# A new numerical technique for warm cloud simulations

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# Warm Clouds


- Rain produced in warm clouds 30% of the total planet rainfall
- 70% of total rain in tropics
- Important for Earth climate and climate changes
- Droplet size distribution affects albedo and cloud fraction→ substantial climate effects

# *Rain formation*

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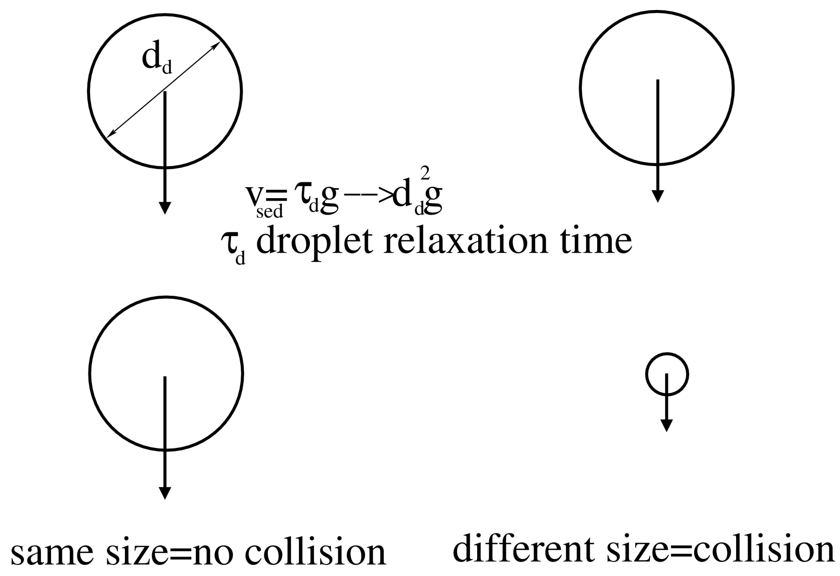
- Activation of Cloud Condensation Nuclei (CCN)
- Growth by condensation
- Growth by mixing/collision due to turbulence
- Growth by gravitational collision

# *The bottleneck problem*

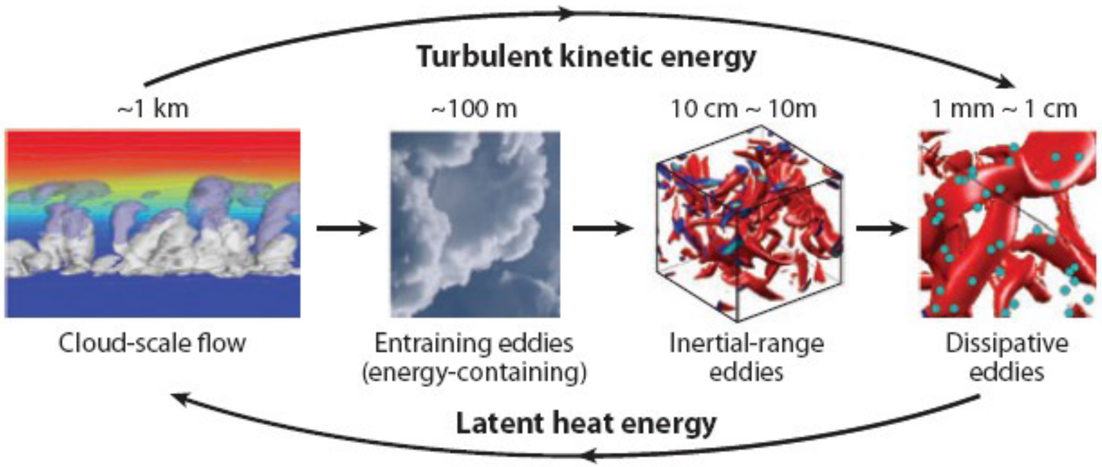



- A broad droplet size distribution necessary for rain formation
- From CCN to final distribution in few minutes (15/20 minutes)

- droplet growth should take hours according to current theories
- nobody knows how rains drops form so quickly, a problem known as the condensation-coalescence bottleneck

