Ice Microphysical Properties Below -40˚C based on Seven NSF Flight Campaigns and NCAR CAM6 Model Simulations

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Science Teams of START08, HIPPO, PREDICT, TORERO, DC3, CONTRAST, ORCAS campaigns.

SAN JOSÉ STATE UNIVERSITY

NSF

NCAR
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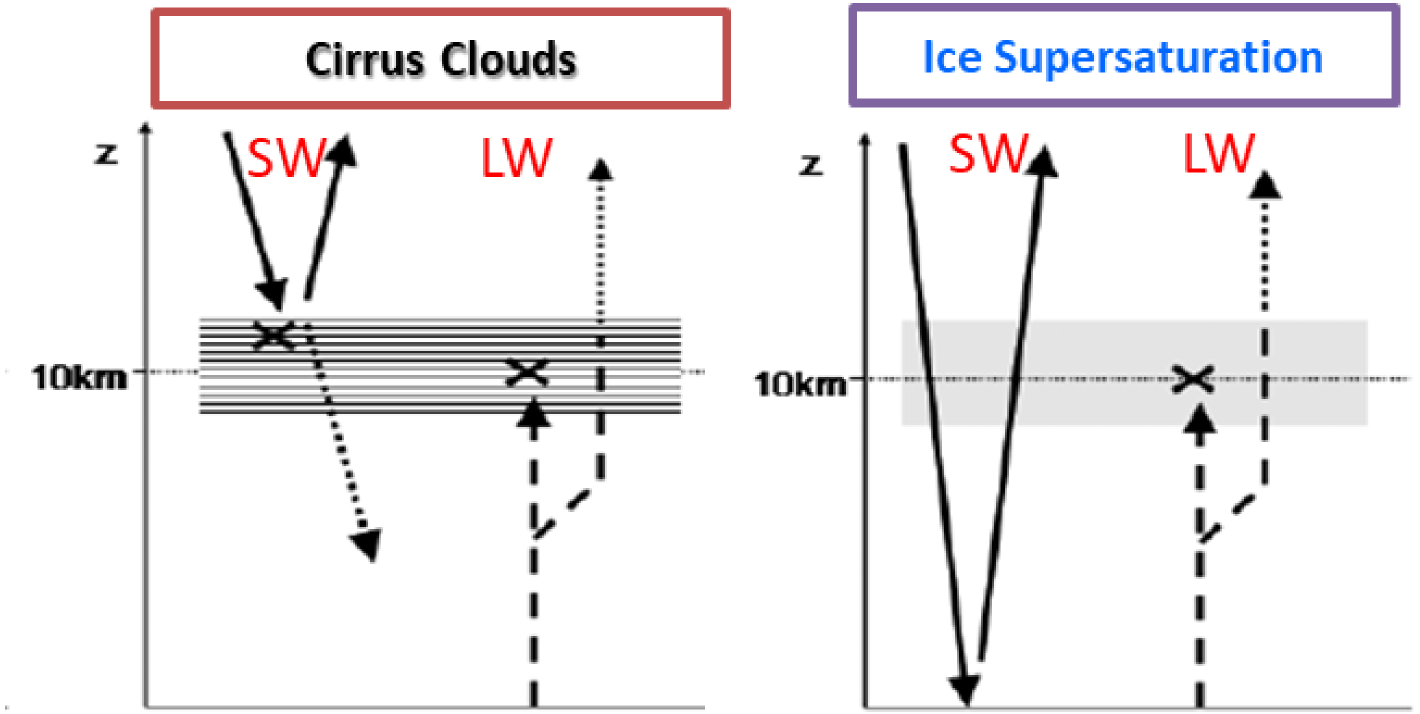
Radiative Effects of Cirrus Clouds



