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Laboratory Experiments on the Droplet Shattering Secondary Ice Production Mechanism

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Session AS3.9, Display 7609 – Chat Wed, 06 May, 16:15 – 18:00 UTC+2

Karlsruhe Institute of Technology, Institute of Meteorology and Climate Research – Atmospheric Aerosol Research

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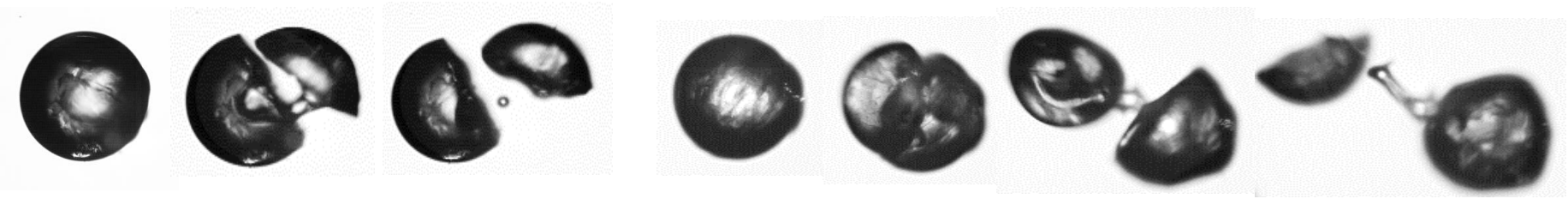
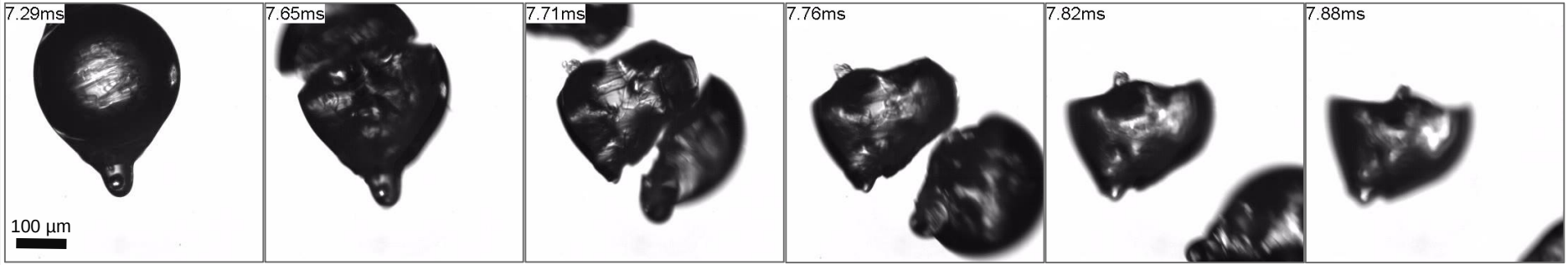


Secondary Ice Production via Droplet Shattering

Observations have shown that the number concentration of ice crystals can exceed the number concentration of ice nucleating particles by several orders in magnitude. Several secondary ice production (SIP) mechanisms have been proposed to explain this discrepancy, with the Hallett-Mossop mechanism being the most well-known.

However, the Hallett-Mossop process is only active in a limited range of temperature, leaving other mechanisms like droplet shattering as valid candidates to explain ice multiplication in clouds.

