Using a Cloud System Approach to demonstrate the impact of a coherent bulk ice cloud scheme in the LMDZ GCM

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Towards a coherent bulk ice ice cloud scheme deduced from thermodynamics

v_m strongly influences UT cloud occurrence & properties
& has potential to influence climate sensitivity (e.g. *Sanderson et al. 2008*)

D_e affects the radiative properties of UT clouds

current version of LMDZ: v_m = f(IWC), D_e = f(T)

v_m is one of the parameters which is tuned to achieve radiative balance (x 0.3)

airborne & ground-based observations: v_m = f(IWC, T)

IWC & T classify distributions of ice crystal size & habit (*Field et al. 2007*)

(review & comparison: *Stubenrauch & Bonazzola, JAMES, subm. Nov 2018*)

construct parametrization from existing ones:

1) empirical parametrizations : v_m = f(IWC, T); D_{eff} = f(v_m)

2) v_m, D_m from moments of size distribution, parametrized as f(IWC, T)

next step: parametrize ice single scattering properties SSP = f(IWC, T)

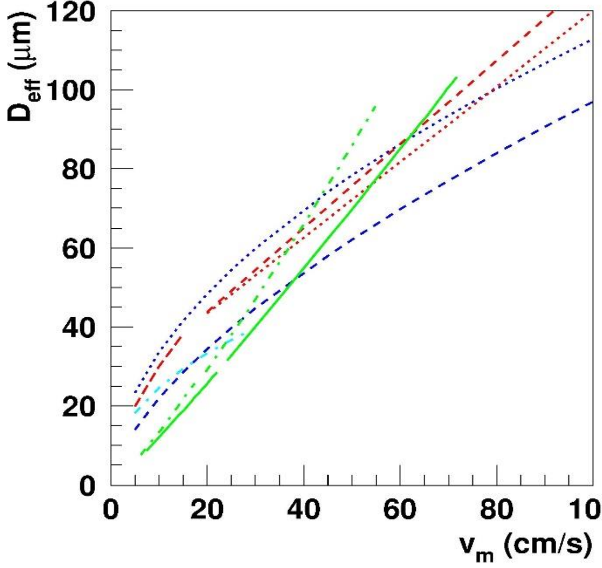
(in cooperation with A. Baran, MetOffice)

coherence by using same measured size distributions for v_m & SSP parameterizations

v_m – D_e relationships

- fall speed v_m & effective ice crystal diameter D_{eff} are closely related, as they both depend on ice area / ice mass

from field campaigns

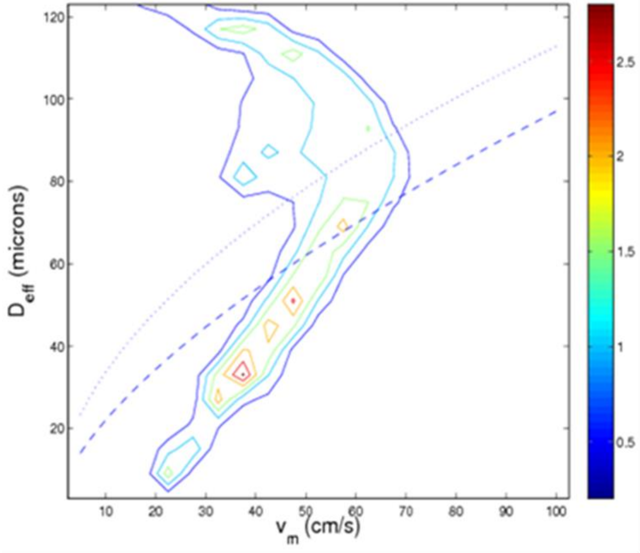


—— F07-F15-B16 (a,b),(A,B) for ice / snow   ·-·-·- F07-F15-B16 b=2, (A,B) for ice / snow

······ anvil cirrus (H03)   - - - - midlatitude cirrus (H03)   ·-·-·- TTL cirrus (SH09)

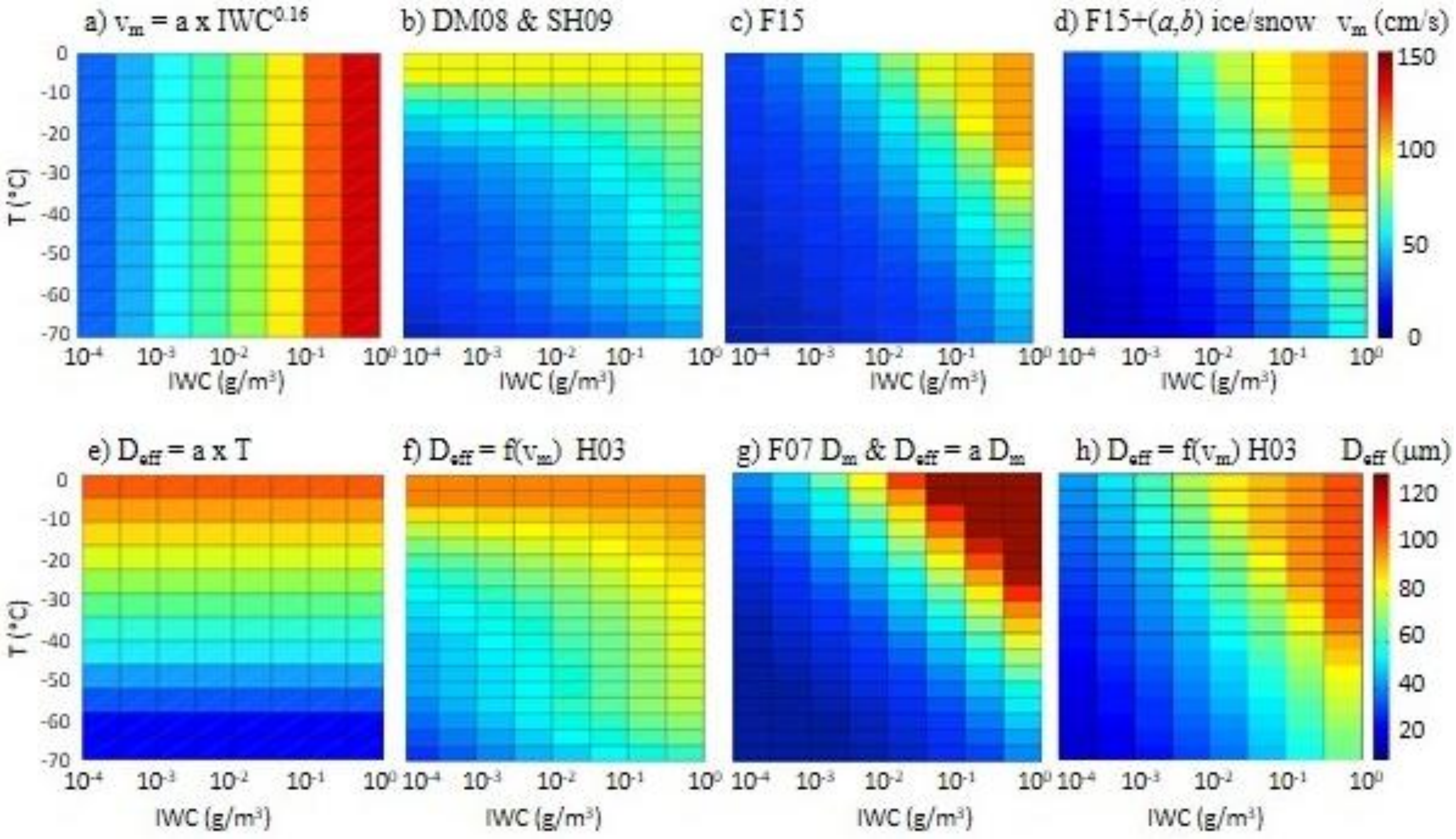
······ anvil cirrus (M11)   - - - - Arctic cirrus (M11)

