Evaluation of vertical mass flux in high-resolution simulations of convective clouds

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Motivation

Craig and Cohen (2006) used the Gibbs canonical ensemble from statistical mechanics to derive equilibrium statistics of a field of cumulus clouds under homogeneous large-scale forcing.

They derived the probability density function of individual cloud mass fluxes, in the limit of non-interacting convective cells, to be exponential:

$$p(m)dm = \frac{1}{\langle m \rangle} e^{-m/\langle m \rangle} dm$$

Mean cloud number density distribution:

$$d\overline{n}(m) = \frac{\langle N \rangle}{\langle m \rangle} e^{-m/\langle m \rangle} dm$$

$\langle N \rangle$: Ensemble mean number of clouds
$\langle m \rangle$: Ensemble mean mass flux per cloud

Validation of their theory with CRM simulations at 2 km horizontal resolution in radiative convective equilibrium for different forcings :

→ **exponential distribution is independent of the forcing**

→ **increasing the forcing mainly increases the number of clouds, not cloud strength**

Is this theory of an exponential mean cloud number density distribution still valid at very high horizontal resolutions (~100 m), where small cumulus clouds are actually resolved?

Model description

Simulations are performed with the anelastic, non-hydrostatic model EULAG (EUlerian/semi-LAGrangian fluid solver), which uses a second order accurate, semi-implicit, non-oscillatory forward in time approach (Prusa et al., 2008).

The underlying transport operator to solve the moist governing equations is formulated for arbitrary curve-linear frameworks and employs the MPDATA (multidimensional positive, definite advection transport) algorithm.

The buoyancy term is expressed by the perturbation of the density potential temperature:

$$\theta_d' = \theta + \overline{\theta}\left(\epsilon\, q_v - q_c - q_p\right)$$

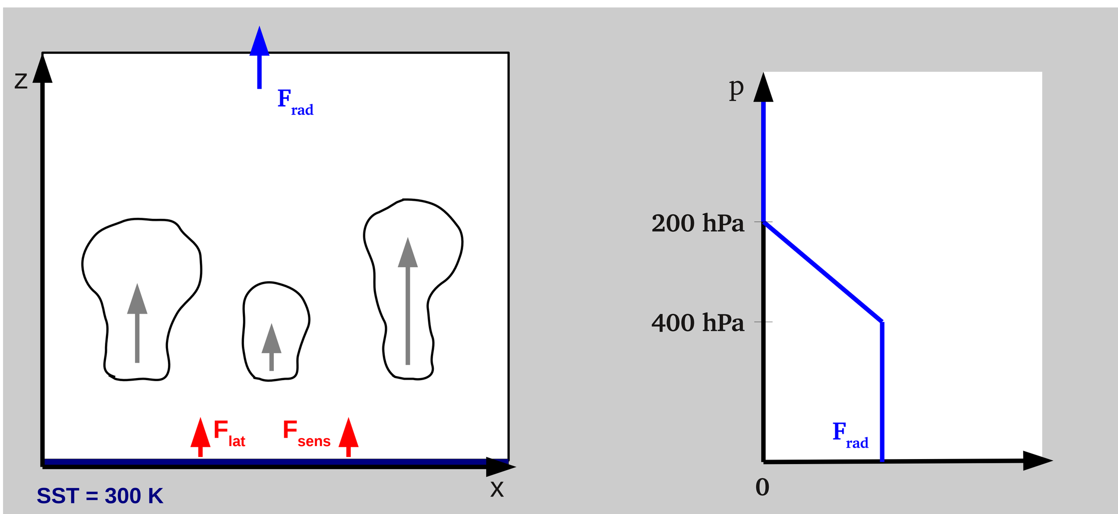
(Mixing ratio of water vapor (q_v), cloud water (q_c) and rain water (q_p))

$$\frac{d\mathbf{u}}{dt} = -\nabla\left(\frac{p'}{\overline{\rho}}\right) + \mathbf{g}\frac{\theta_d'}{\overline{\theta}} - \mathbf{f} \times \mathbf{u}' + \mathbf{M}'$$

