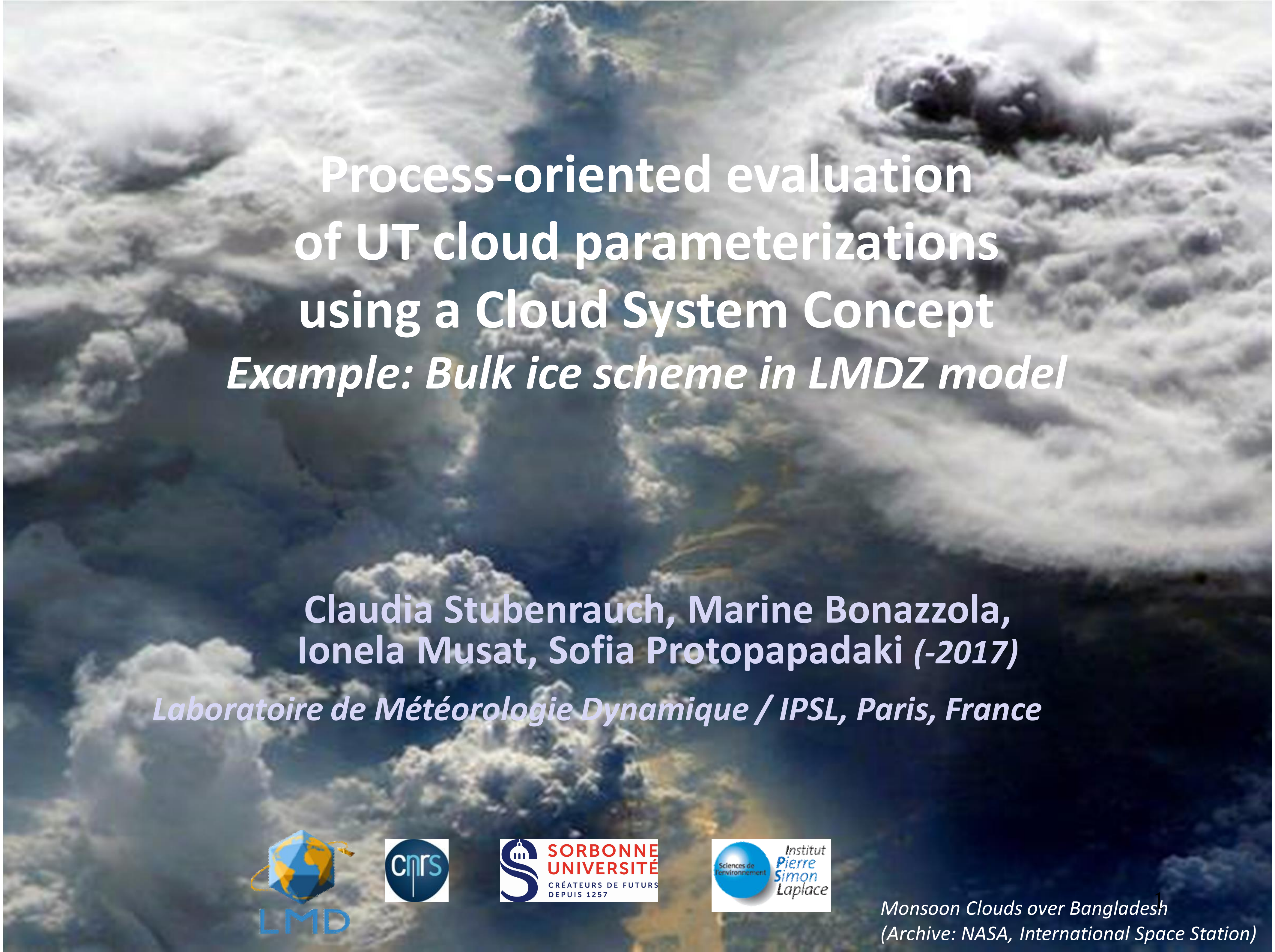
Process-oriented evaluation of UT cloud parameterizations using a Cloud System Concept

Example: Bulk ice scheme in LMDZ model

Claudia Stubenrauch, Marine Bonazzola,
Ionela Musat, Sofia Protopapadaki ***(-2017)***

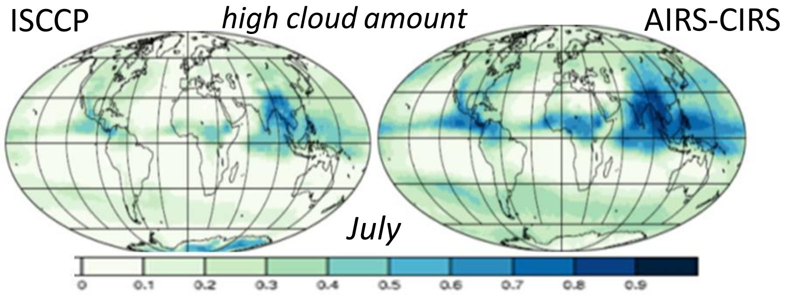
Laboratoire de Météorologie Dynamique / IPSL, Paris, France

LMD | CNRS | SORBONNE UNIVERSITÉ CRÉATEURS DE FUTURS DEPUIS 1257 | Sciences de l'environnement Institut Pierre Simon Laplace



Monsoon Clouds over Bangladesh
(Archive: NASA, International Space Station)

Clouds from IR Sounder (CIRS) -> Cloud System Concept



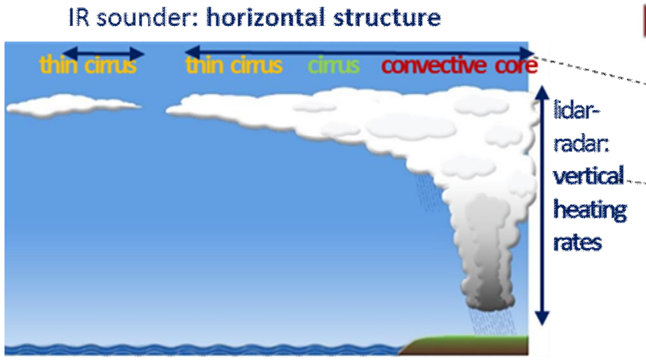
- ➢long time series (HIRS, AIRS, IASI) & good areal coverage
- ➢**good IR spectral resolution -> sensitive to cirrus**

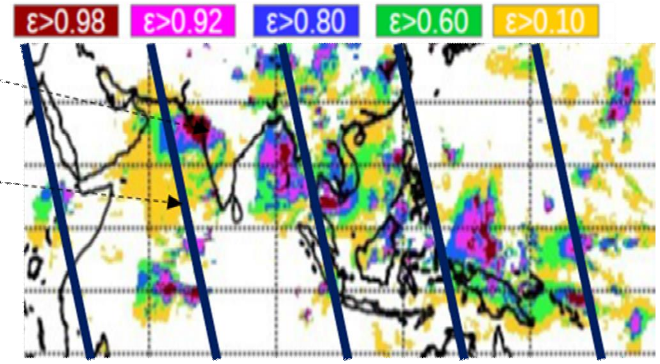
similar performance day & night, COD_{vis} > 0.2, also above low clouds

(*Stubenrauch et al., ACP, 2017*)

cloud systems built from adjacent grid cells with similar p_{cld}; convective cores & cirrus anvil from ε_{cld}