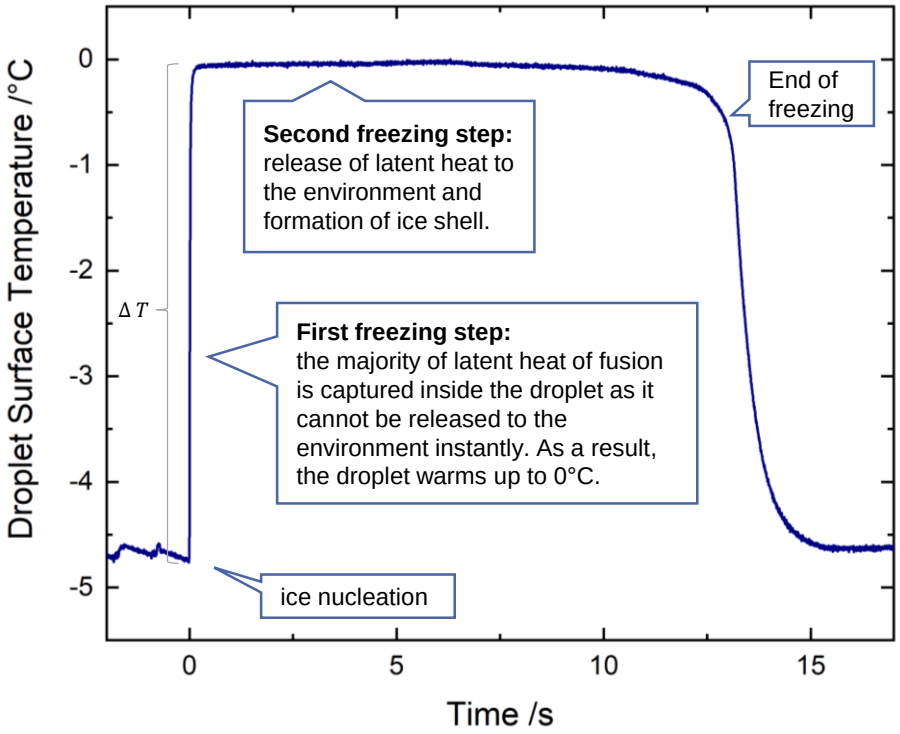


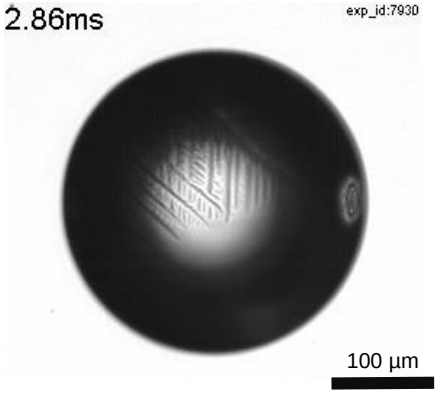
Droplet shattering in laboratory experiment at KIT

Evidence for shattering of freezing water droplets in clouds has been provided by Knight and Knight (1974), who have observed hemispherical fragments of frozen droplets preserved as hailstone embryos.

Recently images of fragmented frozen drizzle droplets taken during in-cloud aircraft-based measurements have been presented by Korolev et al. (2020).

The Freezing of Supercooled Water Droplets





First freezing step:
ice starts spreading in the form of dendrites through the droplet volume as ice nucleation is initiated. The a mass fraction

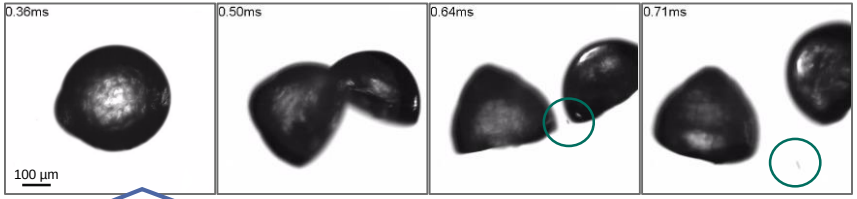
$$f_{ice} \approx \frac{\Delta T}{80\ \mathrm{K}}$$

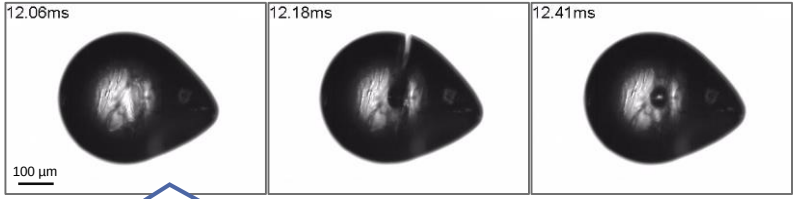
of water is converted to ice.

