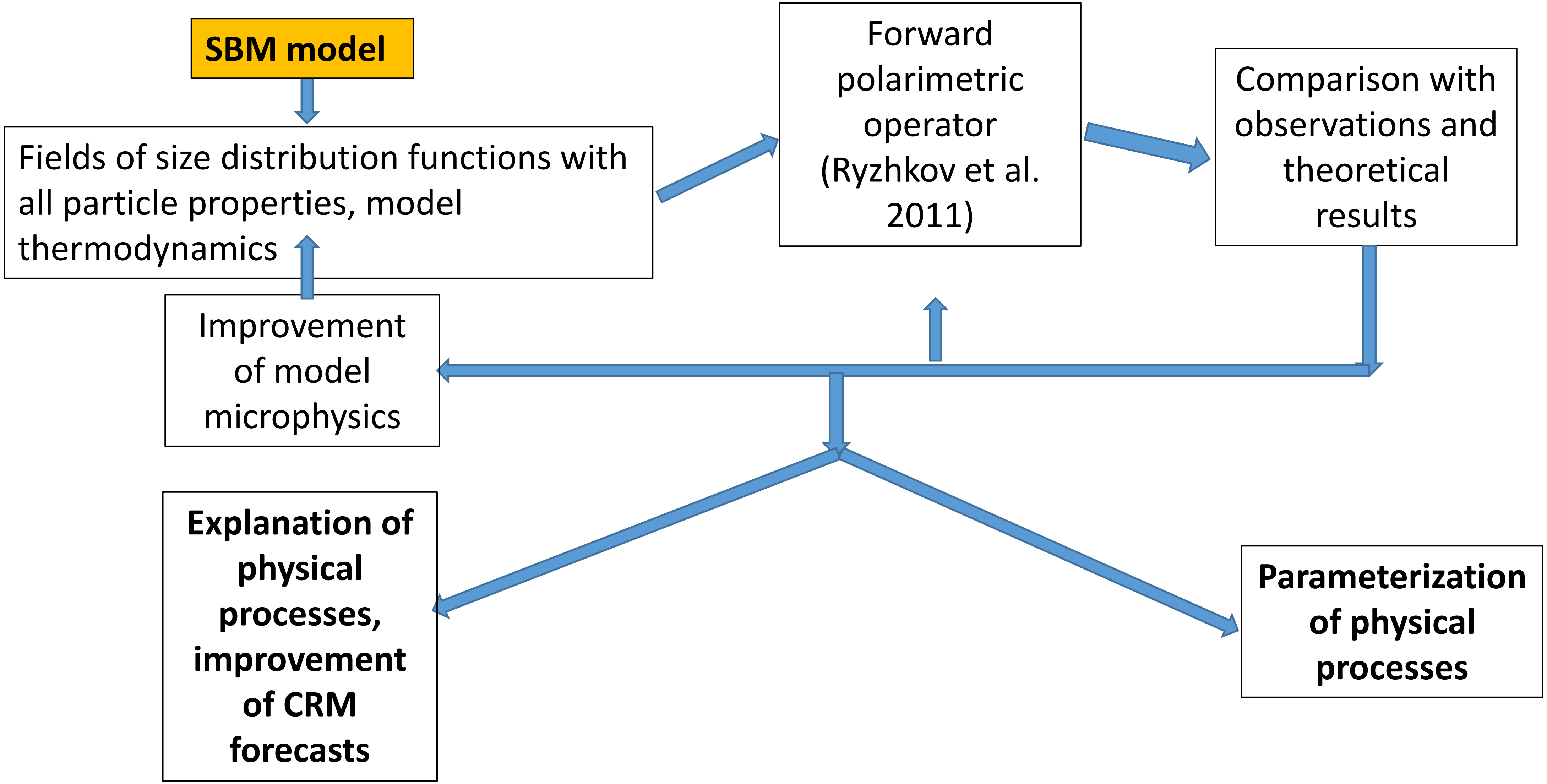
Bin microphysics and its possible application within the POLICE

A. Khain, J. Shpund, E. Ilotoviz (the HUJI, Israel)
and
A. Ryzhkov, J. Snyder, J. Carlin (NSSL, Norman, Oklahoma, USA)

17 October 2018

Coupling of bin microphysics model with dual polarimetric radar



SBM model

Fields of size distribution functions with all particle properties, model thermodynamics

Forward polarimetric operator (Ryzhkov et al. 2011)

Comparison with observations and theoretical results

Improvement of model microphysics

Explanation of physical processes, improvement of CRM forecasts

Parameterization of physical processes

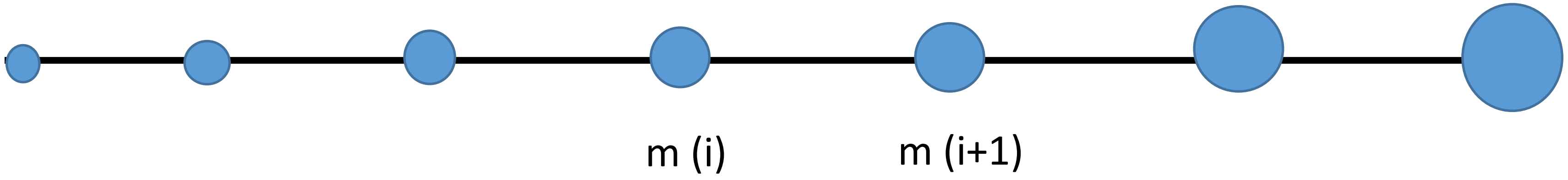
SBM model

Bin Microphysics: specific features

1. **Calculation of size distribution functions for different species**. **HUCM** (43 bins), **WRF/SBM** (33 or 43 bins)

HUCM: aerosols, drops, plate, columnar and dendrite crystals, snow, graupel, hail.
mixed-phase particles: liquid water within snow, graupel, hail, rimed mass within snow (at T<0C):
total ***15*** size distributions

WRF/SBM-current Fast SBM: aerosols; drops, snow, graupel or hail.
mixed-phase particles: liquid water within snow, graupel, hail at T>0C.



Particles in each bin are characterized by density, shape, liquid water fraction, rimed fraction (snow), fall velocity.

SBM model

Bin Microphysics: specific features (Cont.)

2. Bin microphysics solves basic microphysical equations (first principles) (without parameterization). SBM is simpler than any bulk parameterization schemes.

a) Nucleation (Kohler theory),

b) diffusional growth/evaporation, deposition/sublimation- first principle equation system for particle mass and supersaturations

c) collisions/aggregation: stochastic collision equations, turbulence effects (theoretical and laboratory studies)

d) Settling according to the fall velocity of particles,

e) Freezing, melting: utilization of heat balances

f) Breakup (collisional and spontaneous): laboratory measurements, in situ measurement

g) Shedding (laboratory measurements).

h) Ice multiplications (laboratory measurements, in situ measurement)

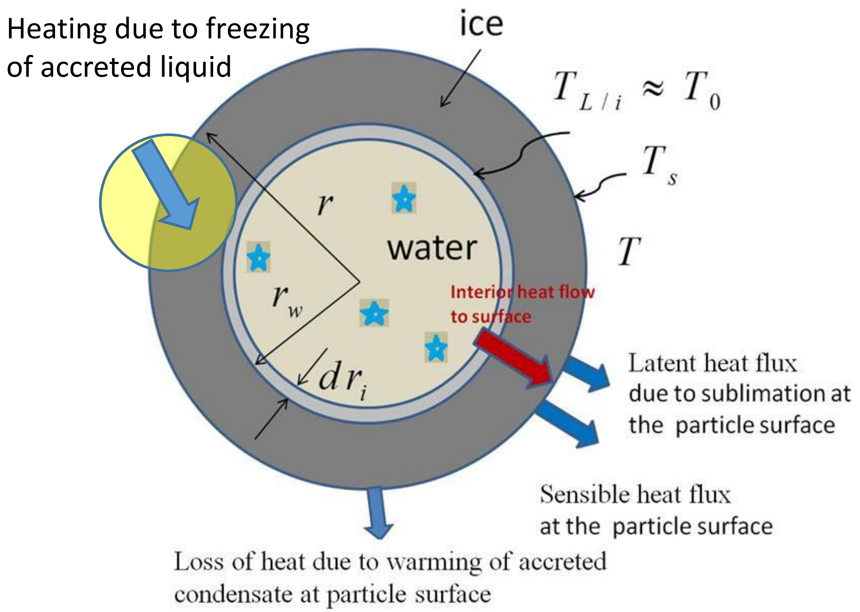
All processes are size dependent. Now averaging with respect of size or number concentration

SBM model

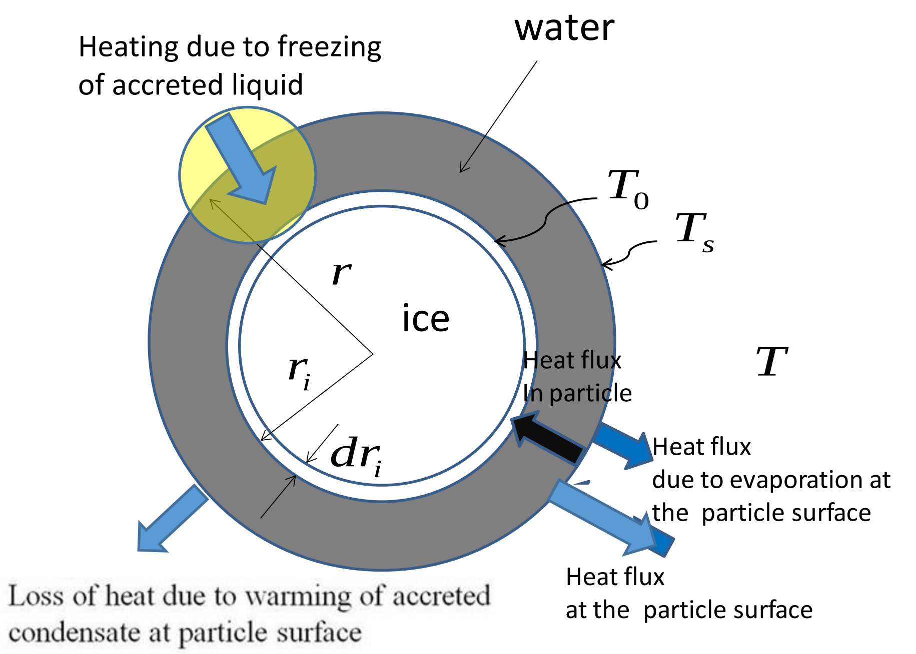
One example: freezing/melting

Heat balances determining the process of freezing of freezing drops and formation of wet growth regime of hail

Freezing drops



Hail-wet growth or melting



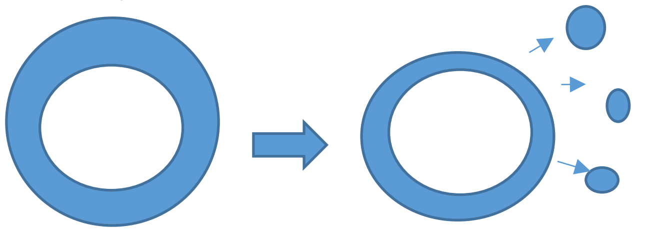
Equation for heat balance on particle surface

$$\underbrace{4\pi r_p f_h K_a(\hat{T}_s - T)}_{\text{Sensible heat from surface}} + \underbrace{\frac{4\pi r_p D_v L_s f_v}{R_v}\left[\frac{e_{\mathrm{sat},i}(\hat{T}_s)}{\hat{T}_s} - \frac{e}{T}\right]}_{\text{Latent heat of sublimation at surface}} + \underbrace{(c_w\mathcal{R} + c_i\mathcal{I})(\hat{T}_s - T)}_{\substack{\text{Heat lost in warming accreted}\\ \text{condensate from } T \text{ to } T_s}}$$

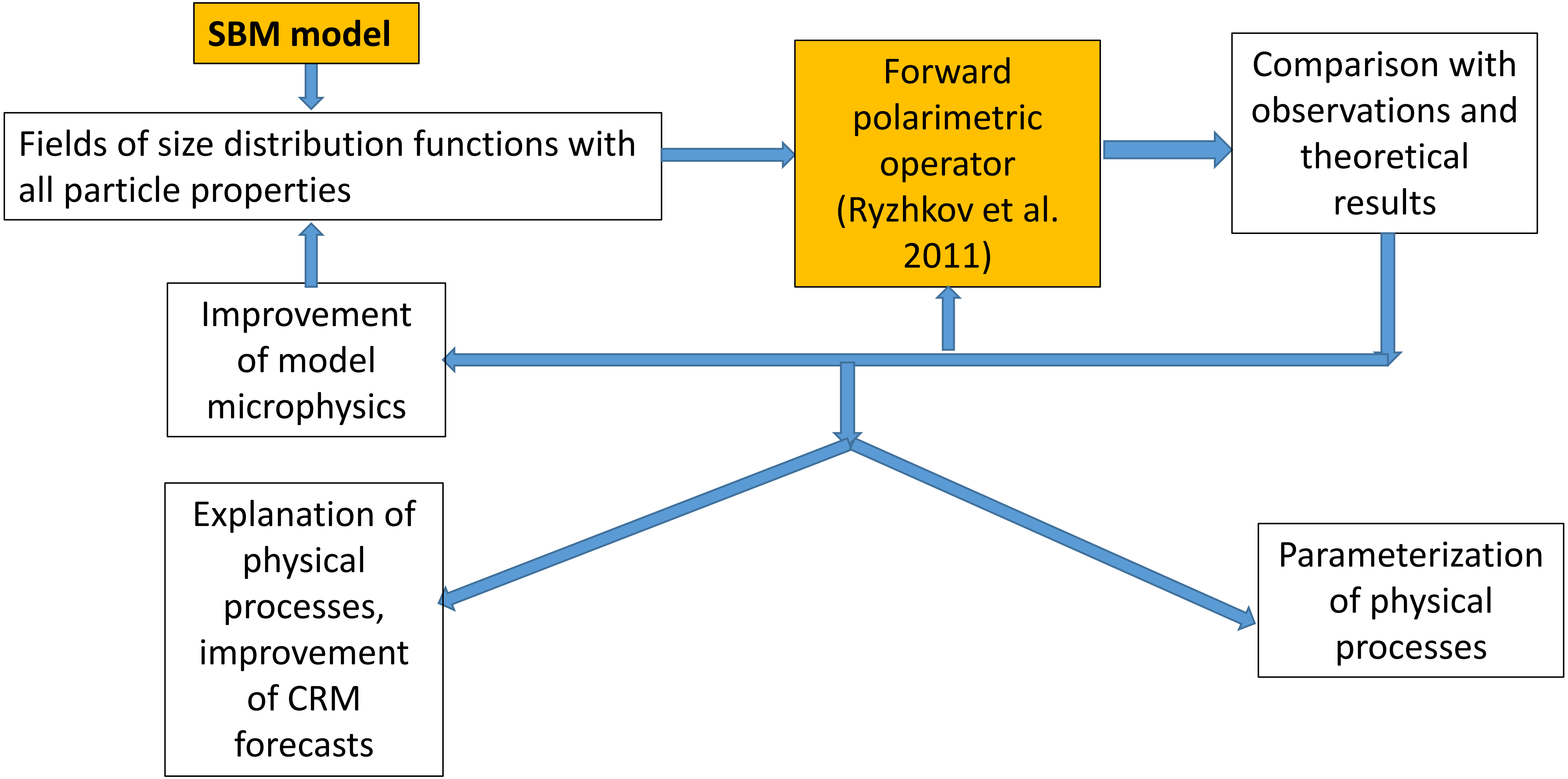
$$= \underbrace{\frac{4\pi r_p r_w K_i(T_{L/i} - \hat{T}_s)}{\delta r_I}}_{\text{Heat flow through shell of ice}} + \underbrace{\mathcal{R}L_m}_{\substack{\text{Latent heat released}\\ \text{by freezing of accretion}}},$$

Phillips et al. 2014, 2015,
Ilotoviz et al., 2016

If the depth of the water film exceeds a critical value, shedding takes place



Coupling of bin microphysics model with dual polarimetric radar



SBM model

Fields of size distribution functions with all particle properties

Forward polarimetric operator (Ryzhkov et al. 2011)

Comparison with observations and theoretical results

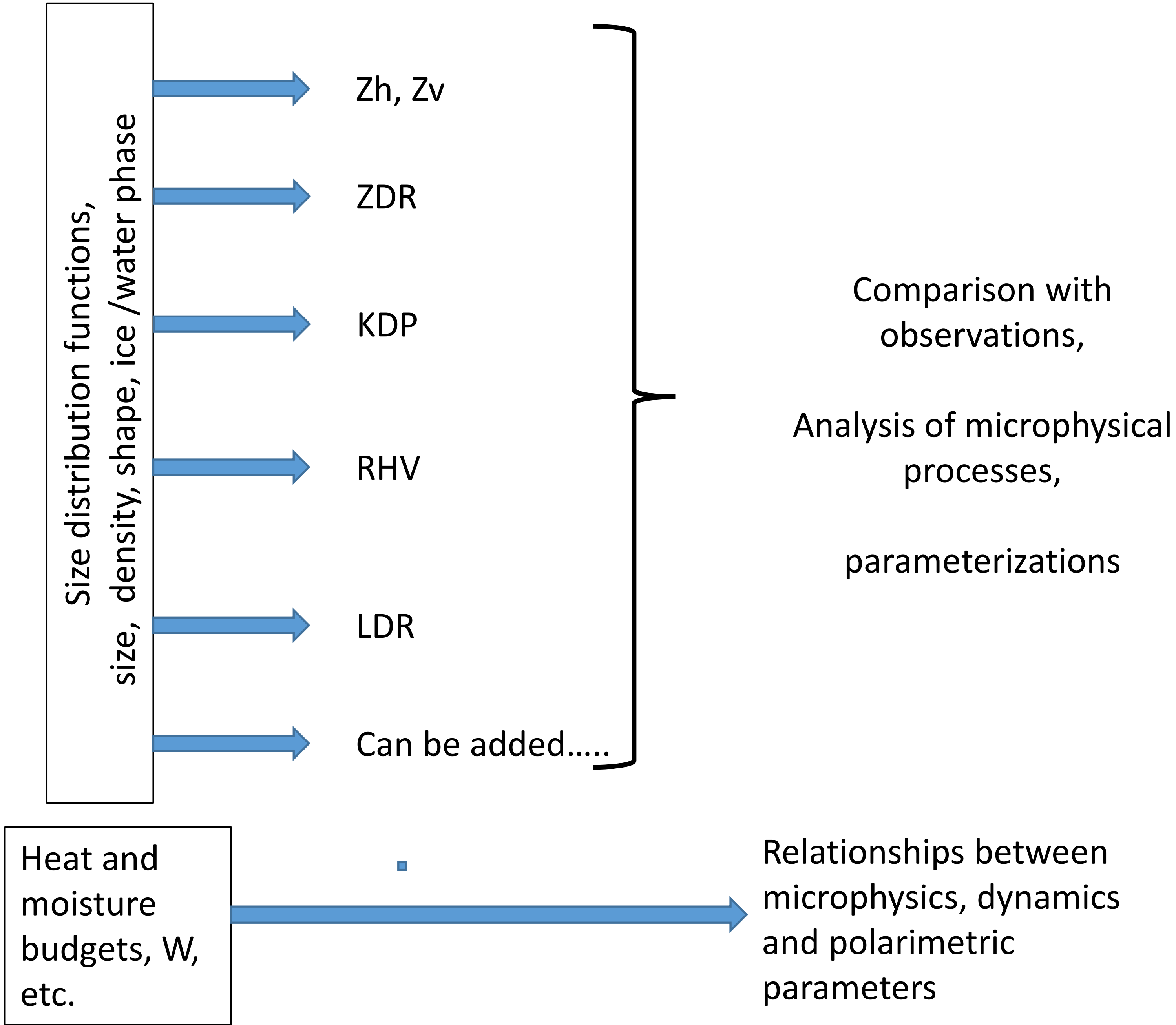
Improvement of model microphysics

Explanation of physical processes, improvement of CRM forecasts

Parameterization of physical processes

Forward polarimetric operator (Ryzhkov et al. 2011)

POLARIMETRIC OPERATOR (Ryzhkov et al. 2011)



Size distribution functions,
size, density, shape, ice /water phase

Zh, Zv

ZDR

KDP

RHV

LDR

Can be added…..

Comparison with observations,

Analysis of microphysical processes,

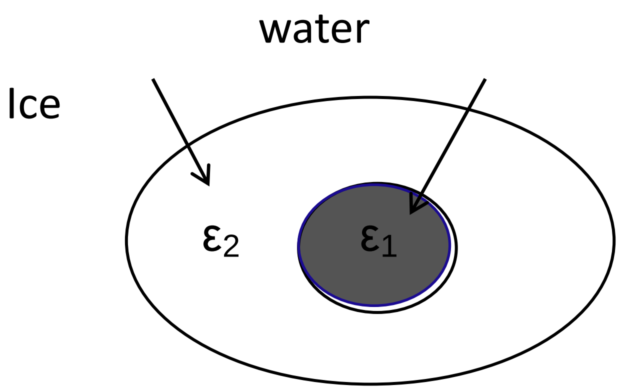
parameterizations

Heat and moisture budgets, W, etc.

Relationships between microphysics, dynamics and polarimetric parameters

Forward polarimetric operator (Ryzhkov et al. 2011)

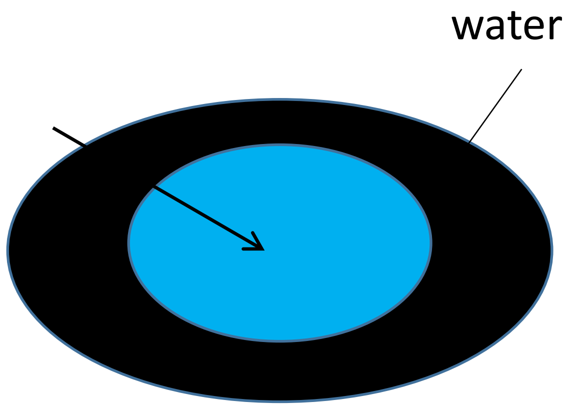
POLARIMETRIC OPERATOR (Ryzhkov et al. 2011)



Freezing drops

Fig. 2. Geometry of two-layer spheroid

melting snow



melting graupel and hail,
wet growth of hail

Computation of dielectric constant ε

Dry snow, graupel and hail:

$$\varepsilon_s = \varepsilon_a \left(\frac{1 + 2 f_{vi} \dfrac{\varepsilon_i - \varepsilon_a}{\varepsilon_i + 2\varepsilon_a}}{1 - f_{vi} \dfrac{\varepsilon_i - \varepsilon_a}{\varepsilon_i + 2\varepsilon_a}} \right)$$

$$\varepsilon_{ws}^{(1)} = \varepsilon_s \left(\frac{1 + 2 f_{vw} \dfrac{\varepsilon_w - \varepsilon_s}{\varepsilon_w + 2\varepsilon_s}}{1 - f_{vw} \dfrac{\varepsilon_w - \varepsilon_s}{\varepsilon_w + 2\varepsilon_s}} \right)$$

f_{vi} Is the volume fraction of ice

f_{vw} Is the volume fraction of water

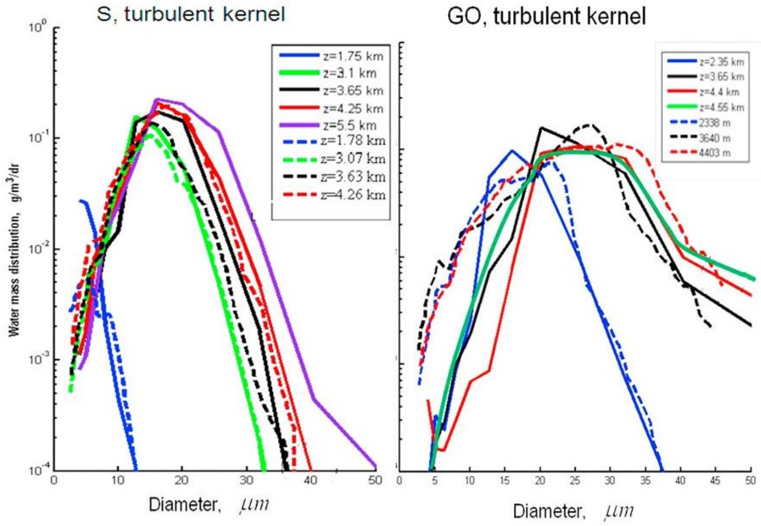
Fields of size distribution functions with all particle properties

Capabilities of SBM

The main criteria of the quality of SBM: capability to simulate size distributions of cloud

Convective clouds in Brazil

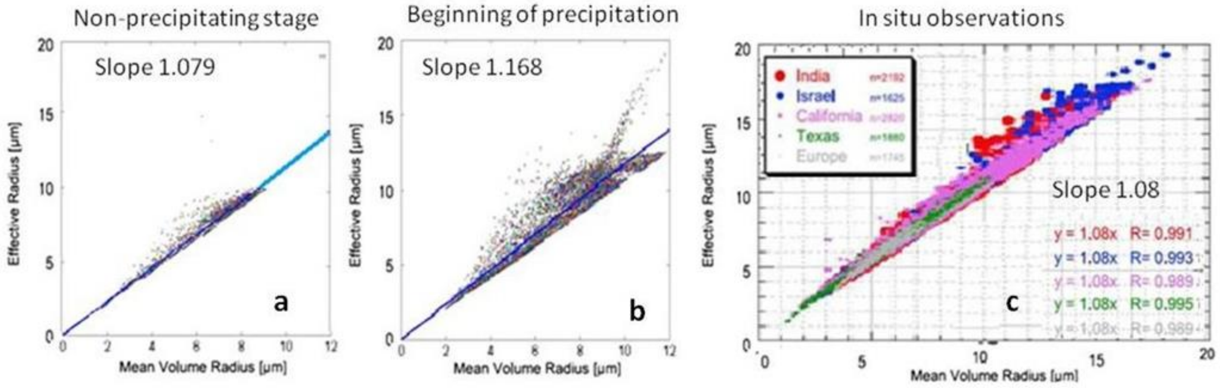
(Benmoshe et al, 2012)



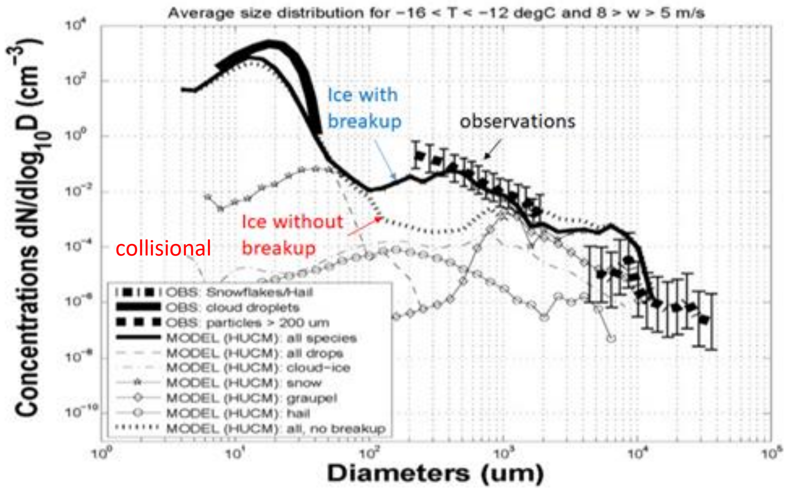
Relationship between mean volume and effective drop radii