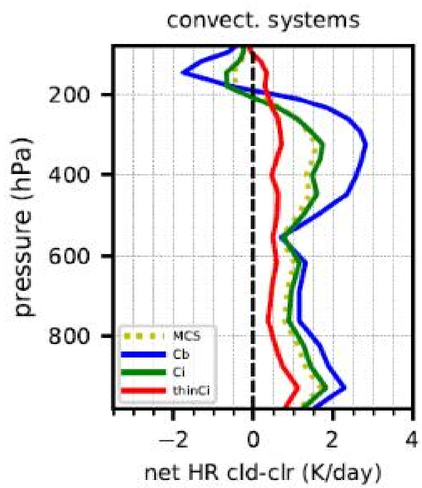
(*Protopapadaki et al., ACP, 2017*)

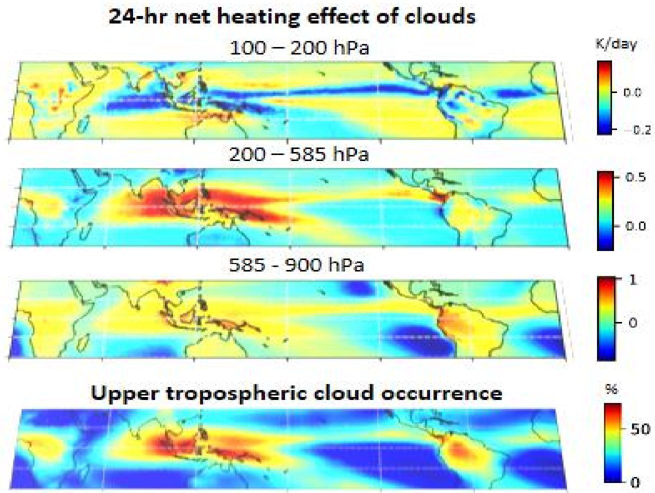




grid cell resolution 0.5°,
sub-grid Cb, Ci, thin Ci fractions
can be adapted to other resolutions
(from 0.25° to GCM resolution)

3D cloud systems from Machine Learning trained on CALIPSO-CloudSat (HR, DZ, RR) / TRMM (LH)





(*Stubenrauch, Caria et al., ACP, 2021*)

Cloud System Concept + 3D HR fields :

1) relation between convection – cirrus anvil
2) process-oriented GCM evaluation
3) dynamical response to atmospheric heating

Bulk ice cloud scheme (v_m & D_{eff}) in a GCM

Cirrus bulk properties = mass- or area-weighted integrals of particle size distribution (PSD)

$m = \boldsymbol{a}\, D^{\boldsymbol{b}}$ $A = \boldsymbol{c}\, D^{\boldsymbol{d}}$ *coefficients depend on ice crystal habit & size*

- Fall speed & ice crystal size distribution impact cirrus life time & radiative effects

$\varepsilon_{cld} = f(D_{eff}, IWC)$

Goal: construct bulk ice cloud scheme which coherently treats ice cloud physics & radiation from reviewed existing parameterizations

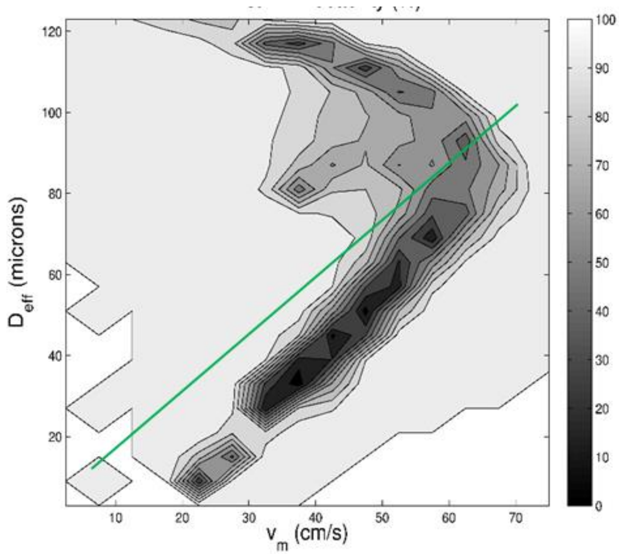
Thermodynamics dictates presence of ice clouds

ice phase controlled by T & IWC by relative humidity

-> v_m , D_{eff} = f(IWC,T) as suggested by airborne & in situ observations

Current version of LMDZ: v_m = f(IWC), D_{eff} = f(T)

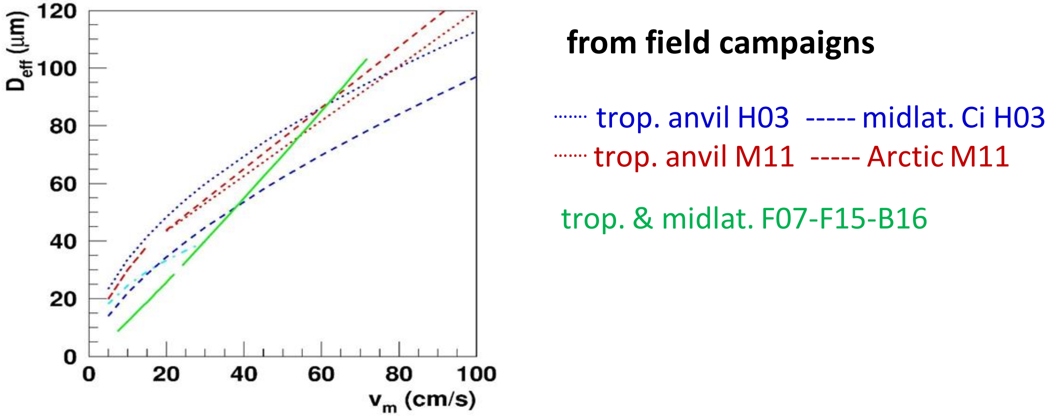
v_m tuned to achieve radiative balance (x 0.3)



