Clouds and precipitation modeling in NWP models: Relevance for data assimilation of satellite observations

*Jean-François Mahfouf**

Météo-France/CNRS – CNRM/GAME

Toulouse (France)

**with contributions from Clotilde Augros, Mary Borderies, Philippe Chambon, Pauline Martinet, Jean-Marcel Piriou*

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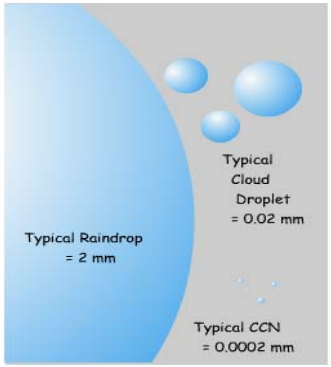
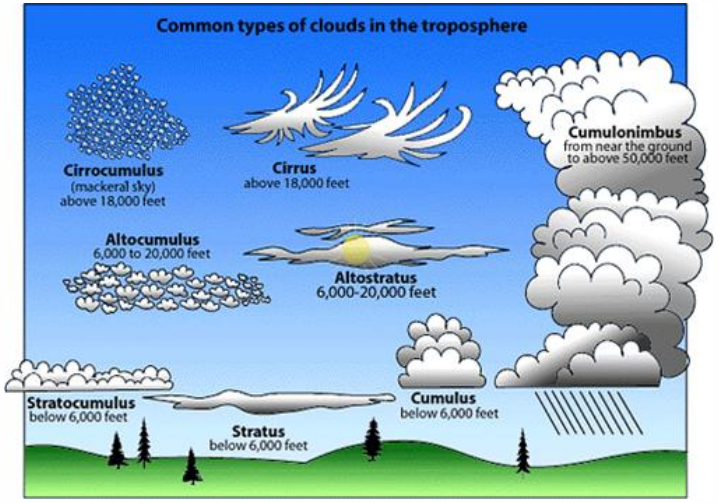
Toujours un temps d'avance

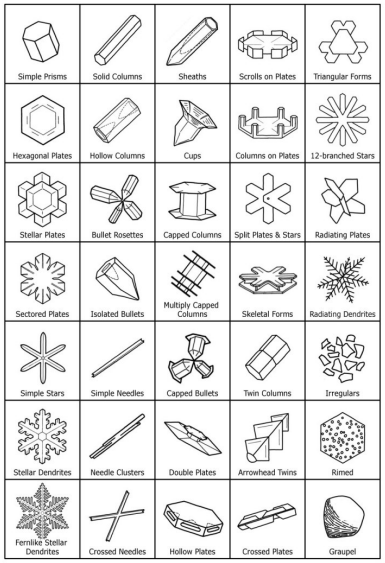
Outline

- Generalities and links with data assimilation
- Recents efforts in clouds and precipitation modeling
- Simulation of satellite radiances and radar data (few examples)
- Conclusion: which level of complexity ?

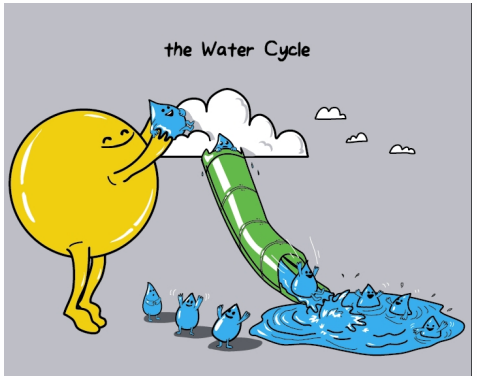
Generalities (1)







Types of Snowflakes ... SnowCrystals.com



Central to the water and energy cycles

Wide range of scales and shapes

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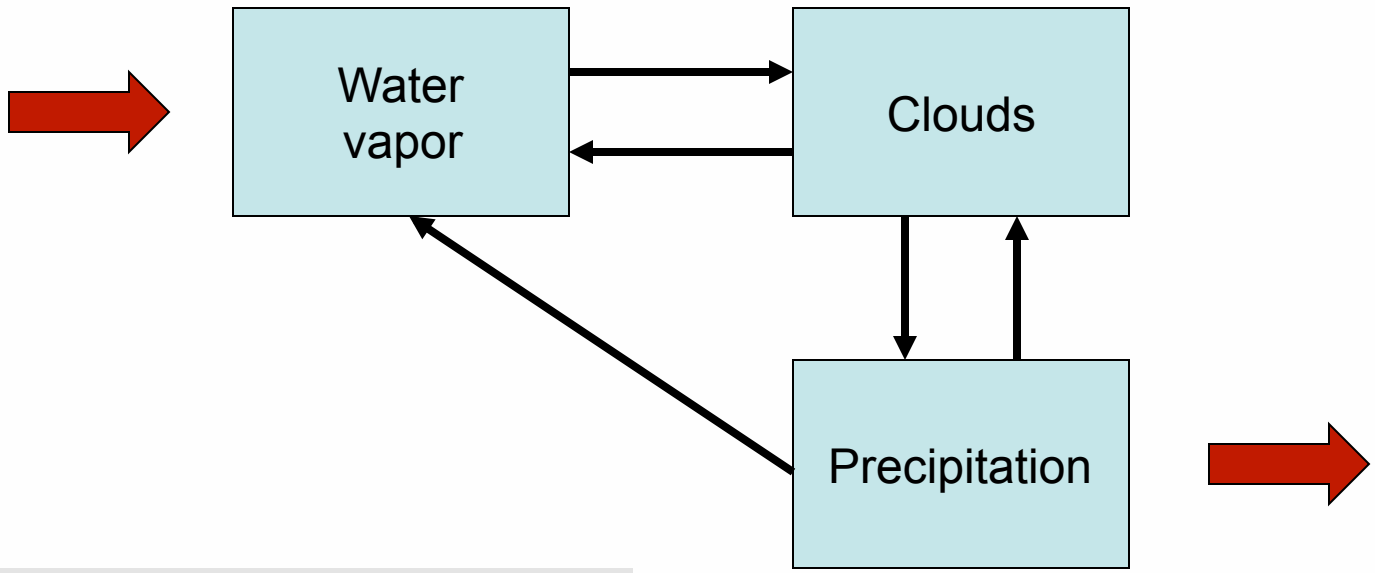
Generalities (2)

Physical parametrizations in NWP models (sub-grid processes) aim at providing a *consistent* description of the water and energy cycles in the atmosphere

-> the so-called « diabatic processes »



Each black arrow corresponding to a phase change is associated with atmospheric energy exchanges (latent heat)

Links with data assimilation (1)

Difficult to achieve such consistent description :

-water cycle: important to account for transport by clouds and losses through precipitation (removal of supersaturations and of conditional instabilities in the vertical)

-energy cycle: importance of latent heat exchanges in the atmosphere, and radiative cooling/warming induced by clouds in the atmosphere and at the surface

For a long time, clouds and precipitation were described in a rather independent manner:

-Precipitation could be generated without a cloud stage

-Clouds properties were diagnosed from « empirical » formulations

=> in terms of data assimilation only observations of surface precipitation could be considered

Links with data assimilation (2)

Satellite radiances correspond to an amount of energy received by an instrument => stronger link with the energy budget in NWP models

On the NWP side :

Clouds and precipitation are needed to compute broadband **radiative fluxes** in the **infra-red** and **solar** parts of the electromagnetic spectrum

On the data assimilation side (for satellite radiances) :

Clouds and precipitation are needed to compute **radiances** in narrow bands of the **infra-red** and **microwave** parts of the electromagnetic spectrum

Links with data assimilation (3)

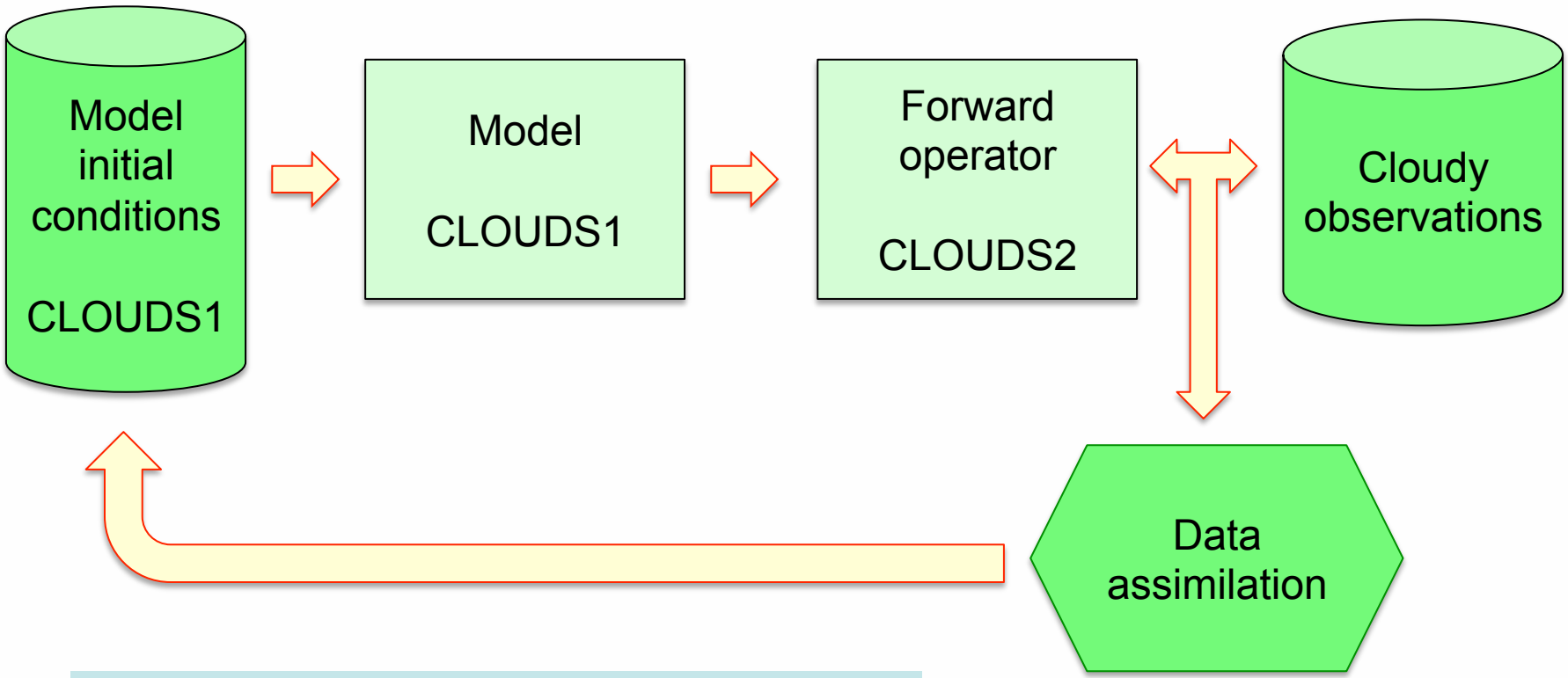
Collaborations between data assimilation sections and physics sections in NWP research groups ?

Unless rare examples, there has been no strong involvement of clouds and precipitation developers for NWP models to fulfill the requirements of data assimilation (simplicity, accuracy, linearity).

From a practical point of view, people involved in data assimilation have used and adapted existing physical parametrizations to fulfill their needs => useful feedbacks given to model developers since clouds and precipitation are evaluated in the observation space (sources of errors non trivial).

In the variational framework, the linearized versions of the clouds and precipitation schemes are required. Their evaluations can also give insight to model developers on the non-linear versions.

