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Towards Prognostic Aerosols in COSMO Microphysics Scheme

Harel Muskatel (IMS), Uli Blahak (DWD),
Pavel Khain (IMS), Alexander Khain (HUJI)

Acknowledgments: Alessio Bozo (ECMWF)

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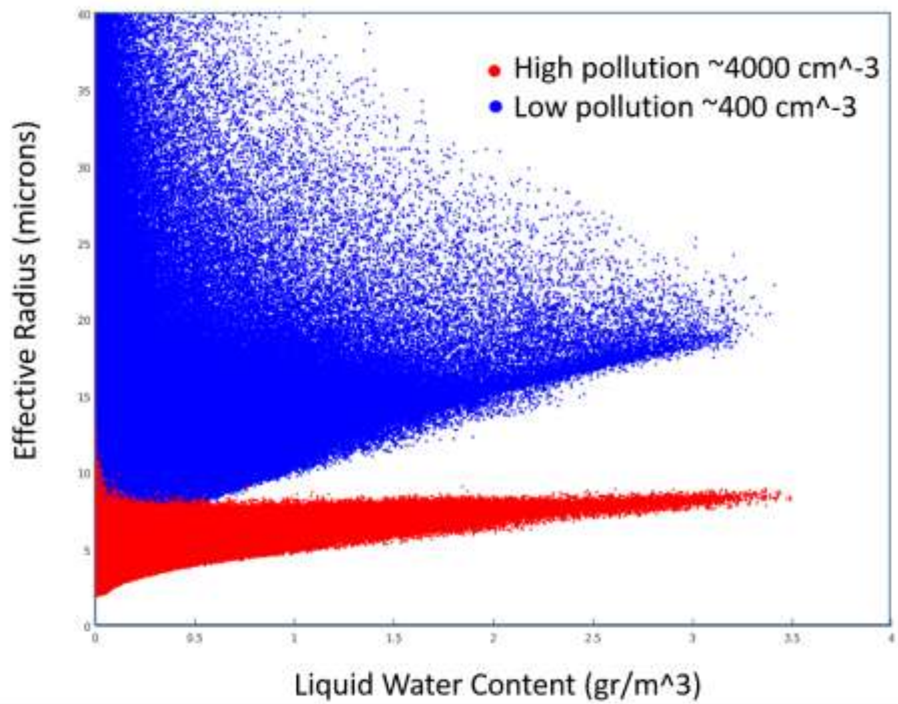
Outline

- Motivation for using prognostic aerosols in radiation & microphysics schemes
- The Segal & Khain (2006) scheme
- New cloud number concentration scenarios in COSMO
- The CAMS model
- Test case of April 25-27, 2018
- Impact on precipitation, radiation, T2m, LWC, R_{eff}
- Overall scores
- Concluding remarks and outlook

Motivation - radiation



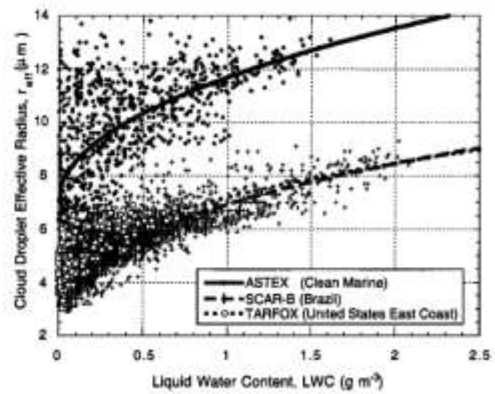


Figure 6. Cloud droplet effective radius (r_{eff}) versus liquid water content (LWC) for cumulus clouds in clean marine air over the northeastern Atlantic Ocean (diamonds, Atlantic Stratocumulus Transition Experiment (ASTEX)), in urban-industrial air off on the U.S. east coast (circles, Tropospheric Radiative Forcing Experiment (TARFOX)), and in air masses dominated by smoke from biomass burning (pluses, Brazil).

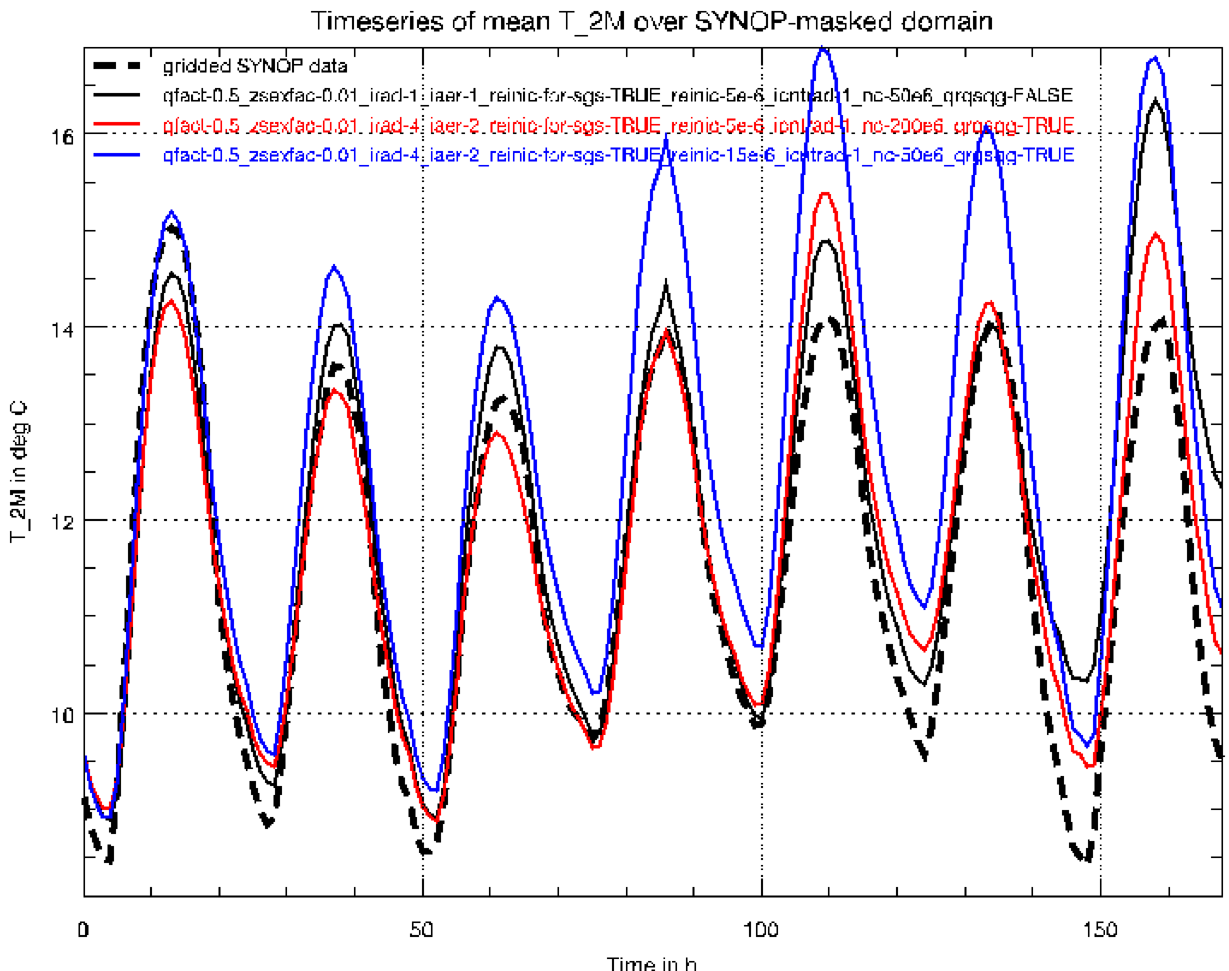
- Effective radius in SGS clouds in operational mode is fixed number ($R_{eff} = 5\ \mu m$)
- Effective radius in grid scale clouds in operational mode is based only on LWC
- For iradpar_cloud=4:

$$R_e = \frac{1}{2}\frac{M_3}{M_2} = c_1\left(\frac{\rho_x}{n_x}\right)^{c_2}$$

Motivation - radiation

Sensitivity of T_{2M} in 7-day experiment to SGS Reff

COSMO-EU / COSMO-DE setup (1-moment microphysics) /**COSMO-DE results:**

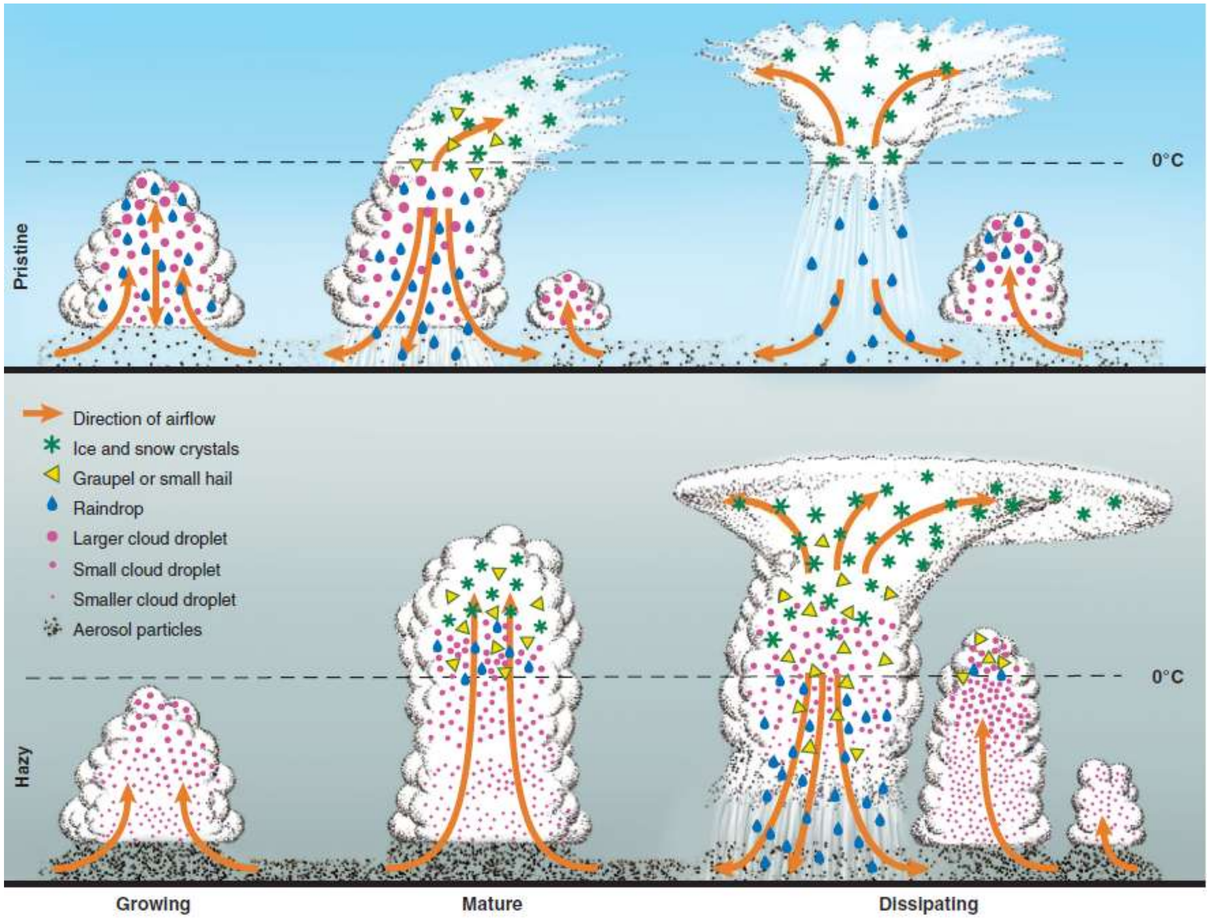


Motivation – clouds formation & precipitation

- Cloud droplets number concentration in the default COSMO 1-mom scheme is fixed to **cloud_num** ($500\ cm^{-3}$). In 2-mom schemes it depends on fixed/climatology aerosols number concentrations
- But variations in the densities of aerosols which act as cloud condensation nuclei CCN can have large impact on cloud formation, dynamics and precipitation

Pristine tropical clouds with low CCN concentration can rain out too quickly to mature to long lived clouds

Polluted clouds with very high CCN concentrations may evaporate before rain can occur



Rosenfeld et al., Science, 321 , 2008

Segal & Khain scheme in COSMO radiation

Option 1: cloud_num_rad

➔ **icloud_num_type_rad = 1**

- $n_C(z)$ has assumed exponentially decreasing vertical profile above z_0:

$$n_C = n_{C0} \begin{cases} \exp\left(-\frac{z-z_0}{\Delta z_{1/e}}\right) & \text{if } z > z_0 \\ 1 & \text{else} \end{cases} \quad \left[\text{kg}^{-1}\right]$$

- **cloud_num_rad** is n_{C0} default 200 cm^{-3}
- dz_oe_cloud_num = $\Delta z_{1/e}$ in [m] (half its value every 6000 m).
- zref_cloud_num = z_0 in [m] (2000 m)

- $R_{e,C}$ from $n_C(z)$ and $q_C(z)$ resp.

$$R_e = c_1 \left(\frac{q_C}{n_C}\right)^{c_2}$$

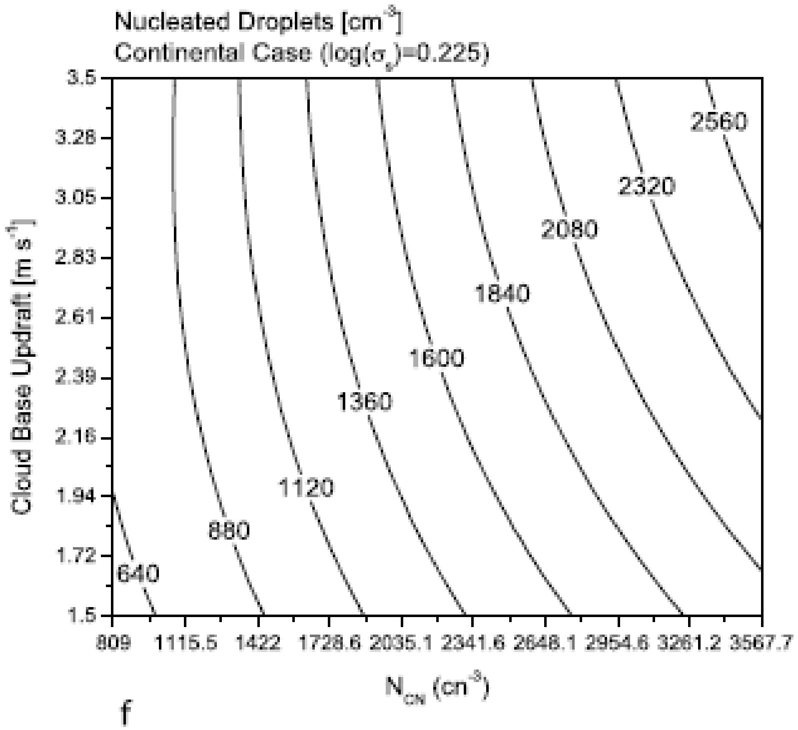
Segal & Khain scheme in COSMO radiation

Option 2: Segal & Khain

➔ **icloud_num_type_rad = 2 (Tegen) / 4 (CAMS)**

- Cloud nuclei profile $n_{CN}(z)$ is estimated from Tegen/CAMS aerosols
- Activation of n_{CN} to n_{CCN} is estimated from Segal & Khain (2006) parameterization based on the estimated vertical velocity at cloud base
- n_C is assumed equal to n_{CCN}
- 4D look-up table:

$$n_{ccn}^{SK} = f(n_{cn}, log(\sigma), r_{mod}, w_{CB})$$



Segal & Khain (2006)

