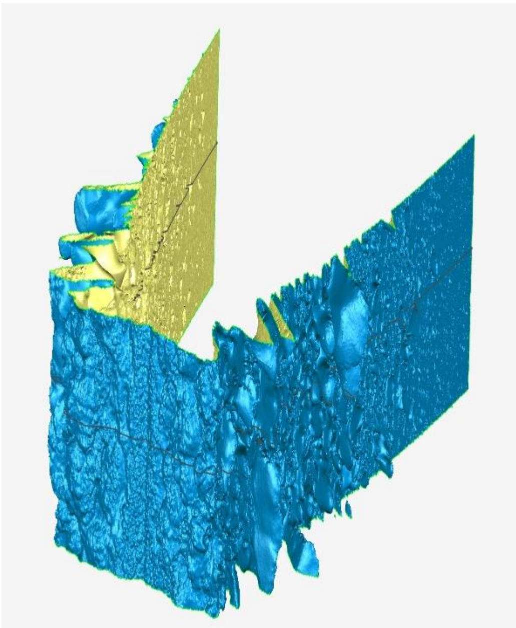
(b) Constant (We_f & h_f/d) scaling



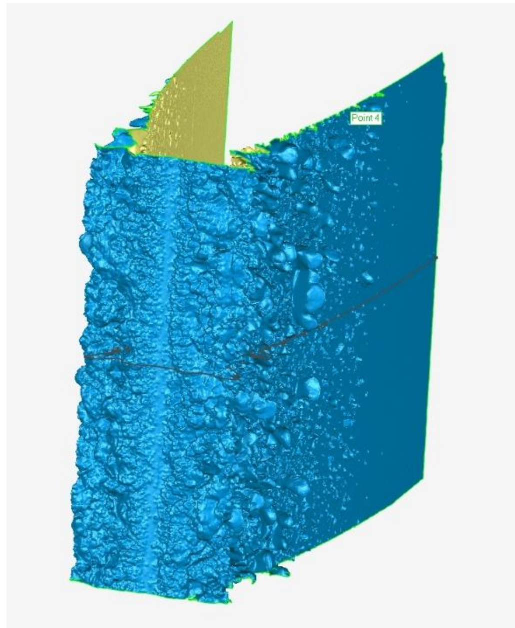
Date/Run	c in	t_{tot} °C	V kt	MVD μm	LWC g/m³	t min	b_0 %	A_c	b_0A_c	n_0	We_L 10^6	We_f 10^{-16}	h_f/d, 10^{-9}
10-20-14/02	72	-10.8	99	171	1.35	18.6	92.4	1.45	1.34	0.30	2.30	1.10	0.59
01-16-15/03	21	-3.1	185	59	0.50	7.3	92.2	1.35	1.25	0.33	2.35	1.01	0.72
01-27-16/01	21	-2.8	226	58	0.56	5.7	92.6	1.44	1.33	0.30	3.50	1.08	0.60

3-D Scanned Ice Shapes

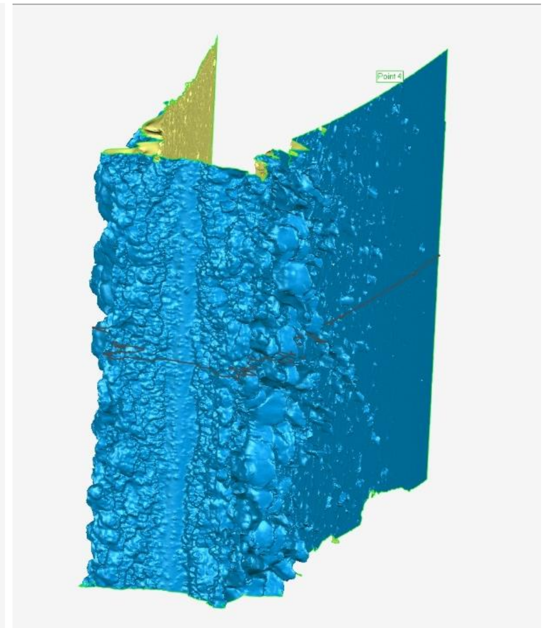
10-20-14/02



01-16-15/03



01-27-16/01



Date/Run	c in	t_{tot} ^{0}C	V kt	MVD μm	LWC g/m^3	t min	b_0 %	A_c	b_0A_c	n_0	We_L 10^6	We_f 10^{-16}	h_f/d, 10^{-9}
10-20-14/02	72	-10.8	99	171	1.35	18.6	92.4	1.45	1.34	0.30	2.30	1.10	0.59
01-16-15/03	21	-3.1	185	59	0.50	7.3	92.2	1.35	1.25	0.33	2.35	1.01	0.72
01-27-16/01	21	-2.8	226	58	0.56	5.7	92.6	1.44	1.33	0.30	3.50	1.08	0.60

Conclusion

- Modified Ruff method evaluated
- Feo method evaluated
- For limited testing at n_0 = 0.2, 0.3 (strong glaze icing),
    - Better match of reference ice shapes with constant We_L provided t_{tot} < -2 °C.
    - All still within the ice shape repeatability.
- Size of ice accretion, icing limits well simulated.
- Large feather simulations need improvement

Acknowledgement

- Personal thanks to
  - Mr. Quentin Schwinn for the imaging & scan data process support.
  - IRT cloud cal team and the crew for their excellent support.