Links with data assimilation (4)



Main goal of the workshop : clarify what should be the content of each green box

My presentation : provide insight on the content of the light green boxes

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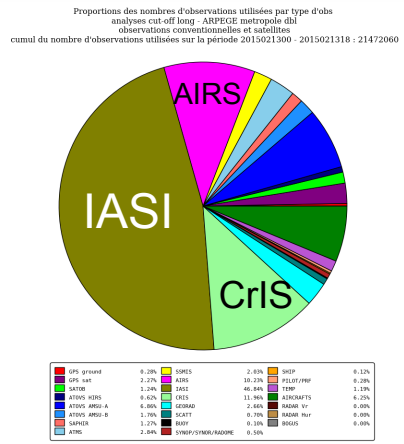
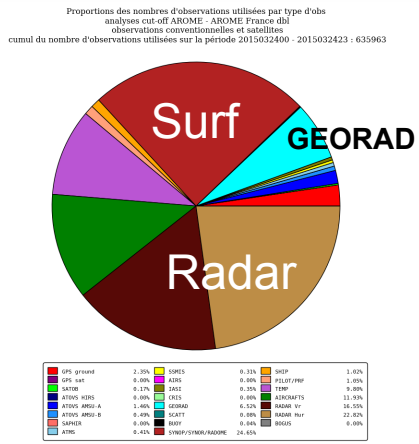
NWP models and observing systems

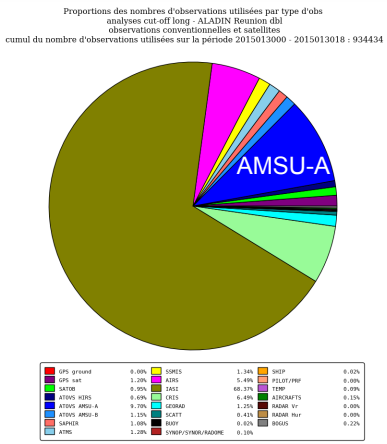
ARPEGE : Global (7.5 -> 35 km)



AROME : LAM Mid-lat. (1.3 km)



ALADIN : LAM Tropics (8 km)



- Importance of polar orbiting satellites for global and regional models over the Tropics – dominance of hyperspectral IR sounders
- Importance of geostationary satellites for regional models over mid-latitudes – but satellite is not the dominant observing system (e.g. ground based radars)

Recent efforts on clouds and precipitation

Better physically based parametrization schemes

Suitability of physical schemes over a wide range of spatial/temporal scales (seamless approach)

More continuous approaches in the description of physical processes

At Météo-France :

-Same physical parametrizations for: surface, radiation, turbulence, and PBL thermals, sub-grid condensation

-Distinct parametrizations for resolved and sub-grid precipitation (cloud microphysics and convection scheme)

-Developments towards a new convection scheme : PCMT

New convection scheme PCMT

PCMT : Prognostic Condensates Microphysics and Transport

- 5 prognostic equations for convective hydrometeors (cloud droplets, ice crystals, rain, snow) and convective vertical velocity
- Grid-scale equations from the convection scheme separate microphysical and transport processes (Piriou et al., 2007)
- Same microphysics (Lopez, 2002) used for resolved and convective clouds and precipitation (called twice)
- Triggering condition, entrainment based on buoyancy concepts
- Closure based on CAPE relaxation time scale and moisture convergence

Piriou et al., (2007)

PCMT prognostic equations (1)

Convective liquid water (or ice)

$$
\begin{aligned}
\frac{\partial}{\partial t}\overline{q_{lc}} &= \mathrm{Advec}(\overline{q_{lc}}) \\
&\quad -\frac{1}{\rho}\frac{\partial}{\partial z}\rho\left[\alpha_u w_u + \alpha_d w_d\right] q_{lc} \\
&\quad +(E_u + E_d)\, q_{lr} - (D_u + D_d)\, q_{lc} \\
&\quad +\mathrm{CondensEvap}_c - \mathrm{AutoconvColl}_c + \mathrm{MeltingIcing}_{lc}
\end{aligned}
$$

Resolved liquid water + Smith (or ice)

$$
\begin{aligned}
\frac{\partial}{\partial t}\overline{q_{lr}} &= \mathrm{Advec}(\overline{q_{lr}}) \\
&\quad -\frac{1}{\rho}\frac{\partial}{\partial z}\rho\left[-\alpha_u w_u - \alpha_d w_d\right] q_{lr} \\
&\quad -(E_u + E_d)\, q_{lr} + (D_u + D_d)\, q_{lc} \\
&\quad +\mathrm{CondensEvap}_r - \mathrm{AutoconvColl}_r + \mathrm{MeltingIcing}_{lr}
\end{aligned}
$$

Piriou et al., (2007)

PCMT prognostic equations (2)

Convective rain (or snow)

$$\begin{aligned}\frac{\partial}{\partial t}\overline{q_{rc}} &= \mathrm{Advec}(\overline{q_{rc}}) \\ &-\frac{1}{\rho}\frac{\partial}{\partial z}\rho\left[\alpha_u(w_u+w_s)+\alpha_d(w_d+w_s)\right]q_{rc} \\ &+(E_u+E_d)\,q_{rr}-(D_u+D_d)\,q_{rc} \\ &+\mathrm{AutoconvColl}_c-\mathrm{Evap}_{rc}+\mathrm{MeltingIcing}_{rc}\end{aligned}$$

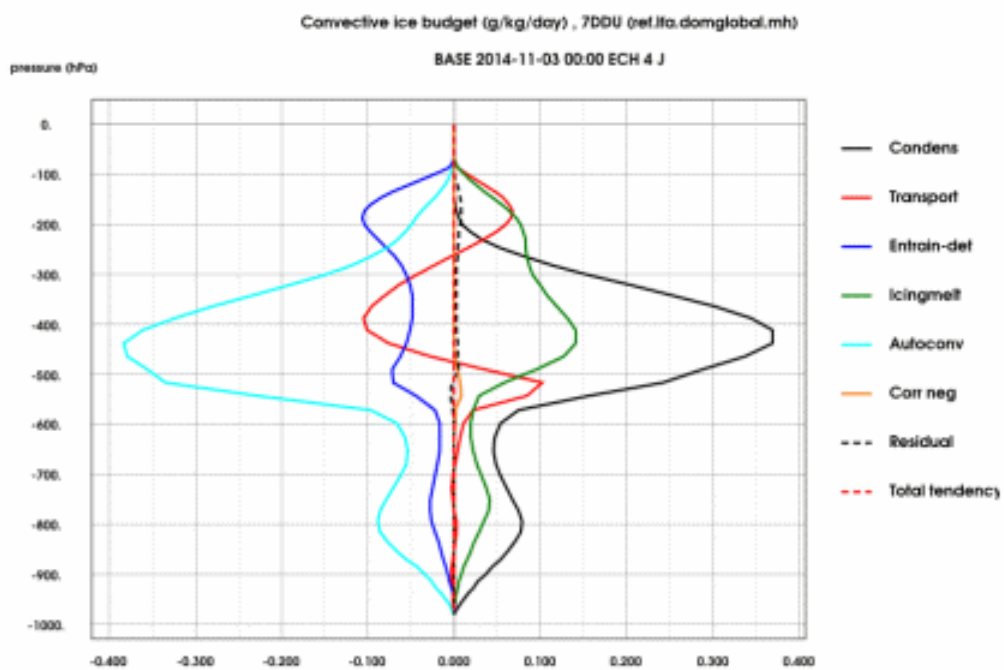
Resolved rain (or snow)

$$\begin{aligned}\frac{\partial}{\partial t}\overline{q_{rr}} &= \mathrm{Advec}(\overline{q_{rr}}) \\ &-\frac{1}{\rho}\frac{\partial}{\partial z}\rho\left[-\alpha_u w_u-\alpha_d w_d+(1-\alpha_u-\alpha_d)w_s\right]q_{rr} \\ &-(E_u+E_d)\,q_{rr}+(D_u+D_d)\,q_{rc} \\ &+\mathrm{AutoconvColl}_r-\mathrm{Evap}_{rr}+\mathrm{MeltingIcing}_{rr}\end{aligned}$$

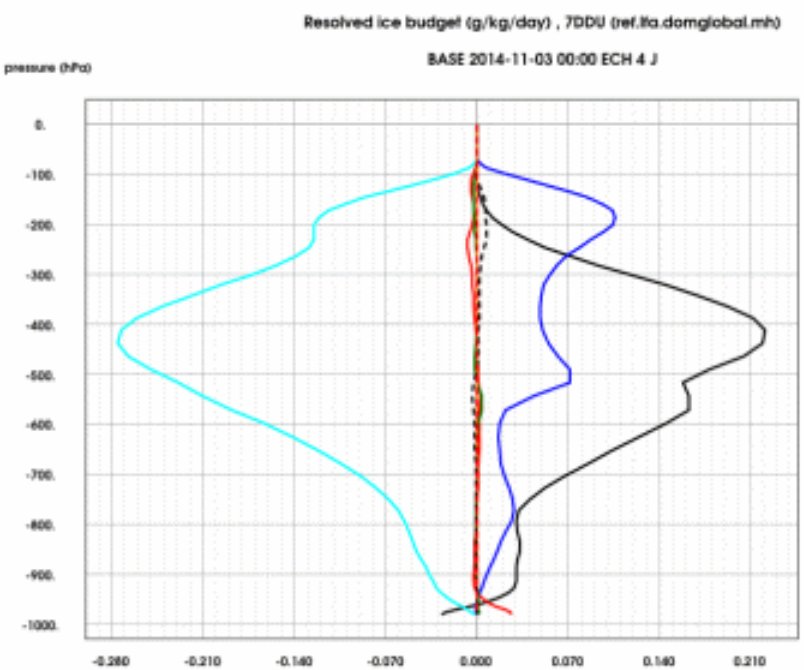
Piriou et al., (2007)

PCMT : water budget for cloud ice

Convective ice CI



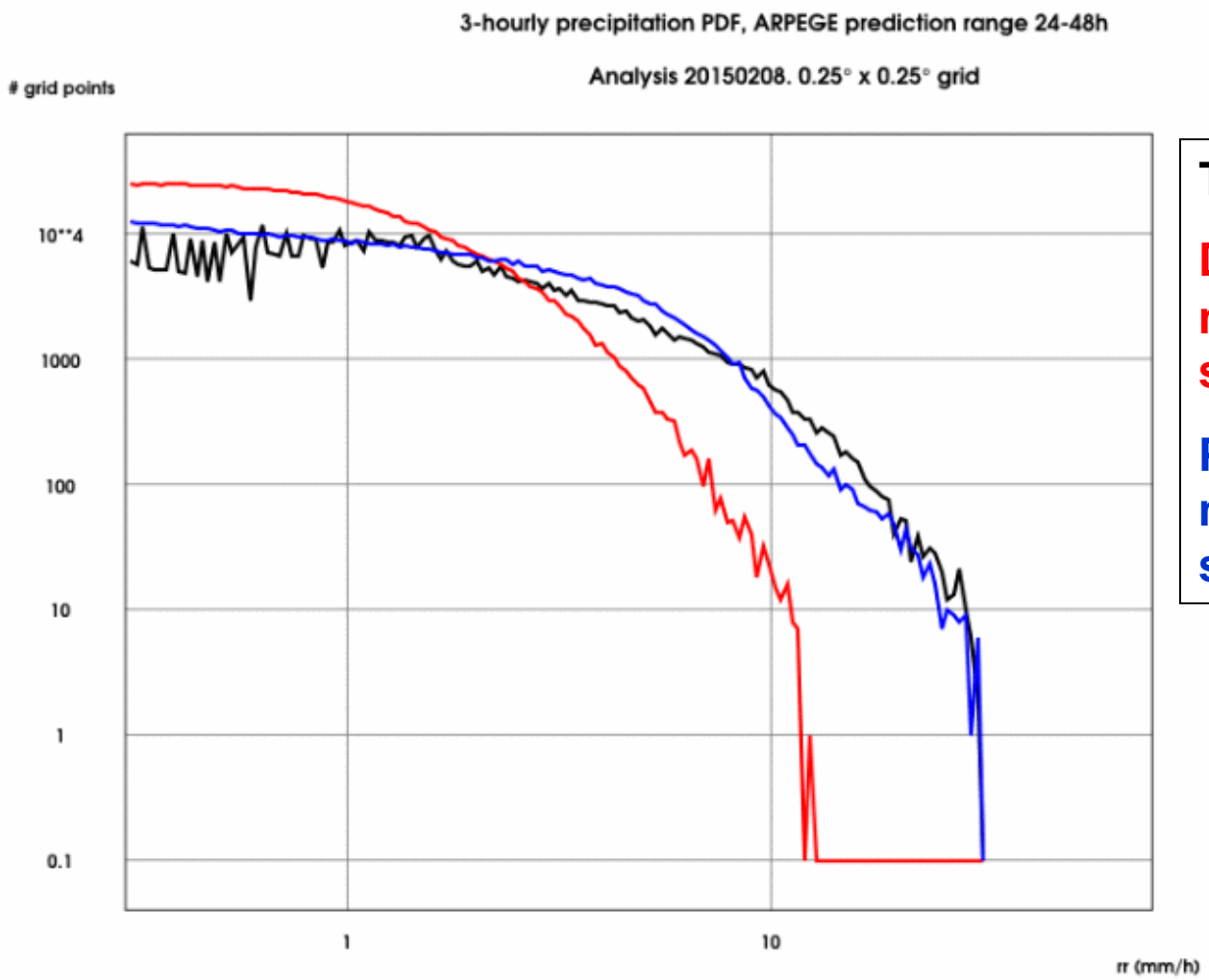
Environmental ice QI



Global budget (4-day average) with ARPEGE

Piriou (2015)