Segal & Khain scheme in COSMO radiation

Option 2: Segal & Khain activation

- In „active“ clouds ($w_{nuc} > w_{cb,min}$ and $q_c > 0$ or clc_con > 0 over several adjacent height layers), activation is at cloud base and n_{CN} decreases exponentially above cloud base (→ autoconversion, accreation).
- All other grid points: derive n_c from lookup table based on local n_{CN} and w_{nuc}
- Let $n_{CCN,SK}$ be the lookup table, then:

$$n_C(z) = \begin{cases} n_{CCN,SK}\left(n_{CN}(z_{cb}), w_{nuc}(z_{cb})\right) \exp\left(-\frac{z-z_{cb}}{\Delta z_{a,1/e}}\right) & \text{if } w \geq w_{cb,min} \wedge q_C(z) > 0 \wedge z \geq z_{cb} \\ n_{CCN,SK}\left(n_{CN}(z), \max[w_{nuc}(z), w_{cb,min}]\right) & \text{else} \end{cases} \quad [\mathrm{kg}^{-1}]$$

- Effective updraft speed w_{nuc} for nucleation, including turbulence, radiative cooling an parameterized convection:

$$w_{eff} = \overline{w} + 0.7\sqrt{\frac{2\,TKE}{6}} - \frac{c_p}{g}\left.\frac{\partial T}{\partial t}\right|_{\text{radiation}}$$

$$w_{nuc} = \max\left[w_{eff}, w^*\right]$$

$$w^* = \left(-g\, z_{topcon} \frac{\overline{w'\Theta'_{v,S}}}{\overline{\Theta_{v,S}}}\right)^{1/3}$$

(convective velocity scale after Deardorff)

→ z_{top_con}: PBL height as determined from $\Theta_v < \Theta_{v,surf}$+0.5 K, or upper bound of lowest continuous „clc_con“ layer

Segal & Khain scheme in COSMO radiation

R_{eff} in SGS clouds:

- SGS water clouds with a fixed R_{eff}: Tuning parameter **reff_ini_c** (default: 5µm) **luse_reff_ini_c_as_reffc_sgs = .TRUE.**
- Improvment: SGS R_{eff} treated same way as in grid scale clouds - luse_reff_ini_c_as_reffc_sgs = .FALSE.

but using $LWC_{SGS} = QC\_RAD/(CLC * radqcfact)$

QC_RAD = QCI_CON * CLC_CON + QC_SGS * CLC_SGS * (1 – CLC_CON)

$$R_e = c_1 \left(\frac{q_C}{n_C}\right)^{c_2}$$

Segal & Khain scheme in COSMO microphysics

Number concentration of cloud droplets in 1-mom scheme options:

➔ **icloud_num_type_gscp = 1**

- Cloud number concentration is a tuning parameter **cloud_num**

  default: $500\ cm^{-3}$

➔ **icloud_num_type_gscp = 4**

Cloud number concentration is calculated using CAMS + SK the same way as for itype_num_type_rad = 4

➔ The new cloud_num (qnc) effects the 1-mom via the auto-conversion parameterization (cloud water → rain water):

$$\frac{d(qc)}{dt} \sim -\frac{qc^4}{qnc^2} = -\frac{qc^2}{xc^2} \quad (xc = \text{mean droplet mass})$$

➔ **The effects on radiation (effective radius) and on microphysics can be separated or combined**

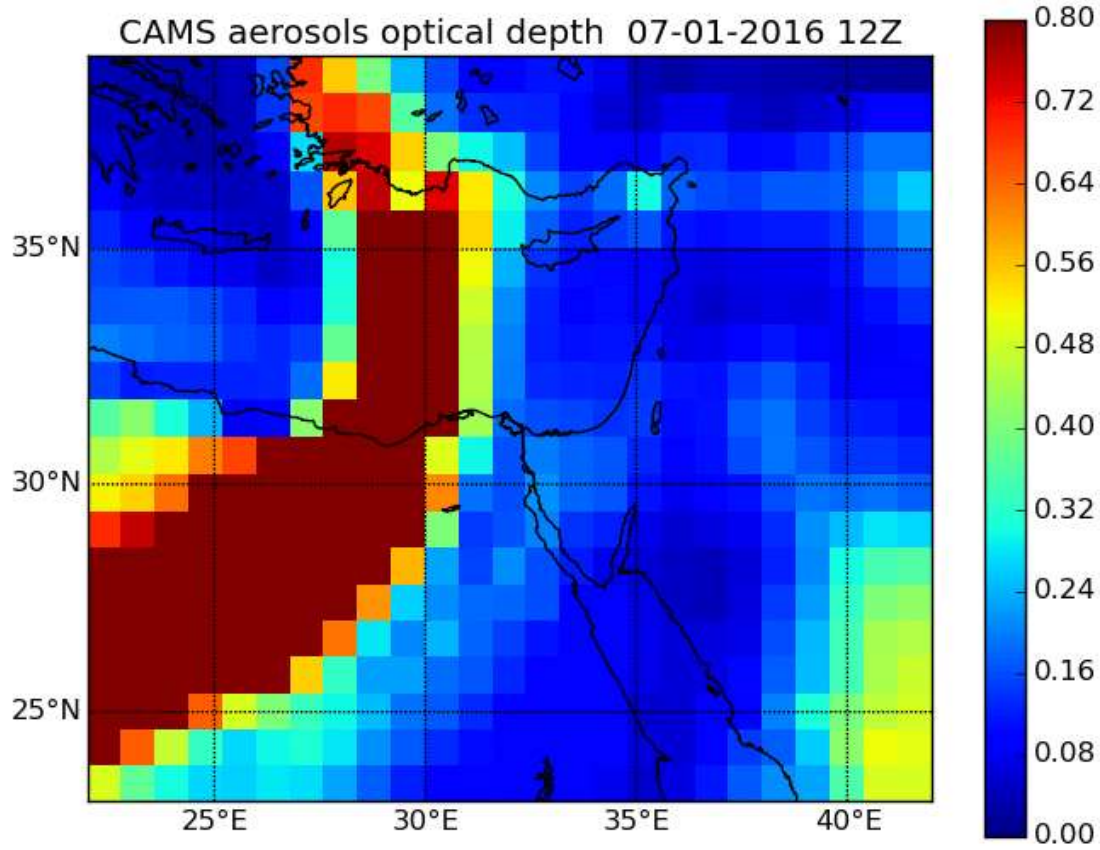
CAMS prognostic aerosols

Atmosphere Monitoring Service

itype_aerosol = 4

- Built on the ECMWF NWP system with additional prognostic aerosol variables
- Input aerosols analysis:
  - NASA/MODIS Terra and Aqua Aerosol Optical Depth at 550 nm
  - NASA/CALIOP CALIPSO Aerosol Backscatter
  - AATSR, PMAP, SEVIRI, VIIRS
- Verification based on AERONET

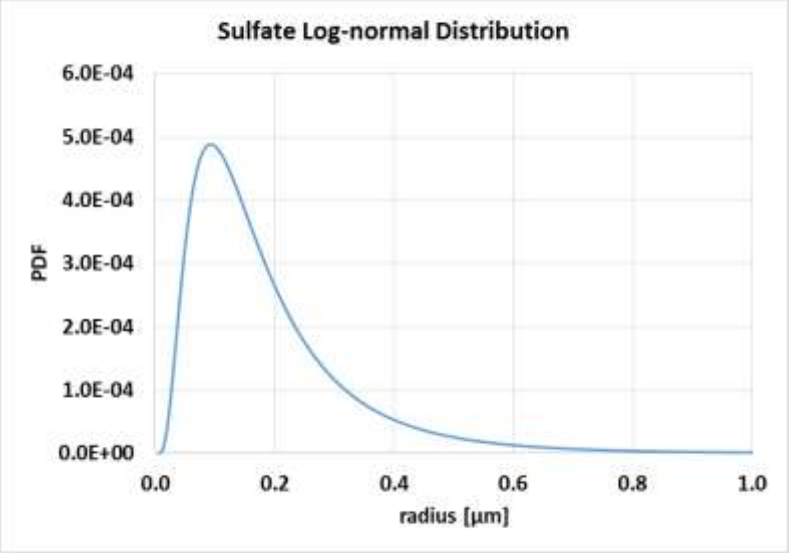
(text adapted from Benedetti CUS2016)



CAMS prognostic aerosols

Aerosol type	size bin limits (sphere radius, μm)	Refr. index source	ρ (kg/m^3)	r_{mod} (μm)	σ
Sea Salt* (80% RH)	0.03-0.5 0.5-5.0 5.0-20	OPAC	1.183e3	0.1992,1.992	1.9,2.0
Dust	0.03-0.55 0.55-0.9 0.9-20	Dubovik et al. 2002/ Woodward et al. 2001/ Fouquart et al. 1987	2.61e3	0.29	2.0
Black carbon	0.005-0.5	OPAC (SOOT)	1.0e3	0.0118	2.0
Sulfates	0.005-20	Lacis et al. (GACP)	1.76e3	0.0355	2.0
Organic matter$^+$	0.005-20	WASO+ OPAC INSO+ SOOT	1.8e3 2.0e3 1.0e3	0.0212 0.471 0.0118	2.24 2.51 2.00

$$n(x,y,z) = MR(x,y,z) * \rho_{air}/\overline{m_v}$$



CAMS prognostic aerosols

name	species	r_{mode} $[\mu m]$	σ	ρ $[kg \cdot m^{-3}]$	$\bar{m}$ $[kg]$
aermr01	sea salt [0.03, 0.5]	0.1992, 1.992	1.9, 2.0	1183	7.5023E-17
aermr02	sea salt [0.5, 5]	0.1992, 1.992	1.9, 2.0	1183	3.3269E-15
aermr03	sea salt [5, 20]	0.1992, 1.992	1.9, 2.0	1183	9.3421E-15
aermr04	Dust [0.03,0.55]	0.29	2.00	2610	2.8694E-16
aermr05	Dust [0.55,0.9]	0.29	2.00	2610	4.7291E-16
aermr06	Dust [0.9,20]	0.29	2.00	2610	1.5570E-15
aermr07	OM Hydrophobic [0.005,20]	0.471, 0.0118	2.51, 2.0	1800	1.7860E-18
aermr08	OM Hydrophilic [0.005,20]	0.0212	2.24	1000	1.3411E-18
aermr09	BC Hydrophobic [0.005,5]	0.0118	2.00	1000	5.9774E-20
aermr10	BC Hydrophilic [0.005,5]	0.0118	2.00	1000	5.9774E-20
aermr11	Sulfate [0.005,20]	0.0355	2.00	1760	2.8658E-18

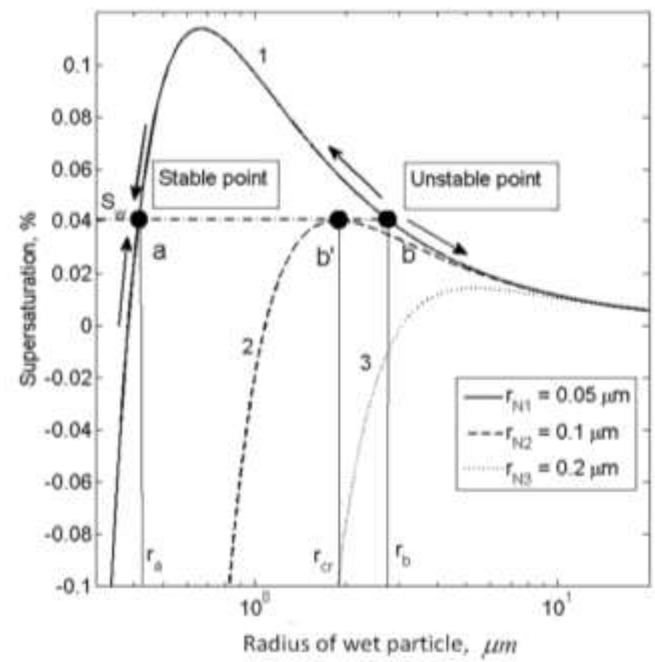
- Only nucleation & accumulation modes are accounted in SK
- $r_{mode,SK} = [0.02\ \mu m, 0.04\ \mu m]$
- Therefore, from CAMS we take only hydrophilic organic matter, black carbon & Sulfate. Other species number concentration is neglected.
- SK was calculated for NaCl. The different chemical composition effects the hygroscopicity factor (B) in the (Kholer equation)

CAMS prognostic aerosols

	ν_N	M_N, kg ml^{-1}	s_N	ρ_N, kg m^{-3}	RH_{del}, % (P&K)	RH_{del}, % (Eq. 5.1.7)	B
NaCl	2	0.058	0.3	2170	75.28	80.1	1.34
KCl	2	0.074	0.3	1990	84.26	84.8	0.962
Li_2CO_3	2	0.073	0.1	2100		92.8	1.02
MgO	0	0.02	0.0	3580		100.	0
$(NH_4)_2S$	3	0.132	0.7	1770	79.97	75.1	0.72
$CaCl_2$	2	0.111	0.7	2160		78.6	0.70
Na_2SO_4	2	0.142	0.6	2680	82	84.6	0.68
NH_4NO	2	0.080	1.1	1725	61.83	58.8	0.78
NH_4Cl	2	0.053	0.5	1527	77.1	71.4	1.03

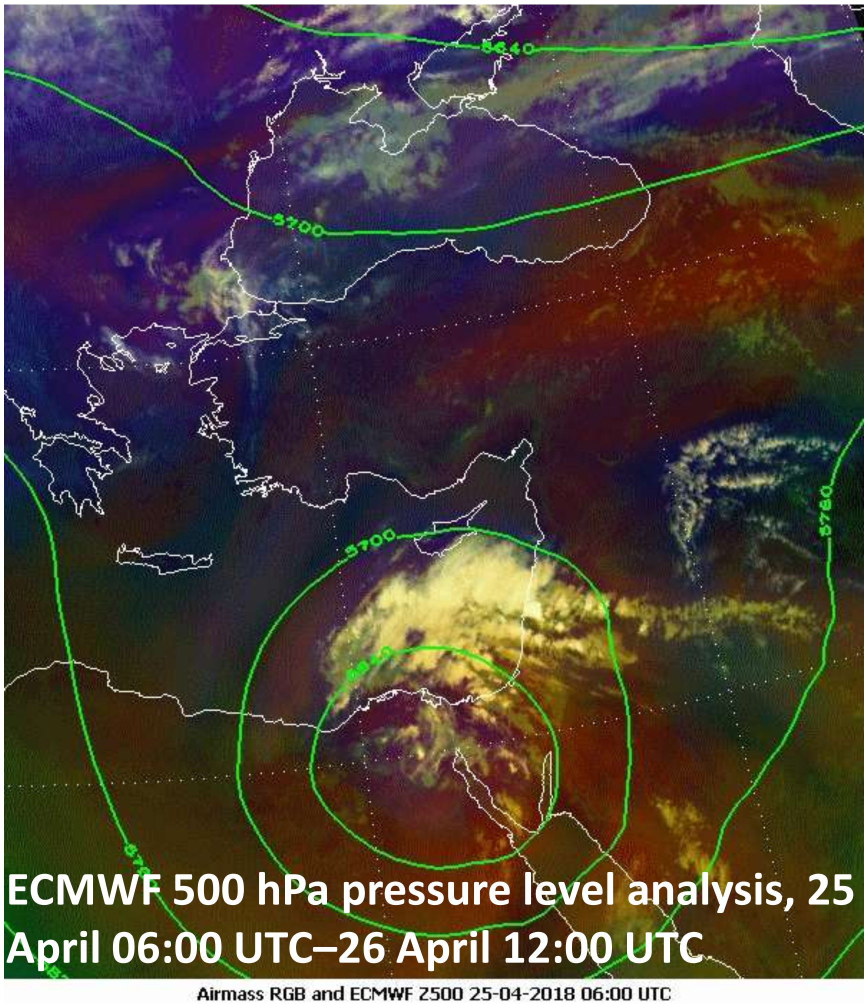
$$r_{N\text{crit}} = \frac{A}{3}\left(\frac{4}{BS^2}\right)^{1/3}$$

