Arctic Mixed-Phase Clouds: Observations and Modeling Challenges

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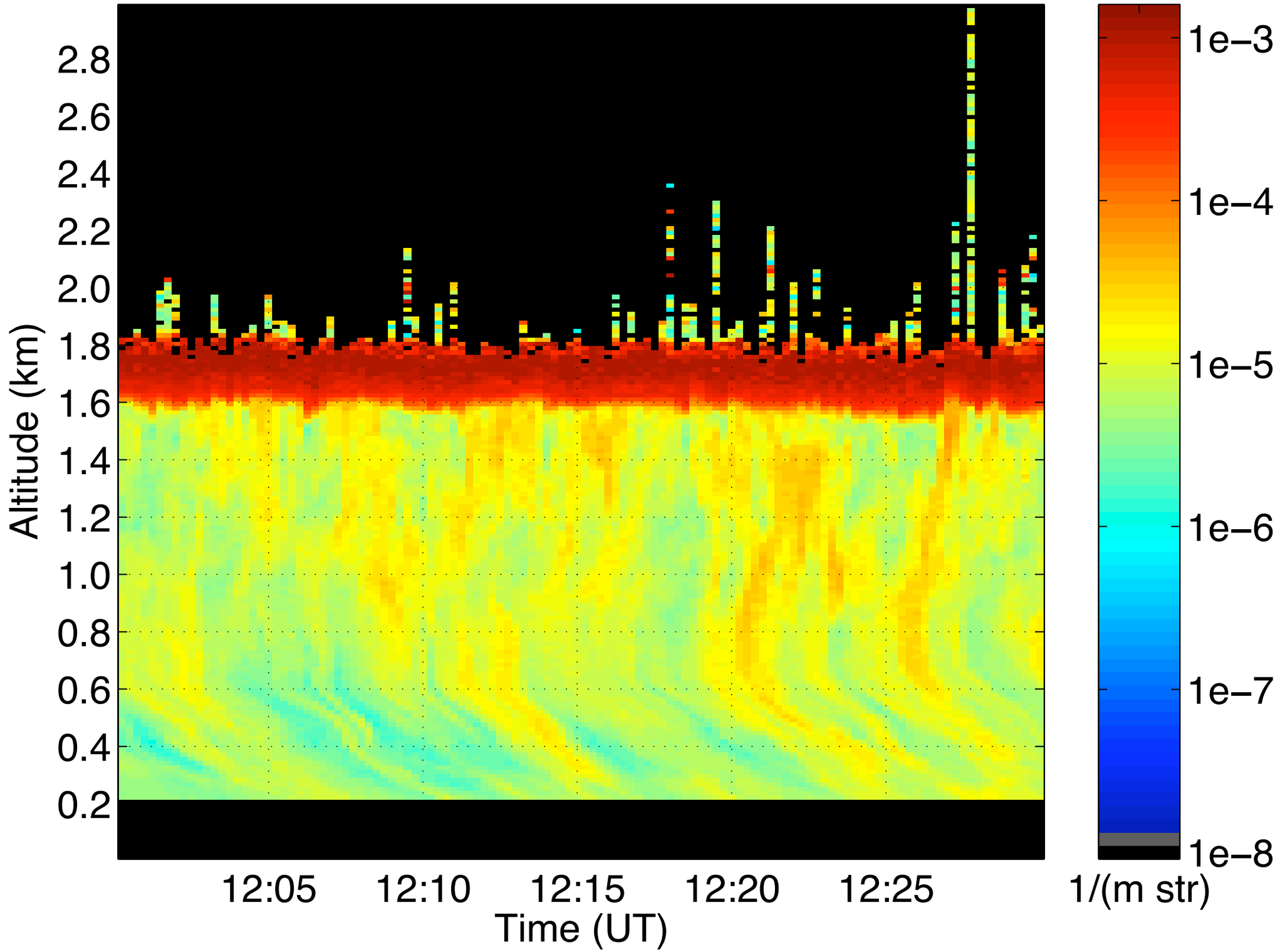
Low-Level Mixed-Phase Clouds

Lidar backscatter cross section (Masked values shown in black and white)



Radiative Influence

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- Commonly observed during several recent Arctic experiments (SHEBA, MPACE, SEARCH, ISDAC)

- Often long-lived, surviving up to several days at a time (de Boer et al., 2008,2009a)

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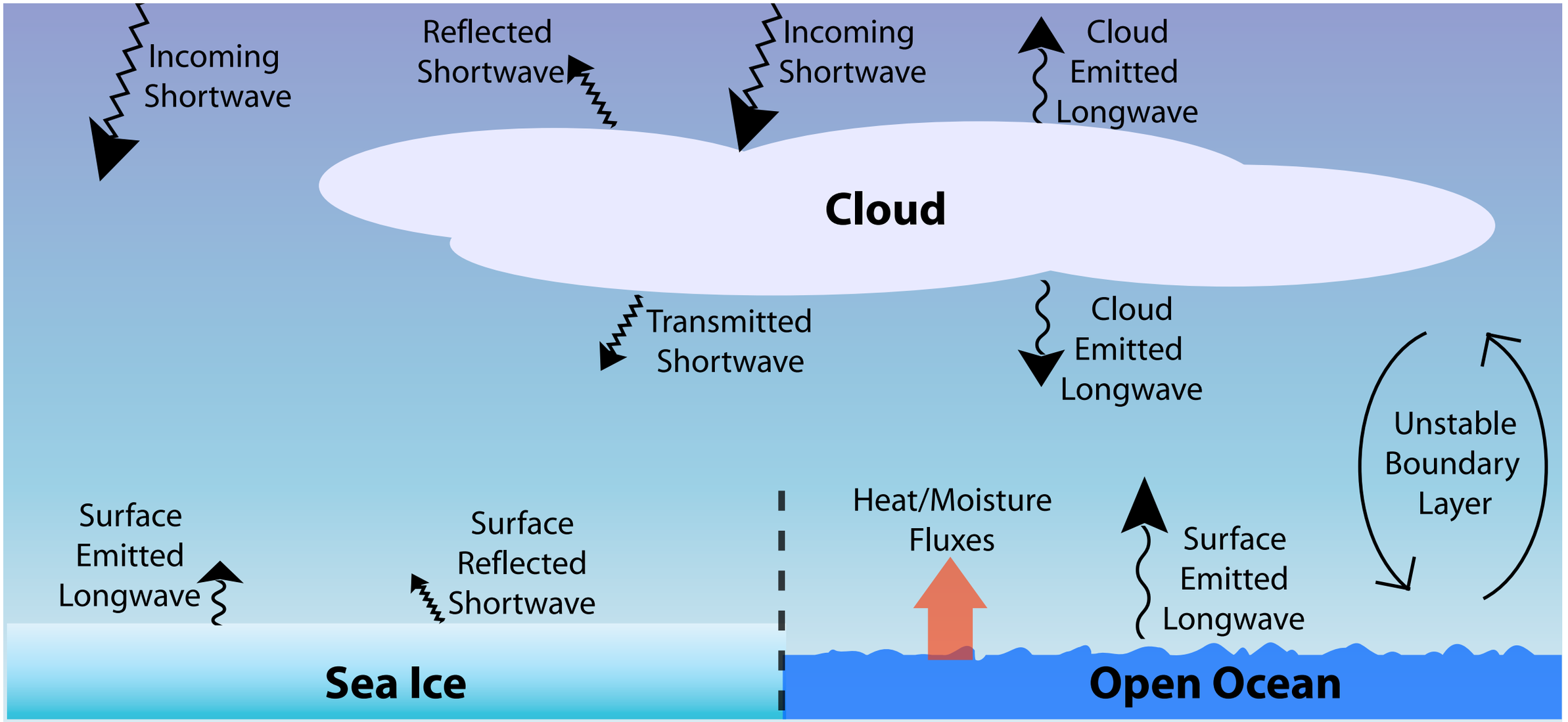
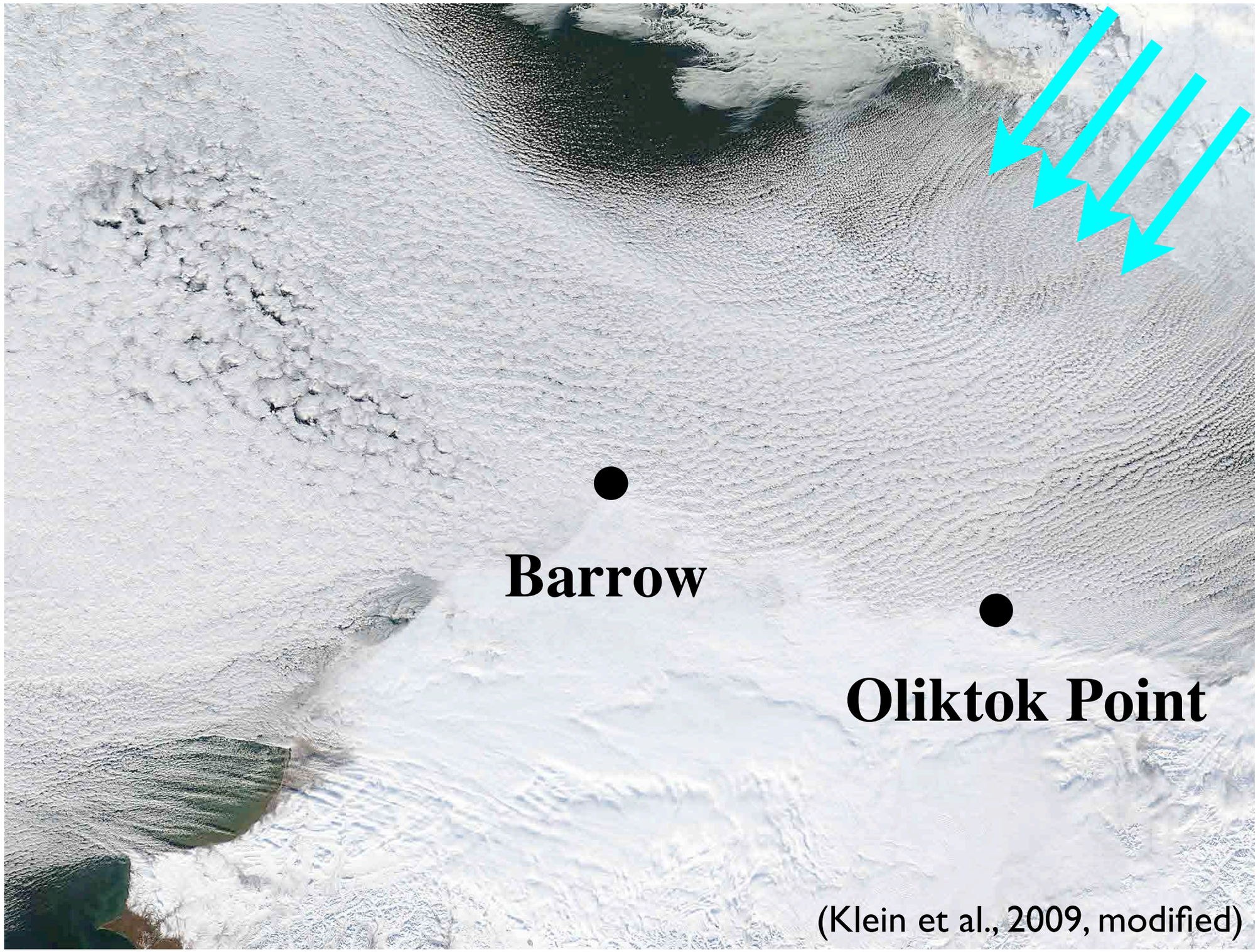
-What about sea-ice effects on clouds?

Mixed-Phase Clouds and Sea Ice



Formation Mechanisms



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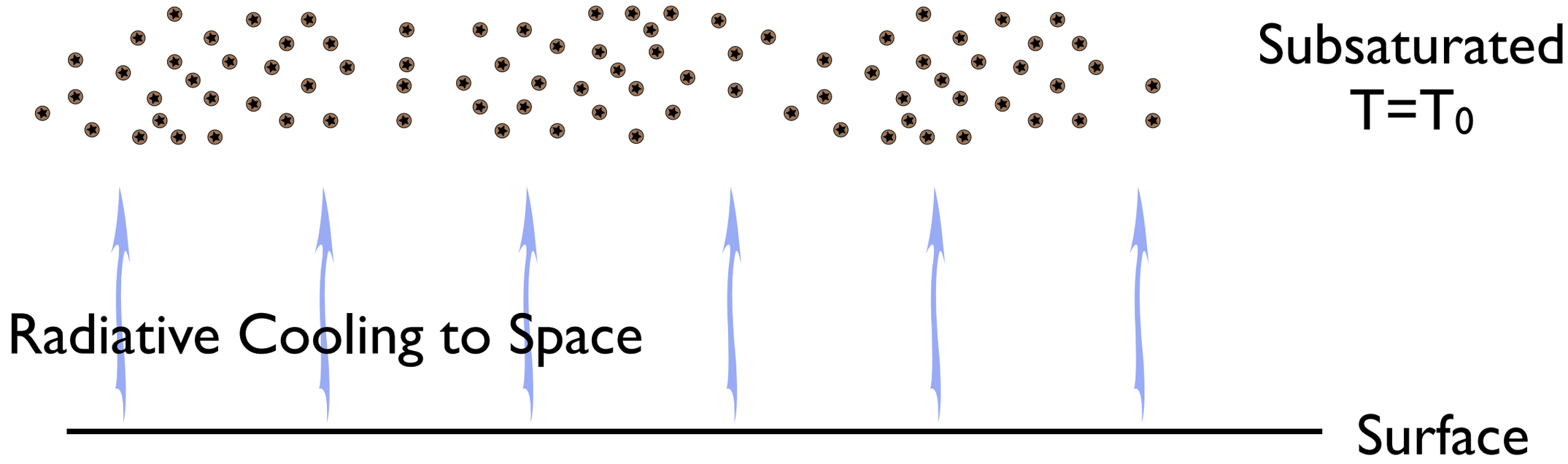