PDF of precipitation rate



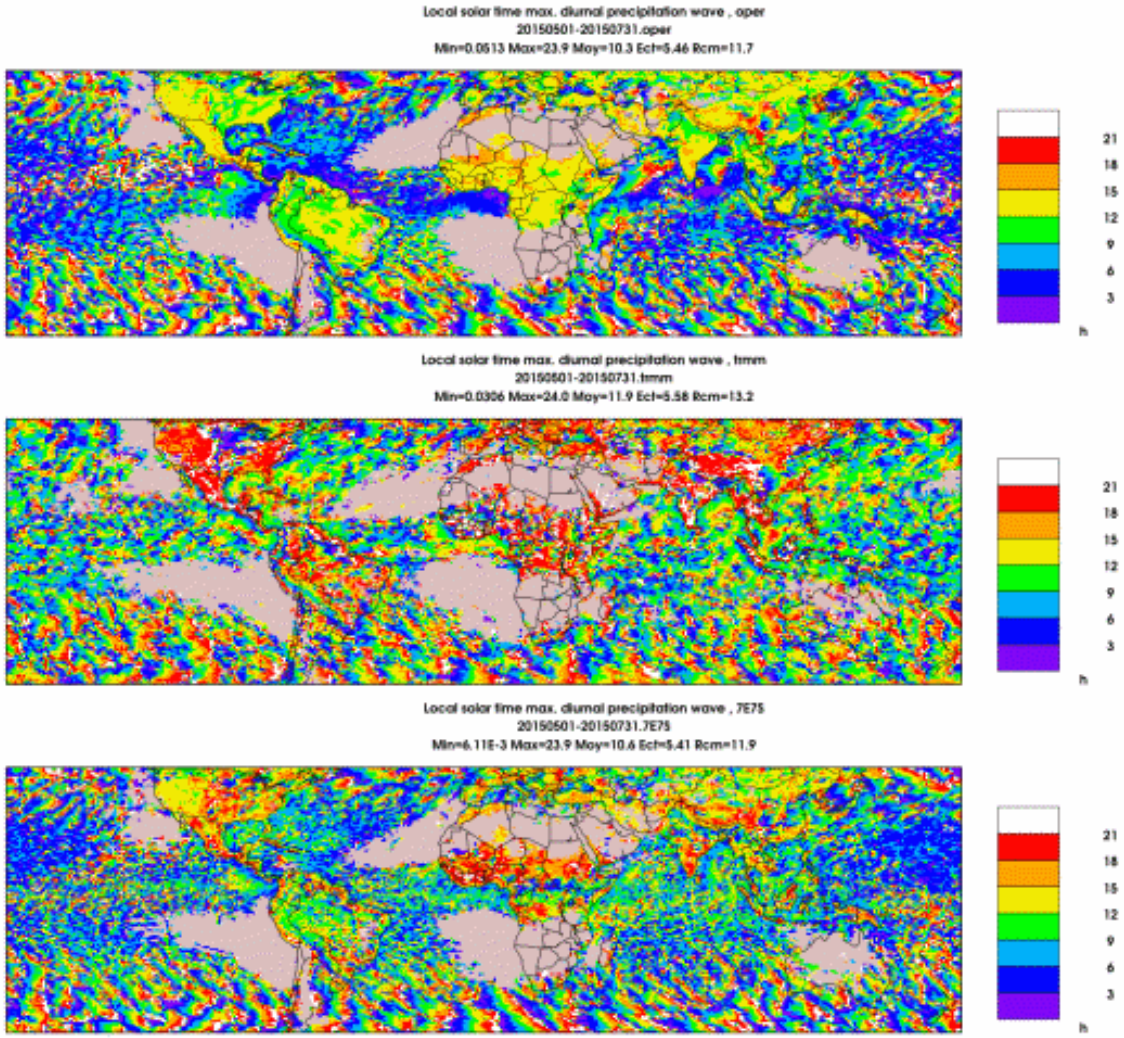
TRMM

Diagnostic mass-flux scheme

Prognostic mass-flux scheme

Piriou (2015)

The diurnal cycle of precipitation



OPER

TRMM

PCMT

Piriou (2015)

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EDMF : turbulence and shallow convection

EDMF : Eddy Diffusivity and Mass Flux scheme => unified framework

All NWP models use now « EDMF » framework:

$$\overline{w'\phi'} = -K\frac{\partial\overline{\phi}}{\partial z} + \frac{M_u}{\rho}\left(\phi_u - \overline{\phi}\right) \quad \text{with} \quad K = cL_{BL89}\sqrt{e}$$

Prognostic TKE Scheme: Cuxart et al. (2000), Bougeault & Lacarrere (89)

Shallow convection from Bechtold et al. (2001) for ARPEGE Pergaud et al. (2009) for AROME

$$\frac{\partial e_T}{\partial t} = advec + P_d + P_\theta - \frac{1}{\rho}\cdot\frac{\partial\overline{\rho w' e_T'}}{\partial z} - c_\varepsilon \cdot \frac{\overline{e}_T^{3/2}}{l_\varepsilon}$$

and

$$L_{BL89} = \left[\frac{\left(l_{up}\right)^{-\frac{2}{3}} + \left(l_{down}\right)^{-\frac{2}{3}}}{2}\right]^{-\frac{3}{2}}$$

Where l_{up} and l_{down} are computed using dry buoyancy following Bougeault and Lacarrère (1989)

NWP model and forward operator : which clouds ?

What level of consistency between the description of clouds and precipitation in the NWP model and in the forward operator ?

In practice, the information on clouds and precipitation given by the NWP model is not sufficient to define the various optical parameters required by a radiative transfer scheme to simulate fluxes, radiances or reflectivities

Radiative transfer schemes need information on :

-phase of particles (liquid, solid, melting)

-shape and density of particles (and orientation if not symmetric)

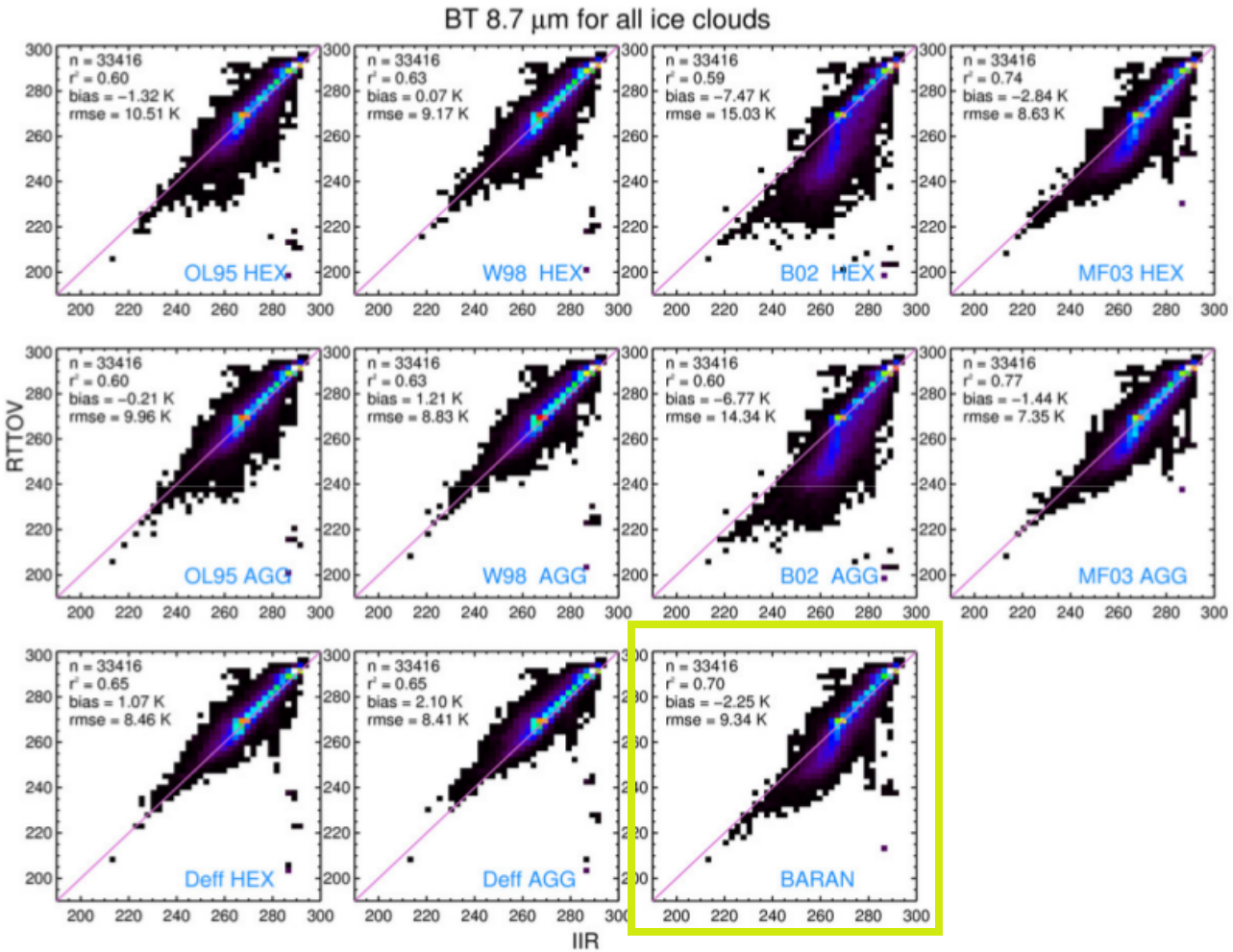
-particle size distribution (PSD) in the volume of interest

-fractional coverage (partition between clear, cloudy and precipitating areas)

-dielectric constant (to derive scattering and absorption coefficients)

NWP models can provide one (or two) moment(s) of the PSD, the phase (temperature based) and the fractional coverage (of cloudy areas)

Evaluation of cloud ice properties in RTTOV

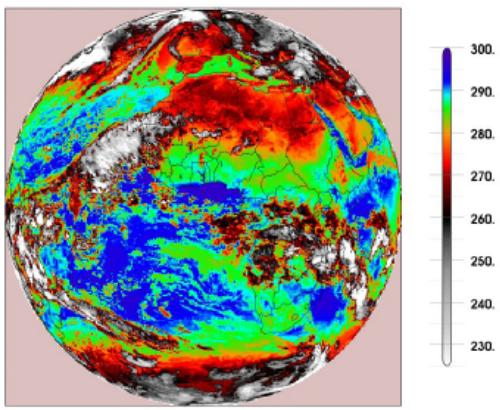


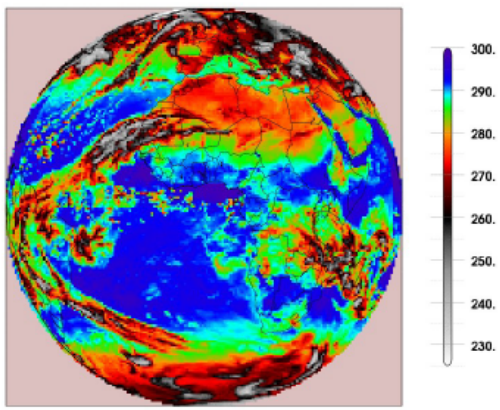
4 different relationships : $D_{eff} = D_{eff}(IWC)$
2 different shapes :
*hexagonal
*aggregates
D_{eff} profile as input

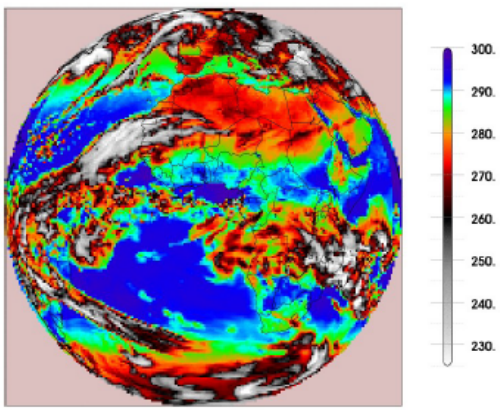
Baran et al. (2013) database
Optical properties are function of IWC and Tc