- $r_{crit,Kohler} \propto B^{-1/3}$. Since $B_{NaCl} \approx 2B_{Sul}$,
- $r_{crit,Sul} \approx 1.24,\ r_{crit,NaCl}$ NC does not chage more than **5%** for a large range of r_{crit}

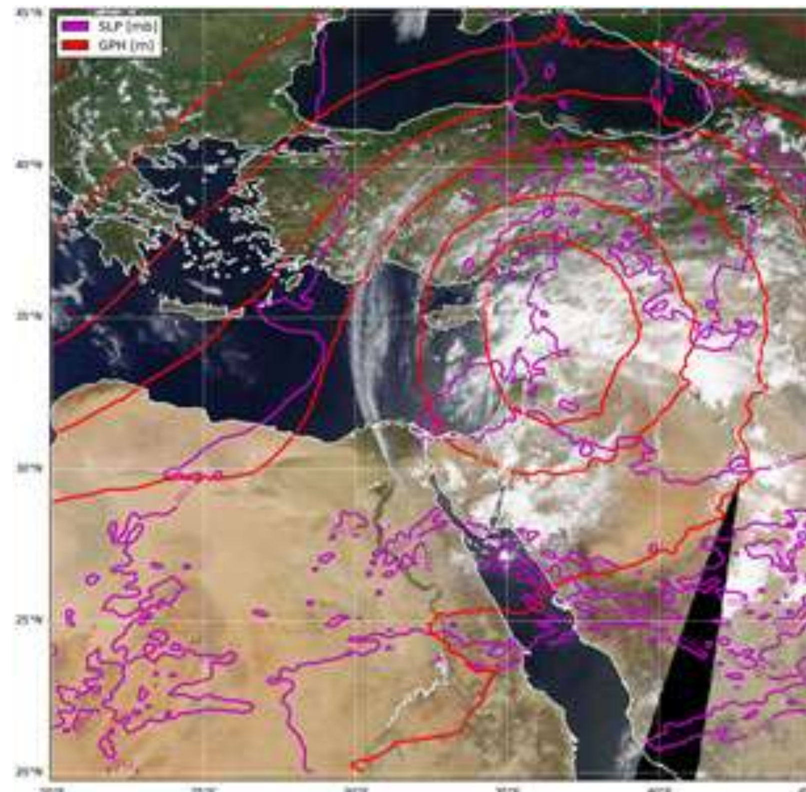


Case study: April 25-27, 2018

- Three days with massive storm cells & flash floods
- 14 deaths. Judean desert and Arava
- Zafit valley disaster: 10 teenager hikers. April 26, 2018 13:15Z.



ECMWF 500 hPa pressure level analysis, 25 April 06:00 UTC–26 April 12:00 UTC



ECMWF NWP synoptic analysis layered over MODIS True Color RGB image, 26 April 12:00 UTC

ttps://www.eumetsat.int/website/home/Images/ImageLibrary/DAT_4038669.html

Case study: April 25-27, 2018

Models Tested:

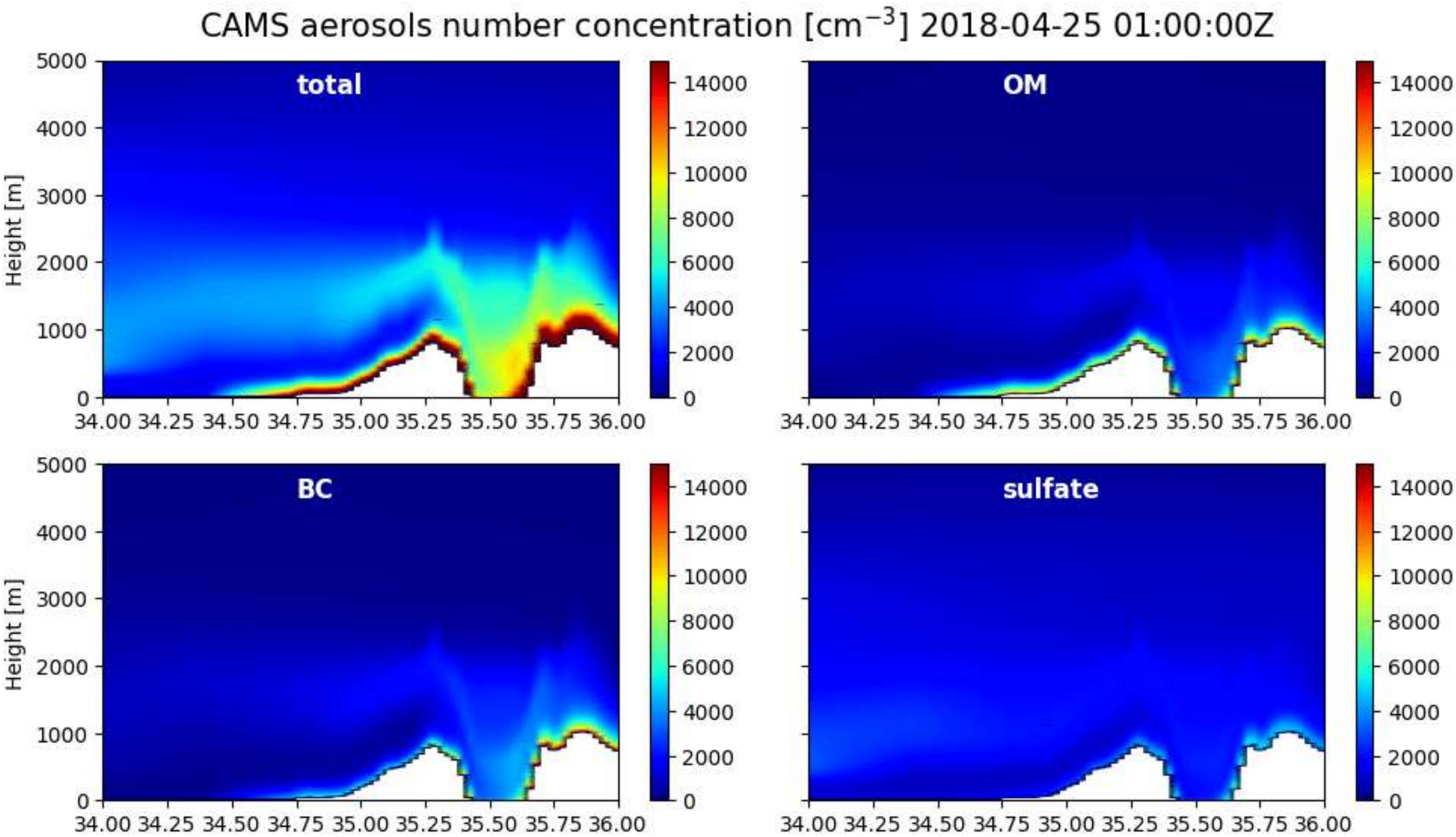
- iradpar_cloud: 1 = old cloud_rad ; 4 = new cloud_rad
- itype_aerosols: 1 = Tanre climatology ; 4 = CAMS
- icloud_num_type_rad : 1 = N_{ccn} fixed ; 4 = N_{ccn} calculated CAMS+SK (for radiation R_{eff})
- icloud_num_type_gscp : 1 = N_{ccn} fixed ; 4 = N_{ccn} calculated CAMS+SK (for microphysics)
- luse_reff_ini_c_as_reffc_sgs: (for radiation)

    F = use the same R_{eff} for SGS as for grid scale clouds

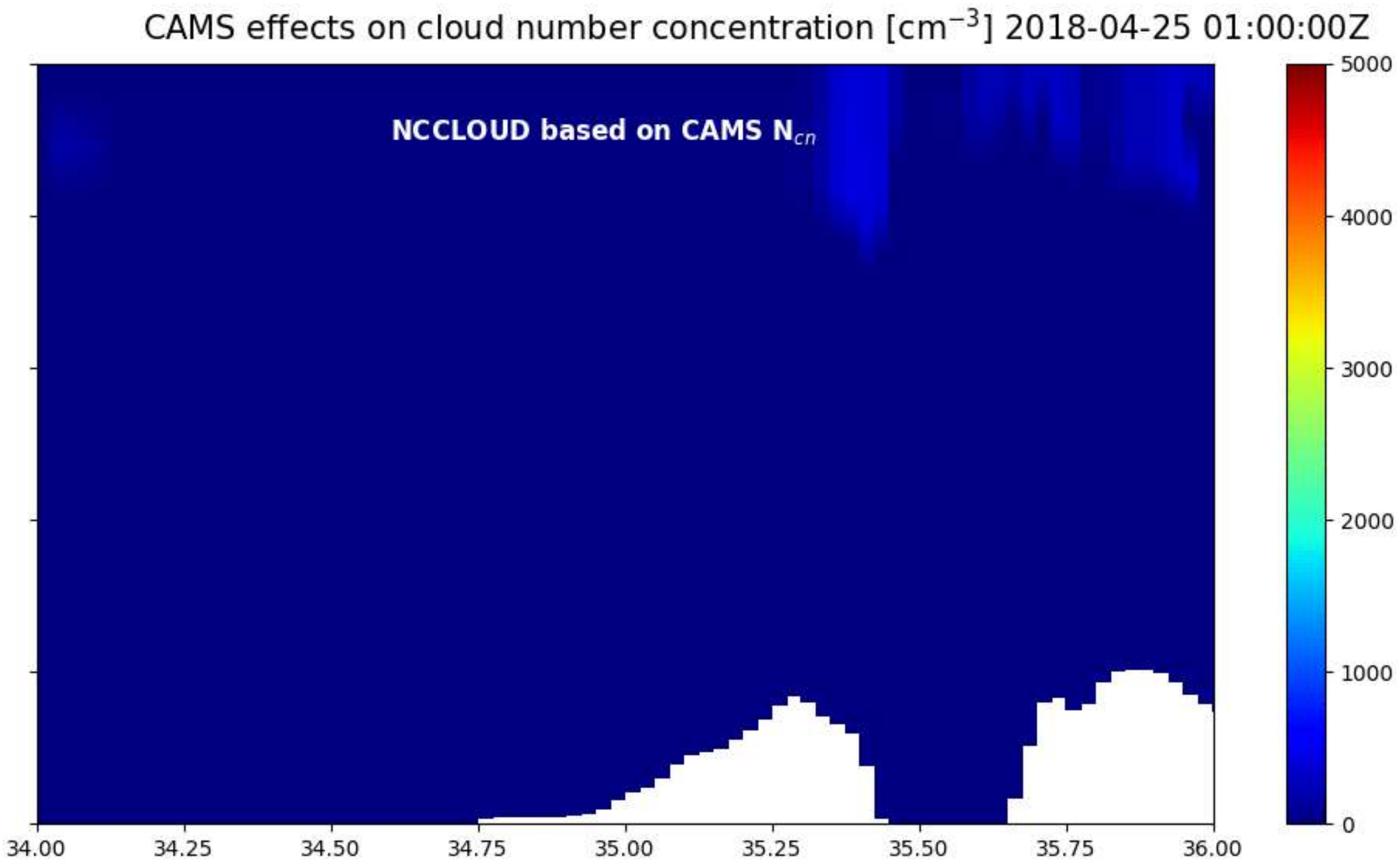
    T = use fixed R_{eff} for SGS clouds

#	iradpar_cloud	itype_aerosol	icloud_num_type_rad	icloud_num_type_gscp	luse_reff_ini_c_as_reffc_sgs
1-oper	1	1	N/A	N/A	N/A
2	4	4	1	1	T
3	4	4	4	1	T
4	4	4	1	4	T
5	4	4	4	4	T
6	4	4	1	1	F
7	4	4	4	1	F
8	4	4	1	4	F
9	4	4	4	4	F