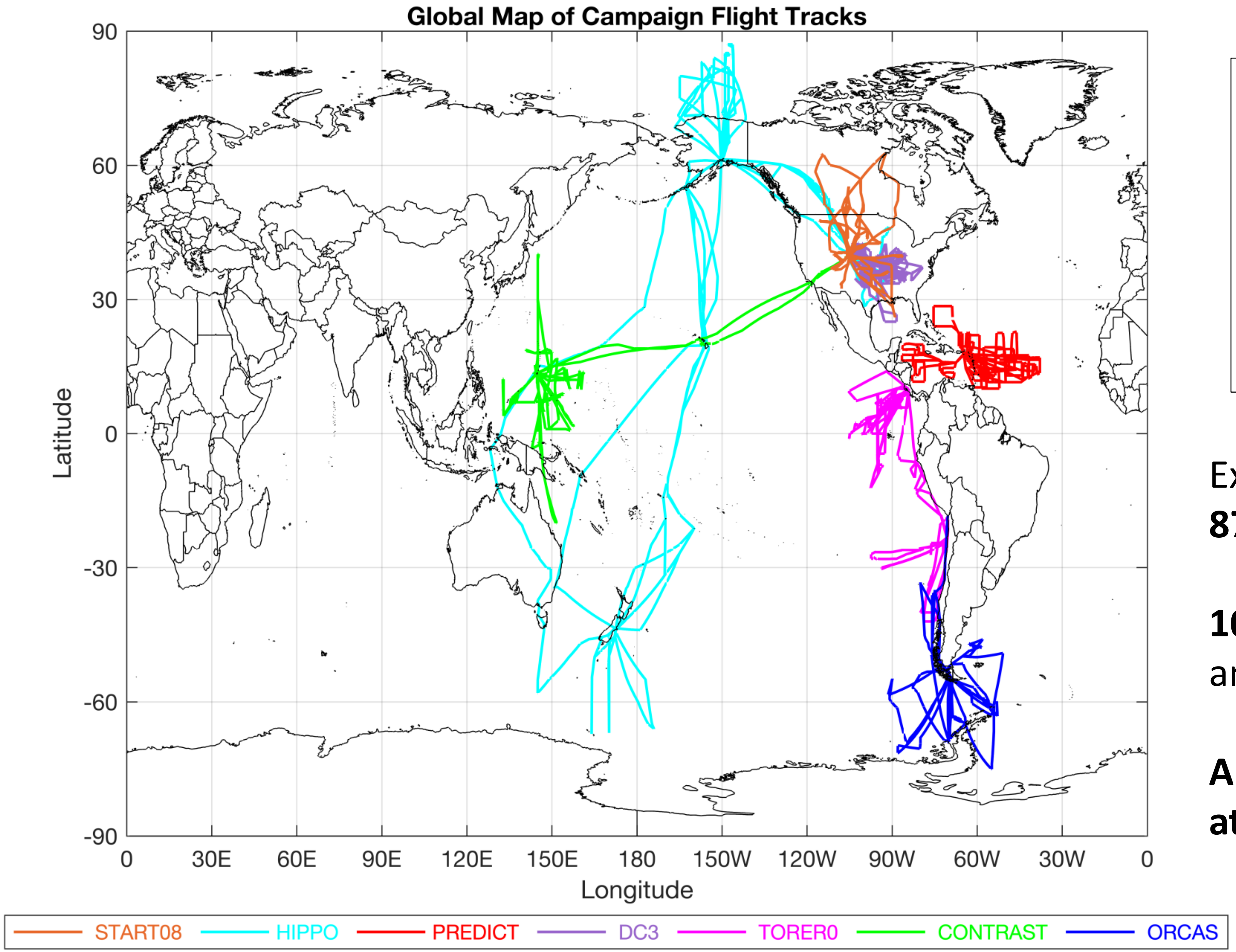
Ice supersaturation (ISS) = RHice – 100%
Prerequisite condition for ice nucleation

Cirrus clouds cover up to 30% - 40% of Earth's surface.
Misrepresenting clear-sky ISS as cirrus clouds: +2.49 W/m^2 average radiative biases at top of the atmosphere. *(Tan et al. 2016)*

1. What are effects of thermodynamic, dynamic conditions on cirrus cloud microphysical properties?
2. What are the aerosol indirect effects on cirrus clouds?
3. How well do model simulations represent ice microphysical properties and the key factors affecting them?

Tan, X., Y. Huang, M. Diao, A. Bansemer, M. A. Zondlo, J. P. DiGangi, R. Volkamer, and Y. Hu. An assessment of the radiative effects of ice supersaturation based on in situ observations, ***GRL***, *2016.*

Seven National Science Foundation (NSF) Flight Campaigns



START08 (2008)
HIPPO (2009 – 2011)
PREDICT (2010)
TORERO (2012)
DC3 (2012)
CONTRAST (2014)
ORCAS (2016)

Extensive spatial coverage from **87°N to 75°S** and **128°E to 38°W**.

1000 flight hours in total; **84 hr in-cloud** and **423 hr clear-sky data at ≤ -40°C** .

Analysis restricted to temperature ≤ -40°C at 1 Hz resolution (~230 m resolution).

Instrumentations and Calibrations

Vertical Cavity Surface Emitting Laser (VCSEL) hygrometer

– Near infrared; 25 Hz -> 1 Hz; Accuracy < 6%; Precision ≤ 1% (Zondlo *et al*. 2010)

– Combine with ±0.3 K temperature uncertainties, **RHice** uncertainties are **7.8%–6.9%** for -78°C to -40°C, respectively.

– Laboratory calibration of VCSEL hygrometer (Diao, DiGangi, Zondlo, Beaton in 2009 – 2018)

Cloud probe

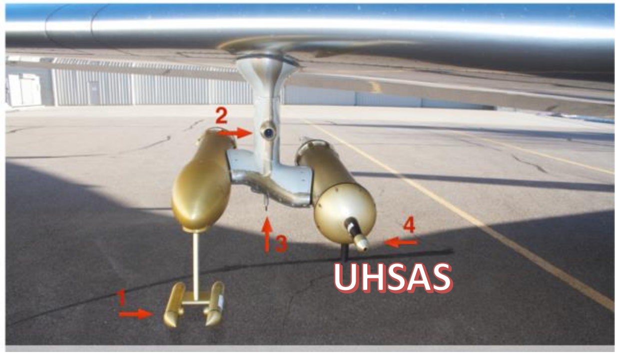
– Fast-Two dimensional cloud (**Fast-2DC**) probe (62.5–3200 μm);

– In-cloud conditions: Nice > 0 L^{-1} in 1-second sample

(Diao et al., 2013, 2014, 2015, 2017; D'Alessandro et al., 2017)

Aerosol probe

– Ultra-High Sensitivity Aerosol Spectrometer (UHSAS) measures aerosols at 0.06 – 1 μm.