Evaluation using IWC from Cloudsat/Caliop

Simulation of METEOSAT IR radiances







Observation

METEOSAT 10 channel 10.8 µm

RTTOV/ARPEGE Simulation

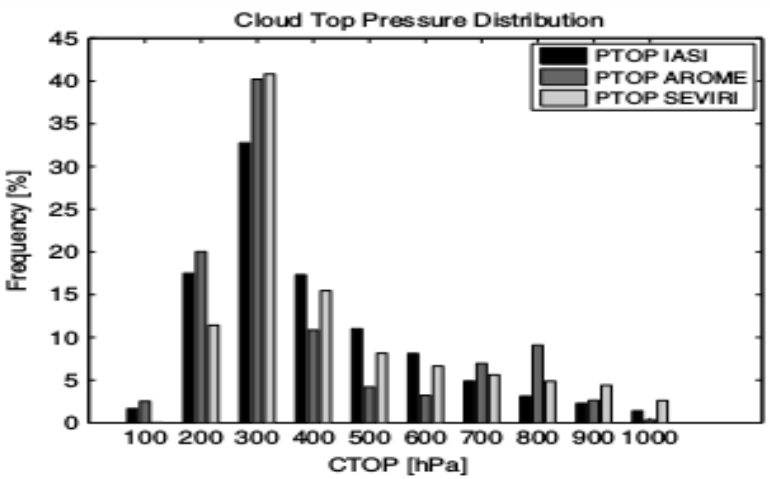
with **old** cloud optical properties

RTTOV/ARPEGE Simulation

with **new** cloud optical properties

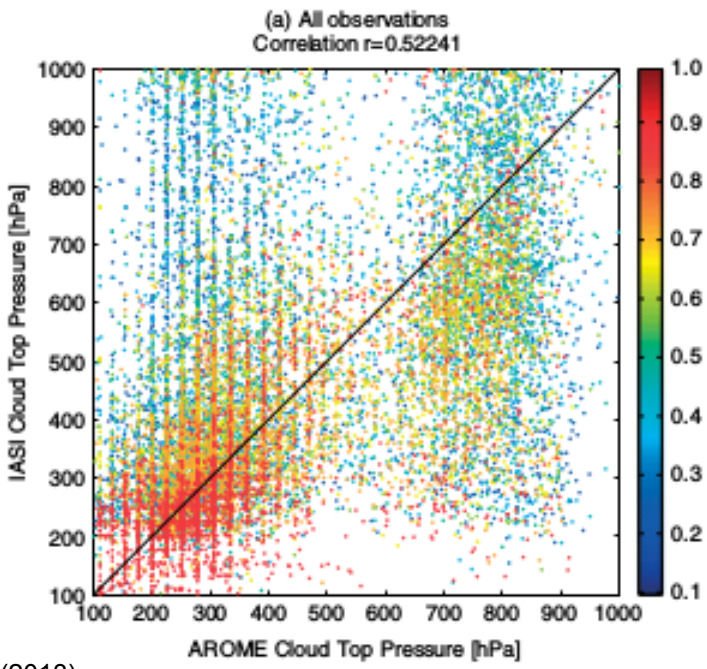
Different specification in the radiative transfer model but same fractional cover and cloud/ice contents

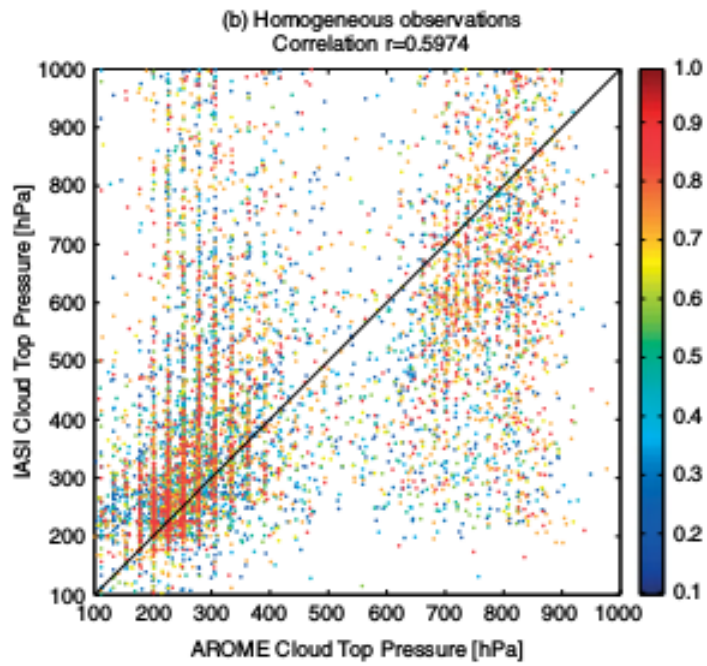
Simulation of IASI cloudy radiances (1)



Simulation of IASI radiances with RTTOV-CLD and the AROME model at 2.5 km (scale issues, displacement errors)

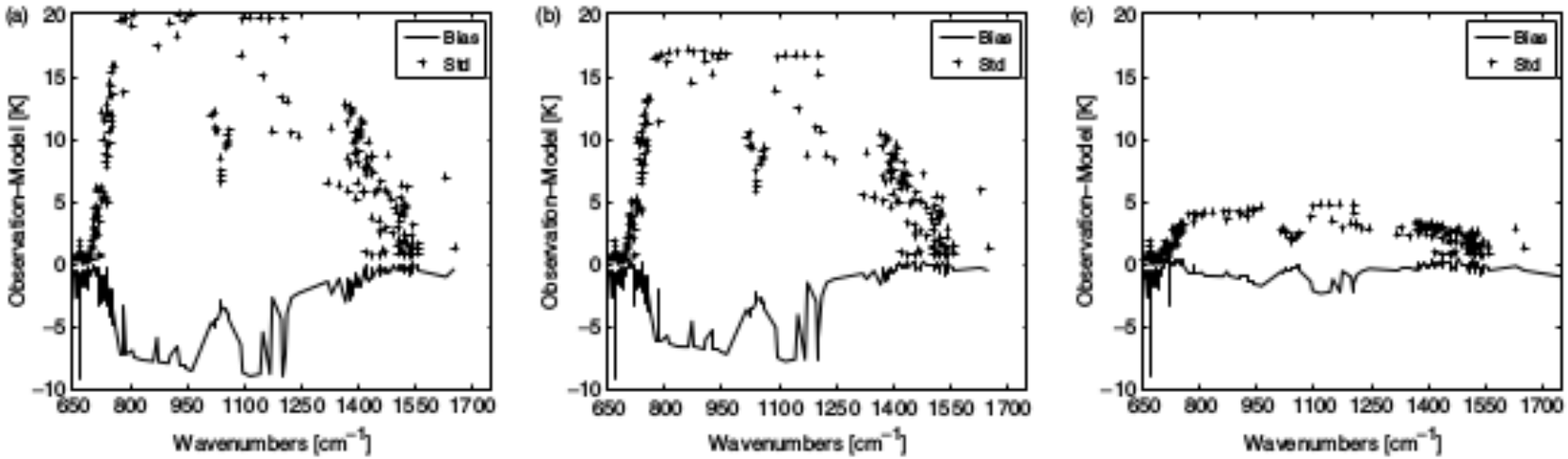
Cloud top pressure deduced from the « CO2 slicing technique »





Martinet et al. (2013)

Simulation of IASI cloudy radiances (2)



All overcast

All homogeneous overcast

All homogeneous overcast plus

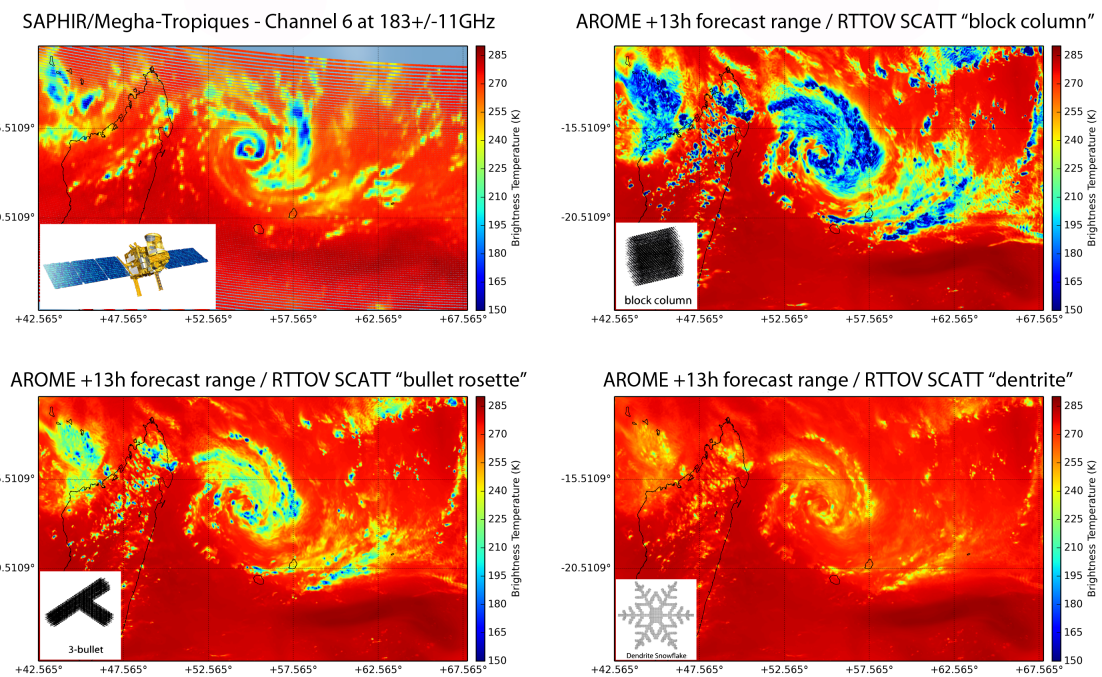
mean AVHRR (11 μm)

$|Tb_{obs}-Tb_{mod}| < 7$ K

Simulated cloudy IASI radiances with RTTOV-CLD and AROME 2.5 km

Martinet et al. (2013)

Simulation of SAPHIR radiances (183 GHz)



At 183 GHz: strong dependency of the radiance to scattering properties of solid hydrometeors

Optimal choice can be made by a « trial and error » approach : smallest differences between T_b obs and T_b sim

AROME (2.5 km) with ICE3 scheme and RTTOV-SCATT including 13 scattering properties of solid particles from Liu data base

Chambon (2015)

Optimal choice different with ALADIN and ECMWF models !

