Meteorological Monographs

Response to comment by Dr Rangno on “Secondary Ice Production: Current State of the Science and Recommendations for the Future” by Field et al.

--Manuscript Draft--

Manuscript Number:	AMSMONOGRAPHS-D-19-0004
Full Title:	Response to comment by Dr Rangno on “Secondary Ice Production: Current State of the Science and Recommendations for the Future” by Field et al.
Article Type:	Reply (online-only)
Corresponding Author:	Paul Field Met Office Exeter, UNITED KINGDOM
Corresponding Author's Institution:	Met Office
First Author:	Paul Field
Order of Authors:	Paul Field
	Paul Lawson
	Philip Brown
	Gary Lloyd
	Chris Westbrook
	Dmitri Moisseev
	Annette Miltenberger
	Athanasios Nenes
	Alan Blyth
	Tom Choularton
	Paul Connolly
	Johannes Buehl
	Jonny Crosier
	Zhiqiang Cui
	Chris Dearden
	Paul DeMott
	Andrea Flossman
	Andy Heymsfield
	Yahui Huang
	Heike Kalesse
	Zamin Kanji
	Alexei Korolev
	Amelie Kirchgaessner
	Sonia Lasher-Trapp
	Thomas Leisner
	Greg McFarquhar
	Vaughan Phillips
	Jeff Stith

	Sylvia Sullivan
Abstract:	.
Suggested Reviewers:	

Response to comment by Dr Rangno on "Secondary Ice Production: Current State of the Science and Recommendations for the Future" by Field et al.

Paul Field. Met Office, Exeter, UK & Univ. of Leeds, UK.
Paul Lawson. SPEC inc. CO, USA.
Philip Brown. Met Office, Exeter, UK.
Gary Lloyd. Univ. Manchester, UK.
Chris Westbrook. Univ. Reading, UK.
Dmitri Moisseev. Univ. Helsinki, Finland.
Annette Miltenberger. Univ. Mainz, Germany.
Athanasios Nenes. Georgia Institute of Technology, GA, USA.
Alan Blyth. NCAS, Univ. Leeds, UK.
Tom Choularton. Univ. Manchester, UK.
Paul Connolly. Univ. Manchester, UK.
Johannes Buehl. Leibniz Institute for Tropospheric Research, Leipzig, Germany.
Jonny Crosier. Univ. Manchester, UK.
Zhiqiang Cui. Univ. Leeds, UK.
Chris Dearden. Univ. Leeds, UK.
Paul DeMott. Colorado State University, CO, USA.
Andrea Flossman. OPGC., Univ. Claremont Ferrand, France.
Andy Heymsfield. NCAR, CO, USA
Yahui Huang. Univ. Leeds, UK.
Heike Kalesse. Univ. Leipzig, Germany.
Zamin Kanji. ETH, Zurich, Switzerland.
Alexei Korolev. Environment Canada, Canada.
Amelie Kirchgaessner. British Antarctic Survey, UK.
Sonia Lasher-Trapp. Univ. Illinois, IL, USA.
Thomas Leisner. FZK, Karlsruhre, Germany.
Greg McFarquhar, CIMMS, Univ. Oklahoma, Norman, OK, USA.
Vaughan Phillips. Lund Univ., Sweden.
Jeff Stith. NCAR, CO, USA.
Sylvia Sullivan. Georgia Institute of Technology. GA, USA.

We thank Dr Rangno for his comments (hereafter referred to as R2019). R2019 Does an excellent job of gathering together and discussing many original publications related to the still unresolved problem of Secondary Ice Production (SIP), and we welcome this additional source of information to appear alongside Field et al. 2017 (F2017).

It is clear that a SIP mechanism is acting in supercooled clouds. It is not clear what the mechanism is. There is a lack of understanding at the detailed process level about what is actually occurring. Is there one process or are there many processes that act in different conditions and interact through the evolution of the cloud? Our goal is to reinvigorate this area of cloud physics research and motivate basic understanding of the processes at play in order to represent them more accurately in models. Currently their representation is crude and hampers our ability to understand the impact of these processes on precipitation formation, cloud feedbacks and climate sensitivity.

R2019 makes several assertions that we will address in this response. Perhaps the main point of concern that led to the comment was that "...the distinction between clouds that produce ice rapidly and the inability of the H-M (Hallett-Mossop) process alone to do that in slightly supercooled cumulus clouds beginning with primary ice nuclei was not made clear..." (R2019). This motivated R2019 to bring to bear an impressive collection of observations spanning 7 decades. What is clear from the references listed in both R2019 and F2017 is the fact that there is no consensus on parameters such as the temperature range SIP is observed to act over, the requirement for number concentrations of small, large or both supercooled cloud droplets or raindrops, or the humidity environment. Without a basic microphysical model to describe SIP it is challenging to determine signal from noise. The comment by Blyth and Latham (1998) suggests that two different schools of thought can interpret the data in opposing ways indicating that the interpretation of aircraft data alone is difficult without a solid underpinning physical model that includes dynamics. What R2019 and F2017 both agree on is that the measured ice crystal number concentration is larger than the measured or expected ice nucleating particle number concentration. Furthermore, F2017 does agree with the R2019 hypothesis that the H-M rime splintering mechanism is not the only potential SIP or even the SIP that acts outside of the laboratory in real clouds. A prime motivation for F2017 was to stimulate new work by bringing new methods to bear on the problem, be they laboratory, remote sensing or improved airborne probes, and derive new fundamental understanding of this process.

