Ice crystal formation and evolution in DC3 campaign

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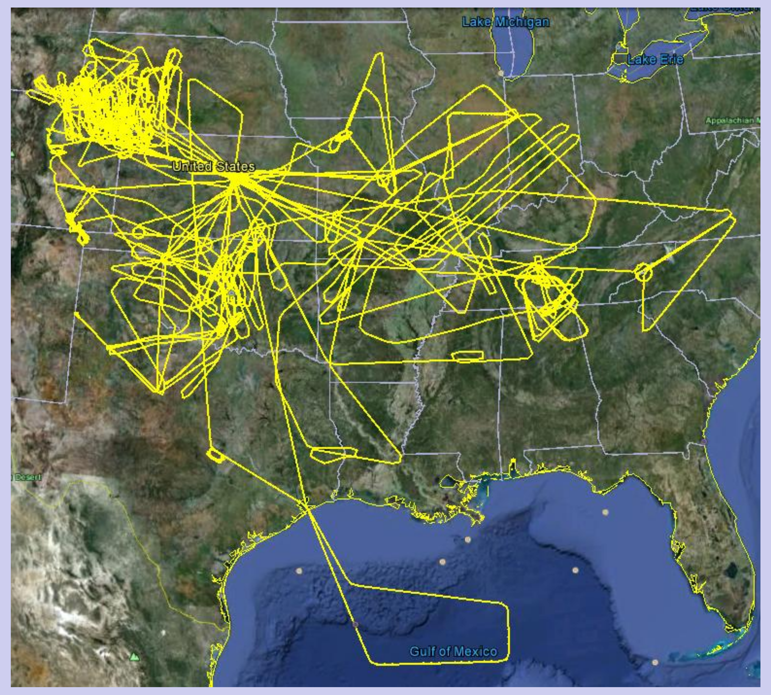
• Cirrus cloud and ice supersaturation

Cirrus clouds have large but highly uncertain impacts on Earth's climate [*Chen et al. 2000*]. Modeling cirrus clouds is challenging because cloud microphysical processes occur at much smaller scales than climate model resolutions. Cirrus cloud formation requires supersaturation of the relative humidity with respect to ice (RHi). However, it has not been studied by using quasi-Eulerian aircraft observations how cirrus clouds initiate from ice supersaturated regions (ISSRs, regions where RHi > 100%), grow in size and eventually dissipate. Here we show the time evolution of cirrus clouds by analyzing the relationship between ice crystal regions (regions where ice crystal number density > 0.06 #/cm^3) and ISSRs.

VCSEL hygrometer on the NSF Gulfstream V research plane



• Deep convective clouds & chemistry experiment (DC3) campaign

The DC3 campaign includes 26 flights from May 18 - June 30, 2012, which took place over central plain of North America, investigating the impact of deep midlatitude continental convective clouds. The campaign provided large amount samplings around convective generated cirrus clouds, which is very helpful for analyzing ice crystal formation and evolution in convective regions. The analyses in this study were all restricted to temperature (T) ≤ - 40 °C (~**69.5 hrs**), including ~**11.2 hrs** of ice supersaturation and ~**21.1 hrs** of ice crystal observations. The mean true air speed is 237 m/s.

GV instruments	Principal Investigator	Measurement	Accuracy	Precision
VCSEL hygrometer	Mark Zondlo, Princeton U.	Water vapor	6%	≤ 1%
2-DC	Dave Rogers, NCAR	Ice particle number density (Nc) and mean diameter (Dc)	Measurement range: 25-800 µm	
CO_RAF	Teresa Campos, NCAR	CO	± 5%	± 5%
O3_NCAR	Teresa Campos, NCAR	O3	± 9%	0.8 ppbv

•Definitions of ice crystal regions (ICRs) and ice supersaturated regions (ISSRs)

ISSRs: regions with spatially continuous ISS.
ICRs: regions with spatially continuous ice crystal distribution.
"**With ice crystals**" as where the ice crystal number density (Nc) ≥ 0.06 #/cm^3 during the 1 Hz measurements, while the remaining regions are considered to be clear-sky regions.
One ISSR+ICR sample: a set of spatially continuous ISSRs and ICRs.
In total, **2529** ISSR+ICR samples were observed in DC3.