Second freezing step:
in order to convert the remaining water to ice, latent heat must be removed to the environment through the droplet‘s surface. As a consequence, the ice shell forms at the droplet‘s surface that grows inwards. As water expands upon freezing, the ice shell exerts pressure on the inner core of the droplet that can result in violent rupture of the ice shell e.g. droplet shattering and the production of secondary ice particles.

Further reading:
Pruppacher and Klett, 1997

Secondary Ice Production Mechanisms Associated with Droplet Freezing





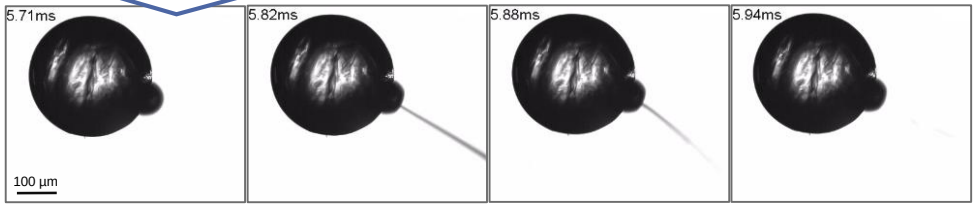
Breakup: complete breakup of a droplet while ejecting a smaller ice particle (marked with a circle in the third and fourth frame above).
Sometimes the two halves don't separate fully (incomplete breakup).

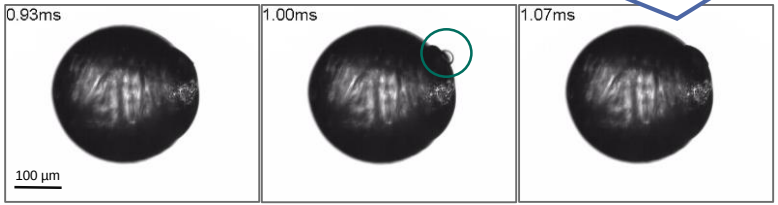
Jetting: ejection of liquid (?) from the droplet interior. Ejected substance might contain ice particles!

Freezing droplets react to the increasing pressure inside the droplet core not only by breakup, but via other mechanisms as well: cracking, bubble burst and jetting.

Cracking: pressure release by transient appearance of a crack in the droplet. In this video, the cracking is accompanied by the capture of an air bubble. Small secondary ice particles could be ejected during cracking.

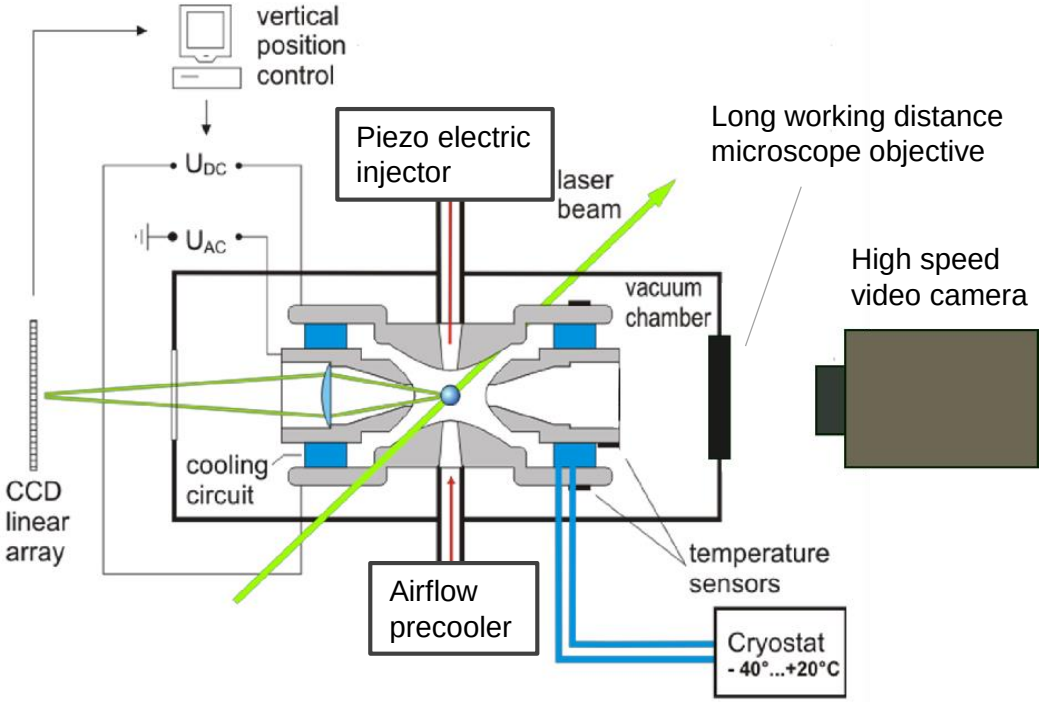
Bubble burst: small bubble forms on the surface of the freezing droplet and bursts eventually. If the bubble was partly or completly frozen at the time of bursting, secondary ice particles could be produced during bubble bursts. Bubbles can also form on the tip of a spicule (spicular bubble burst).