from LMDZ simulation



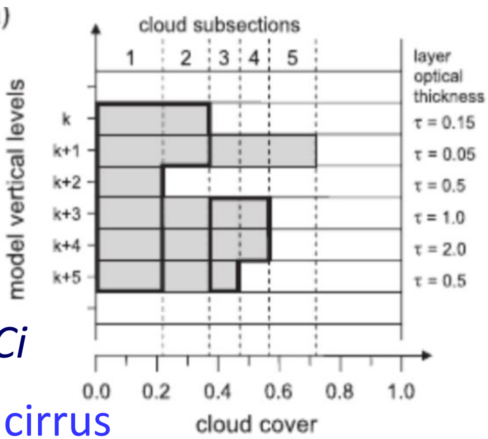
Direct relation between v_m & D_{eff} needs more realistic v_m (*scaled by 0.9*)
=> need to adjust remaining tuning parameters for radiation balance
(*EPMAX & RQH*)

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



Stubenrauch & Bonazzola,
JAMES subm. Nov 2018

New diagnostics using AIRS/IASI cloud observation simulator



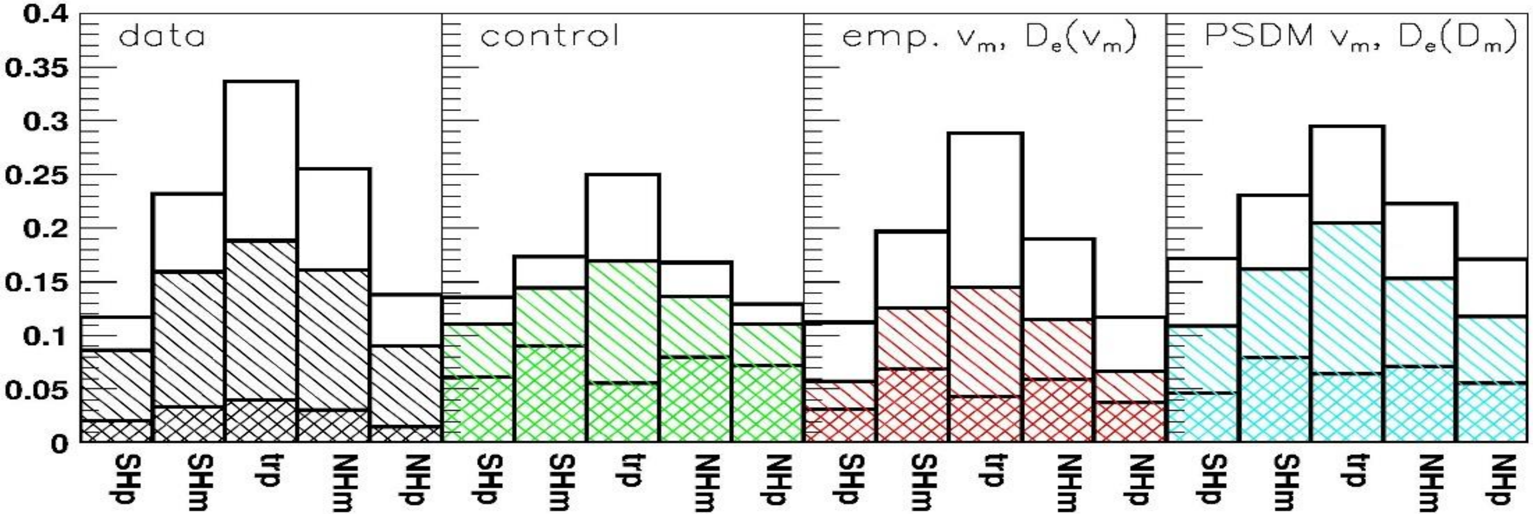
IR Sounders provide cloud height p_{cld} & emissivity ε_{cld}; **sensitive to cirrus**

- 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-level 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)



Stubenrauch et al., JAMES, subm. Jan. 2019

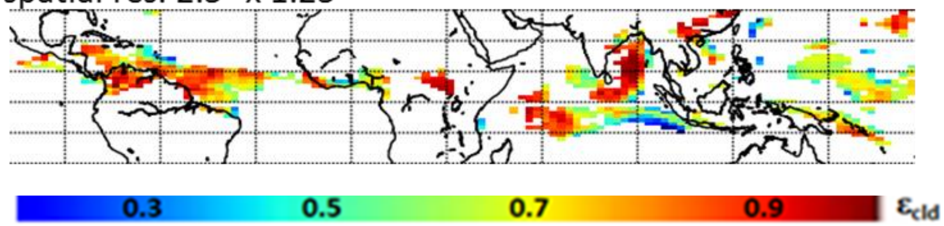
Control simulation too few high clouds with too many Cb
New bulk ice schemes -> increased high clouds, with more Ci & thin Ci, in better agreement with observations

UT Cloud System Concept to assess GCM parameterizations

Cloud System Concept (similar p_{cld} & horizontal ε_{cld} structure -> convective cores & anvils) **relates the anvil properties to processes shaping them**

-> process-oriented evaluation of detrainment / convection / microphysics parameterizations