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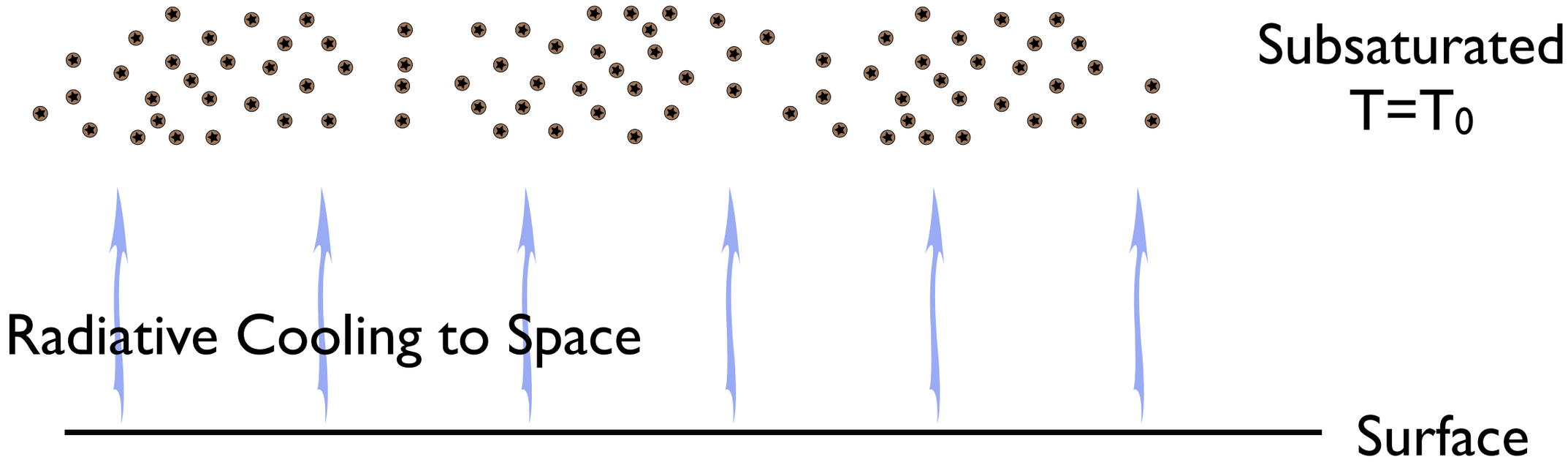
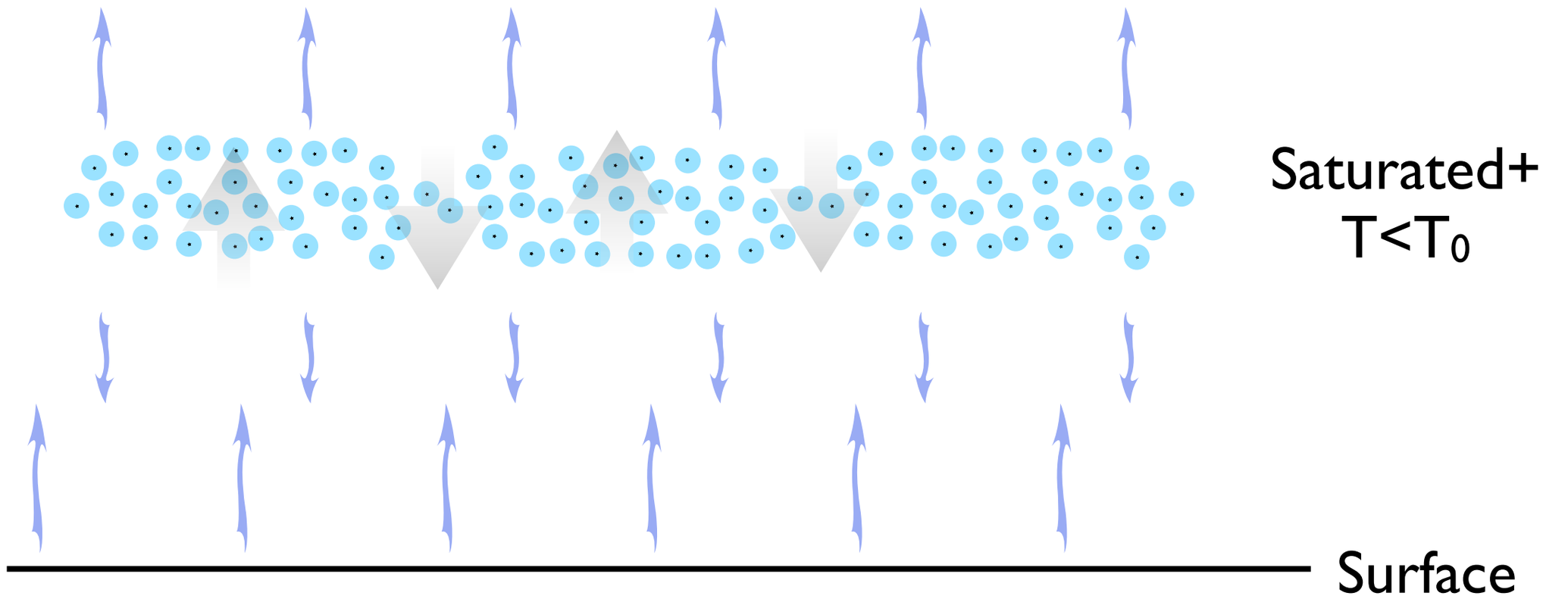
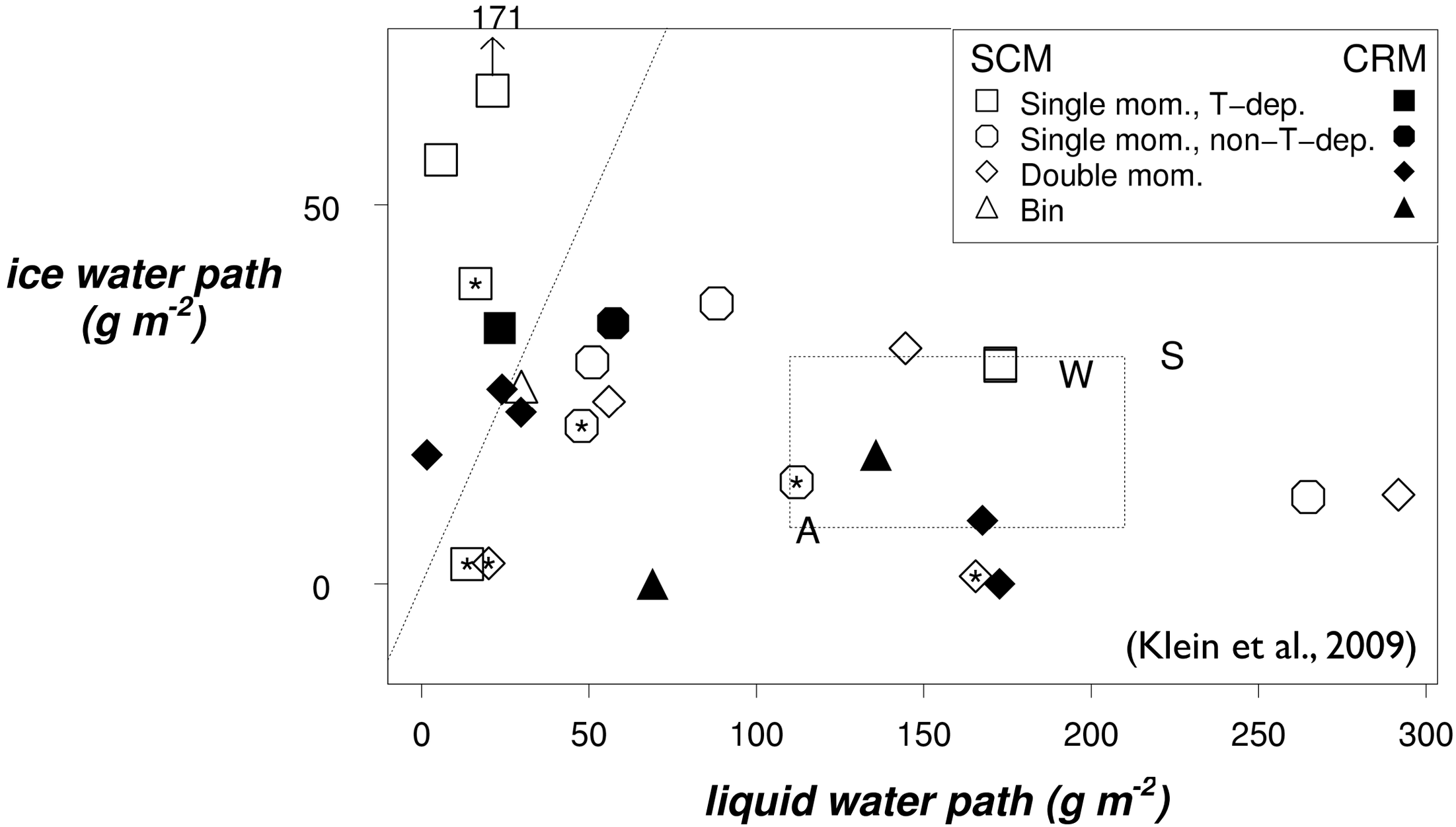
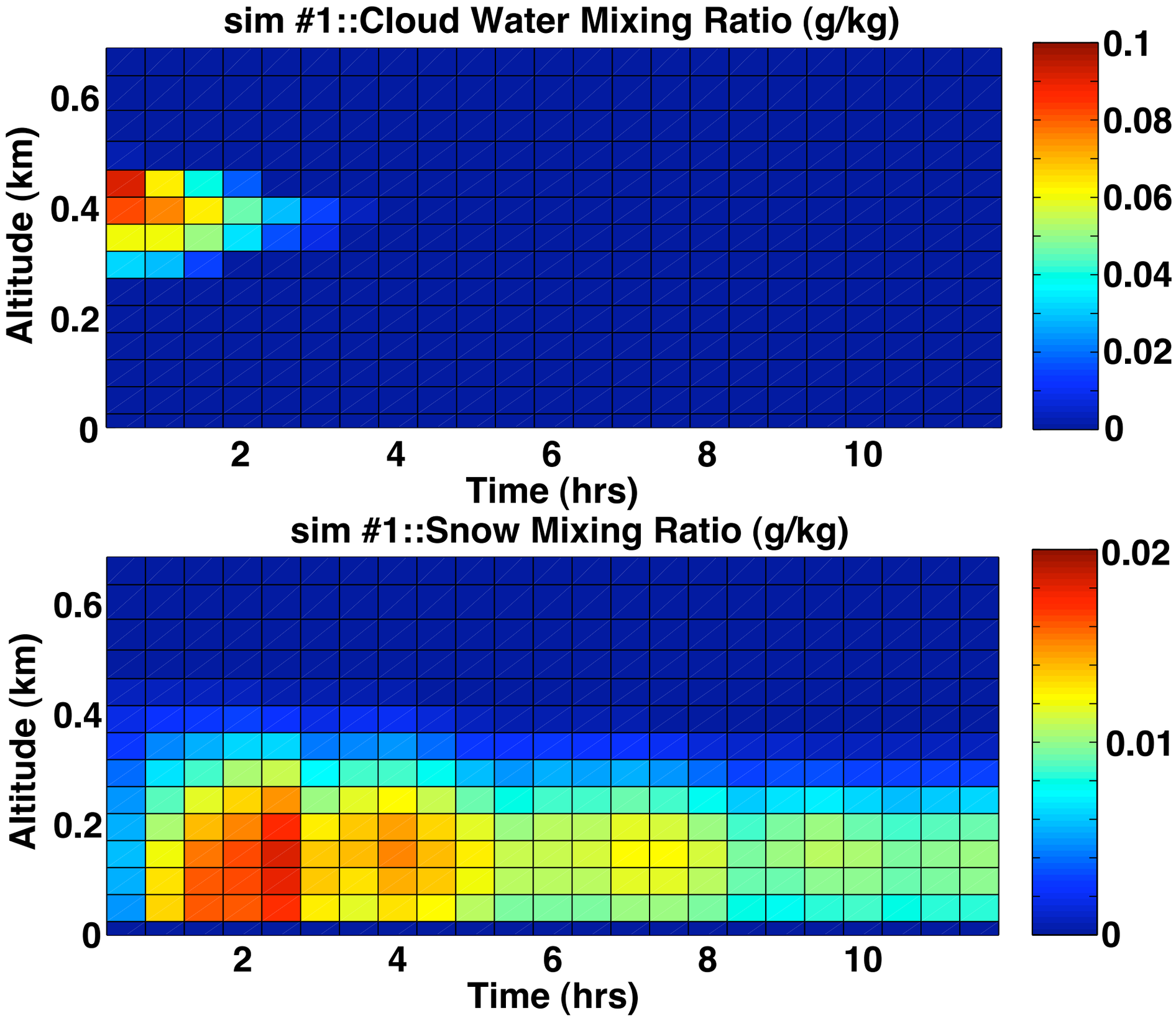




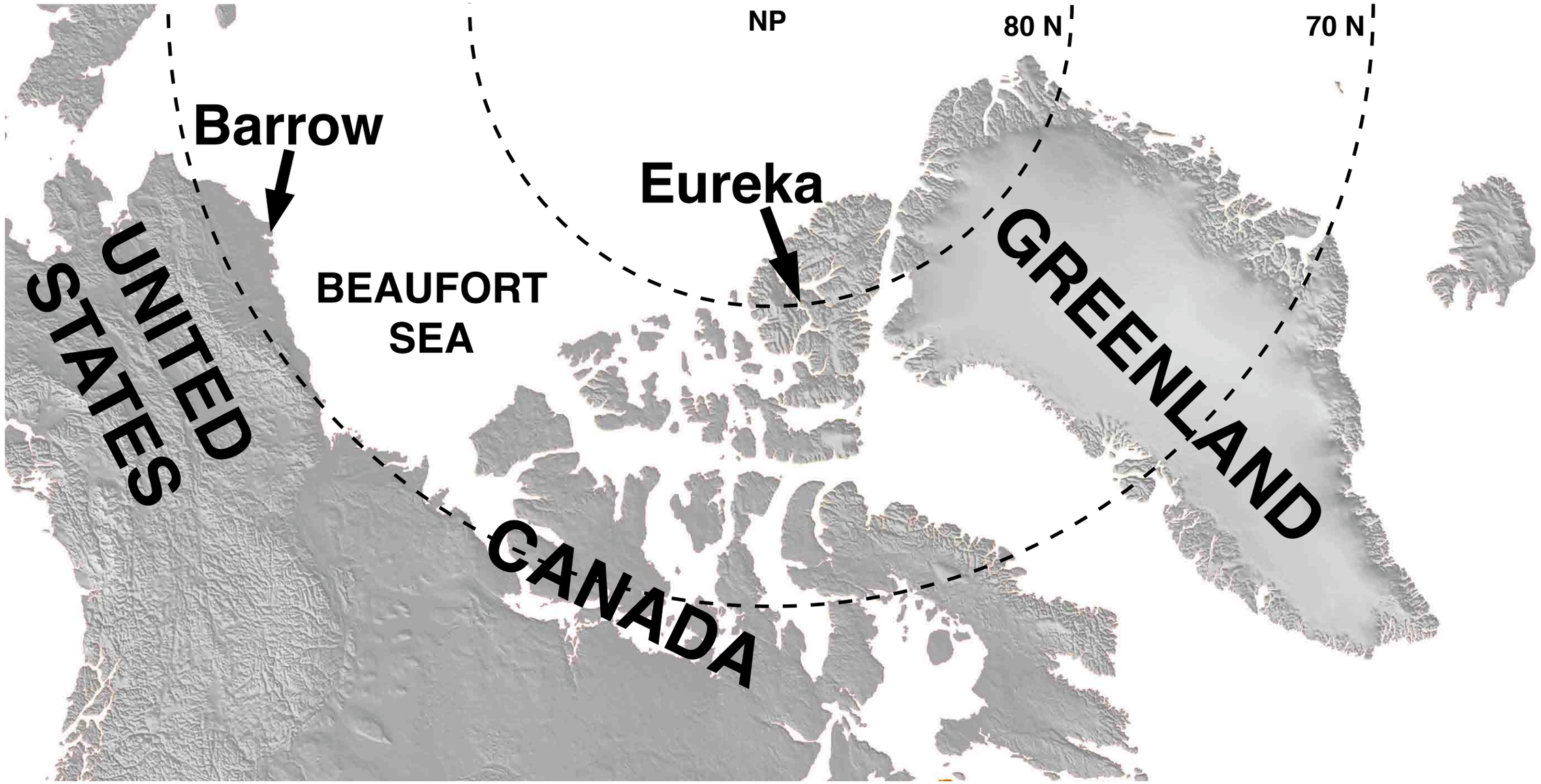
Simulation


171
50
0
SCM
CRM
Single mom., T–dep.
Single mom., non–T–dep.
Double mom.
Bin
W
S
A
(Klein et al., 2009)
0
50
100
150
200
250
300
ice water path (g m-2)
liquid water path (g m-2)

Simulation

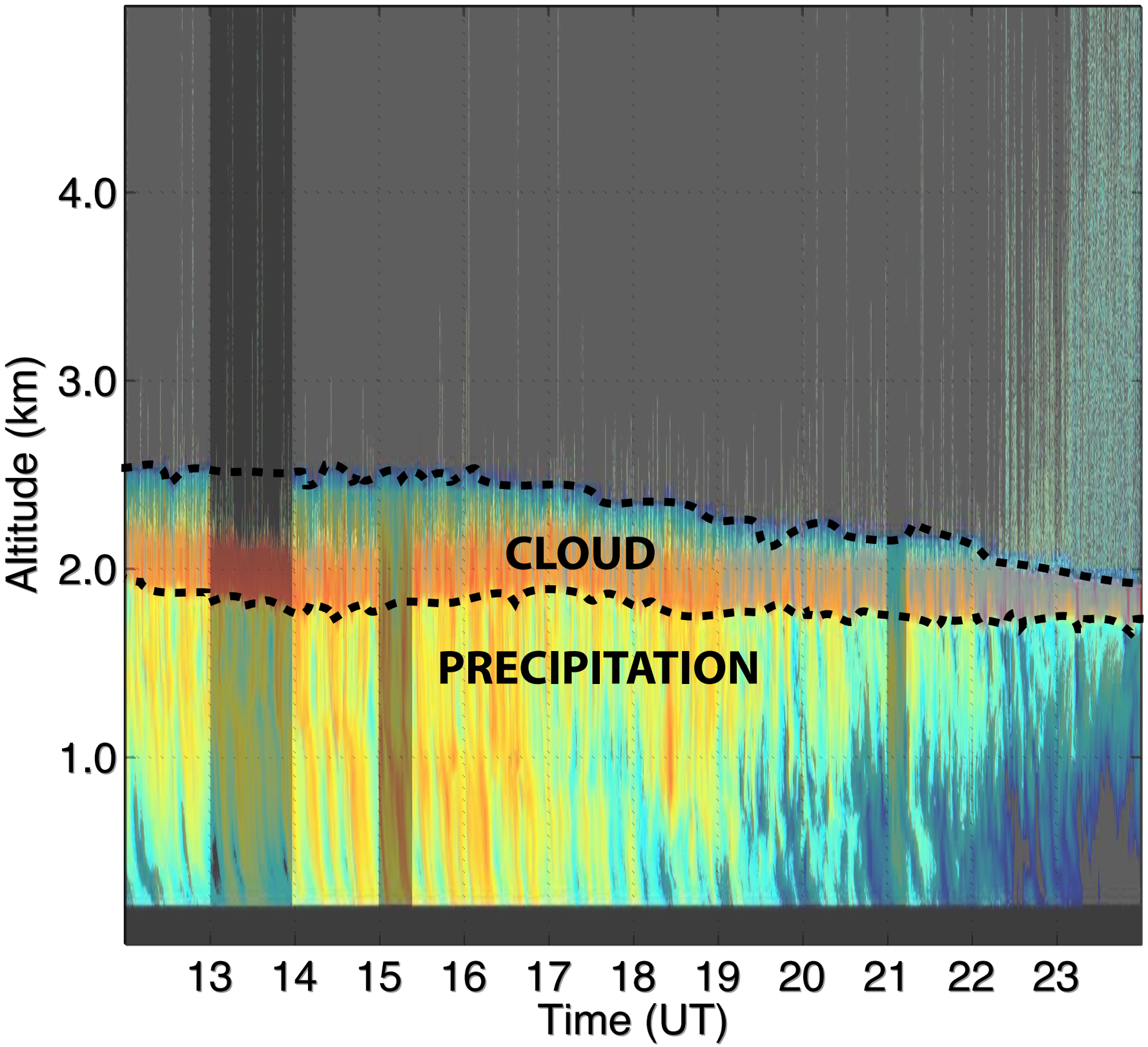

sim #1::Cloud Water Mixing Ratio (g/kg)
Altitude (km)
0
0.2
0.4
0.6
2
4
6
8
10
Time (hrs)
0.1
0.08
0.06
0.04
0.02
0
sim #1::Snow Mixing Ratio (g/kg)
Altitude (km)
0
0.2
0.4
0.6
2
4
6
8
10
Time (hrs)
0.02
0.01
0