Experimental Setup

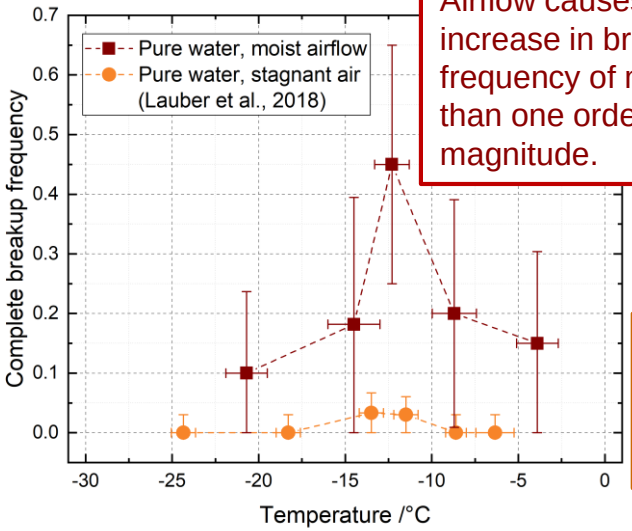
See also contribution 2889 by Judith Kleinheins et al.
https://doi.org/10.5194/egusphere-egu2020-2889



- More than 700 individual water droplets have been levitated in a temperature controlled electrodynamic balance setup.
- Droplets are exposed to a flow of cold air from below, simulating free fall conditions.
- Droplet freezing and SIP events are observed with a high speed video camera (*Phantom v710 Vision Research*).
- Variable experimental conditions:
  - Moist (ice saturated) and dry airflow (T_{dew}=-40°C)
  - Pure water droplets and droplets of aqueous solution of sea salt analogue (2.9 mg/L SSA)
  - Airflow temperature from -1°C to -30°C

SIP Rates in Moist Airflow vs. Stagnant Air

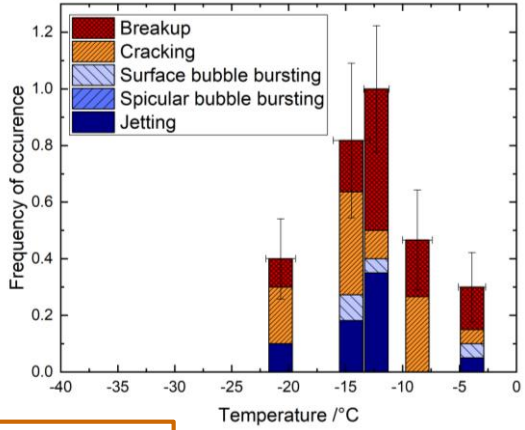
Droplet Material: pure water (HPLC grade)
Droplet diameter: (325 ± 23) µm
Airflow humidity: moist



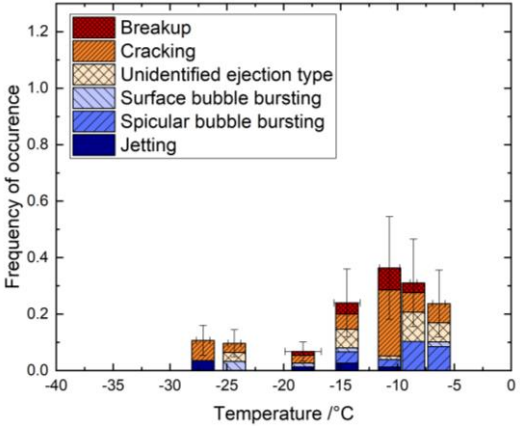
Airflow causes an increase in breakup frequency of more than one order in magnitude.

