Effects of cloud turbulence on collision-coalescence in maritime shallow convection

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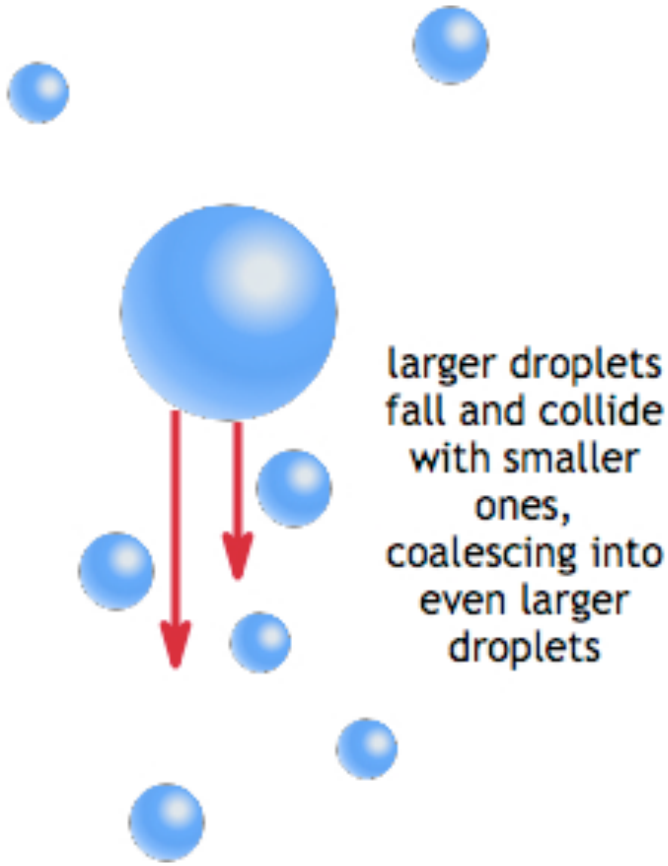
Wyszogrodzki et al., 2013: Turbulent collision-coalescence in maritime shallow convection, *Atmos. Chem. Phys. Discus*.
Grabowski and Wang, 2013: Growth of cloud droplets in a turbulent environment. *Ann. Rev. Fluid Mech.*



The textbook explanation of rain formation in ice-free clouds: gravitational collision-coalescence…

Time evolution of the droplet spectrum: the Smoluchowski equation::

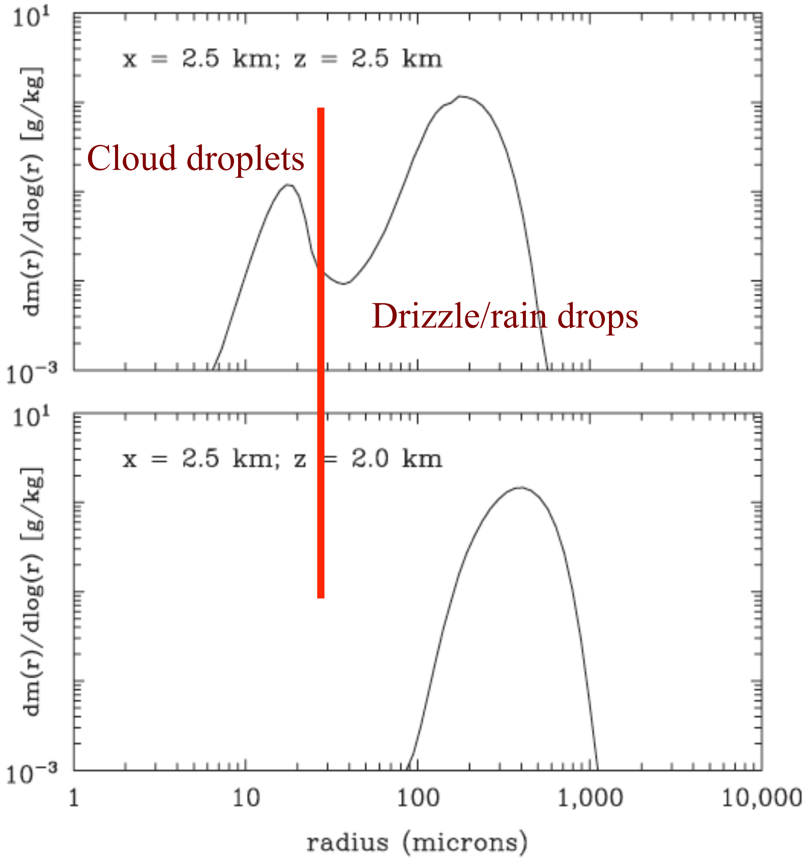
$$\frac{\partial n(x,t)}{\partial t} = \frac{1}{2}\int_0^x K(x-y,y)n(x-y,t)n(y,t)\,dy - \int_0^\infty K(x,y)n(x,t)n(y,t)\,dy$$

In a 3D cloud model:

-droplet activation

-growth by condensation of water vapor

-transport in the physical space (advection + sedimentation)



Bin warm-rain microphysics of Grabowski et al. (2011):

- Prediction of the spectral shape of cloud droplets and drizzle/rain; 112 bins;

- Prediction of the supersaturation and thus relating the concentration of activated cloud droplets to local value of the supersaturation; additional variable, concentration of activated CCN, needed.

