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Ice Crystal Formation and Evolution in Five Campaigns: START08, HIPPO Global, DC3, PREDICT and TORERO

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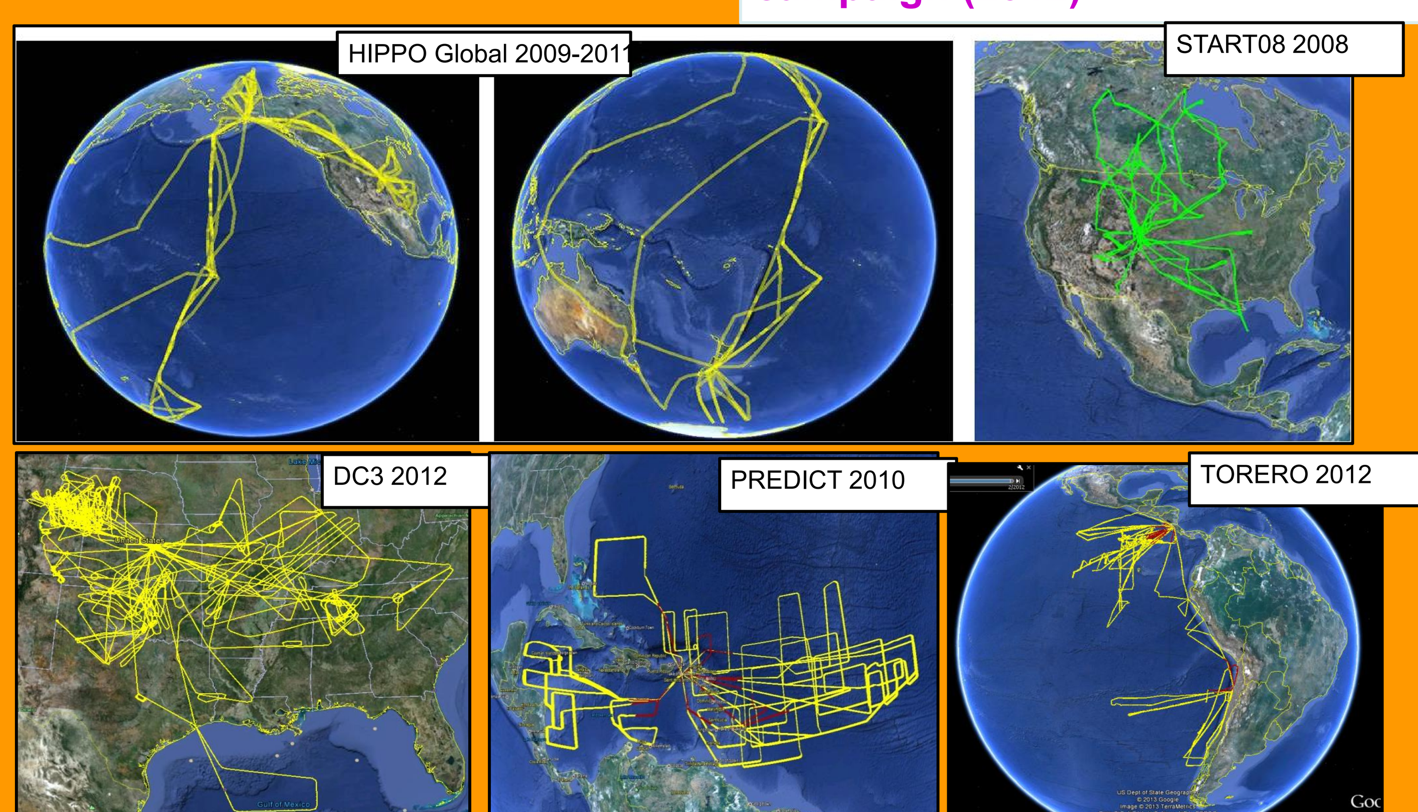
• Cirrus cloud and ice supersaturation

Cirrus clouds have large but highly uncertain impacts on Earth's climate [*Chen et al. 2000*]. Cirrus cloud formation requires supersaturation of the relative humidity with respect to ice (RHi). However, it has not clear how ice crystal regions 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 and ISSRs at temperature (T) ≤ - 40 °C.