Complete breakup frequency peaks at 45% at -12.3°C in moist airflow.

Moist airflow (Keinert et al., submitted to JAS)



Stagnant air (Lauber et al., 2018, JAS)



The overall SIP frequency is enhanced for droplets freezing in airflow.

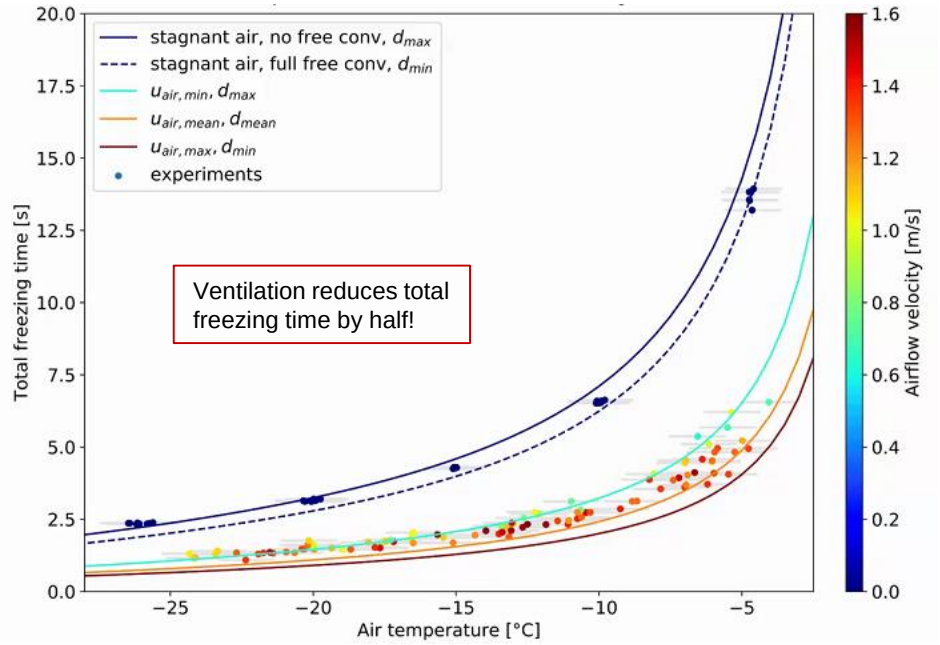
Breakup and Cracking dominate over bubble bursts in pure water droplets.

Enhancement of Secondary Ice Production for Droplets Freezing in Free Fall

Karlsruhe Institute of Technology

Why is the droplet shattering frequency enhanced for droplets freezing in airflow?

Droplets freezing in free fall or in airflow ventilated. Ventilation enhances the rate of heat removal to the environment during the second freezing step. As our infrared measurements of the freezing droplet temperature show, ventilation results in a significant reduction of the total freezing time and therefore a faster growth rate of the ice shell. The earlier study by Dye and Hobbs (1968) suggested faster ice shell growth allows less time for adaption to the increasing mechanical stresses which results in a higher fragmentation frequency.

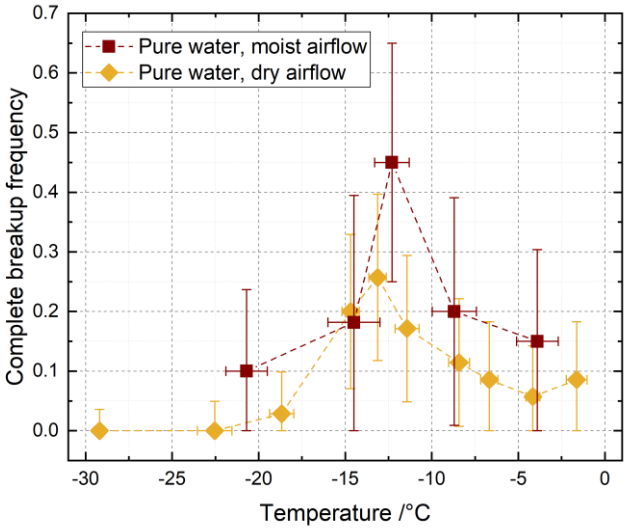


Ventilation reduces total freezing time by half!