References:
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Straka, J.M. Cloud and precipitation microphysics - principles and parameterizations, 1st ed., Cambridge University Press (2009).
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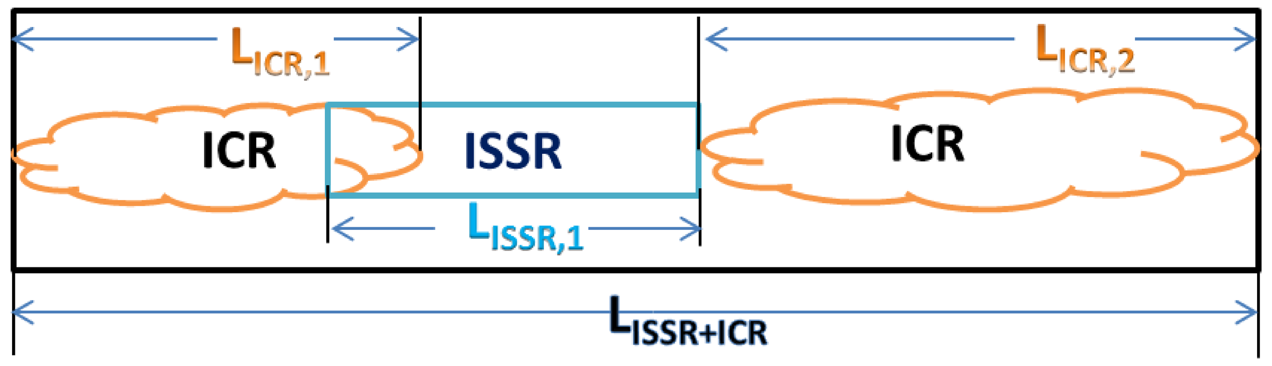
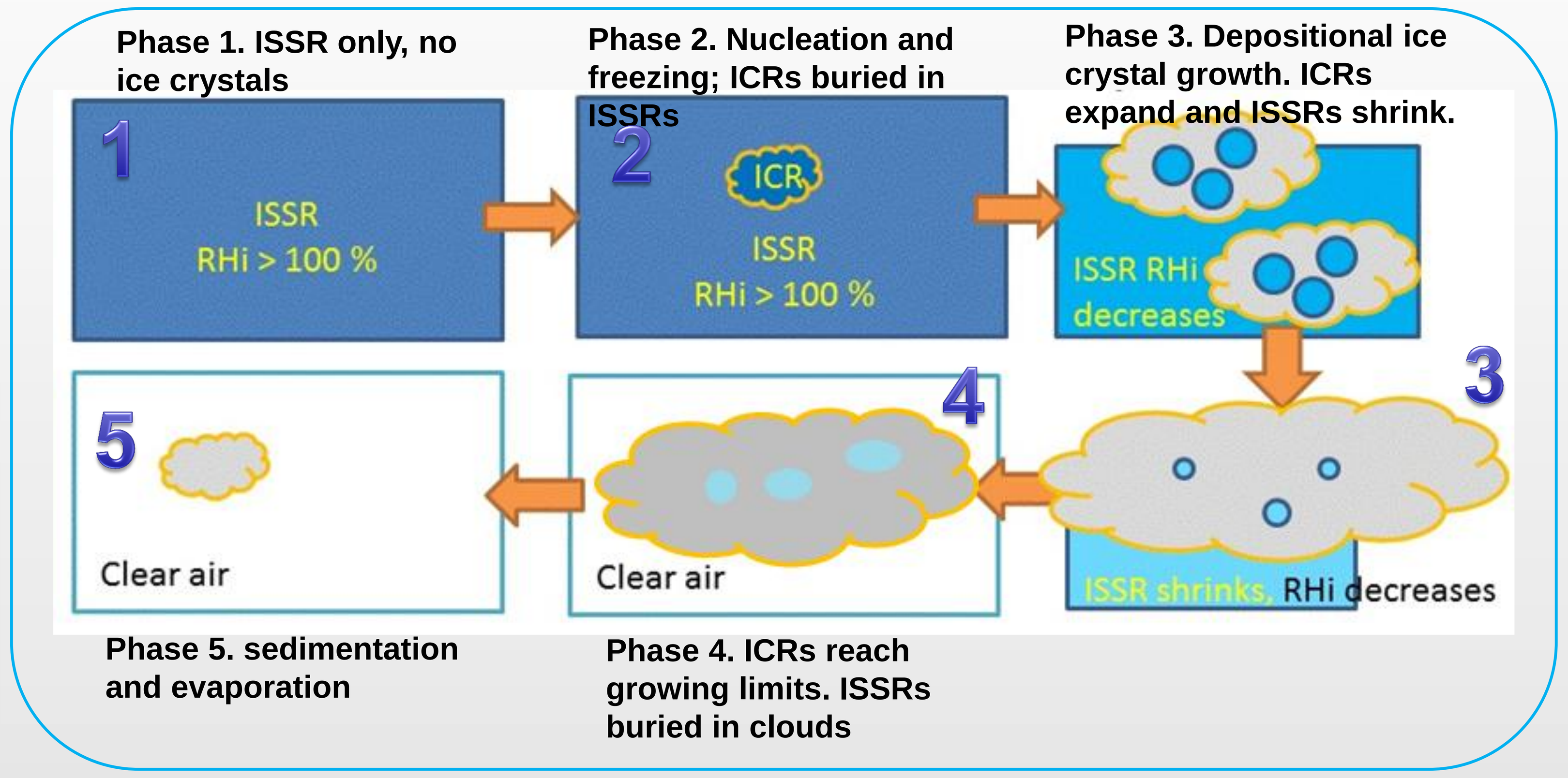
•Five phases of ice crystal region evolution