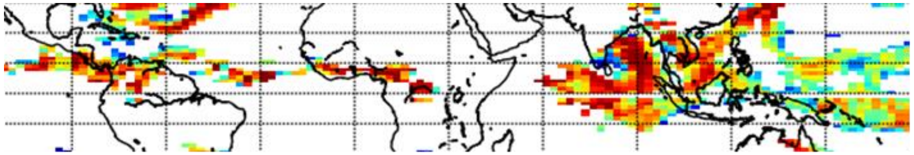
spatial res. 2.5° x 1.25°



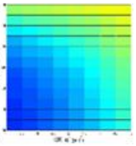
nominal fall speed & precipitation efficiency

v_m = f(IWC), De = f(T), ε = f(De, IWC)

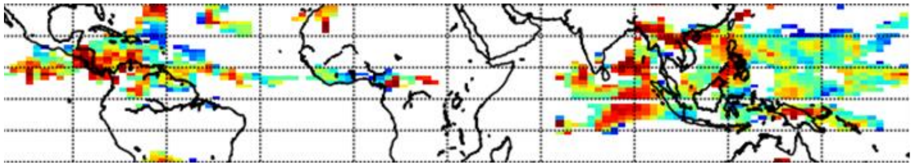
scaled v_m too small compared to observations



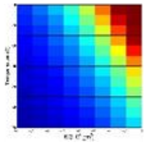
v_m adapted from *Deng & Mace 2008*



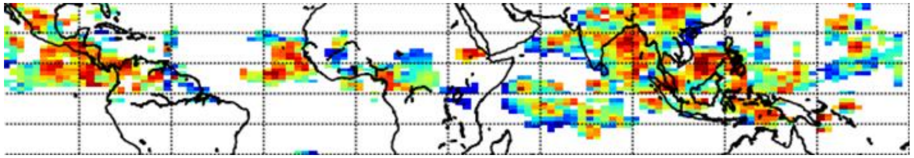
v_m = f(IWC, T)



v_m from PSD moment parameterization (*Field 2007)*

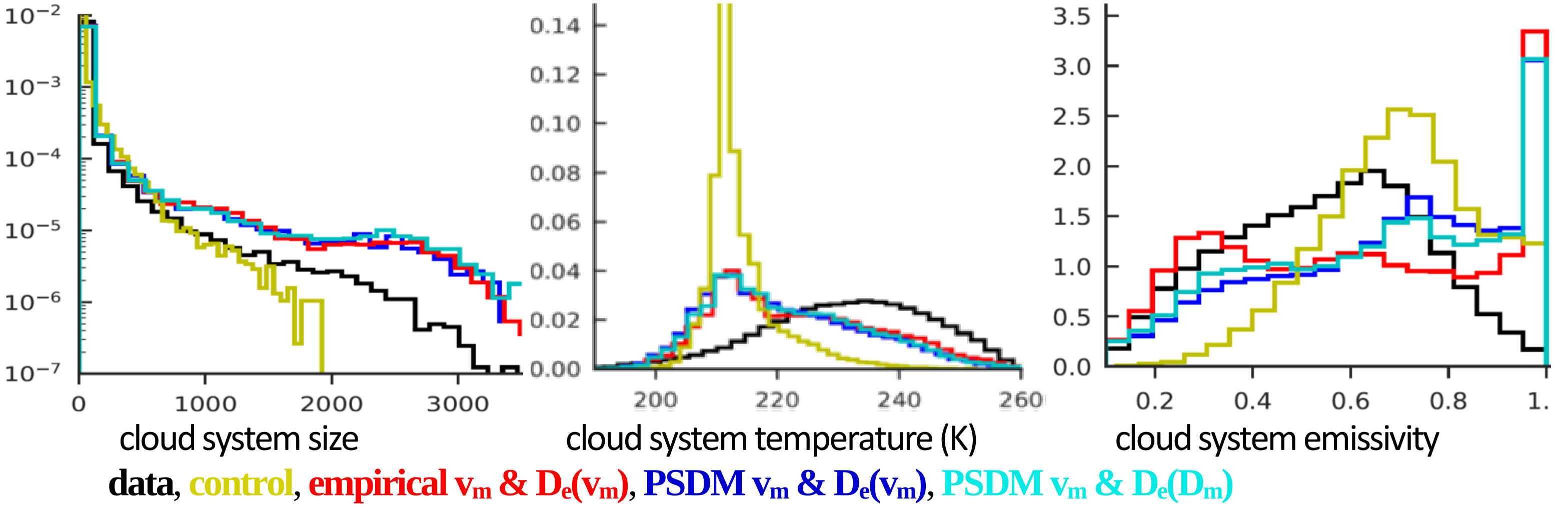


horizontal cloud system emissivity structure sensitive to v_m, De



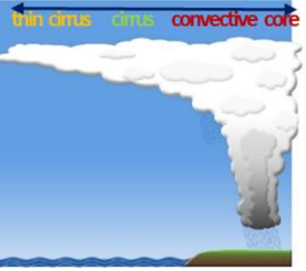
AIRS snapshot 3 July 2008 AM

New diagnostics using UT cloud system statistics



Effect of new ice schemes

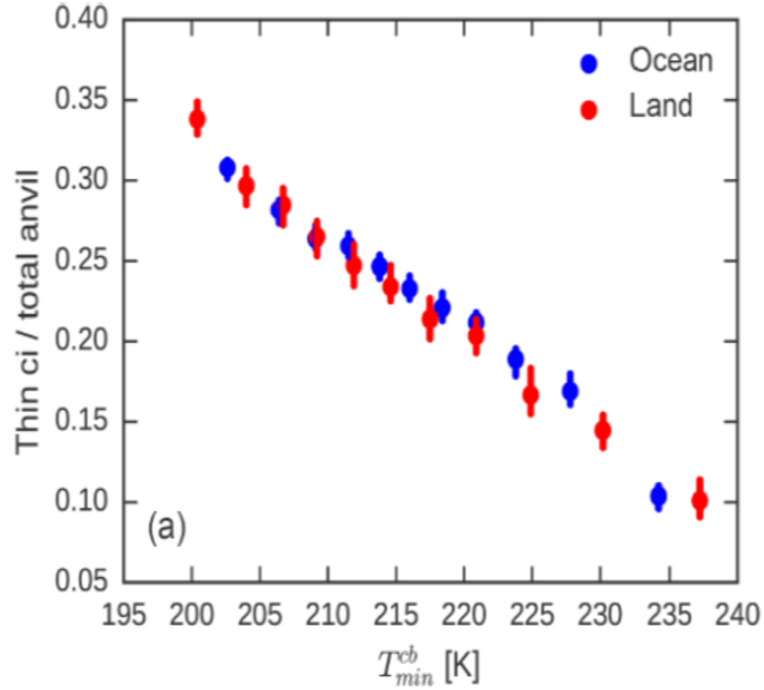
new ice schemes (& more realistic v_m) in better agreement with observations: larger system sizes, broader T distributions, decreased anvil emissivity



link anvil structure to convective depth

Protopapadaki et al. ACP 2017

15 years AIRS; ***tropical UT cloud systems*** (p_{cld}-$p_{tropopause}$ < 250 hPa or p_{cld} < 440 hPa);
convective core (Cb): ε_{cld}>0.98; ***mature systems***: Cb fraction within system 0.1 – 0.3