(Khain et al. 2013)

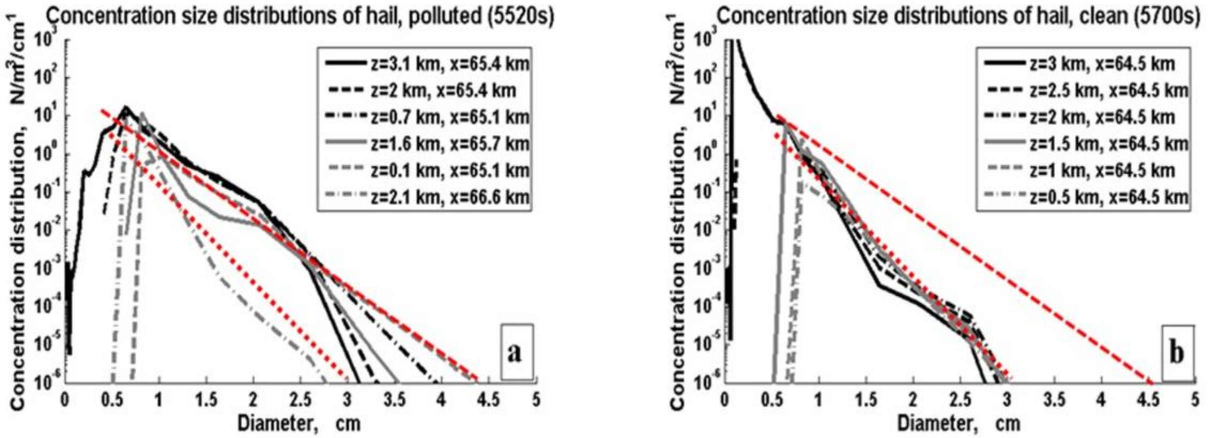
Rosenfeld, Freud, 2012



Deep convection in STEPS,2000 (Phillips et al, 2017)



Hail storm in Oklahoma (Ilotoviz et al., 2016, 2018)



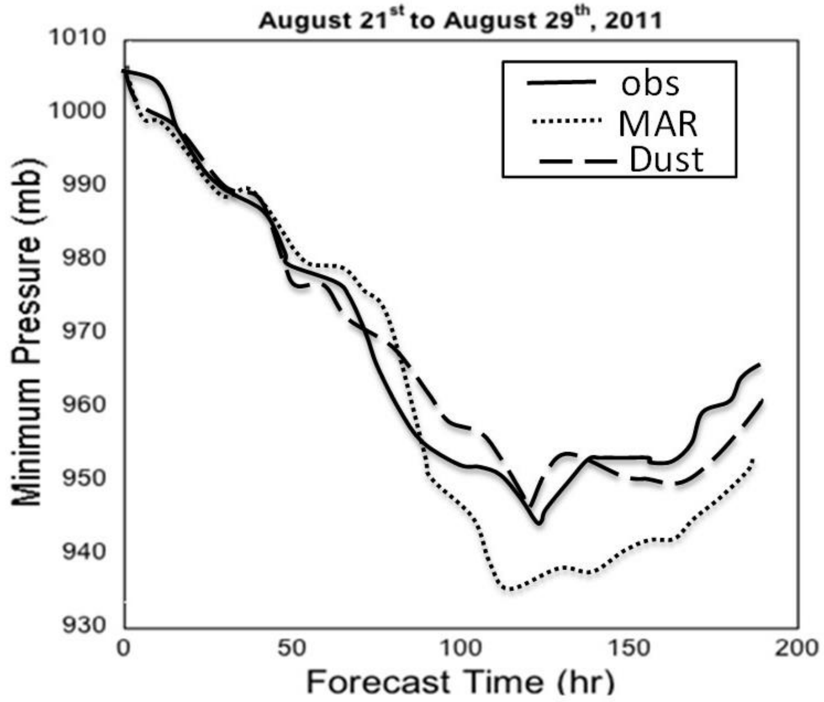
Fields of size distribution functions with all particle properties

Comparison with bulk-microphysics: examples

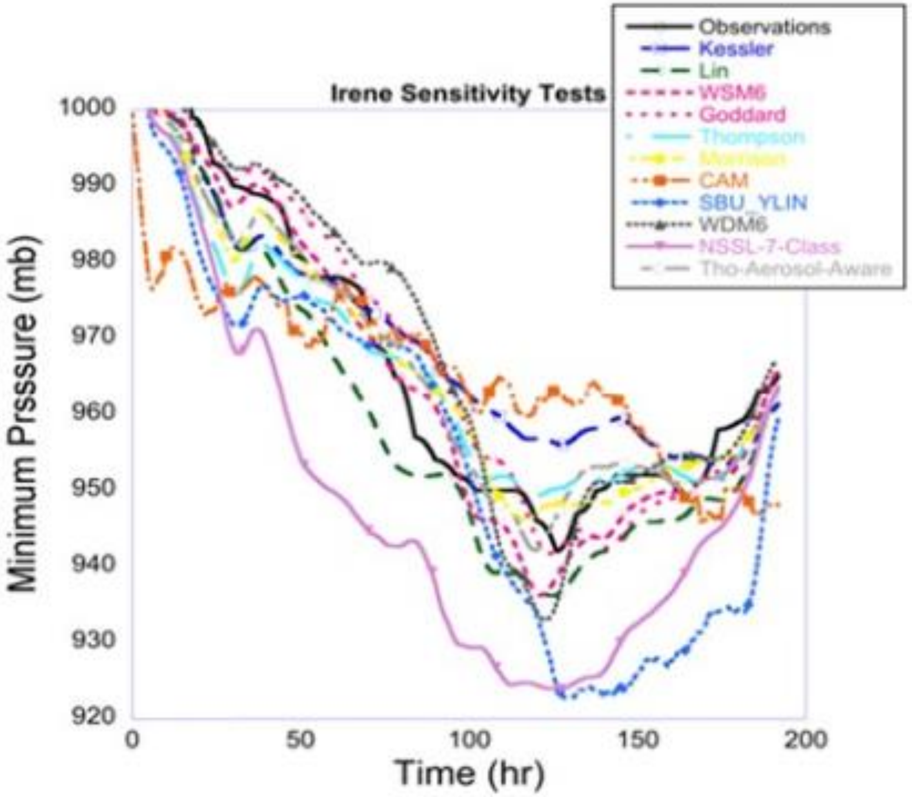
Example 1: Simulation of hurricane Irene, 2011

Khain et al. (2016)

SBM

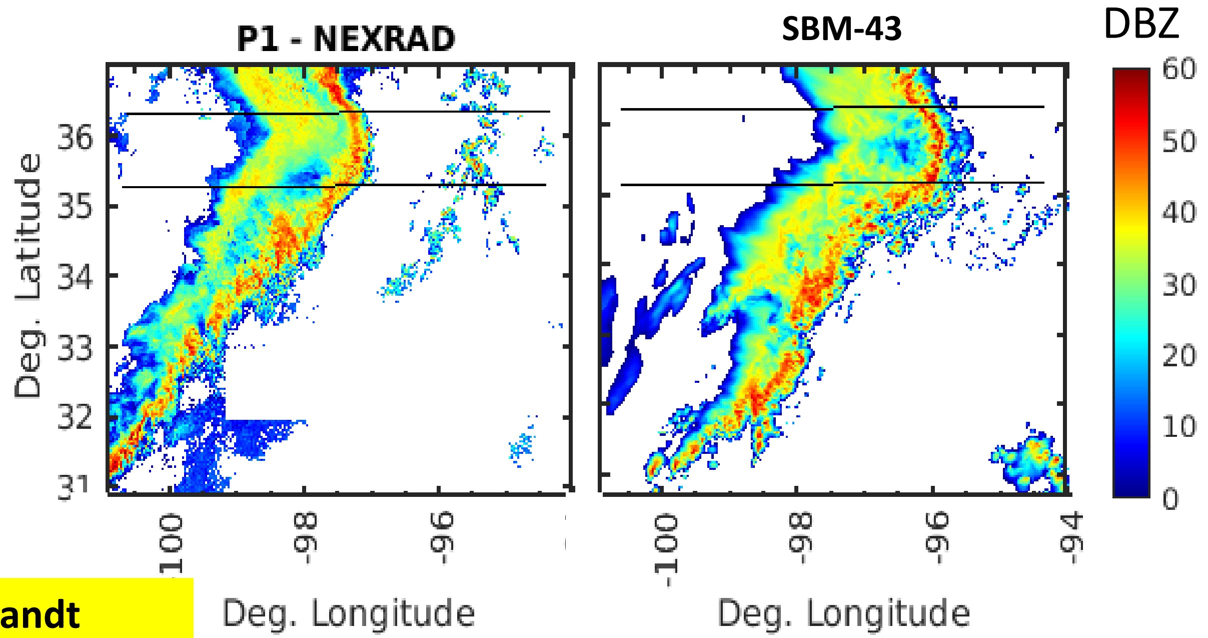


Different bulk-parameterization schemes

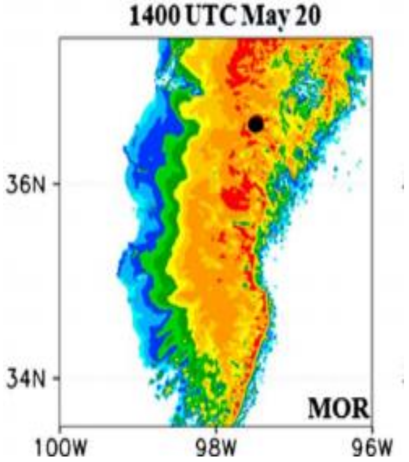


Fields of size distribution functions and cloud parameters

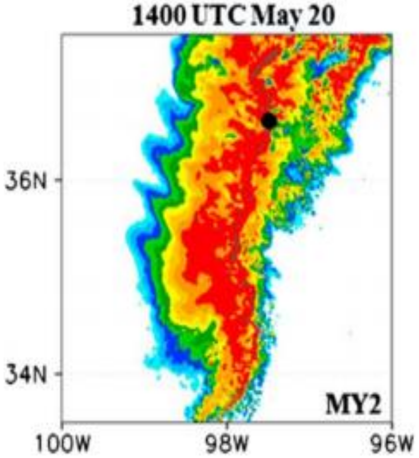
Example 2: The 20 May and 23–24 May MCS event (Shpund et al. 2018)



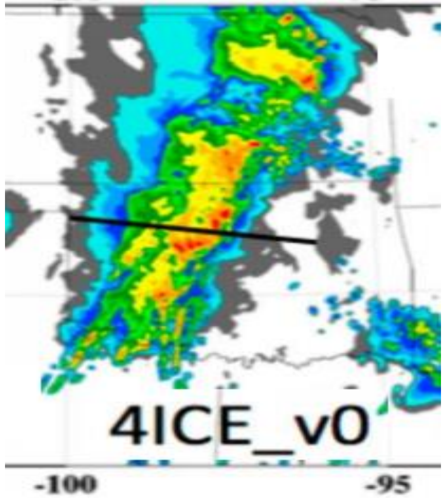
Morrison



Milbrandt and Yau, 2006

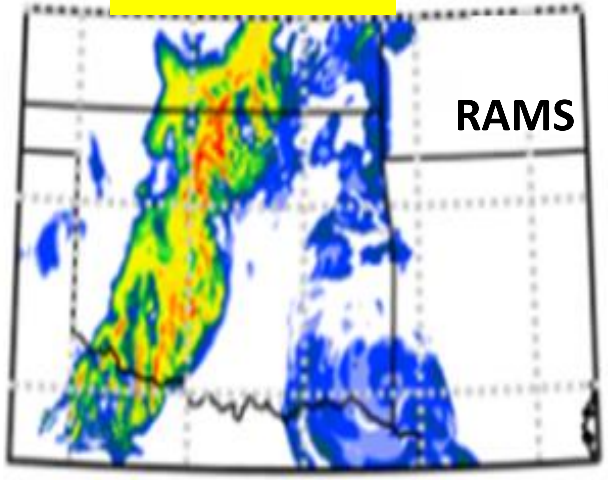


Tao et al. 2016

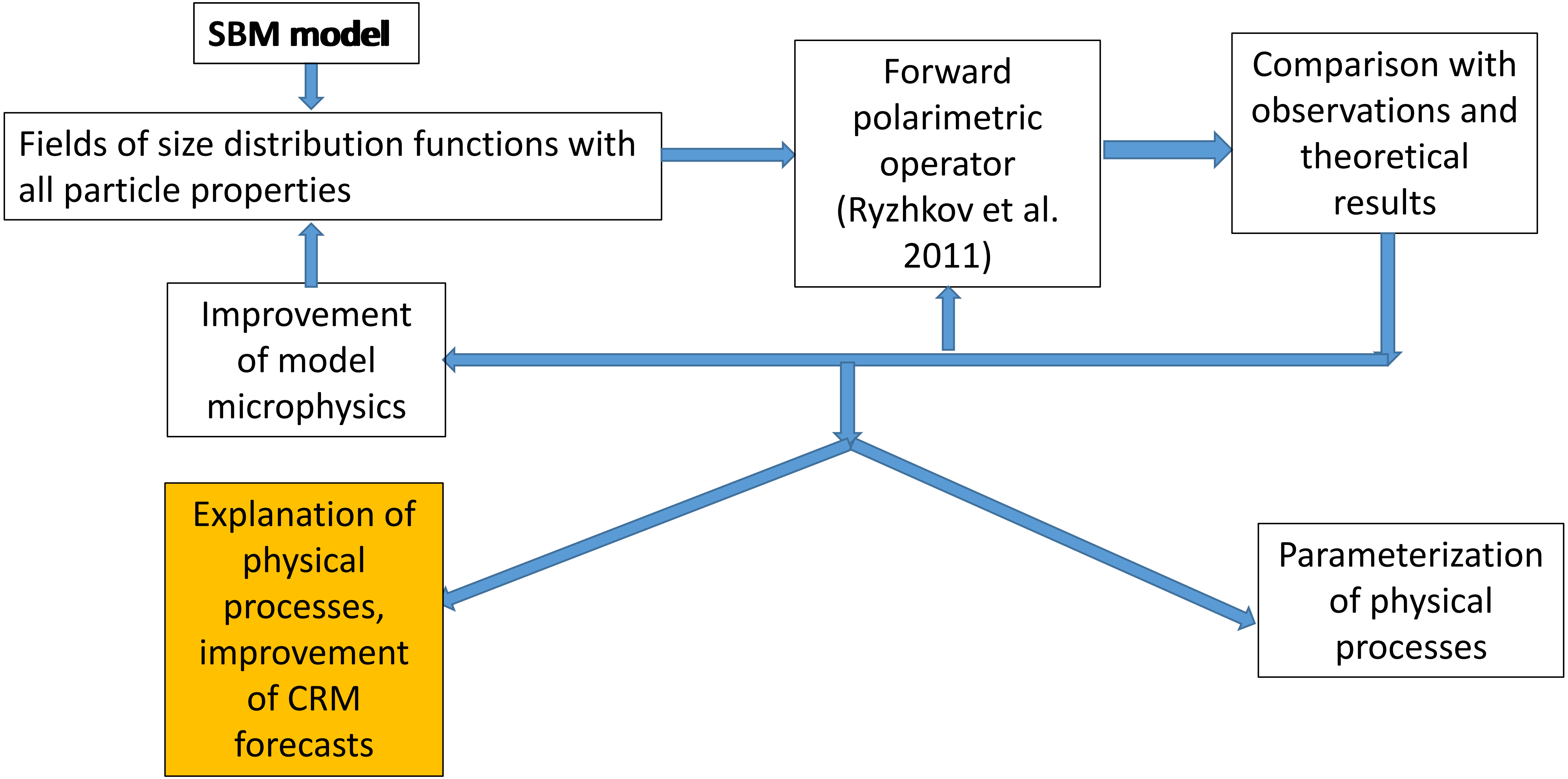


Tao et al. 2016

Marinescu et al. 2016



Coupling of bin microphysics model with dual polarimetric radar



SBM model

Fields of size distribution functions with all particle properties

Forward polarimetric operator (Ryzhkov et al. 2011)

Comparison with observations and theoretical results

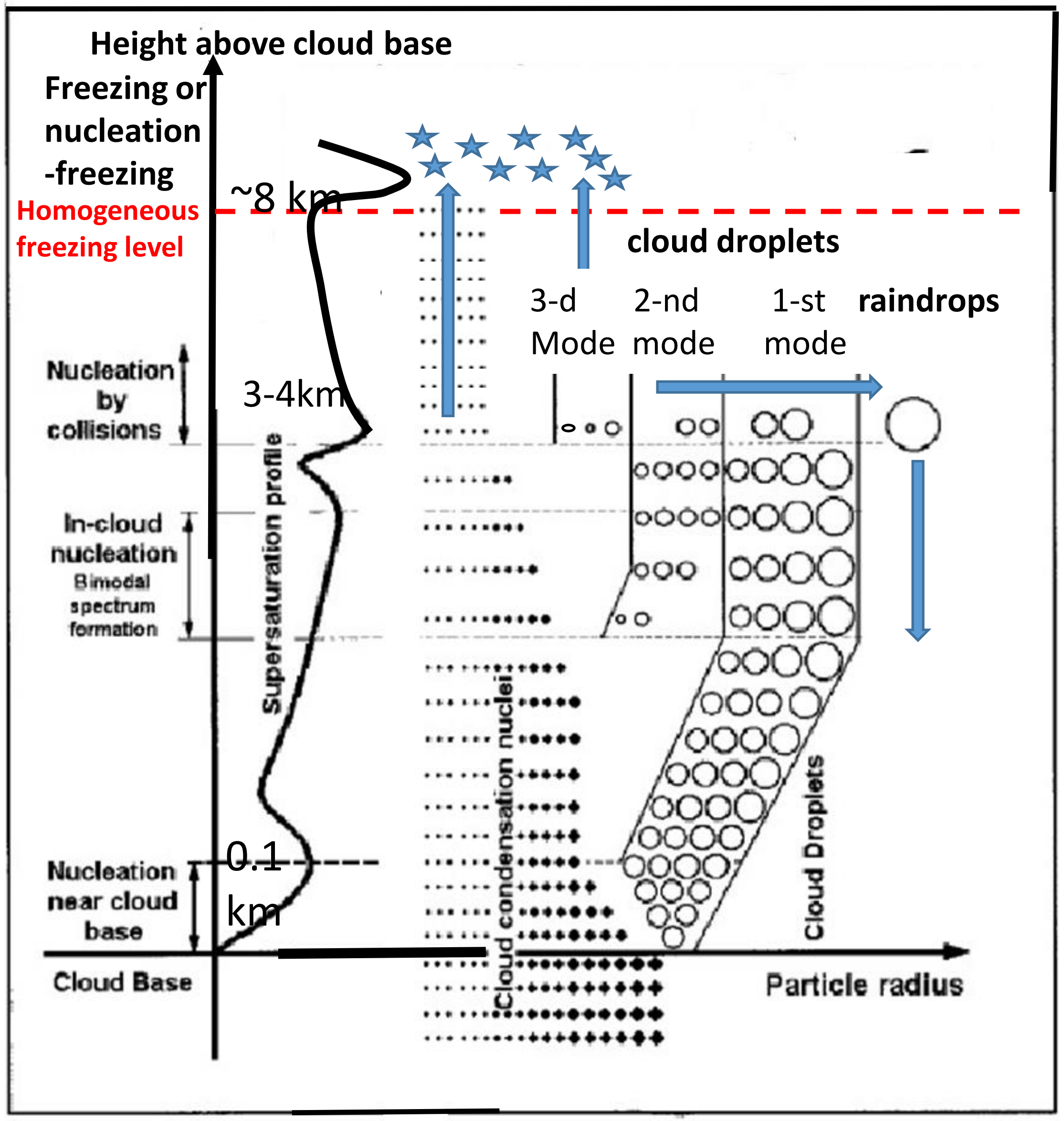
Improvement of model microphysics

Explanation of physical processes, improvement of CRM forecasts

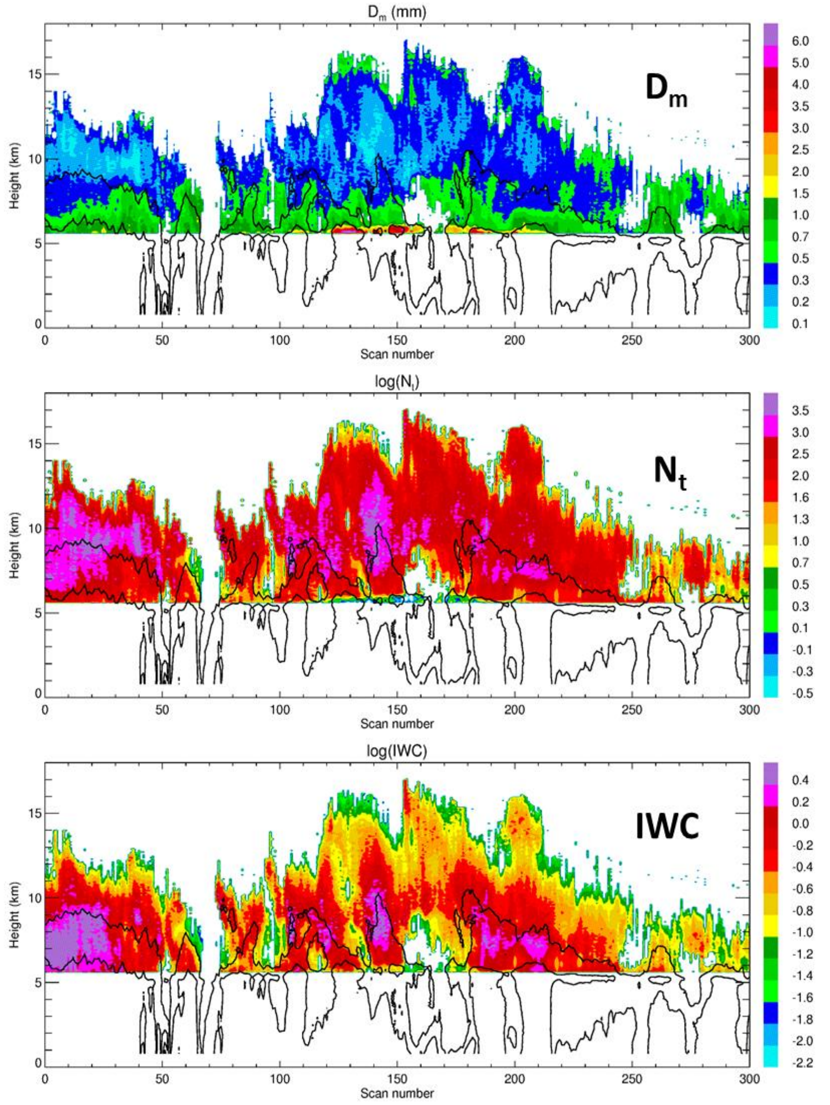
Parameterization of physical processes

Explanation of physical processes, improvement of CRM forecasts

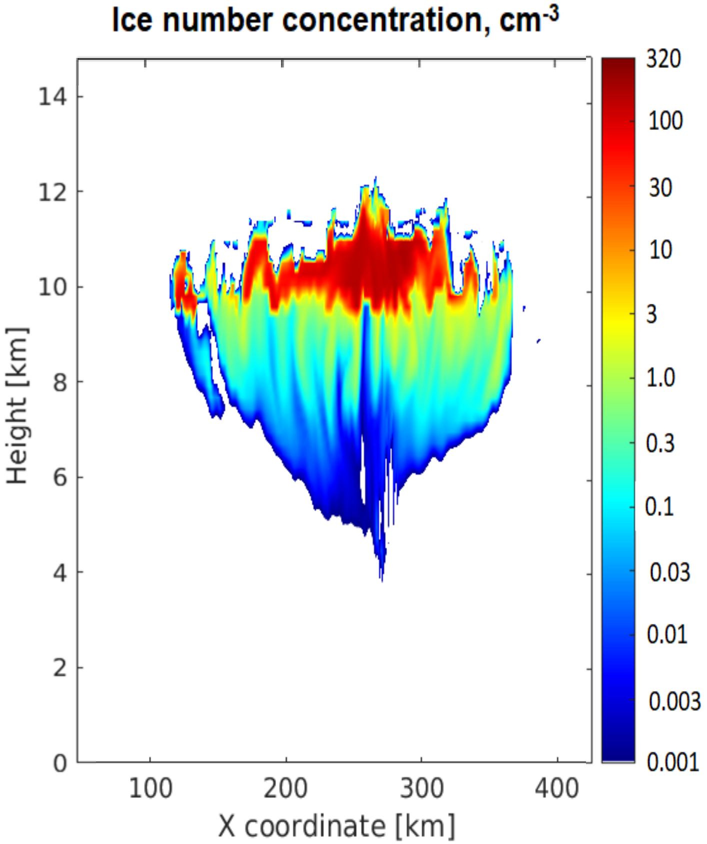
Example 1: Formation of extremely high ice crystal concentration above the level of homogeneous freezing

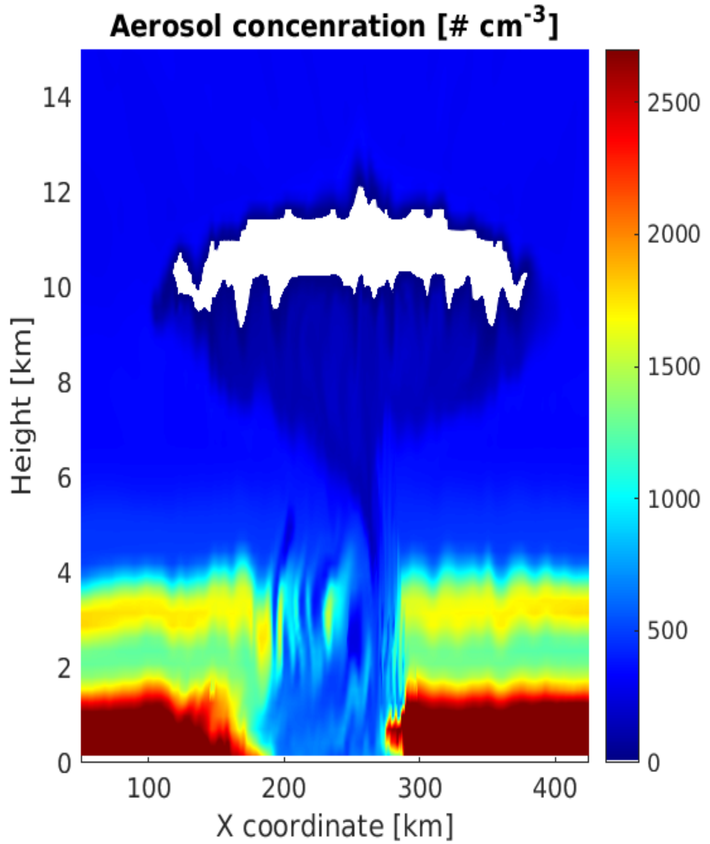


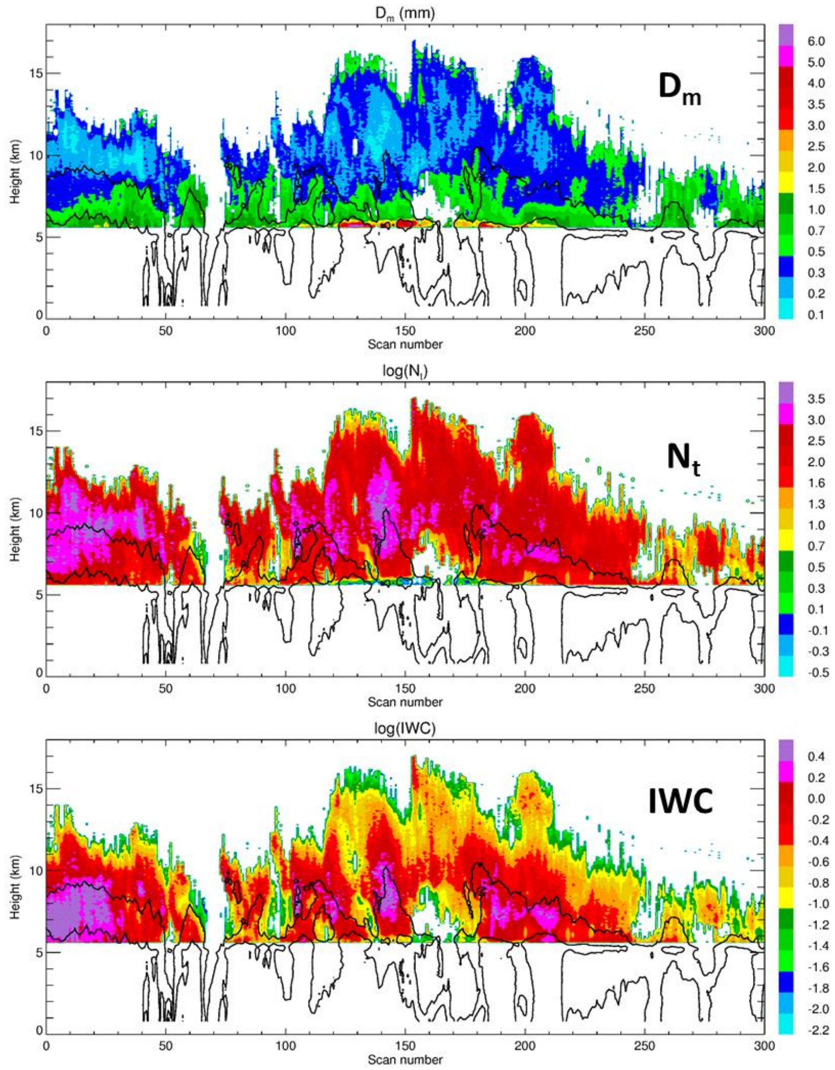
Ryzhkov, 2017



Explanation of physical processes, improvement of CRM forecasts







Deep convective cloud. CCN distribution contains ultra small (0.005 um) particles