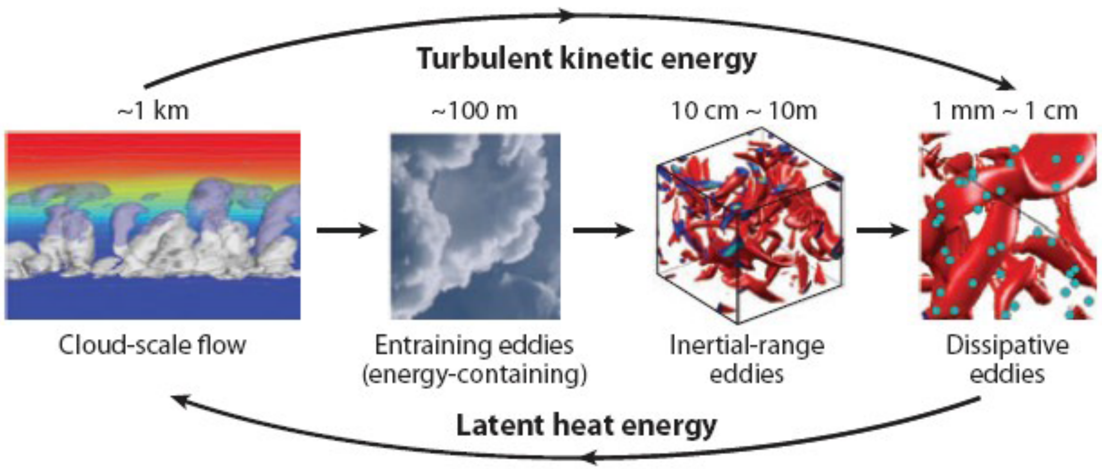
# Role of turbulence/1

- Clouds are considered the largest source of uncertainty in climate prediction (Shiogama & Ogura, Nature 2014)
- it is very difficult to parameterize the small-scale dynamics and turbulence effects (microphysics) s in a global climate model where grid boxes are typically 250 km wide and 1 km high
- Turbulence affects cloud microphysics by entrainment, stirring, and mixing, resulting in strong fluctuations and intermittency in temperature, humidity, aerosol concentration, and cloud particle growth and decay (Bodenschatz et al., Science 2010)



# *Role of turbulence/2*

- Turbulence enhances droplets collision rate→ sling effect (Falkovich et al., Nature 2002)
- Tangling clustering instability in stratified turbulence (Elperin et al, PoF 2013) → see next talk
- Turbulence affects growth by condensation (Vaillancourt et al., JAS 2001, Lanotte et al., JAS 2009)