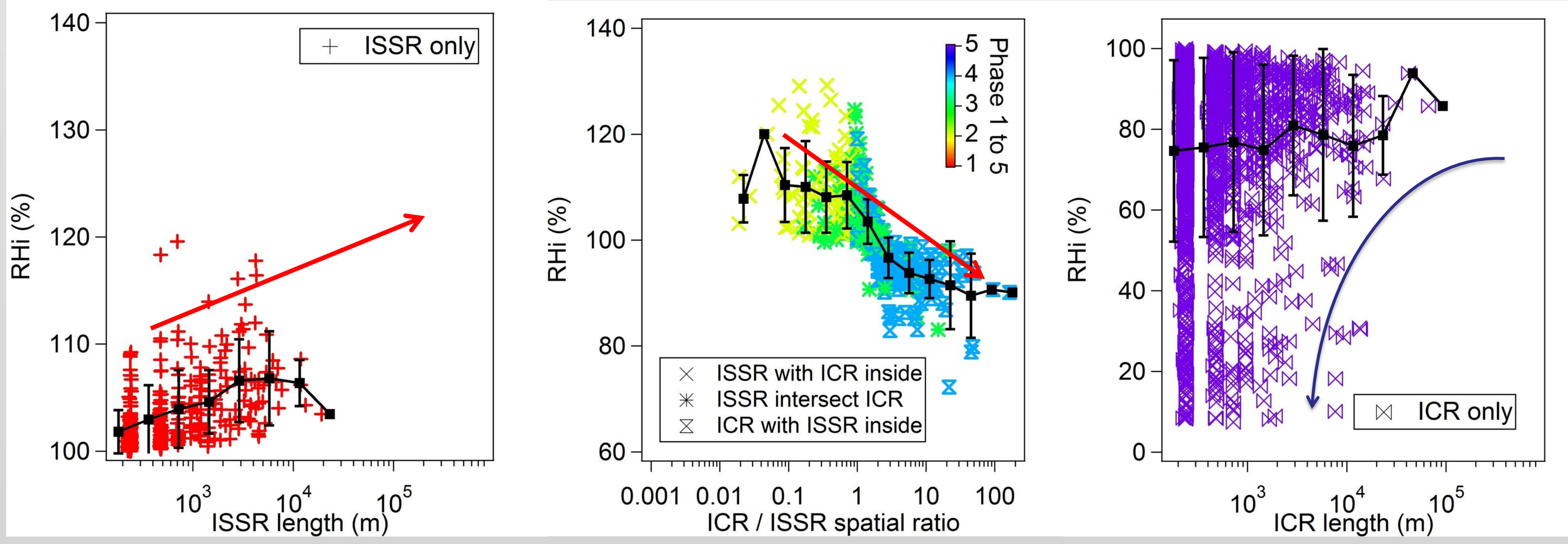
one ISSR + ICR sample



Pha-se	Description	Spatial ratio M = sum(L_{ICR}) / $L_{ISSR+ICR}$	Spatial ratio N = sum(L_{ISSR}) / $L_{ISSR+ICR}$	Number of samples (ISSR + ICR)
1	Clear-sky ISSRs	0	1	322
2	Nucleation	0 < M < 1	1	88
3	Early growth of ice crystals	0 < M < 1	0 < N < 1	152
4	Later growth of ice crystals	1	0 < N ≤ 1	266
5	Evaporation/sedimentation	1	0	1701



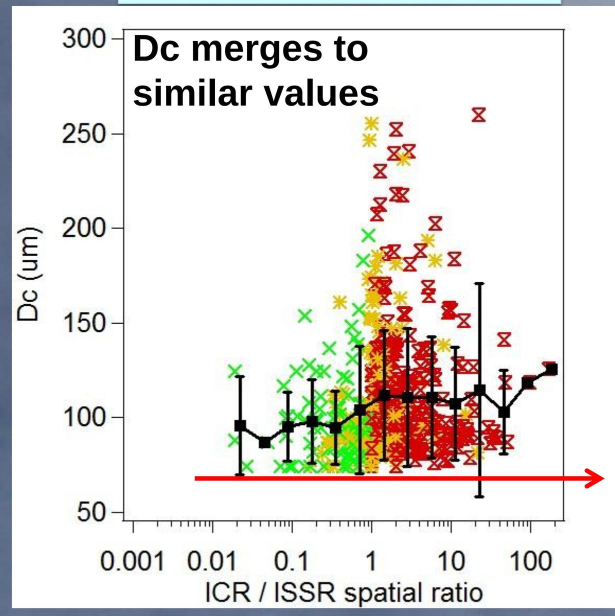
Phase 1 Clear-sky ISSRs | **Phase 2+3+4 Ice crystal nucleation and growth** | **Phase 5 Sedimentation/ evaporation**