Explanation of physical processes, improvement of CRM forecasts

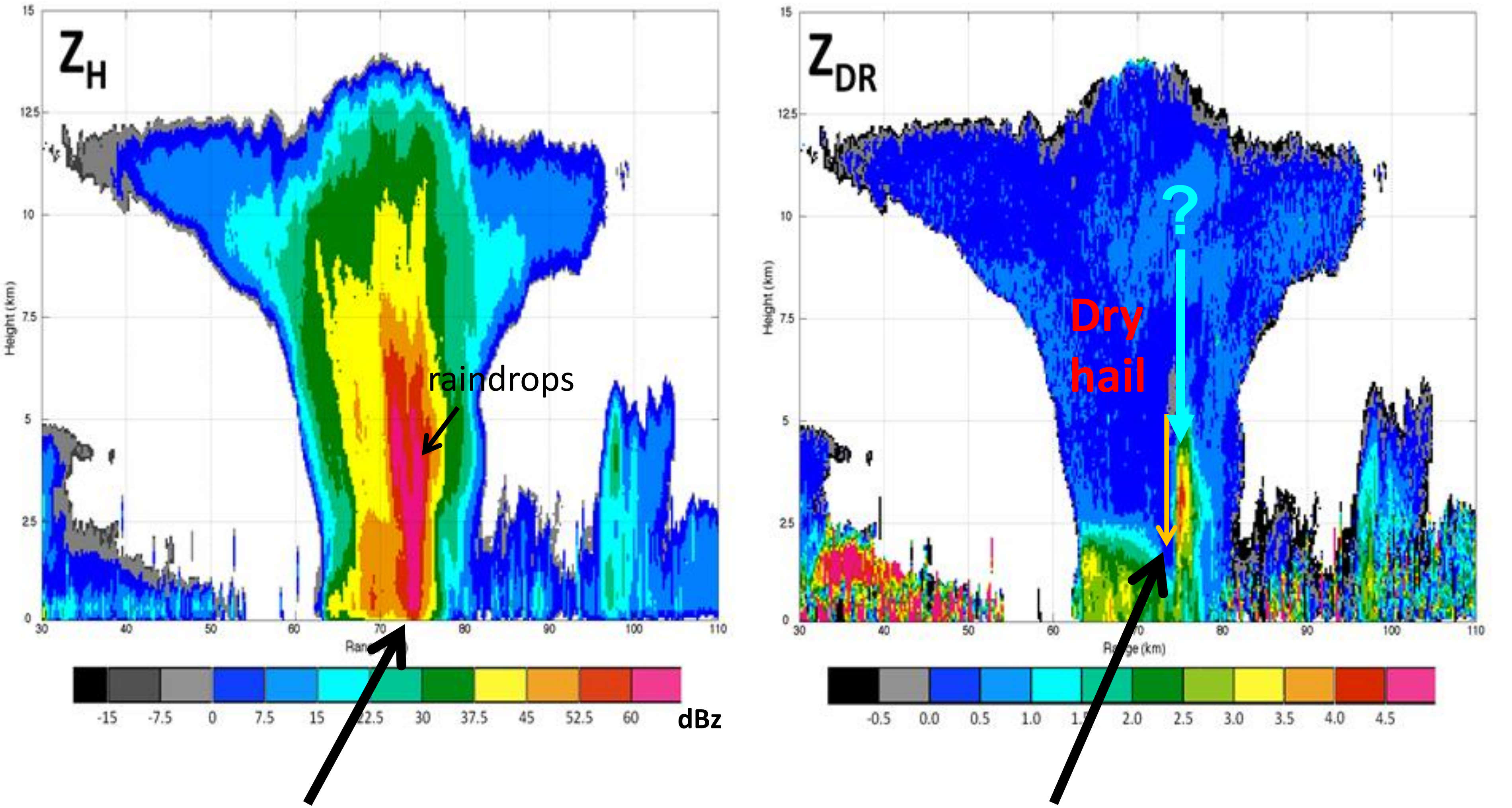
Example 2: Mechanisms of hail formation: how we see it using microphysical model and polarimetric radar (The Hebrew University Cloud model, HUCM)

(Ilotoviz, Khain, Ryzhkov, 2016, 2018)

Radar reflectivity and Zdr column in a thunderstorm in Oklahoma (1.6.2008)

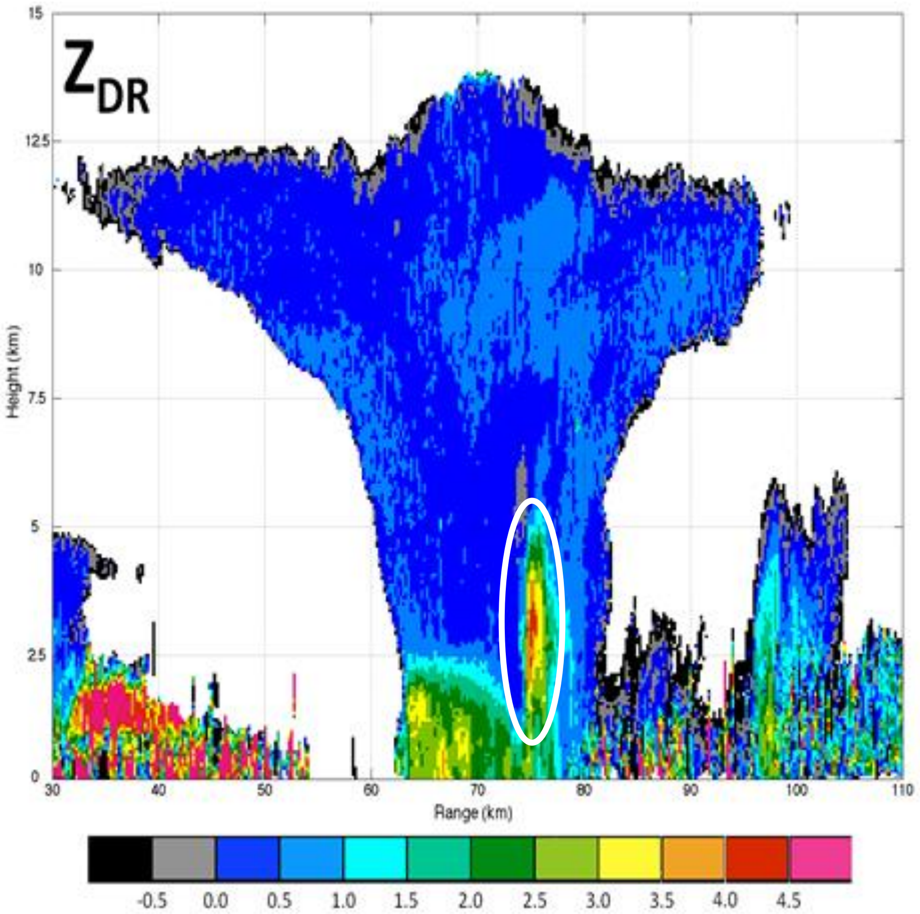
Reflectivity

Differential reflectivity

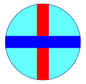
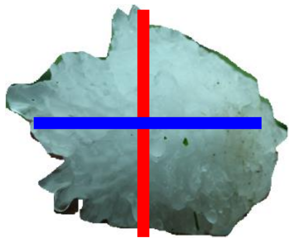
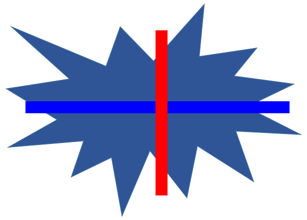
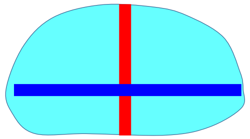


High reflectivity: rain or hail?

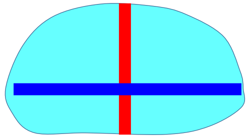
$Z_{DR} \approx 0$ dB **reflectivity is high, but hail is dry!**



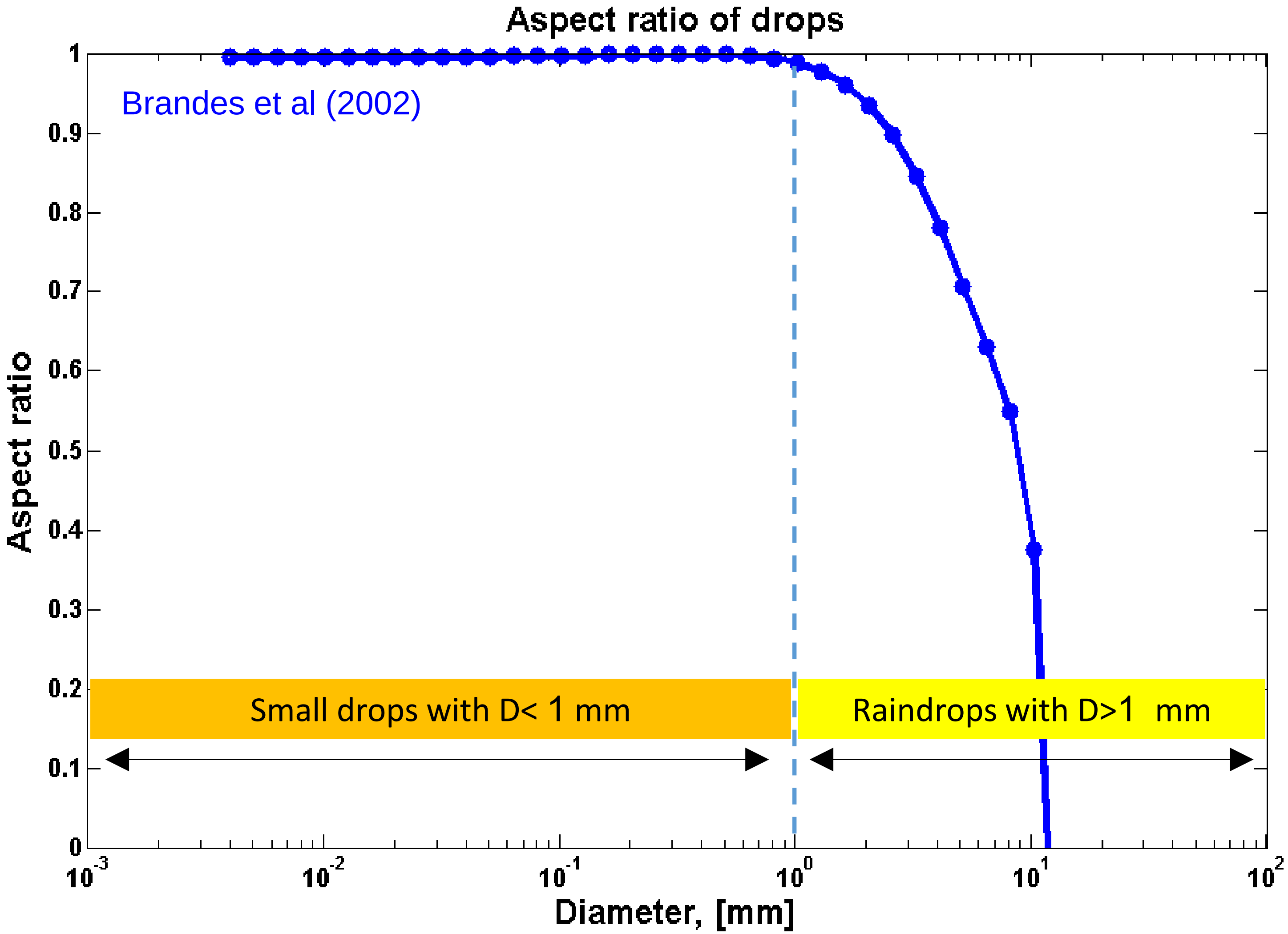
The column with high Z_{DR} *is called* Z_{DR} Column

Reflectivity	Differential reflectivity		
Z_H low	$Z_{DR} = 0$ dB		**Cloud droplets**
Z_H high	$Z_{DR} \approx 0$ dB • Close to spherical • Rotate during their fall		**Graupel and dry hail**
Z_H low	$Z_{DR} > 0$ dB		**Snow**
Z_H high	$Z_{DR} > 0$ dB		**Raindrops**

$$High\ \ Zdr + \ high\ reflectivity\ mean\ that\ particles\ are\ large\ and\ non-spherical.$$



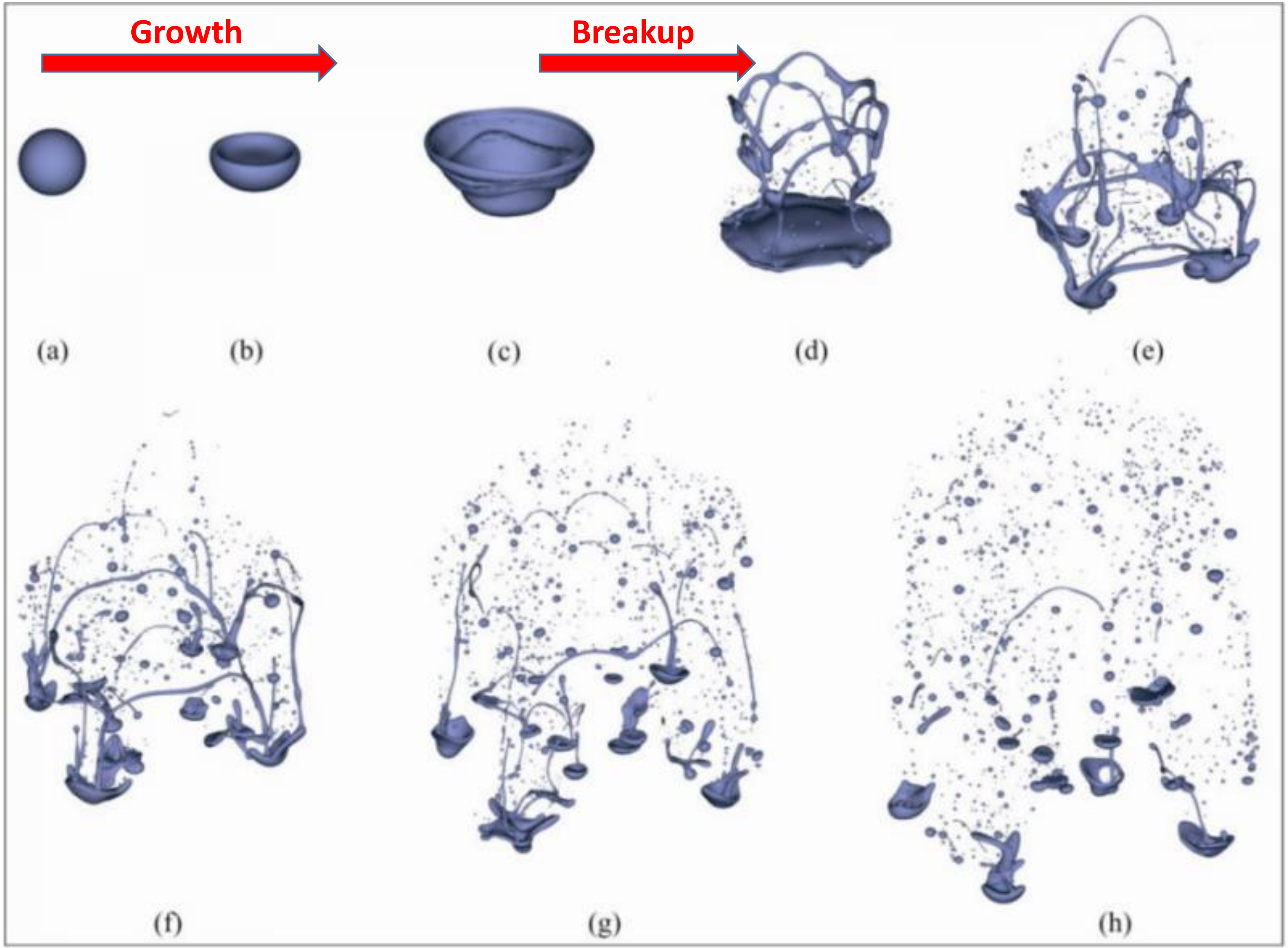
Might be raindrops?



Small drops with D< 1 mm

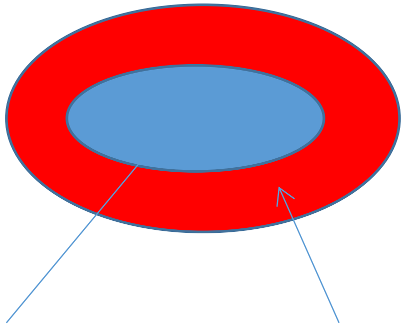
Raindrops with D>1 mm

Spontaneous breakup of raindrops with D>6mm



Non-spherical particles.
2) Freezing drops
3) Hail in wet growth, melting hail

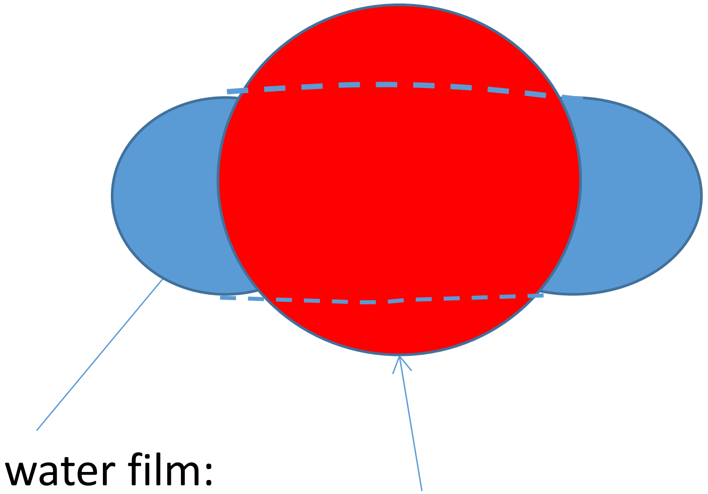
Freezing drops



water

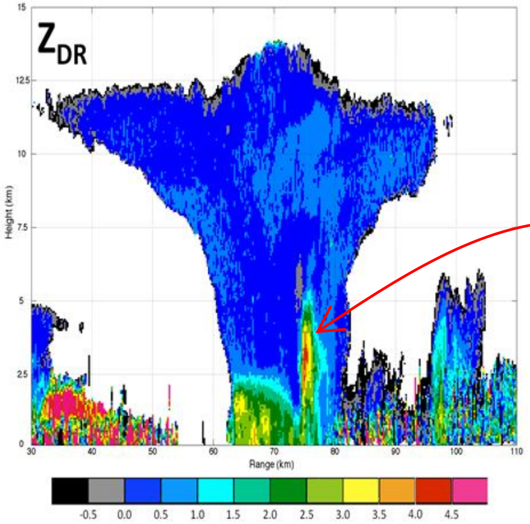
ice shell

Hail in wet growth
and melting hail



Liquid water film:
Water torus

ice



Hail growing in wet growth regime provides high Z_{DR}

3. Mechanism of formation of big hail

Simulations:

Hail storm in Oklahoma on 1 June 2008

In both cases observations CCN concentration was around 3000-4000 cm-3

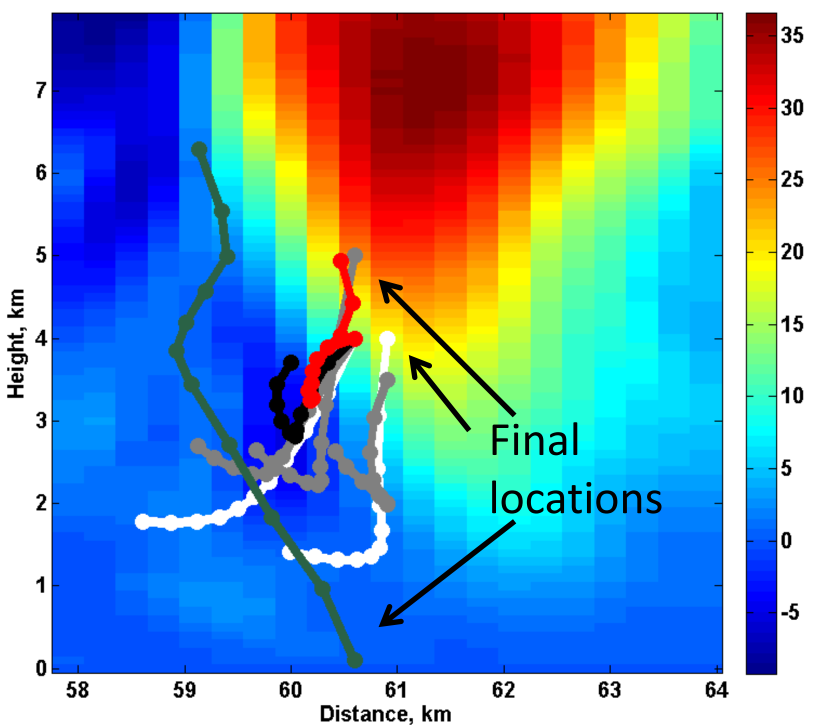
- CCN concentrations were ranged from 100 cm^{-3} to 5000 cm^{-3}

Radar parameters: wavelength=5.6 cm, C-band

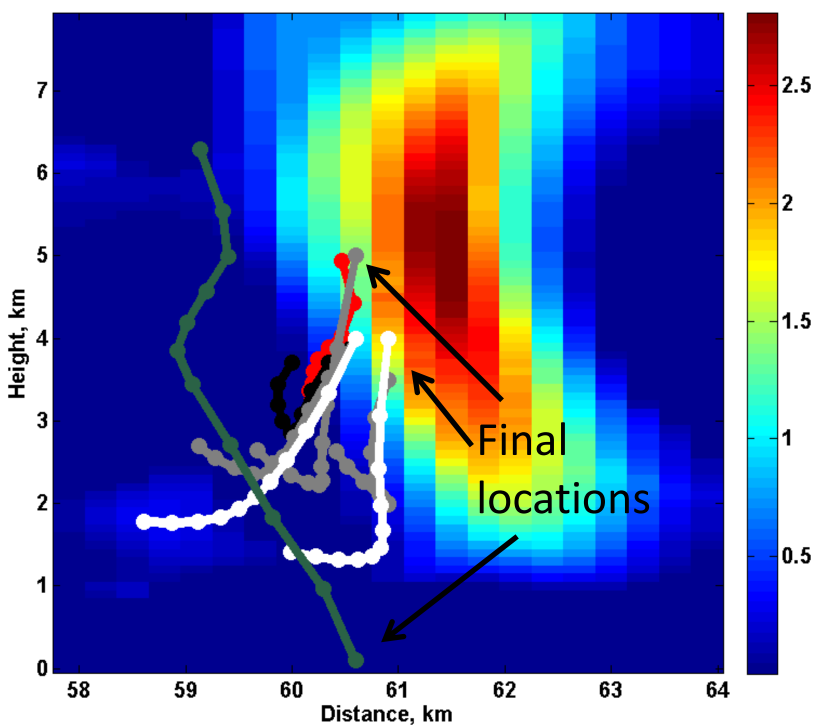
Questions:

1) Why do Zdr columns arise in cloud updrafts?
2) Why do large raindrops appear in cloud updrafts?
3) How are Zdr columns related to hail

4) How hail and Zdr columns are related to aerosols?