gravitational kernel:

$$K_{ij} = \pi\,(a_i + a_j)^2\,|v_i^t - v_j^t| E_{ij}^g$$

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generalized kernel (gravity plus turbulence):

$$K_{ij} = K_{ij}^{tg}\,E_{ij}^g\,\eta_E$$

Saffman and Turner (*JFM* 1956)
Wang et al. (*JAS* 2005)
Grabowski and Wang (*ARFM* 2013)

$$K_{ij}^{tg} = 2\pi R^2 \langle |w_r(r=R)| \rangle\, g_{ij}(r=R)$$

$$R = a_i + a_j$$

$$w_r = \boldsymbol{r} \cdot (V_i - V_j)/r$$ radial relative velocity

g_{ij} radial distribution function

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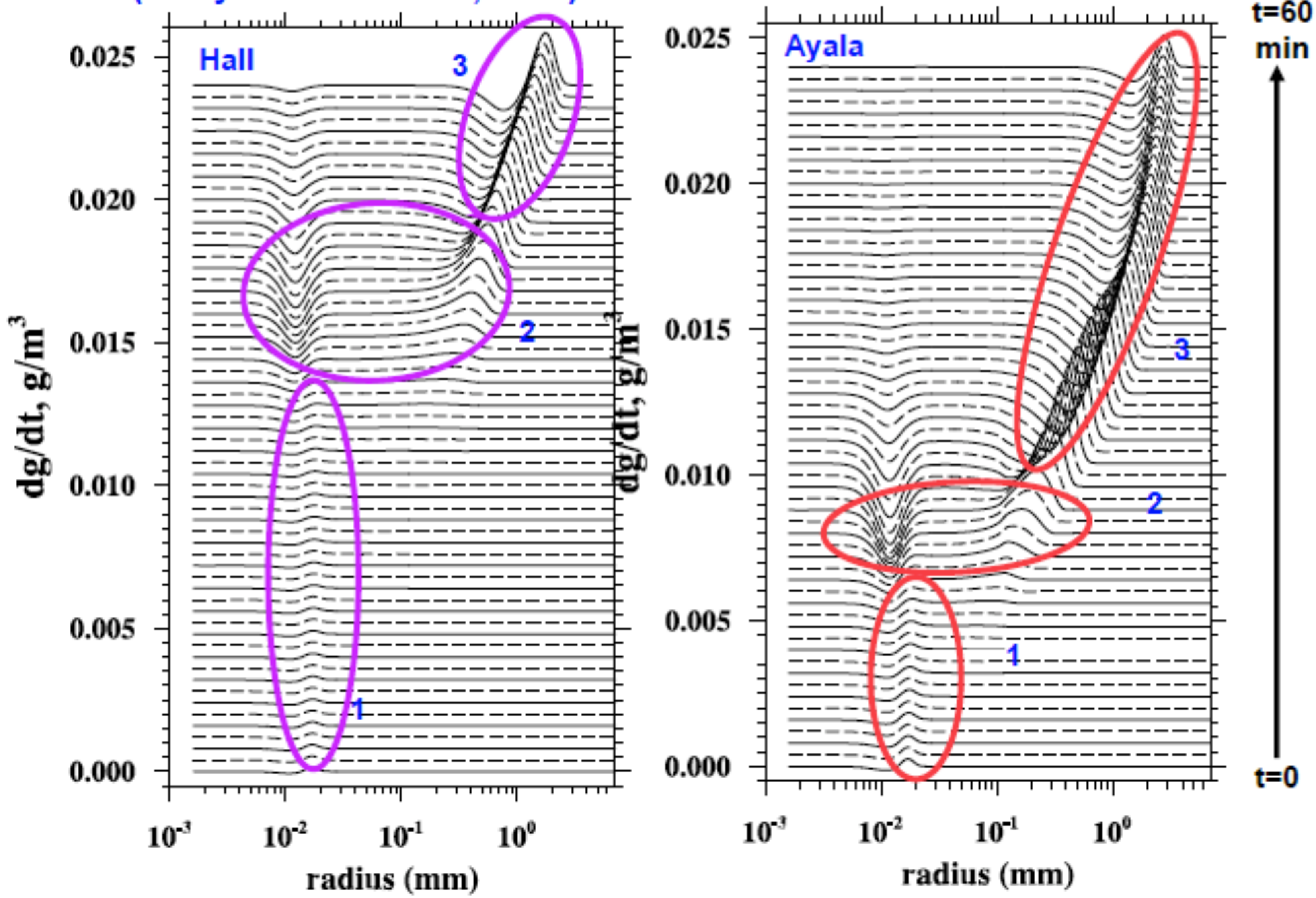
The kernel depends on two parameters describing small-scale turbulence:

- eddy dissipation rate ε
- Taylor microscale Reynolds number Re_λ

1. Autoconversion; 2. Accretion; 3. Hydrometeor self-collection (Berry and Reinhardt, 1974)



without turbulence

with turbulence, ε = 400 cm^2s^{-3}

A Large Eddy Simulation Intercomparison Study of Shallow Cumulus Convection

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Peter G. Duynkerke,[f*] Hongli Jiang,[g] Marat Khairoutdinov,[h] David Lewellen,[i] Chin-Hoh Moeng,[j]
Enrique Sanchez,[k] Bjorn Stevens,[l] and David E. Stevens[m]