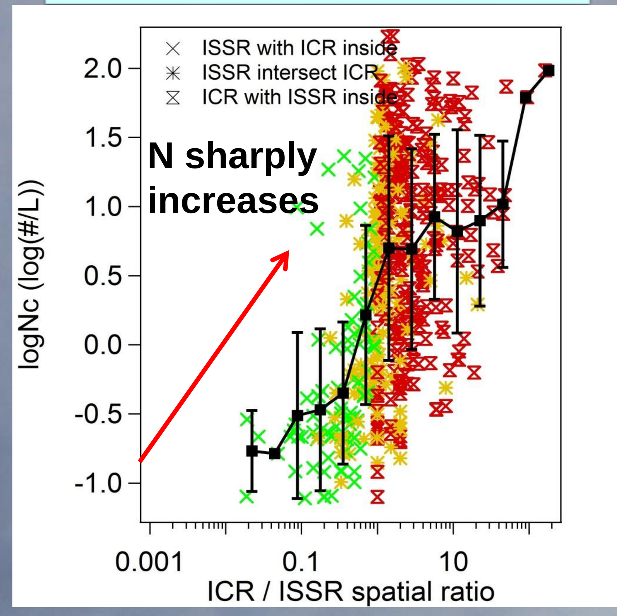
Phase 1: Clear-sky ISSRs phase: birthplace of cirrus clouds.
Phase 2: Nucleation phase: ICRs start to form inside the ISSRs.
Phase 3: Early growth phase: ICRs and ISSRs are adjacent or they intersect each other. RHi decreases as ICR size expands.
Phase 4: Later growth phase: ICRs take over the space and ISSRs are imbedded in ICRs. The whole ICR+ISSR is no longer fully supersaturated.
Phase 5: Ice crystals evaporate and sediment. No more ISS. RHi decreases as ICR size shrinks. Note the wide distribution of RHi (from 100% to 10%) for aged ICRs.