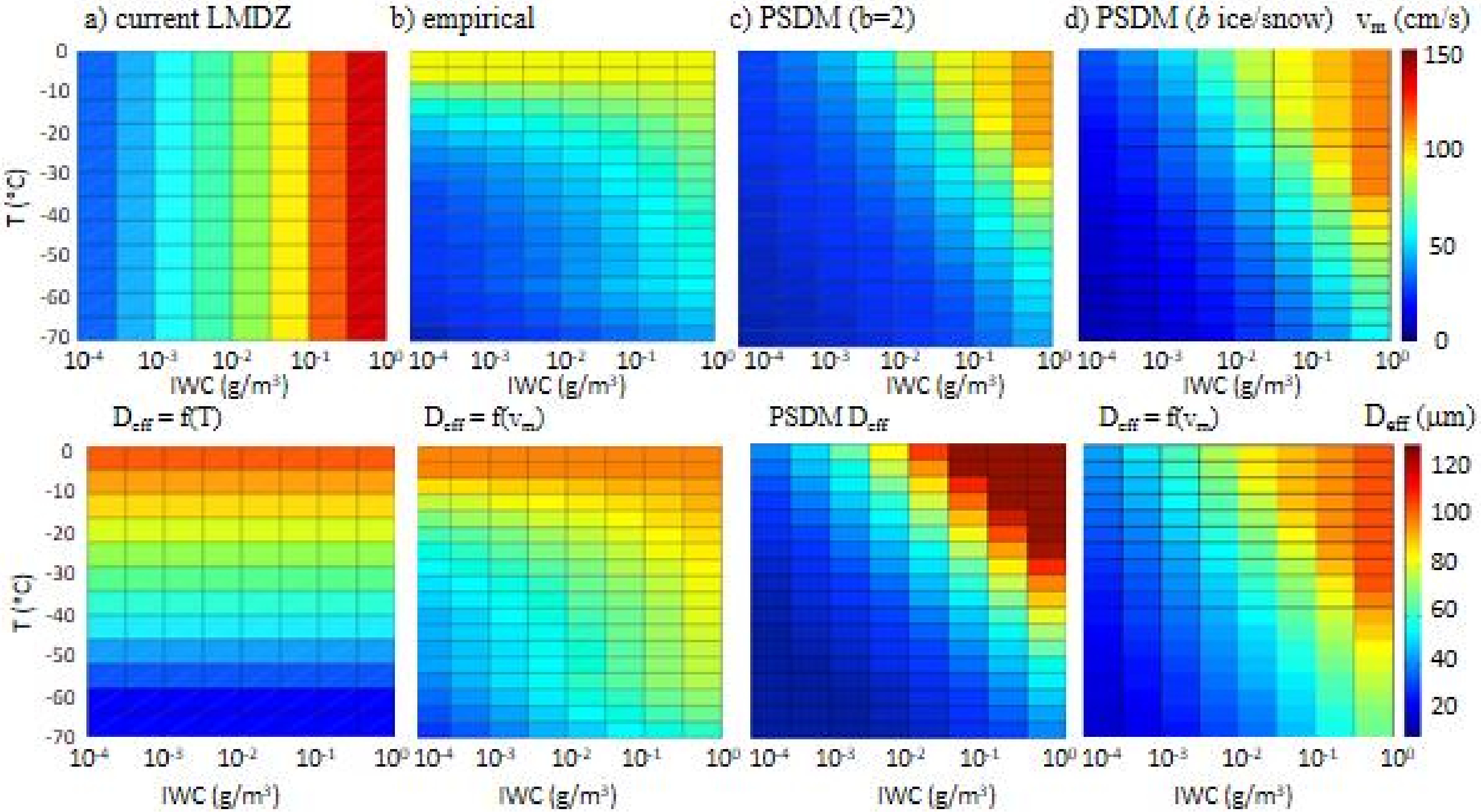
Synthesis : v_m & $D_{eff} = f(T, IWC)$

Stubenrauch, Bonazzola et al., JAMES 2019

v_m & D_{eff} are closely related,
as they both depend on ice mass / ice area



empirical : v_m = f(IWC, T) *Deng & Mace 2008 / Schmitt & Heymsfield 2009*; D_{eff} = f(v_m)
v_m, D_{eff} from moments of PSD, parameterized as f(IWC, T) *Field et al. 2007 / Furtado et al. 2015 / Baran et al. 2016*



v_m

D_{eff}

Tuning parameters most relevant for high clouds

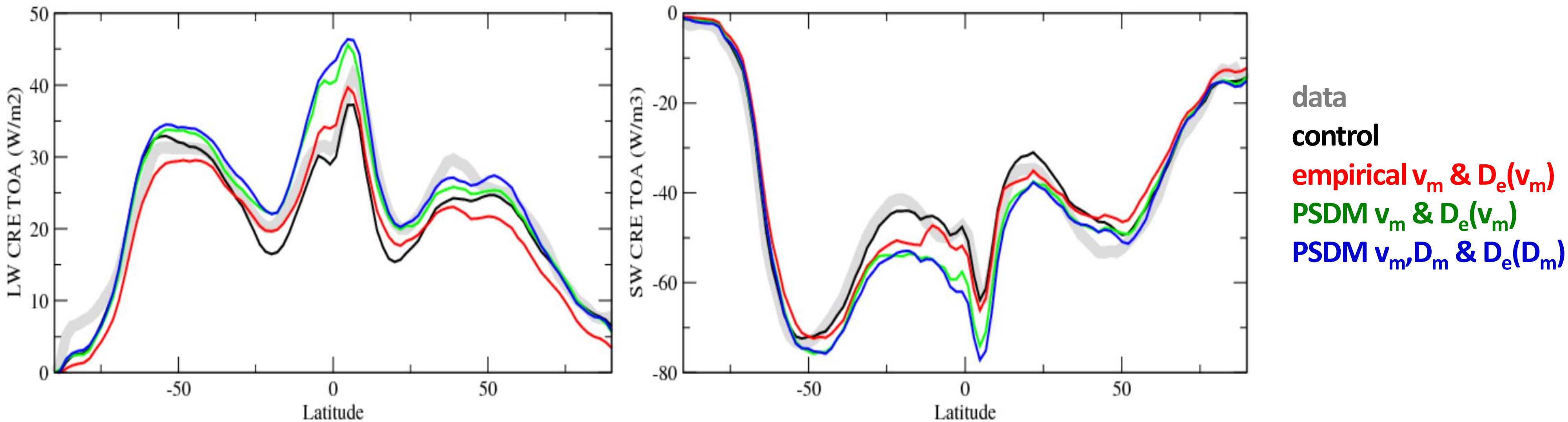
	FALLICE	EPMAX	RQH
CNTRL	0.3	0.9985	0.40
(a) New parameterizations			
Empirical v_m and D_{eff} (v_m)	0.9	0.9990	0.08
PSDM v_m and D_{eff}	0.9	0.9988	0.11
PSDM v_m and D_{eff} (v_m)	0.9	0.9988	0.11
(b) Sensitivity studies			
FALLICE+	0.5	0.9985	0.40
RQH−	0.3	0.9985	0.10
EPMAX+	0.3	0.9990	0.40
Scaled PSDM v_m	0.3	0.9985	0.40

FALLICE: scaling of fall speed

EPMAX: maximum precipitation efficiency

RQH: rel. width of sub-grid water distribution above 250 hPa (*ratqsh*)

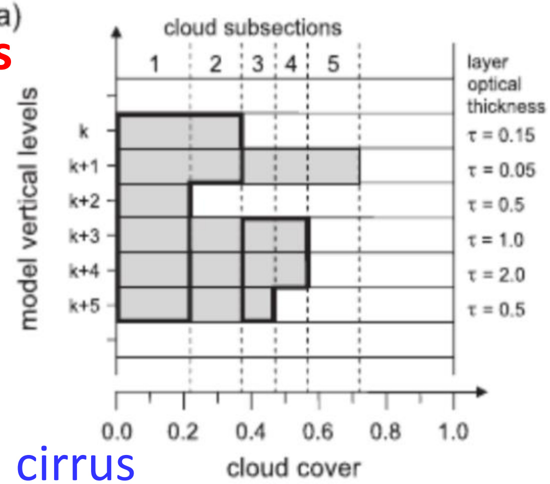
In order to introduce realistic fall speed, RQH had to be reduced by a factor of 4



PSDM parameterization & tuning -> slightly too absorbing & too reflective in the tropics

New diagnostics using CIRS cloud observation simulator

IR Sounders provide cloud height p_{cld} & emissivity ε_{cld}; **sensitive to cirrus**