JAS 2003

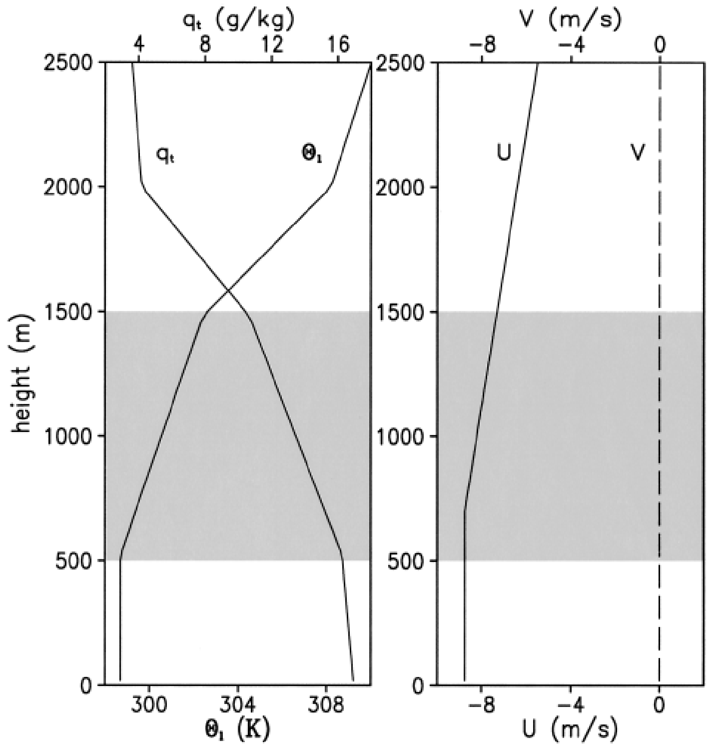
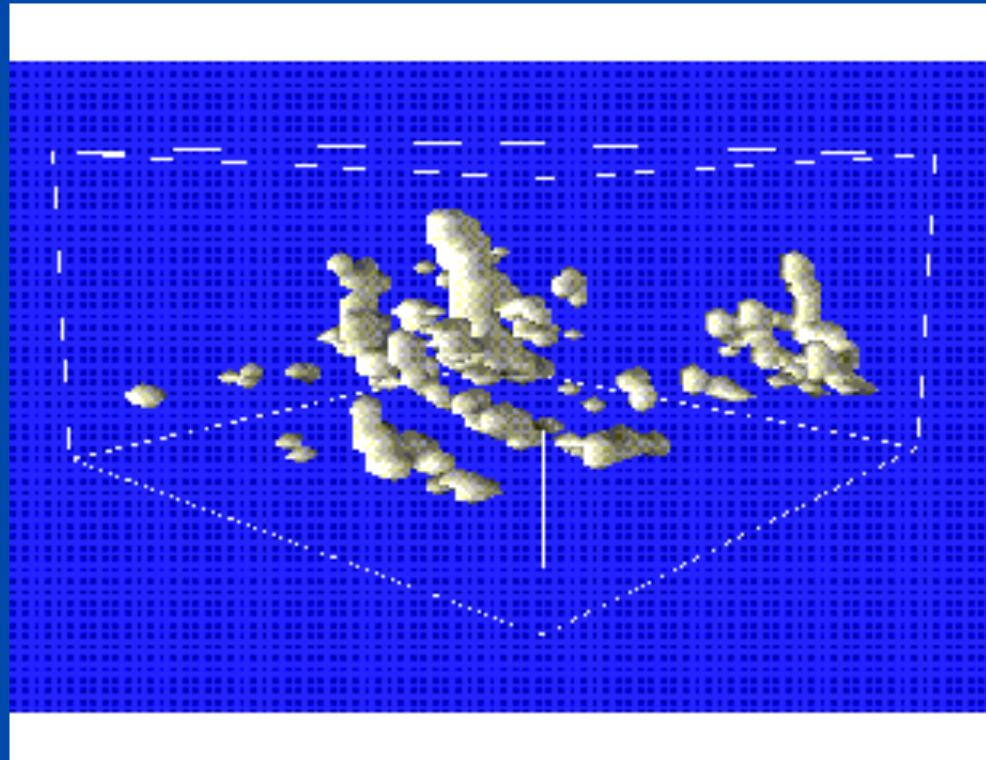


FIG. 1. Initial profiles of the total water specific humidity q_t, the liquid water potential temperature θ_ℓ, and the horizontal wind components u and v. The shaded area denotes the conditionally unstable cloud layer.

Δx=Δy=50m; Δz=20m



The Barbados Oceanographic and Meteorological Experiment (BOMEX) case (Holland and Rasmusson 1973)

Turbulent enhancement in LES simulation:

$$\epsilon = C_{\text{eps}}(\text{TKE})^{3/2}/\Delta$$

$$\Delta = (\Delta x + \Delta y + \Delta z)/3$$

$$C_{\text{eps}} = 0.845$$

$$Re_\lambda = 15^{1/2}(u_{\text{rms}}/v_K)^2$$

v_K is the Kolmogorov velocity

u_{rms} (in m s^{-1}): $u_{\text{rms}} = 2.02 \cdot (\epsilon/400.)^{1/3}$

ϵ in $\text{cm}^2\,\text{s}^{-3}$

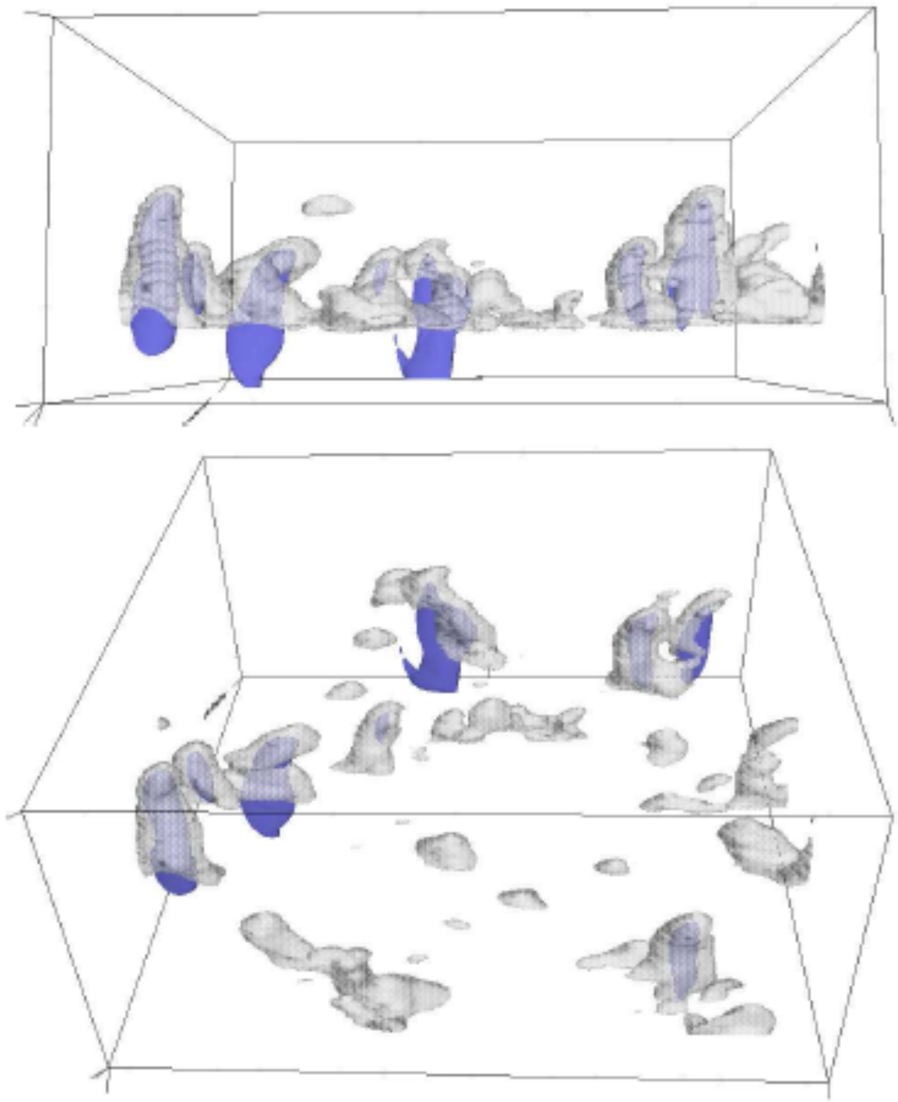
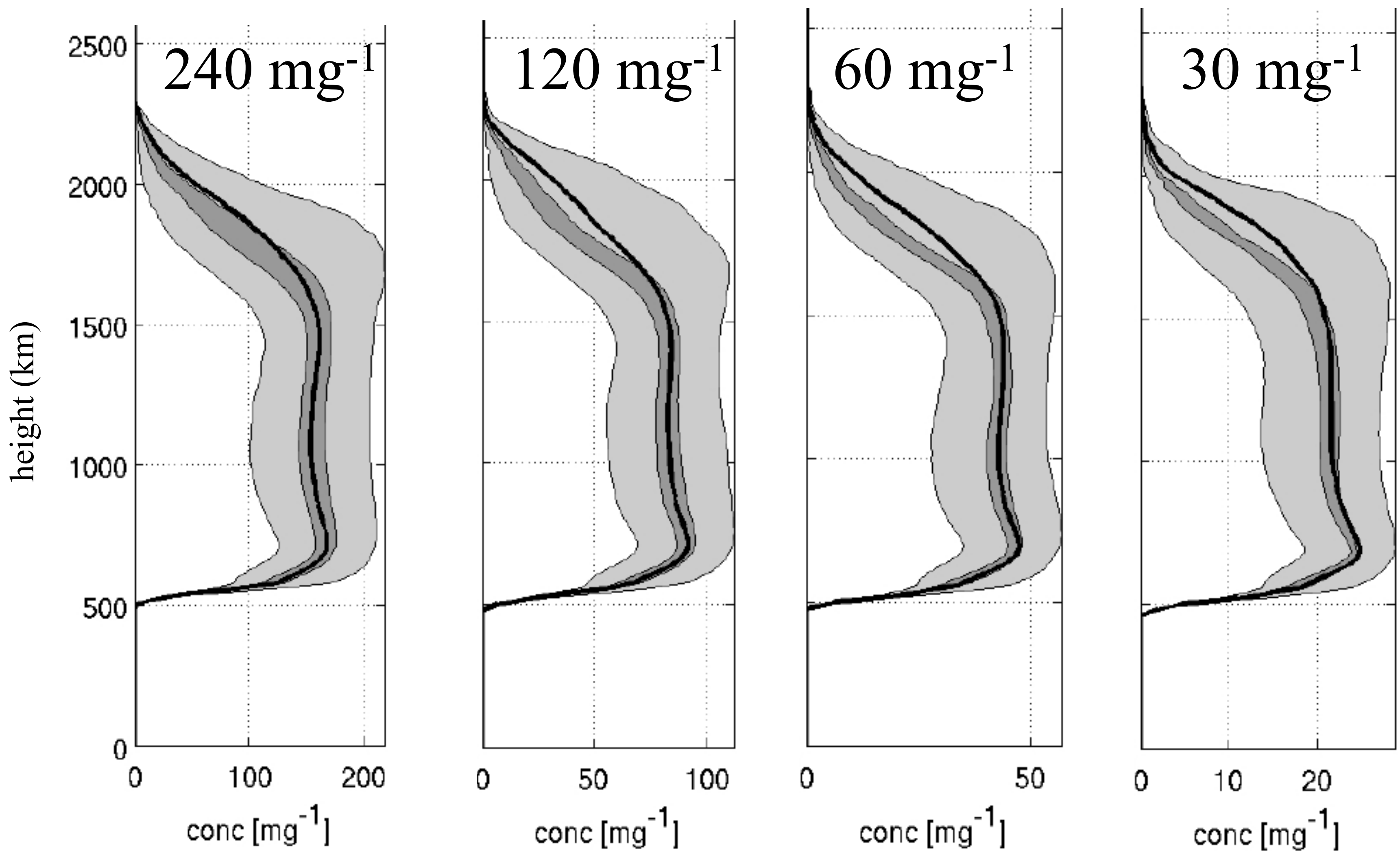
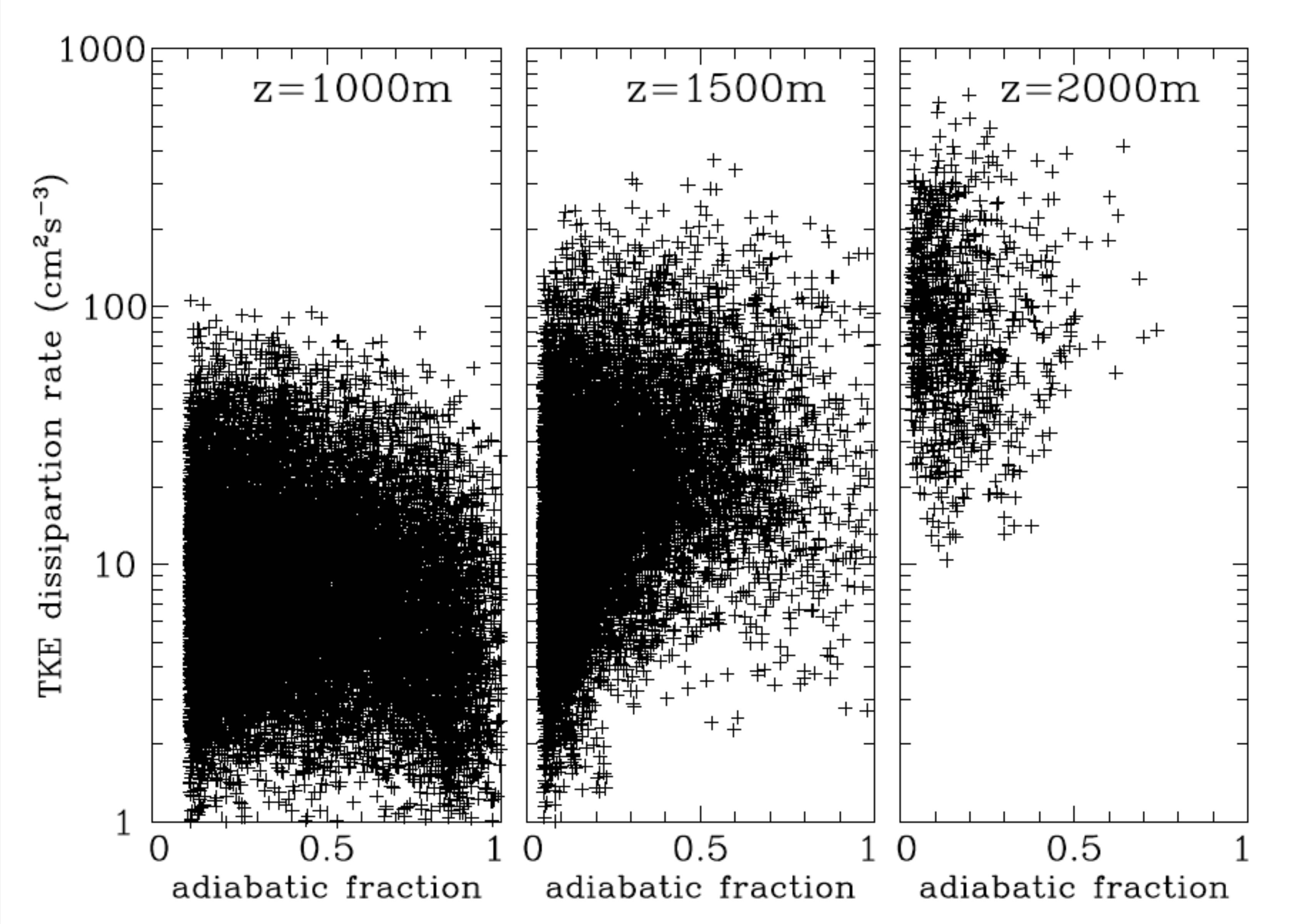