Deeper convective cores -> stronger max rain rate
-> T^{cb}_{min} good proxy for convective strength

Deeper convection leads to relatively more thin cirrus within larger anvils
(similar land / ocean)

relation robust *using different proxies :*
T_{min}^{Cb} / LNB(max mass)

increasing convective depth

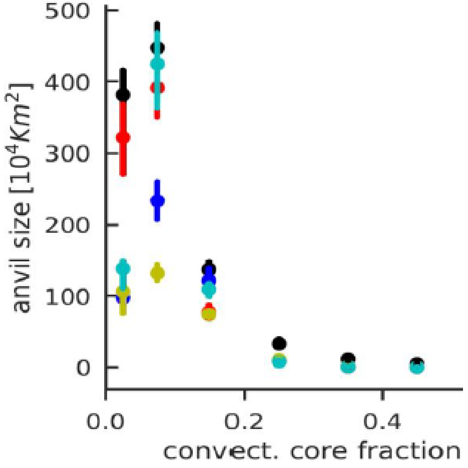
Why ?
H1: UT environmental predisposition (at higher altitude larger RH, T stratification)
H2: UT humidification from cirrus outflow

Does the relationship change in a warmer climate ?

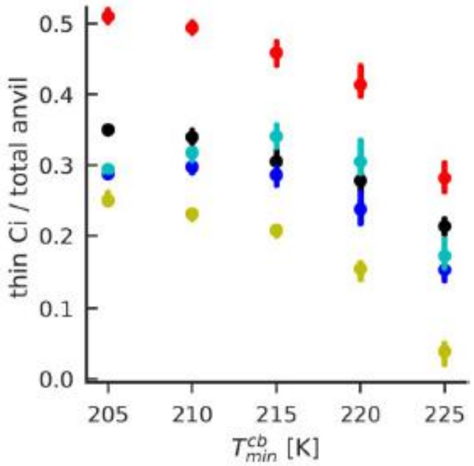
CRM

GCM

process-oriented UT cloud system behaviour



increasing age of system



increasing convective depth

data

control v_m =0.3 x f(IWC)
D_{eff} = f(T)

empirical v_m(IWC,T)& D_{eff}(v_m)

PSDM v_m & D_{eff}(v_m)

PSDM $v_{m,}$ D_m & D_{eff}(D_m)

Stubenrauch et al., JAMES, subm. Jan 2019

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

Summary & Outlook

- **bulk ice cloud schemes should coherently couple v_m** (*cloud physics*) **& D_e** (*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_e is now directly linked to v_m** (or to same size distribution)

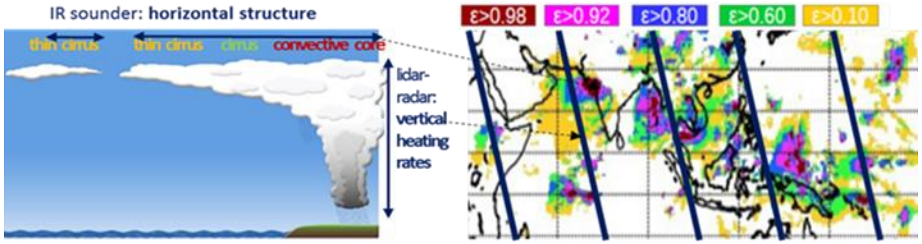
- **Cloud System diagnostics provides powerful constraints:**

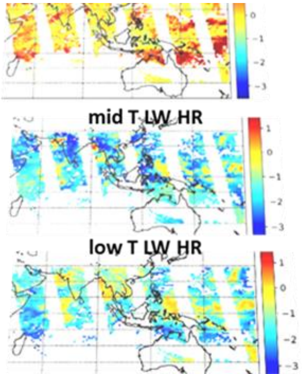
  new bulk ice schemes -> larger cloud systems & slightly less emissive anvils,
  in better agreement with AIRS observations