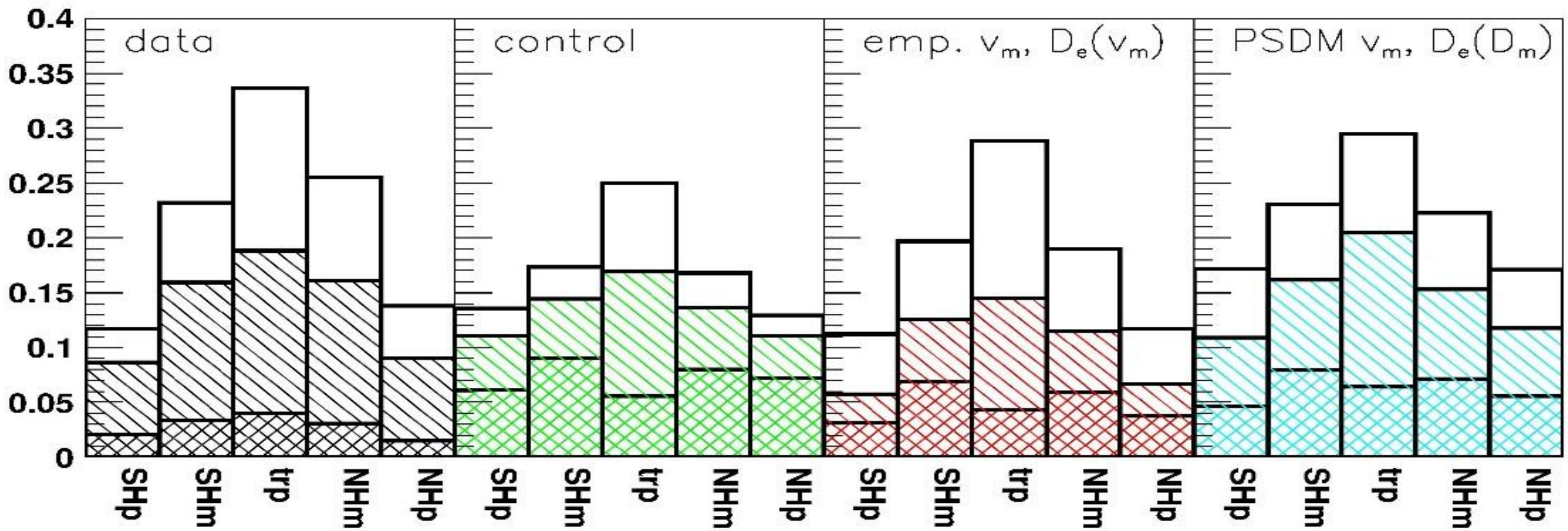


- construct clouds from vertically contiguous cloudy layers
- clouds divided into sub-sections of similiar vertical structure
- keep only sub-sections with IR optical depth > 0.1
- filter observation times: 1:30AM, 9:30AM, 1:30PM, 9:30PM LT

-> *total & high cloud cover, p_{cld}, T_{cld}, ε_{cld}, z_{cld}, fraction of Cb, Ci, thin Ci*

advantages: allows to evaluate i) sub-grid fractions of Cb, cirrus & thin cirrus
ii) diurnal cycle of UT cloud properties

UT cloud cover & its composition (Cb, Ci, thin Ci)



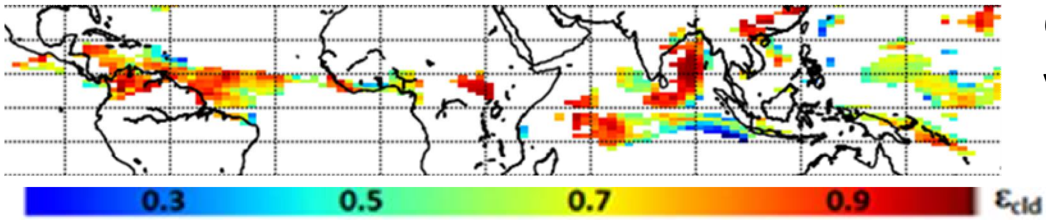
Control simulation too few high clouds with too many Cb
New bulk ice schemes -> increased high clouds, with more Ci & thin Ci, in better agreement with observations

UT Cloud System Concept to assess GCM parameterizations

Cloud System Concept relates anvil properties to processes shaping them
-> process-oriented evaluation of detrainment / convection / microphysics parameterizations

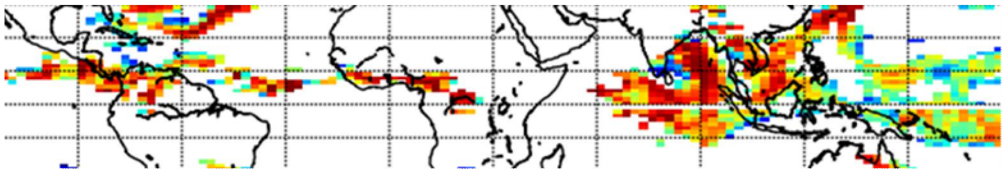
Example: Towards coherent bulk ice cloud scheme deduced from thermodynamics in LMDZ

spatial res. 2.5° x 1.25°

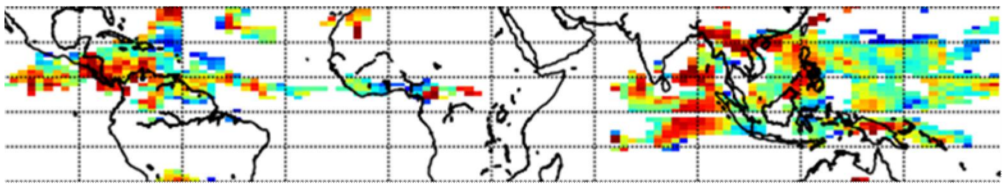


***Current LMDZ model*: v_m = f(IWC), De = f(T)**
v_m tuned to achieve balance (x 0.3)

***observations*: v_m = f(IWC,T), De = f(IWC,T)**

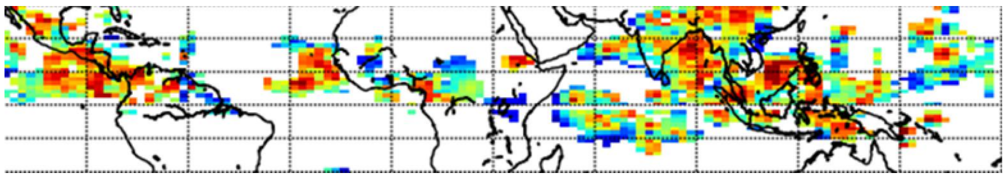


***empirical*: v_m = f(IWC,T), De = f(v_m)**
Deng & Mace (2008), Heymsfield et al. 2003



***PSDM*: v_m, De from moments of ice crystal size distributions as f(IWC,T)**
Field et al. (2007), Furtado et al. 2015, Baran et al. 2016

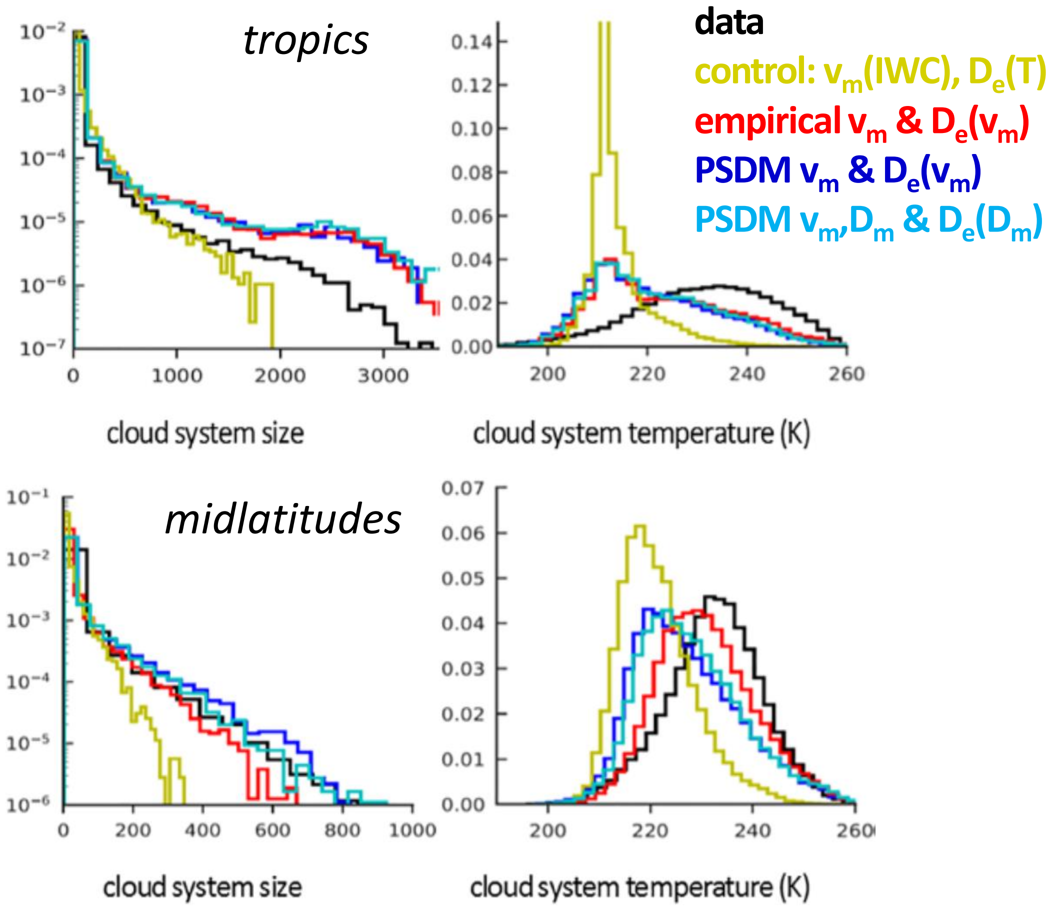
horizontal cloud system emissivity structure sensitive to v_m, De