Fig. 4. Snapshots of cloud water mixing ratio (transparent gray) and rain water mixing ratio (solid blue) at the 6th hour of the simulation. The isosurfaces show values $q_c = 0.05\ \mathrm{g\,kg^{-1}}$ and $q_r = 0.02\ \mathrm{g\,kg^{-1}}$.

N^0_{CCN} versus droplet concentration

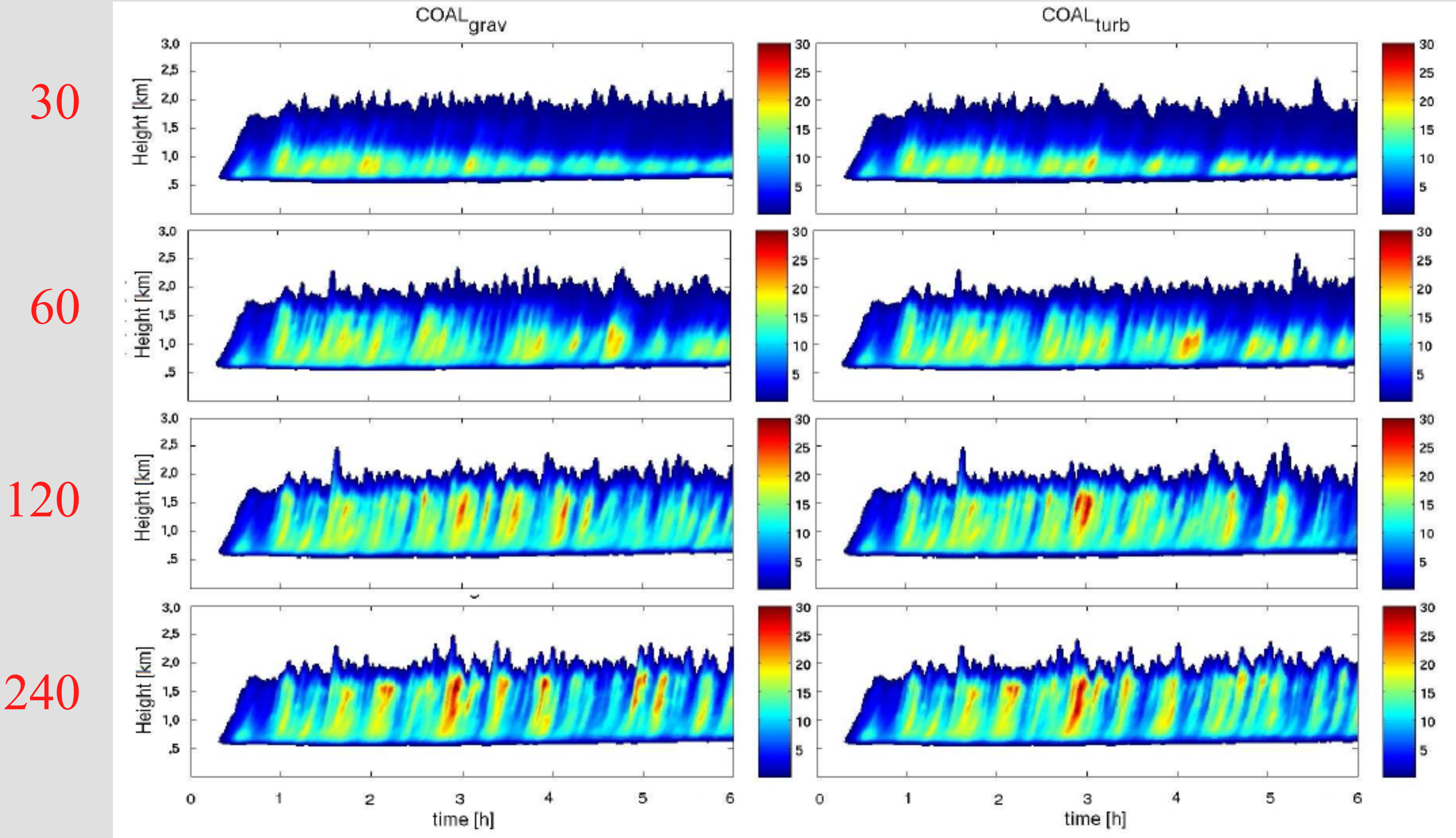


droplet concentration (mg^{-1})



N120 simulation; all cloudy points (q_c > 0.1g/kg) with $\varepsilon > 1 cm^2/s^3$; hours 3-6

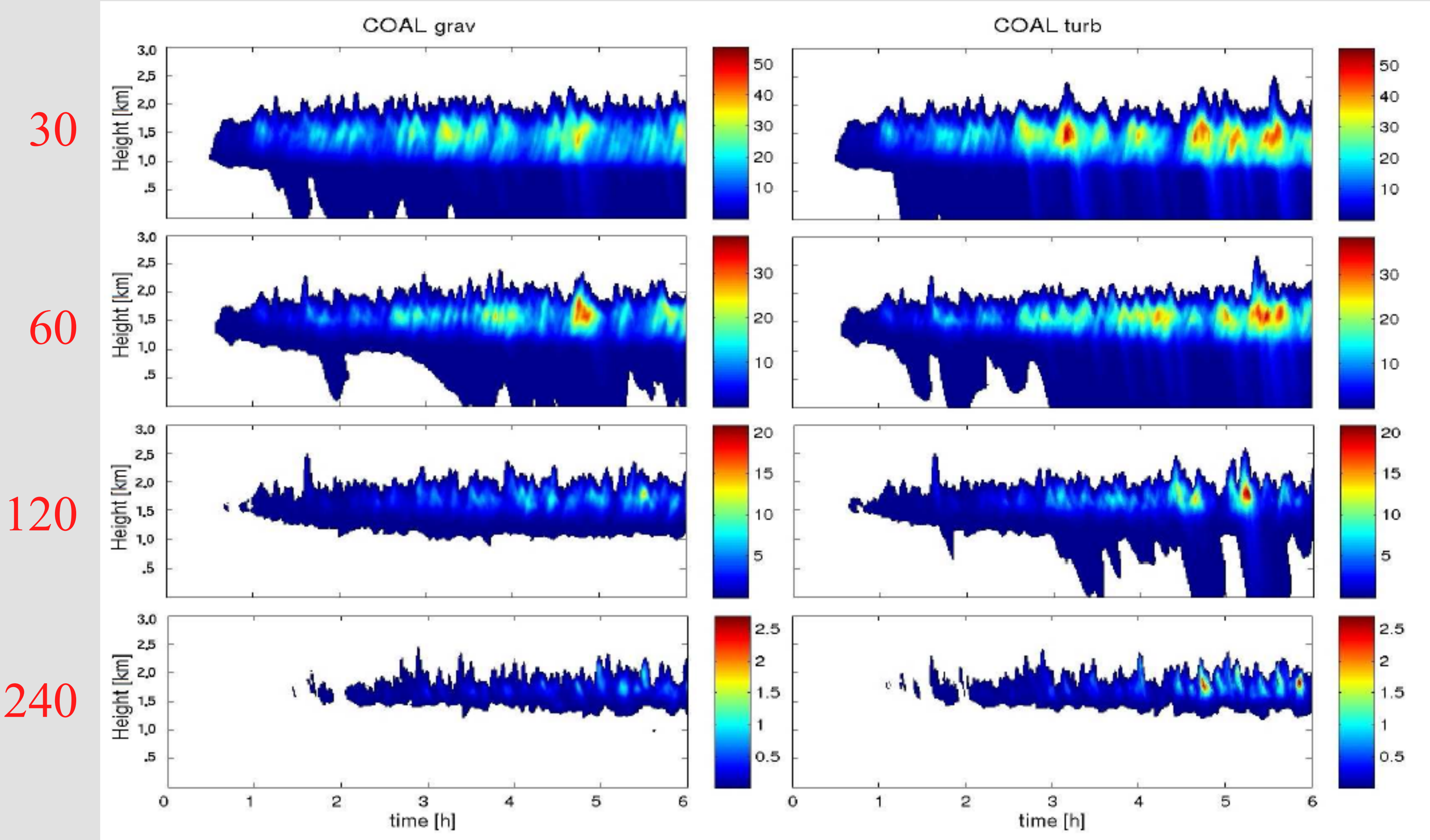
Domain-averaged cloud water mixing ratio (r < 25 μm)