- **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

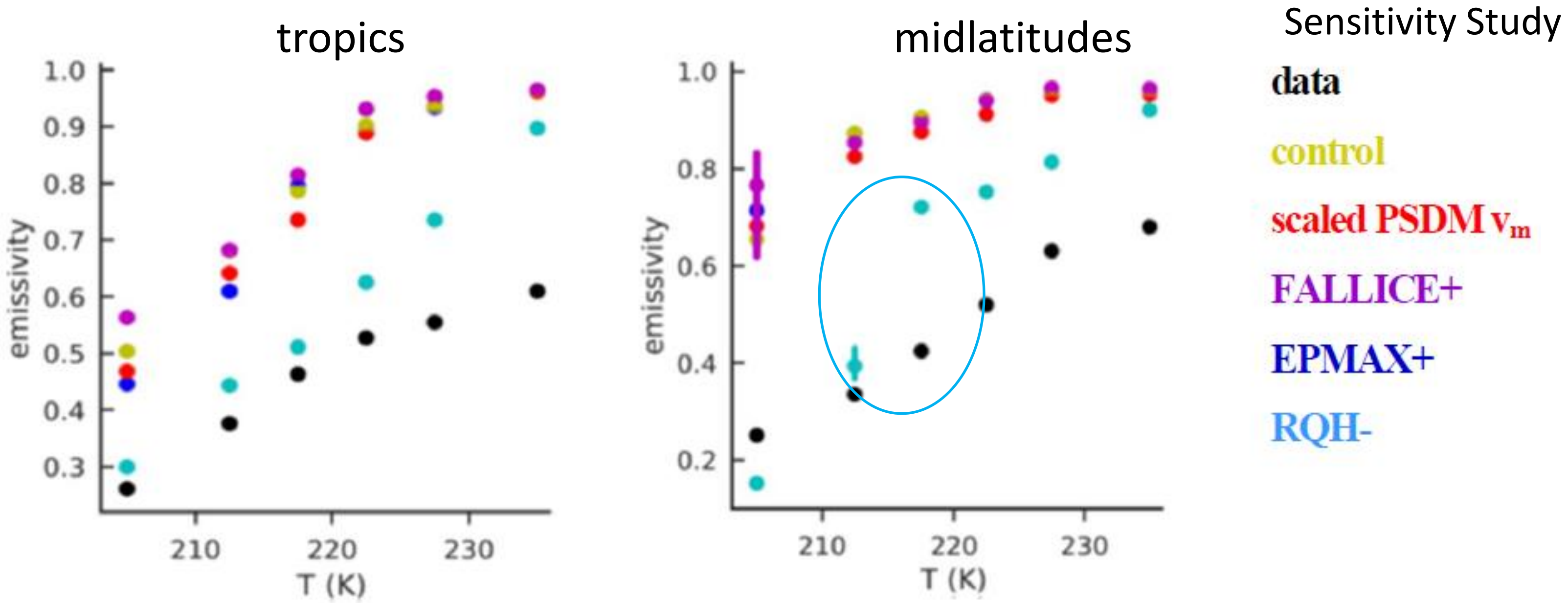




expanded LW heating rates

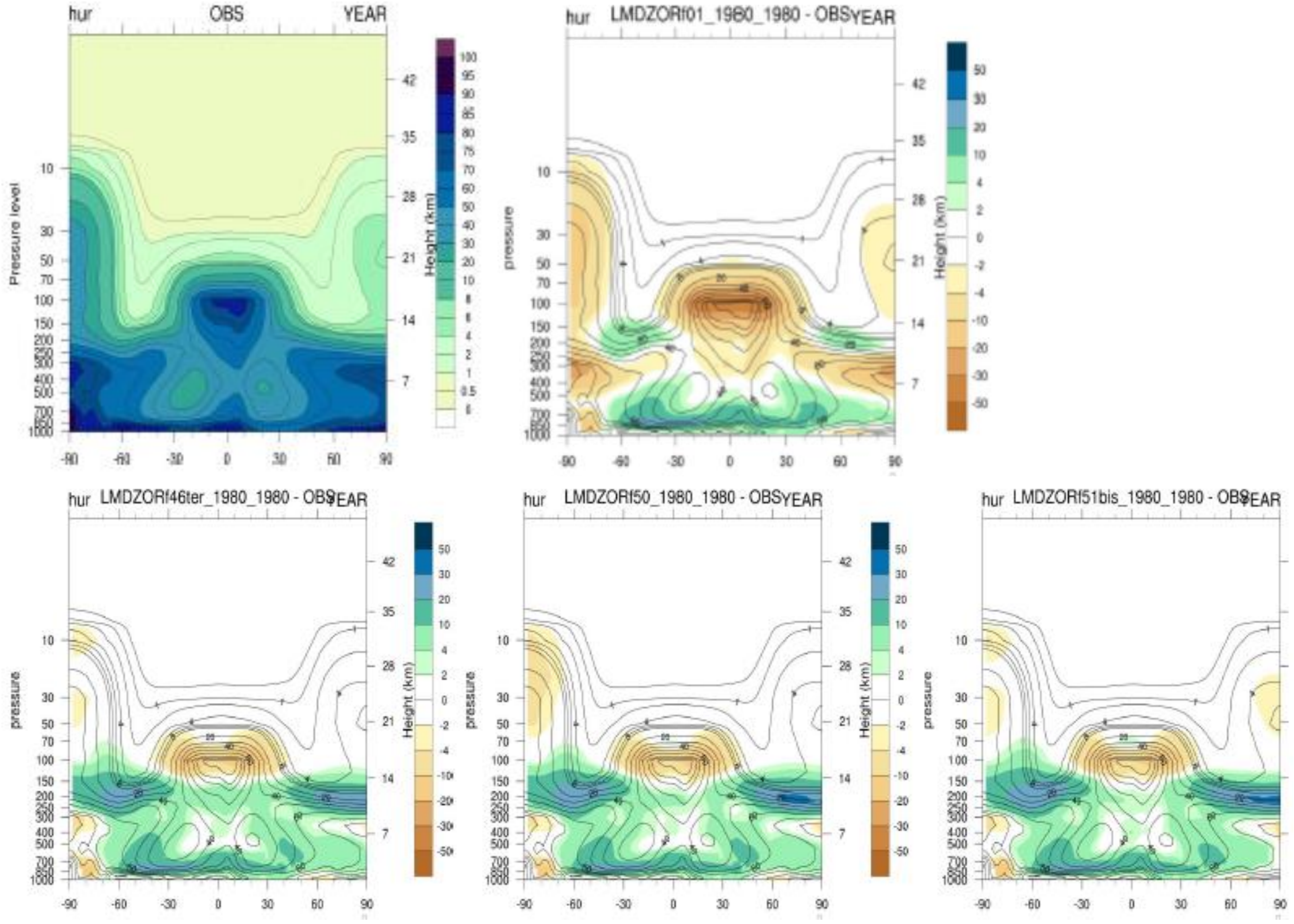
- **next step: improve formulation of sub-grid UT rel. water variability (RQH threshold) using AIRS climatology** of *Kahn et al. 2009, 2011*

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)**

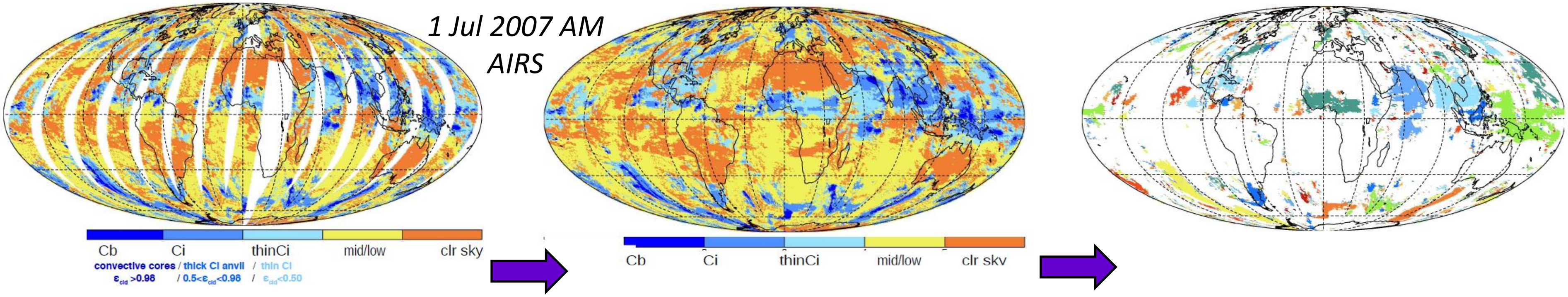
Atmospheric Humidity changes



From cloud retrieval to cloud systems

clouds are **extended objects**, driven by dynamics -> **organized systems**

Method: 1) group adjacent grid boxes with high clouds of similar height (p_{cld})