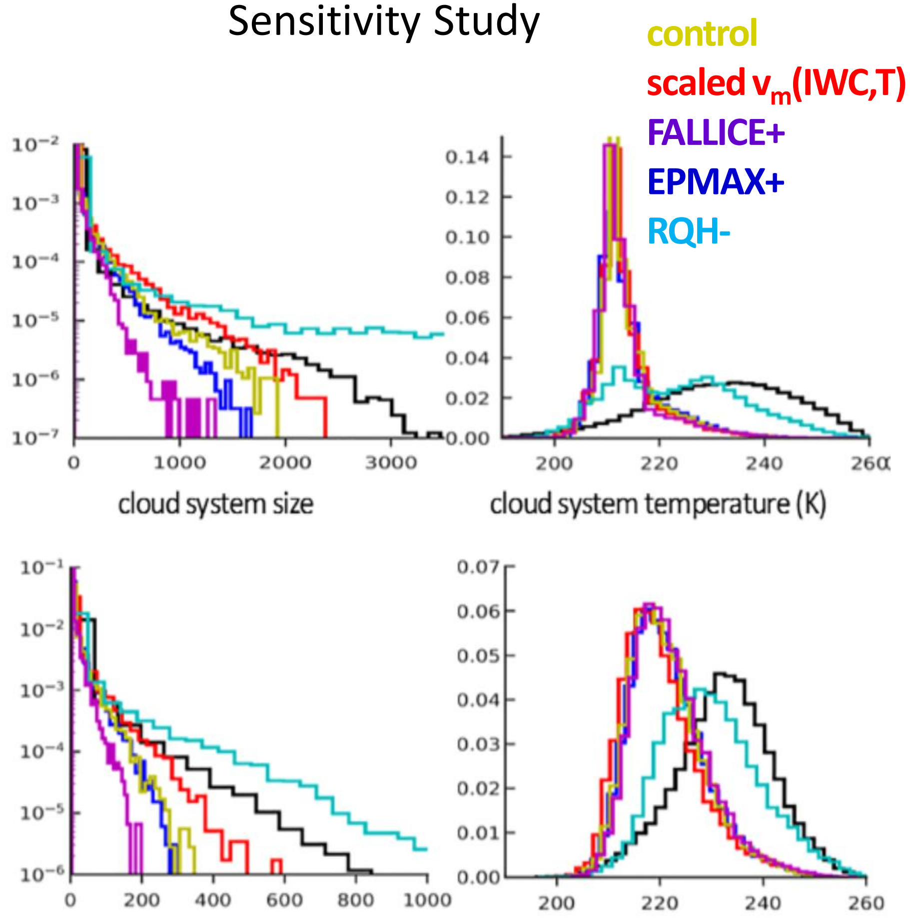
AIRS snapshot 3 July 2008 AM

UT cloud system statistics

New ice schemes



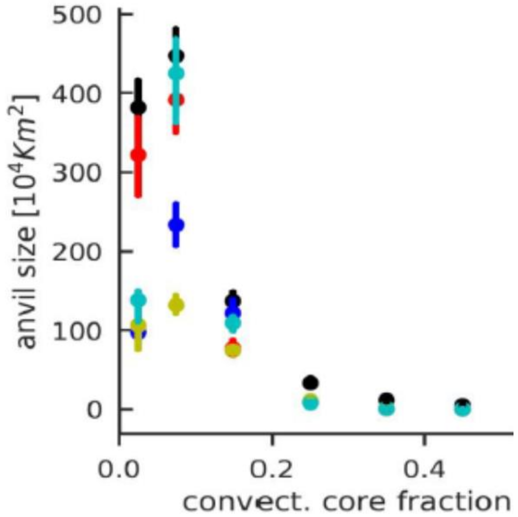
Sensitivity Study

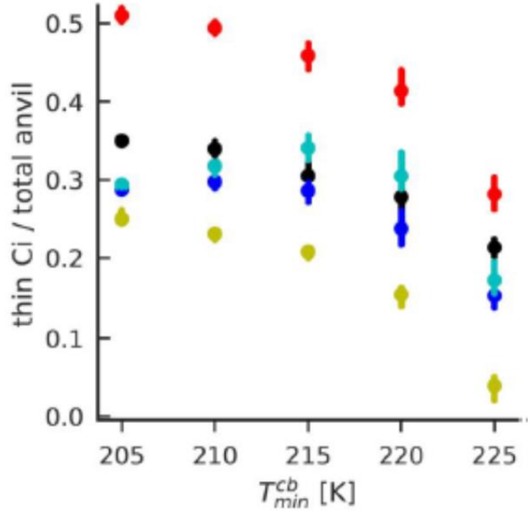


New parameterizations -> improvement of cloud system property distributions

Introduction of IWC-T dependence -> improvement of cloud system size distribution
Decrease of RQH -> improvement of cloud system T distribution

process-oriented UT cloud system behavior





data

control v_m =0.3 x f(IWC)
D_e = f(T)

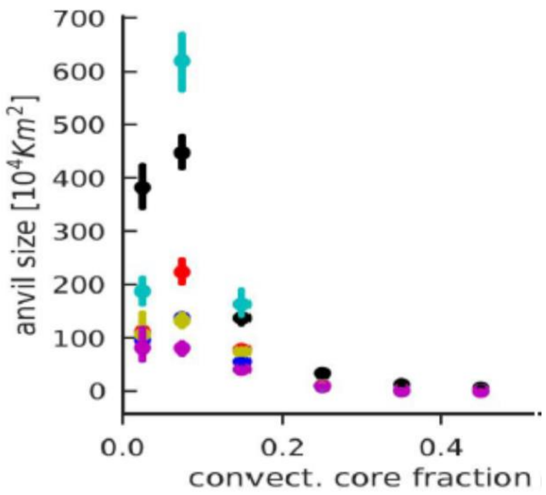
empirical v_m(IWC,T)& $D_e(v_m)$

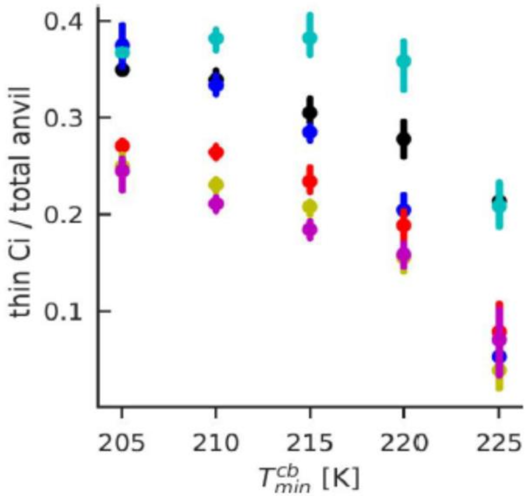
PSDM v_m & $D_e(v_m)$

PSDM v_m & D_e

increasing age of system

increasing convective depth





Sensitivity studies

data

control

scaled PSDM v_m

FALLICE+

EPMAX+

RQH-

New process-oriented diagnostics based on Cloud System Concept powerful constraint:

more realistic v_m –D_{eff} -> more realistic anvil size & ε horizontal structure (increasing thin Ci) development