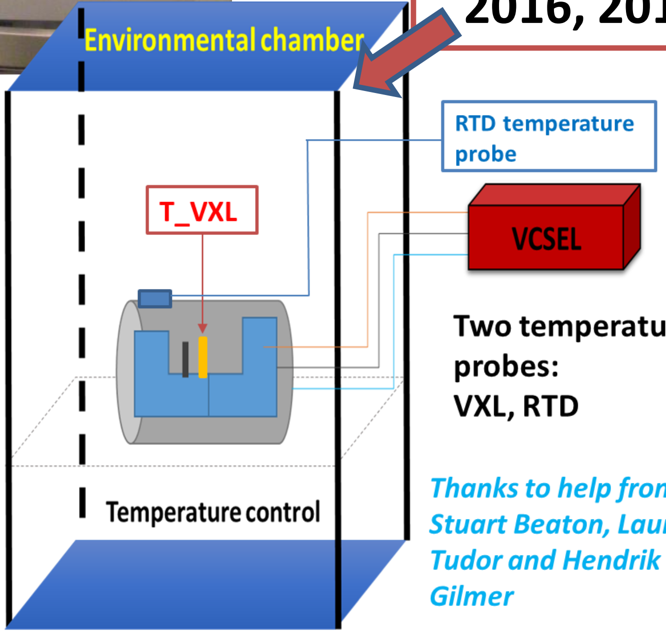


Laboratory Calibrations of the VCSEL Hygrometer

Calibration in 2009 – 2013

Pressure (100–1013 hPa)
Temperature (-90–30°C)
H_2O (0.5–4×10^5 ppmv)

Calibration in 2016, 2018



Two temperature probes: VXL, RTD

Thanks to help from Stuart Beaton, Laura Tudor and Hendrik Gilmer

NCAR CESM2/CAM6 Model Simulations

NCAR **CESM2** / Community Atmosphere Model Version 6 (**CAM6**)

- Two types of simulations
    - Nudged simulations: towards U,V and T from MERRA2 data.
    - Free-running simulations
- MG2 microphysics (Gettelman and Morrison 2015; Gettelman et al., 2010)
- 0.9º x 1.25º with 32 vertical layers

Variable	IWC, Ni, Di	In-cloud	RHice	σ_w	Aerosols
Observation	62.5 – 3200 µm	> 1 particle per second	Murphy & Koop, 2005	variance of 200 seconds	Na500 & Na100 (>500nm, >100nm)
CAM6 model	> 62.5 µm	Ni > 10^{-2} L^{-1} & IWC > 10^{-5} g m^{-3}	same	wsub = sqrt (2/3*TKE)	same

Acronyms:

IWC: ice water content; **Ni**: ice crystal number concentration; **Di**: number-weighted mean diameter

RHice: relative humidity with respect to ice; **w**: vertical velocity; **Na**: aerosol number concentration

Regional variations – Tropics, Midlatitude, Polar Regions in the Northern and Southern Hemispheres (NH and SH)

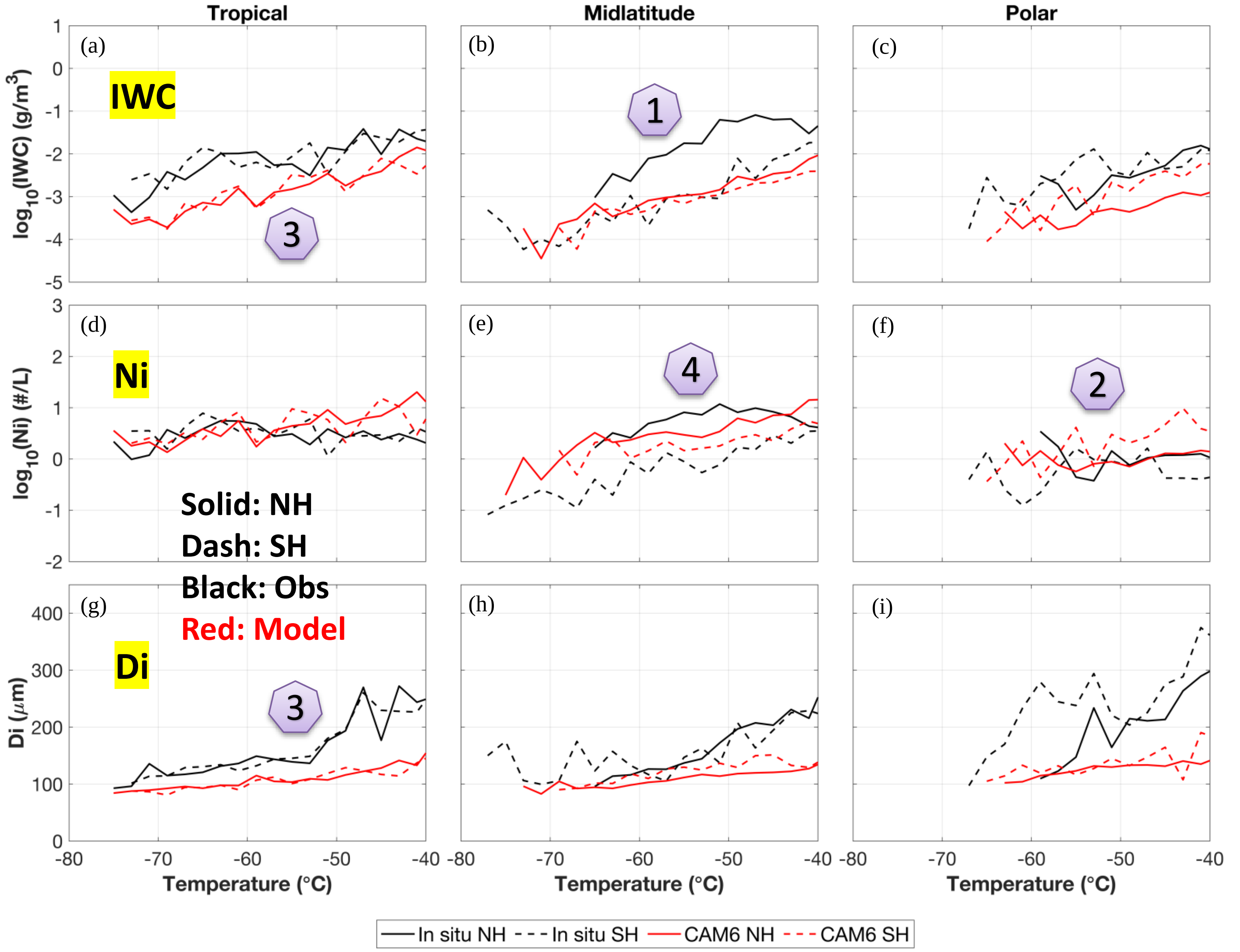
Observations shows:

- (1) Higher IWC and Ni in NH midlatitude than SH midlatitude;
- (2) Higher Ni in tropics than polar regions.

CAM6 model shows:

- (3) Smaller IWC and Di, likely underestimating ice crystal sedimentation and growth.
- (4) Smaller Ni in NH midlat, likely underestimating aerosol indirect effects on Ni.

Patnaude, R., M. Diao, X. Liu, S. Chu, Effects of Thermodynamics, Dynamics and Aerosols on Cirrus Clouds Based on In Situ Observations and NCAR CAM6 Model, ***Atmos. Chem. Phys.***, submitted.



Effects of Relative Humidity (RHi) on Cirrus Clouds

(1) Observations:

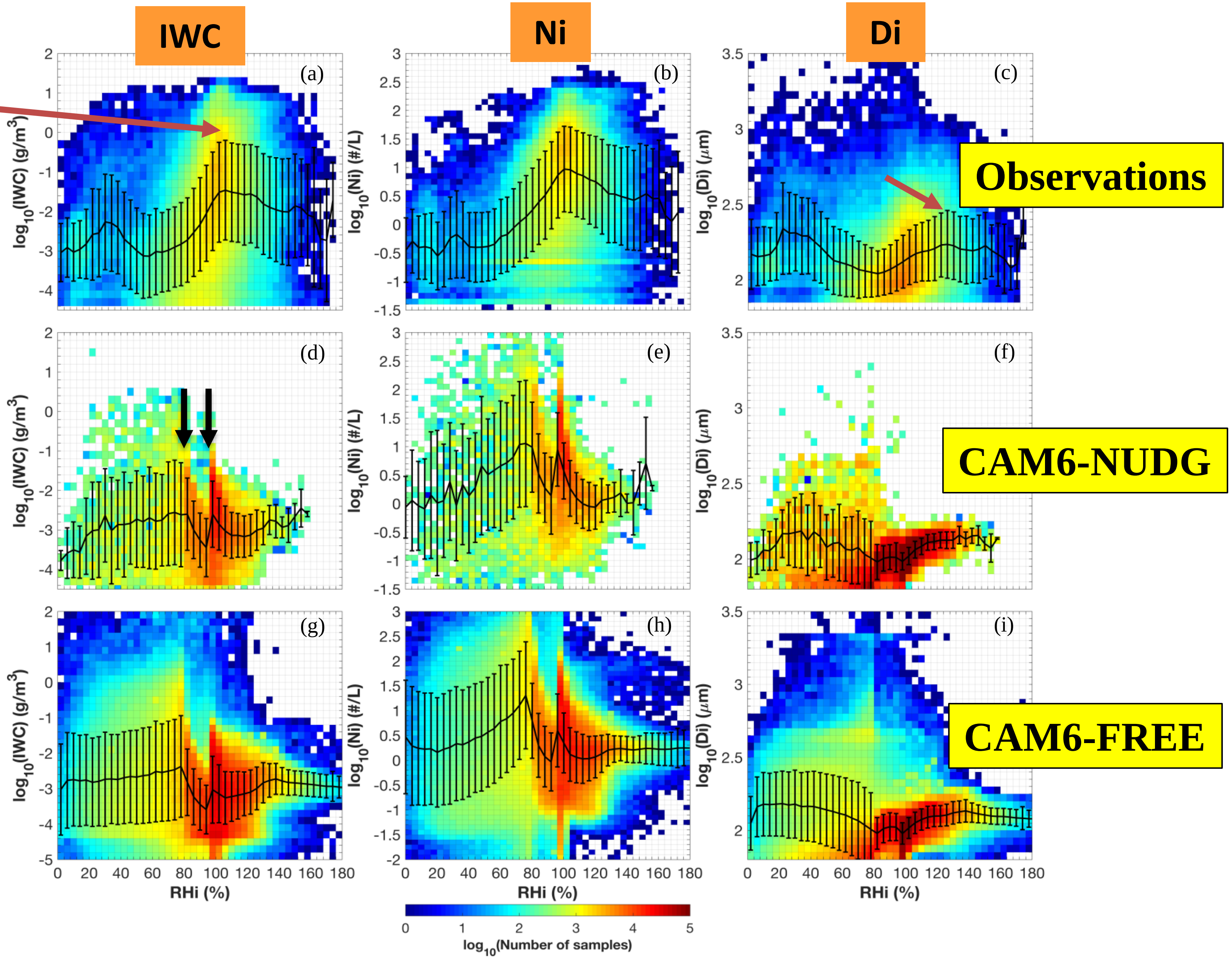
- IWC and Ni peak at **110% RHi**
- Di peaks at 130% RHi

(2) Simulations:

- IWC and Ni peak at **80% RHi**, a secondary peak at 100%
- Di peaks at 130% RHi but much higher at subsaturation
- Simulated ice cloud fraction (CFi) is affected by $\mathbf{RH_{min} = 80\%}$ and $RH_{max} = 110\%$:

$$CF_i = \min(1, RH_d^2)$$

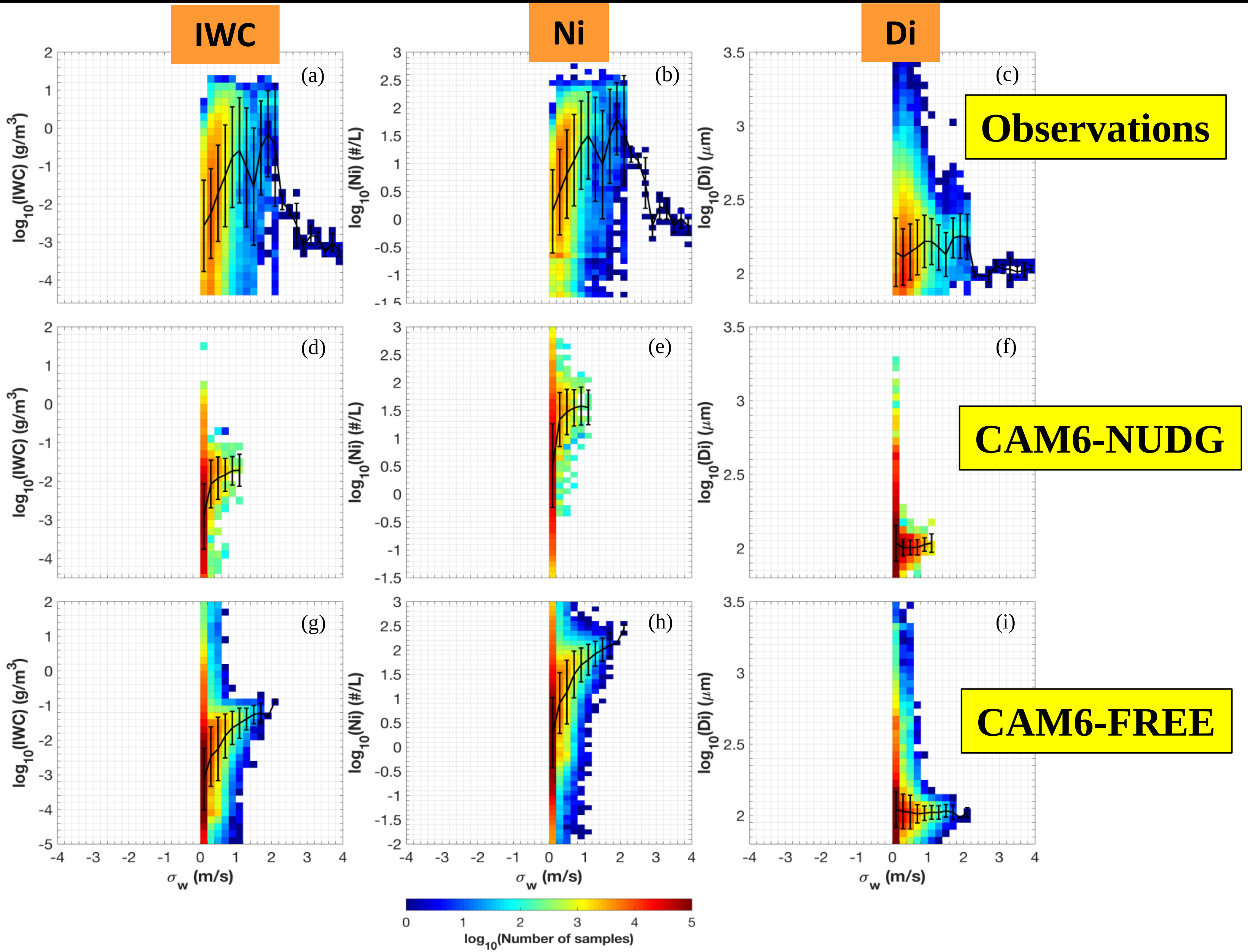
$$RH_d = \max\left(0, \frac{RH_{ti} - RHi_{\min}}{RHi_{\max} - RHi_{\min}}\right)$$



Effects of Vertical Velocity (σ_w) on Cirrus Clouds

- Both observations and simulations show increasing IWC and Ni with increasing σ_w.