Gravitational kernel

Turbulent kernel

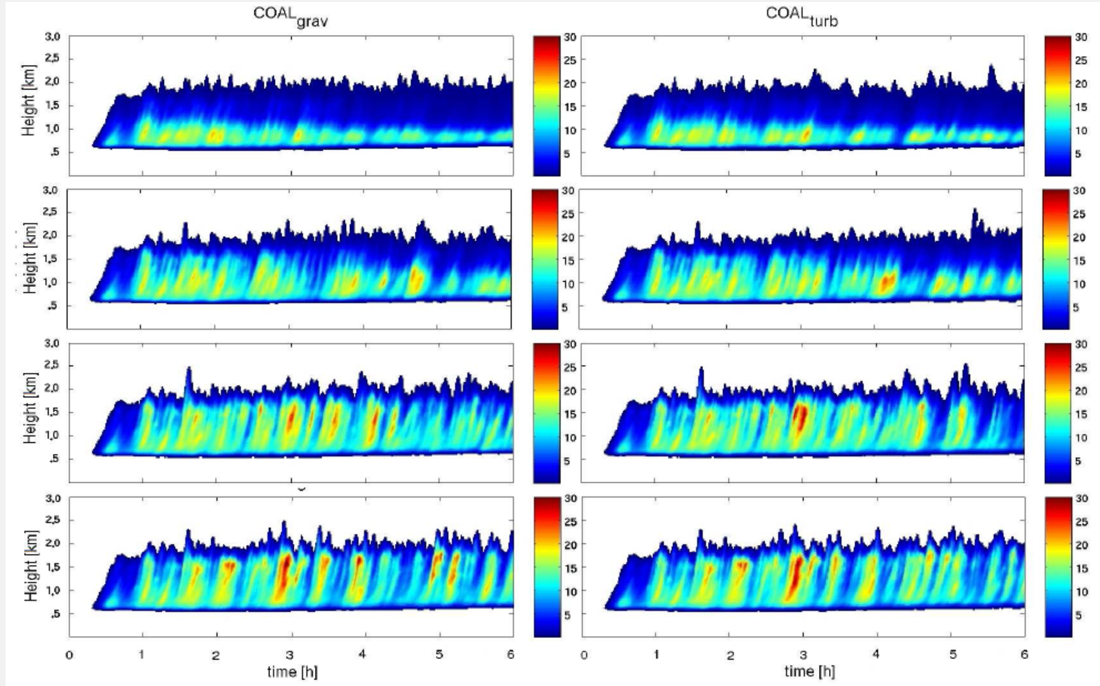
Domain-averaged drizzle/rain water mixing ratio (r > 25 µm)