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Simulation of polarimetric radar data (1)

One moment cloud scheme (AROME and **MESO-NH**): ICE3 with 6 water species (water vapor, cloud water, rain water, graupel, snow aggregates and pristine ice)

PSD : Exponential for rain, snow and graupel, generalized Gamma for cloud water and pristine ice

Densities are given by mass-diameter relationships $m = aD^b$

What we would like to simulate :

-horizontal reflectivity Z_{hh}

-differential reflectivity Z_{dr}

-differential phase Φ_{dp}

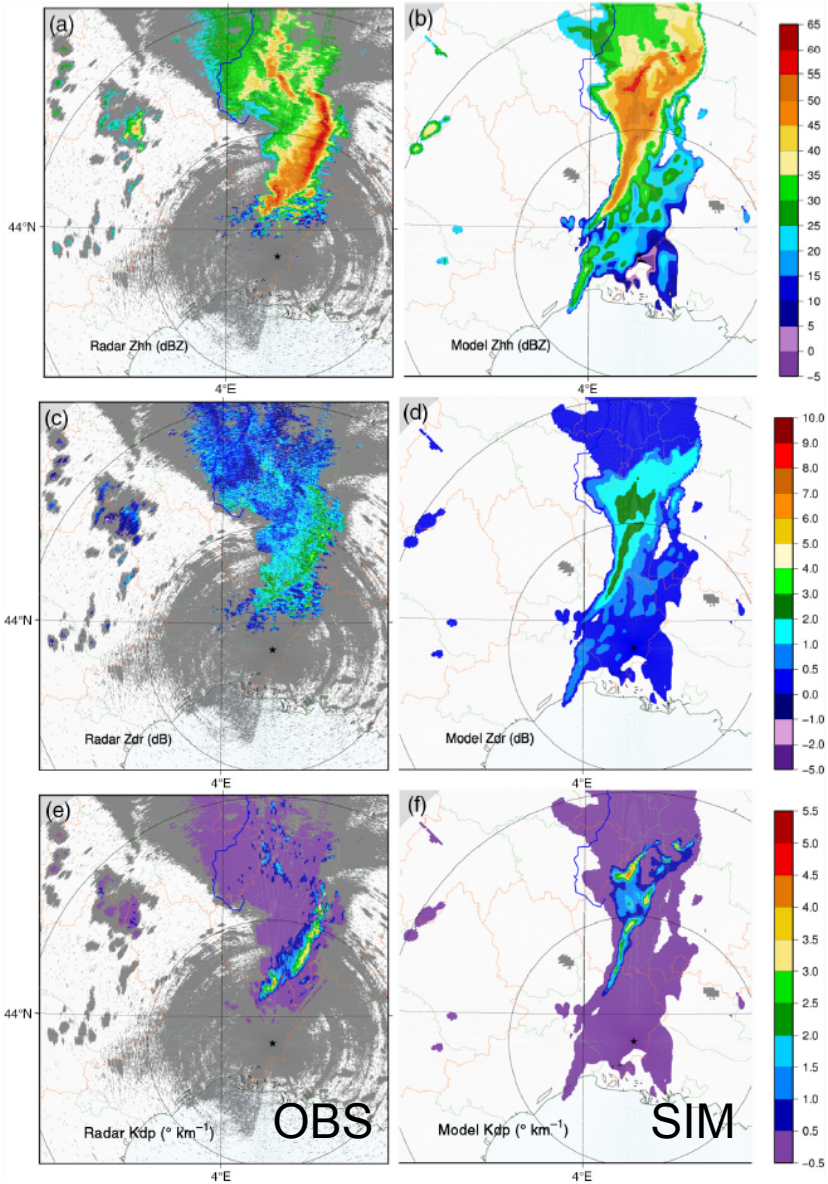
-specific differential phase K_{dp}

-co-polar correlation coefficient ρ_{hv}

What needs to be specified with some level of arbitrariness:
-raindrop shape : axis ratio $r = f(D_{eq})$
-dielectric function for snow and graupels (Maxwell-Garnett)
-dielectric properties for melting graupels

Ground based dual pol radars during HYMEX

Simulation of polarimetric radar data (2)



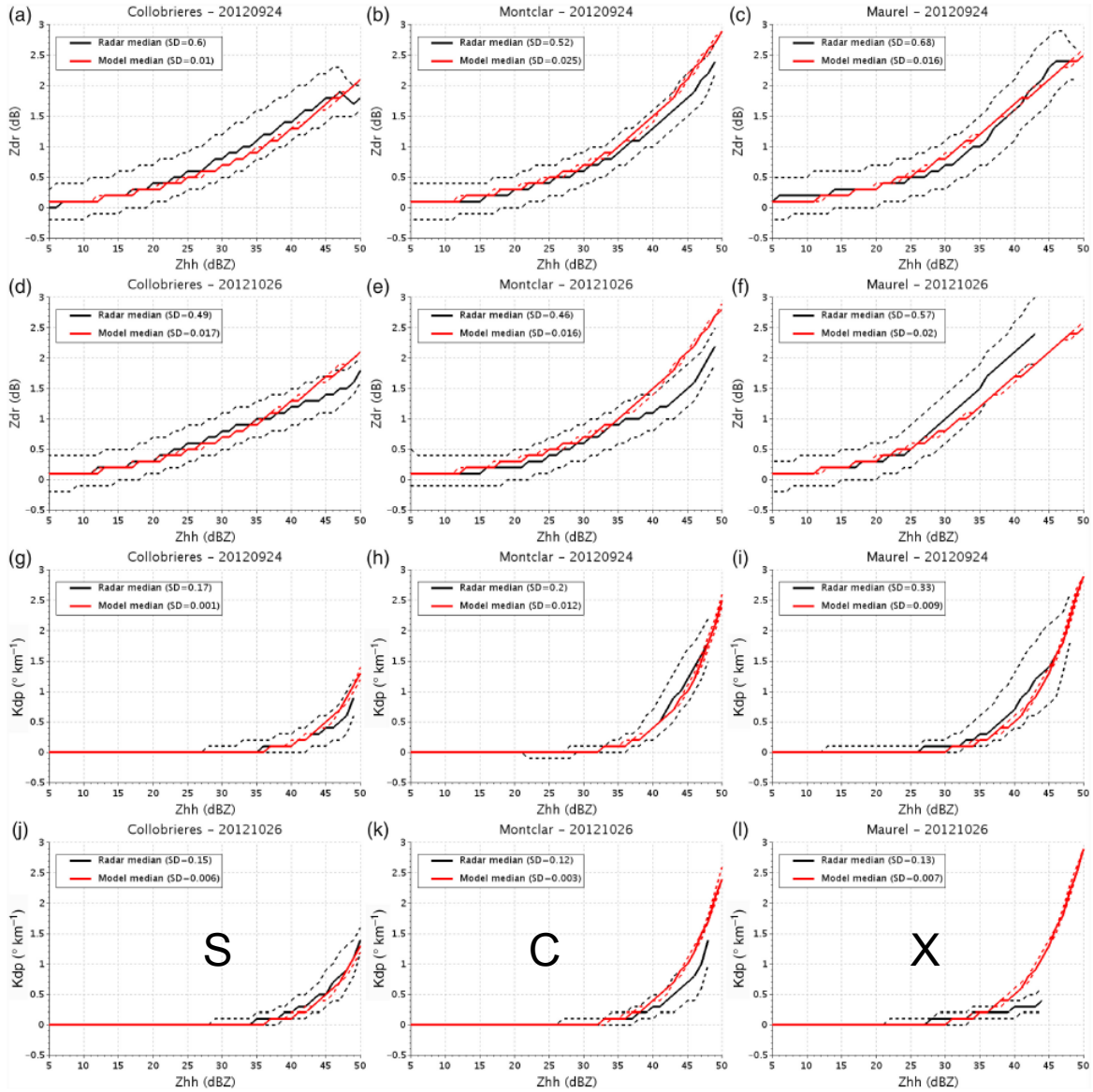
Z_{hh}

Z_{dr}

K_{dp}

Augros et al. (2014)

Simulation of polarimetric radar data (3)



$Z_{dr} = f(Z_{hh})$

$K_{dp} = f(Z_{hh})$

MODEL

RADAR

Lack of variability in the model

-> one moment scheme

Augros et al. (2014)

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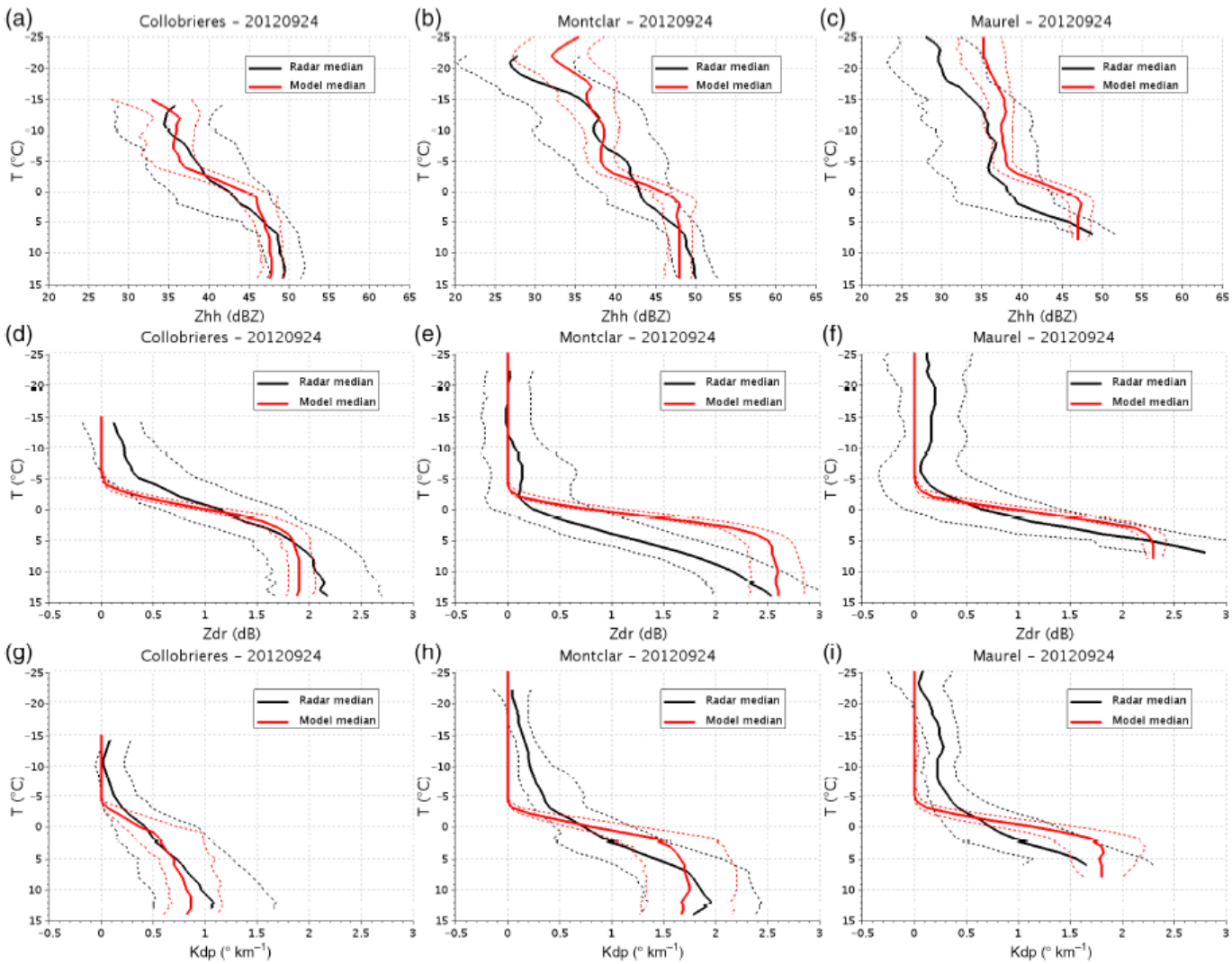
Simulation of polarimetric radar data (4)