Observations



Barrow: 09/04-11/04
Eureka: 08/05-present
High Spectral Resolution Lidar
MMCR (35 GHz)
Radiosondes

Observations

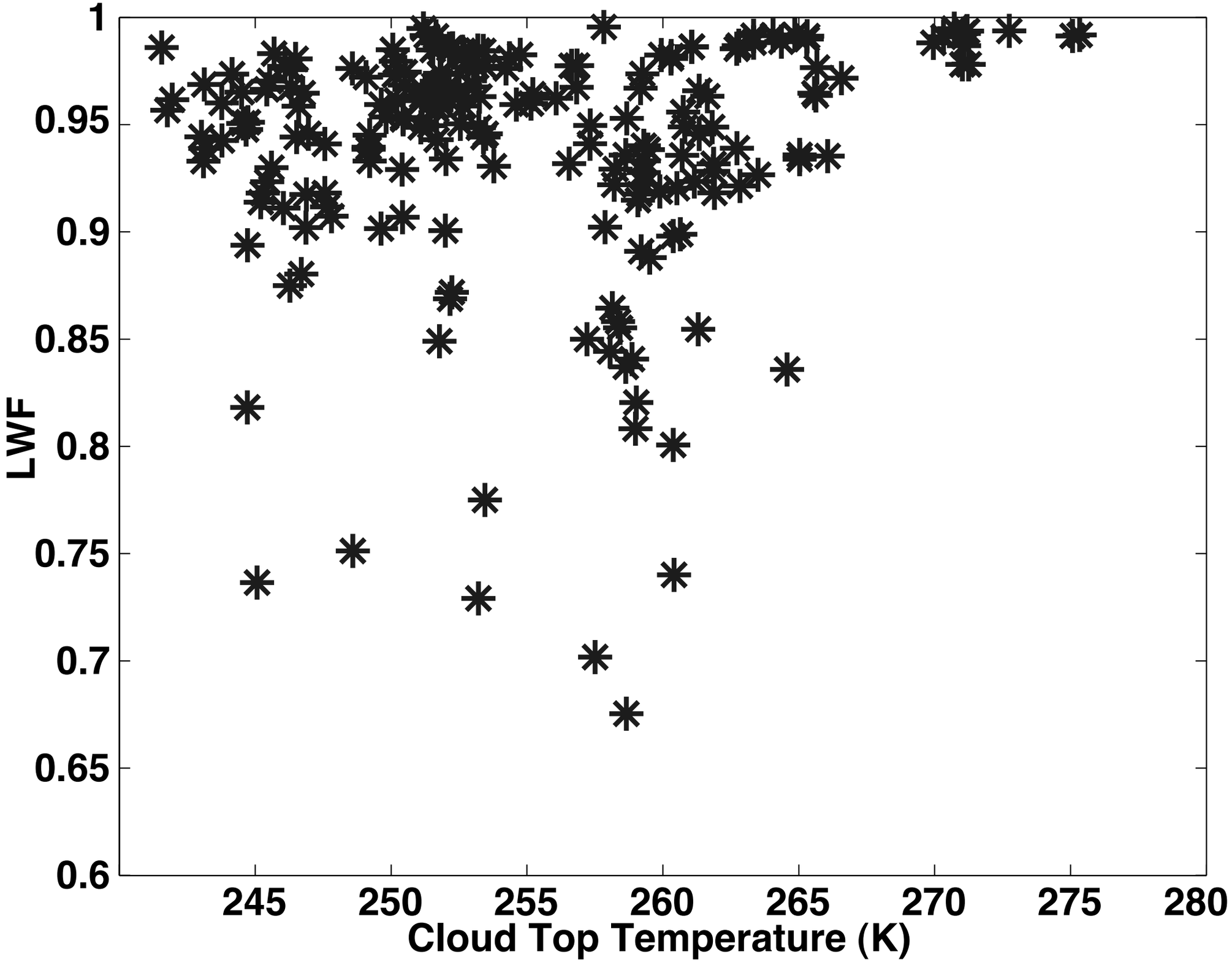


Single-layer mixed phase stratus observations

- 216 hours from Barrow (fall 2004)

- 1240 hours from Eureka (fall 2005-2007)

Temperatures



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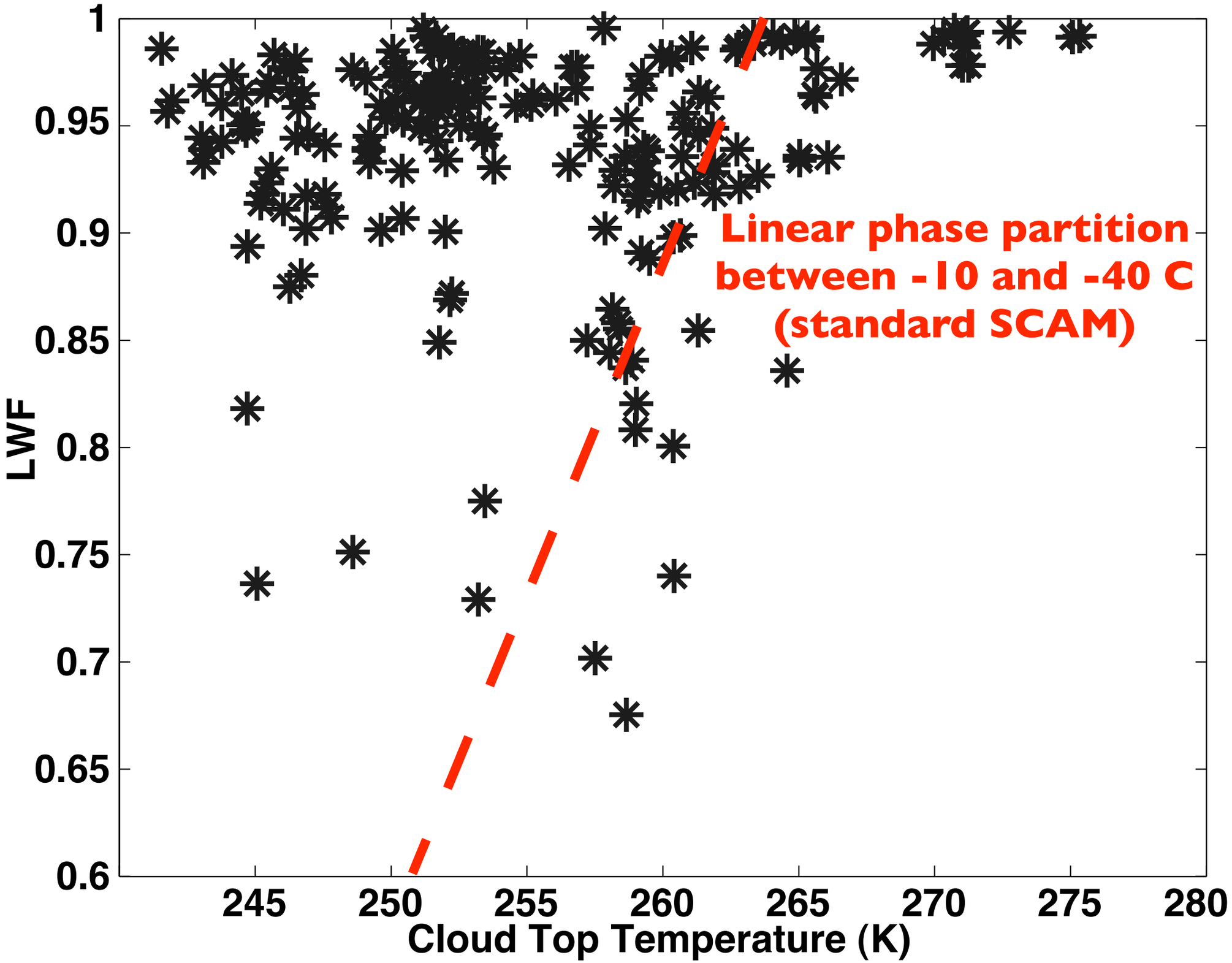
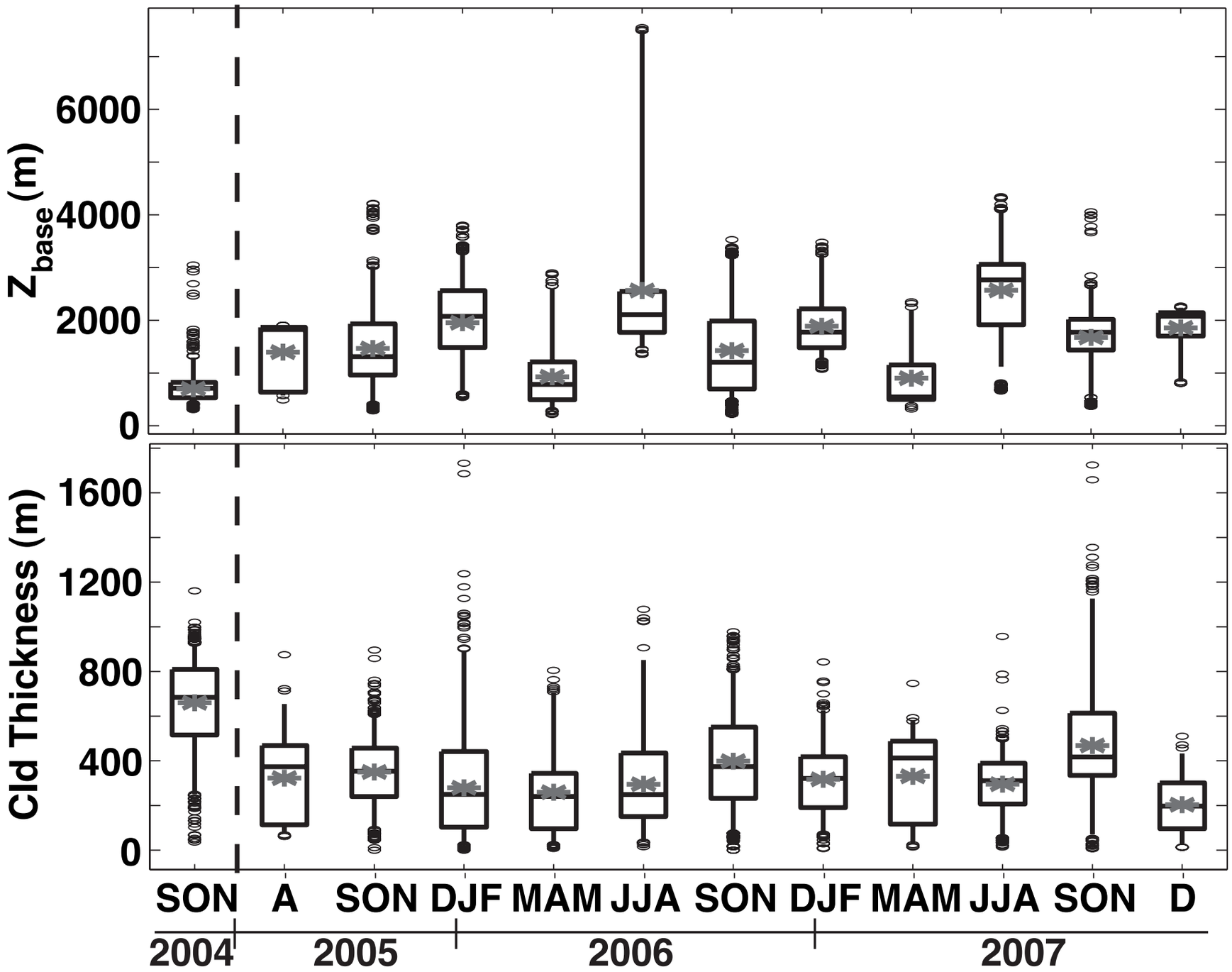


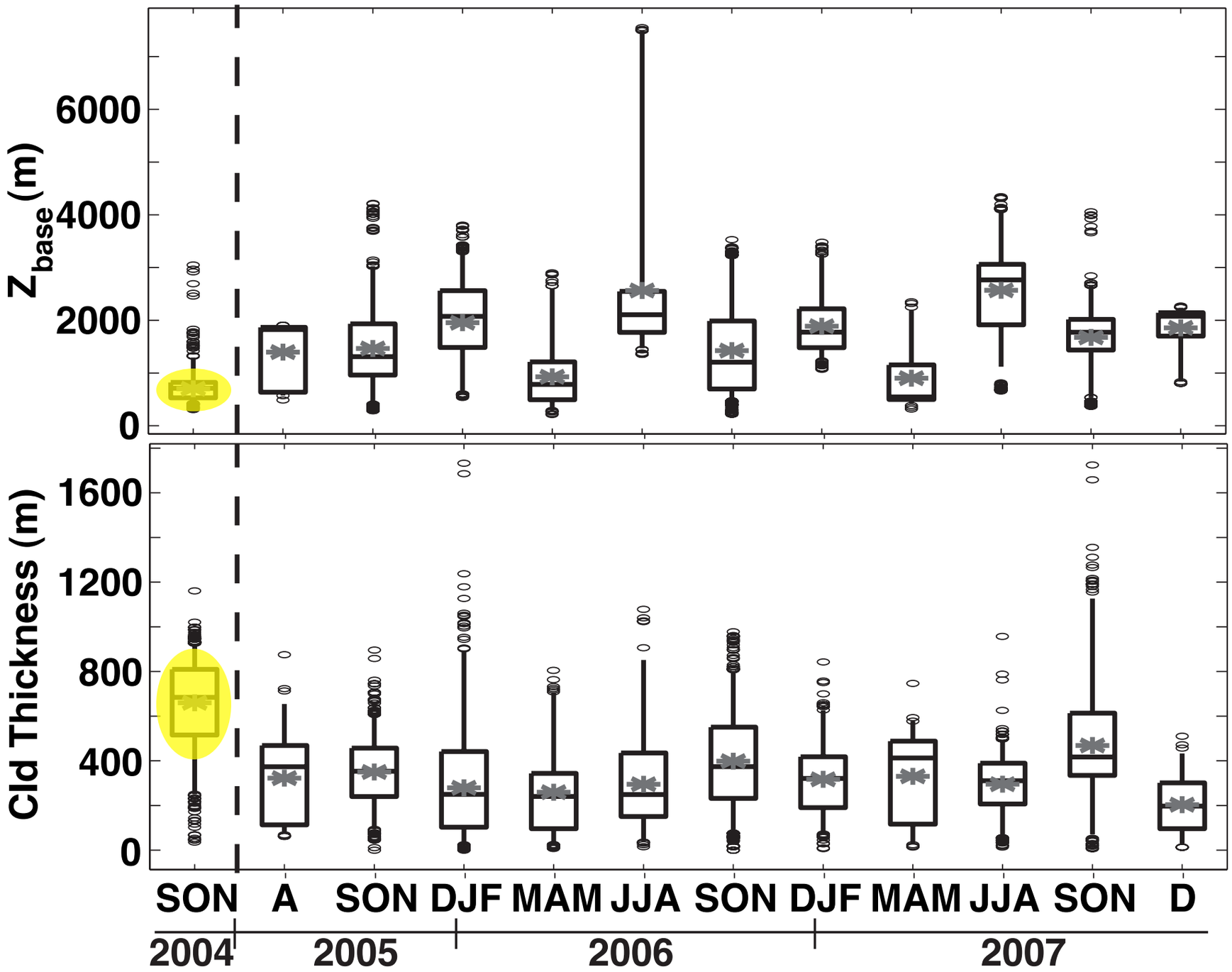
Macrophysical Properties



696 m (Barrow)
1670 m (Eureka)

674 m (Barrow)
331 m (Eureka)