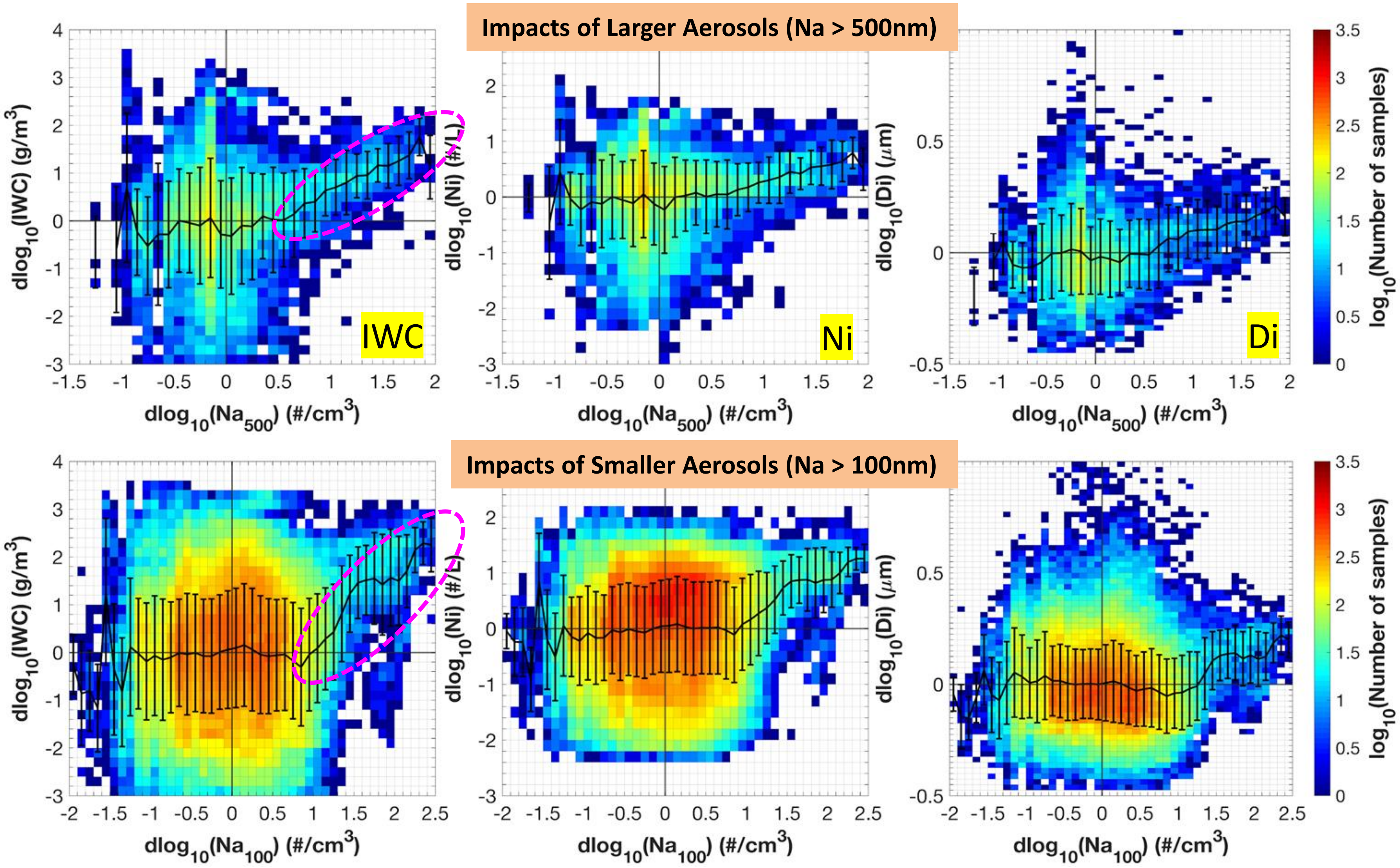
- Simulations show **lower** maximum σ_w, likely due to missing gravity waves from topography, fronts, and convection, since only σ_w from turbulence is included.



Aerosol Indirect Effects on Ice Microphysical Properties

(1) Isolate aerosol indirect effect: Remove T effects by using **delta values**, i.e., 1-s datum subtracts T-binned averages.

(2) Observations show increasing IWC, Ni and Di, especially when Na500 and Na100 is higher than average by a factor of 3 and 10, respectively.



Patnaude, R. and M. Diao, Aerosol indirect effects on cirrus clouds based on global aircraft observations, ***Geophys. Res. Lett.***, 47, doi:10.1029/2019gl086550, 2020.