Vertical wind speed [ms^{-1}] (4620 sec)



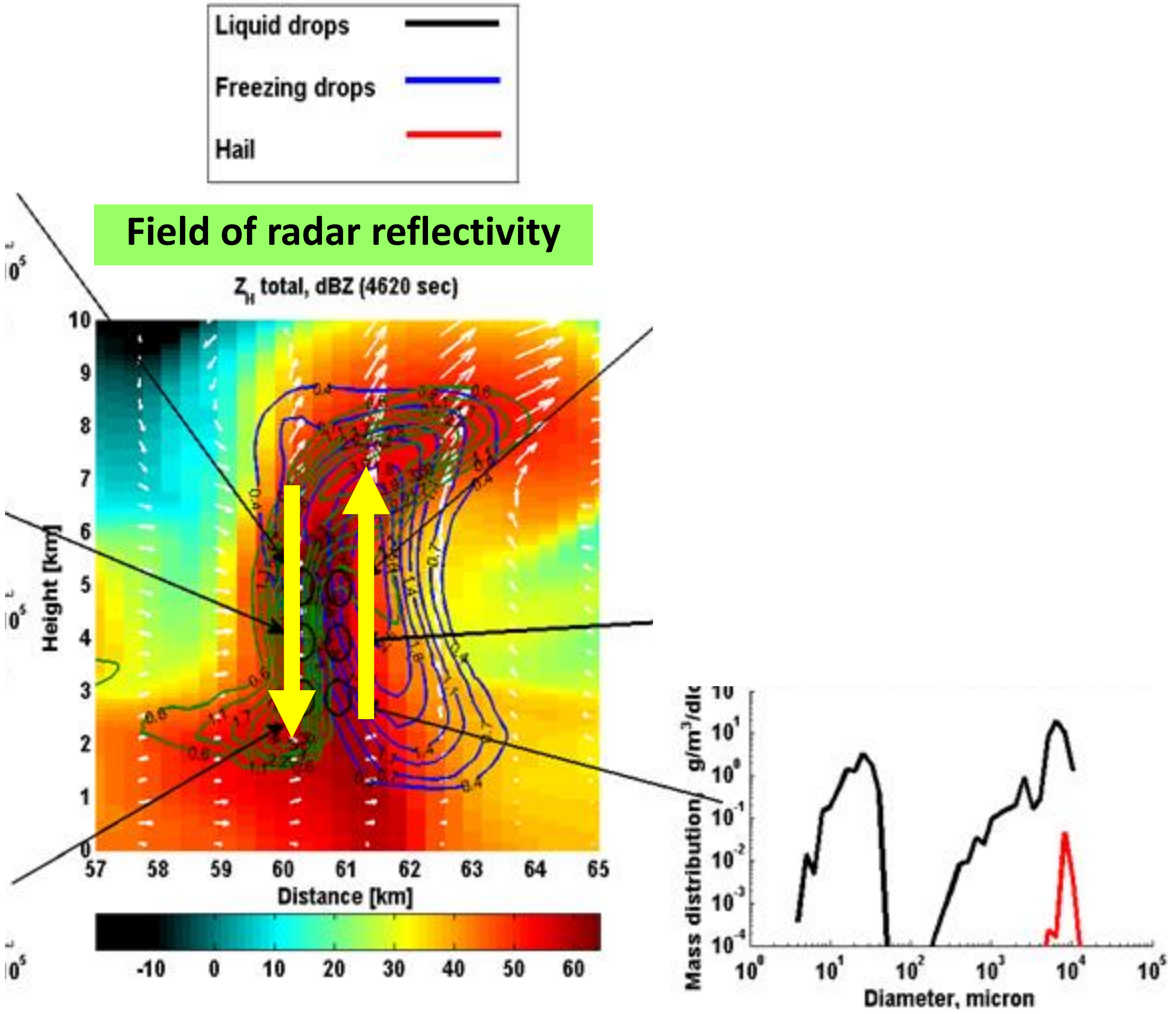
Cloud water content [g/m^3] (4620 sec)

$V_t = 3ms^{-1}$ ⬜ $V_t = 6ms^{-1}$ ▨ $V_t = 9ms^{-1}$ ⬛

$V_t = 12ms^{-1}$ 🟥 $V_t = 15ms^{-1}$ 🟩

Large raindrops penetrate cloud updraft and grow there.

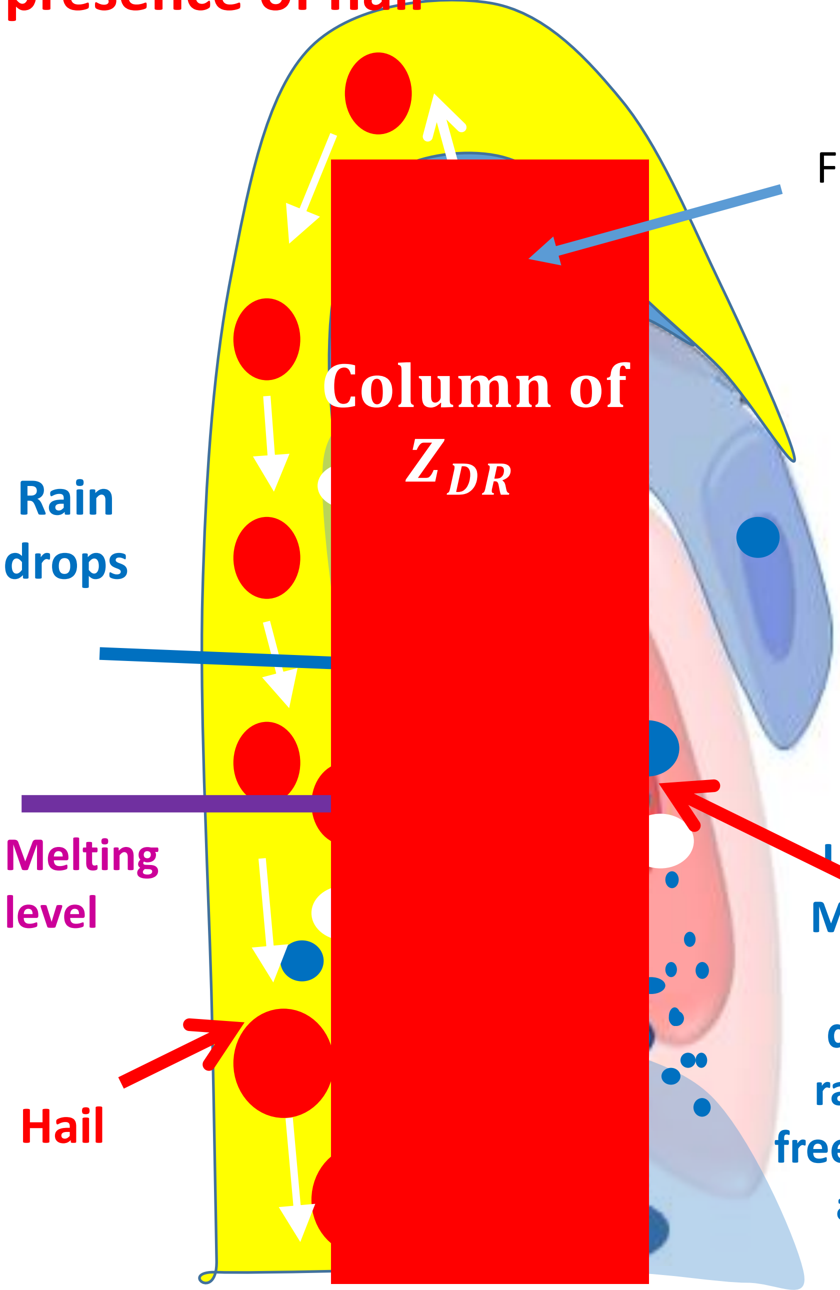
Growth of raindrops, freezing and hail formation



1

Blue-CWC, green-hail

Formation of big hailstones and Zdr column at the mature stage in the presence of hail



Freezing drops

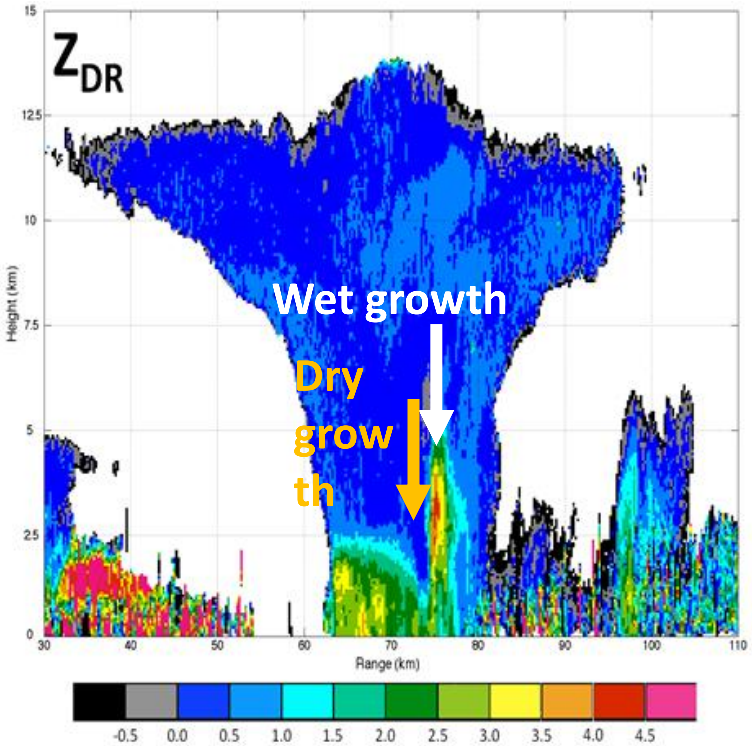
Column of Z_{DR}

Rain drops

Melting level

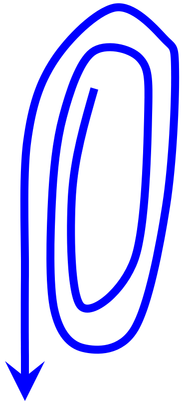
Hail

Updrafts: Mixture of cloud droplets, raindrops, freezing drops and hail

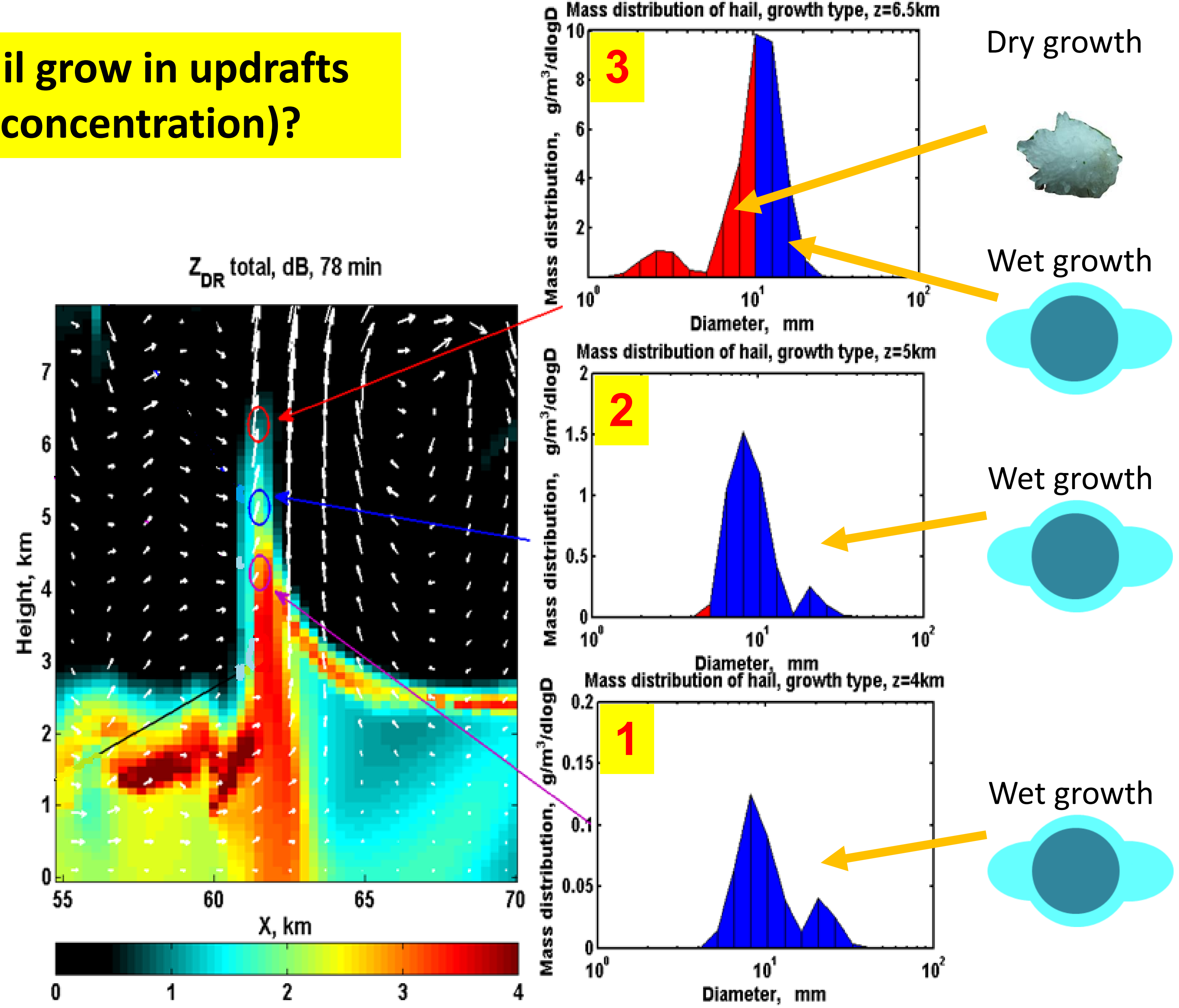


Several layers show alternation of wet and dry growth

This hailstone made two oscillations



How does hail grow in updrafts (high CCN concentration)?



Dry growth

Wet growth

Wet growth

Wet growth

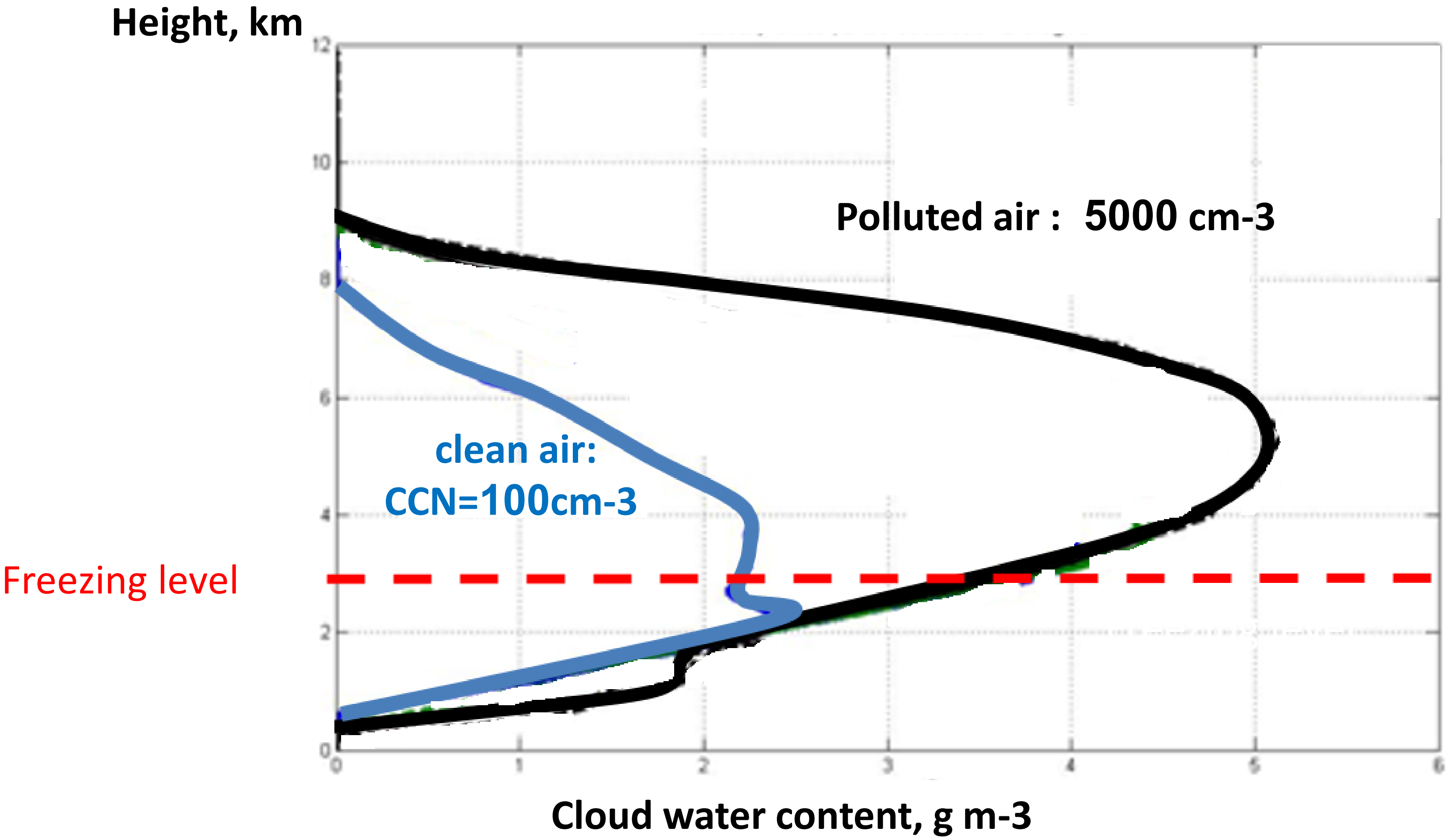
Simulations of hail storm in polluted and clean environment

Questions:

1) **Why do Zdr columns arise in cloud updrafts?** √
2) **Why do large raindrops appear in cloud updrafts?** √
3) **How are Zdr columns related to hail** √

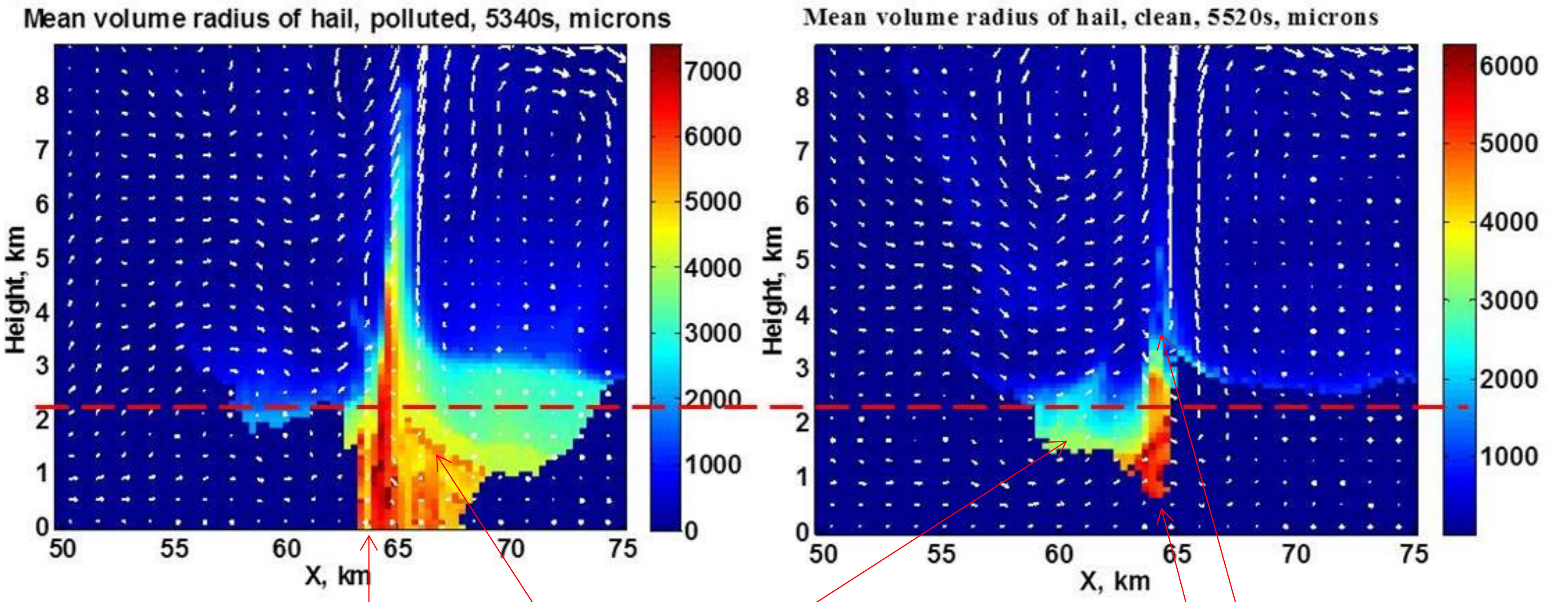
4) How hail and Zdr columns are related to aerosols?

