A Possible Role for Immersion Freezing in Mixed-Phase Stratus Clouds

Gijs de Boer, Tempei Hashino, Gregory J. Tripoli and Edwin W. Eloranta
The University of Wisconsin - Madison

(1) Introduction
Ice formation appears to a dominant factor controlling the lifecycle of Arctic mixed-phase clouds. To date, our understanding of ice formation in these long-lasting cloud structures does not explain the formation of observed ice amounts. Particularly puzzling are observations taken from the 2004 Mixed-Phase Arctic Clouds Experiment (M-PACE) at the ARM North Slope of Alaska site (NASA) which show continuous mixed-phase clouds present with only minimal ice forming nuclei (IN) available. In-situ measurements of both ice particle and IN concentrations show IN concentrations multiple orders of magnitude lower than the ice particle concentrations. This discrepancy leads to the belief that certain classical nucleation mechanisms, such as contact, condensation and deposition freezing are not primarily responsible for ice production, as all require free IN for activation. Immersion freezing is not included with this grouping, however, as it is unclear whether immersed IN would be observed at all with instruments commonly used to measure IN concentrations, such as the Continuous Flow Diffusion Chamber (CFDC).

Here, we investigate the potential role of immersion freezing in Arctic mixed-phase stratus. A theory on how immersion freezing fits into the lifecycle of these clouds, as well as a review of previous studies supporting this theory are presented.

(2) Mixed-Phase Arctic Stratus from M-PACE
- Ice crystals concentrations often significantly exceed measured IN concentrations (particularly for M-PACE) (Mossop, 1970; Fridlind et al., 2007), meaning contact and depositional nucleation likely are unlikely the driving nucleation mechanism.
- Ice crystal concentrations often significantly exceed measured IN concentrations (particularly for M-PACE) (Mossop, 1970; Fridlind et al., 2007), meaning contact and depositional nucleation likely are unlikely the driving nucleation mechanism.
- Ice crystal concentrations often significantly exceed measured IN concentrations (particularly for M-PACE) (Mossop, 1970; Fridlind et al., 2007), meaning contact and depositional nucleation likely are unlikely the driving nucleation mechanism.
- Ice crystal concentrations often significantly exceed measured IN concentrations (particularly for M-PACE) (Mossop, 1970; Fridlind et al., 2007), meaning contact and depositional nucleation likely are unlikely the driving nucleation mechanism.
- Ice crystal concentrations often significantly exceed measured IN concentrations (particularly for M-PACE) (Mossop, 1970; Fridlind et al., 2007), meaning contact and depositional nucleation likely are unlikely the driving nucleation mechanism.
- Ice crystal concentrations often significantly exceed measured IN concentrations (particularly for M-PACE) (Mossop, 1970; Fridlind et al., 2007), meaning contact and depositional nucleation likely are unlikely the driving nucleation mechanism.

So which one drives ice production in Arctic Stratus?
- Homogeneous freezing is insignificant >35 C (Hagen et al., 1981; Sassen and Dudd, 1988; Jensen et al., 1998, others) Arctic stratus are observed at temperatures significantly above this (de Boer et al., 2008 in preparation).
- Ice crystal concentrations often significantly exceed measured IN concentrations (particularly for M-PACE) (Mossop, 1970; Fridlind et al., 2007), meaning contact and depositional nucleation likely are unlikely the driving nucleation mechanism.

To date, our understanding of ice formation in these long-lasting cloud structures does not explain the formation of observed ice amounts. Particularly puzzling are observations taken from the 2004 Mixed-Phase Arctic Clouds Experiment (M-PACE) at the ARM North Slope of Alaska site (NASA) which show continuous mixed-phase clouds present with only minimal ice forming nuclei (IN) available. In-situ measurements of both ice particle and IN concentrations show IN concentrations multiple orders of magnitude lower than the ice particle concentrations. This discrepancy leads to the belief that certain classical nucleation mechanisms, such as contact, condensation and deposition freezing are not primarily responsible for ice production, as all require free IN for activation. Immersion freezing is not included with this grouping, however, as it is unclear whether immersed IN would be observed at all with instruments commonly used to measure IN concentrations, such as the Continuous Flow Diffusion Chamber (CFDC).

Here, we investigate the potential role of immersion freezing in Arctic mixed-phase stratus. A theory on how immersion freezing fits into the lifecycle of these clouds, as well as a review of previous studies supporting this theory are presented.