It is difficult to use aircraft to study individual microphysical processes when the fundamental understanding of what is occurring at the scale of individual hydrometeors is missing. Even employing ground based observations, used to avoid the potential artifacts introduced by aircraft sampling, are not immune to being impacted by other artifacts (e.g. wind-blown surface ice particles: (Vali et al. 2012, Farrington et al. 2016, Beck et al. 2018). This makes it difficult to interpret and use results from these sites to understand SIP. That said, careful analysis of ground based data that attempts to filter out wind-blown frost has pointed to the action of SIP at -15C (e.g. Magnani et al. 2019).

New detailed laboratory work exploiting high speed digital imagery (e.g. Emersic and Connolly 2017), environmental control of parameters outside of the range of the original H-M experiments and conditions at the surface of the hydrometeors needs to be undertaken. For instance, novel investigations were made by Lauber et al. (2018) of the freezing of levitated droplets that experience bubble bursting, jetting, cracking, and breakup. They were able to quantify the importance of parameters such as droplet size and temperature. Using these approaches provides testable hypotheses of SIP that can be challenged in the field with aircraft and remote sensing.

We will need to repeat airborne observations with new instrumentation. For instance, Heymsfield and Willis (2014) suggested that the high FSSP concentrations of ice reported by Stith et al. (2004) might be due to shattering of large ice on the inlets (tube) of the FSSP and cautioned against using these observations to specify secondary ice concentrations. Although R2019 rightly points out that interarrival time analysis was used in the 1970s as identified (e.g. Cooper 1977) in Field et al. (2006), it is unfortunately not sufficient to remove all artifacts on its own. Replacement probe tips to reduce particle shattering and deflection into the sample volume are also required (Korolev et al. 2013) and new techniques, such as digital holography offer new techniques to improve our detection of shattering events. Repeat observations are necessary to improve our quantitative survey of SIP and allow for critical tests of SIPs hypothesised from the new wave of laboratory studies.

It is important to point out that capabilities for ice nucleation measurements have advanced in recent years (Kanji et al., 2017) and critical assessment of uncertainties have been occurring (e.g., DeMott et al., 2017). Unfortunately, some results from DeMott et al. (2016) have been misconstrued in R2019 as suggesting that oceans are rich sources of high temperature ice nucleating particles (INP). In fact DeMott et al. (2017) showed that oceans are generally weak sources of high temperature INP produced from sea spray. It is still the case that no primary ice nucleation pathways can explain enhanced ice concentrations that are attributed to secondary processes.

Another point raised in R2019 was that droplet sizes are critical for the operation of SIP. We agree with this assertion and stated that large droplets are required for SIP. We would argue that the statement in R2019 that “drizzle-sized drops up to about 500 µm diameter were always found,” qualitatively agrees with our statement rather than disagrees. This highlights that we need to be careful when we use statements about low or high concentrations, large or small droplet sizes. These need to be given together and quantified. The nature of droplet size distributions also means that stating a single size and concentration is not sufficient to describe the hydrometeor population and that we should give the spectral parameters of a fit to the observations or the concentrations for at least two sizes. The presence of 500 micron droplets indicates that there will be larger particles present too, although in lower concentrations. As was discussed in F2017, the threshold primary ice nucleation concentration required to start a cascade of SIP is not constrained, but the low values quoted ($10^{-5} – 10^{-3}$ L^{-1}) are challenging for current probes to detect if these large (~>1mm) particles are indeed the initial particles that freeze.

A renaissance of remote sensing is occurring as ground-based and airborne radars are upgraded to allow multi- parameter detection of dual polarisation, differential reflectivity, attenuation and doppler velocities (e.g. Kumjian and Lombardo 2017), allowing information about the alignment and shape of hydrometeors to be obtained. When combined with coincident aircraft measurements, new laboratory-derived SIP hypotheses can be better tested through observations. This will lead to new modelling studies to explore alternative SIP hypotheses that act in different temperature regimes and interact with the hydrometeor populations in different ways than the HM process (e.g. Phillips et al. 2018, Sullivan et al. 2018).

These new areas of research will lead to progress in quantitatively understanding and representing SIP. Together R2019 and F2017 provide a useful reference for new researchers working on these phenomena.