$Z_{hh} = f(T)$

$Z_{dr} = f(T)$

$K_{dp} = f(T)$

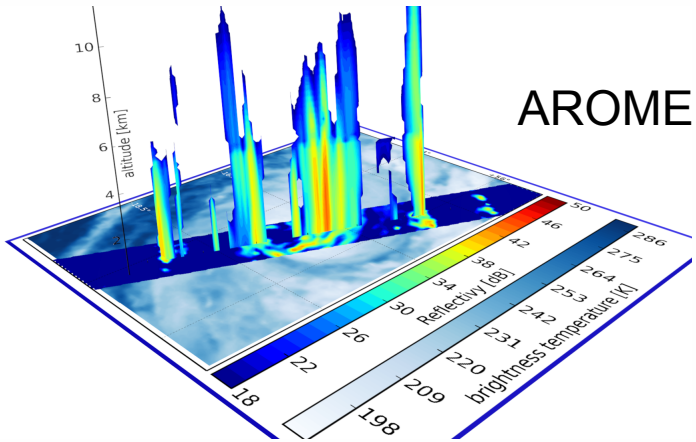
MODEL

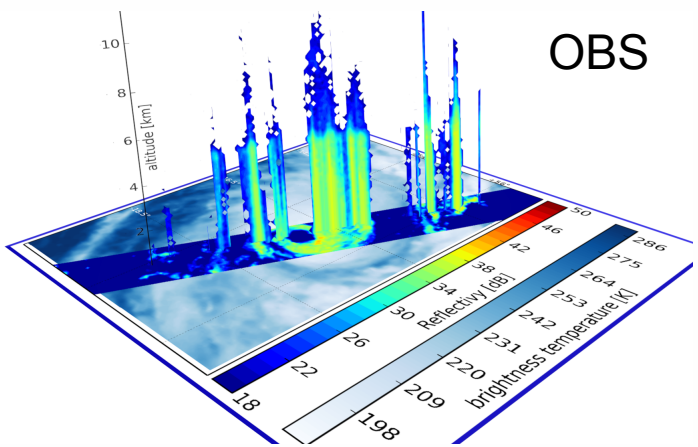
RADAR

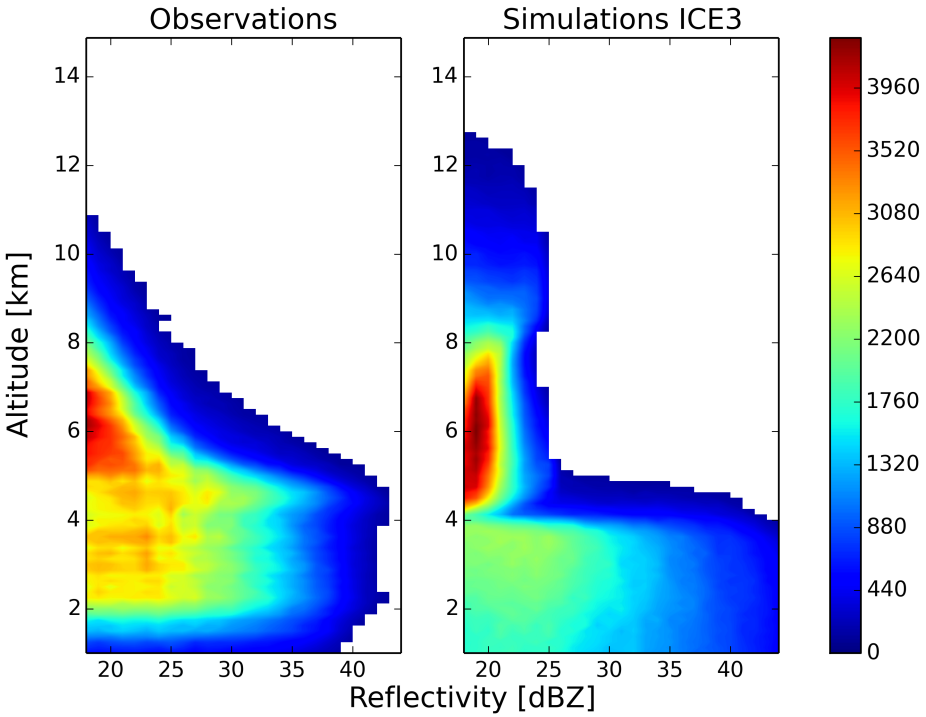
Augros et al. (2014)

S C X

Simulation of GPM DPR with AROME (1)







2D histograms (10 days) of DPR reflectivities in Ku band using microphysics consistent with ICE3 in SDSU radar simulator

Cyclone Bansi (Ka DPR reflectivity)

Borderies (2015)

Various possible PSD specifications

Microphysical Schemes	Hydrometers	Particle Size Distribution (m^{-3})	Intercept Parameters (m^{-4})	Slope Parameter (m^{-1})	Density ($kg\ m^{-3}$)
Lin	Rain	$N_r(D)=n_{or}\exp(-\lambda_r D_r)$	$n_{or}=8\times10^6$	$\lambda_r=(\pi\rho_w n_{or}/\rho q_r)^{1/4}$	1000
(Rutledge and	Snow	$N_s(D)=n_{os}\exp(-\lambda_s D_s)$	$n_{os}=3\times10^6$	$\lambda_s=(\pi\rho_s n_{os}/\rho q_s)^{1/4}$	100
Hobbs, 1983)	Graupel	$N_g(D)=n_{og}\exp(-\lambda_g D_g)$	$n_{og}=4\times10^4$	$\lambda_g=(\pi\rho_g n_{og}/\rho q_g)^{1/4}$	917
WSM6	Cloud	Monodisperse $Nc=1\times10^8$	$n_{or}=8\times10^6$	$\lambda_r=(\pi\rho_w n_{or}/\rho q_r)^{1/4}$	1000
(Hong et al.,	Rain	$N_r(D)=n_{or}\exp(-\lambda_r D_r)$	$n_{os}=2\times10^6\exp(0.12(T-T_0))$	$\lambda_s=(\pi\rho_s n_{os}/6\rho q_s)^{1/4}$	1000
2006; Hong et	Snow	$N_s(D)=n_{os}\exp(-\lambda_s D_s)$	$n_{og}=4\times10^6$	$\lambda_g=(\pi\rho_g n_{og}/\rho q_g)^{1/4}$	100
al., 2004)	Graupel	$N_g(D)=n_{og}\exp(-\lambda_g D_g)$			500
	Ice	$N_i(D)=5.38\times10^7(2.08\times10^{22}\times D^8)^{0.75}$			
WDM6	Cloud	$N_c(D)=3\lambda c^3 n_c D_c^2\exp(-\lambda_c D_c)^3$	$n_{or}=8\times10^6$	$\lambda_c=(\pi\rho_w\Gamma(2)n_c/6\Gamma(1)\rho q_c)^{1/3}$	1000
(Lim and	Rain	$N_r(D)=\lambda r^2 n_r D_r\exp(-\lambda_r D_r)$	$n_{os}=2\times10^6\exp(0.12(T-T_0))$	$\lambda_r=(\pi\rho_w\Gamma(5)n_r/6\Gamma(2)\rho q_r)^{1/3}$	1000
Hong, 2010)	Snow	$N_s(D)=n_{os}\exp(-\lambda_s D_s)$	$n_{og}=4\times10^6$	$\lambda_s=(\pi\rho_s n_{os}/6\rho q_s)^{1/4}$	100
	Graupel	$N_g(D)=n_{og}\exp(-\lambda_g D_g)$		$\lambda_g=(\pi\rho_g n_{og}/\rho q_g)^{1/4}$	500
	Ice	$N_i(D)=5.38\times10^7(2.08\times10^{22}D^8)^{3/4}$			
Thompson	Cloud				1000
(Thompson et	Rain	$N_r(D)=n_{or}\exp(-\lambda_r D_r)$	$n_{or}=(9\times10^9-2\times10^6)\tanh((10^{-4}-q_r)$		1000
al., 2008)	Snow	$N_s(D)=M_2^4/M_3^3(490.6\exp(-20.78$	$4\times10^4)/2+(9\times10^9+2\times10^6)/2$		
	Graupel	$M_2D/M_3+17.46\exp(-3.29DM_2/$	$M_2=\int D^2 N_s(D)dD\ M_3=\int D^3$		400
	Ice	$M_3)(M_2D/M_3)^{\mu s}))$	$N_s(D)dD$		890
		$N_g(D)=n_{og}\exp(-\lambda_g D_g)$	$n_{og}=\max(10^4, \min(200/q_g,$ $5\times10^6))$		
Milbrandt	Cloud	$N_c(D)=3n_c\lambda^6 D^5\exp(-\lambda_r D_r)^3$		$\lambda_c=(\pi\rho_w\Gamma(5)n_c/6\Gamma(2)\rho q_c)^{1/3}$	1000
(Milbrandt	Rain	$N_r(D)=n_{or}\exp(-\lambda_r D_r)$	$n_{oc}=n_c\lambda_c^2/\Gamma(2)$	$\lambda_r=(\pi\rho_w\Gamma(4)n_r/6\Gamma(1)\rho q_r)^{1/3}$	1000
and Yau,	Snow	$N_s(D)=n_{os}\exp(-\lambda_s D_s)$	$n_{os}=n_s\lambda_s^2/\Gamma(2)$	$\lambda_s=(\pi\rho_w\Gamma(4)n_s/6\Gamma(1)\rho q_s)^{1/3}$	100
2005)	Graupel	$N_g(D)=n_{og}\exp(-\lambda_g D_g)$	$n_{og}=n_g\lambda_g^2/\Gamma(2)$	$\lambda_g=(\pi\rho_w\Gamma(4)n_g/6\Gamma(1)\rho q_g)^{1/3}$	400
	Ice	$N_i(D)=n_{oi}\exp(-\lambda_i D_i)$	$n_{oi}=n_i\lambda_i^2/\Gamma(2)$	$\lambda_i=(440\rho_w\Gamma(4)n_i/\Gamma(1)\rho q_i)^{1/3}$	500
	Hail	$N_h(D)=n_{oh}\exp(-\lambda_h D_h)$	$n_{oh}=n_h\lambda_h^2/\Gamma(2)$	$\lambda_h=(\pi\rho_w\Gamma(4)n_h/6\Gamma(1)\rho q_h)^{1/3}$	900
Meso-NH	Cloud	$N_c(D)=3\lambda c^9 n_c D_c^6\exp(-\lambda_c D_c)^3/\Gamma(3)$			1000
(Pinty and	Rain	$N_r(D)=n_{or}\exp(-\lambda_r D_r)$	$n_{or}=8\times10^6$	$\lambda_r=4.1R^{-0.21}\times10^3$	1000
Jabouille,	Snow	$N_s(D)=n_{os}\exp(-\lambda_s D_s)$	$n_{os}=2.5\times10^6 S^{-0.94}$	$\lambda_s=2.29S^{-0.45}\times10^3$	
1998)	Graupel	$N_g(D)=n_{og}\exp(-\lambda_g D_g)$	$n_{og}=5\times10^5((\rho q_g/19.6\times5\times10^5\Gamma(2.$	$\lambda_g=$	
	Ice	$N_c(D)=3\lambda c^9 n_c D_c^6\exp(-\lambda_c D_c)^3/\Gamma(3)$	$8))^{-1/3.3})^{0.5}$	$(\rho q_g/19.6\times5\times10^5\Gamma(2.8))^{-1/3.3}$	

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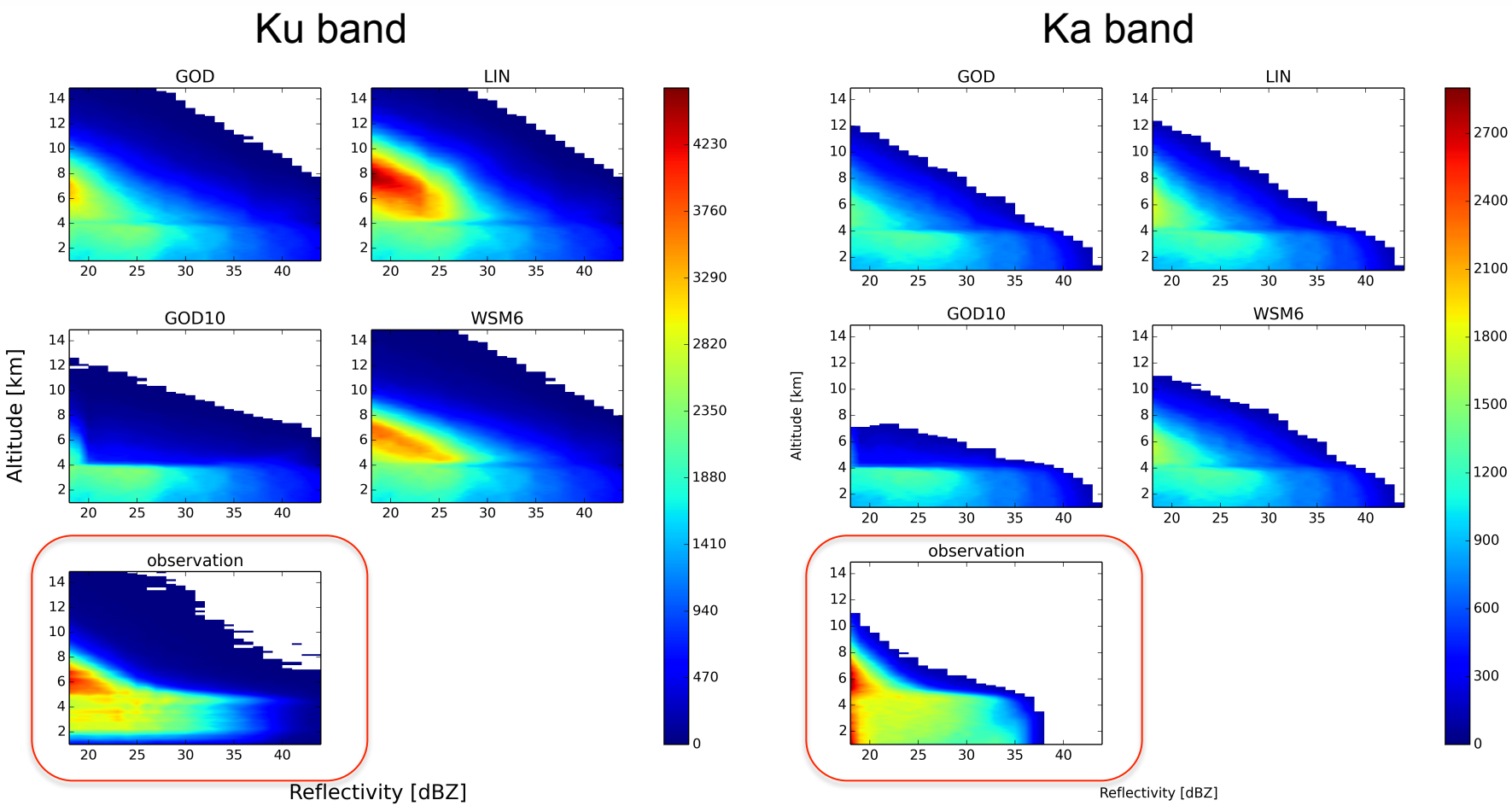
Simulation of GPM DPR with AROME (2)