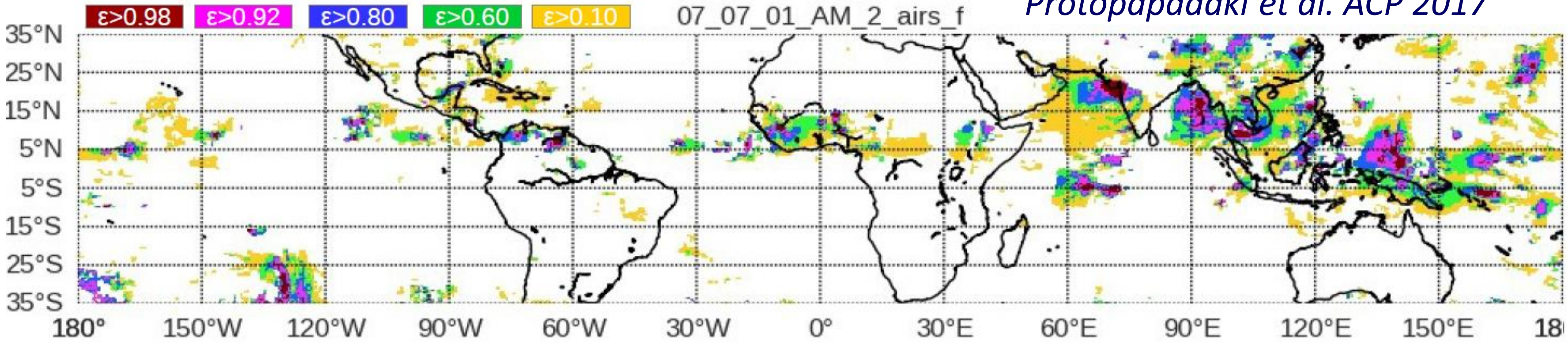


1 Jul 2007 AM
AIRS

fill data gaps using PDF method

build UT cloud systems

2) use ε_{cld} to distinguish convective core, thick cirrus, thin cirrus *(only IR sounder)*



Protopapadaki et al. ACP 2017

30N-30S: UT cloud systems cover 25%, those without convective core 5%
50% of these originate from convection *(Luo & Rossow 2004, Riihimaki et al. 2012)*

v_m – D_e Strategies for LMDZ GCM

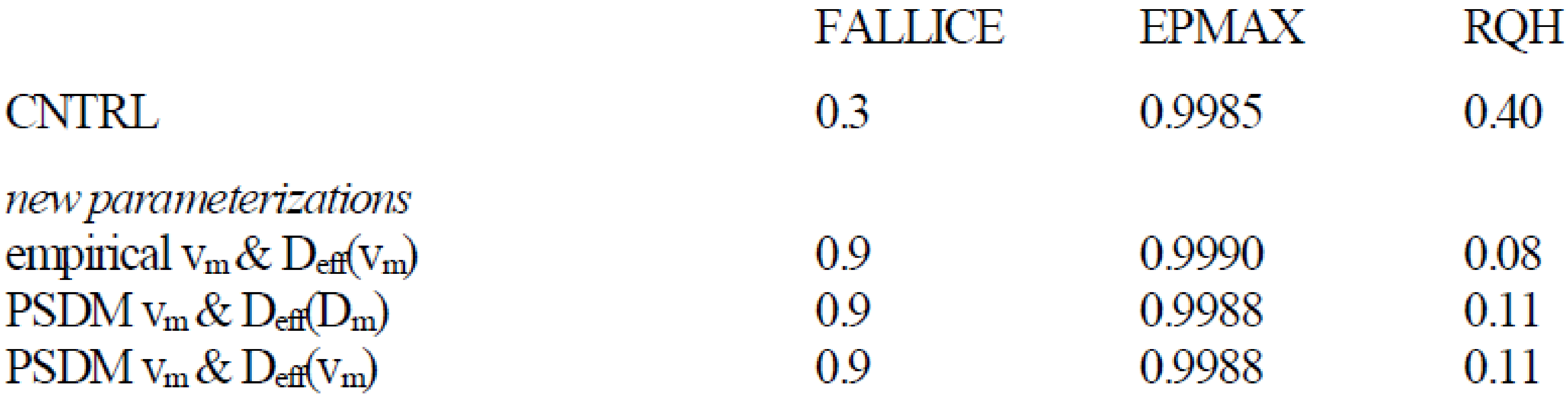
- v_m = f(IWC, T) of DM08 & SH09
  D_{eff} = f(v_m) of H03 (mean between synoptic & anvil cirrus)
  empirical v_m & D_e=f(v_m)

- 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)

Tuning parameters most relevant for high clouds

FALLICE: scaling of fall speed
EPMAX: maximum precipitation efficiency
RQH: Rel. width of sub-grid water distribution above 250 hPa