References

Beck, A. and Henneberger, J. and Fugal, J. P. and David, R. O. and Lacher, L. and Lohmann, U., Impact of surface and near-surface processes on ice crystal concentrations measured at mountain-top research stations. Atmospheric Chemistry and Physics, 18, 8909-8927, 2018.

Blyth, A. M. and Latham, J. Comments on cumulus glaciation papers by P.V. Hobbs and A.L. Rangno. Q. J. R. Meteorol. Soc., 124, 1007-1008. doi-org/10.1002/qj.49712454716.

Paul J. DeMott, et al. Sea spray aerosol as ice nucleating particles.
Proceedings of the National Academy of Sciences May 2016, 113 (21) 5797-5803; DOI: 10.1073/pnas.1514034112

DeMott, P. J., Hill, T. C. J., Petters, M. D., Bertram, A. K., Tobo, Y., Mason, R. H., Suski, K. J., McCluskey, C. S., Levin, E. J. T., Schill, G. P., Boose, Y., Rauker, A. M., Miller, A. J., Zaragoza, J., Rocci, K., Rothfuss, N. E., Taylor, H. P., Hader, J. D., Chou, C., Huffman, J. A., Pöschl, U., Prenni, A. J., and Kreidenweis, S. M.: Comparative measurements of ambient atmospheric concentrations of ice nucleating particles using multiple immersion freezing methods and a continuous flow diffusion chamber, Atmos. Chem. Phys., 17, 11227-11245, https://doi.org/10.5194/acp-17-11227-2017, 2017.

Emersic, C., and Connolly, P.J. Microscopic observations of riming on an ice surface using high speed video. ATMOSPHERIC RESEARCH, 185, 65-72, DOI: 10.1016/j.atmosres.2016.10.014.

Farrington, R. J., Connolly, P. J., Lloyd, G., Bower, K. N., Flynn, M. J., Gallagher, M. W., Field, P. R., Dearden, C., and Choularton, T. W.: Comparing model and measured ice crystal concentrations in orographic clouds during the INUPIAQ campaign, Atmos. Chem. Phys., 16, 4945-4966, https://doi.org/10.5194/acp-16-4945-2016, 2016.

Field, P.R., R.P. Lawson, P.R. Brown, G. Lloyd, C. Westbrook, D. Moisseev, A. Miltenberger, A. Nenes, A. Blyth, T. Choularton, P. Connolly, J. Buehl, J. Crosier, Z. Cui, C. Dearden, P. DeMott, A. Flossmann, A. Heymsfield, Y. Huang, H. Kalesse, Z.A. Kanji, A. Korolev, A. Kirchgaessner, S. Lasher-Trapp, T. Leisner, G. McFarquhar, V. Phillips, J. Stith, and S. Sullivan, 2017: Secondary Ice Production: Current State of the Science and Recommendations for the Future. *Meteorological Monographs*, **58**, 7.1–7.20, https://doi.org/10.1175/AMSMONOGRAPHS-D-16-0014.1

Kanji, Z.A., L.A. Ladino, H. Wex, Y. Boose, M. Burkert-Kohn, D.J. Cziczo, and M. Krämer, 2017: Overview of Ice Nucleating Particles. *Meteorological Monographs*, **58**, 1.1–1.33

Kumjian, M.R. and Lombardo, K.A. Insights into the Evolving Microphysical and Kinematic Structure of Northeastern US Winter Storms from Dual-Polarization Doppler Radar. MONTHLY WEATHER REVIEW, 145, 1033-1061, DOI: 10.1175/MWR-D-15-0451.1.

Lauber, A., A. Kiselev, T. Pander, P. Handmann, and T. Leisner, 2018: Secondary Ice Formation during Freezing of Levitated Droplets. *J. Atmos. Sci.*, **75**, 2815–2826.

Mignani, C., Creamean, J. M., Zimmermann, L., Alewell, C., and Conen, F.: New type of evidence for secondary ice formation at around −15 °C in mixed-phase clouds, Atmos. Chem. Phys., 19, 877-886, https://doi.org/10.5194/acp-19-877-2019, 2019.

Phillips, V.T., S. Patade, J. Gutierrez, and A. Bansemer, 2018: Secondary Ice Production by Fragmentation of Freezing Drops: Formulation and Theory. *J. Atmos. Sci.*, **75**, 3031–3070

Stith, J.L., J.A. Haggerty, A. Heymsfield, and C.A. Grainger, 2004: Microphysical Characteristics of Tropical Updrafts in Clean Conditions. J. Appl. Meteor., 43, 779–794, https://doi.org/10.1175/2104.1

Sullivan, S. C., Hoose, C., Kiselev, A., Leisner, T., and Nenes, A.: Initiation of secondary ice production in clouds, Atmos. Chem. Phys., 18, 1593-1610, https://doi.org/10.5194/acp-18-1593-2018, 2018.

Vali, G. , Leon, D. and Snider, J. R. (2012), Ground-layer snow clouds. Q.J.R. Meteorol. Soc., 138: 1507-1525.