•Ice crystal number density (Nc) and mean diameter (Dc) evolution

Mean diameter Dc



Number density logNc



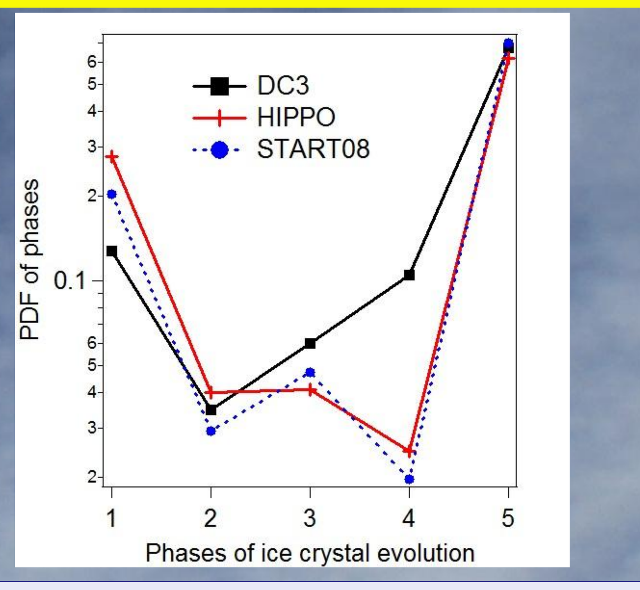
Growth rate of a single ice crystal

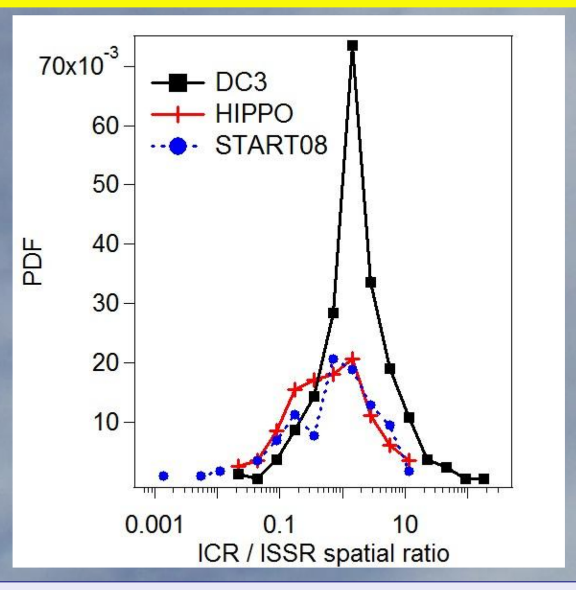
$$\frac{dD_{ice}}{dt} = \frac{1}{D_{ice}}\left(S_{v,out} - S_{v,eq}\right) * G_i(T,P)$$

Rogers and Yau, 1989 and *Straka*, 2009

[1] Mean diameter of ice crystals merges into a constant value as ice crystals grow, which agrees with the theory of ice crystal growth rate.
[2] Number density of ice crystals continues to increase throughout the ICR evolution. The increasing Nc agrees with previous simulations, where new ice crystals continue to form as the air parcel continues to be uplifted [Spichtinger and Gierens, 2009].

Ice crystal lifetime phases and comparisons with other campaigns (START08 & HIPPO1-5)





[1] DC3 campaign shows more ICRs with ISS buried inside (Phase 4), while in START08 and HIPPO Global campaigns, ISS disappears faster once ice crystals are formed, suggesting in DC3 ice crystals do not consume water vapor over saturation as fast as those in START08 and HIPPO.
[2] ICR/ISSR ratio peaks at higher value in DC3 than the other two campaigns, suggesting that ice crystals grow relatively fast in DC3 so that most ICRs are larger than ISSRs, which indicates that the dominance of Phase 4 in DC3 is contributed by continued strong uplift which maintains the ISS inside ICRs instead of inefficient depositional growth.

Implications to understanding ice crystal evolution

1. We provided a new and simple method to distinguish three phases of ice cloud evolution by using in-situ and quasi-Eulerian sampling of two common parameters: 1) RHi 2) presence/absence of ice crystals.
2. We demonstrated the importance of separating out various evolution phases of ice crystals in Eulerian view observation, since they have different properties of RHi, Nc and Dc.
3. We compared ice crystal evolution between various geographical location and meteorological background. Our finding improves the understanding of the relative lifetime of ice crystal evolution.
4. Our result facilitates the comparison between in situ Eulerian observation and Lagrangian view cloud simulation/ parameterization.