CAMS aerosols number concentration

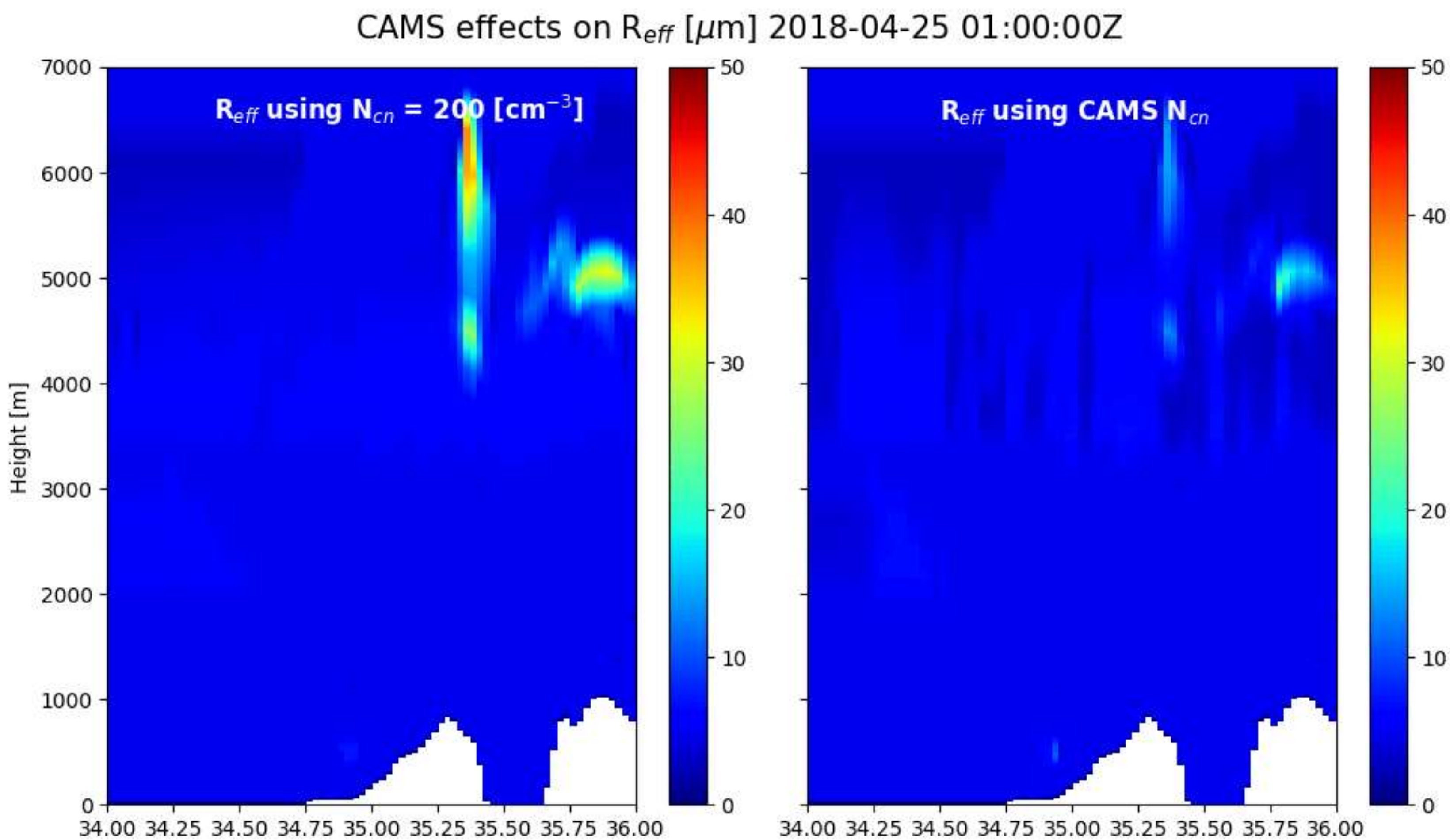


New cloud droplets number concentration



icloud_num_type_gscp/rad = 4

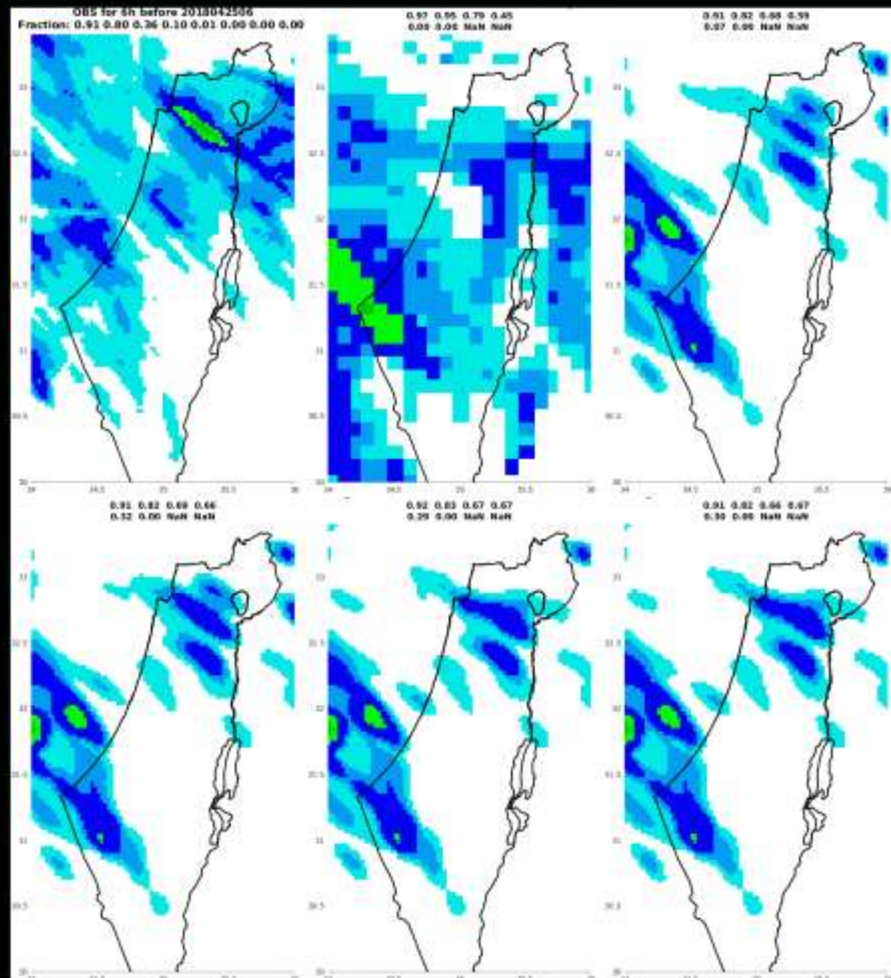
R_{eff} based on CAMS & Segal and Khain



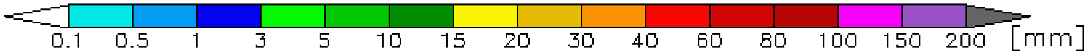
icloud_num_type_rad = 1 **icloud_num_type_rad = 4**