Borderies (2015)

GOD : Tao (2003)
GOD10 : improved GOD
LIN : Lin et al. (1983)
WSM6: Hong et al. (2004)

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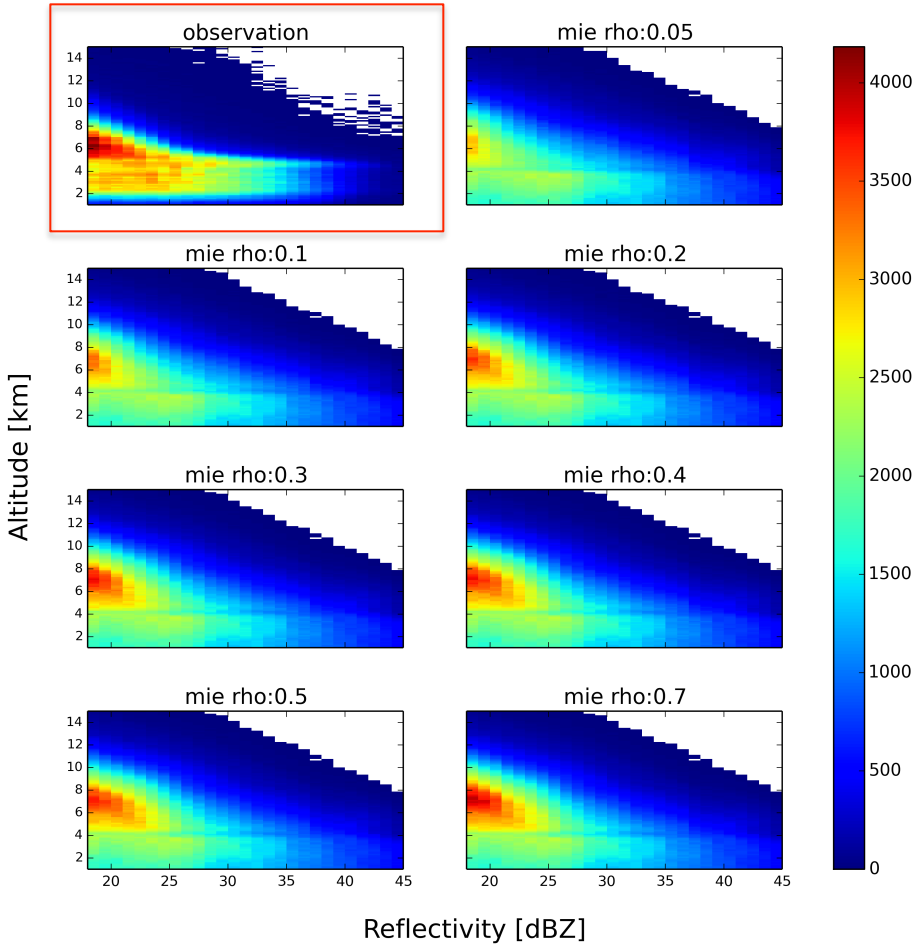
Simulation of GPM DPR with AROME (3)

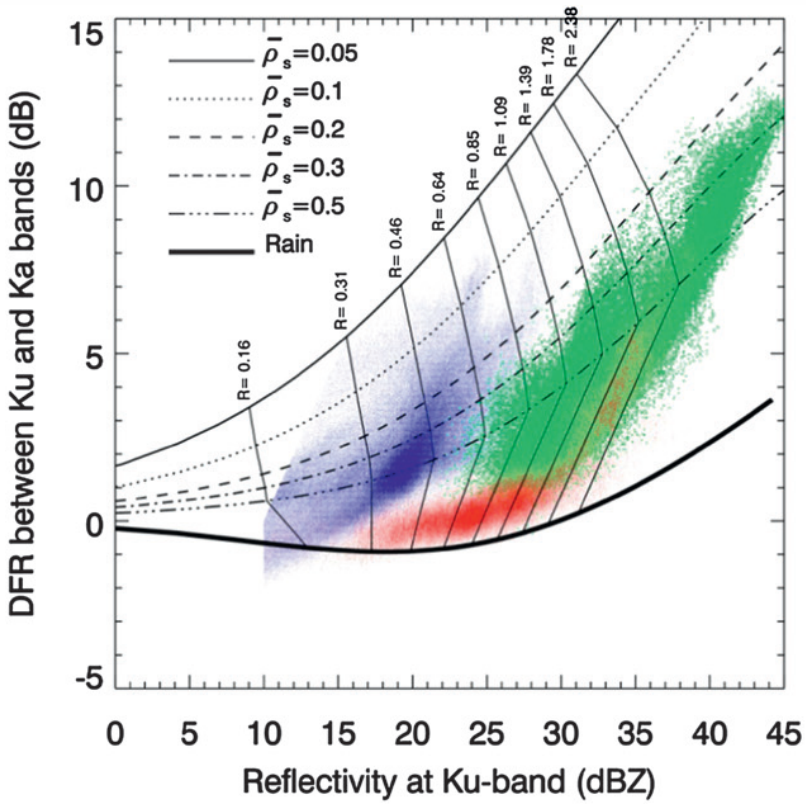


Borderies (2015)

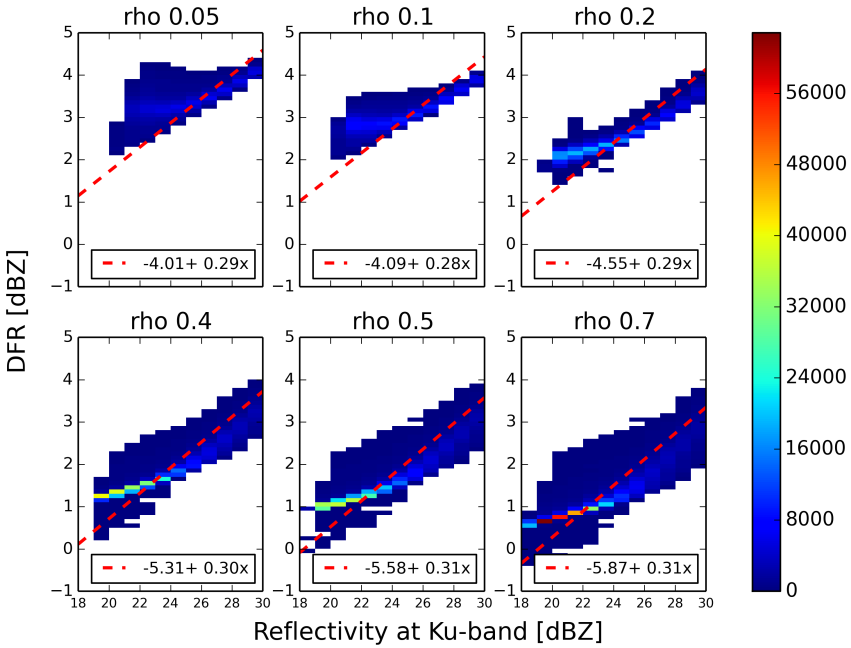
Sensitivity of Ku radar reflectivity simulation to snow density with GOD PSD

Simulation of GPM DPR with AROME (4)

Use of the Differential Frequency Ratio (DFR) to constrain the snow density specification (ρ_{snow}) in the radar simulator



From Liao and Meneghini (2011)



Same scatterplot and linear regression with observations => ρ_{snow} = 0.4

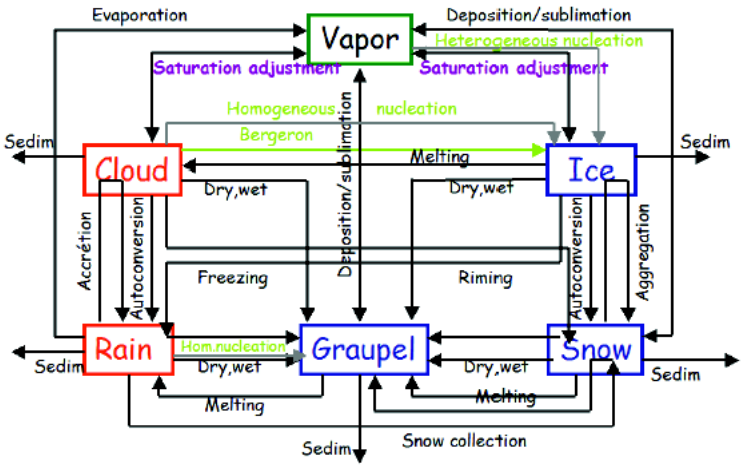
Borderies (2015)

Appropriate level of complexity ?

Difficult to build a microphysical scheme that can be suitable over a wide range of time steps (from few seconds to tenth of minutes)

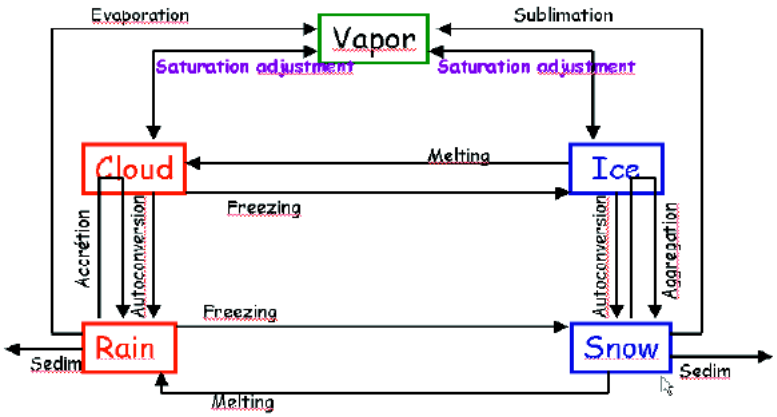
Global NWP: one-moment prognostic scheme is probably enough for the next years (in stratiform and convective parts)

Convective-scale NWP: two-moment schemes are expensive but could be a better choice



AROME (ICE3)

(Caniaux, 1993 – Pinty and Jabouille, 1998)



ARPEGE

(Lopez, 2002 – Bouteloup et al., 2005)

Improved microphysical schemes

Development of two-moment microphysical schemes => additional variables for number concentration (coupling with CCNs and IFNs)

Interest in three-moment microphysical schemes => 6th order moment (reflectivity) as a prognostic variable (Milbrandt and Yau, 2005) – Better than one and two-moment schemes for the assimilation of radar reflectivities (Laroche et al., 2005)

A more continuous approach for solid hydrometeors (avoiding the definition of particle categories) has been recently proposed by Milbrandt and Morrisson (2015)

Improved schemes => more physical but more prognostic variables

Do we need to initialize all these prognostic variables ?

What is the best assimilation framework for the inclusion of such variables ?

Microphysics and data assimilation (1)

$$Z \propto \int N(D) D^6 dD$$

$$LWC \propto \int N(D) D^3 dD$$

$$N = \int N(D) dD$$

Observables depending upon PSD

Twin experiments in a 2D-Var context (Laroche et al.,2005):
rain sedimentation and
evaporation below cloud base (2km)

Microphysical scheme evolving in time various moments M_m of the PSD.