Macrophysical Properties



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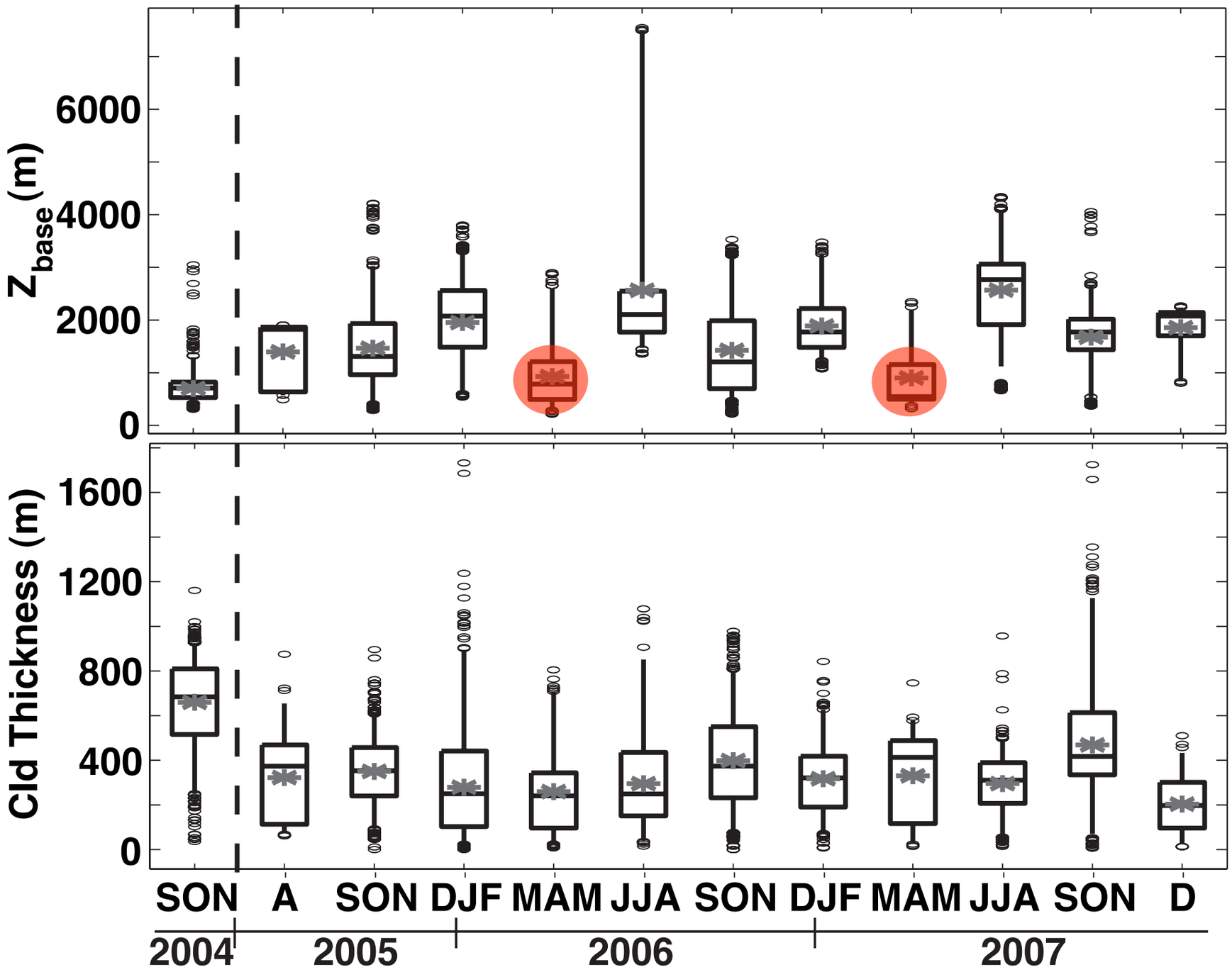

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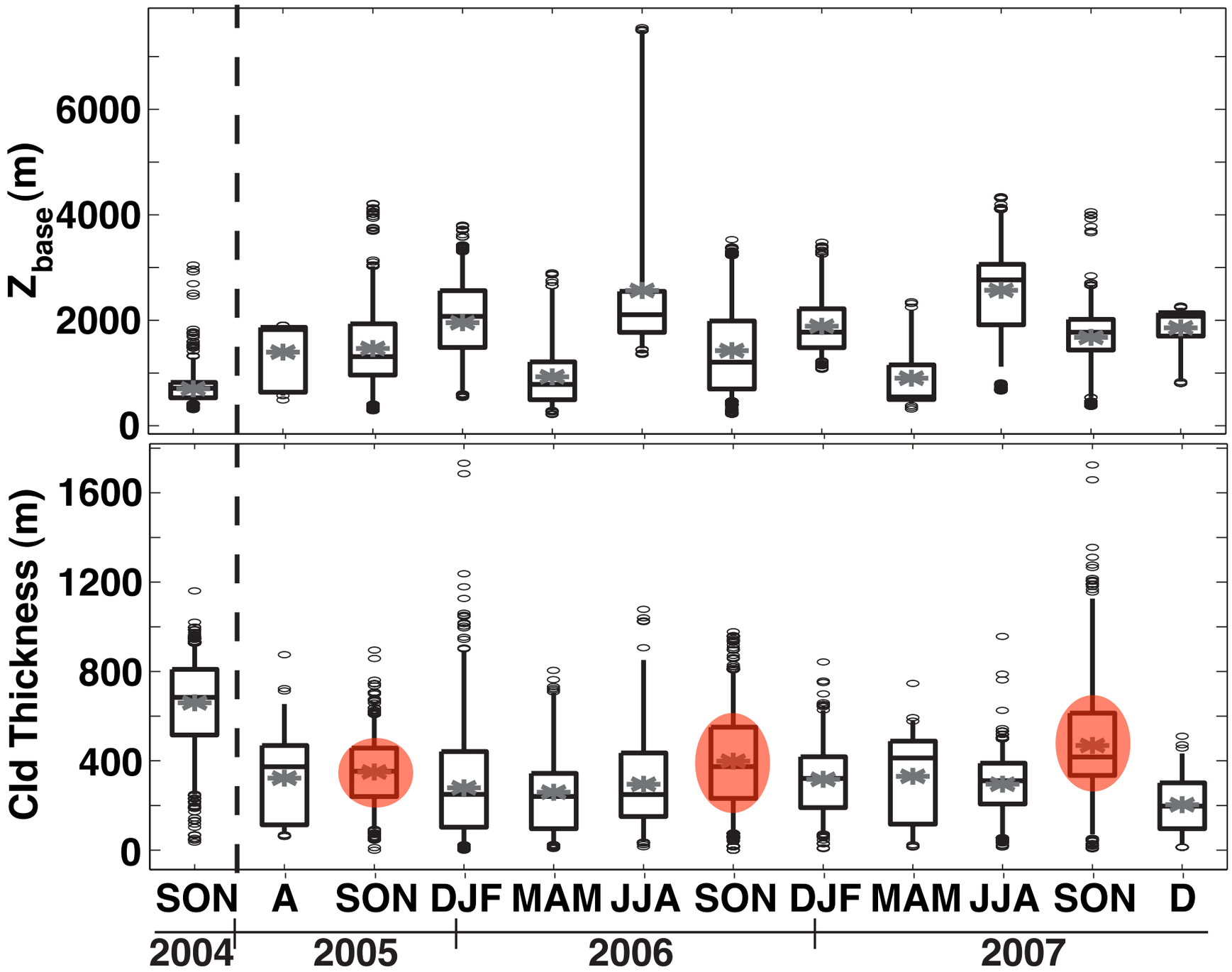

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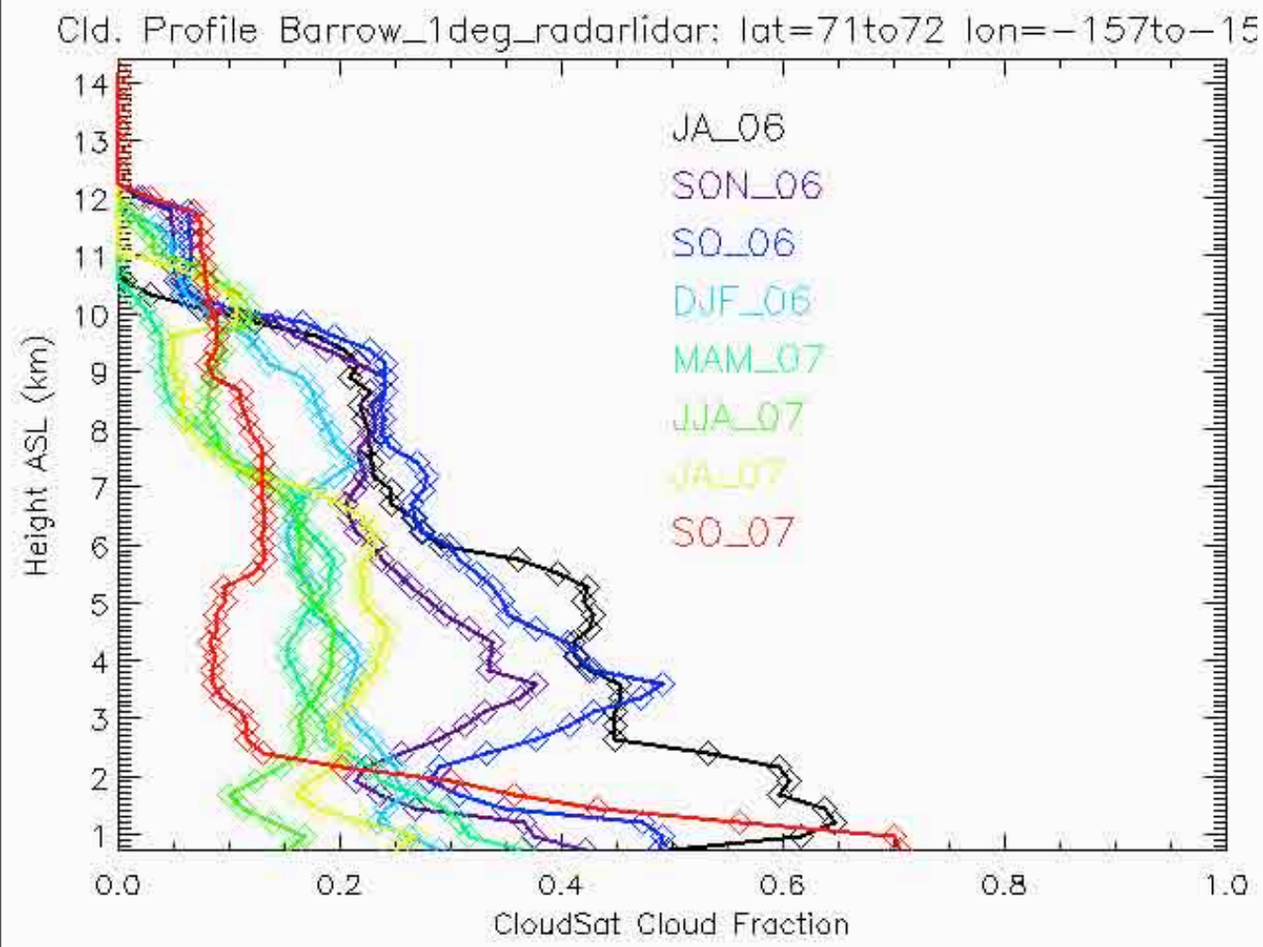
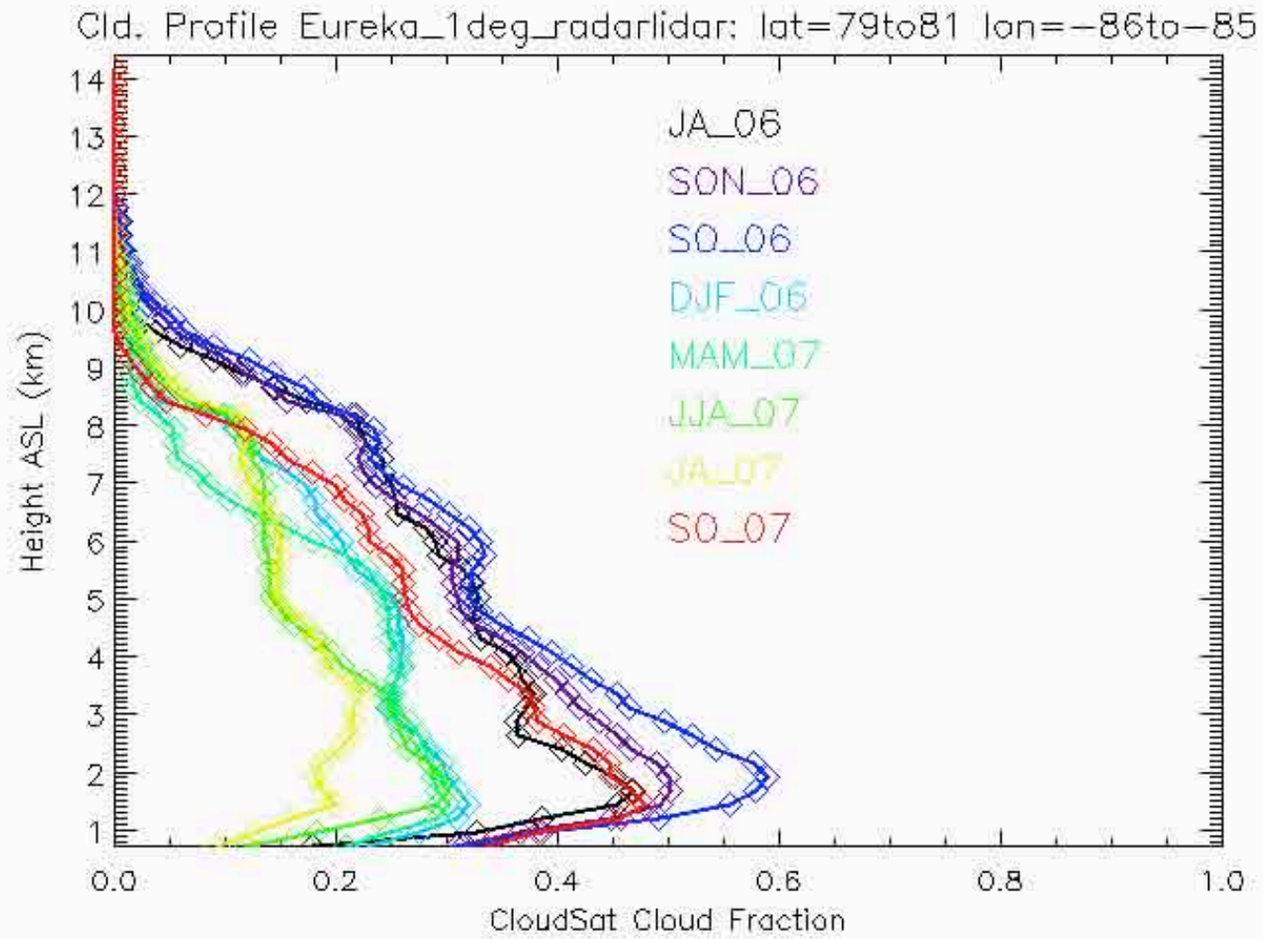
Macrophysical Properties

From A-Train





Barrow **Eureka**

(Images courtesy of Jennifer Kay)

Ice Formation

- **Primary Ice Formation** (Pruppacher and Klett, 1997)

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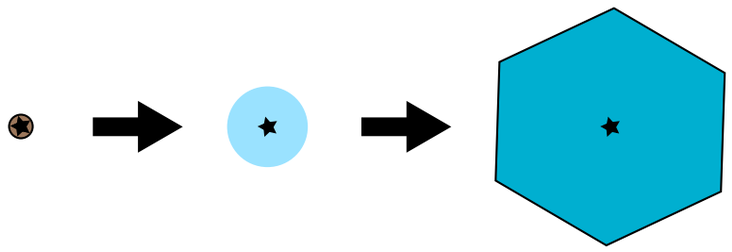

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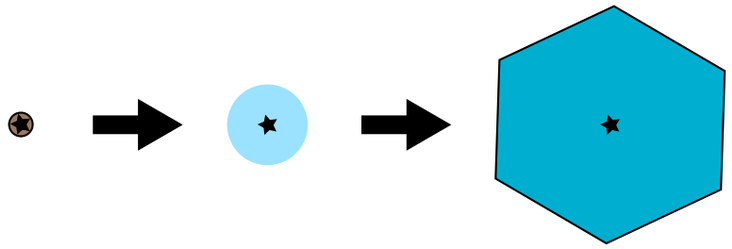
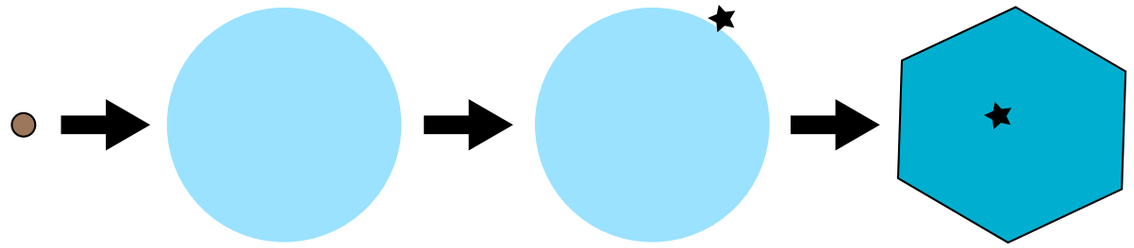