Tuning adjustment of UT sub-grid water variability (RQH) -> larger anvils & more thin cirrus

Summary & Outlook

- **bulk ice cloud schemes should coherently couple v_m** (*cloud physics*) **& D_{eff}** (*cloud radiative effects*)
  -> realistic v_m -> adjusted tuning -> UT water sub-grid variability had to be reduced for radiation balance
- **v_m =f(IWC,T) instead of f(IWC); D_{eff} is now directly linked to v_m** (or to same size distribution)
- **Cloud System diagnostics provides powerful constraints:**
  new bulk ice schemes -> larger cloud systems & slightly less emissive anvils,
  in better agreement with CIRS observations
- **Cloud System Concept links anvils to convection, allows process-oriented evaluation:**
  behavior of anvils with increasing convective depth & along statistical life cycle
  -> new bulk ice schemes seem to improve this behavior

Stubenrauch, C. J., Bonazzola, M., Protopapadaki, S. E., & Musat, I., **New cloud system metrics to assess bulk ice cloud schemes in a GCM**. J. Advances in Modeling Earth Systems, 11, doi:10.1029/2019MS001642, 2019

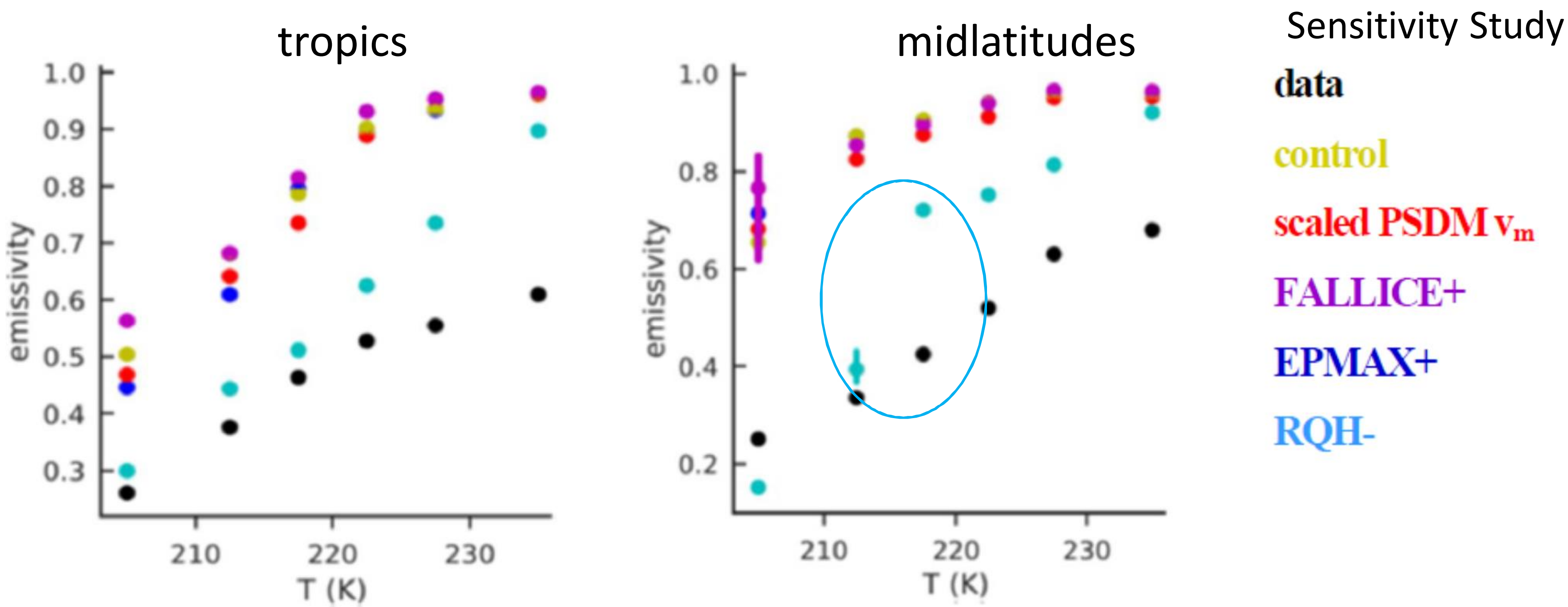
- **Replace D_e directly by β_{ext}, ω_0, g (λ, IWC, T) of** ***Baran et al. 2016 :***
  - Fits adapted to bandwidths of LMDZ RT & integrated into LMDZ code
  - tuning & simulation; save radiative heating rates to output for evaluation with

  radiative heating rates deduced from A-Train Observations & Machine Learning

Stubenrauch, C. J., Caria, G., Protopapadaki, S. E., & Hemmer, F., **3D Radiative Heating of Tropical Upper Tropospheric Cloud Systems derived from Synergistic A-Train Observations and Machine Learning**, Atmos. Chem. Phys., 21, doi:10.5194/acp-21-1015-2021, 2021

- **next step: improve formulation of sub-grid UT rel. water variability (RQH threshold) using AIRS climatology** of *Kahn et al. 2009, 2011*