Vertical profiles of CWC in polluted and Clean cases



In polluted case supercooled CWC is much higher than in the clean case

Effects of aerosols on hail size



CCN=3000 cm-3

CCN=100 cm-3

No growth by recirculation, within updrafts because of low CWC

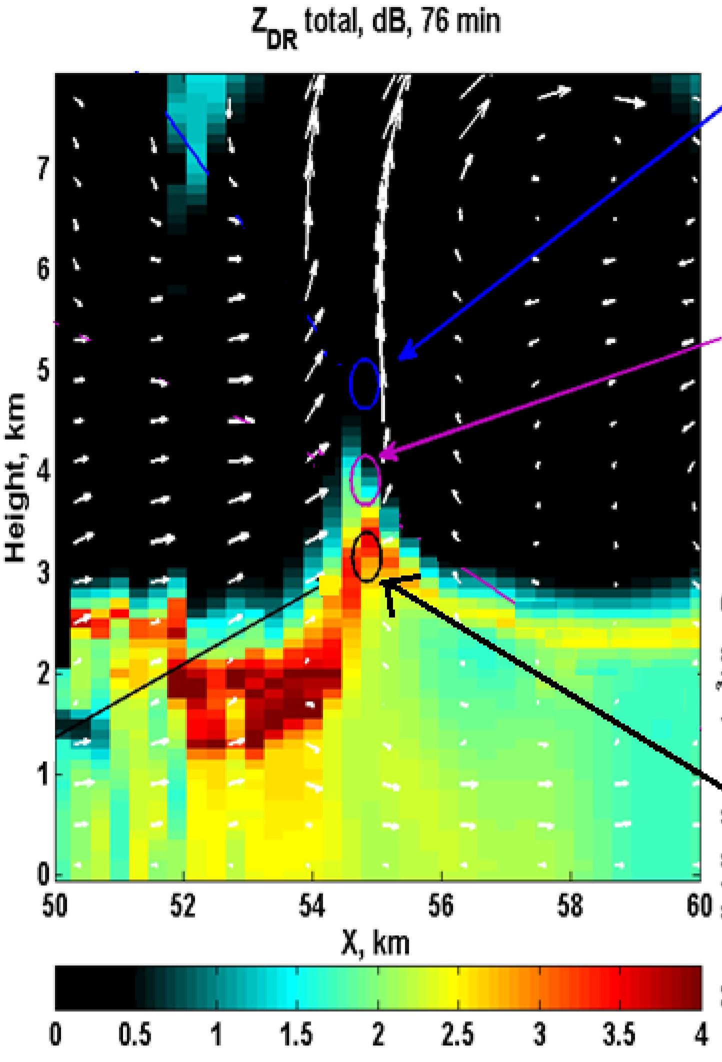
Melting of smaller hail

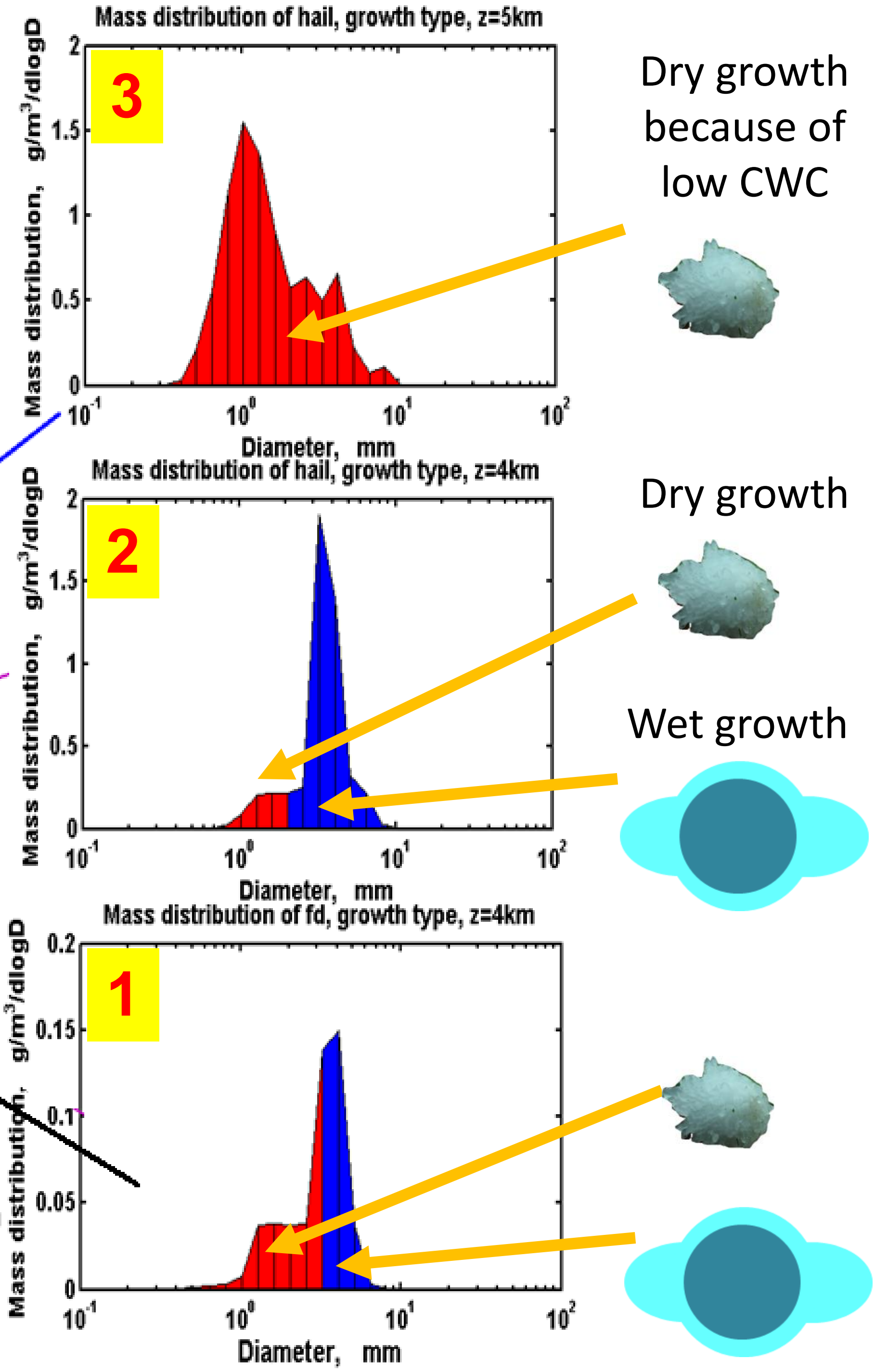
Large hailstones

Increase in mean volume radius is because of melting the smallest hail particles

The SIZE OF HAIL is LARGER at HIGH CCN CONCENTRATION

In clean air wet growth is below 4 km. Above: dry growth



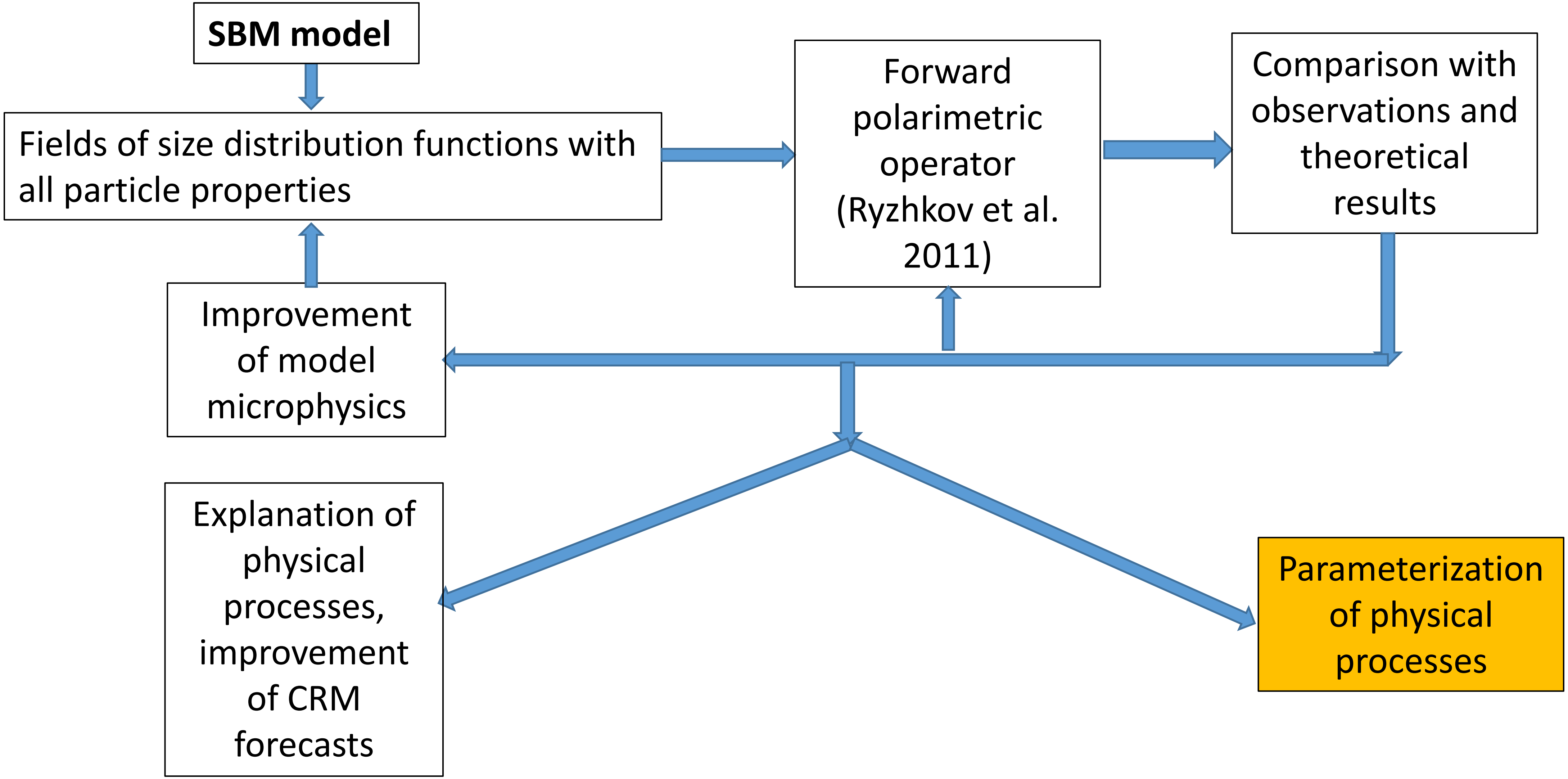


Dry growth because of low CWC

Dry growth

Wet growth

Coupling of bin microphysics model with dual polarimetric radar



SBM model

Fields of size distribution functions with all particle properties

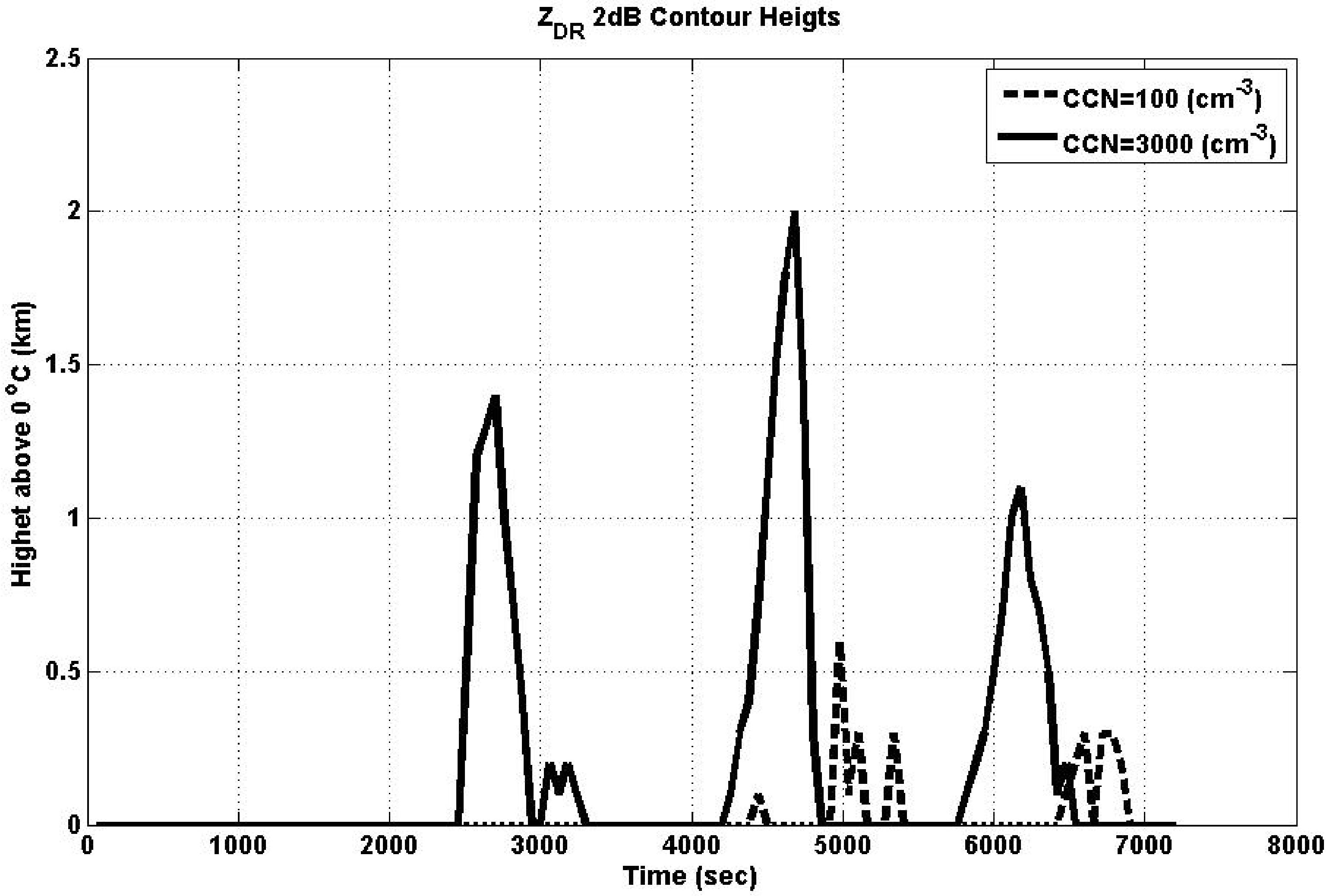
Forward polarimetric operator (Ryzhkov et al. 2011)

Comparison with observations and theoretical results

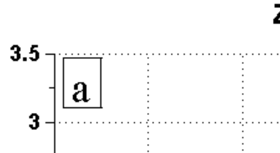
Improvement of model microphysics

Explanation of physical processes, improvement of CRM forecasts

Parameterization of physical processes

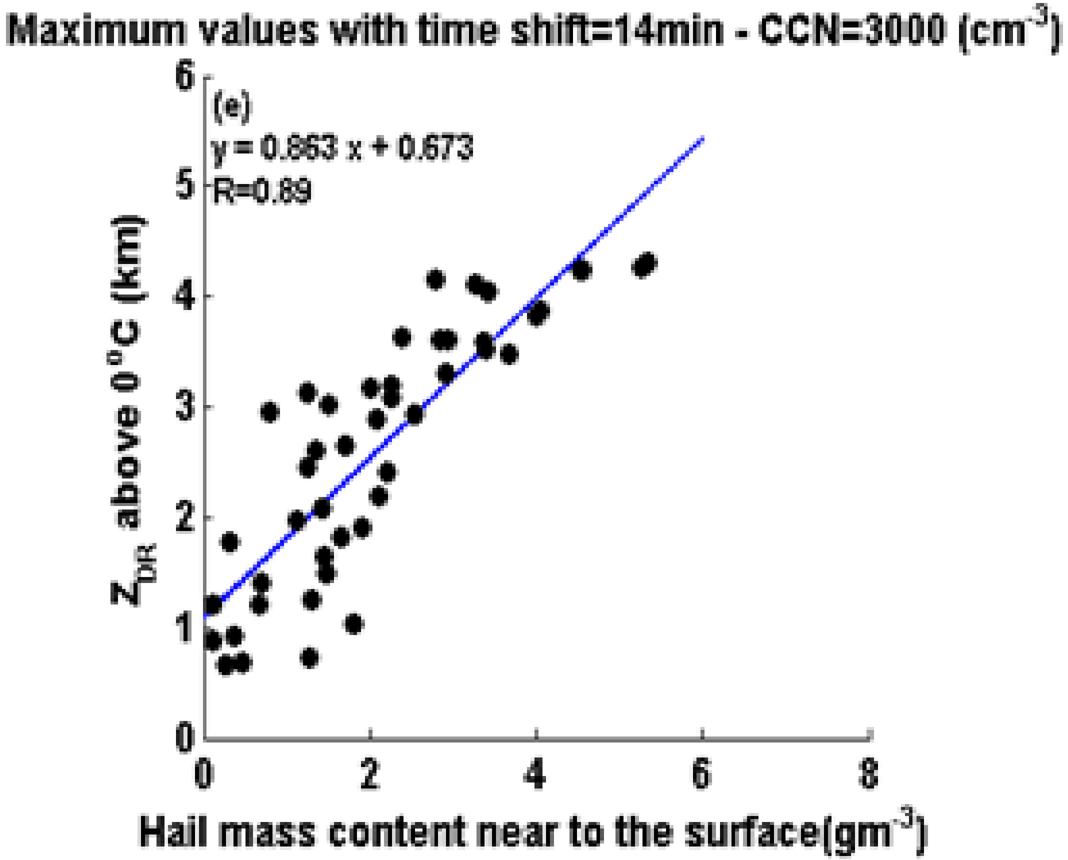


Zdr COLUMNS ARE HIGHER IN POLLUTED AIR



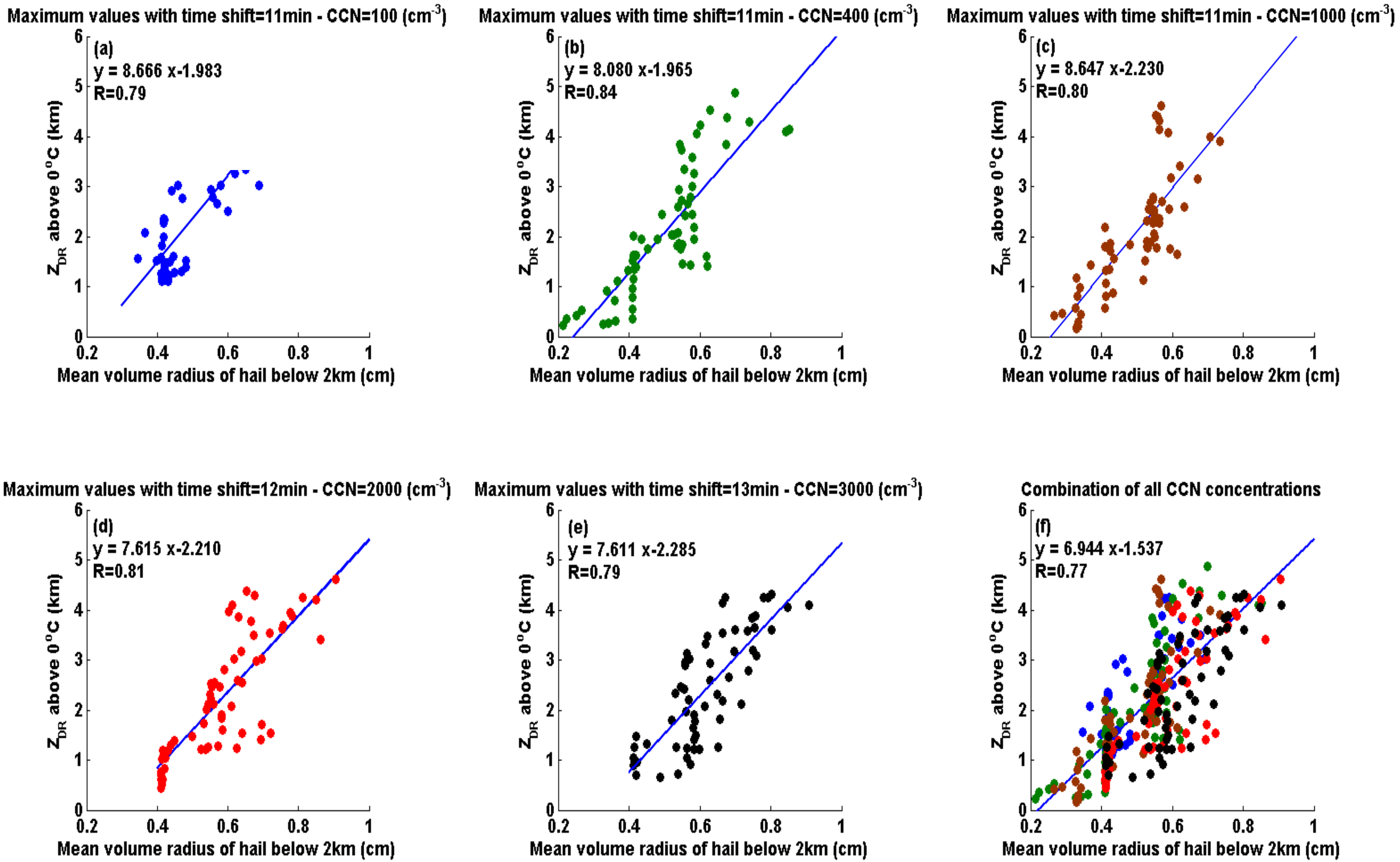
Parameterization of physical processes

Relationship
Between Zdr and hail mass content



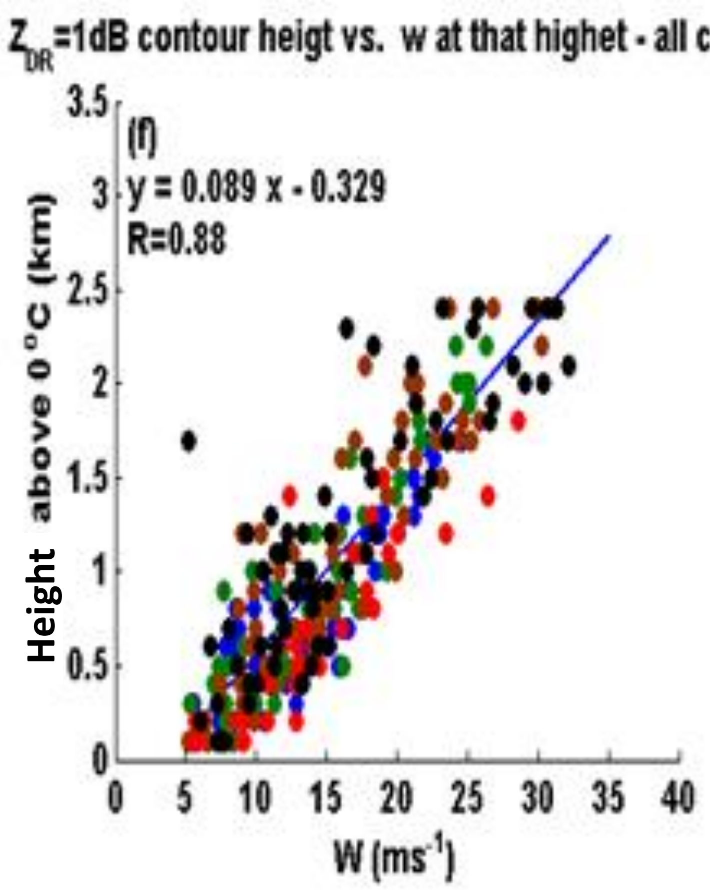
Hail falls ~15-20 min after Zdr column reaches its maximum height.
The higher Zdr column, the stronger the hail shaft is.

Mean volume hail radius vs. Zdr



Parameterization of physical processes

Relationship
Between Zdr and vertical velocity

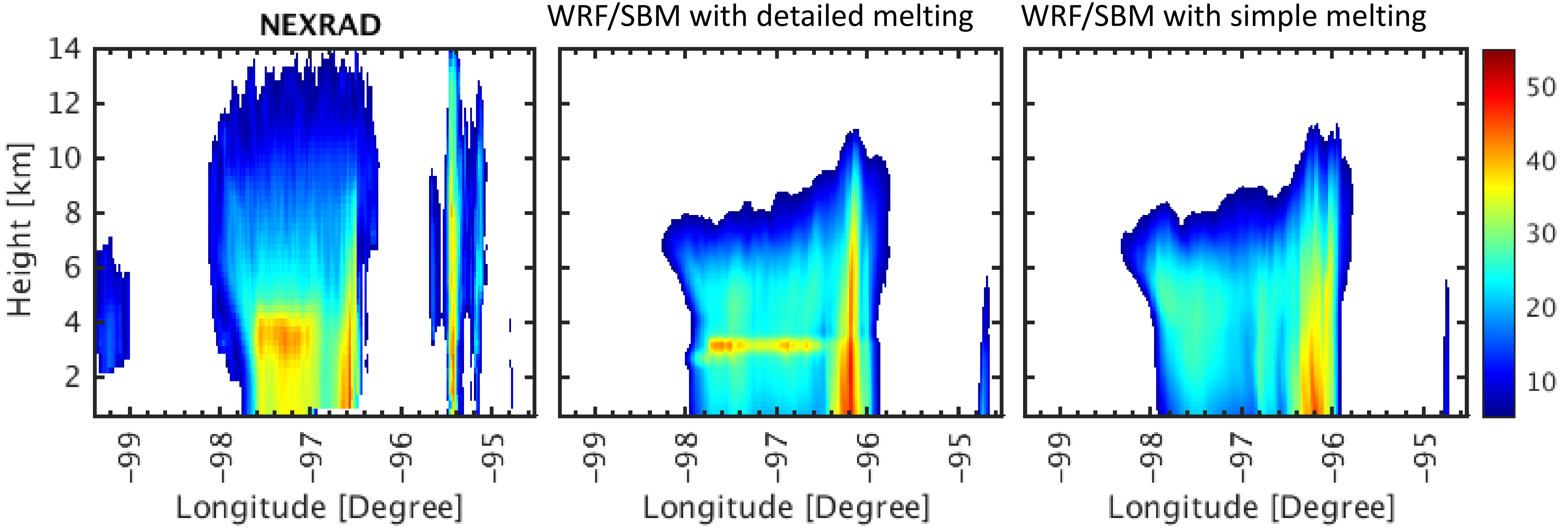


Vertical velocity can be evaluated by the height (and other parameters) of Zdr columns

Explanation of physical processes, improvement of Cloud Resolving Models

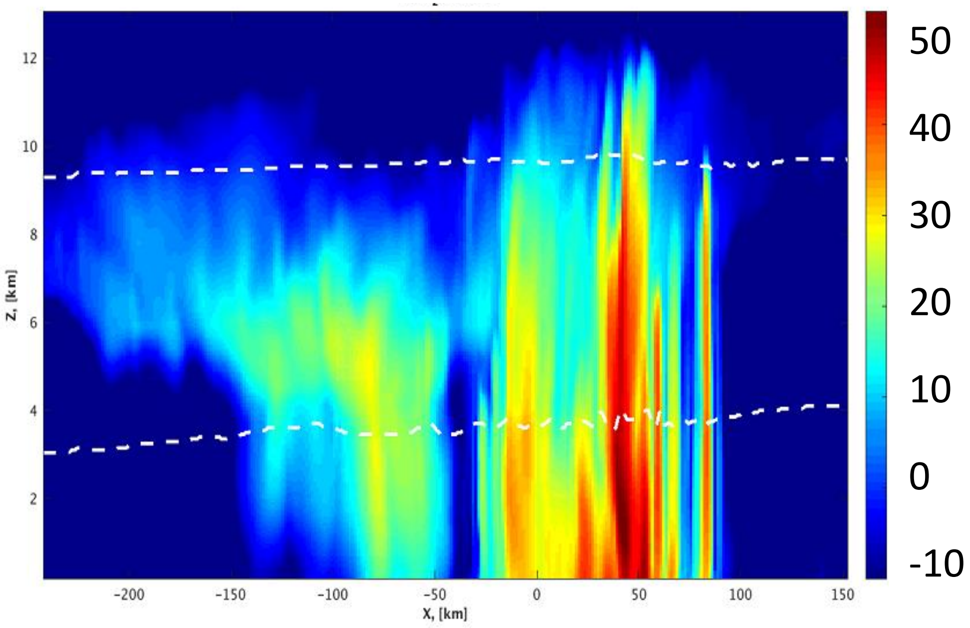
Example 3: The 20 May and 23–24 May MCS event (new WRF/SBM)