# *Turbulence and droplet condensation: a Brief Excursus*

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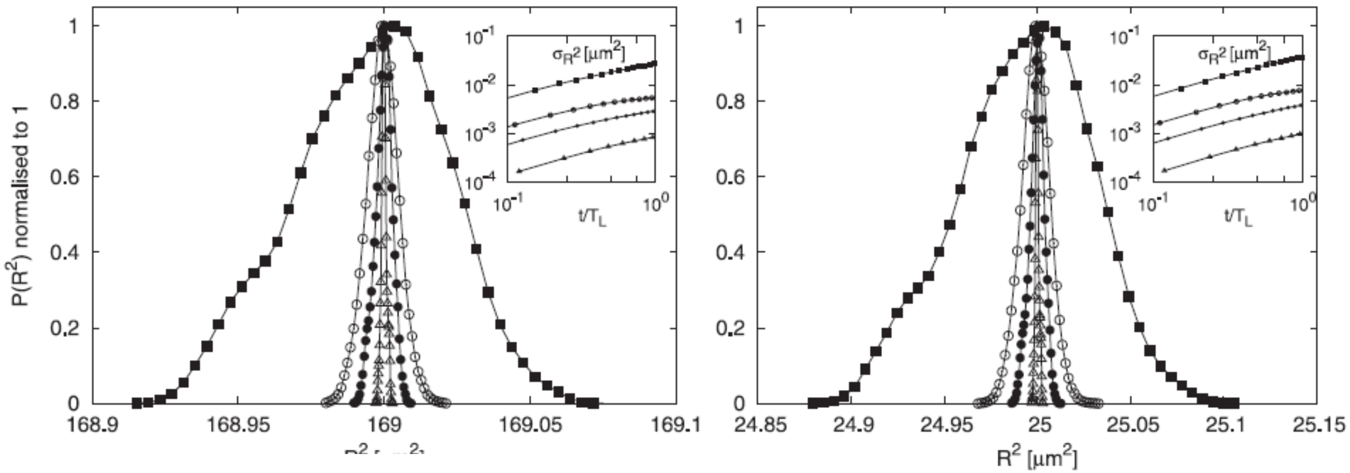
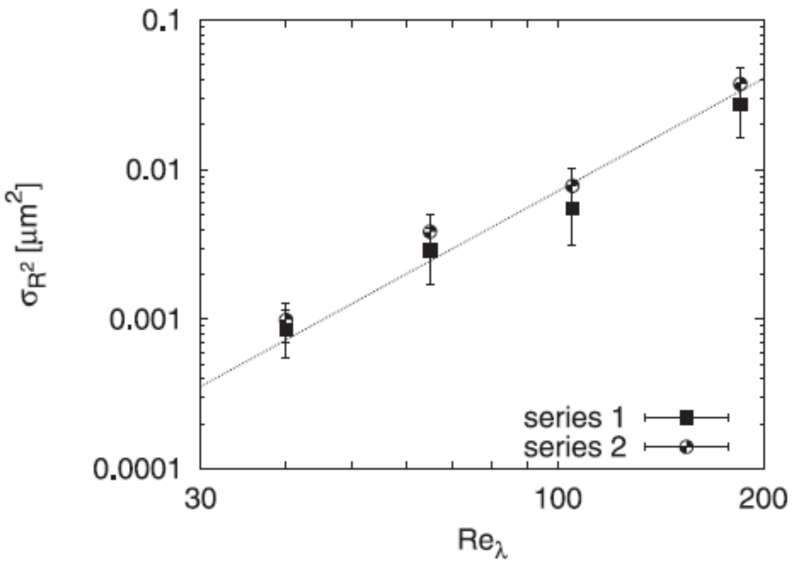
- turbulence has been indicated as the key missing link to solve the bottleneck problem
- first DNS of turbulence/cloud interactions done by Vaillancourt et al. 2002. Domain 10cm, resolution $80^3$ grid points, droplets 50000→ Conclusion: negligible effect of the small-scale turbulence on droplet spectra broadening
- Celani et al. 2007, resolving large-scale fluctuations 2D cloud→ Conclusion: dramatic increase in the width of the droplet spectrum is qualitatively found although the dynamics of the small scales is not resolved
- Paolo & Sharif, 2009, same conclusions but 3D simulation obtained adding an arbitrary large-scale forcing on the supersaturation equation field.
- Current state of the art: Lanotte et al 2009, 3D DNS simulations increasing size of the cloud up to 70 cm→ turbulence affects droplet spectra broadening mechanism by increasing the cloud size.

# *Spectral broadening due to turbulence*




- Increase of standard deviation with Reynolds number : Importance of large scales!
- Upper limit $T_L < \tau_s$

$$\sigma_{R^2} \propto A_3 A_1 v_\eta \tau_\eta^2 Re_\lambda^{5/2}$$

- Lower limit $T_L > \tau_s$

$$\sigma_{R^2} \propto A_3 A_1 v_\eta \tau_\eta \tau_s Re_\lambda^{3/2}$$

Lanotte, Seminara, Toschi, JAS 2009

# *Our objectives*

1) We focus just on droplet growth by condensation (we neglect growth by collisions at the moment) in homogeneous isotropic turbulence
2) Can small-scale turbulence and condensational growth "alone" solve the bottleneck problem?
3) Has Droplet spectra variance in warm cloud been correctly evaluated so far?
4) Metodologies: -Direct Numerical Simulation DNS, -Large Eddy Simulation LES
5) Description of a new Multiscale Tool