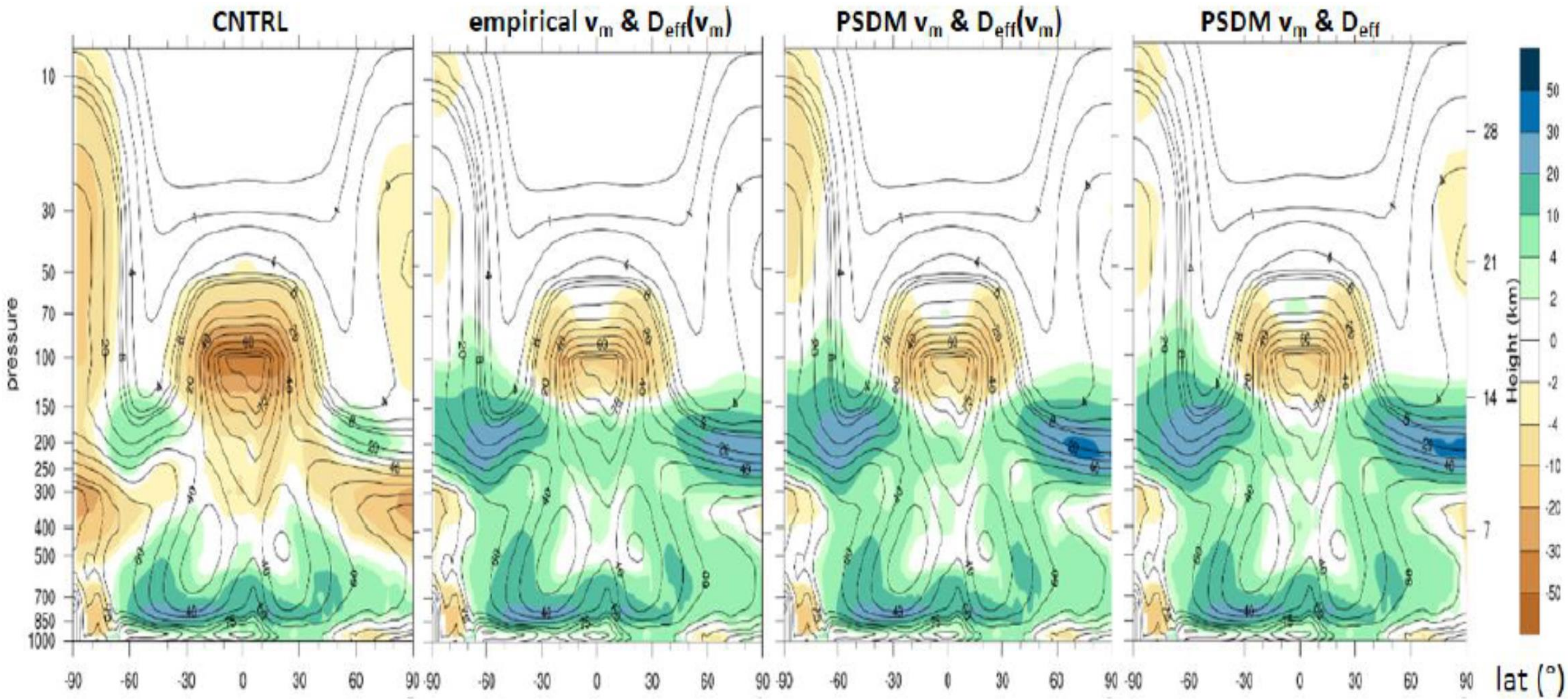
ε – T relation of UT cloud systems



- Decreasing RQH leads to smaller cloud system emissivity at colder T, in better agreement with the data
- **Midlatitudes: height at which RQH is applied should be different than in tropics (250 hPa)**

spare slides

Atmospheric Humidity changes



rel. humidity profiles compared to ERA-Interim:
new parameterizations less dry in tropical but too wet in higher latitude upper troposphere
=> RQH should depend on latitude / season & land / ocean

Analytical expressions: *D* -> bulk properties

PSD generally expressed as :

$$\mathbf{N(D) = N_0\, D^{\mu} e^{-\lambda D}}$$

D maximum dimension ice crystals, λ slope, μ dispersion; exponential PSD: $\mu=0$

decrease in λ -> PSD broadening; PSD bends down for smaller crystals, when $\mu > 0$

Cirrus bulk properties = mass- or area-weighted integrals of PSD,

with $m = a\, D^{b}$ $A = c\, D^{d}$

b=3 for sphere, b = 2 for aggregates, b = 1.5 for dendrites

$$\mathbf{IWC} = \int \mathbf{m(D)\, N(D)\, dD} = \int a\, N_0\, D^{b+\mu} e^{-\lambda D}\, dD = a\, N_0\, \Gamma(b+\mu+1)/\lambda^{(b+\mu+1)}$$

$$\mathbf{D_m} = \int D^3\, N(D)\, dD \,/ \int D^2\, N(D)\, dD = (b+\mu+0.67)/\lambda$$ *Mitchell et al. 1991*

> coefficients depend on ice crystal habit & size, can they be assumed to be constant with T ?
> Field 2007 supposes aggregates (b = 2) in PSD moment parameterization

$v_t \sim (m/A)^{0.6}\, D^{0.3}\, f(p)$ $\mathbf{v_t = A D^{B}}$

$$\mathbf{v_m} = \int \mathbf{m(D)\, v_t(D)\, N(D)\, dD} \,/ \int \mathbf{m(D)\, N(D)\, dD}$$

$$\mathbf{v_m = A D_m^{\,B}}$$ *Heymsfield et al. 2013*

A & B for 3 D ranges
(Heymsfield et al. 2013)

A & B for 2 D ranges
(Furtado et al. 2015)

PSD moment parameterization

Field et al. 2007 (F07): **13000 PSDs, of 4 field campaigns (tropics & midlatitudes)**

$$M_n = \int D^n N(D)\, dD = A(n) * e^{B(n)*T} * M_2^{C(n)}$$

$M_2 = IWC / a$ $D_m = M_3 / M_2 = a M_3 / IWC$ $v_m = AD_m^B$ —

$v_m = A M_B$

ice : $A = 1042 / B = 1.0$ (SI units)

snow : $A = 14.3 / B = 0.416$

for each D the smallest v_t of both:

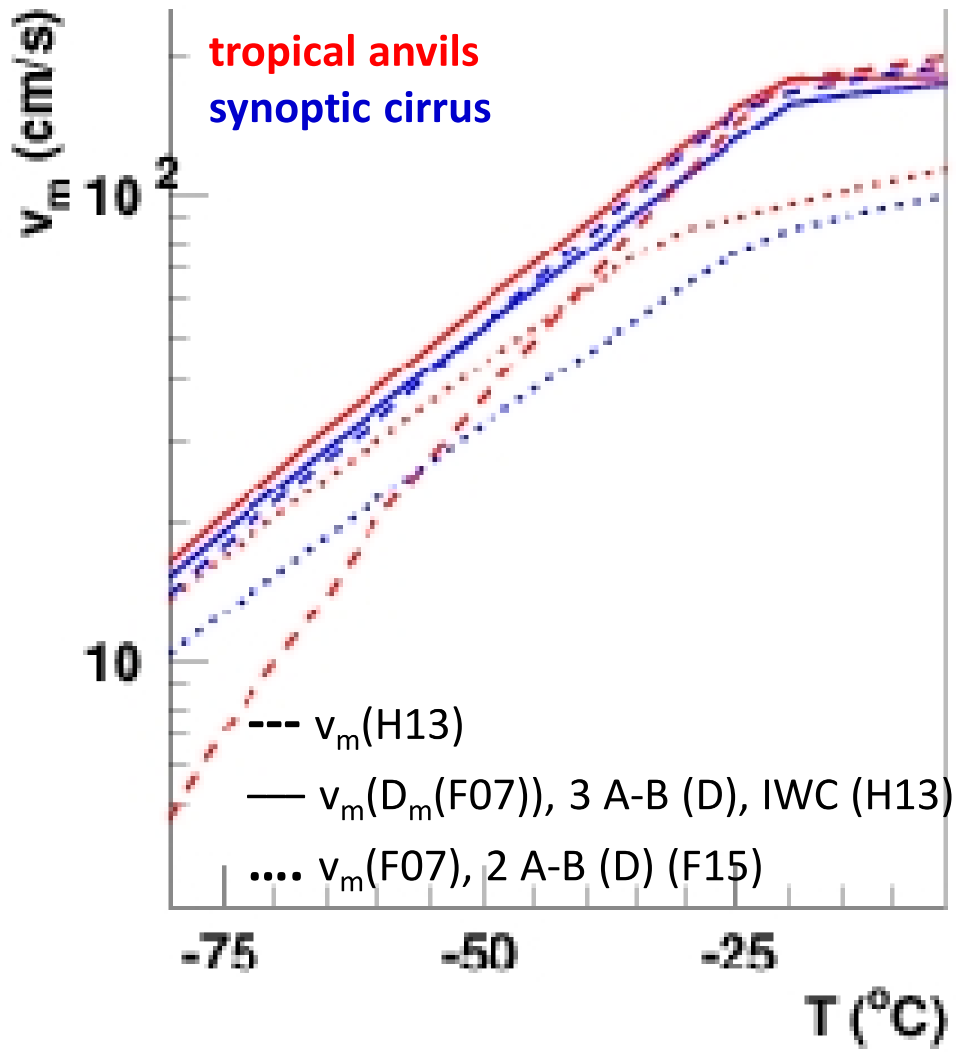
ice D < 600 μm & snow D > 600 μm

Furtado et al. 2015 (F15)