Case study: April 25-27, 2018

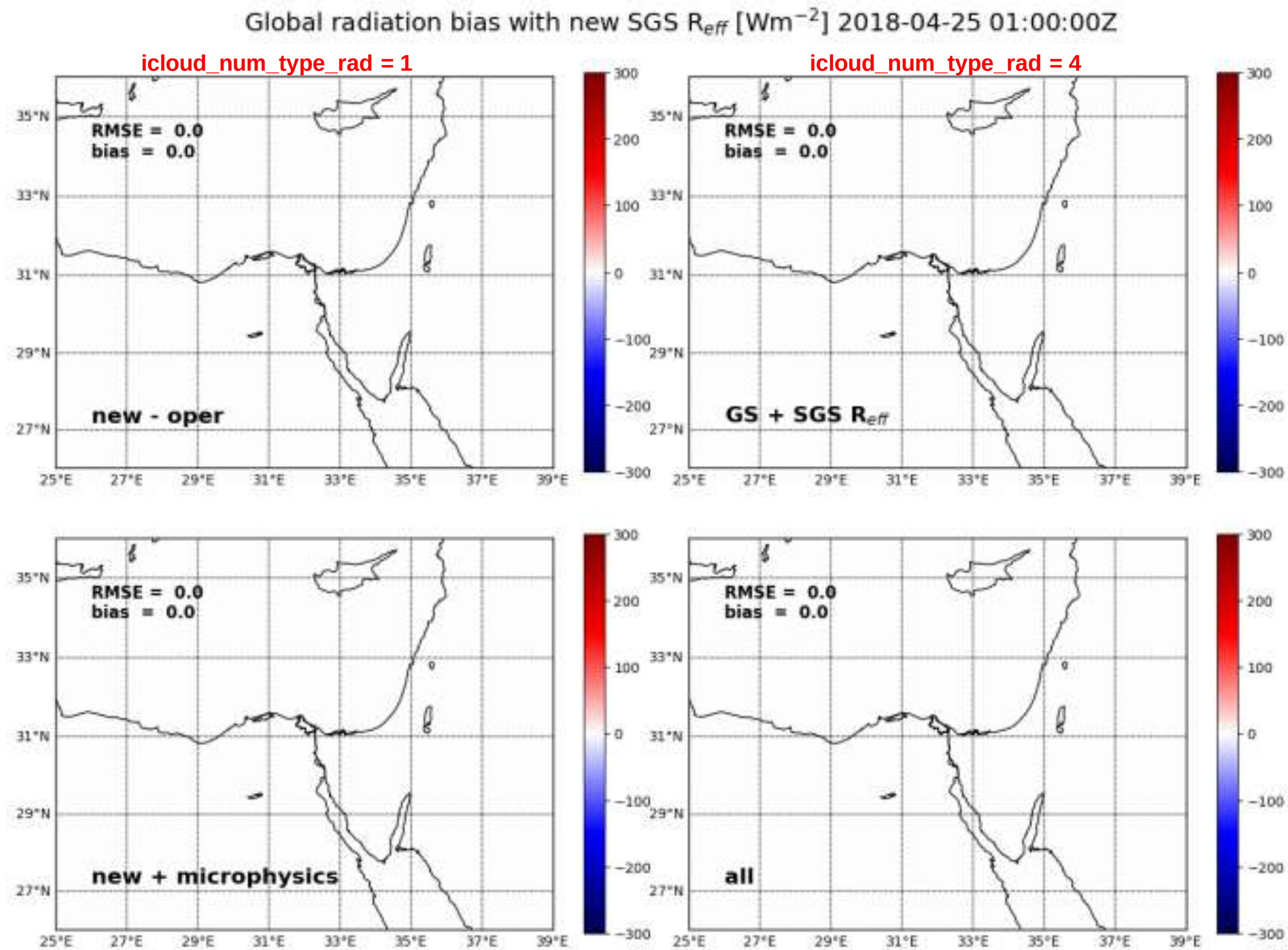
OBS EC COSMO oper



C-CAMS icloud_num_type_gscp=4 icloud_num_type_gscp+rad=4



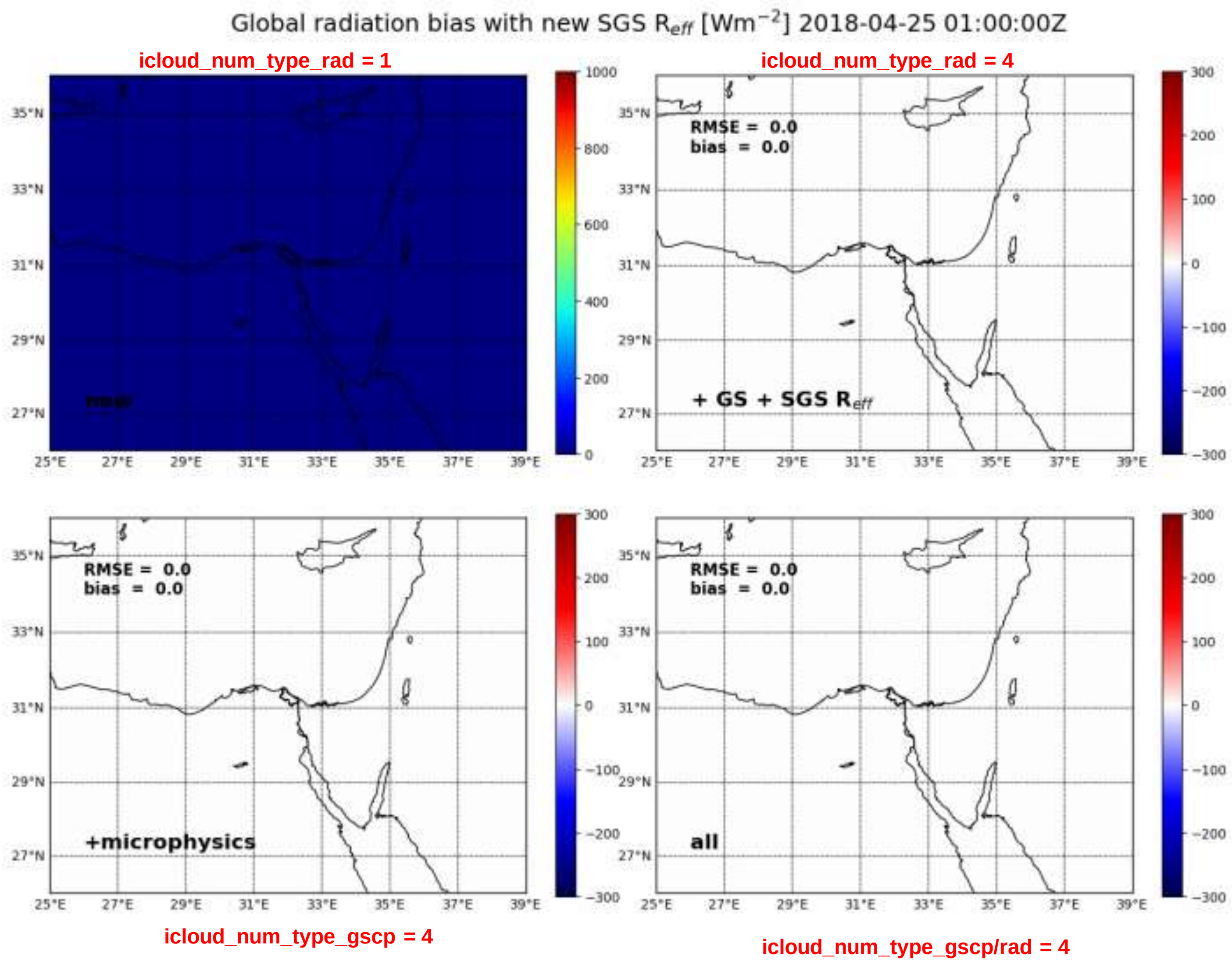
Impact on radiation



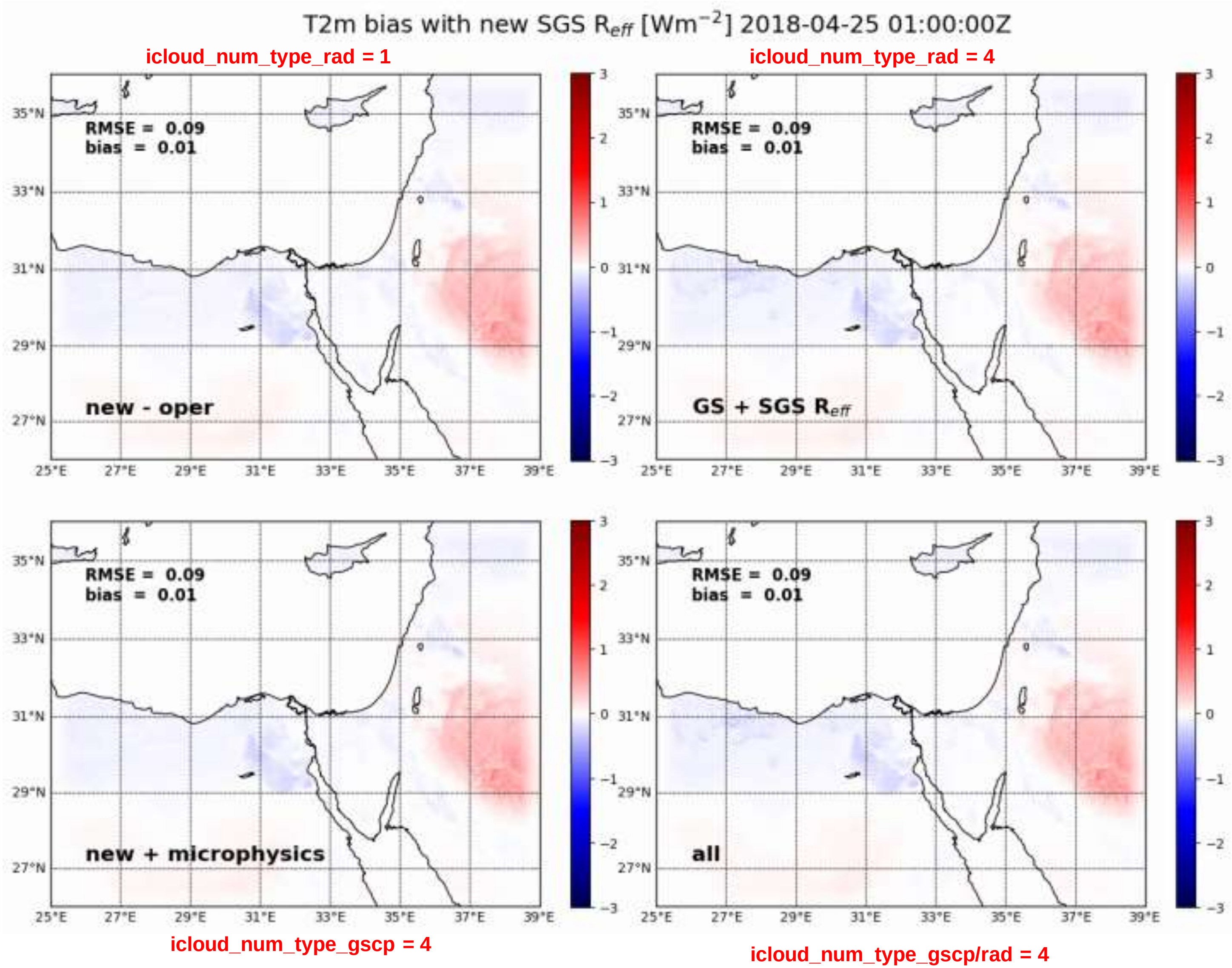
icloud_num_type_gscp = 4

icloud_num_type_gscp/rad = 4

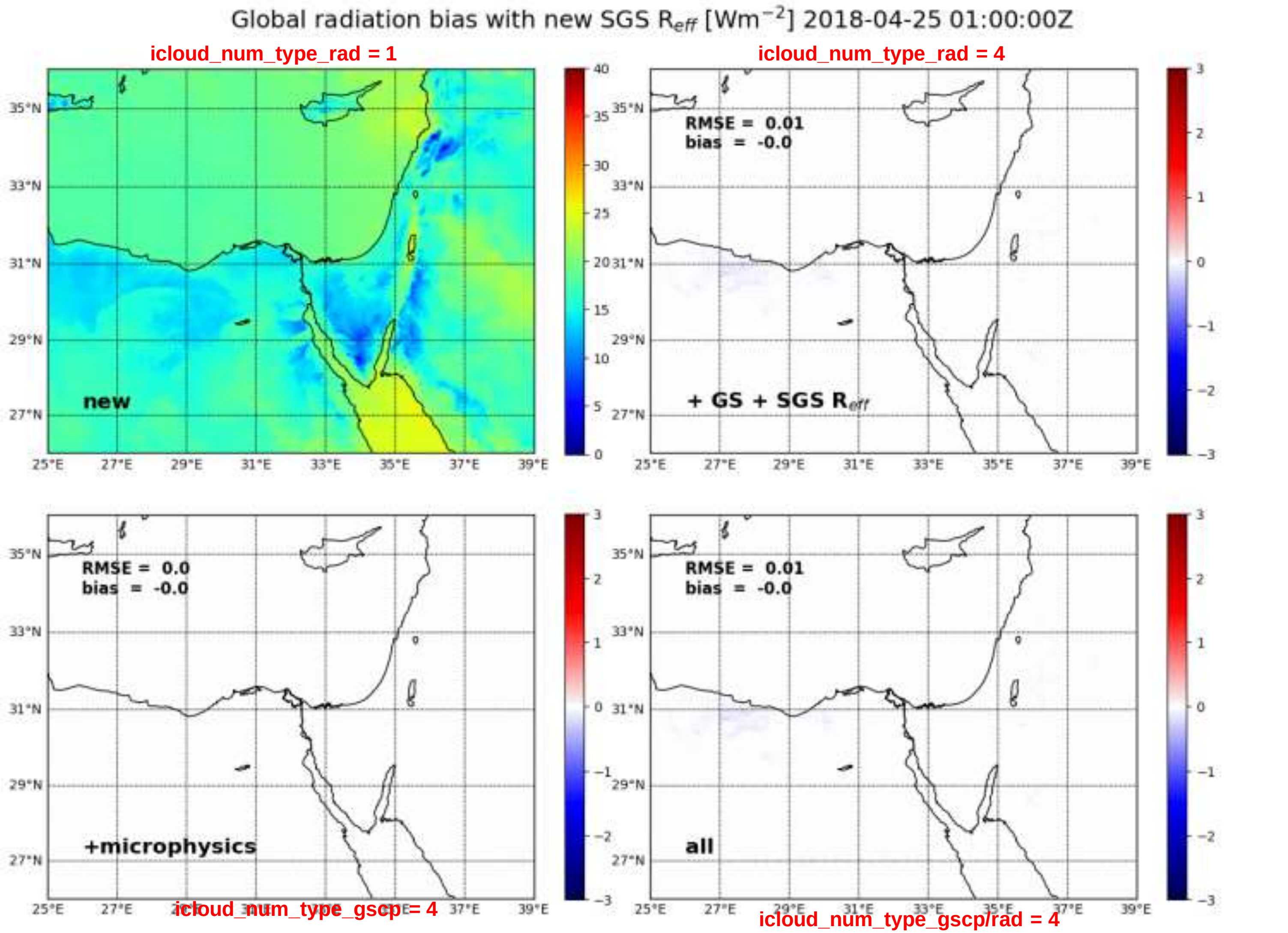
Impact on radiation



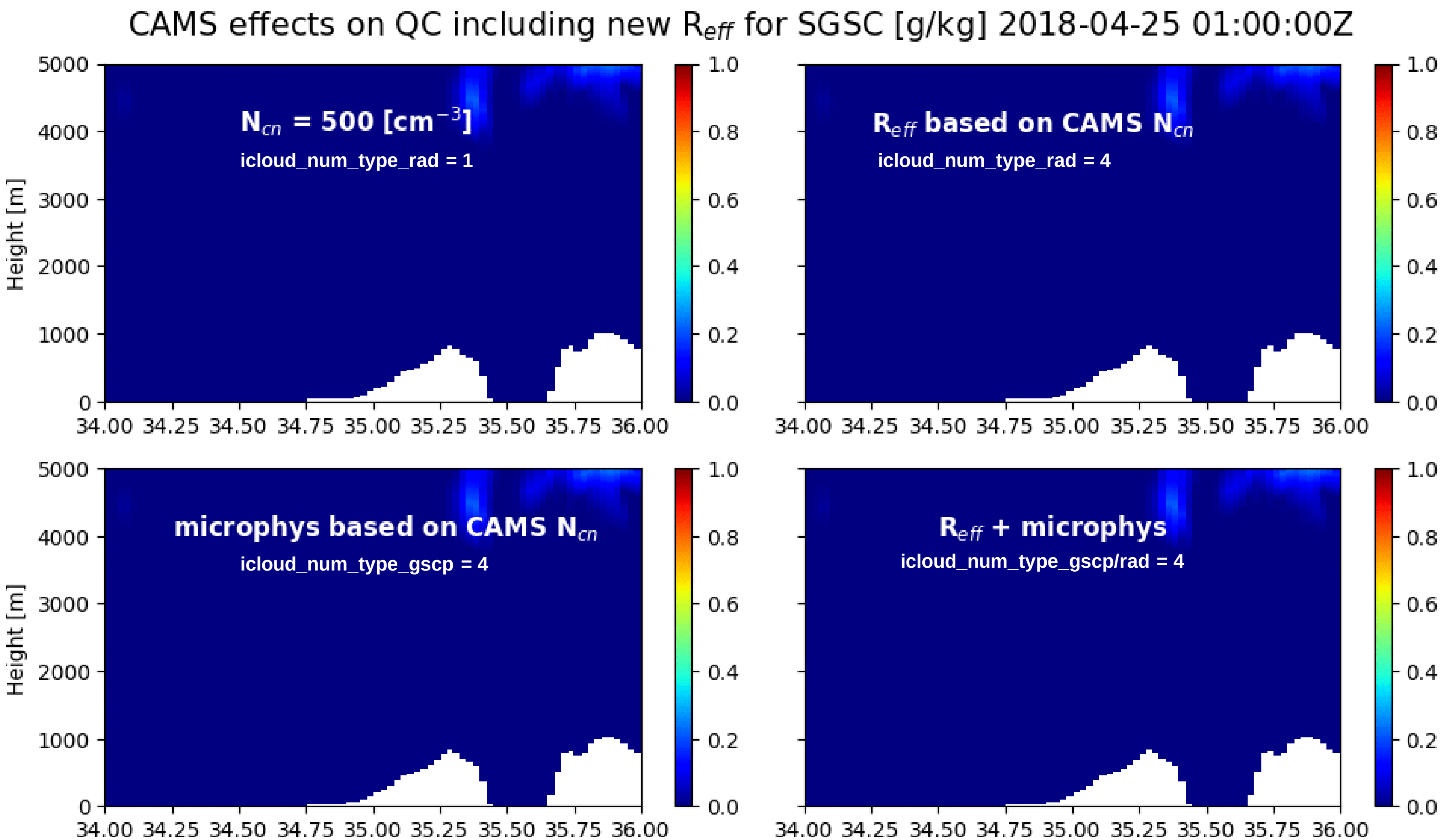
Impact on T2m



Impact on T2m

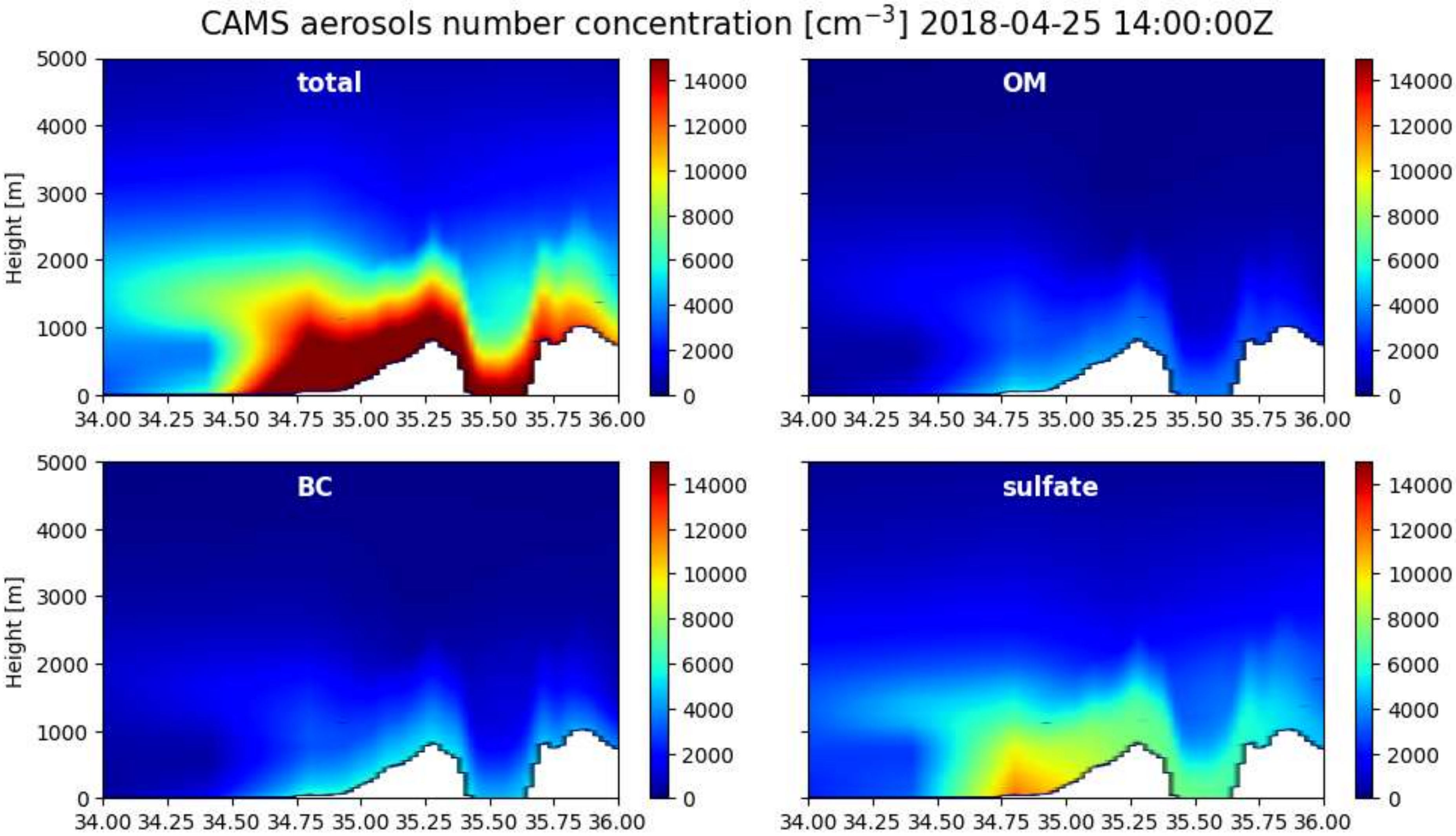


Impact on LWC



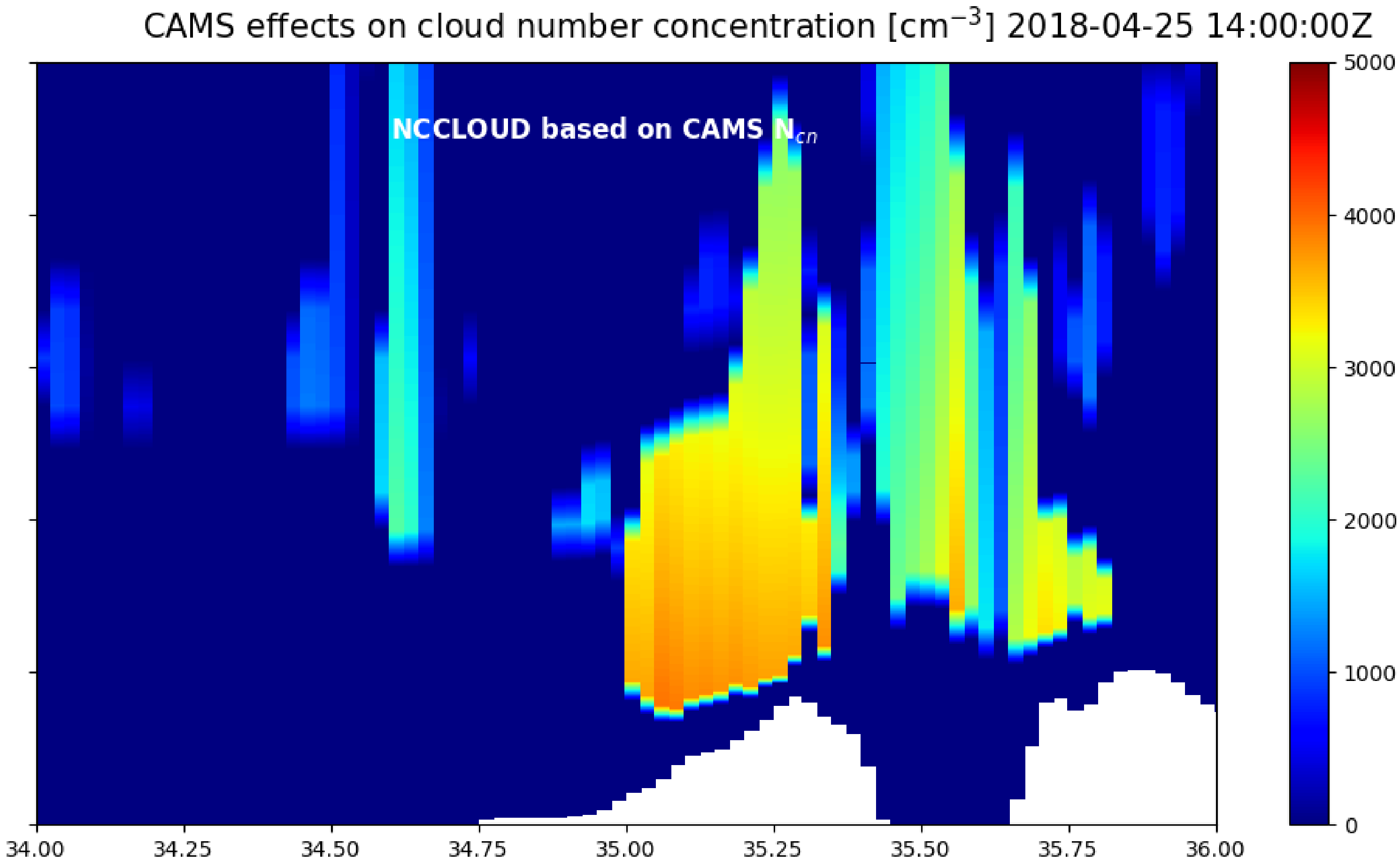
CAMS aerosols number concentration at

Peak event April 25 14Z



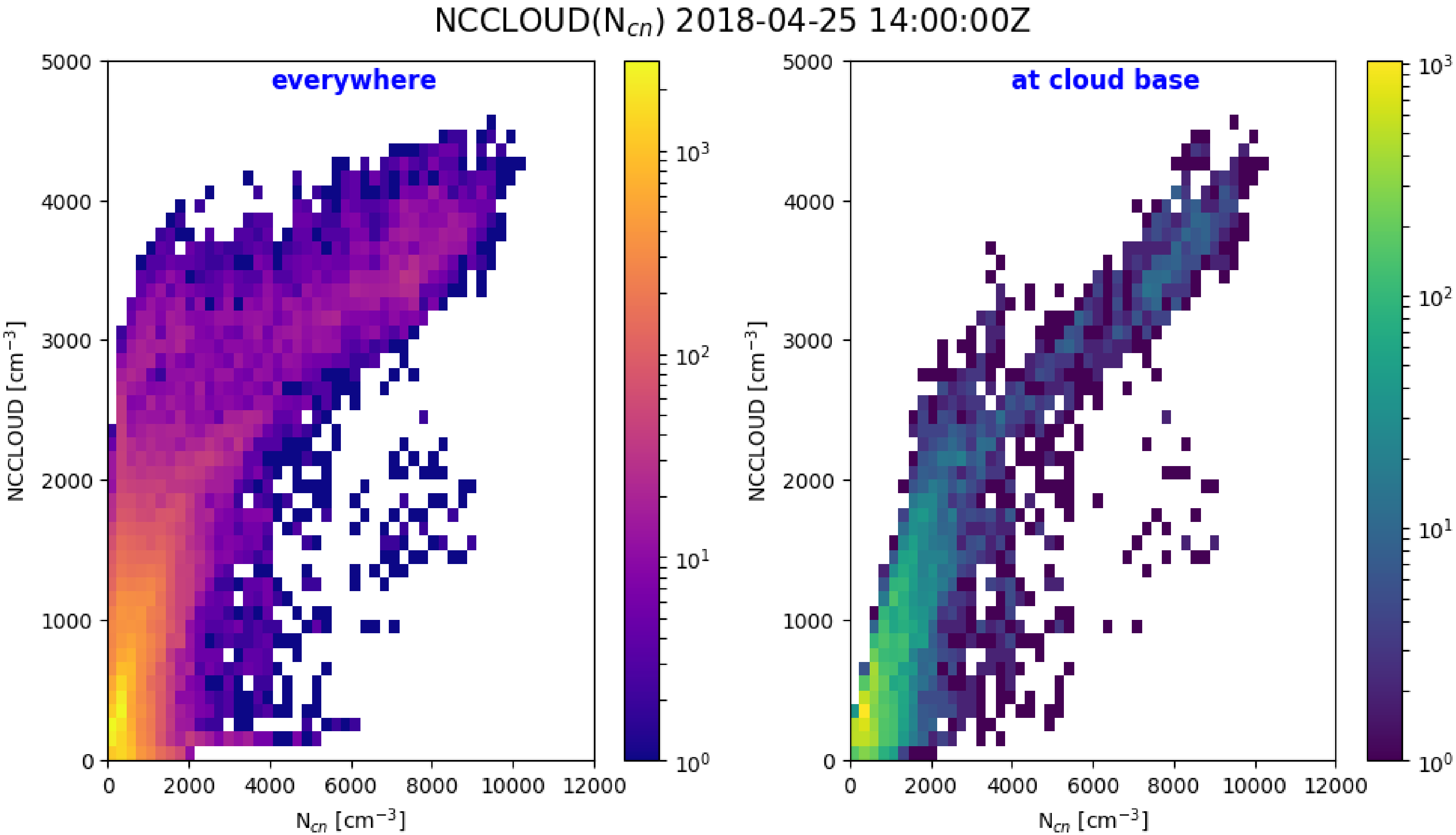
New cloud droplets number concentration

Peak event April 25 14Z