- Nucleation through free IN



(Contact)

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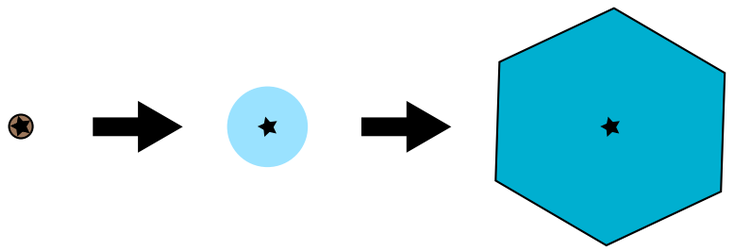

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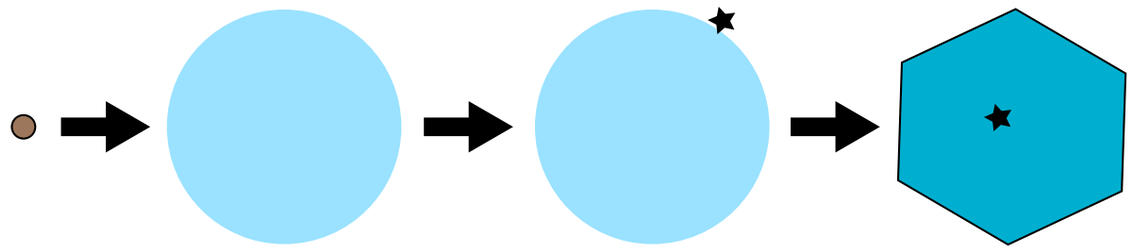

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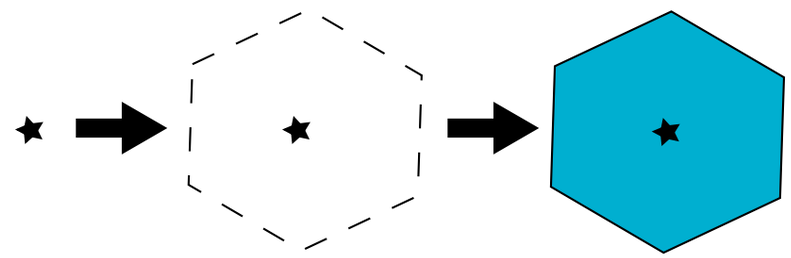

(Deposition)

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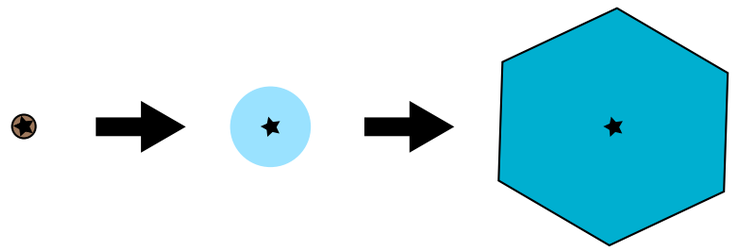

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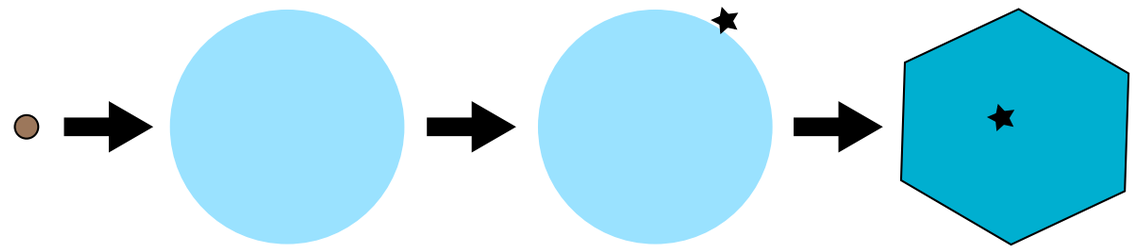

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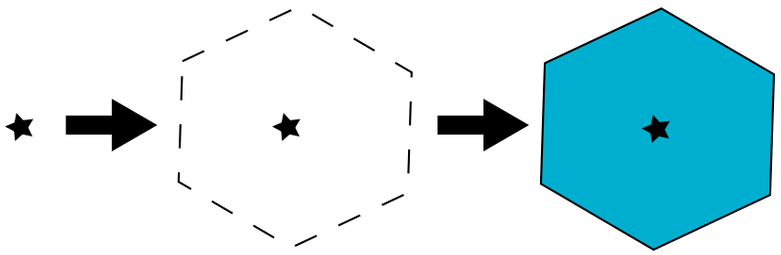
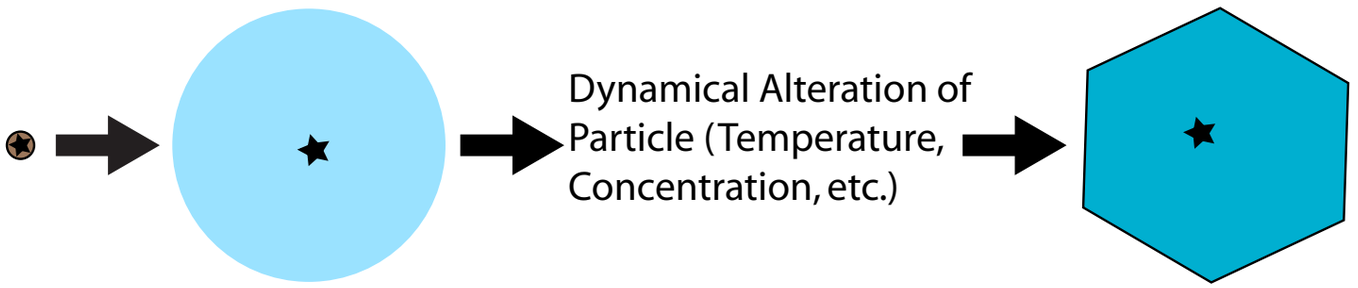


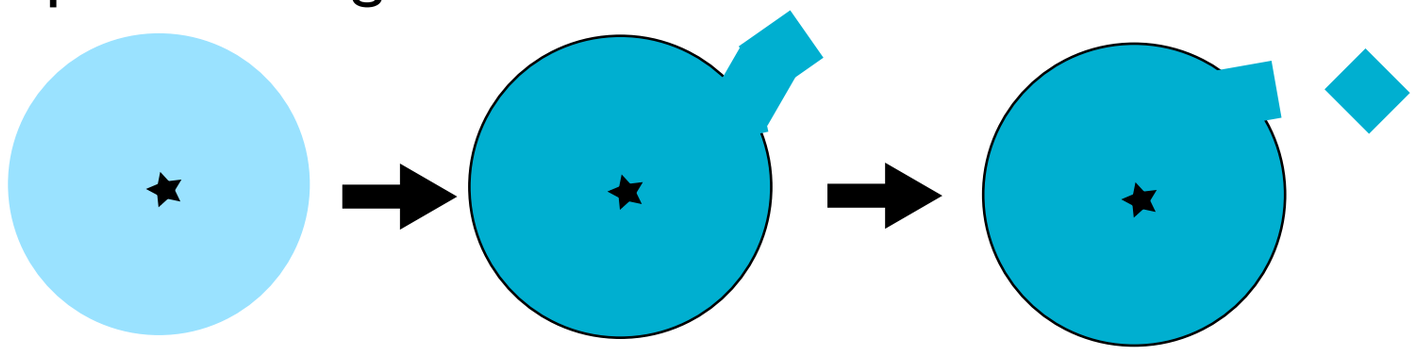
(Deposition)

- Immersion nucleation

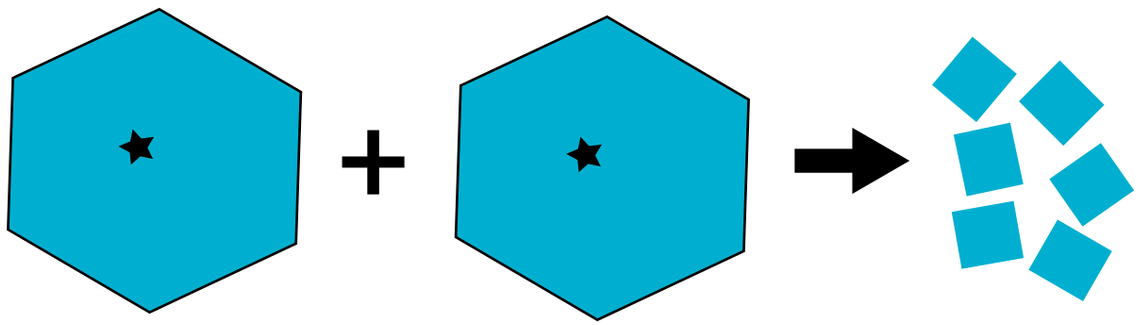


Ice Formation

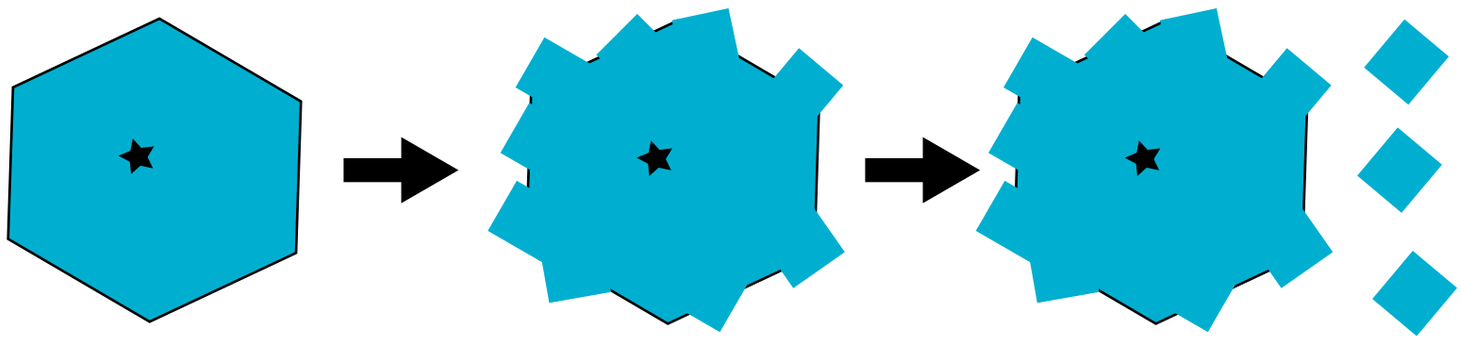
- Secondary Ice Formation
  - Multiplication mechanisms
    - Drop shattering:



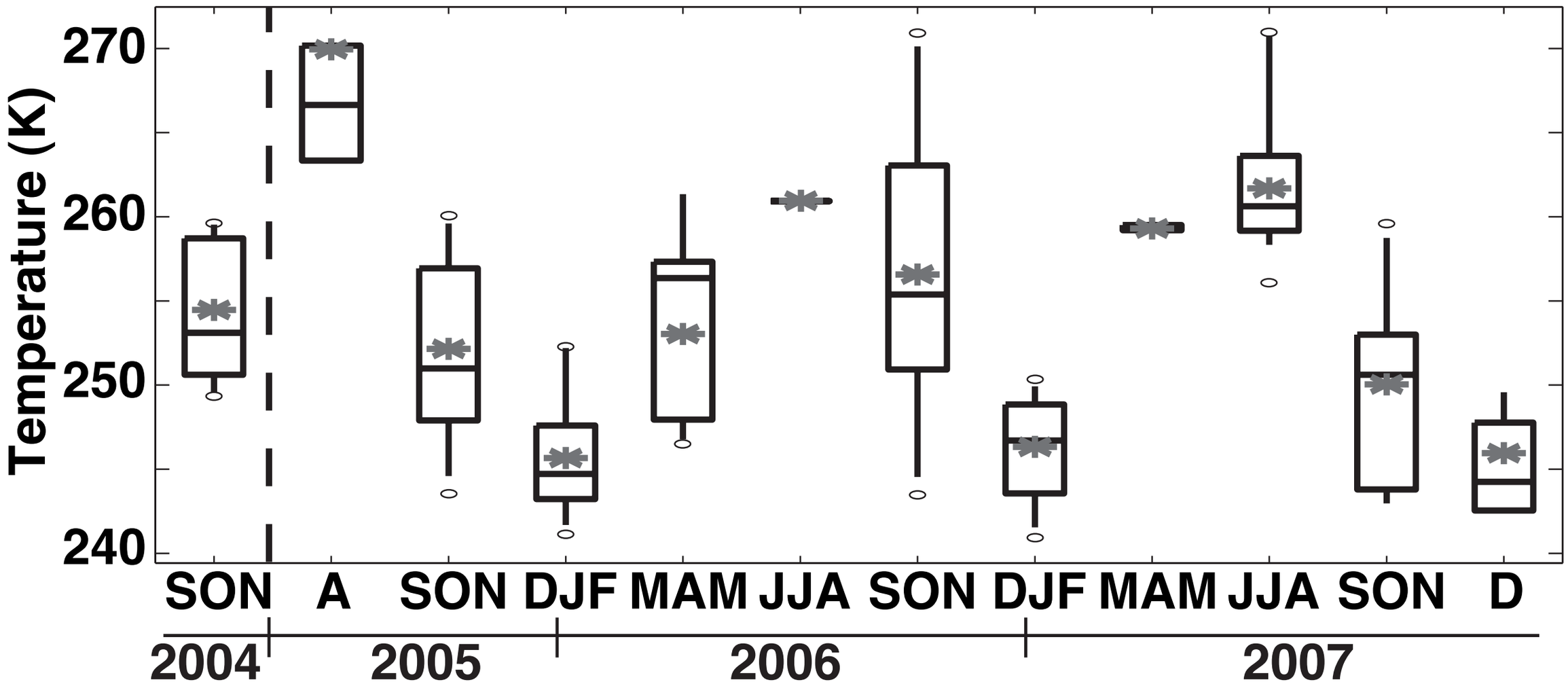
    - Ice-Ice Collisions:



- Splinter ejection during riming (Hallett-Mossop, 1974)