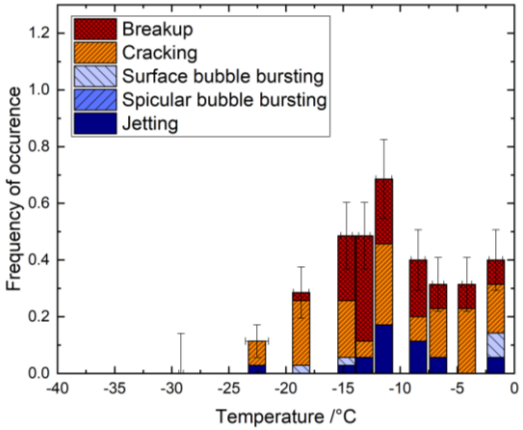
For more information on the freezing dynamics and thermal measurements, see Display 2889 by Judith Kleinheins et al. https://doi.org/10.5194/egusphere-egu2020-2889

SIP Rates in Dry vs. Moist Airflow

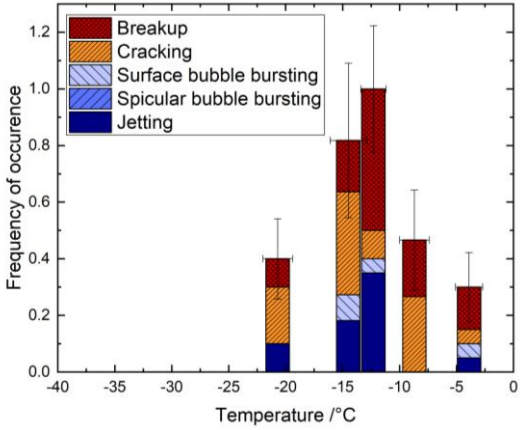
Droplet Material: pure water (HPLC grade)
Droplet diameter: (315 ± 16) µm
Airflow humidity: dry (T_{dew}= - 40°C)



Dry airflow
(Keinert et al., submitted to JAS)



Moist airflow
(Keinert et al., submitted to JAS)

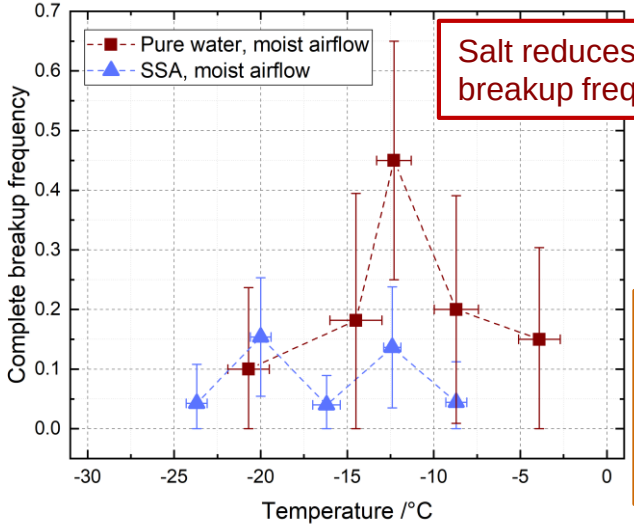


In dry airflow the complete breakup frequency is lower than in moist airflow.

Likewise the overall SIP rate is reduced in dry airflow compared to droplets freezing in moist airflow.