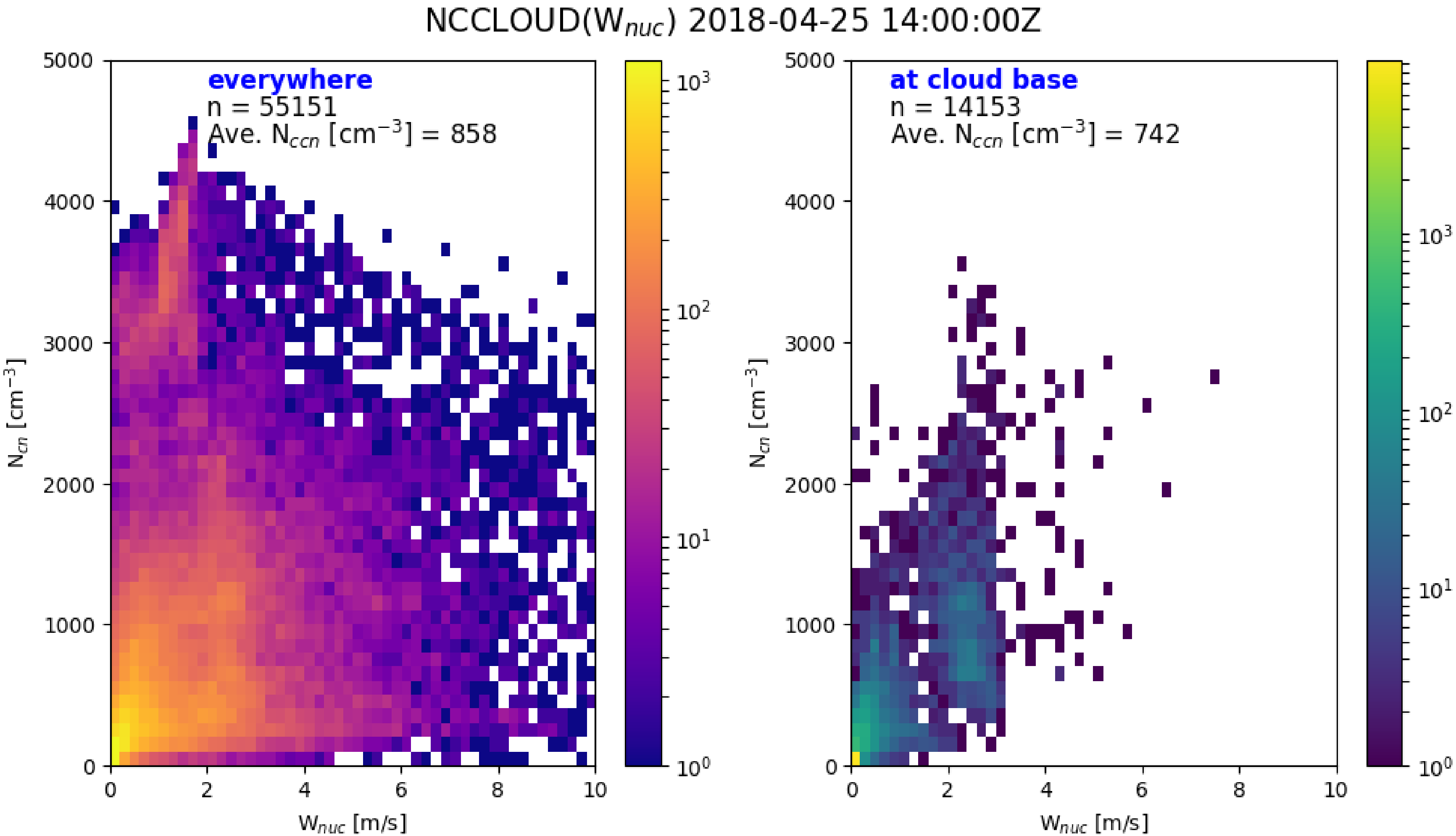
New cloud droplets number concentration

Peak event April 25 14Z



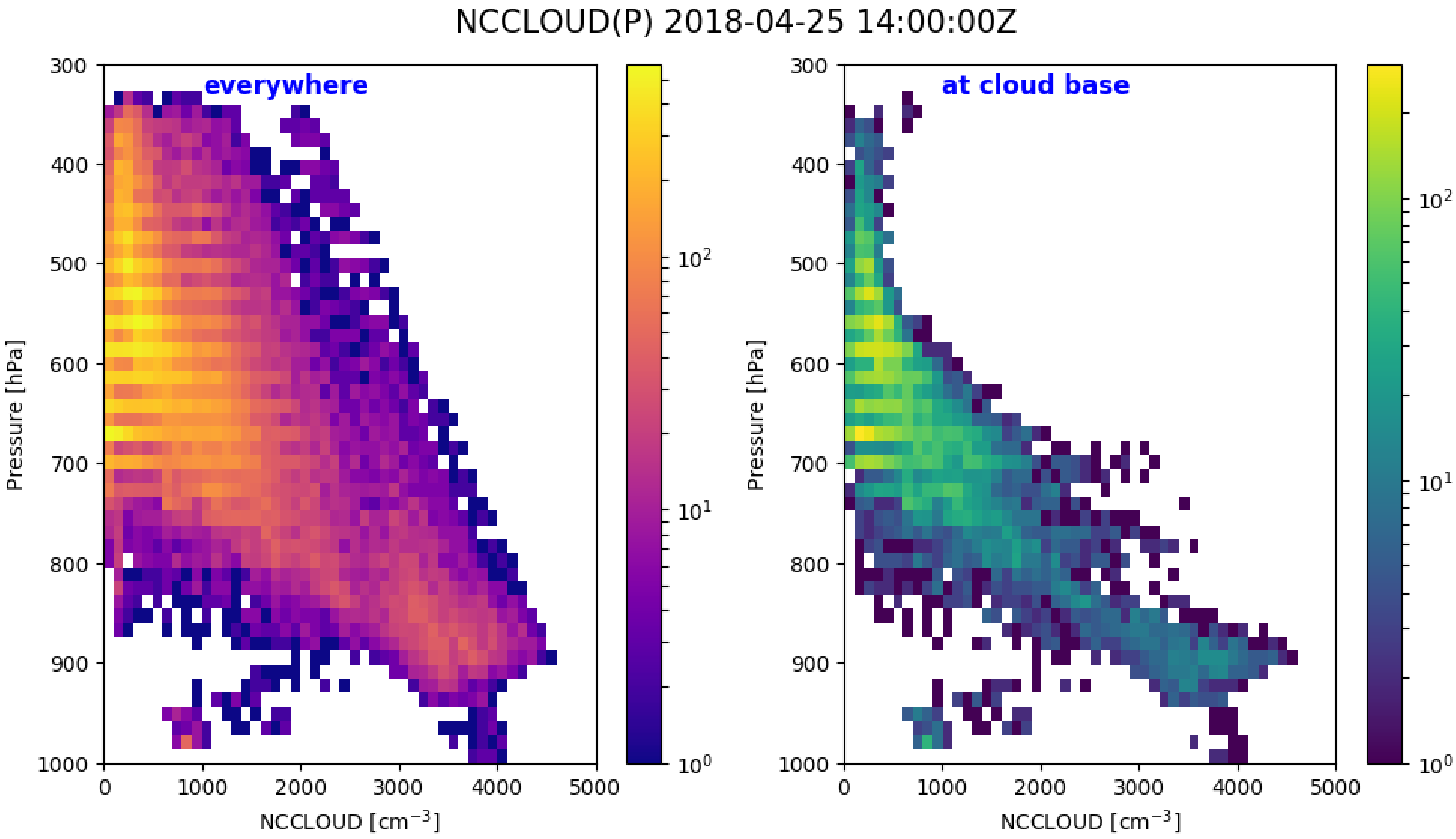
New cloud droplets number concentration

Peak event April 25 14Z



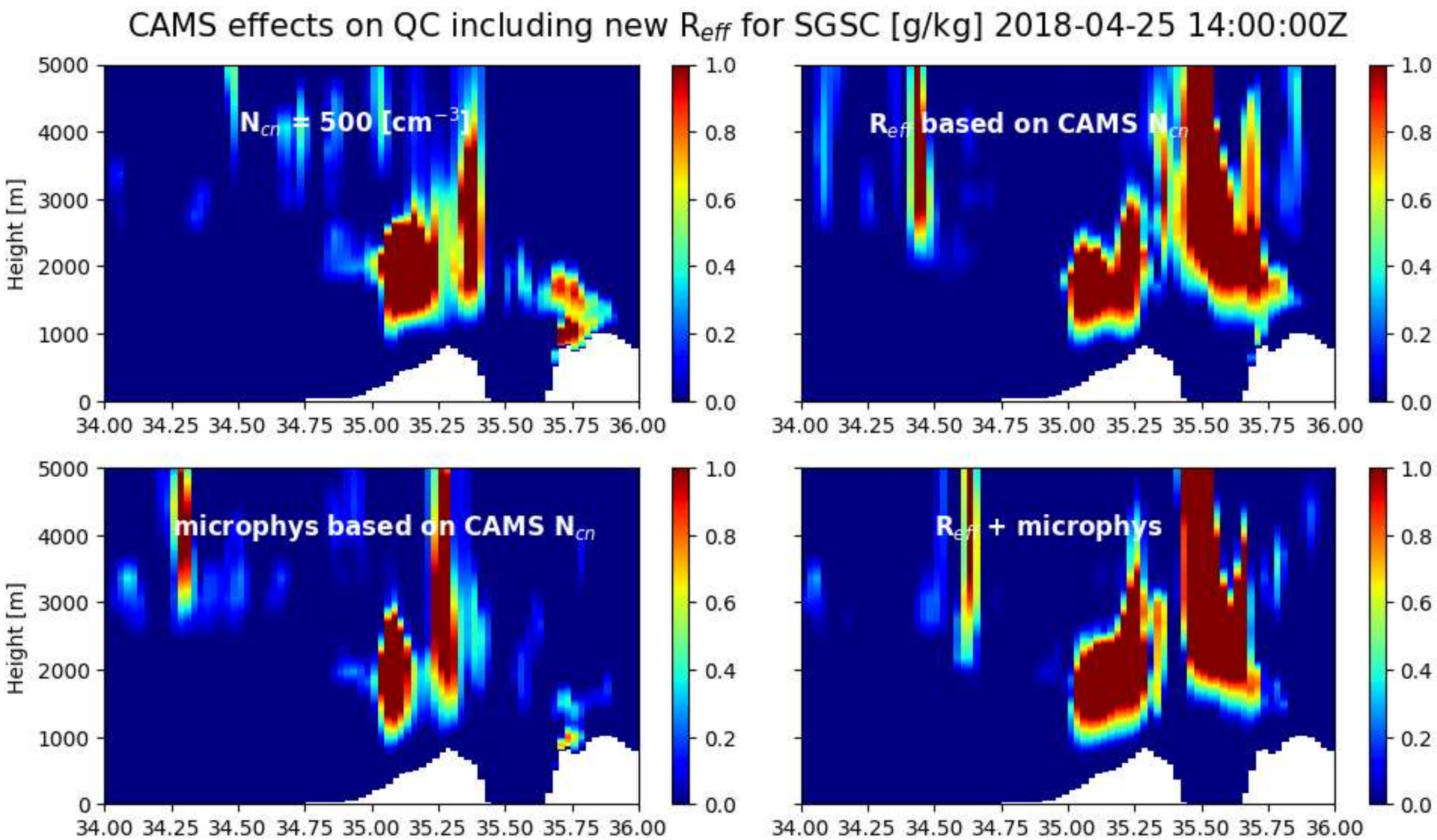
New cloud droplets number concentration

Peak event April 25 14Z



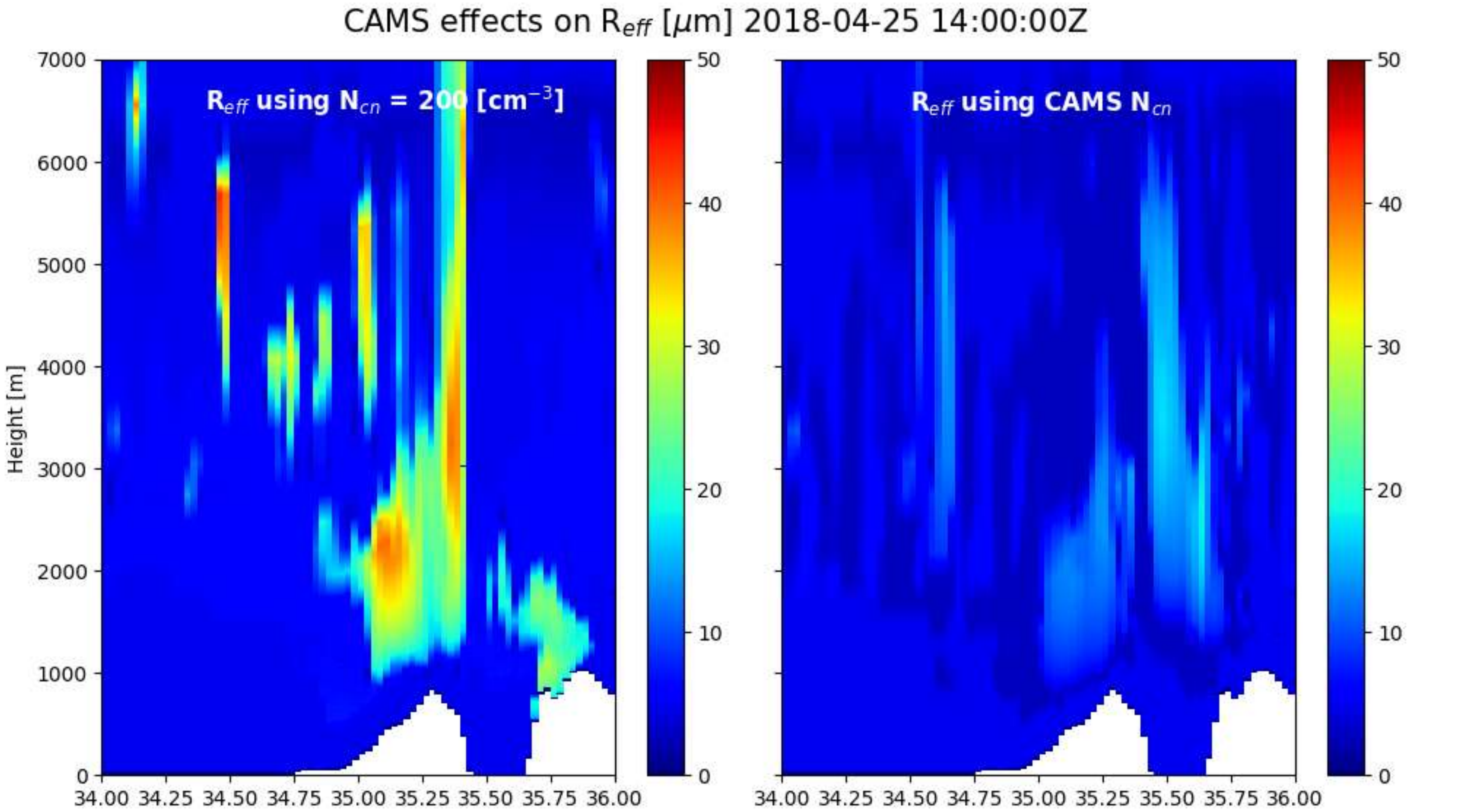
Impact on LWC

Peak event April 25 14Z



R_{eff} based on CAMS & Segal and Khain

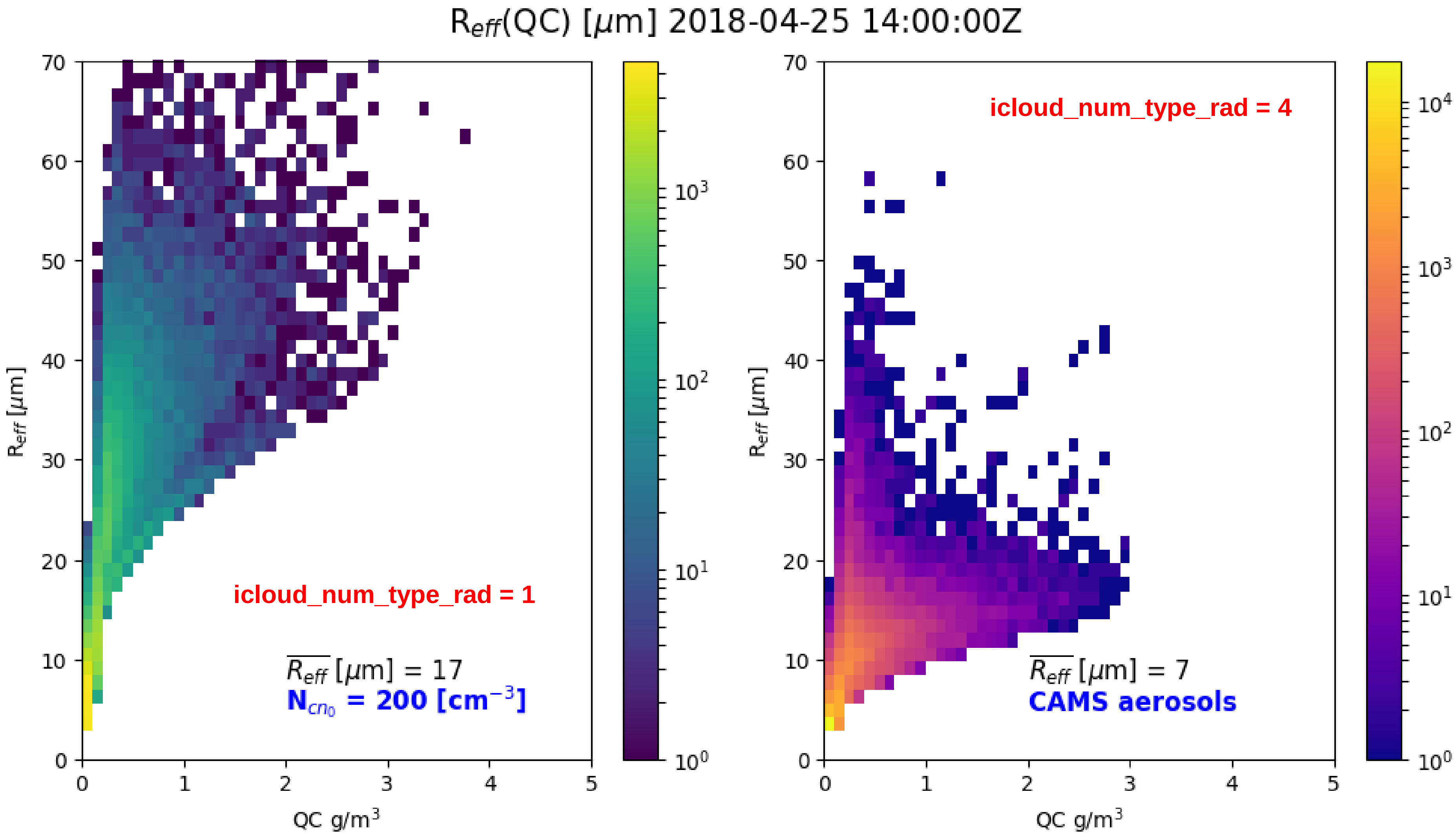
Peak event April 25 14Z



icloud_num_type_rad = 1 **icloud_num_type_rad = 4**

R_{eff} based on CAMS & Segal and Khain

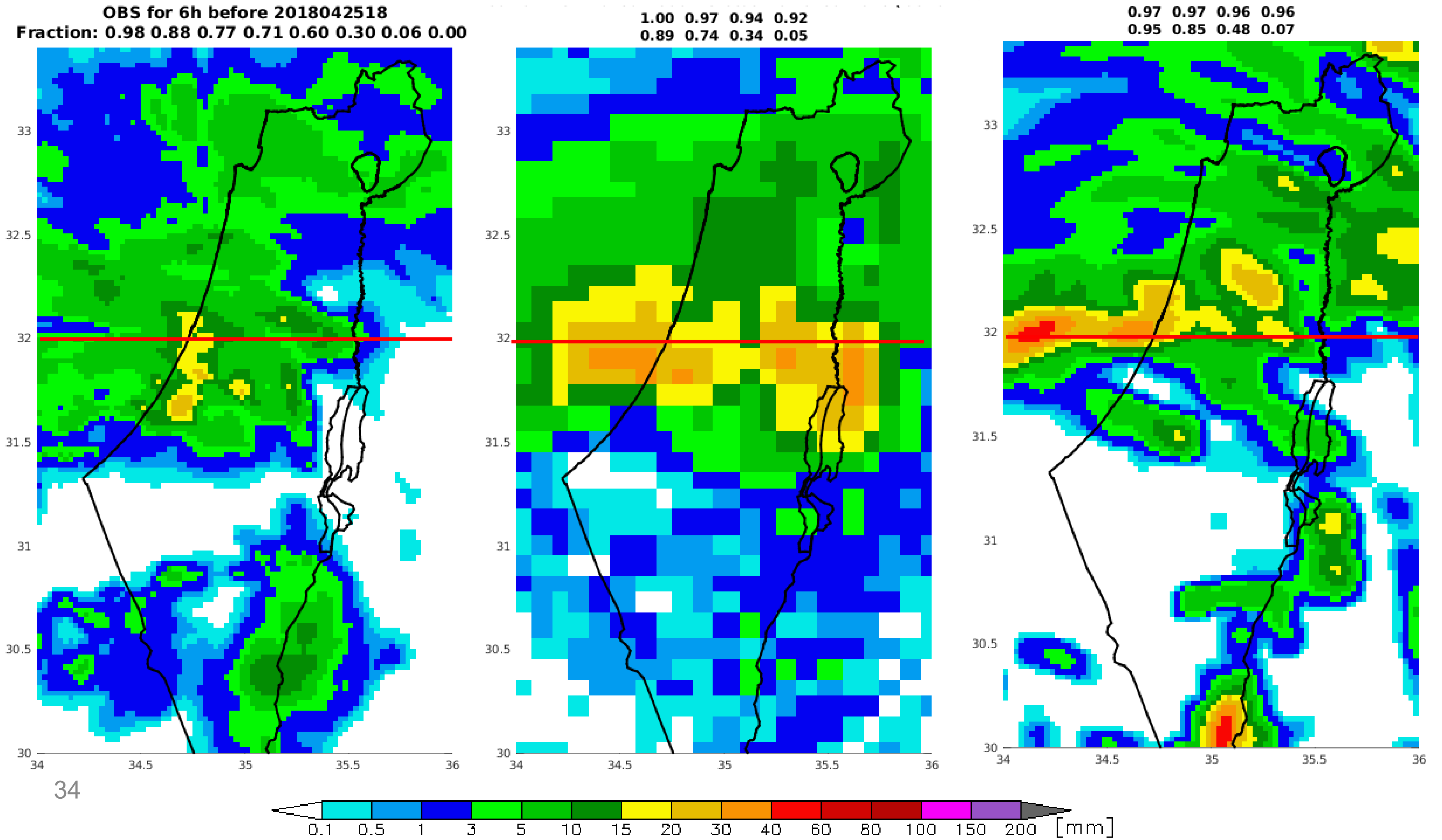
Peak event April 25 14Z



Case study: April 25-27, 2018