(3) Fundamentals
Primary Ice Nucleation Modes
- Homogeneous freezing
- Condensation nucleation
- Contact nucleation
- Depositional nucleation
- Immersion nucleation

So which one drives ice production in Arctic Stratus?
- Homogeneous freezing is insignificant >35 C (Hagen et al., 1981; Sassen and Dudd, 1988; Jensen et al., 1998, others) Arctic stratus are observed at temperatures significantly above this (de Boer et al., 2008 in preparation).
- Ice crystal concentrations often significantly exceed measured IN concentrations (particularly for M-PACE) (Mossop, 1970; Fridlind et al., 2007), meaning contact and depositional nucleation likely are unlikely the driving nucleation mechanism.
- Ice crystal concentrations often significantly exceed measured IN concentrations (particularly for M-PACE) (Mossop, 1970; Fridlind et al., 2007), meaning contact and depositional nucleation likely are unlikely the driving nucleation mechanism.
- Ice crystal concentrations often significantly exceed measured IN concentrations (particularly for M-PACE) (Mossop, 1970; Fridlind et al., 2007), meaning contact and depositional nucleation likely are unlikely the driving nucleation mechanism.
- Ice crystal concentrations often significantly exceed measured IN concentrations (particularly for M-PACE) (Mossop, 1970; Fridlind et al., 2007), meaning contact and depositional nucleation likely are unlikely the driving nucleation mechanism.
- Ice crystal concentrations often significantly exceed measured IN concentrations (particularly for M-PACE) (Mossop, 1970; Fridlind et al., 2007), meaning contact and depositional nucleation likely are unlikely the driving nucleation mechanism.

To date, our understanding of ice formation in these long-lasting cloud structures does not explain the formation of observed ice amounts. Particularly puzzling are observations taken from the 2004 Mixed-Phase Arctic Clouds Experiment (M-PACE) at the ARM North Slope of Alaska site (NASA) which show continuous mixed-phase clouds present with only minimal ice forming nuclei (IN) available. In-situ measurements of both ice particle and IN concentrations show IN concentrations multiple orders of magnitude lower than the ice particle concentrations. This discrepancy leads to the belief that certain classical nucleation mechanisms, such as contact, condensation and deposition freezing are not primarily responsible for ice production, as all require free IN for activation. Immersion freezing is not included with this grouping, however, as it is unclear whether immersed IN would be observed at all with instruments commonly used to measure IN concentrations, such as the Continuous Flow Diffusion Chamber (CFDC).

Here, we investigate the potential role of immersion freezing in Arctic mixed-phase stratus. A theory on how immersion freezing fits into the lifecycle of these clouds, as well as a review of previous studies supporting this theory are presented.

(4) Secondary Processes
Some Examples:
- Drop shattering
- Ice-Ice collisions
- Splinter ejection during the riming process

How do these processes contribute?
- Drop shattering may result in 15 ice fragments/drop, but only in about 10% of drops larger than 50 µm, multiplying total ice by factor of 2, rarely (if ever) greater than factor of 10. (Pruppacher and Klett, 1997)
- Ice-Ice collisions (Rango and Hobbs, 2001) require significant ice to be present initially and would require a several order of magnitude multiplication factor.
- Splinter ejection during the riming process appears to be limited to air temperatures of -3° to -8° C. (Hallett and Mossop, 1984). Additionally, the production of this is estimated at 1 splinter per 250 larger than 12 µm drops rimed onto one crystal (Koenig, 1977; Beheng, 1982,1987; Cotton et al. 1986).

- Although these and likely other (e.g. evaporation freezing, Fridlind et al., 2007) mechanisms may be active within mixed-phase stratus, it remains unproven that any of these mechanisms would serve as a dominant nucleation mechanism covering the discrepancy in ice observed in these clouds and IN measurements.

(5) Theory
Why Immersion Freezing?
- Bigg (1980) observed sulfuric acid coating on aerosol particles during the winter.
- Blanchet (2007) hypothesises that this sulfur coating is the result of anthropogenic emissions from Siberia, and are transported throughout the Arctic.
- This coating of soluble material inhibits ice formation on these particles, a process confirmed in the laboratory by Bertram and Girard, preventing uniform rapid ice formation.
- Shupe (2006) illustrated that ice formation is seemingly linked to areas of upward vertical motion. This indicated that the formation of ice is tied into the internal dynamics of the cloud system, and likely an alteration of the aerosol or cloud particles involved in nucleation.
- Additionally, Shupe illustrated that ice water content and liquid water content seem to vary in phase with each other, hinting that liquid growth may lead to ice formation.
- In-situ measurements from Rango and Hobbs (2001) reveal that ice crystal concentrations are highly proportional to the concentration of drops larger than 20 µm.

(6) Conceptual Model
- Growth of these ice particles uses up available moisture, and further droplet growth (and therefore ice formation) is halted. The ice particles rapidly grow to a size where they precipitate from the cloud layer, and the cycle starts over.

(7) Model Advancement
- This figure illustrates widespread disagreement in liquid water path predictions by 26 different models for the same single layer mixed-phase stratus case (from ARM M-PACE intercomparison case 1, Klein et al., 2008 in preparation). The blue shading represents the range of LWP values obtained using Turner's MWR retrieval.
- Current models have limited ability to handle the immersion freezing process. Most utilize temperature only to determine whether immersion freezing is active.

(8) Contact Info. / Acknowledgements
Gijs de Boer (gdeboer@wisc.edu) tel: 608-263-6847
This work was supported by the United States Department of Energy (DE-FG02-06ER64187) and NASA (NNX10AI26I). Thanks to Matt Shupe, Hugh Morrison, Paul DelMott, Ann Fridlind Jean-Pierre Blanchet and Eric Girard for helpful discussions, and to the 4th Pan-GC5S organizing committee for assistance with funding to attend this meeting.