Shpund, Khain, Ryzhkov, Snyder, 2018

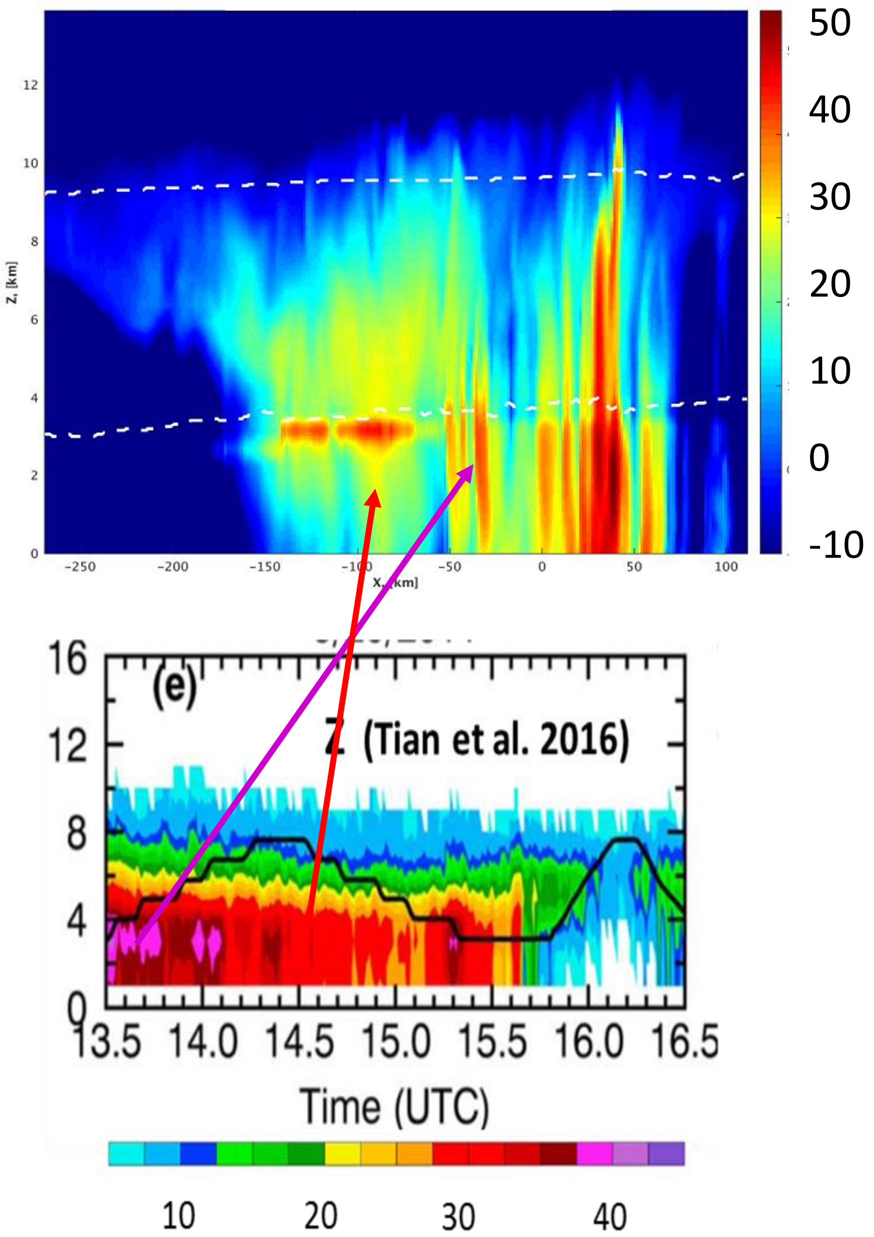


Radar reflectivity

Simple melting



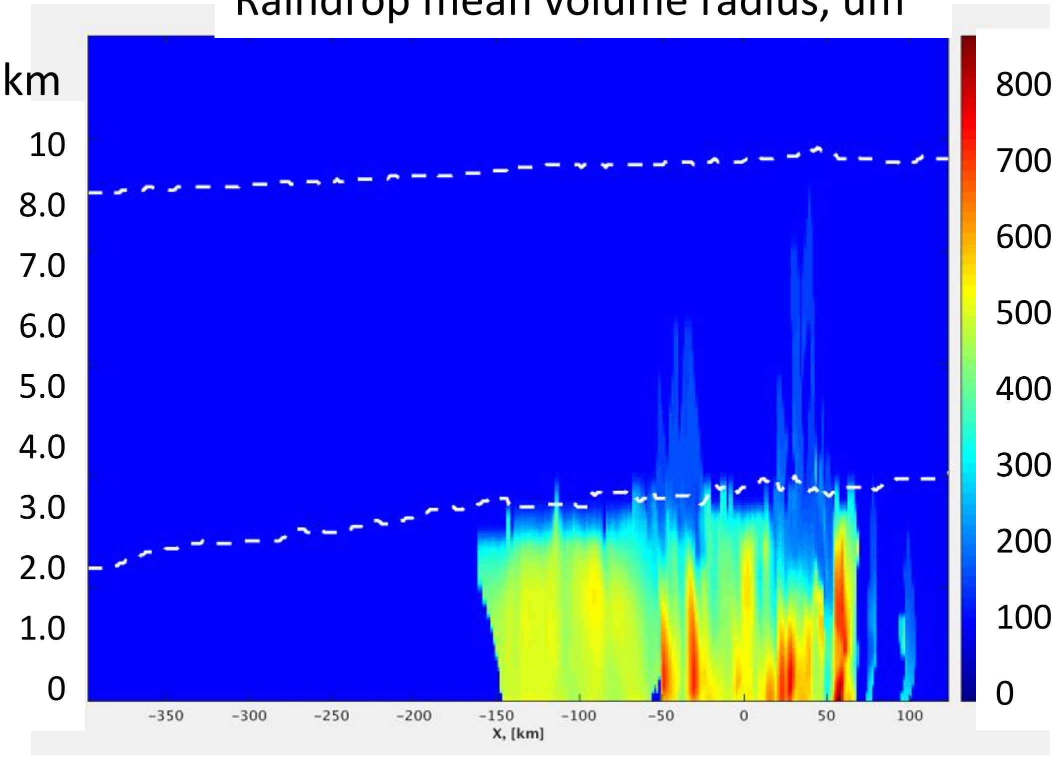
detailed melting



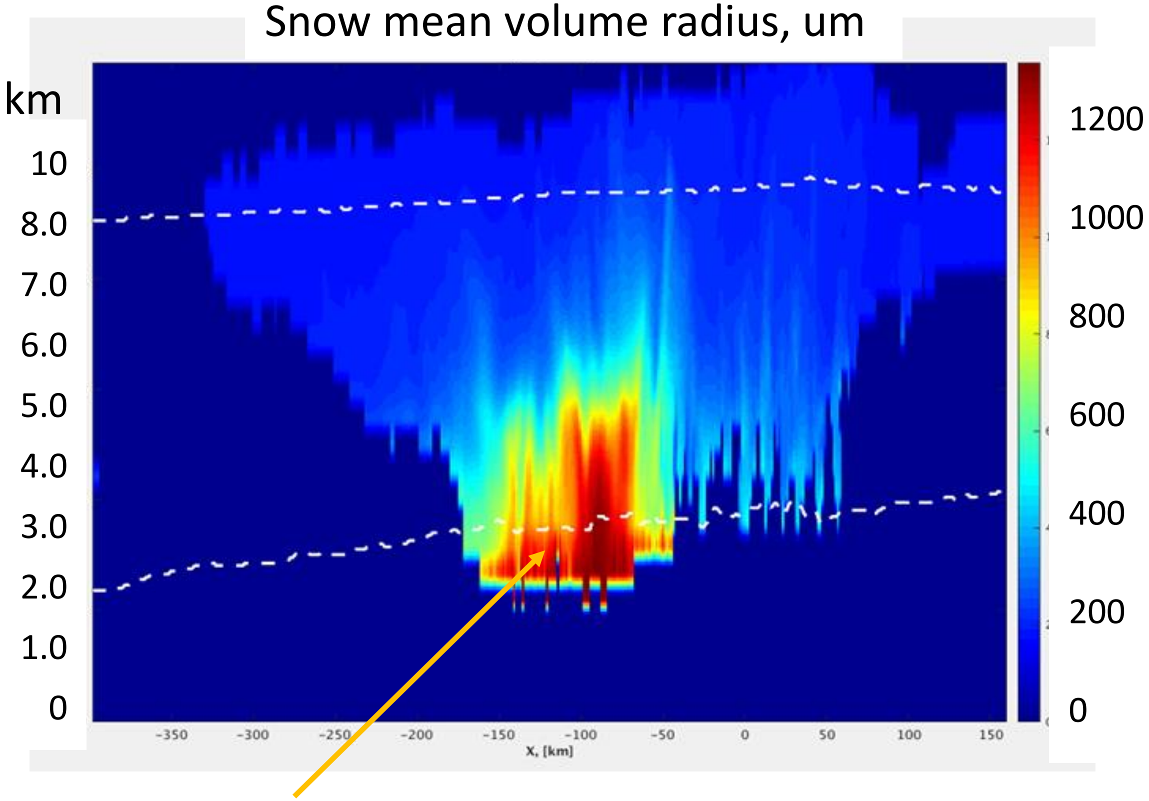
observations

Particle sizes

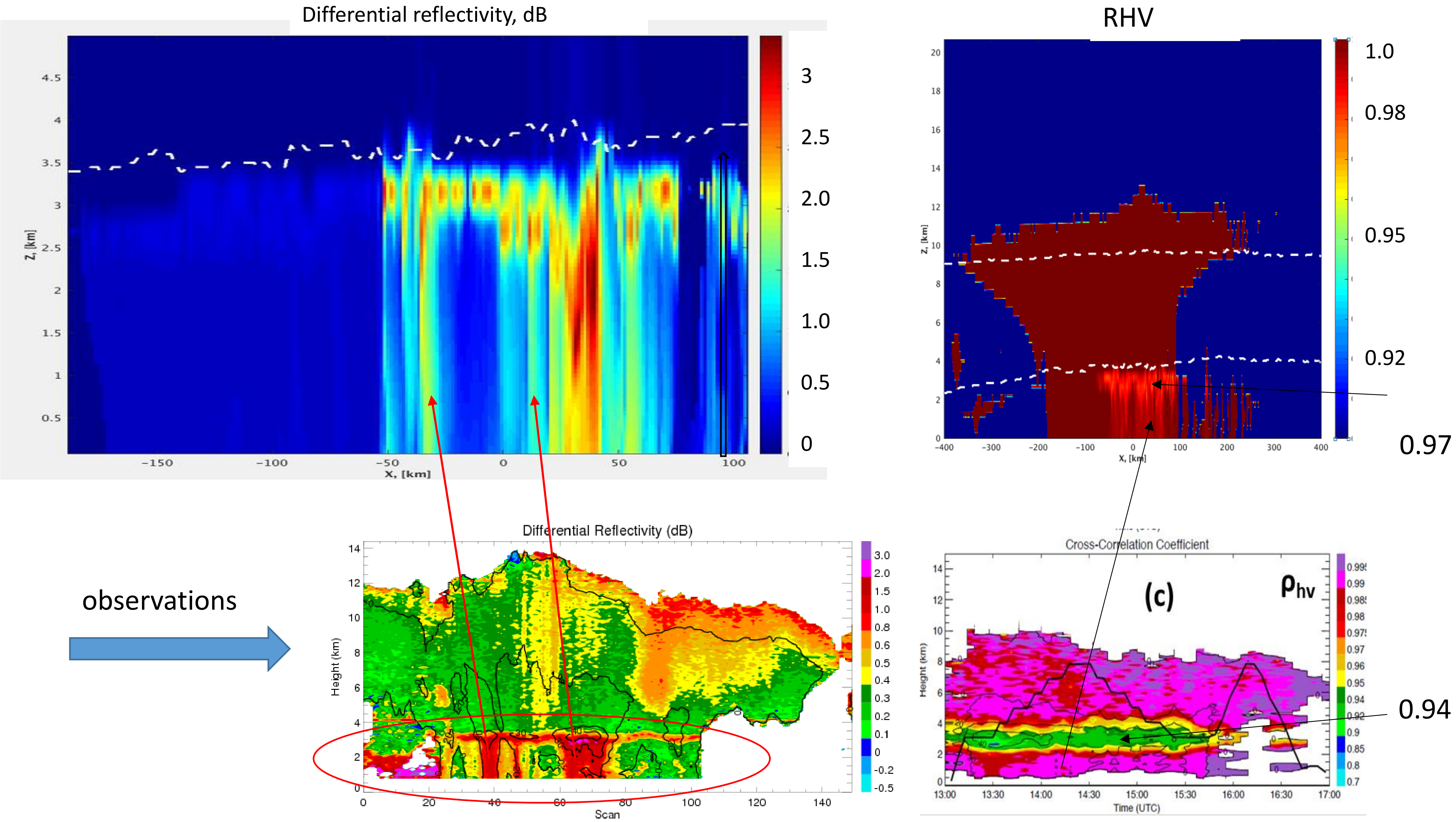
Raindrop mean volume radius, um



Snow mean volume radius, um



Snow growth in the melting layer by collisions



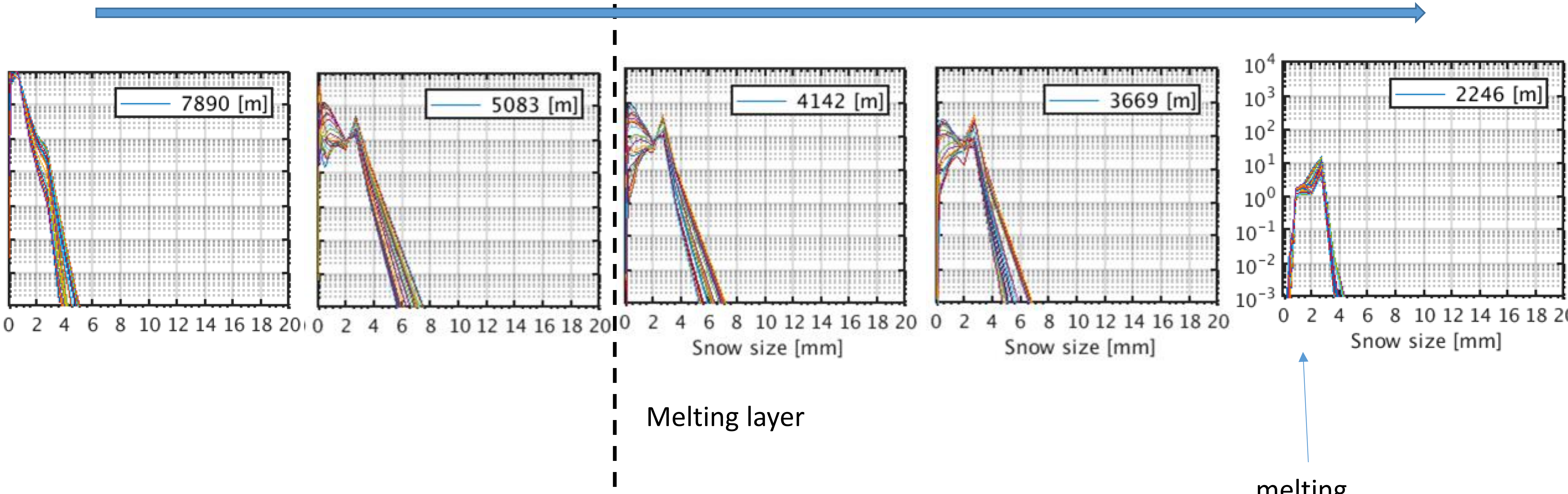
observations

PROBLEMS

Example: Snow size distributions at different heights in the stratiform area

T=0C

down



Melting layer

melting

In observations maximum size is close to 15 mm

CONCLUSION AND PERSPECTIVES

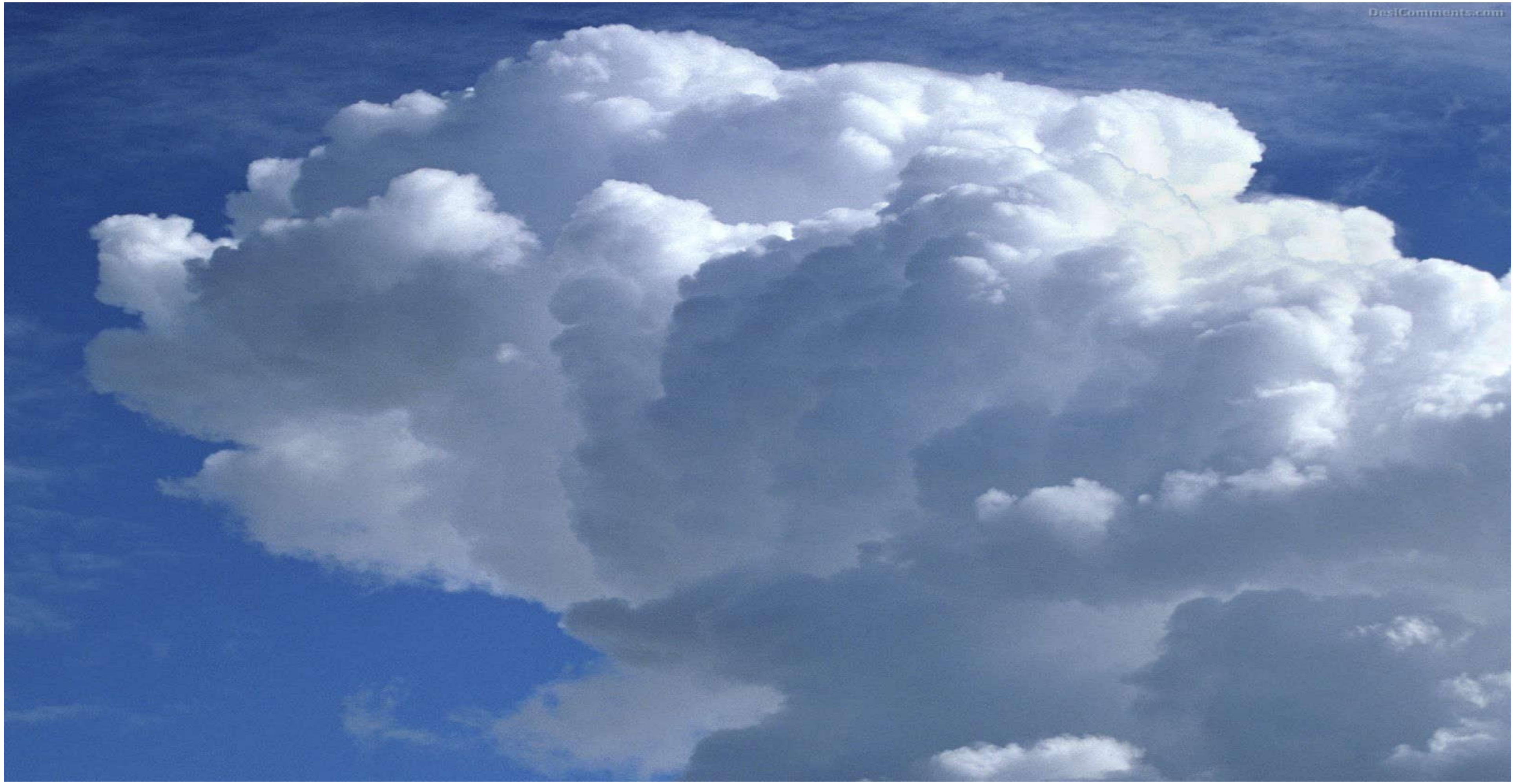
1) We presented several examples how coupling of bin-microphysics model and polarimetric measurements allow us to explain physics of several phenomena: a) high ice crystal concentration at the upper levels, b) Hail formation and growth, 3) formation of bright bands and growth of snow within melting layer.

2) We saw close relationship between palarimetric signals and microphysical and dynamical characteristics of cloud-related phenomena and aerosol concentration. This opens the possibility to express microphysical structure via polarimetric features.

Direct consequence is an improvement of assimilation procedures and short range weather forecast.

3) Monitoring of polarimetric data→ monitoring microphysical structures and rates of microphysical processes, evaluation of such parameters as ice concentration, cloud cover, vertical velocities, and rates of microphysical processes under different weather situations→ better understanding of components of climate forcing (necessary for understanding climate and climate change)

Thank you!



PERSPECTIVES

We presented several examples how coupling of bin-microphysics model and polarime
measurements allow us to explain several physical phenomena : high ice crystal conce
the upper levels, Hail formation and growth, formation of bright bands and growth of
melting layer.

1) Large hail stones are formed in updrafts polluted clouds due to process of recirculation.

2) The main mechanism of hail growth in polluted clouds is accretion of super cooled CWC

3) The main mechanism of hail formation in clean clouds is raindrop freezing just above freezing level

4) Hail size is larger in polluted case.

5) Accumulated hail at the surface is much larger in polluted clouds

HAIL

Zdr -Hail relationship

6*)* Zdr columns *in polluted* clouds are caused by large raindrops and hail containing liquid water fraction. Raindrops and hail penetrate cloud updrafts due to the mechanism of recirculation.

High values of Zdr and deep Zdr columns precede the big hail.

7*) In clean air the* values of Zdr are low because raindrops are small (<1 mm). Most of raindrops form at low levels where W is not high.

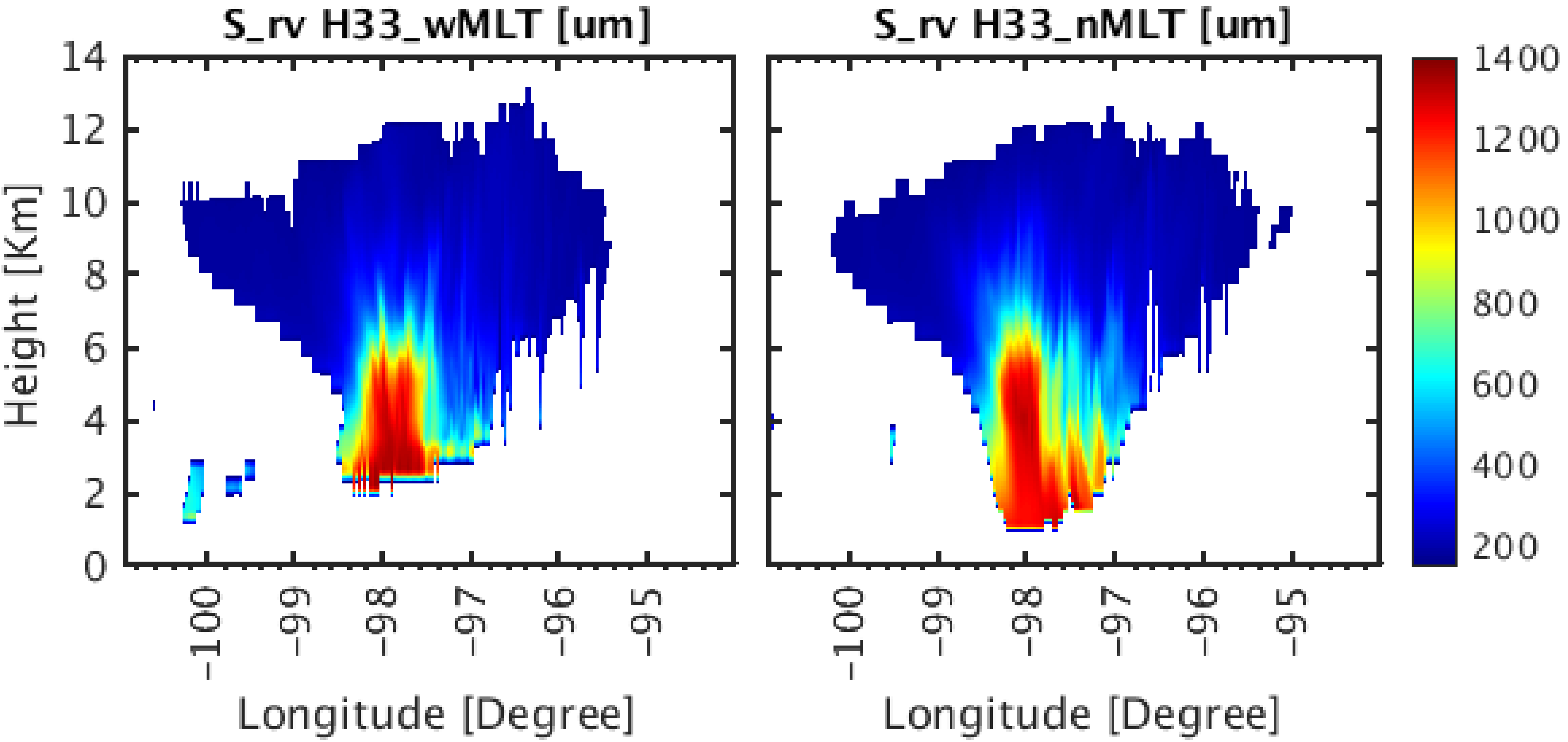
9) Hail falls 15-20 min after the Zdr column reaches its maximum.

10) Low Zdr columns correspond to low hail size.

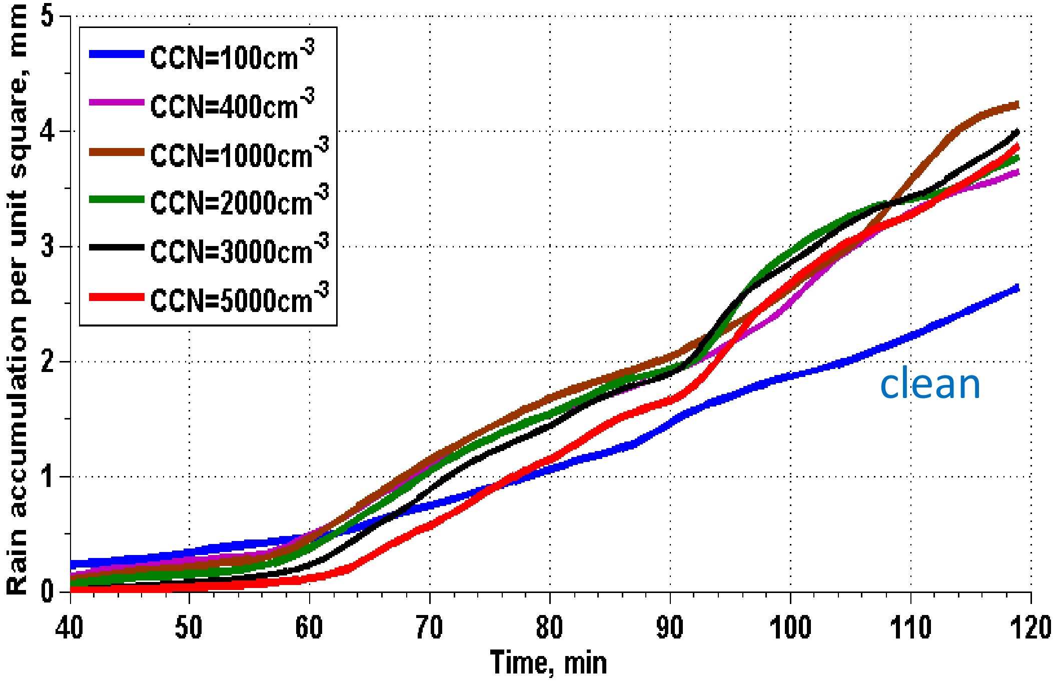
11) Zdr above freezing level and the height of Zdr columns can be used to evaluate W and hail size, as well as hail mass content.

Perspectives.

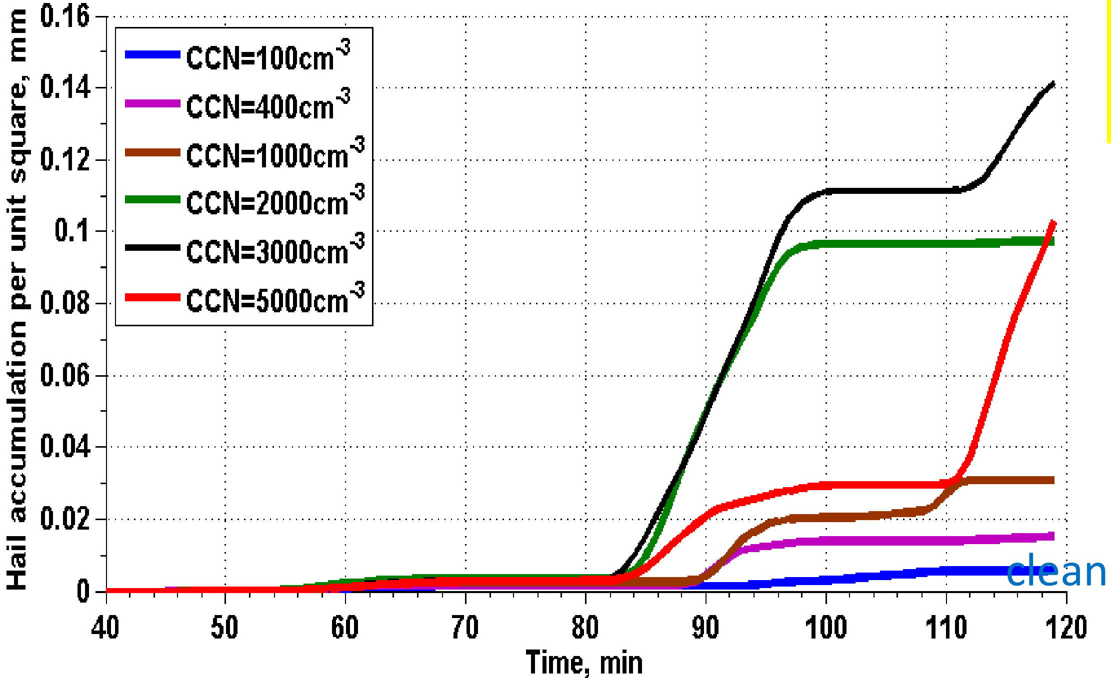
Very good


S_rv H33_wMLT [um]
S_rv H33_nMLT [um]
Height [Km]
14
12
10
8
6
4
2
0
−100
−99
−98
−97
−96
−95
Longitude [Degree]
1400
1200
1000
800
600
400
200