Peak event April 25 12Z-18Z

OBS EC COSMO oper



Case study: April 25-27, 2018

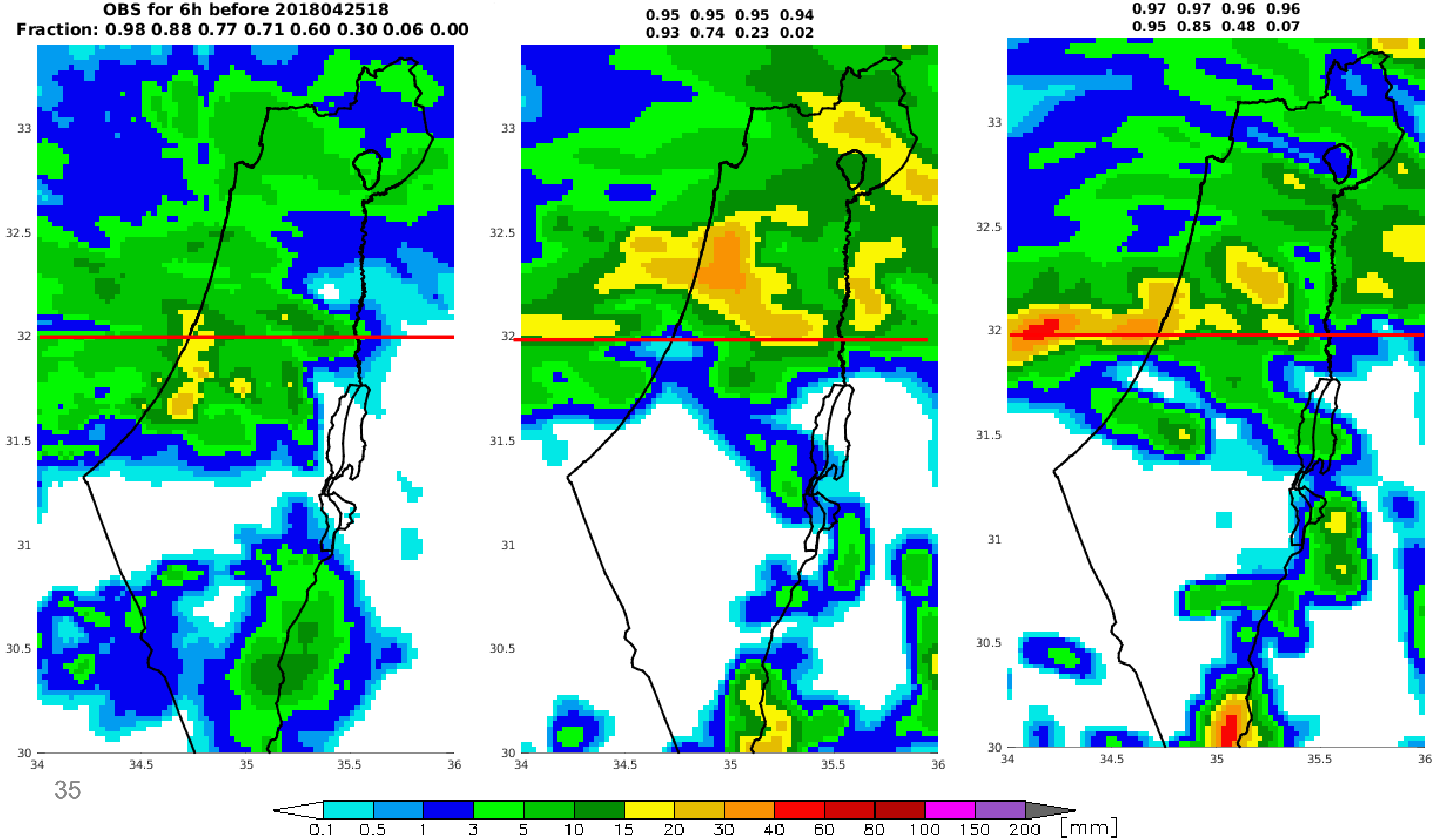
Peak event April 25 12Z-18Z

OBS

New cloud_rad

CAMS background aerosols

COSMO oper



Case study: April 25-27, 2018

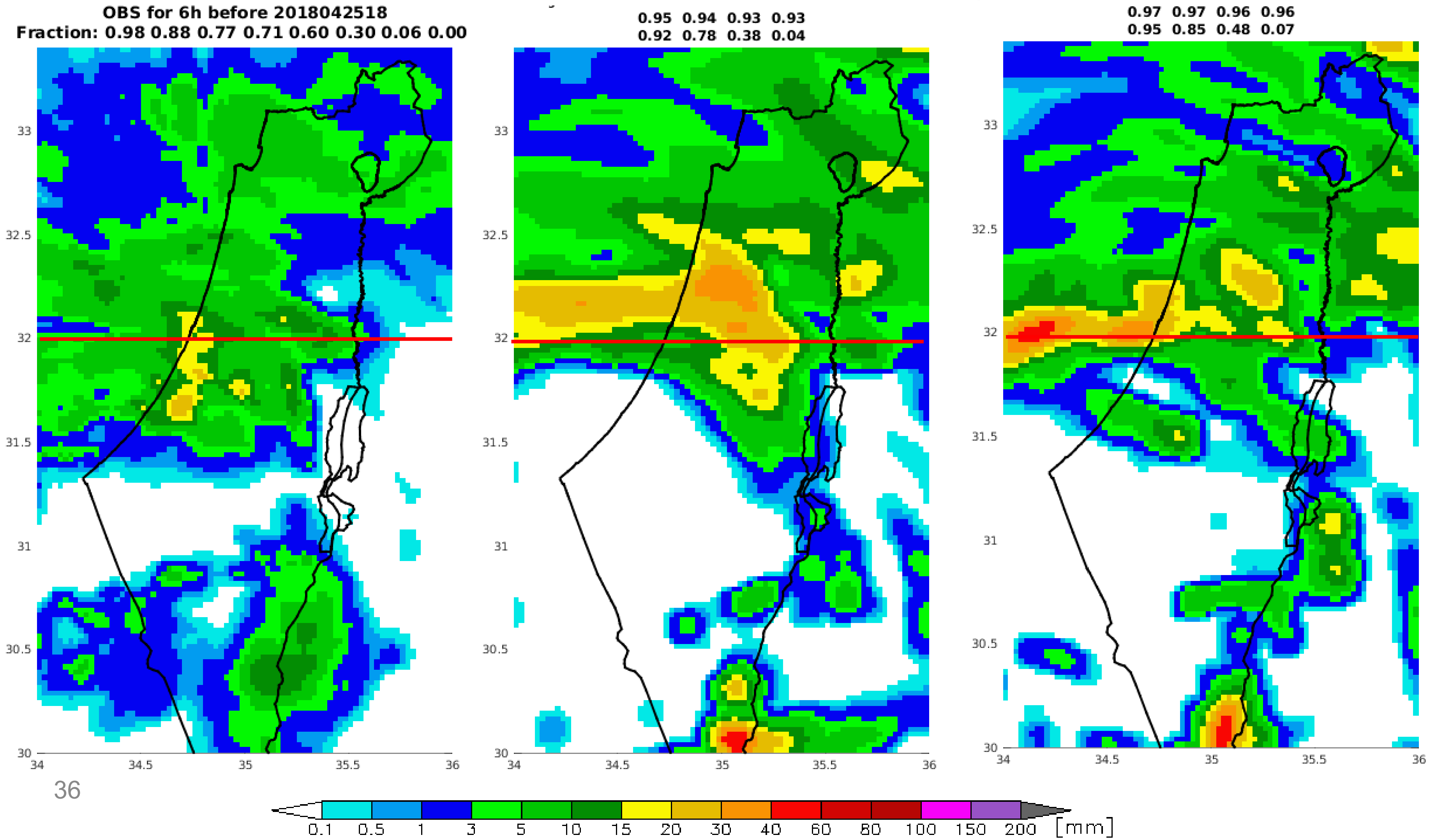
New cloud_rad

CAMS background aerosols

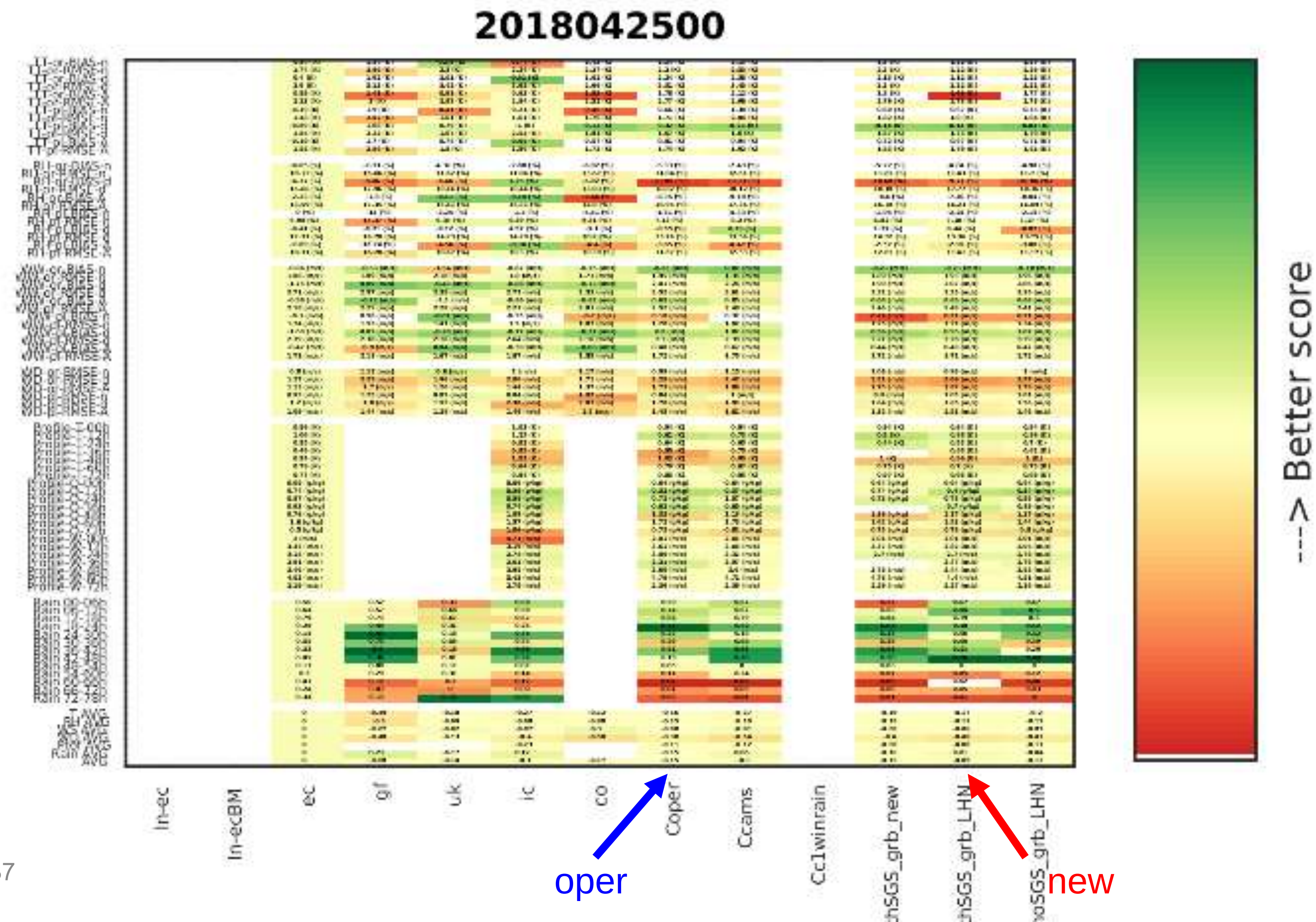
CAMS & SK Ncn → rad + microphysics

OBS

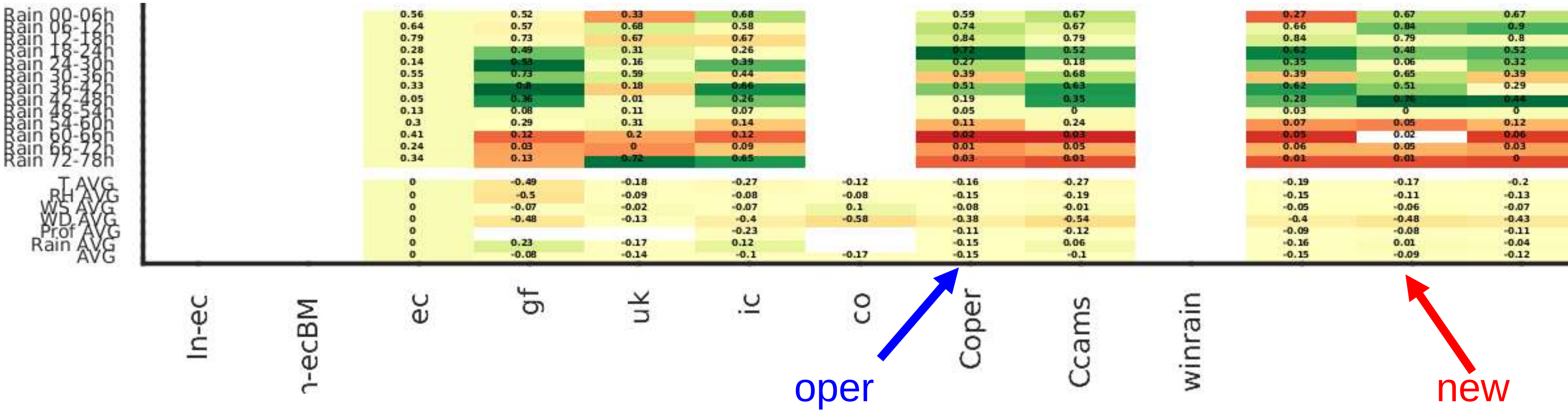
COSMO oper



Total forecast scores



Total forecast scores



- All averaged scores: T, RH, WS, Prof., Rain (except WD) showed better results for the new all-included scheme compared to the operational set-up
- More testing are on its way…

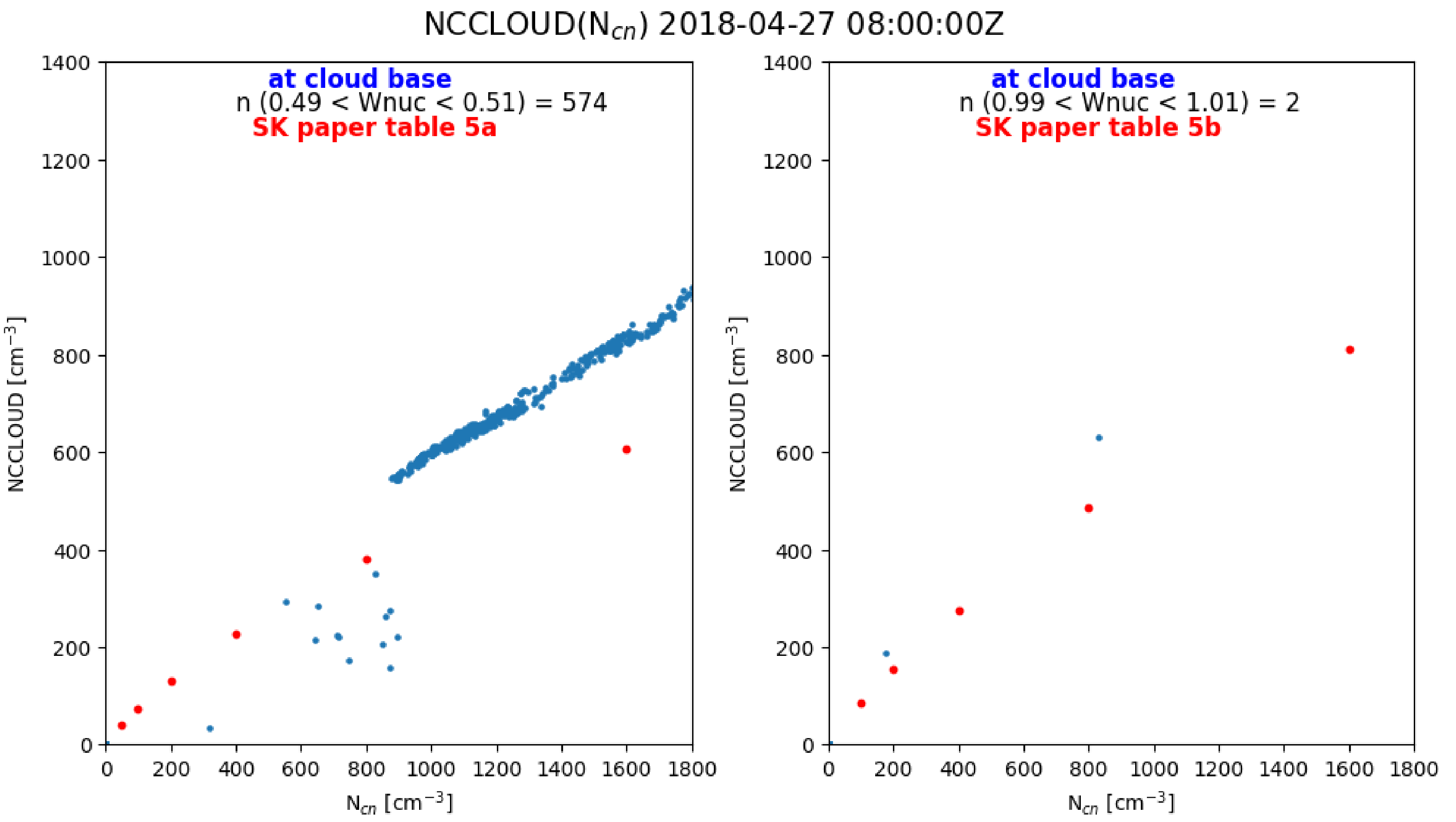
Concluding remarks and outlook

- A new cloud droplets number concentration based on CAMS prognostic aerosols concentrations and Segal & Khain nucleations scheme is implemented.
- More realistic approach to define cloud droplets densities and effective radii of grid scale and sub-grid scale clouds
- High sensitivities of radiation, T2m, rain, QC etc.
- Next steps:

    1. Implementation of Khain et al. approach to effective radius + LWC
    2. 2-mom scheme
    3. Ice nucleation
    4. Mixed aerosols types
    5. Testing against observations
    6. Test version in IMS (?)


Thank You for Listening
and Happy New Hebrew Year!

New cloud droplets number concentration



New cloud droplets number concentration