Aerosol Indirect Effects (AIE) on Ice Microphysical Properties

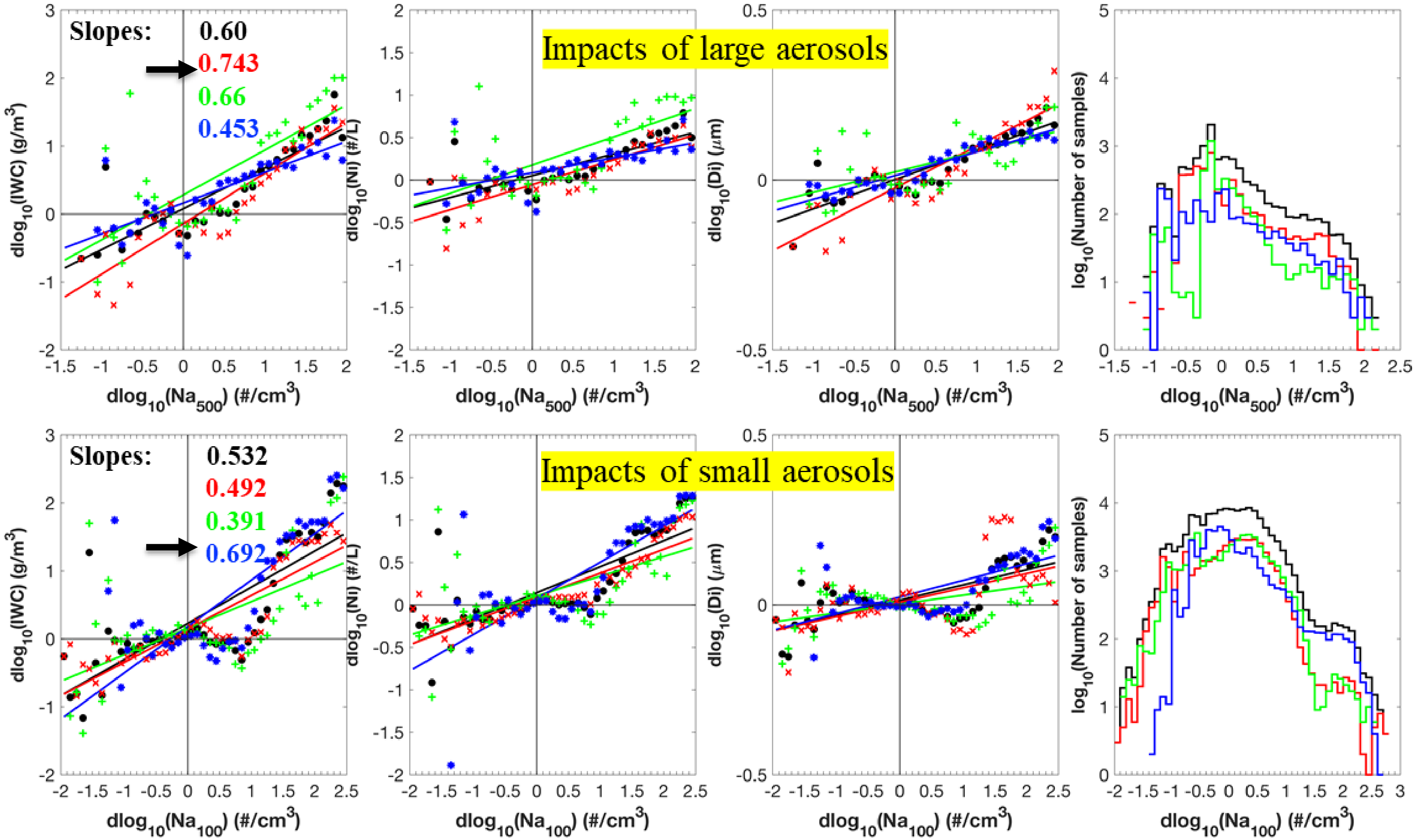
Linear regression of IWC, Ni, Di wrt. Na_{500} and Na_{100}

- Higher slope, larger AIE
- **Na500** more effective at higher T (and lower w), possibly heterogeneous nucleation;
- **Na100** more effective at lower T (and higher w), possibly homogeneous nucleation.
- $d\log_{10}(IWC) =$ $a + \mathbf{b} * d\log_{10}(Na_{500})$

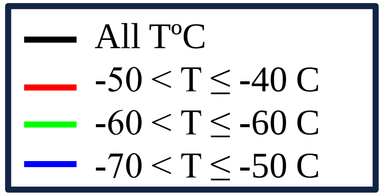
  $b_{Na500} = 0.18–0.33$; [1]

  $b_{Na100} = 0.23–0.43$; [1]

  $b_{model} = 0.1–0.3$. [2-4]



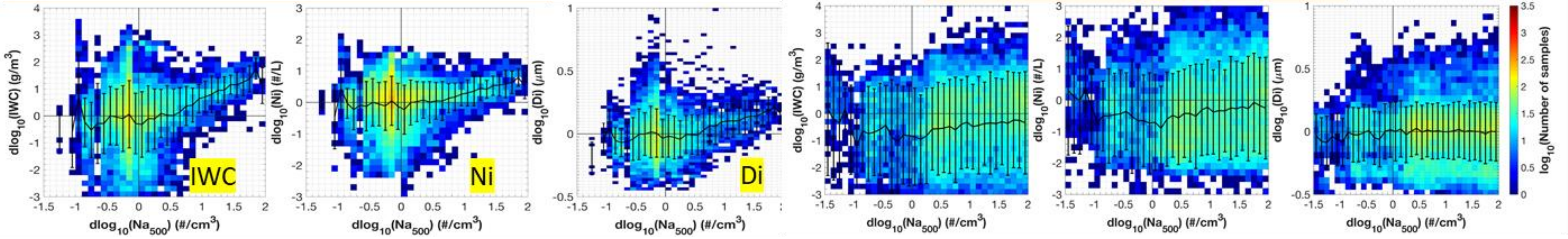
[1] Patnaude and Diao, GRL, 2020;
[2] Kärcher & Lohmann, 2002;
[3] Kay & Wood, 2008;
[4] Liu & Shi, 2018



Aerosol Indirect Effects in CAM6 Simulations

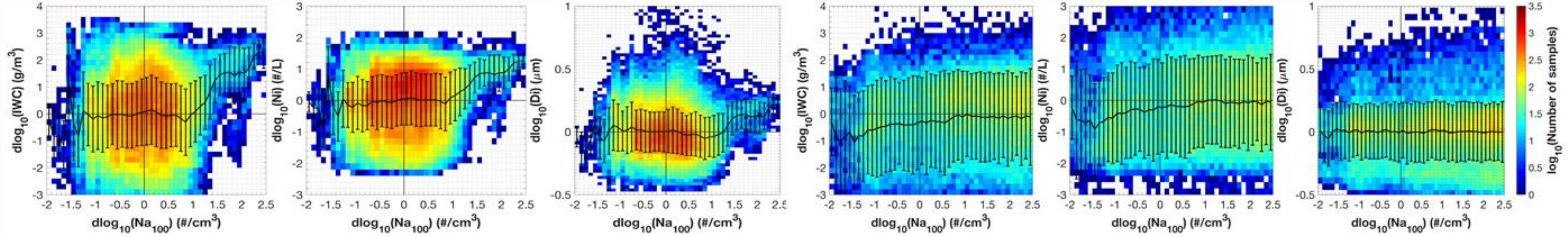
Impacts of Larger Aerosols (Na > 500nm)