Temperatures



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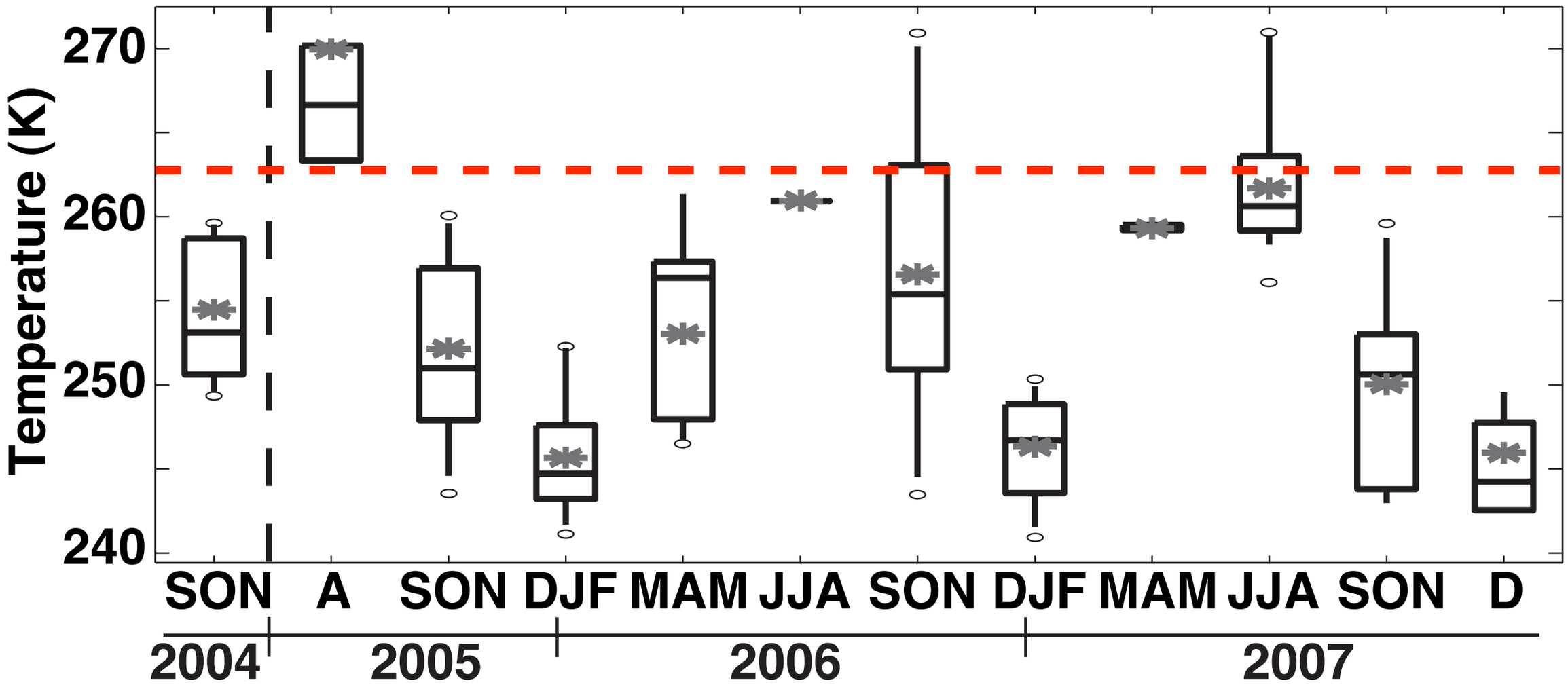
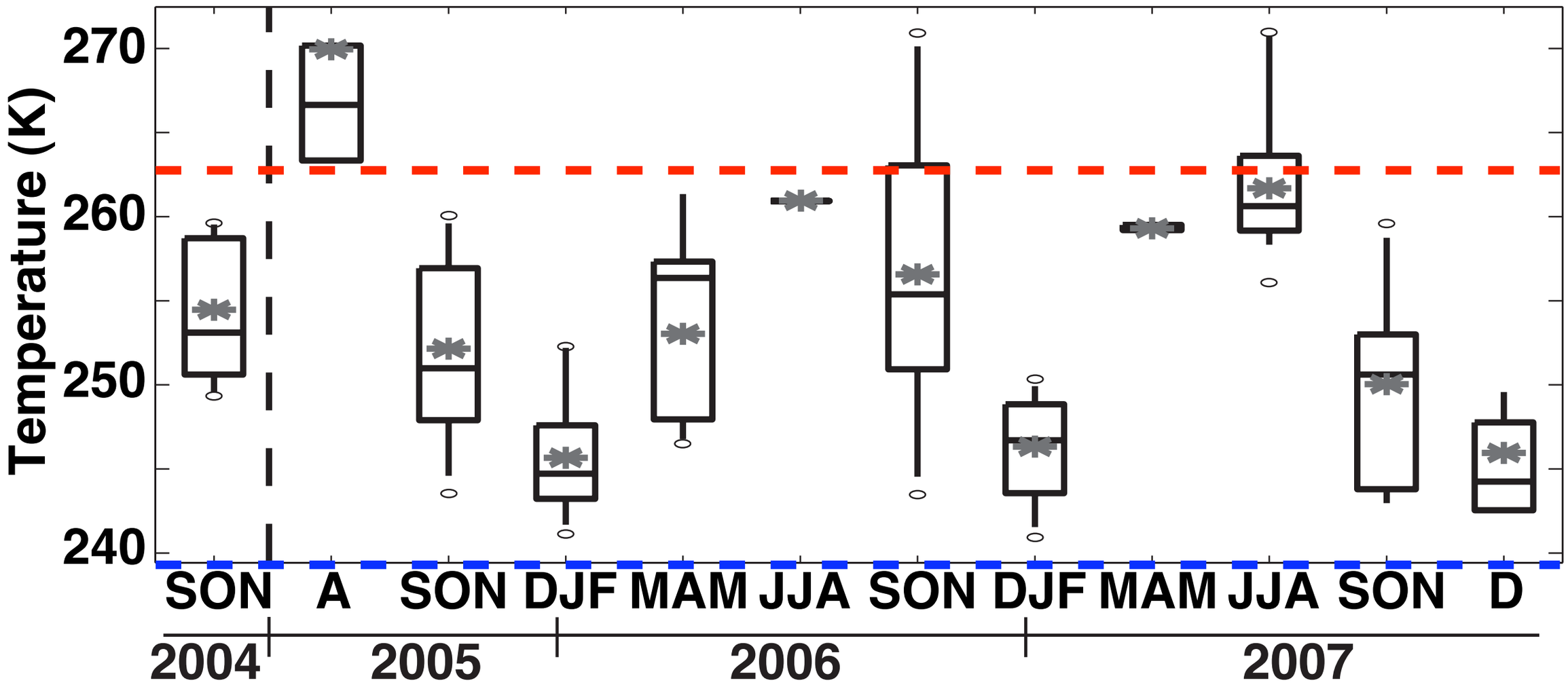


Splinter Ejection (> -8°C)(Heymsfield and Mossop, 1984)

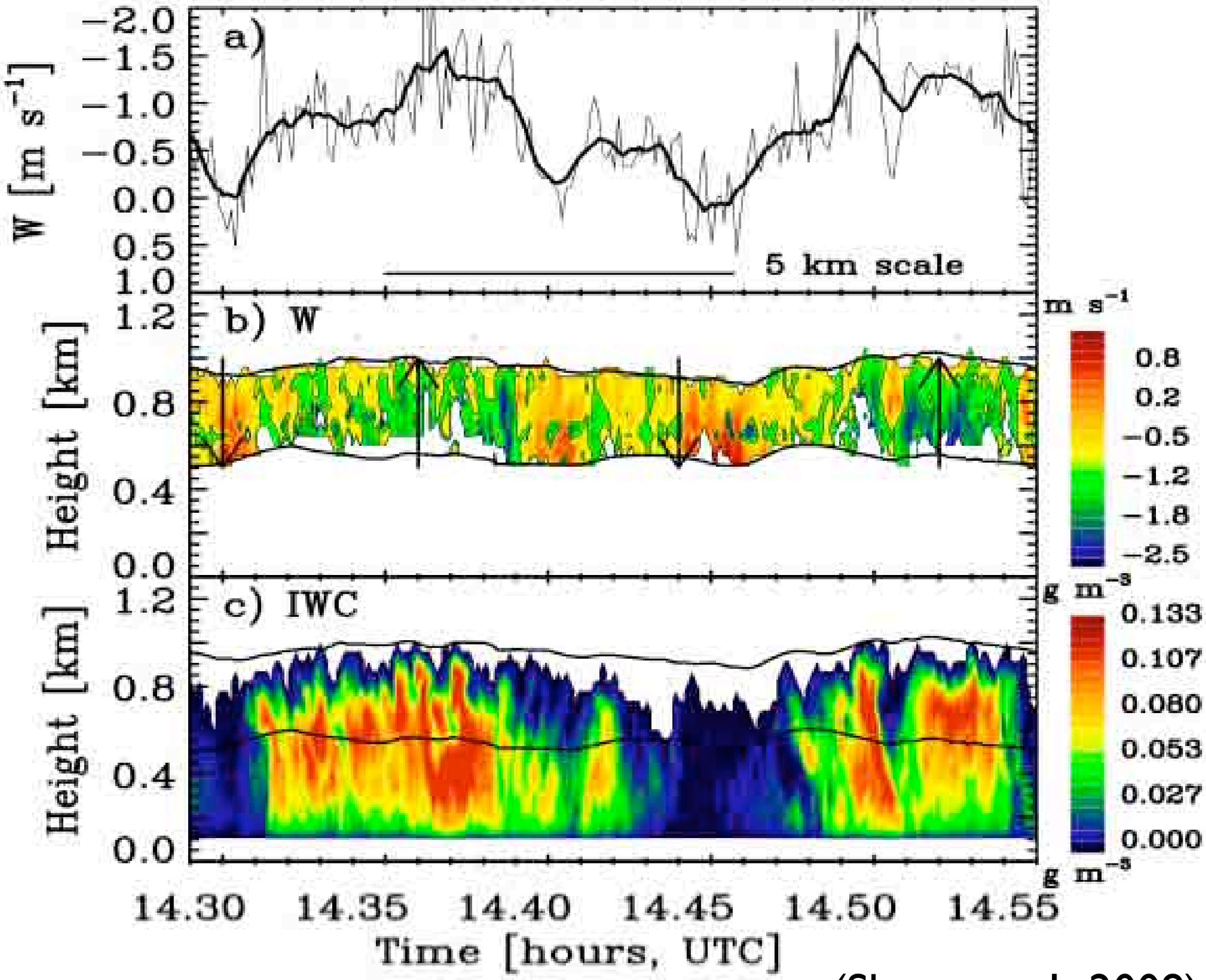
Temperatures



Splinter Ejection (> -8°C)(Heymsfield and Mossop, 1984)

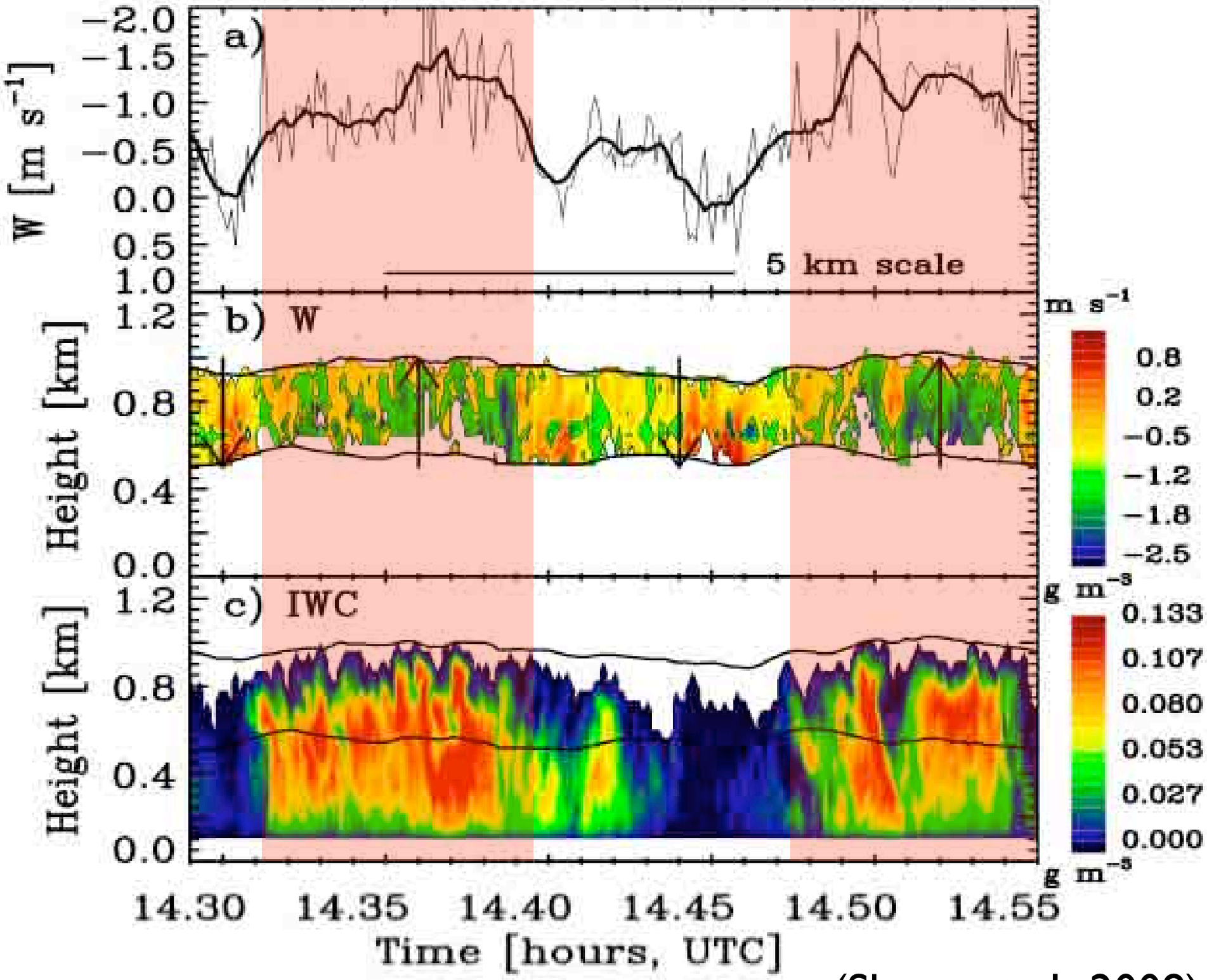
Homogeneous Freezing (< -35°C)(Hagen et al., 1981; Jensen et al., 1998)

Vertical Motion



(Shupe et al., 2008)

Vertical Motion



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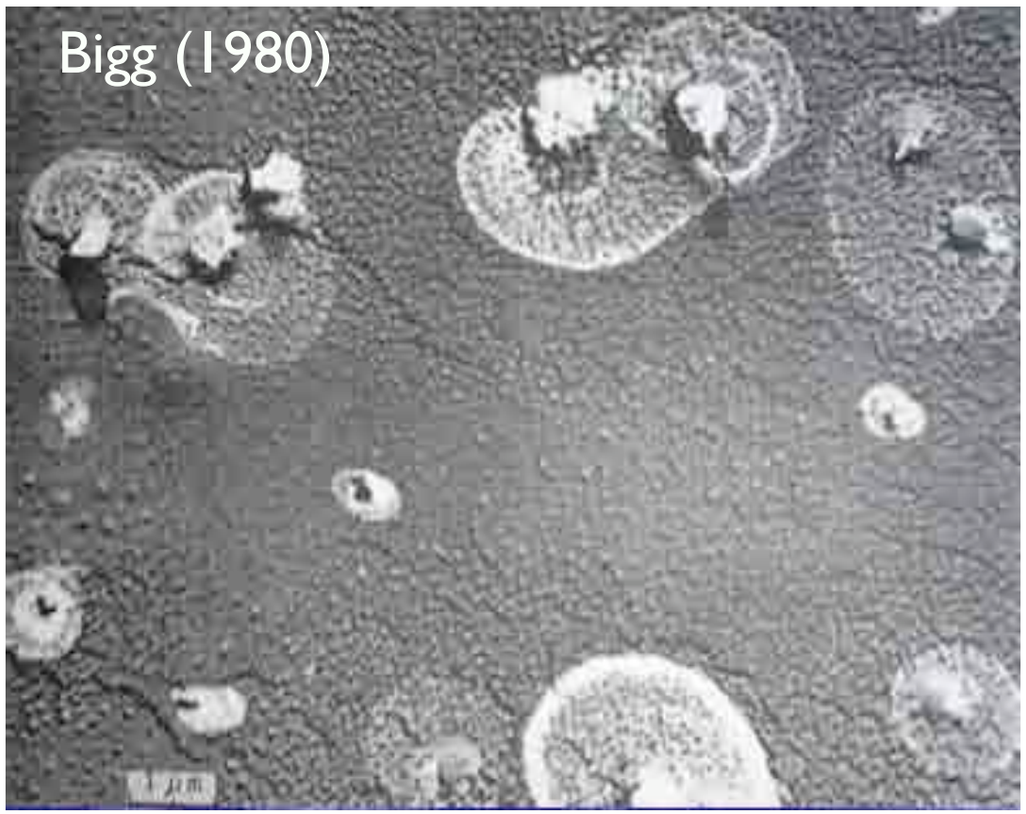
Ice Formation

Observational Clues



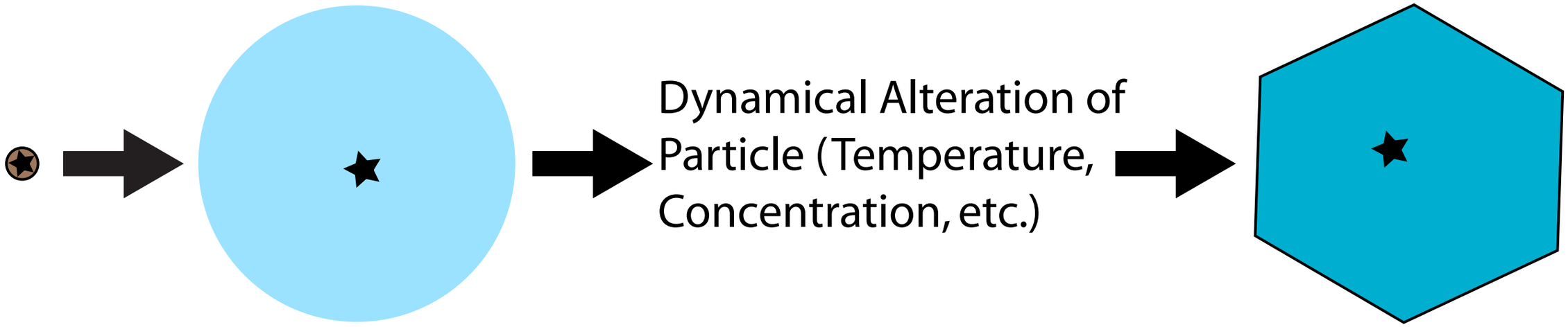
Aerosols:

- Bigg (1980) observed sulfuric acid coating on aerosol particles during winter
- Sulfuric coating is water soluble, transforming possible IN into CCN.
- Sulfate is primarily produced through the oxidation of SO_2 in clouds, through reactions with peroxides or ozone (Kreidenweis et al., 2003). SO_2 is produced in the oxidation of dimethylsulfide (DMS) (along with sulfuric acid (H_2SO_4) and methanesulfonic acid (MSA)). The MSA and H_2SO_4 are transformed to the particle phase through condensation on pre-existing biogenic particles. (Gabric, 2005; Leck et al., 2002). SO_2 also has anthropogenic sources.