$$\frac{d\theta'}{dt} = -\mathbf{u}\,\nabla\theta_e + F_\theta$$

Control simulation: set-up

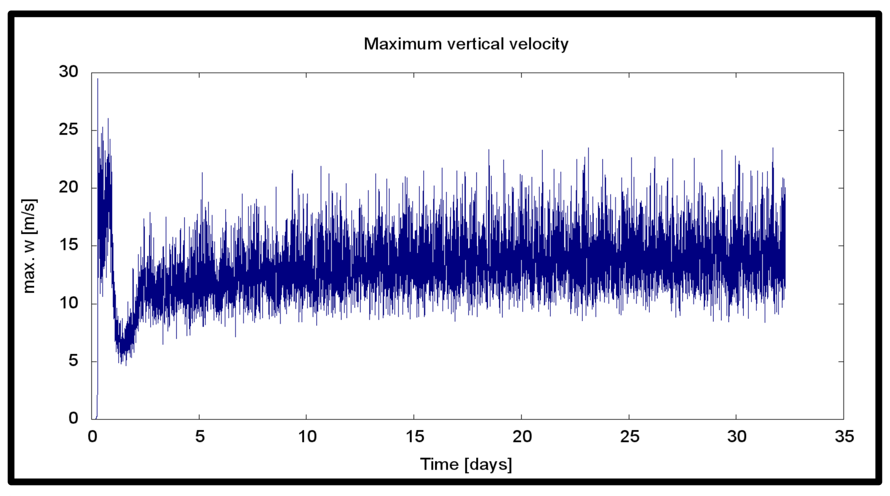
- 3D model domain: 128 km *128 km * 20 km
- 2 km horizontal, 200 m vertical resolution
- Sea Surface Temperature fixed at Θ_{surf} = 300 K
- Periodic boundary conditions in x and y
- Rayleigh damping layer at top of the domain
- Horizontally homogeneous radiative cooling rate F_{rad}

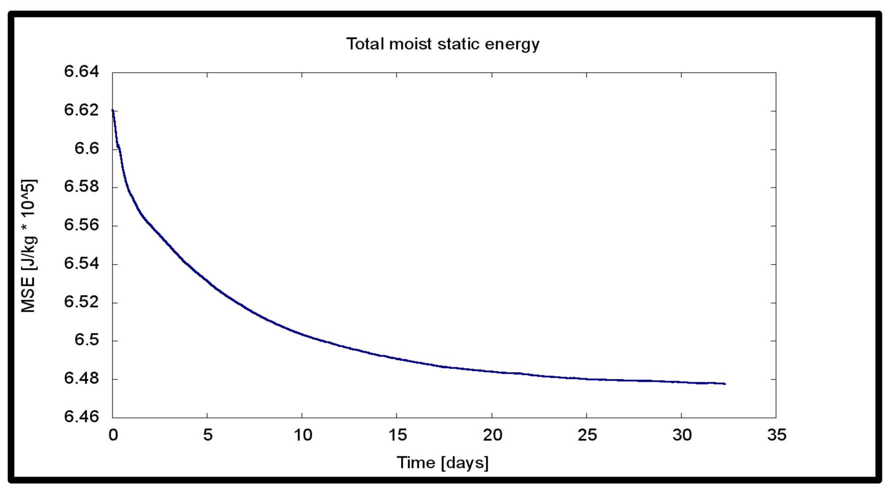


Bulk parametrization of surface fluxes of latent and sensible heat (Grabowski, 1998), where U is a measure of the surface wind taking into account the convective velocity scale.

$$F_\Phi = C_d U\left(\Phi_{srf} - \Phi_{z=0}\right)$$

Evolution to quasi-equilibrium





The model is run with F_{rad}= - 8 K/day from an initial horizontally homogeneous state with no convection:

→ high frequency variability (~1 h) can be directly related to convective activity

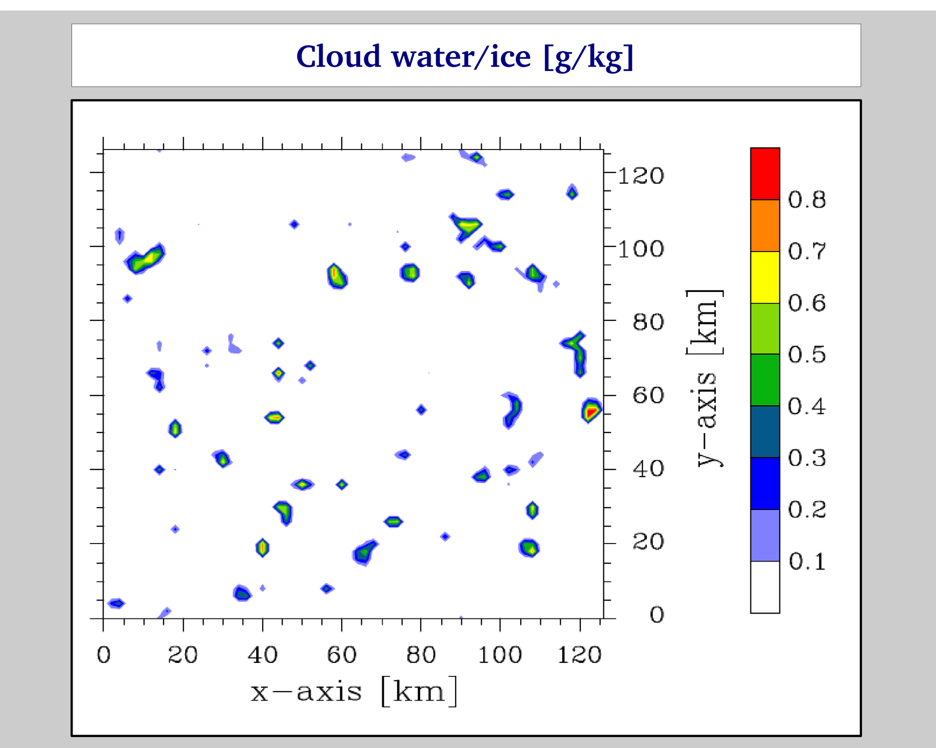
→ long, slow trend of the overall spin-up towards radiative convective equilibrium (~30 days)

In equilibrium, the input of energy into the system (surface fluxes) provides exactly the energy required by convection to offset F_{rad}.