slope of v_m (F07-H13) & (F07-F15)
same for tropical anvils & synoptic
(parameterization combines measurements)

compares well with synoptic cirrus of H13

2 A-B instead of 3 A-B : smaller v_m
max values at 100 cm/s



Empirical parameterizations : $v_m = f(T, IWC)$

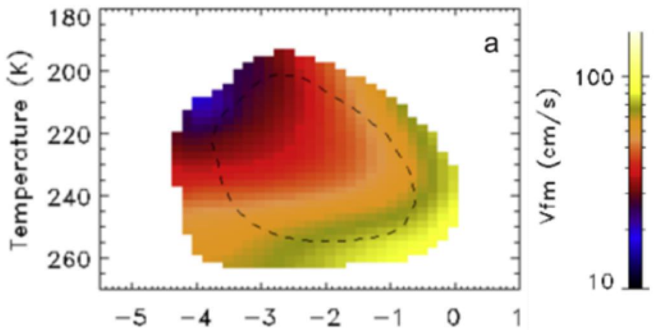
- ***Heymsfield et al. 2007 (H07):*** **20000 PSDs from 2 field campaigns**
  tropical anvils (T > -70°C) & synoptic cirrus (T>-54°C)

- ***Deng & Mace 2008 (DM08):*** **from longterm ARM in situ statistics, retrieved from radar measurements; 1999-2005 -> 30000 hrs**

convective: TWP ARM (T> -75°C) synoptic: SGP ARM (T>-65°C)

similar behaviour

vm increases with IWC & T



- ***Mitchell et al. 2011 (M11):*** **3 recent field campaigns**

young anvil cirrus, aged anvil cirrus, in situ cirrus, Arctic cirrus

similar bevahour; except Artic cirrus : v_m not dependent on IWC

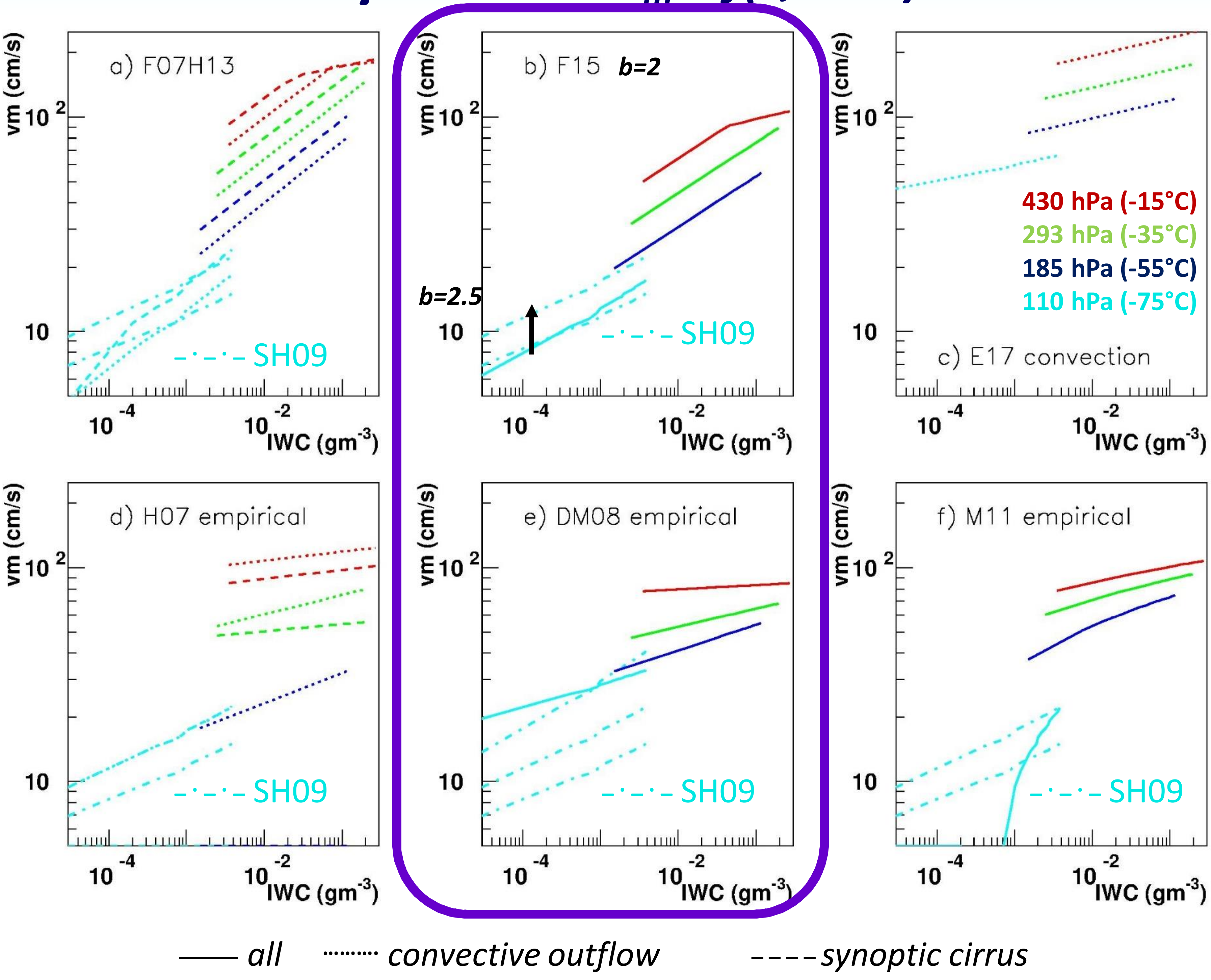
TC4 (Costa Rica, Jul-Aug 2007), NAMMA (African Monsoon, 2006) , ISDAC (Arctic, Apr 2009)

- ***Elsaesser et al. 2017 (E17): convective outflow*** **from 4 field campaigns**

TC4, NAMMA, MC3E (20 May 2011), SPARTICUS (Jan-Jun 2010) -> GISS GCM

Schmitt & Heymsfield 2009 (SH09): **2 field campaigns (-86°C - -56°C)** v_m = f(IWC)

Synthesis : $v_m = f(T, IWC)$



$v_m - D_e$ Strategies for LMDZ GCM

- v_m = f(IWC, T) of DM08 & SH09
  D_{eff} = f(v_m) of H03 (mean between synoptic & anvil cirrus)
  empirical v_m & D_e=f(v_m)

- v_m = F07 PSD momentum & F15 A-B couples for ice / snow
  D_{eff} = f(v_m) of H03 (mean between synoptic & anvil cirrus)
  PSDM v_m & D_e=f(v_m)
  or
  D_m = F07 PSD momentum
  D_{eff} = 0.17 x D_m (assumed aggregates, *fitted to D_{eff}-v_m, Baran et al. 2016*)
  PSDM v_m,D_m & D_e=f(D_m)

Next step: use for radiative transfer directly
single scattering property (SSP) parameterization f(IWC,T) of Baran et al. 2016
(same PSDs as in F07)