Minimisation of a cost-function : initial and upper conditions of predictive moments

At model lid : PSD prescribed from an exponential distribution with Z varying in time

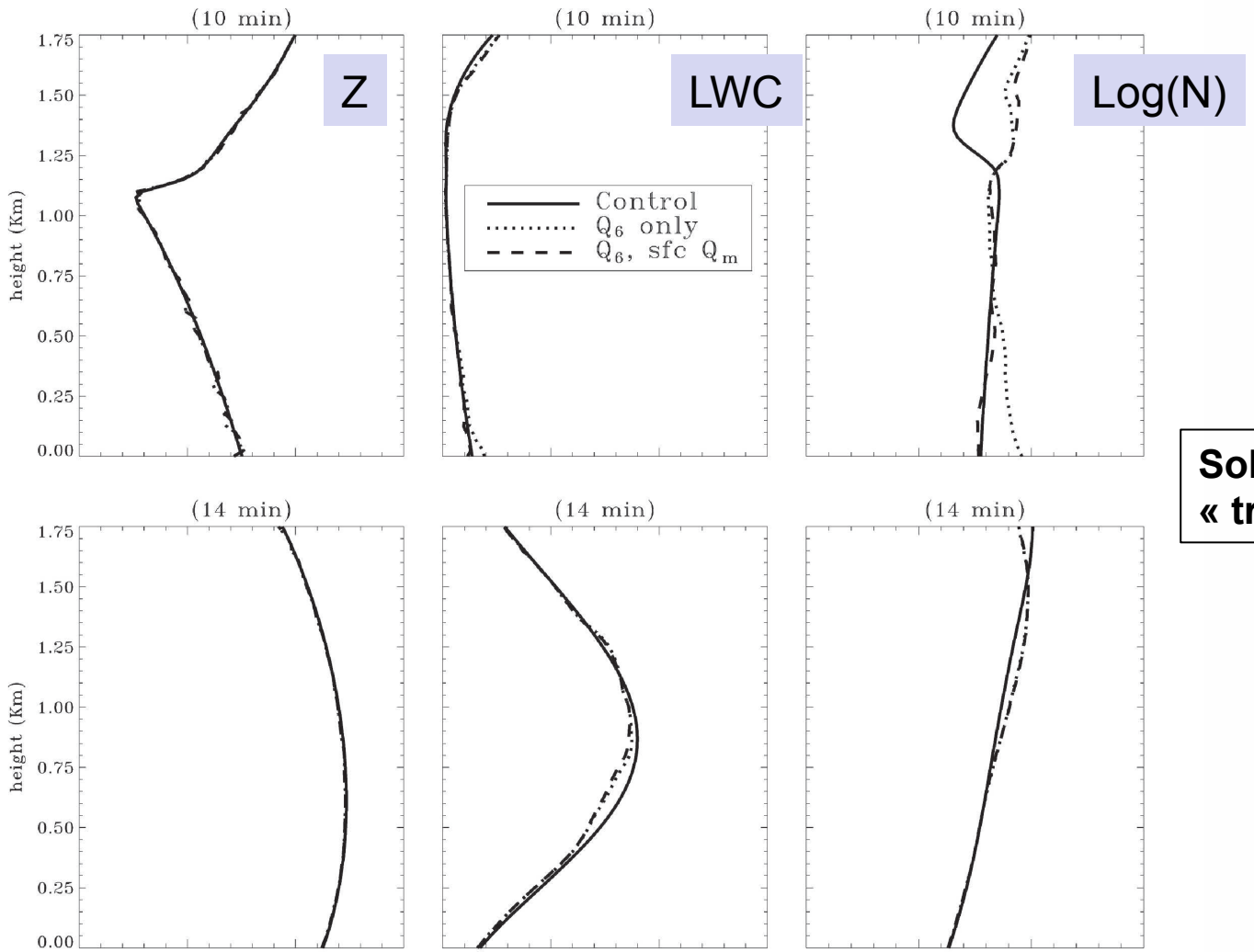
First-guess: exponential distribution with N_o halfed

Assimilation window: 8 min

Microphysics and data assimilation (2)

10 min

14 min



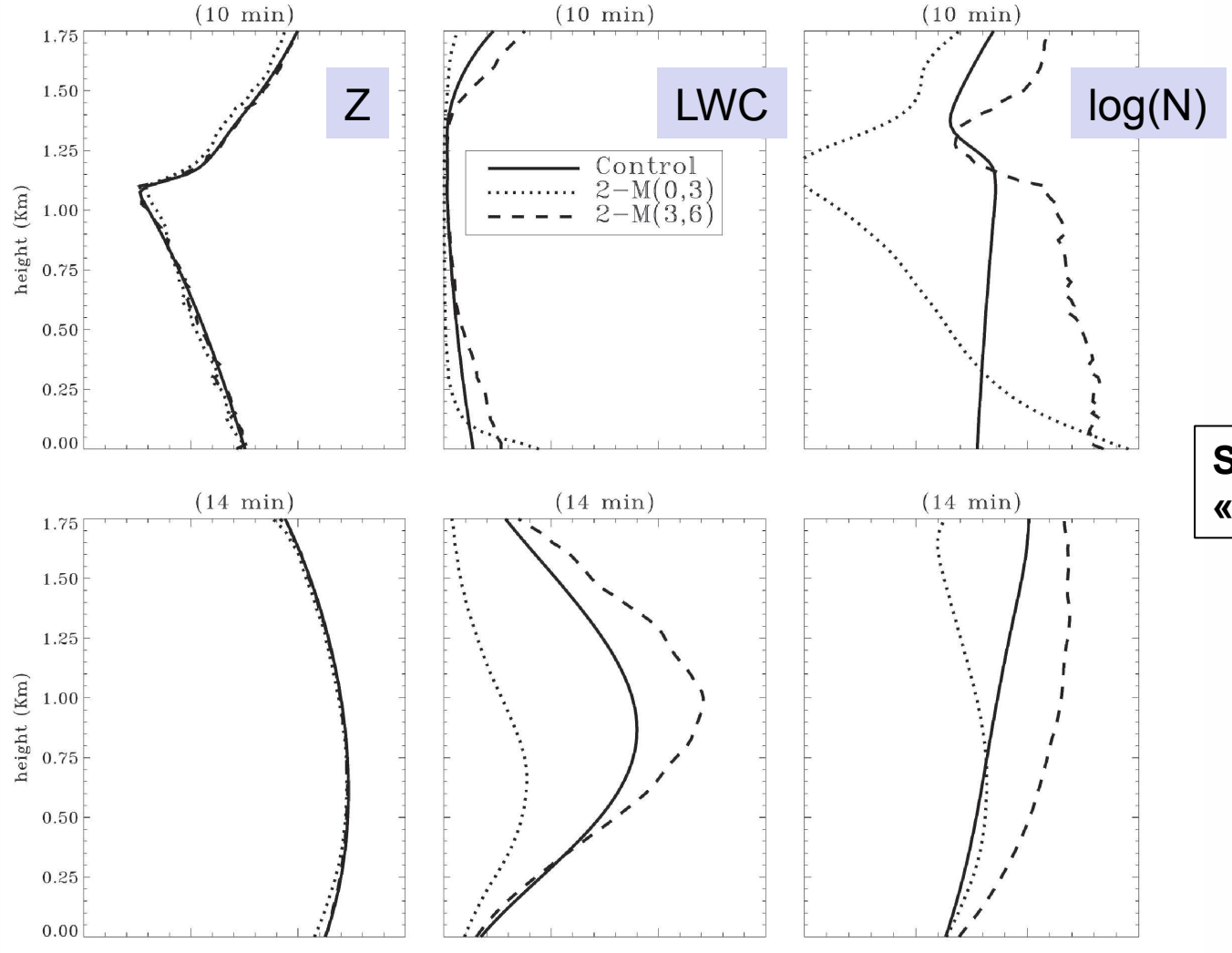
Solid line = « truth »

Three-moment scheme (M_0,M_3,M_6)

Microphysics and data assimilation (3)

10 min

14 min



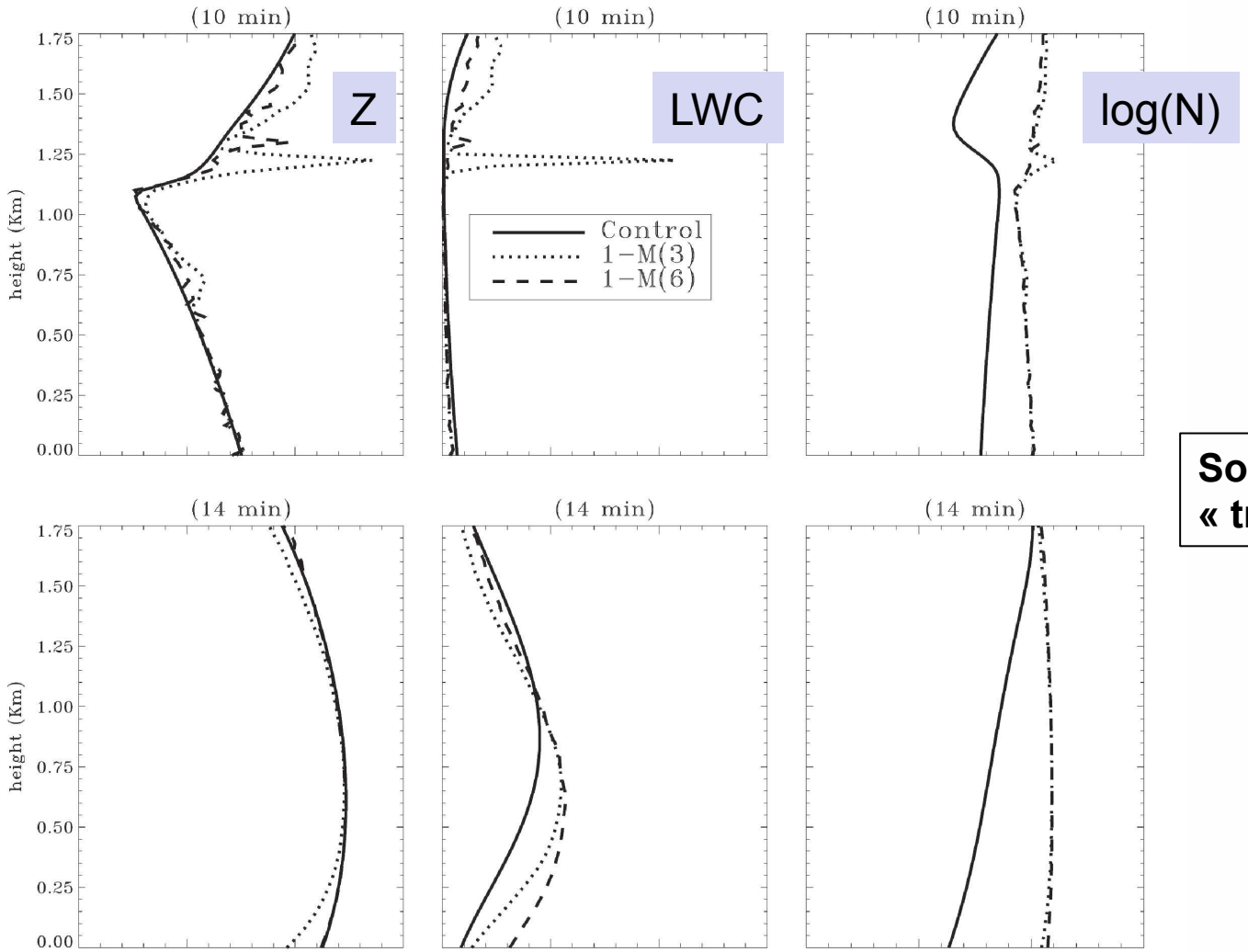
Solid line = « truth »

Two-moment schemes (M_0,M_3) and (M_3,M_6)

Microphysics and data assimilation (4)

10 min

14 min



Solid line = « truth »

One-moment scheme (M_3) and (M_6)

Conclusions

Improvements in clouds and precipitation description in NWP during the last 10 years. Importance of systematic comparisons of model results in obs space

More consistency between the various phases of water (vapor, cloud, precipitation) together with the radiative processes (beneficial to the simulation of radiances and reflectivities)

More continuity between physical processes (dry convection, shallow convection, deep convection) – Validity of tangent linear approximation

More complex microphysical schemes allow to reduce the number of degrees of freedom when simulating cloudy radiances (and radar reflectivities)

Ensemble techniques should in principle be able to handle additional prognostic variables (and their background error covariances)

Synergy between observations (MW, IR, VIS, active, passive) is the best way to address the inversion problem in cloudy and precipitating areas

Questions

What is the level of details and of consistency for data assimilation (e.g. PSD, fractional coverage, …) ?

Does it depends upon the observations to be assimilated ?

Are they additional requirements specific to data assimilation ?

Could they depend upon the data assimilation of interest (var, ensemble) ?

What is the importance of the validity of the tangent-linear approximation ?

How to address scale issues between model resolution and satellite footprint ?

What are the requirements in order to progress towards the assimilation of IR and VIS radiances ?

What is the relevance in quantifying and/or reducing systematic model errors (biases) from physical processes in data assimilation ?

Thank you for your attention !

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