Accumulated rain under different aerosol concentrations

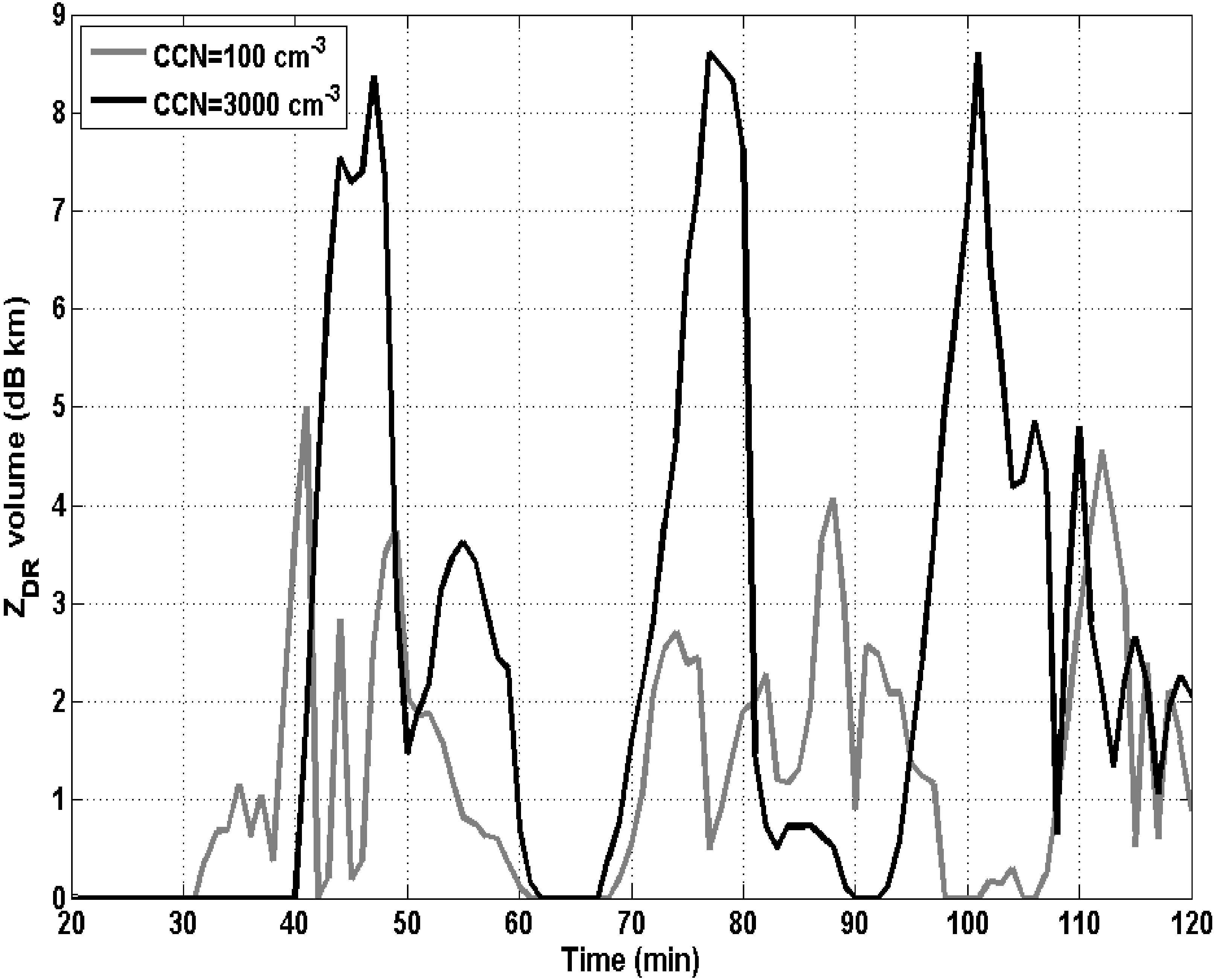


Accumulated hail under different aerosol concentrations

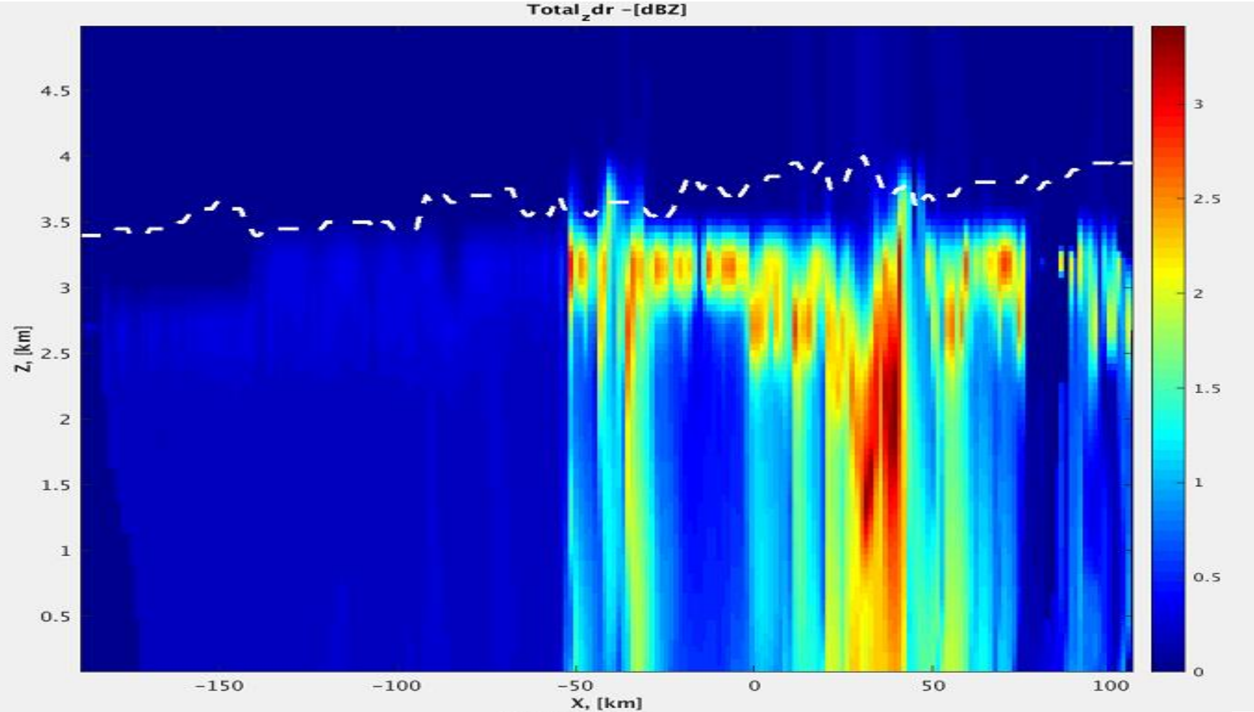


1) **ACCUMULATED RAIN is lower IN CLEAN AIR**

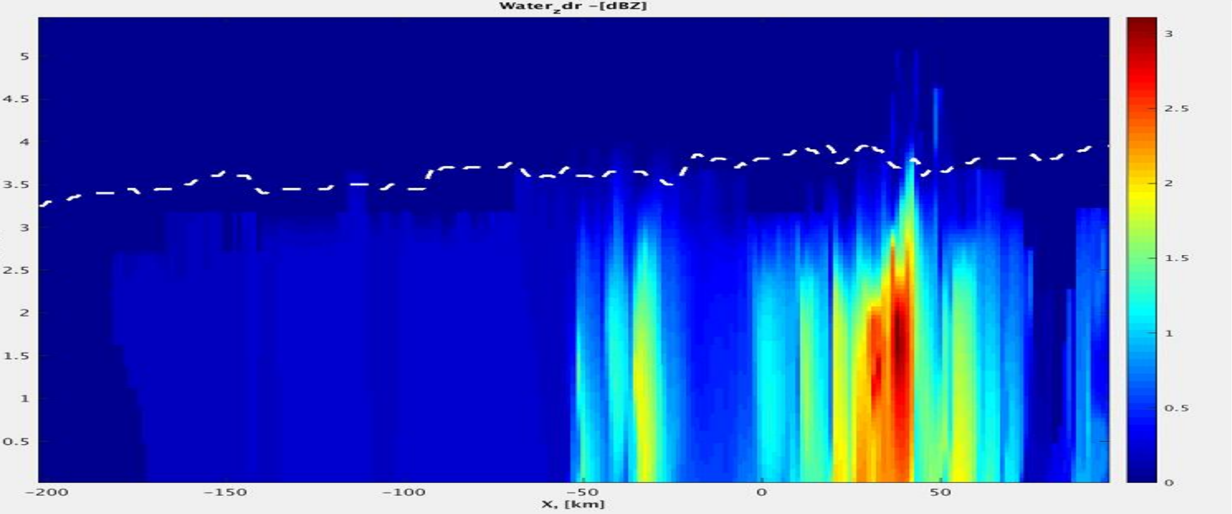
2) **ACCUMULATED HAIL is MINIMUM in CLEAN AIR**



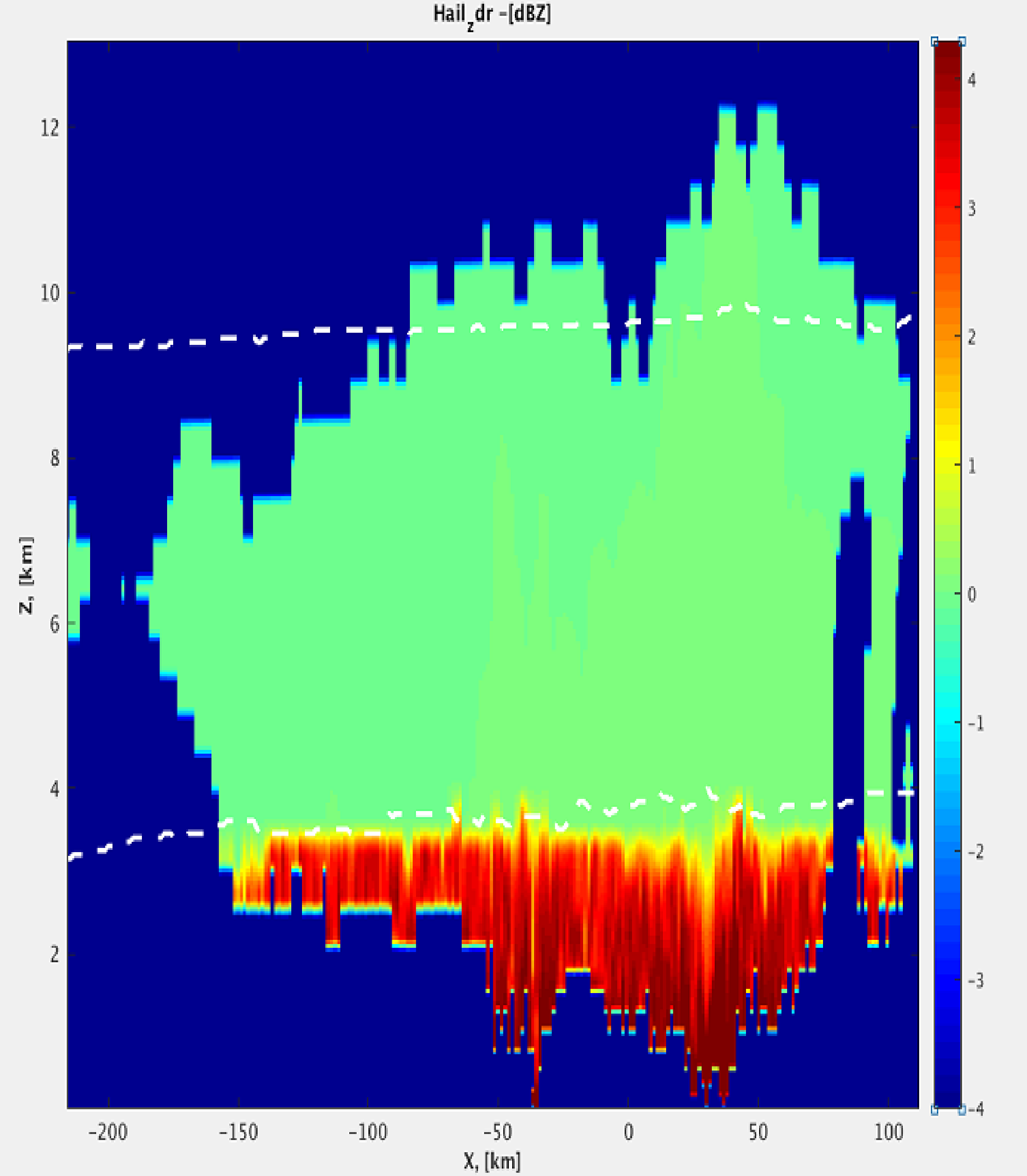
CCN=100 cm^{-3}
CCN=3000 cm^{-3}
Z_{DR} volume (dB km)
Time (min)
0
1
2
3
4
5
6
7
8
9
20
30
40
50
60
70
80
90
100
110
120



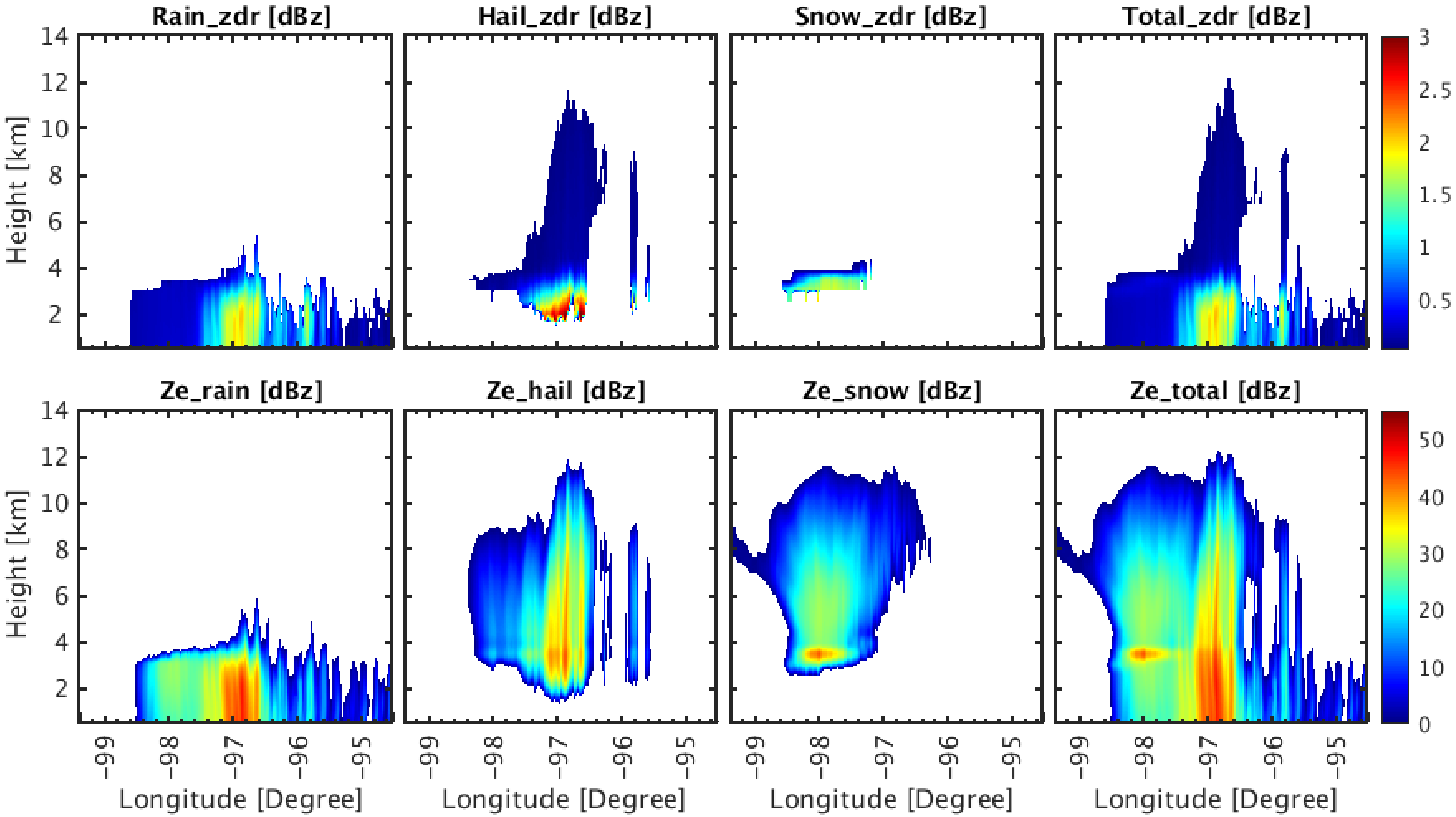
Total$_z$dr -[dBZ]



Water$_z$dr -[dBZ]



Hail$_z$dr -[dBZ]

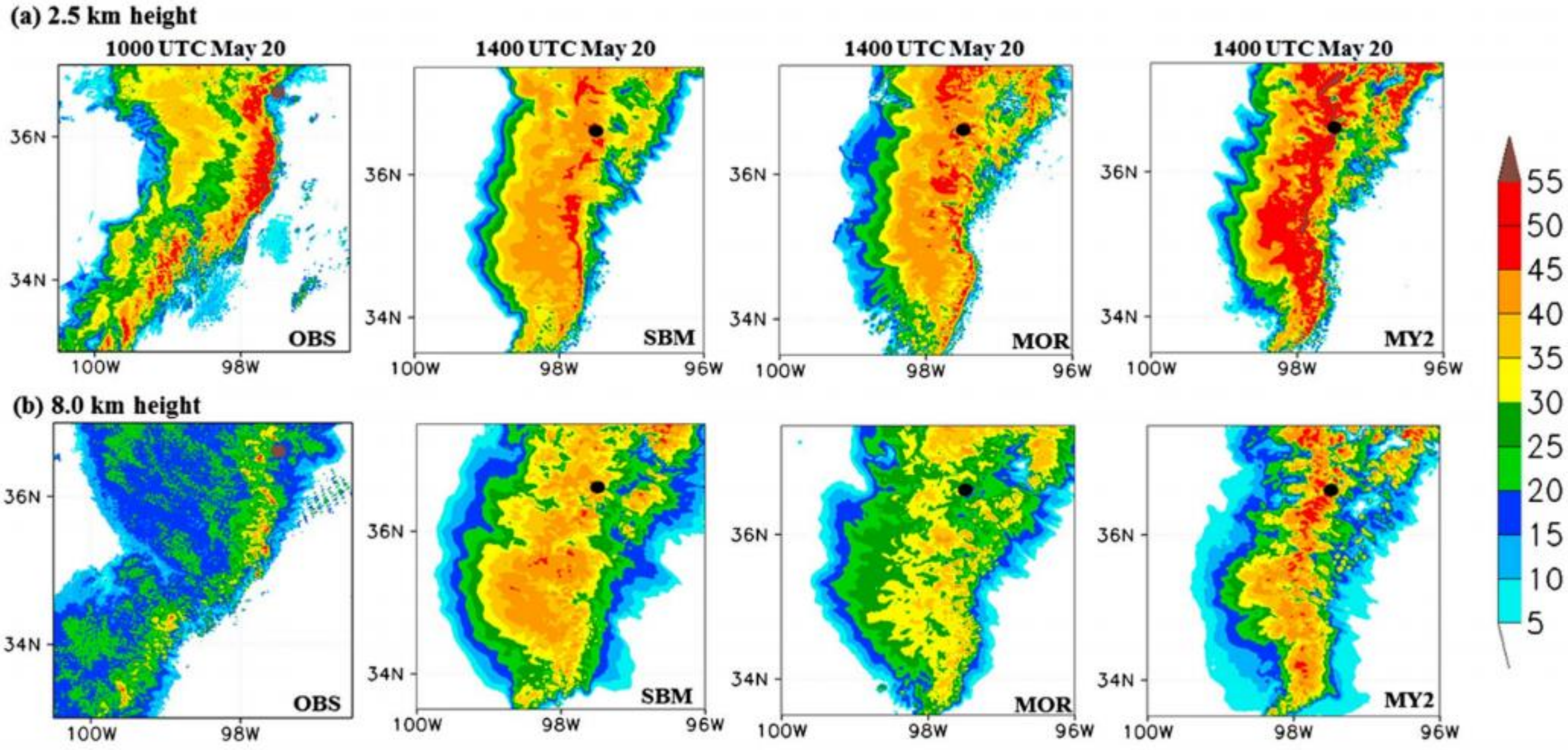

Rain_zdr [dBz]
Hail_zdr [dBz]
Snow_zdr [dBz]
Total_zdr [dBz]
Ze_rain [dBz]
Ze_hail [dBz]
Ze_snow [dBz]
Ze_total [dBz]
Height [km]
14
12
10
8
6
4
2
3
2.5
2
1.5
1
0.5
50
40
30
20
10
0
−99
−98
−97
−96
−95
Longitude [Degree]

Applications of bin-microphysics for parameterization goals

Polarimetric operator and its utilization

Further directions in development of bin-microphysics models

1. New effective advection scheme



Improving representation of convective transport for scale-aware parameterization: 1. Convection and cloud properties simulated with spectral bin and bulk microphysics Jiwen Fan1, Yi-Chin Liu1,2, Kuan-Man Xu3, Kirk North4

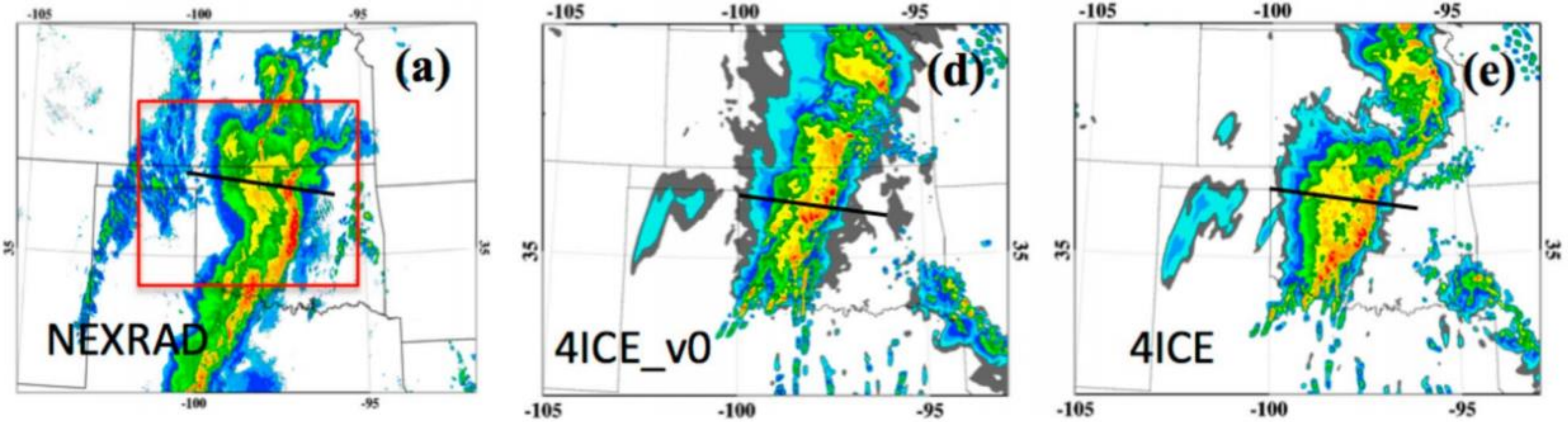
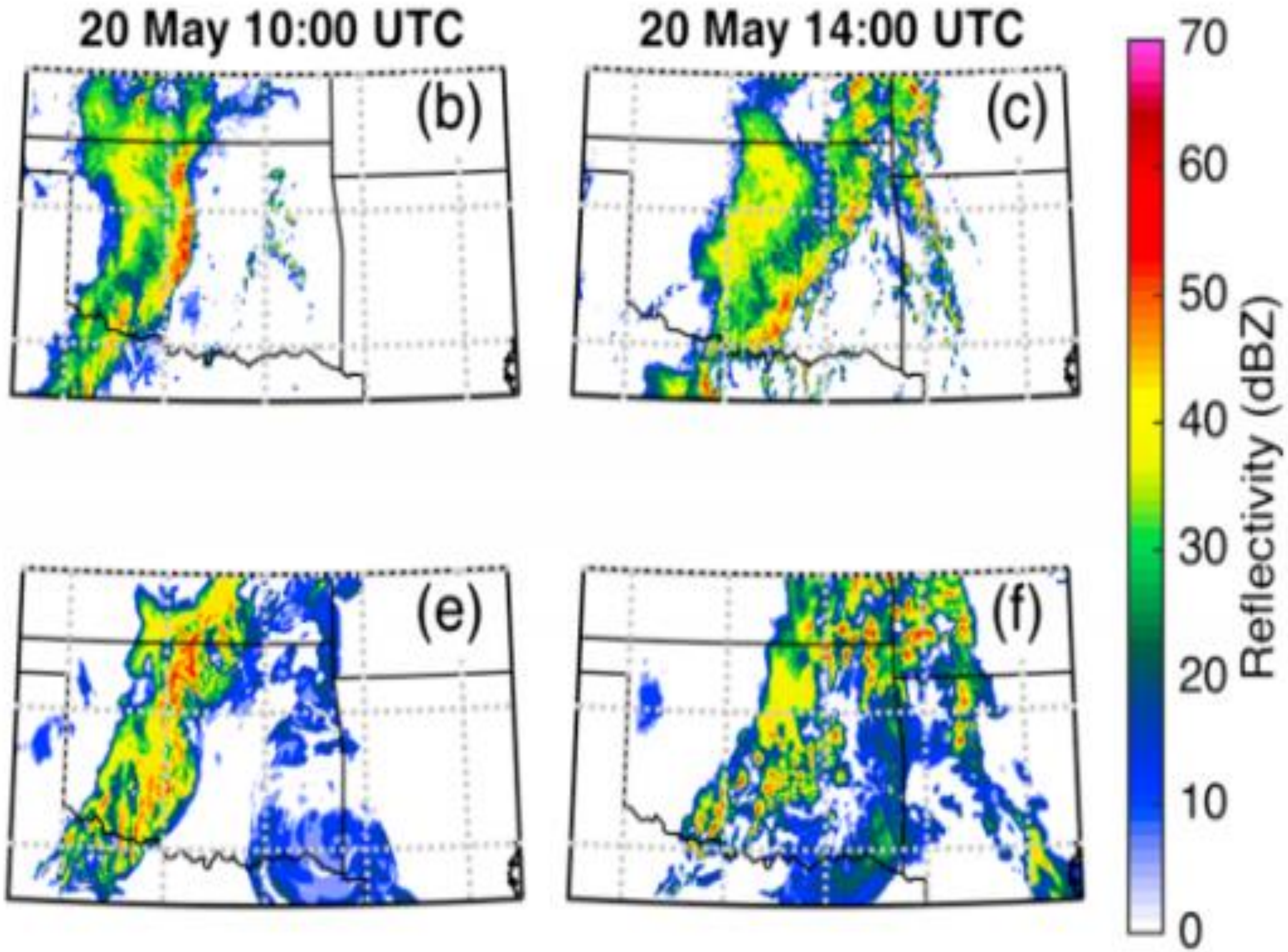


Figure 3. Composited radar reflectivity from (a) NEXRAD observations and NU-WRF simulations with the (b) Graupel, (c) Hail, (d) original 4ICE, (e) modified 4ICE, and (f) modified 4ICE with no rain evaporation correction at 10 UTC on 20 May 2011. The precipitation analysis area is indicated by the red boundary. Longitude and latitude values are shown along the horizontal and vertical edges, respectively.

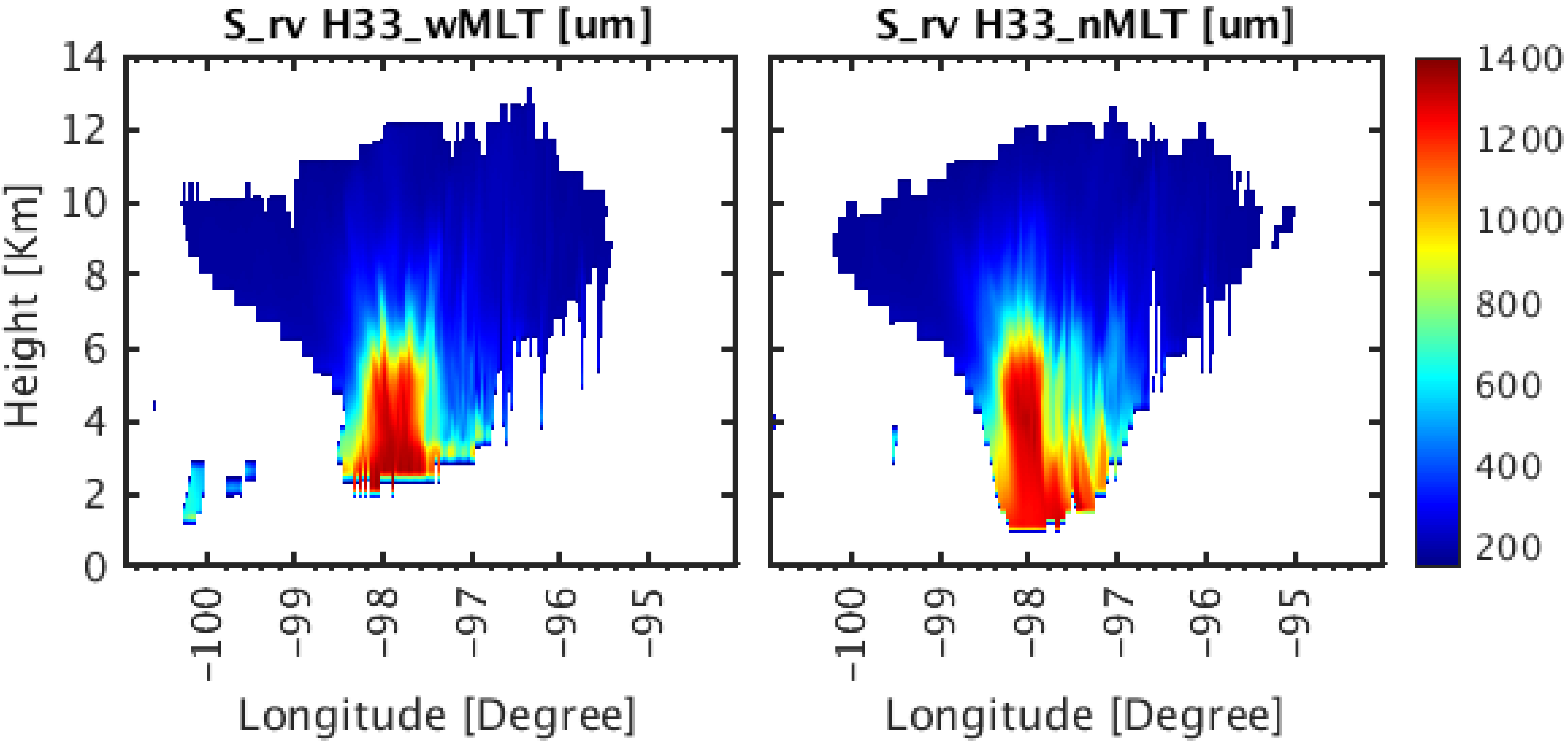
Tao, W.-K., D. Wu, S. Lang, J.-D. Chern,