1. Stratosphere-Troposphere Analyses of Regional Transport campaign (2008)
2. HIAPER Pole-to-Pole Observations (HIPPO) Global campaign (2009-2011)
3. PRE-Depression Investigation of Cloud-systems in the Tropics (PREDICT) campaign (2010)
4. Deep Convective Clouds & Chemistry (DC3) campaign (2012)
5. Tropical Ocean tRoposphere Exchange of Reactive halogen species and Oxygenated VOC (TORERO) campaign (2012)



GV instruments	Principal Investigator	Measurement	Accuracy	Precision
VCSEL hygrometer	Mark Zondlo, Princeton U.	Water vapor (Zondlo et al., 2010)	6%	≤ 1%
2-DC	Dave Rogers, NCAR	Ice particle number density (Nc) and mean diameter (Dc)	Measurement range: 25-800 µm (Korolev et al., 2011)	
SID-2H instrument	Andrew Heymsfield, NCAR	Ice particle Nc and Dc	Measurement range: 1-50 µm (Cotton et al., 2010)	

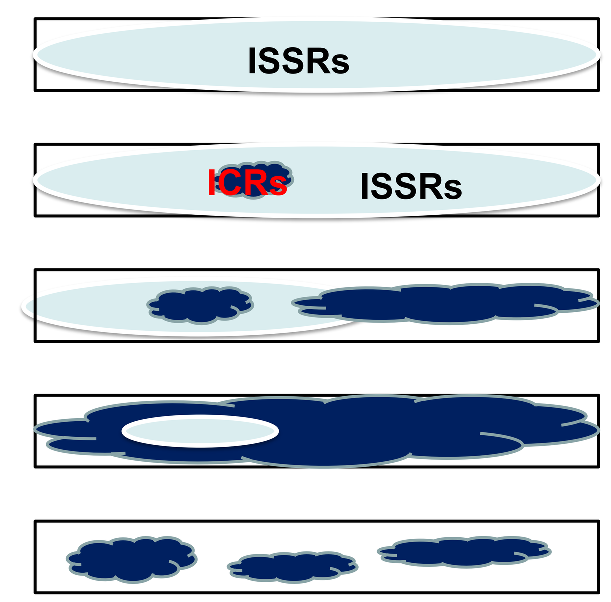
•Definitions of ice crystal regions (ICRs) and ice supersaturated regions (ISSRs)

ISSRs: regions with spatially continuous ISS.
ICRs: regions with spatially continuous ice crystal distribution.
"**With ice crystals**" as where the ice crystals are observed 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.

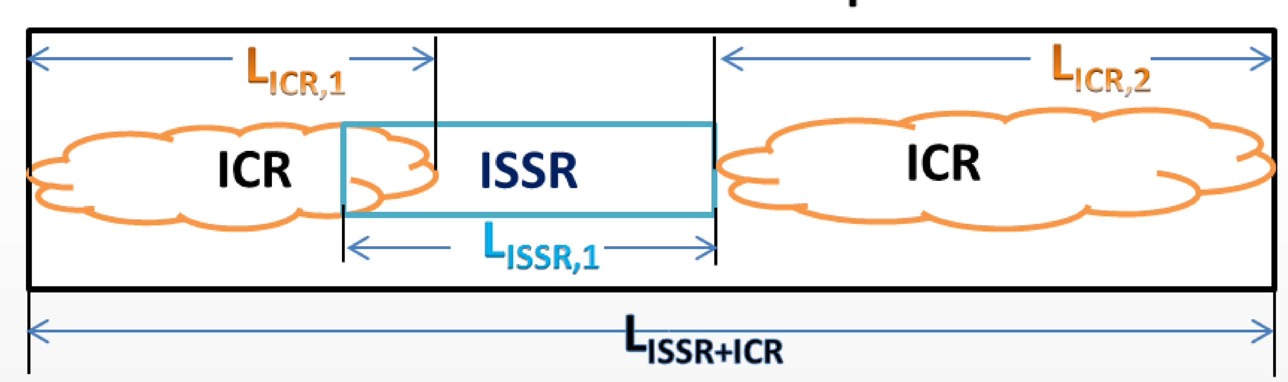
References:
Chen, T., W.B. Rossow and Y.C. Zhang (2000), Radiative effects of cloud-type variations. *J. Clim.*, 13, 264-286.
Diao, M., Zondlo, M. A., Heymsfield, A. J., Beaton, S. P. and Rogers, D. C.: Evolution of ice crystal regions on the microscale based on in situ observations, Geophysical Research Letters, 40, 3473-3478, doi:10.1002/grl.50665, 2013.
M. Diao, M. A. Zondlo, A. J. Heymsfield, L. M. Avallone, M. E. Paige, S. P. Beaton, T. Campos, and D. C. Rogers. Cloud-scale ice supersaturated regions spatially correlate with high water vapor heterogeneities. *Atmos. Chem. Phys. Discuss.*, 13, 22249–22296, 2013.