CAM6 Simulations at 1 degree



Impacts of Smaller Aerosols (Na > 100nm)

CAM6 Simulations at 1 degree

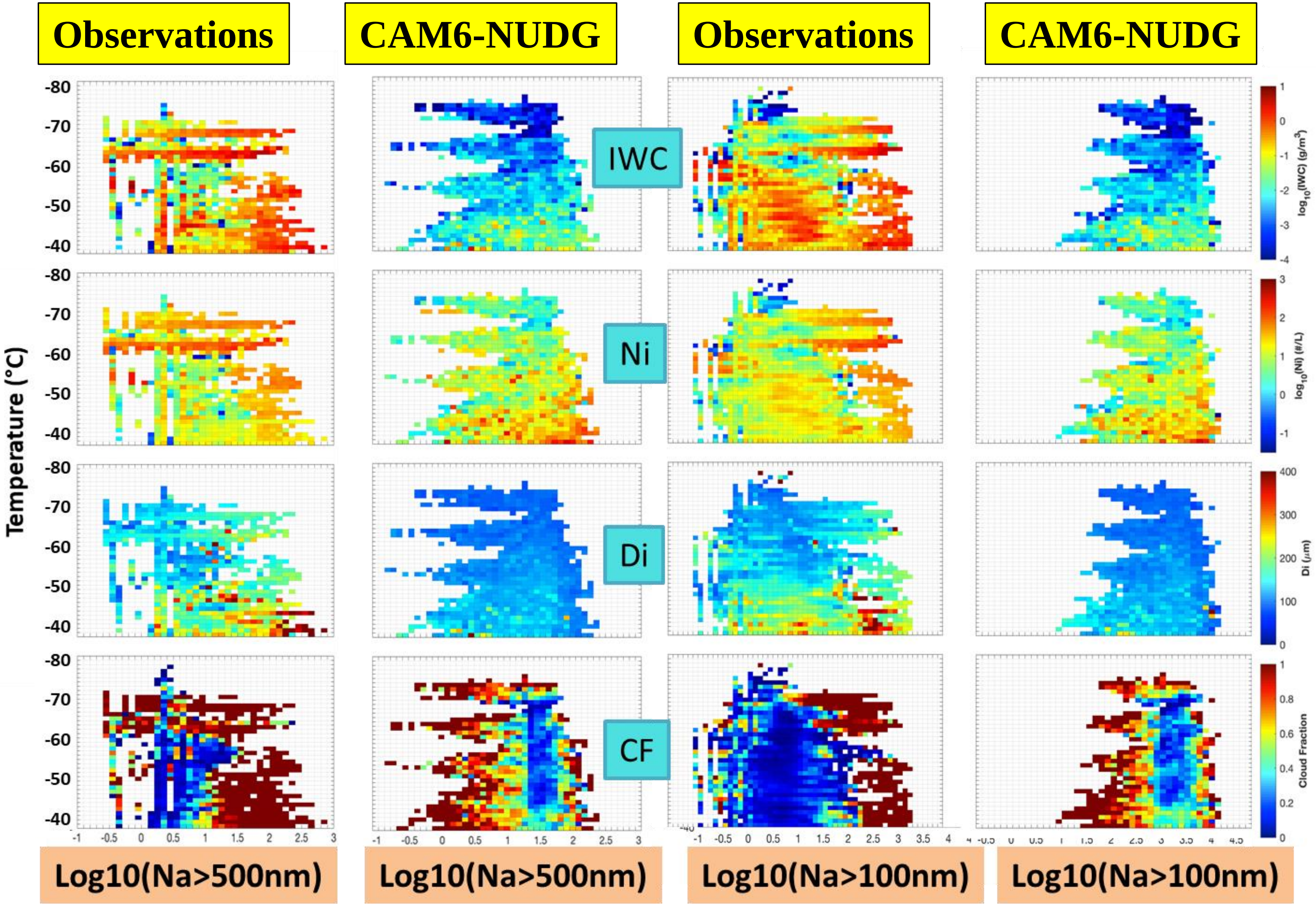


(1) Increases of IWC, Ni are seen in CAM6, but much **weaker**

(2) **No sudden increases** of aerosol indirect effects (AIE) at higher Na in CAM6

(3) Di is almost constant in CAM6

Aerosol Indirect Effects on Cirrus Microphysical Properties



(1) CAM6 shows **smaller IWC, Di** especially at **T < -60ºC**

(2) Aerosol indirect effects:

Obs shows **higher IWC, Ni, and Di** at higher Na.

CAM6 shows increase of Ni, smaller increases of IWC, and decrease of Di at higher Na.

(3) CAM6 shows increasing cloud fraction with higher Na, but **at 10 times higher Na than obs.**

(Patnaude et al., ACP, submitted)

Conclusions

1. Regional variation in two hemispheres
(a) Obs show higher Ni in NH midlat and tropics
(b) Model shows smaller IWC, Di everywhere, and smaller Ni in NH midlatitudes

2. Effects of RHi and vertical velocity
(a) Obs show IWC, Ni peak at RHi = 110%; Model peaks at RHi = 80%
(b) Narrow range of σw in the simulation (missing waves, convection)

3. Aerosol indirect effects on cirrus clouds (larger and smaller Na)
(a) Non-monotonic relationships. Sudden increase of IWC, Ni and Di at higher Na500 and Na100
(b) Isolate thermodynamic and dynamical impacts when analyzing AIE
(c) Model shows weaker AIE than obs, and no sudden increases of IWC, Ni or Di

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