Moist Static Energy = c_p*T + g*z + L_v*q

The equilibrium state

Horizontal Slice through the domain at z = 1.8 km



1) Criterion to define cloudy grid points:

w > 1 m/s **and** q_c > 1.e-3 g/kg

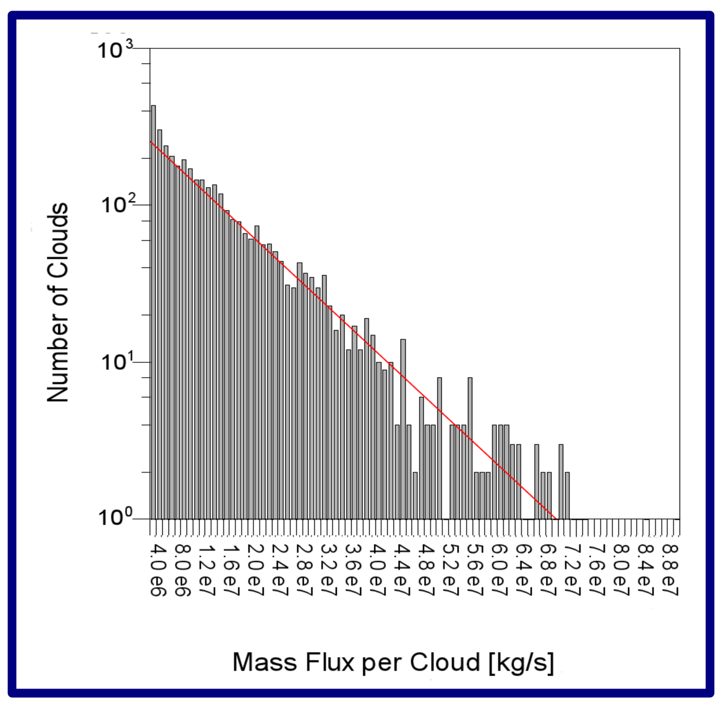
2) Search for adjacent cloudy grid points

3) Compute mass flux per cloud: $m_i = \rho * \sigma_i * \langle w_i \rangle$

(σ_i:size of the cloud, ρ:density of air, $\langle w_i \rangle$:average vertical velocity)

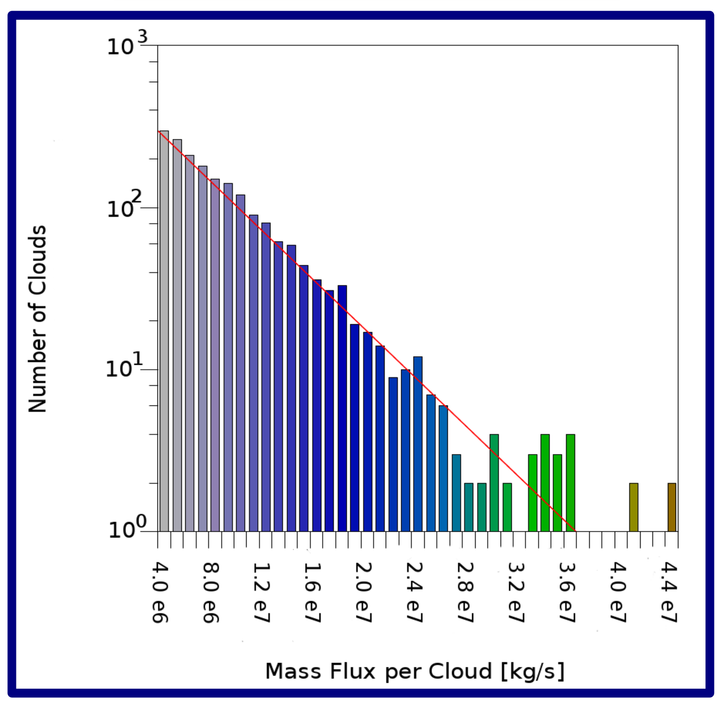
Exponential distribution of mass flux per cloud

- 8 K/day radiative cooling



~ 36 clouds per time step

- 4 K/day radiative cooling



~ 18 clouds per time step

Results of the simulations with EULAG at 2 km horizontal resolution for different forcings:

1) Mean cloud number density distribution is exponential, independent of the forcing.

2) Increasing the forcing by some factor increases the mean number of clouds in the domain by a similar factor.

Outlook

Repeat simulations for different cooling rates while step-wise increasing the horizontal resolution.

Answer questions:

1) Is the distribution of mass flux per cloud exponential at cloud resolving resolutions?

2) Is the distribution at high resolution sensitive of the forcing?

Evaluate entrainment rates in the high-resolution simulations

Focus on entrainment per cloud statistics

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