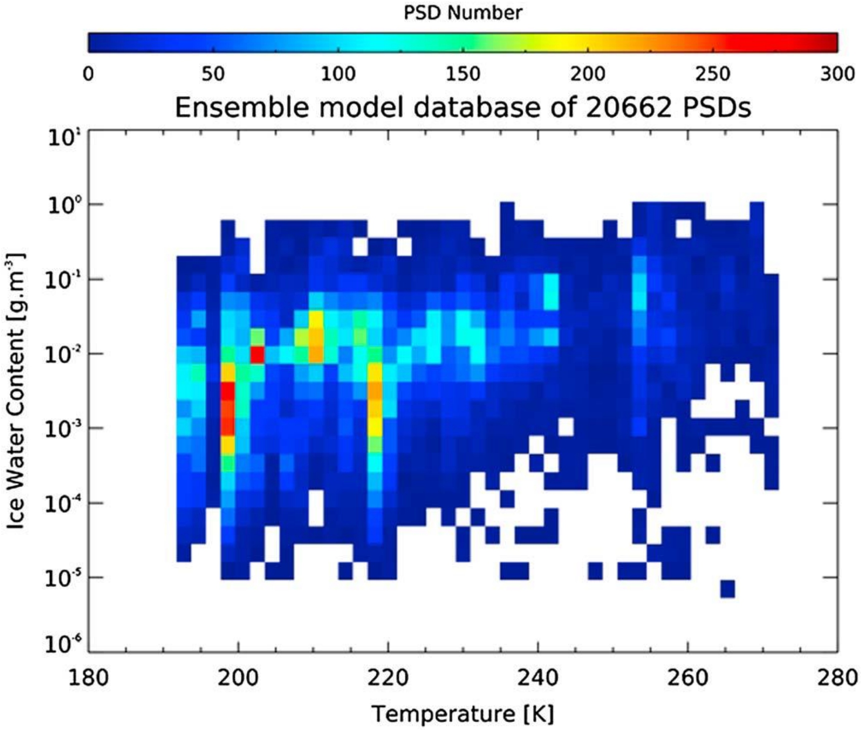


	FALLICE	EPMAX	RQH
CNTRL	0.3	0.9985	0.40
new parameterizations			
empirical v_m & $D_{eff}(v_m)$	0.9	0.9990	0.08
PSDM v_m & $D_{eff}(D_m)$	0.9	0.9988	0.11
PSDM v_m & $D_{eff}(v_m)$	0.9	0.9988	0.11

De <-> ice crystal size distribution

cloud physics – radiation parameterization

Baran et al. JGR 2014



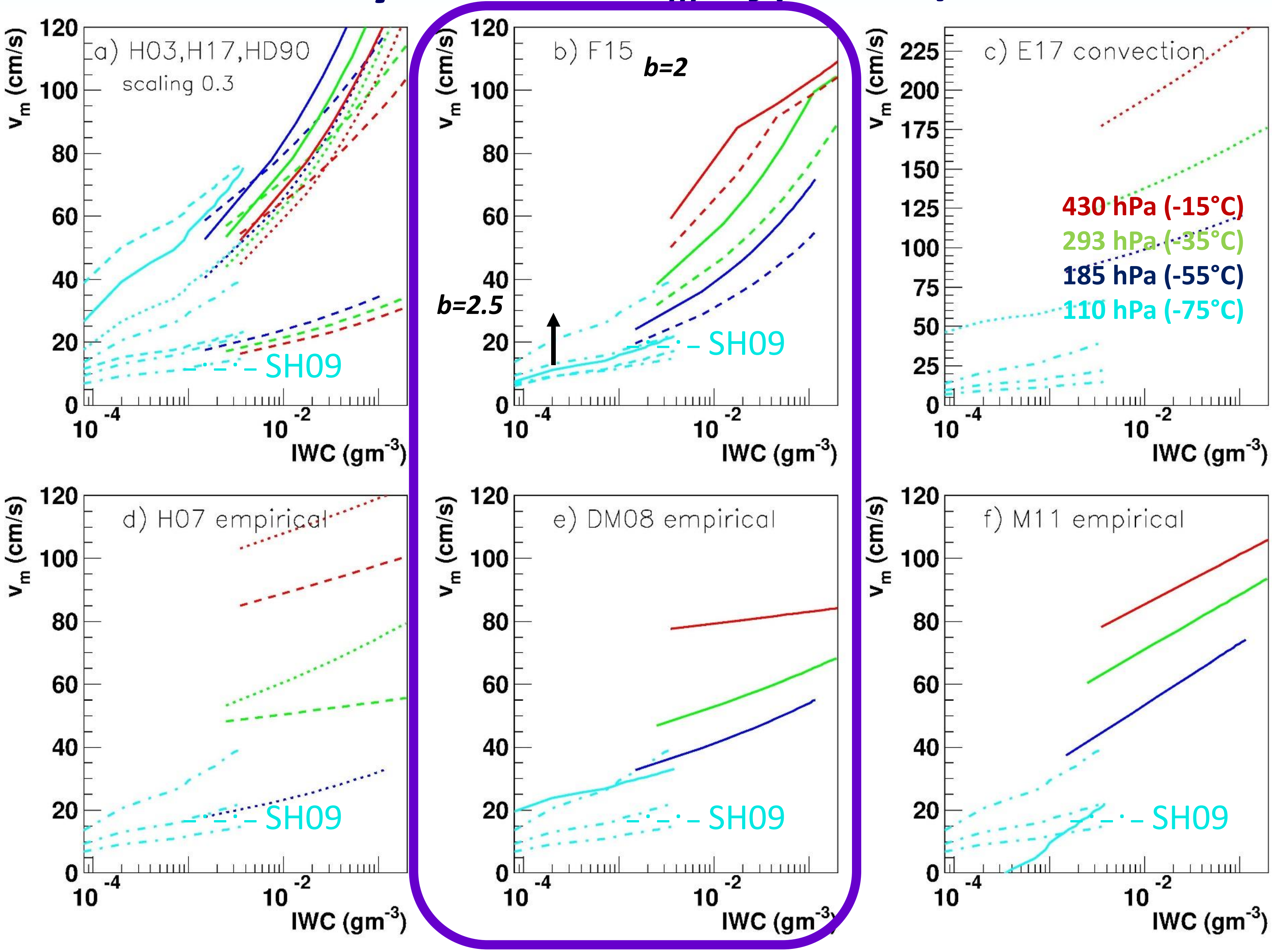
describe single scattering properties (β_{ext}, β_{sca}, g) as function of IWC / T

using parameterized in situ size distributions

ensemble model size distribution has 6 habits as fct of size

integrated in Met Office Unified Model

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



·········· *convective outflow* - - - - *synoptic cirrus* —— *both*

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

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

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

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

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

$\mathbf{v_m = AD_m^{\;B}}$ *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:

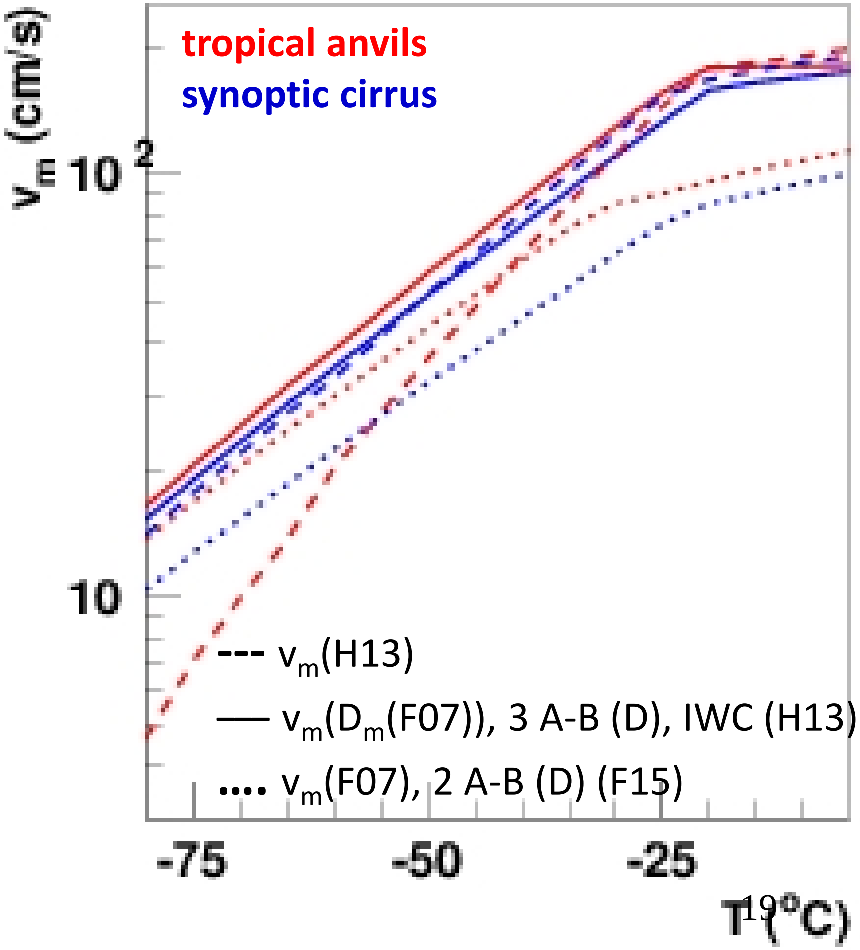
ice D < 600 μm & snow D > 600 μm

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



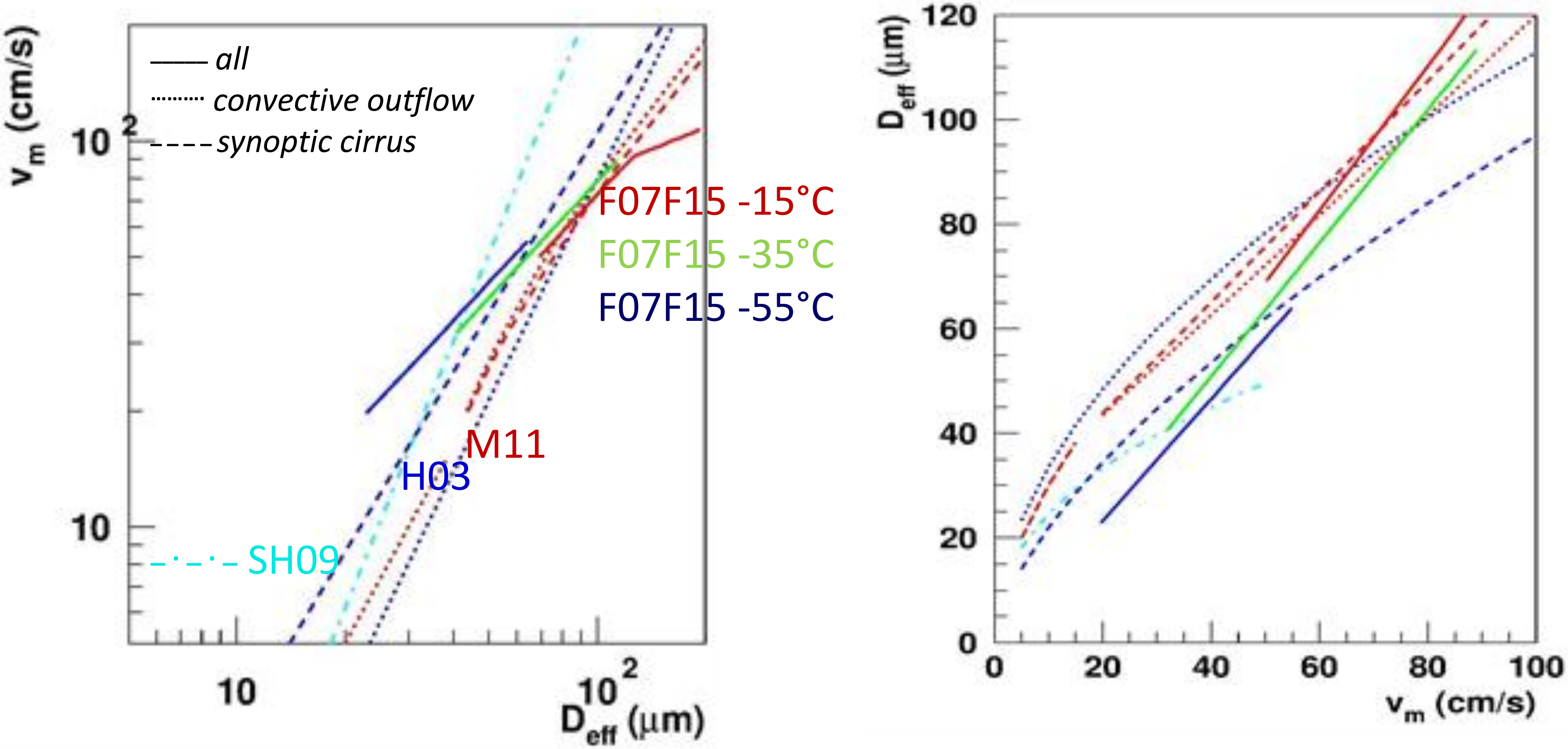
Synthesis : v_m - D_e

Analytical expression of D_e:

$$D_e = 3/2\ IWC / (\rho_{ice} \int A(D)\, N(D)\, dD) = 3\, a\, \Gamma(b+\mu+1) / (2\, \rho_{ice}\, c\, \Gamma(d+\mu+1))$$

uncertainties: a: 54%, c: 11%, b & d: < 10% (*e.g. Erfani & Mitchell 2016*)

-> $D_e - v_m$ relationships from field campaigns:



$D_{eff} = f(v_m)$ of H03 (mean between synoptic & anvil cirrus)

D_m of F07 PSD momentum, $D_{eff} \sim D_m$ (as b=2, *Baran et al. 2016)*