From in-situ measurements:

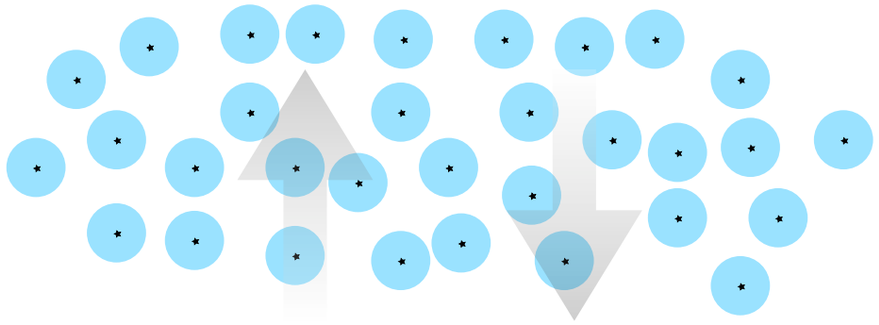
- Ice crystal concentrations strongly proportional to concentration of drops larger than 20 μm. (Rangno & Hobbs, 2001)

Immersion Freezing



Immersion Freezing

Conceptual Model for Mixed-Phase Stratus



Initialization

Immersion Freezing

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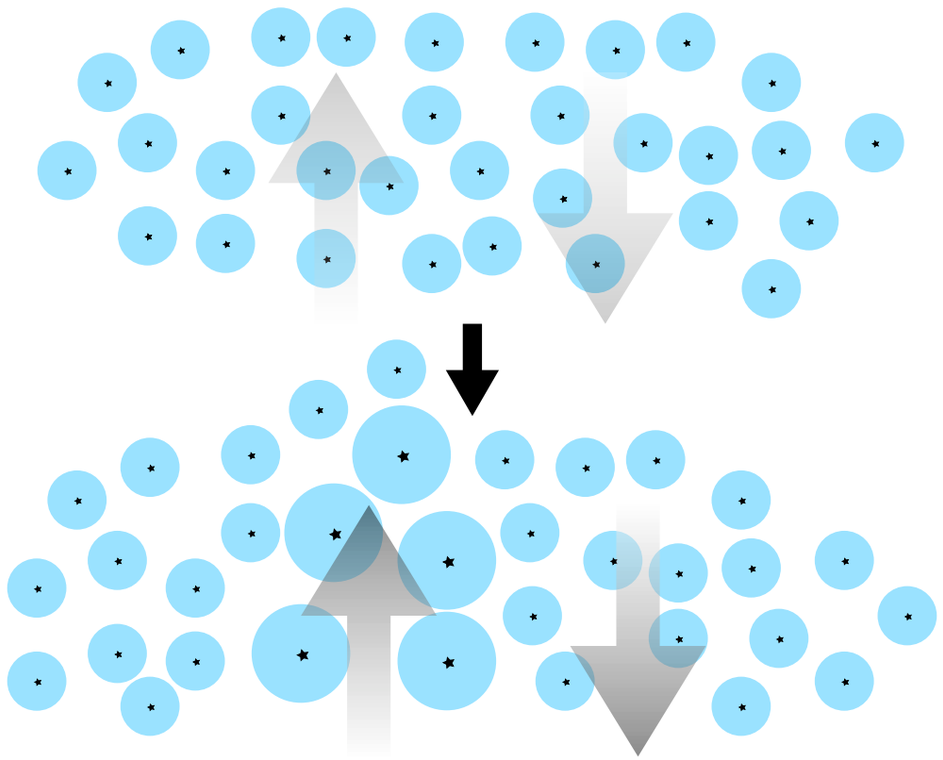

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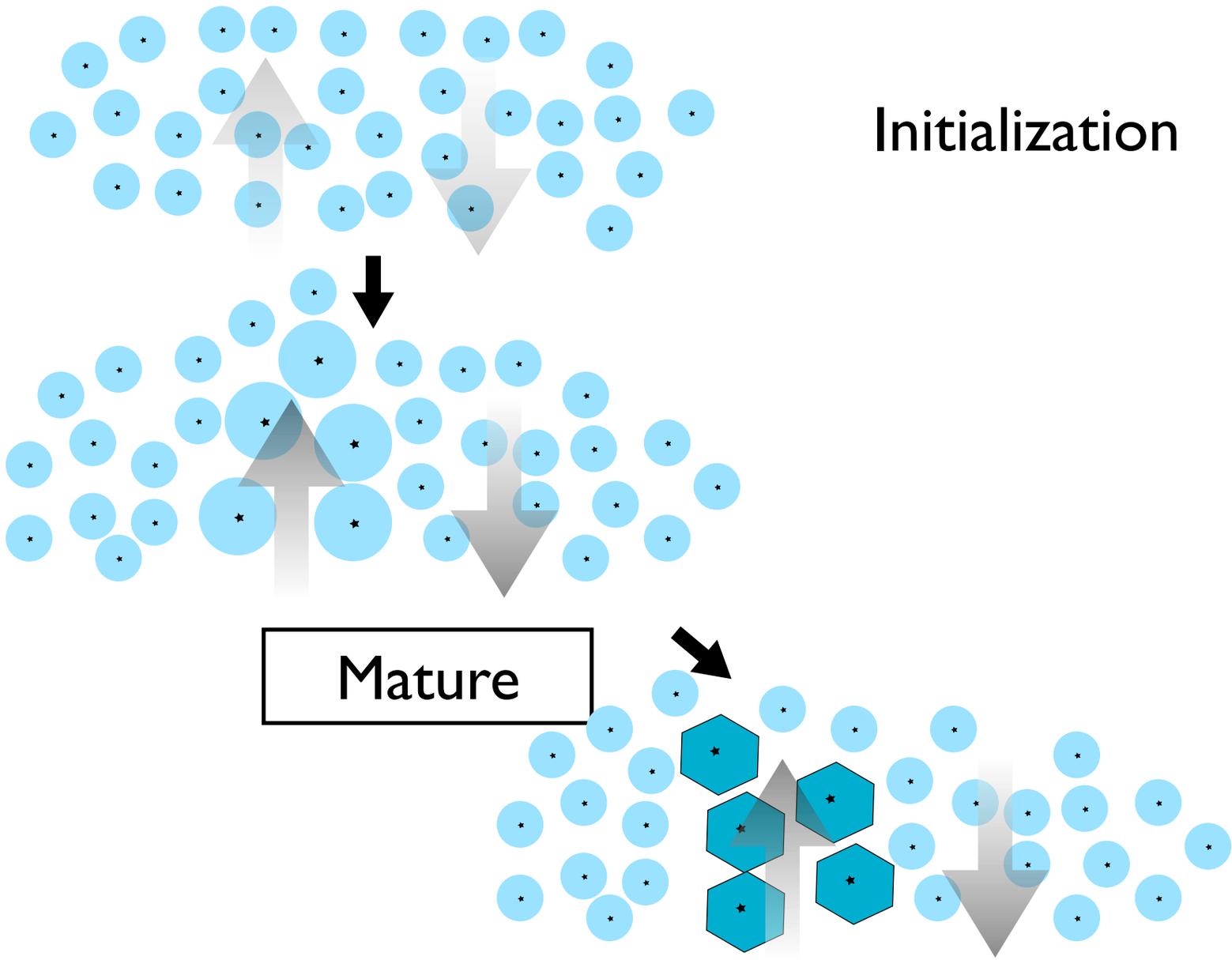

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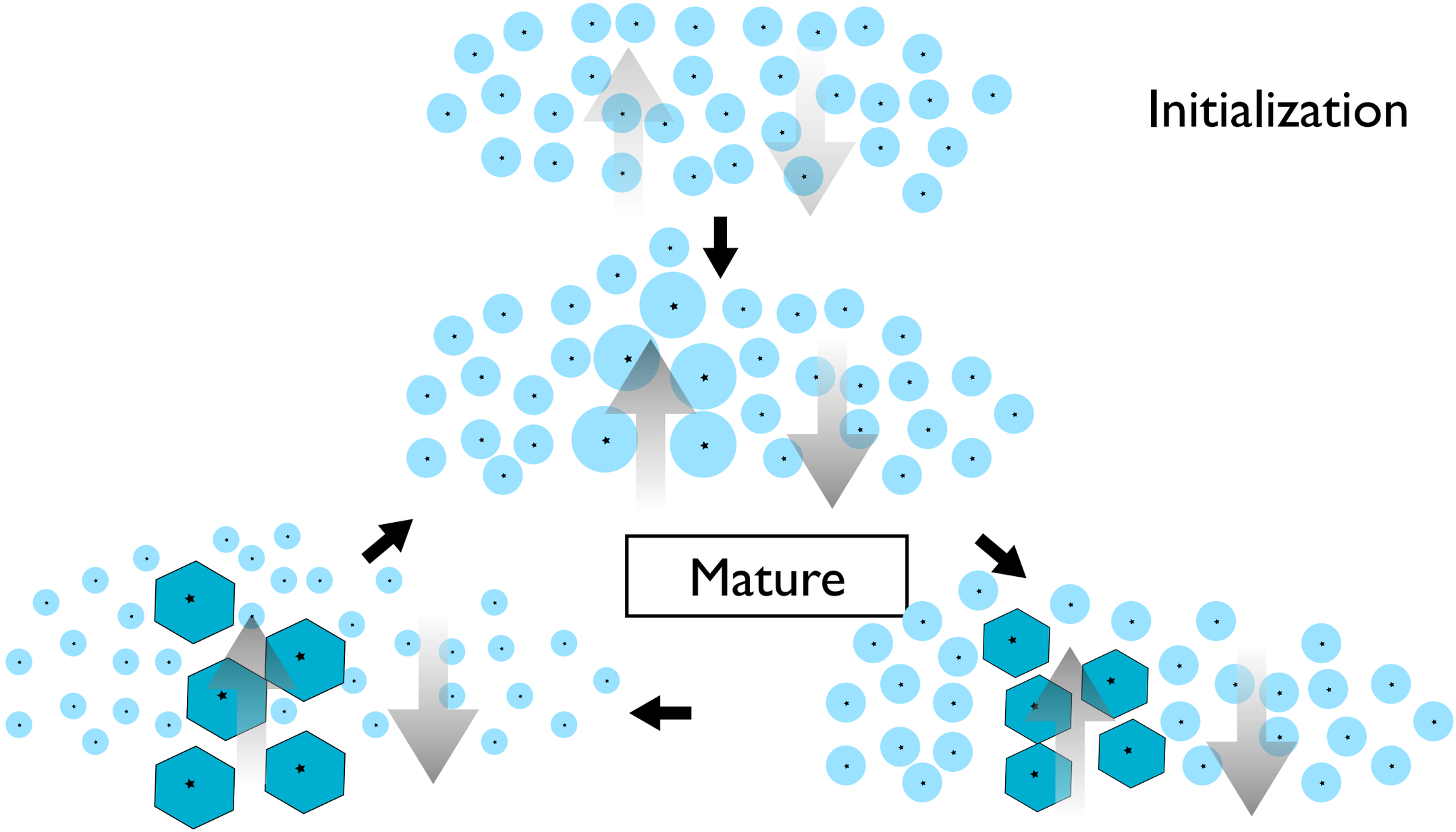
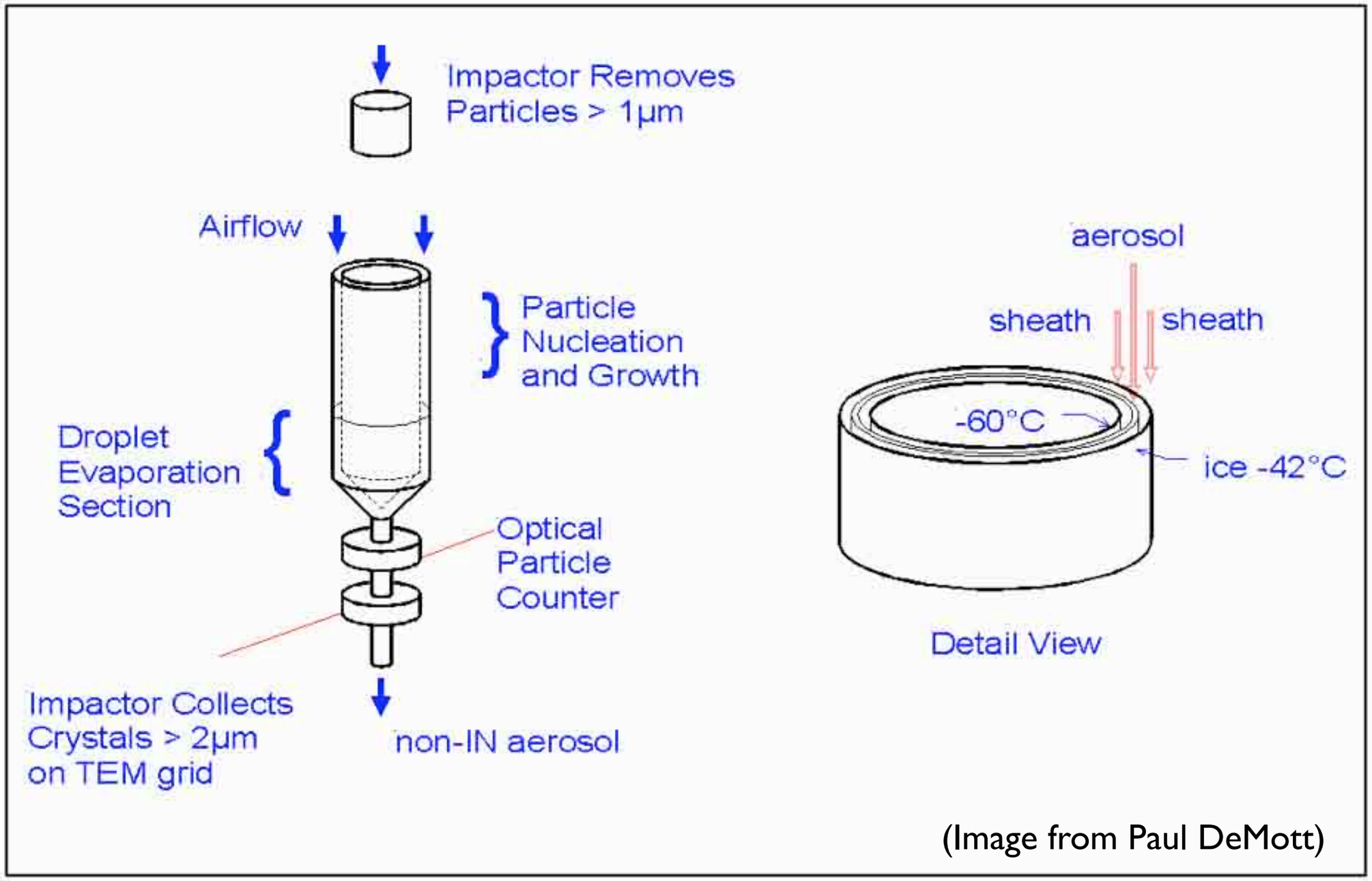


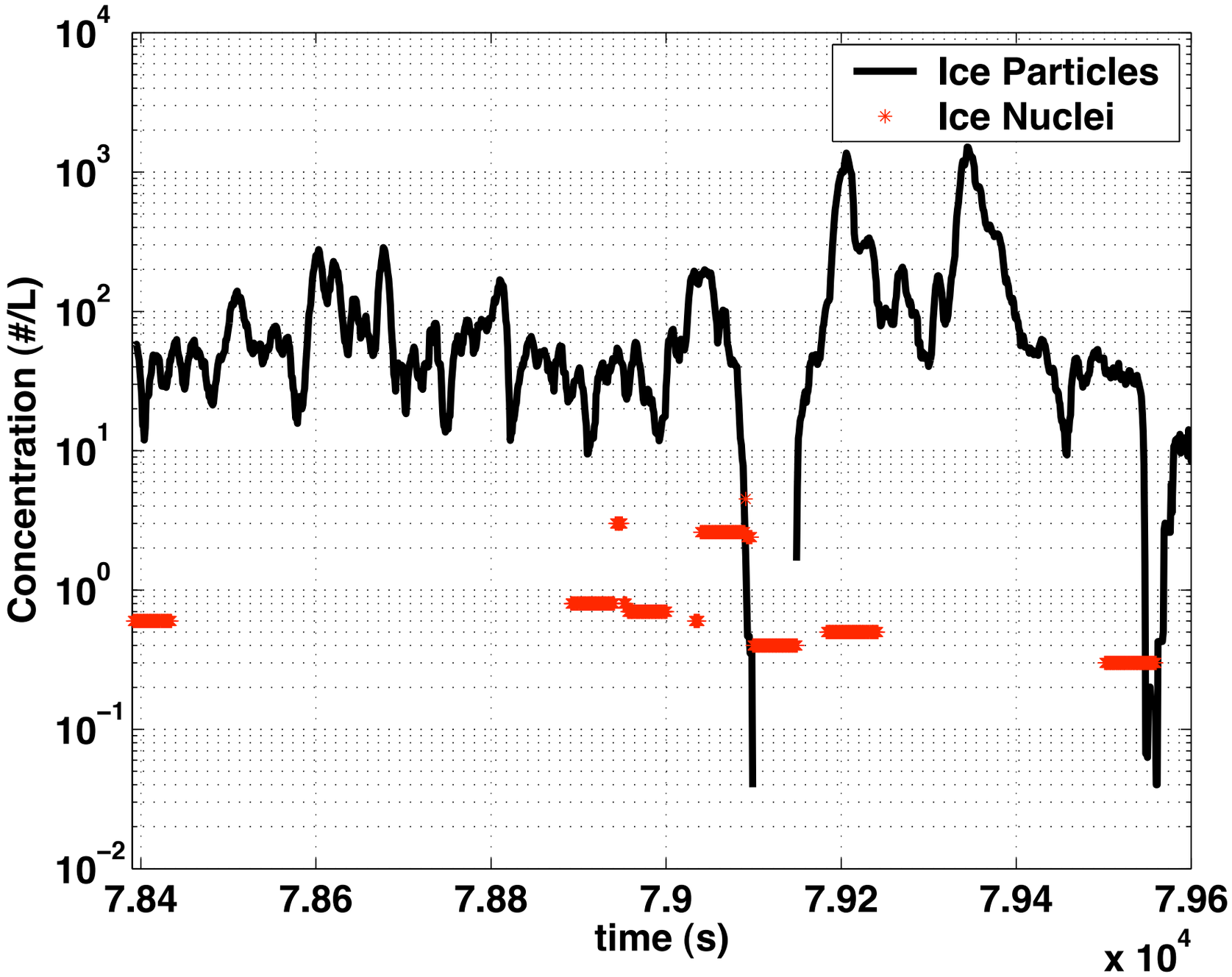
Simulation Challenges



(Image from Paul DeMott)

Simulation Challenges

- Ice nucleation schemes based on CFDC data...