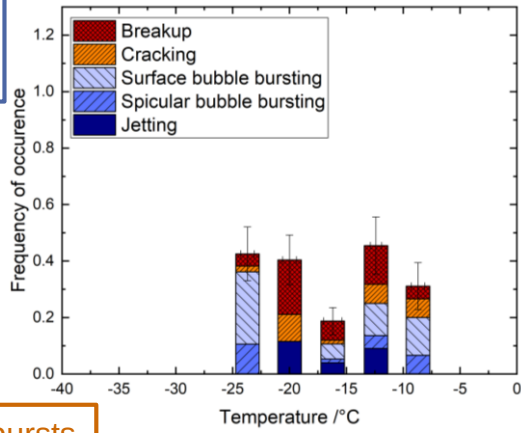
SIP Rates in SSA vs. Pure Water Droplets

Droplet Material: aqueous solution of sea salt analogue (SSA, Instant Ocean): 2.9 mg/L
Droplet diameter: (303 ± 25) µm
Airflow humidity: moist

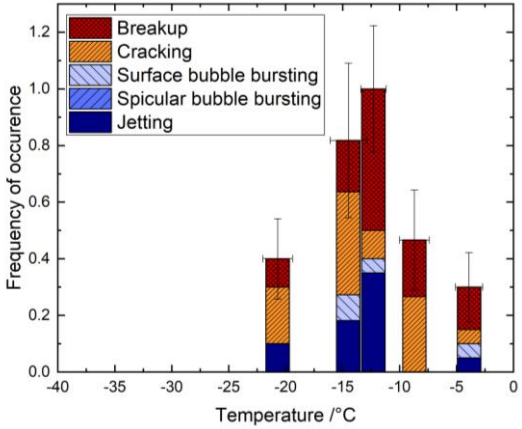


Salt reduces the breakup frequency.

SSA droplets (Keinert et al., submitted to JAS)



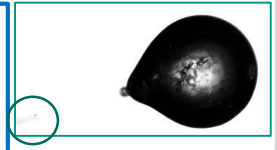
Pure droplets (Keinert et al., submitted to JAS)



Bubble bursts become prevalent in freezing SSA droplets.

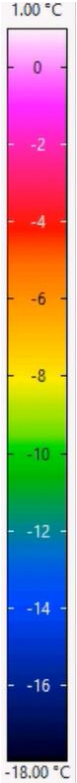
In SSA droplets multiple bubble bursts per freezing droplet were commonly observed.

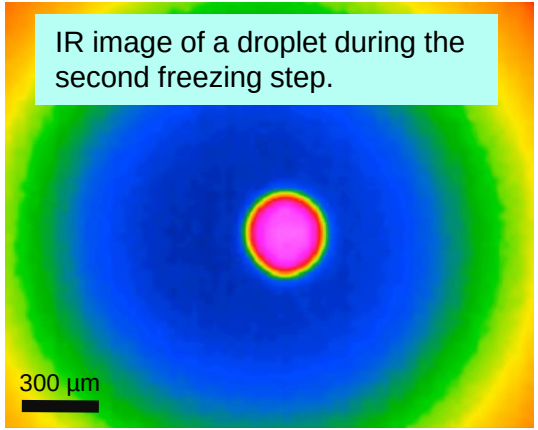
Spicular bubble bursts were only observed in SSA droplets and remained absent in pure water droplets.