# Complicated Multiscale Problem

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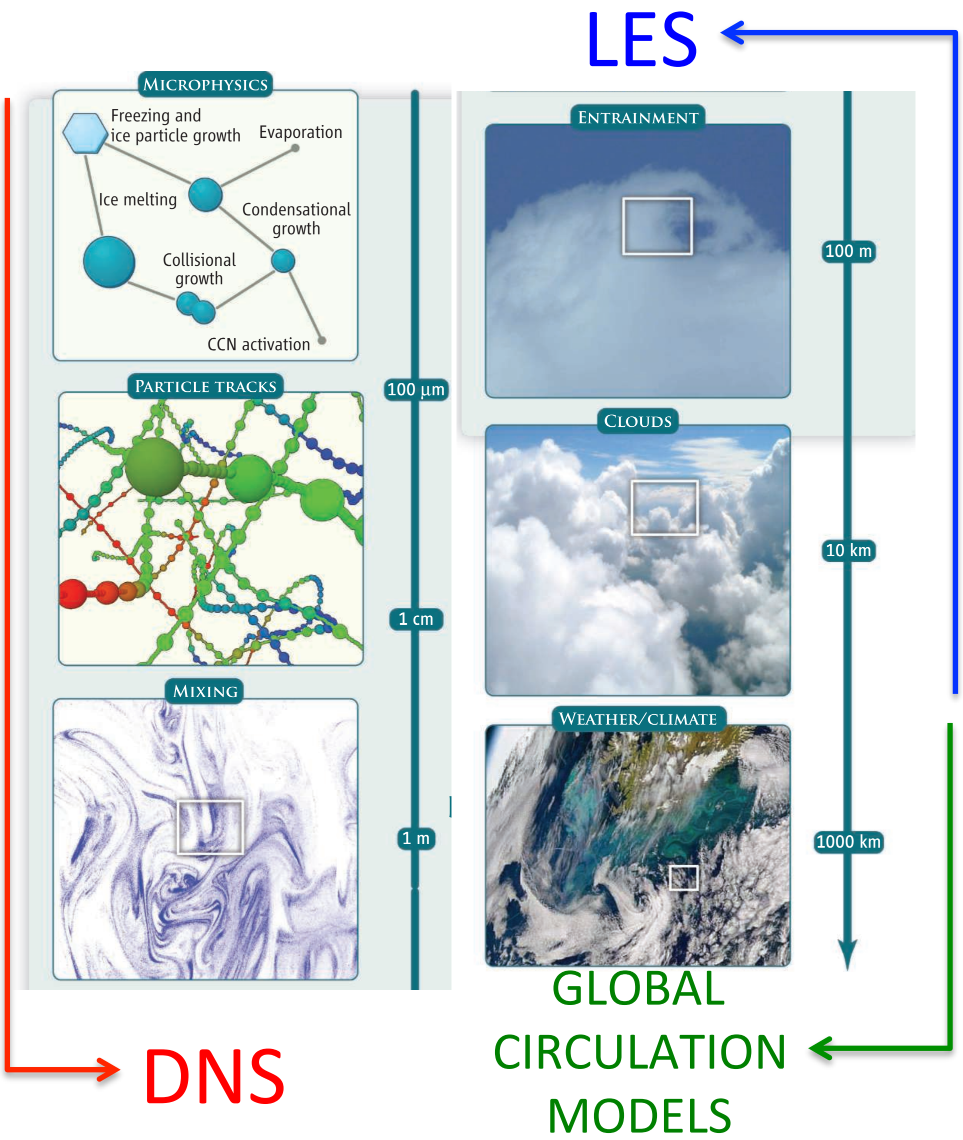


Pictures taken from Bodenschatz et al., Science 2010

- Direct numerical simulations: resolving all the details of the flow
- Limited value of Reynolds number also with massive supercomputers
- Largest simulation so far: $512^3$, $10^8$ droplets (cube of 70 cm), Lanotte et al 2009
- Ideal simulation of homogeneous cloud: $65536^3$, $10^{15}$ droplets (100 m)