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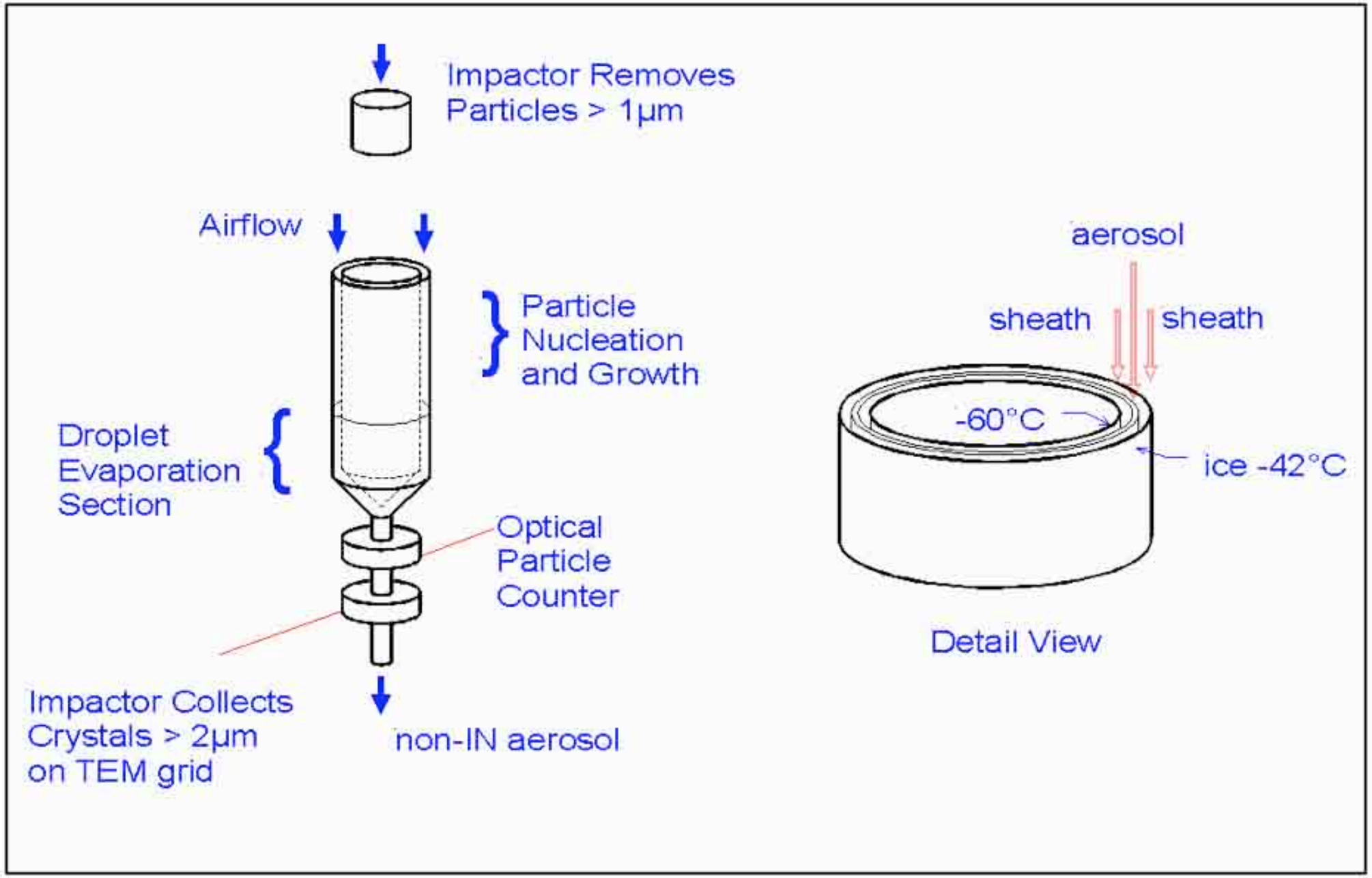


Summary

-Low-level, mixed-phase stratiform clouds are common in the Arctic

-Feedback mechanisms between regulating interactions between these clouds and sea ice are not yet well understood

-Models have a difficult time representing mixed-phase microphysics, in part due to uncertainties in ice nucleation

-Observations provide clues to help solve nucleation mystery, and immersion freezing may play active role in ice nucleation

-There appears to be a fundamental disconnect between observations and simulation of ice nucleation

References

Curry, J.A., W.B. Rossow, D. Randall, and J.J. Schramm (1996), **Overview of Arctic cloud and radiation characteristics**, *J. Climate*, 9, 1731-1764.

de Boer, G., E.W. Eloranta, and M.D. Shupe (2009), **Arctic mixed-phase stratiform cloud properties from multiple years of surface-based measurements at two high-latitude locations**, Submitted to JAS.

-----, T. Hashino and G. J. Tripoli (2009), **A theory for ice nucleation through immersion freezing in mixed-phase stratiform clouds**, Submitted to Atmos. Res..

-----, de Boer, G., G. J. Tripoli and E.W. Eloranta (2008), **Preliminary comparison of cloudsat-derived microphysical quantities with ground-based measurements for mixed-phase cloud research in the arctic**, J. Geophys. Res., 113.

Garbric, A,J., B. Qu, P. Matrai and A.C. Hirst (2005), **The Simulated Response of Dimethylsulfide Production in the Arctic Ocean to Global Warming**. *Tellus*, 57B, 391-403.

Herman, G. and R. Goody (1976), **Formation and persistence of summertime Arctic clouds**, *J. Atmos. Sci.*, 33, 1537-1553.

Heymsfield, A.J., and S.C. Mossop (1984), **Temperature dependence of secondary ice crystal production during soft hail growth by riming**, Quart. J. Roy. Meteor. Soc., 110, 765-770.

Jensen, E.J., and Coauthors (1998), **Ice nucleating processes in upper tropospheric wave-clouds observed during SUCCESS**, Geophys. Res. Lett., 25, 1363-1366.

Kay, J.E., T. L'Ecuyer, A. Gettelman, G. Stephens and C. O'Dell (2008), **The contribution of cloud and radiation anomalies to the 2007 Arctic sea ice extent minimum**, Geophys. Res. Lett., 35, L08503, doi: 10.1029/2008GL033451.

Klein, S.A., and co-authors (2009), **Intercomparison of model simulations of mixed-phase clouds observed during the ARM Mixed-Phase Arctic Cloud Experiment. Part I: Single-layer cloud**, Submitted to QJRMS.

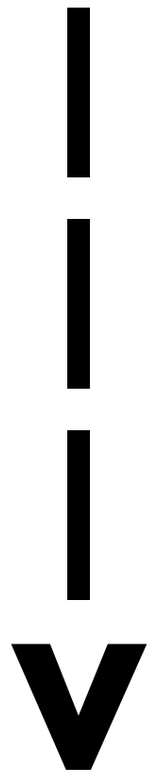
Kreidenweis, S.M., and co-authors (2003), **Modification of Aerosol Mass and Size Distribution Due to Aqueous-Phase SO2 Oxidation in Clouds: Comparison of Several Models**. *J. Geophys. Res.,* 108, 4213.

Leck, C., M. Norman and E.K. Bigg (2002), **Chemical Composition and Sources of the High Arctic Aerosol Relevant for Cloud Formation**, *J. Geophys. Res.*, 107, 4135.

Schweiger, A.J., J. Zhang, R.W. Lindsay and M. Steele (2008), **Did unusually sunny skies help drive the record sea ice minimum of 2007?**, Geophys. Res. Lett., 35, L10503, doi:10.1029/2008GL033463.

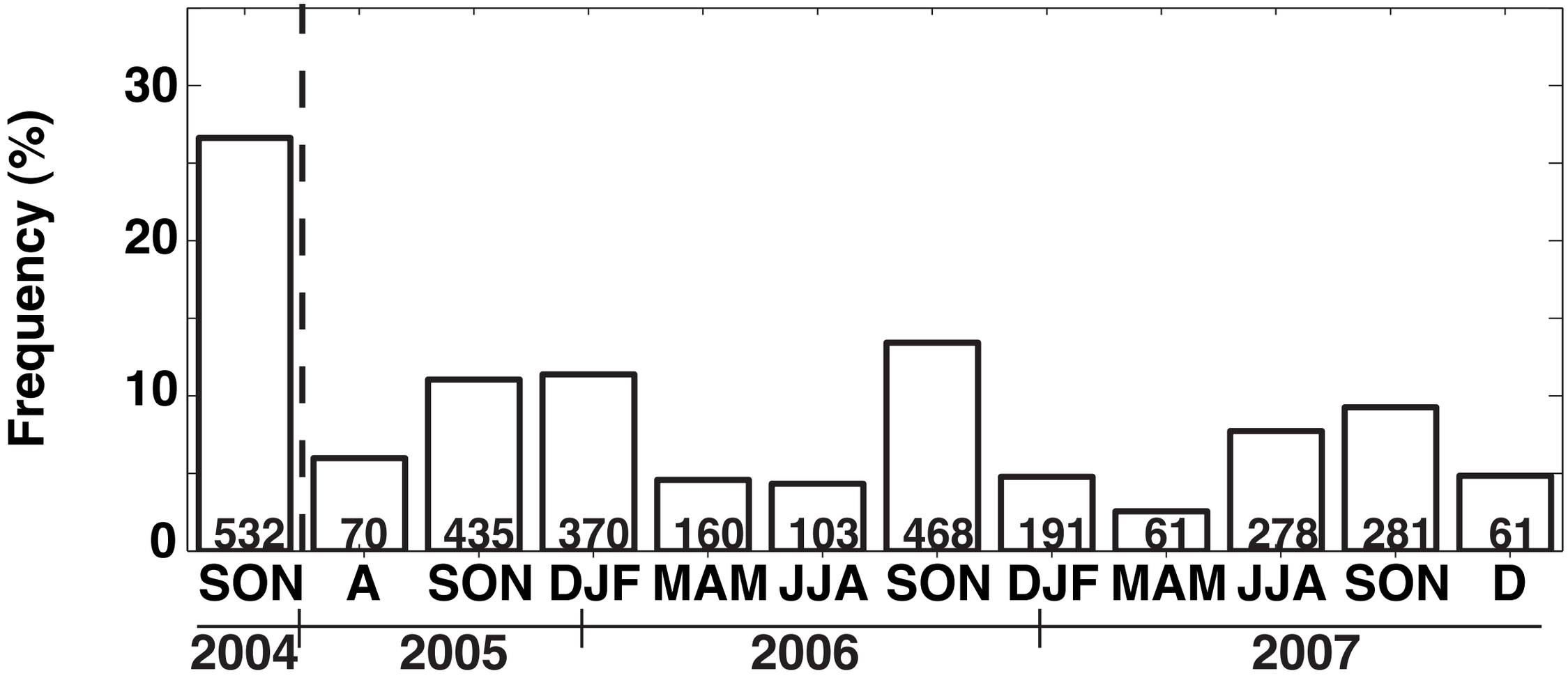
Shupe, M.D., P. Kollias, P.O.G. Persson, and G.M. McFarquhar (2008), **Vertical motions in Arctic mixed-phase stratiform clouds**, *J. Atmos. Sci.*, 65, 1304-1322.

EXTRA SLIDES



Macrophysical Properties

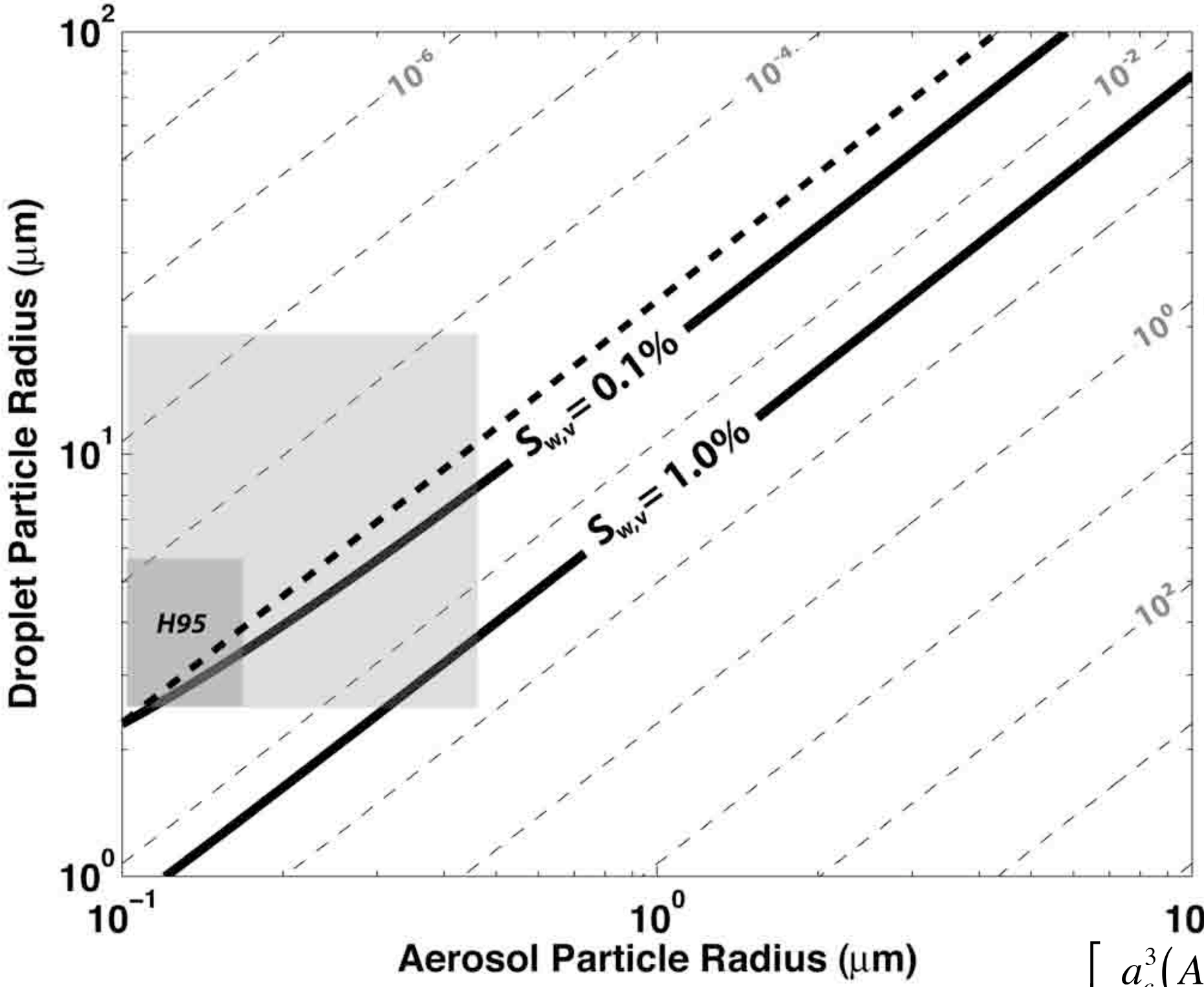
Cloud Frequency



26% (Barrow)

8% (Eureka)

Immersion Freezing



$$r_{N,c} = \left[\frac{a_c^3 \left(A - s_{v,w} a_c \right)}{A + \left(B - s_{v,w} \right) a_c} \right]^{1/3}$$