Gravitational kernel

Turbulent kernel

Cloud water



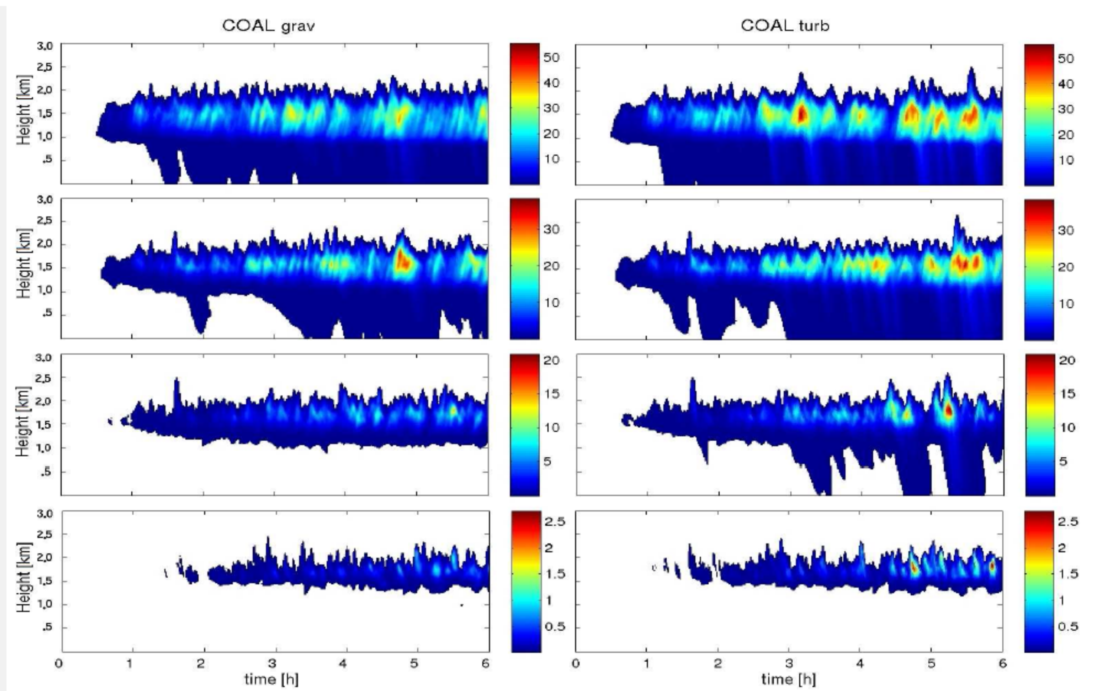
30

60

120

240

Drizzle/rain water



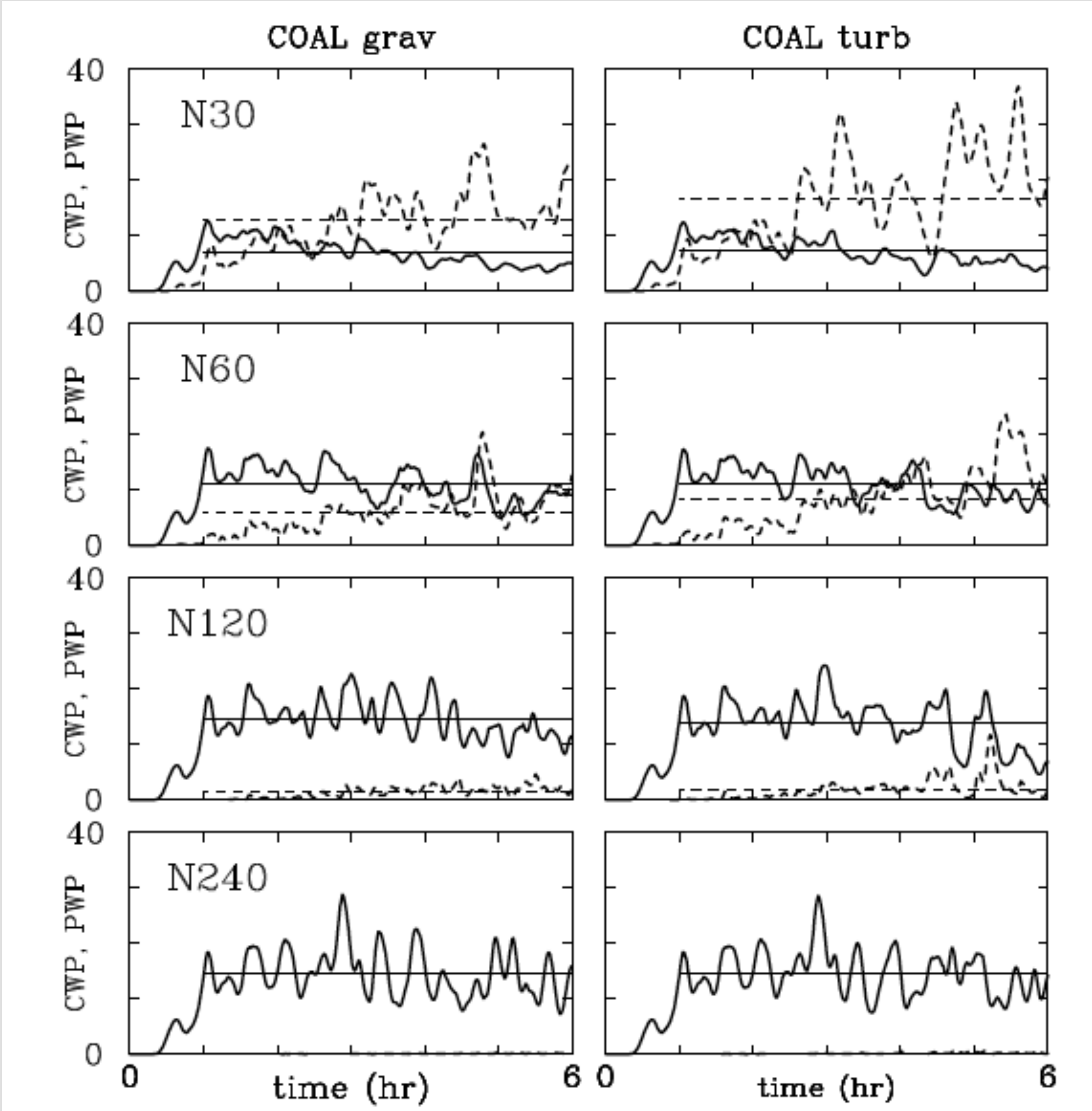
30

60

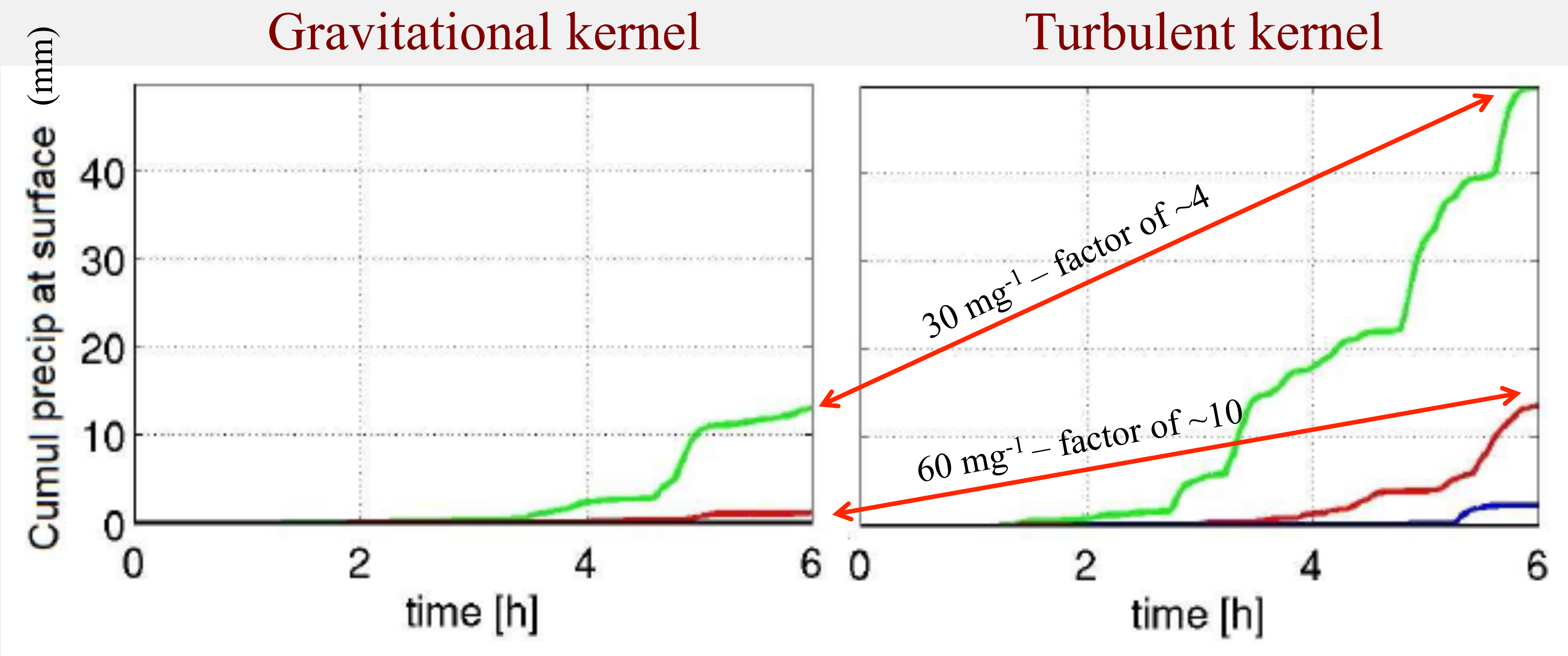
120

240

Domain-averaged cloud water path (CWP, solid line) and precip water path (PWP, dashed line)



Surface rain accumulation from the cloud field:



Summary:

Small-scale turbulence appears has a significant effect on collisional growth of cloud droplets and development of warm rain in shallow cumuli.

Not only rain tends to form earlier in a single cloud, but also turbulent clouds seem to rain more. This is a combination of microphysical and dynamical effects.

The (perhaps surprising) magnitude of this effect calls for further observational and modeling studies to provide more support for these findings.