•Five phases of ice crystal region evolution

Phase 1: Clear-sky ISSRs
Phase 2: Ice crystal nucleation
Phase 3: Ice crystal early growth
Phase 4: Ice crystal later growth
Phase 5: Sedimentation/evaporation

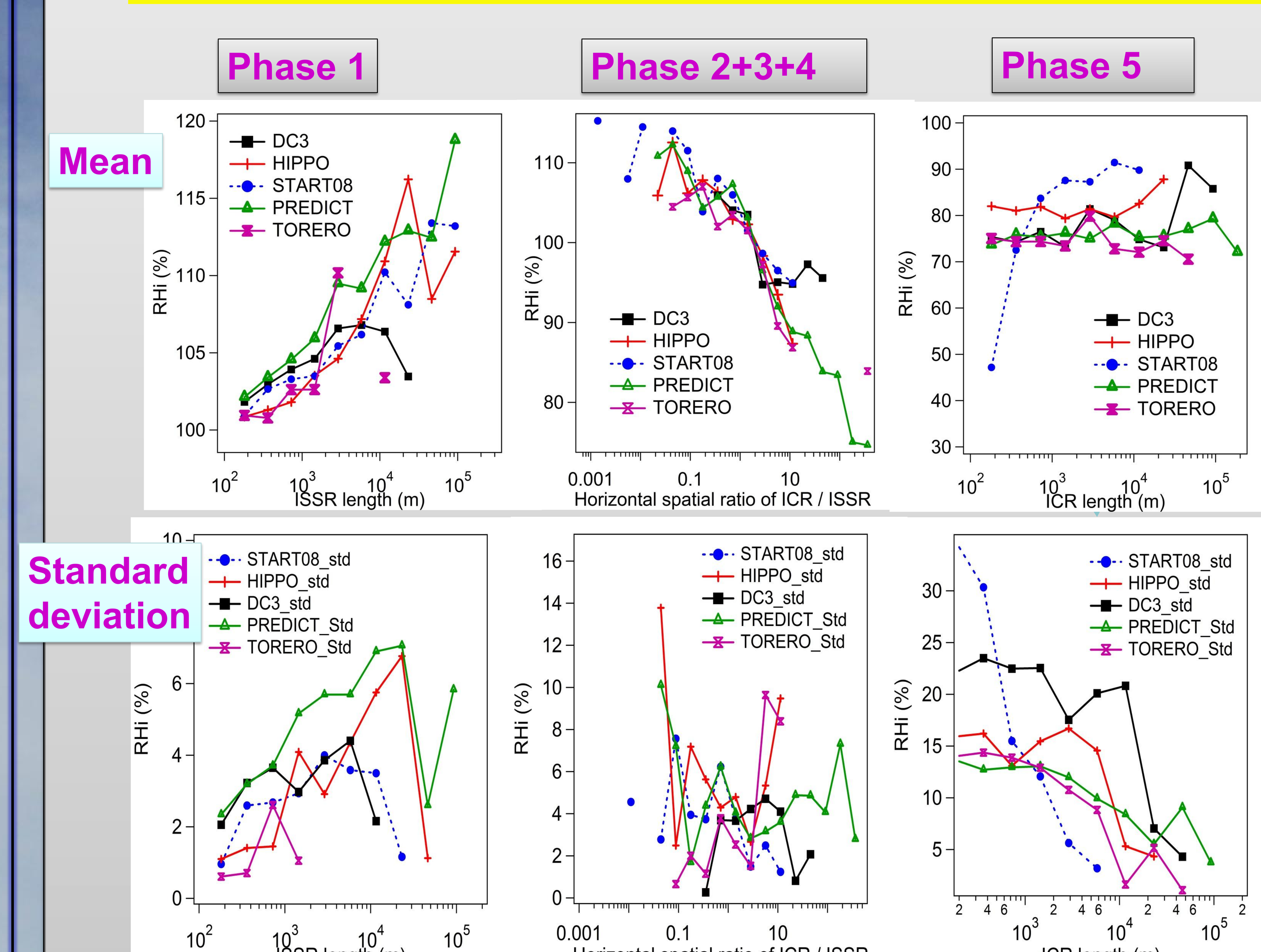


one ISSR + ICR sample

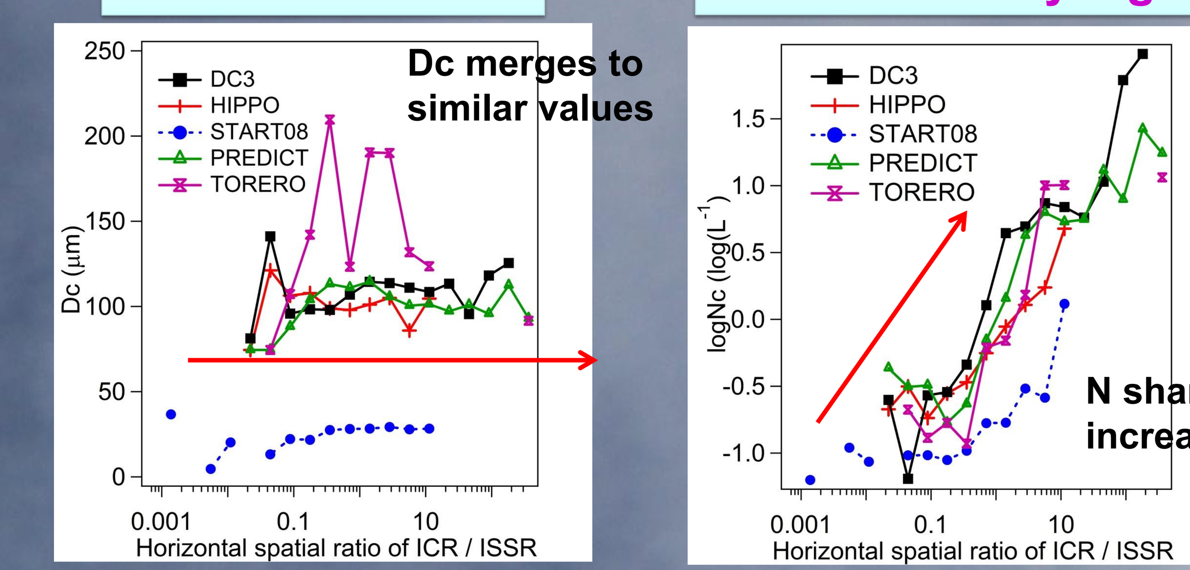


Pha-se	Description	Spatial ratio M = sum(L_{ICR}) / $L_{ISSR+ICR}$	Spatial ratio N = sum(L_{ISSR}) / $L_{ISSR+ICR}$
1	Clear-sky ISSRs	0	1
2	Nucleation	0 < M < 1	1
3	Early growth of ice crystals	0 < M < 1	0 < N < 1
4	Later growth of ice crystals	1	0 < N ≤ 1
5	Evaporation/sedimentation	1	0

•RHi mean and standard deviation evolution



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



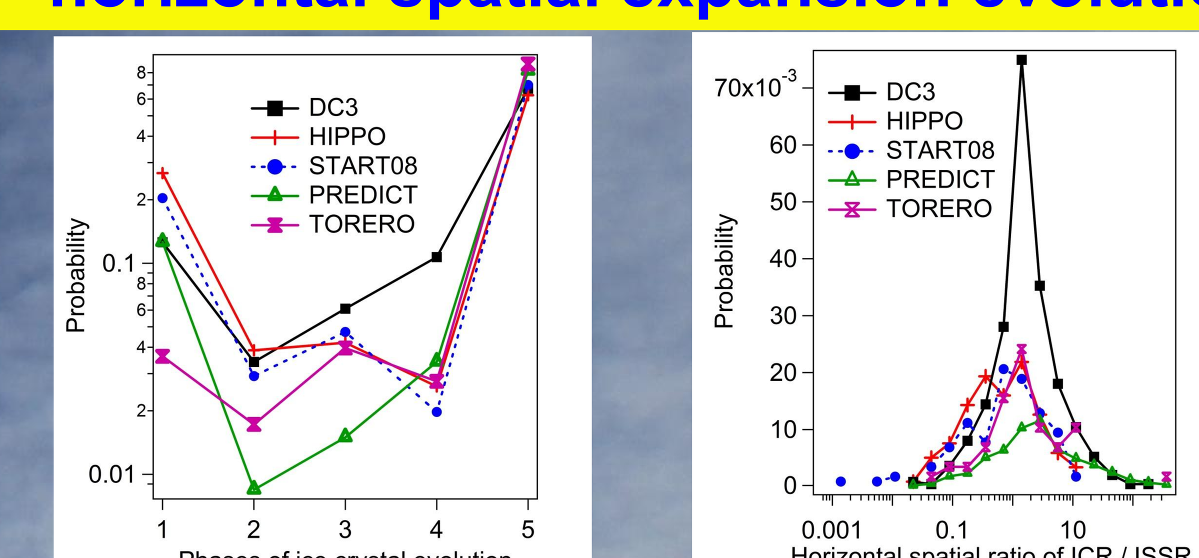
Growth rate of a single ice crystal

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

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 region lifetime phases and horizontal spatial expansion evolution



[1] **DC3 shows more Phase 4** (ICRs with ISS buried inside) than other campaigns, suggesting that either the ICRs do not consume H_2O efficiently, or continued strong uplift maintained ISS inside ICRs in DC3.
[2] **PREDICT shows less Phase 2** (ISSRs with ICRs buried inside), suggesting that ICRs expand immediately once they are formed in ISSRs.
[3] The peak of ICR/ISSR ratio happens at higher value in DC3 than the other two campaigns, suggesting that **ICRs expand relatively fast in DC3** so that most ICRs are larger than ISSRs. This finding further indicates that the dominance of Phase 4 in DC3 is contributed by strong uplift 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.