Spicular bubble burst with ejection

Current Projects:
Thermal Imaging of Freezing Droplets

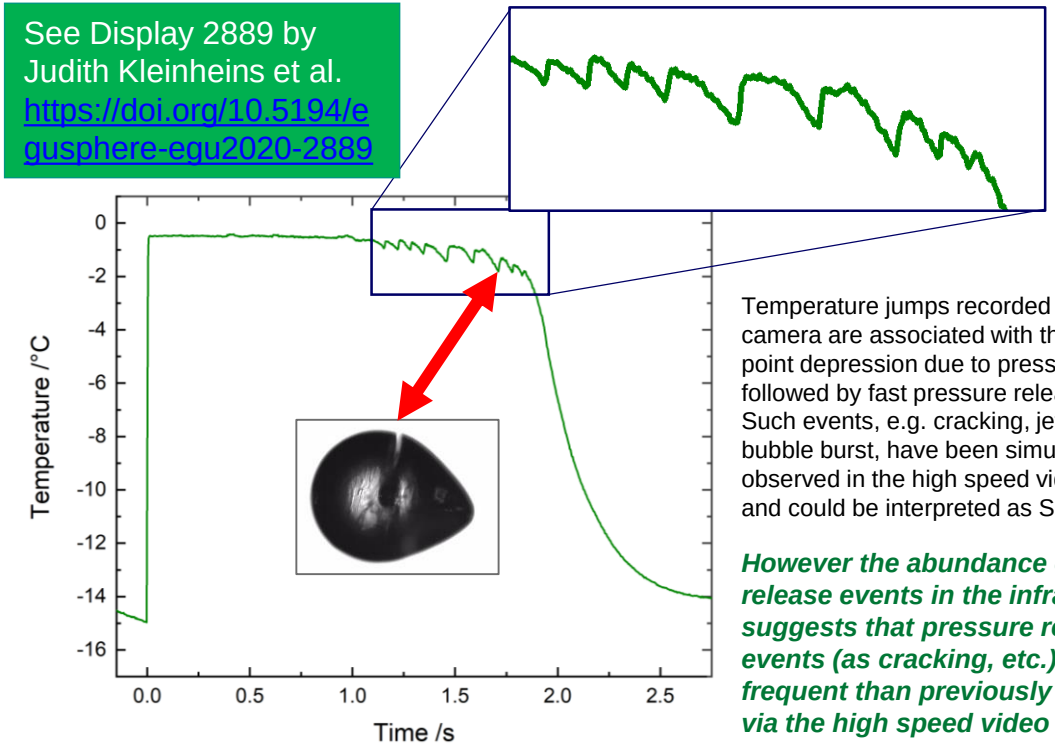




IR image of a droplet during the second freezing step.

Recently a high-resolution infrared thermography system has been added to the existing setup. Monitoring the droplet temperature during freezing allows for measurements of the pressure inside the freezing droplet.

See Display 2889 by Judith Kleinheins et al. https://doi.org/10.5194/egusphere-egu2020-2889



Temperature jumps recorded with the IR camera are associated with the melting point depression due to pressure rise followed by fast pressure release events. Such events, e.g. cracking, jetting and bubble burst, have been simultanously observed in the high speed video footage and could be interpreted as SIP events.

However the abundance of pressure release events in the infrared data suggests that pressure release events (as cracking, etc.) are more frequent than previously observed via the high speed video camera.

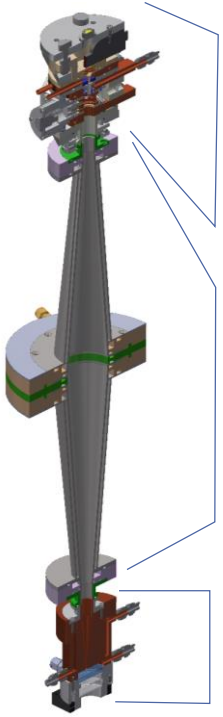
Current Projects: IDEFIX
Ice Droplets splintEring on FreezIng eXperiment

Quantification of secondary ice particles produced during droplet freezing and rime splintering

Up to now counting secondary ice particles produced during droplet shattering was only possible by examining the high speed video footage. Therefore only secondary ice particles larger than 5 µm could be detected.

In the upcoming experiment IDEFIX, we are aiming to detect the secondary ice particles smaller than the threshold of visual detection. Additionally, it will give clarification of the relative contributions of cracking, jetting and bubble bursts to the SIP mechanism.

IDEFIX will also reassess the secondary ice production by rime splintering (Hallett-Mossop-Process).



Secondary ice production section: levitated droplets or mounted graupel are held in a temperature and flow controlled environment. Emitted secondary ice particles proceed to the particle growth section.

Particle growth section: secondary ice particles grow by diffusion of water vapor.

Regarding the rime splintering experiments, contact Dr. Susan Hartmann, TROPOS Leipzig, Germany hartmann@tropos.de

Secondary ice quantification section: detection and counting of secondary ice particles by impaction on supercooled sugar solution.

Appendix

Acknowledgements

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Literature

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