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Secondary ice production within mixed-phase clouds in cold air outbreaks over the North Atlantic.

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In-cloud measurements of ice crystal concentrations often greatly exceed ice nucleating particle (INP) concentrations. This discrepancy can be accounted for by secondary ice production (SIP), describing mechanisms producing new ice crystals from the presence of existing primary ice particles. As ice particle formation in clouds strongly influences precipitation and earth's radiative balance, accurate representation of SIP processes is critical for global climate and weather prediction model simulations. However, the dominant SIP mechanisms operating in different cloud systems remain poorly understood. This study aims to improve understanding of SIP within mixed-phase clouds associated with cold air outbreaks (CAOs). We examine in-situ ice particle and ice-nucleating particle measurements made in October-November 2022, using the UK FAAM BAE 146 research aircraft, during a set of CAOs in the North-western Atlantic over the Labrador Sea. This flight campaign comprised part of the M-PHASE project, part of the NERC-funded CloudSense programme, which aims to reduce uncertainties in climate sensitivity due to clouds. Detailed measurements of cloud microphysical properties were made to study the evolution of stratocumulus clouds as they advect southwards before breaking up under increasingly convective conditions.

In-cloud ice crystal concentrations measured with 2D-S (size range 10 - 1280 µm) and HVPS (size range 150 µm - 19.2 mm) optical array probes frequently exceeded INP concentrations measured at the same temperature. Peak ice particle concentrations greater than 200 L^{-1} were recorded on numerous flights, several orders of magnitude above INP concentrations. These ice concentration enhancements were observed between -5 and -10 ^{o}C, within the active temperature range for the Hallett-Mossop SIP process. Analysis of corresponding ice particle imagery from the 2D-S and Cloud Particle Imager instruments shows that small hollow columns, often mixed with larger heavily rimed particles, were the dominant ice crystal habits, providing further evidence of rime splintering. A second ice concentration peak at around -17^{o}C was also observed. Large irregularly shaped ice crystals were present during this period, suggesting that fragmentation due to ice-ice collisions may be another active SIP mechanism.

We identify a series of SIP events across the flight campaign, with their short-lived nature suggesting ice multiplication is active across limited spatial extents. These segments of elevated

ice concentrations are heavily populated by ice crystals of diameter < 100μm. Overall, SIP is observed to increase across convective regions of the CAO, with stratocumulus regions upwind often consisting mainly of supercooled water.

This work provides critical information for numerical modelling studies requiring detailed representation of SIP processes within mixed-phase clouds across the transition region from stratocumulus to convective regimes in CAOs.