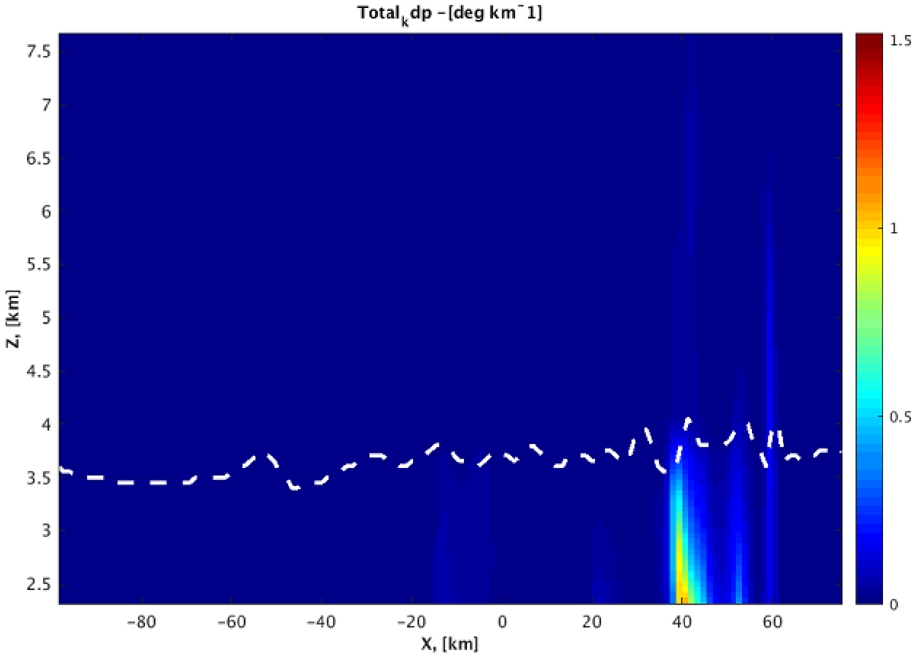

20 May 10:00 UTC

20 May 14:00 UTC

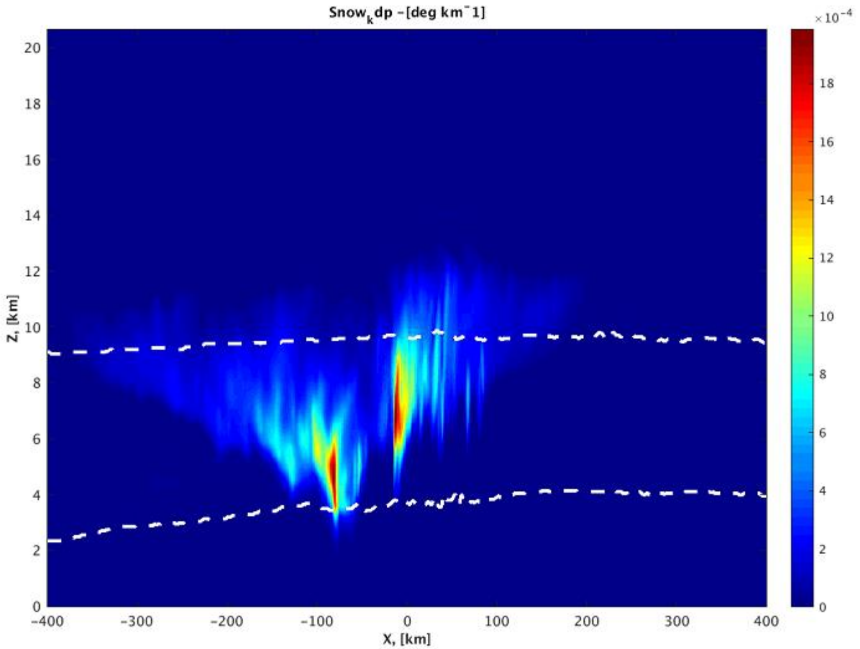
RAMS

Marinescu, P. J., S. C. van den Heever

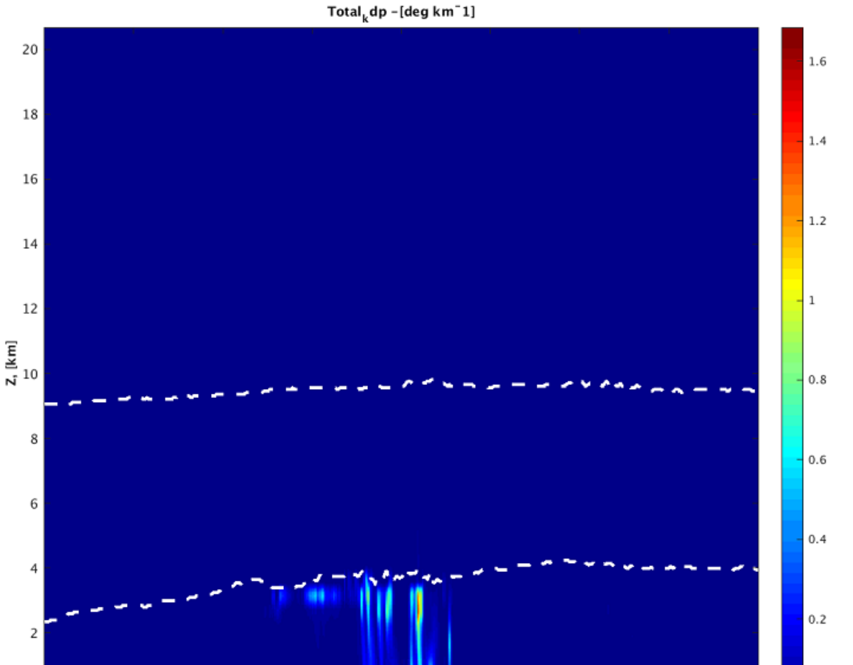

S_rv H33_wMLT [um]
S_rv H33_nMLT [um]
Height [Km]
0
2
4
6
8
10
12
14
-100
-99
-98
-97
-96
-95
Longitude [Degree]
Longitude [Degree]
1400
1200
1000
800
600
400
200



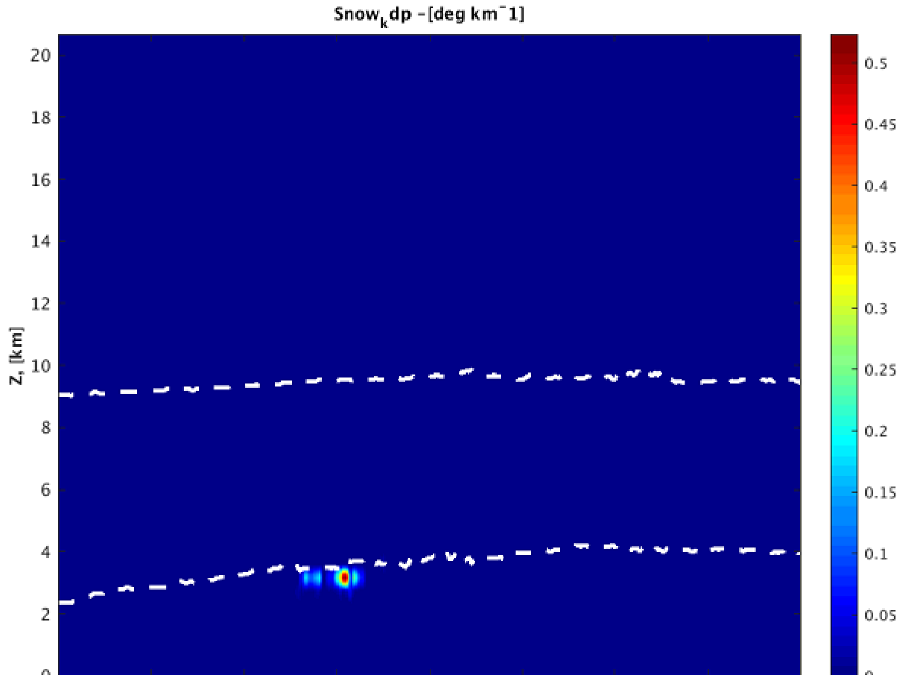
Total$_k$dp -[deg km¯1]
Z, [km]
7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
-80
-60
-40
-20
0
20
40
60
X, [km]
1.5
1
0.5
0



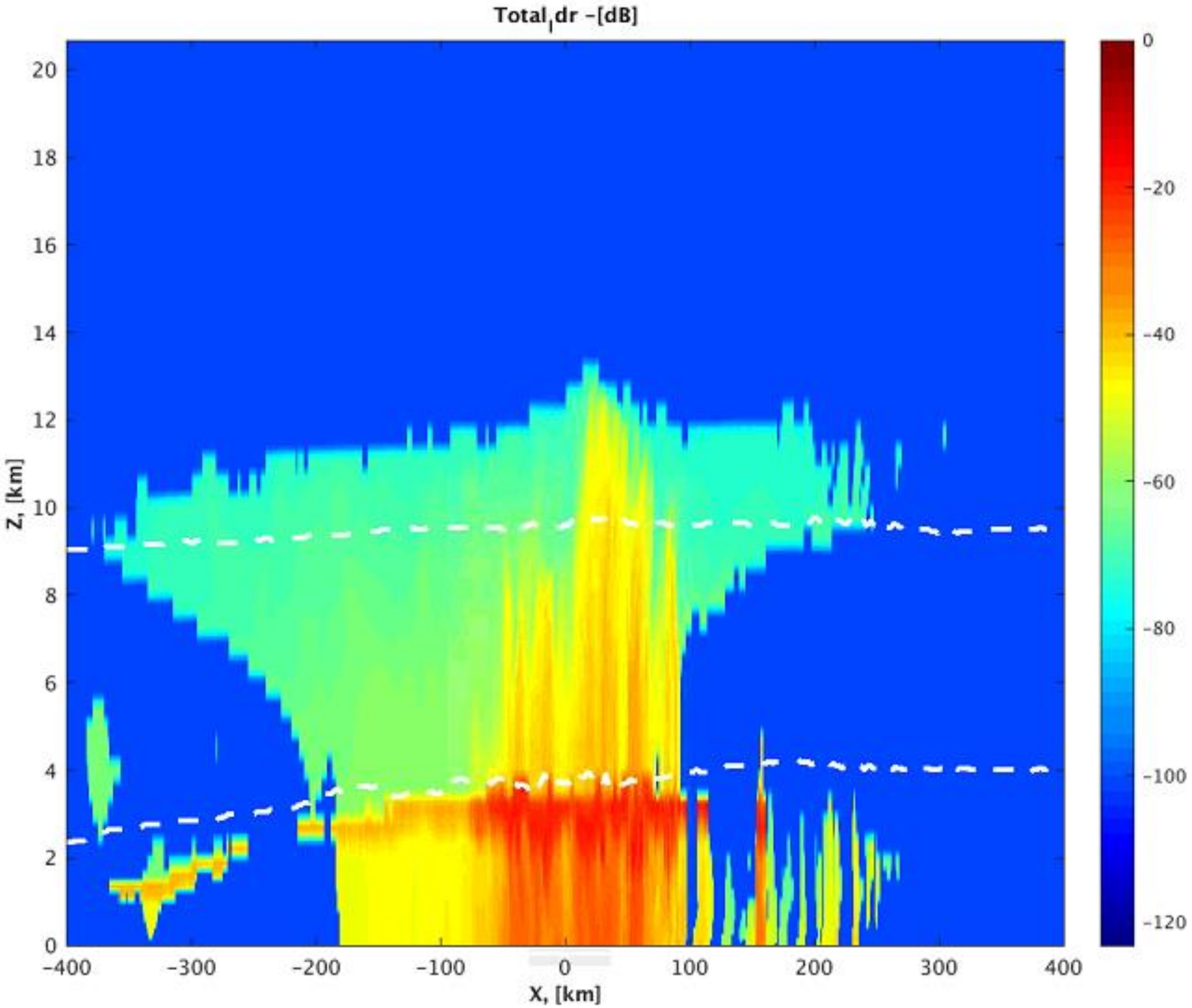
Snow$_k$dp -[deg km¯1]
$\times 10^{-4}$
Z, [km]
20
18
16
14
12
10
8
6
4
2
0
-400
-300
-200
-100
0
100
200
300
400
X, [km]
18
16
14
12
10
8
6
4
2
0

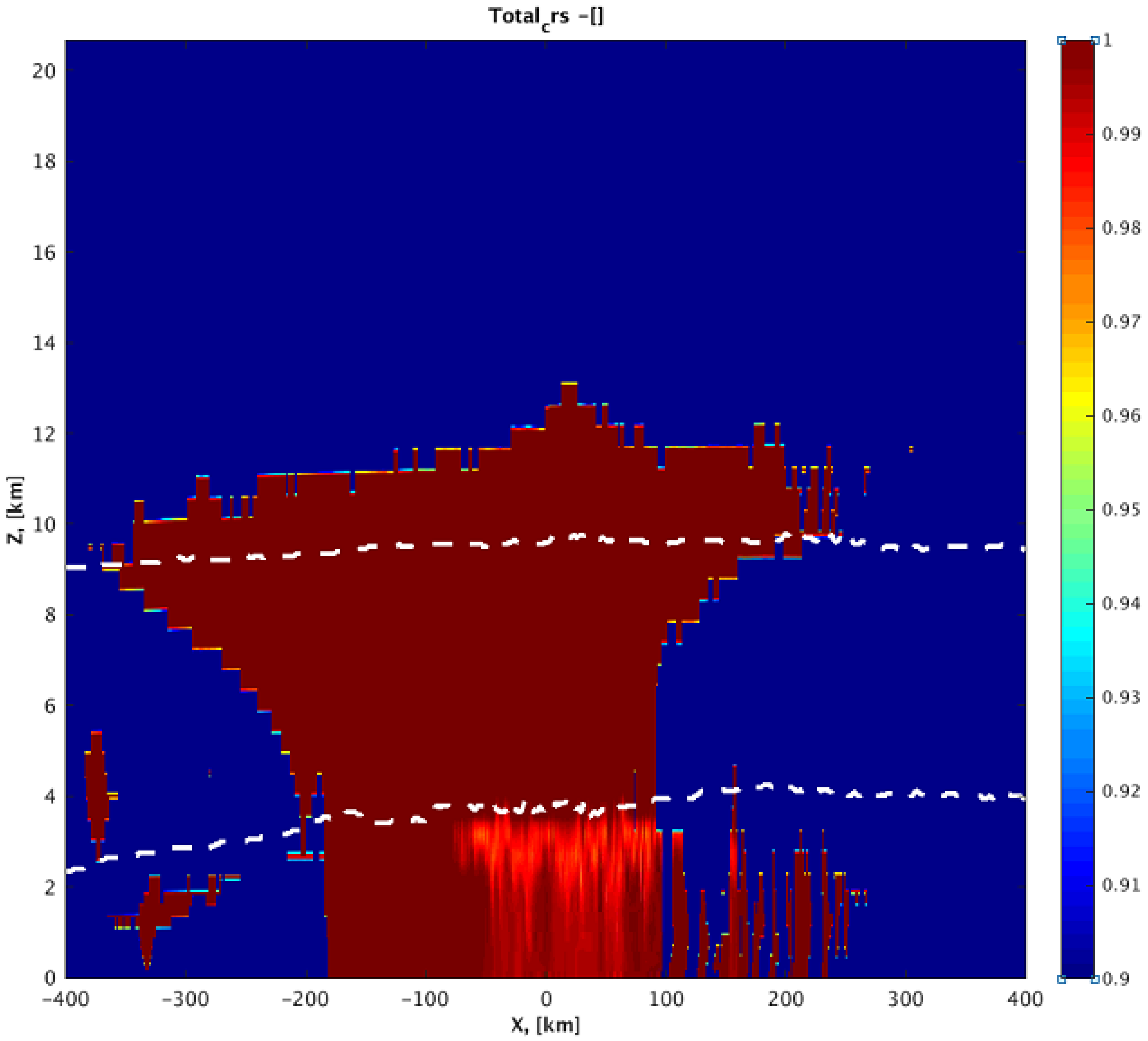


Total$_k$dp -[deg km¯1]
Z, [km]
20
18
16
14
12
10
8
6
4
2
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2

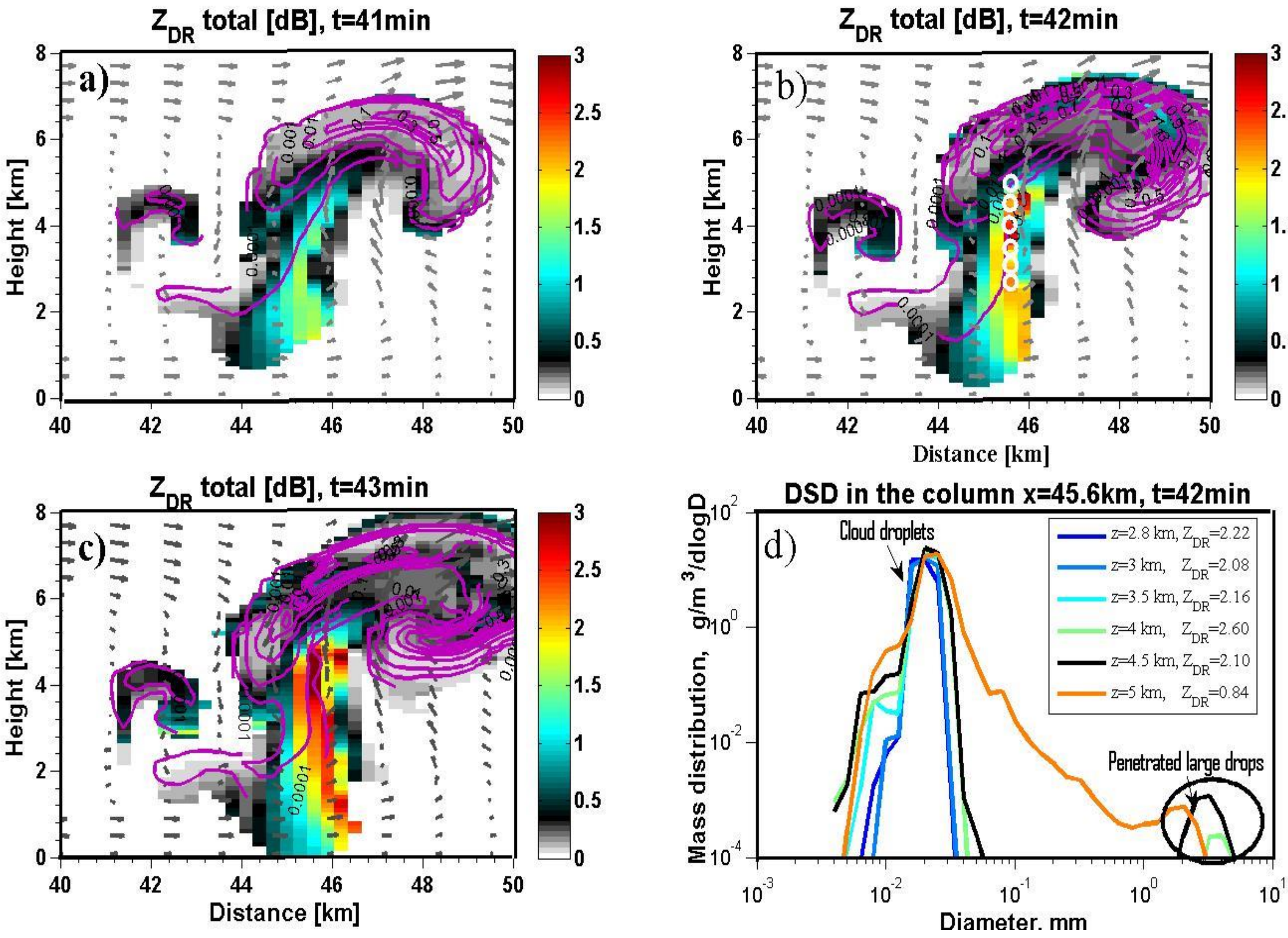


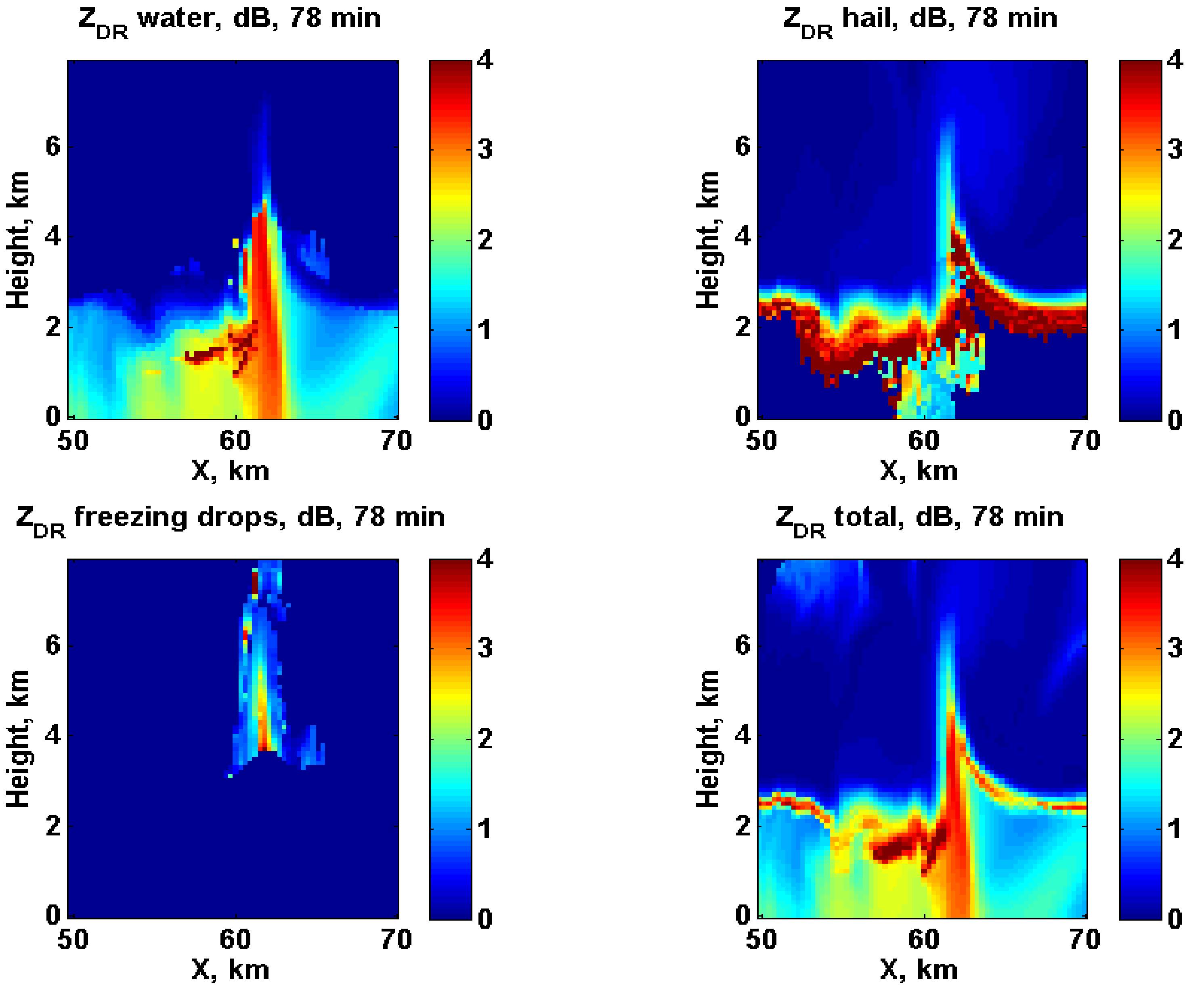
Snow$_k$dp -[deg km¯1]
Z, [km]
20
18
16
14
12
10
8
6
4
2
0
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0


Total$_l$dr -[dB]
Z, [km]
20
18
16
14
12
10
8
6
4
2
0
X, [km]
-400
-300
-200
-100
0
100
200
300
400
0
-20
-40
-60
-80
-100
-120


Total$_c$rs -[]
Z, [km]
0
2
4
6
8
10
12
14
16
18
20
X, [km]
-400
-300
-200
-100
0
100
200
300
400
1
0.99
0.98
0.97
0.96
0.95
0.94
0.93
0.92
0.91
0.9

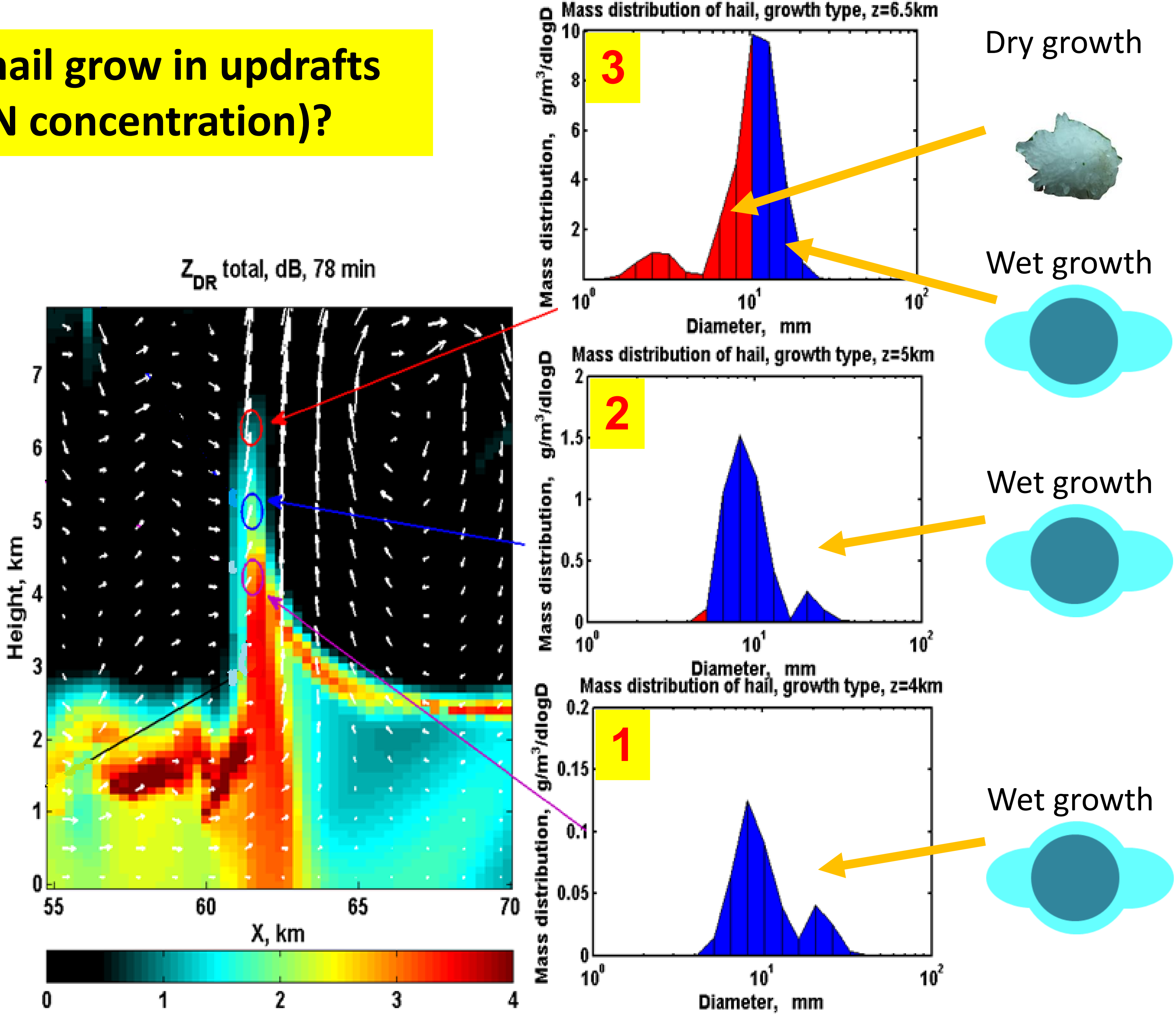
Arising of Zdr column





Contribution of different hydrometeors to Zdr

How does hail grow in updrafts (high CCN concentration)?



Dry growth

Wet growth

Wet growth

Wet growth

Parameterization of physical processes

Statistics