# *Turbulence and condensation: mathematical model*

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Eulerian framework: Navier-Stokes + supersaturation field s
→ s>0 condensation s<0 evaporation

$$\partial_t \mathbf{u} + \mathbf{u} \cdot \nabla \mathbf{u} = -\frac{1}{\rho} \nabla p + \nu \nabla^2 \mathbf{u} + \mathbf{f}, \quad \nabla \cdot \mathbf{u} = 0$$

$$\partial_t s + \mathbf{u} \cdot \nabla s = \kappa \nabla^2 s + A_1 w - \frac{s}{\tau_s} + f_s \qquad \tau_s^{-1} = \frac{4\pi \rho_w A_2 A_3}{V} \sum_{i=1}^{N} R_i$$

Possible large scale forcing of supersaturation

Phase relaxation time scale

Lagrangian framework: droplet dynamics

$$\frac{d\mathbf{V}_i(t)}{dt} = -\frac{\mathbf{V}_i - \mathbf{v}_i[\mathbf{X}_i(t), t]}{\tau_d} + g\mathbf{z}$$

$$\frac{d\mathbf{X}_i(t)}{dt} = \mathbf{V}_i(t)$$

$$\frac{dR_i(t)}{dt} = A_3 \frac{s[\mathbf{X}_i(t), t]}{R_i(t)}$$

Droplet modeled as point particles

Force acting on droplets: Stokes drag and gravity

Same formulation of Lanotte et al., JAS 2009

# *Numerical Methodology*

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- Combined Eulerian/Lagrangian Solver
- Pseudo-spectral code
- 2/3 rule for dealiasing
- Tri-linear interpolation to evaluate fluid velocity and saturation field at the droplet position
- Tri-linear extrapolation to calculate droplet feedback on the saturation field
- Full MPI parallelization for both carrier and dispersed phase
- Computational time step linearly scales up to 10000 cores → huge simulations

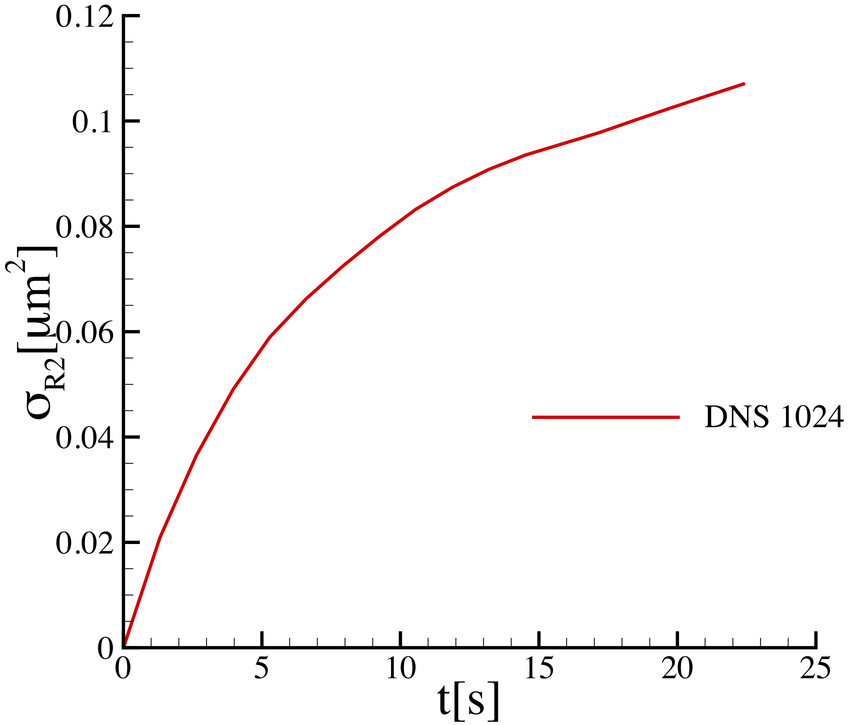
# New enlarged DNS simulation

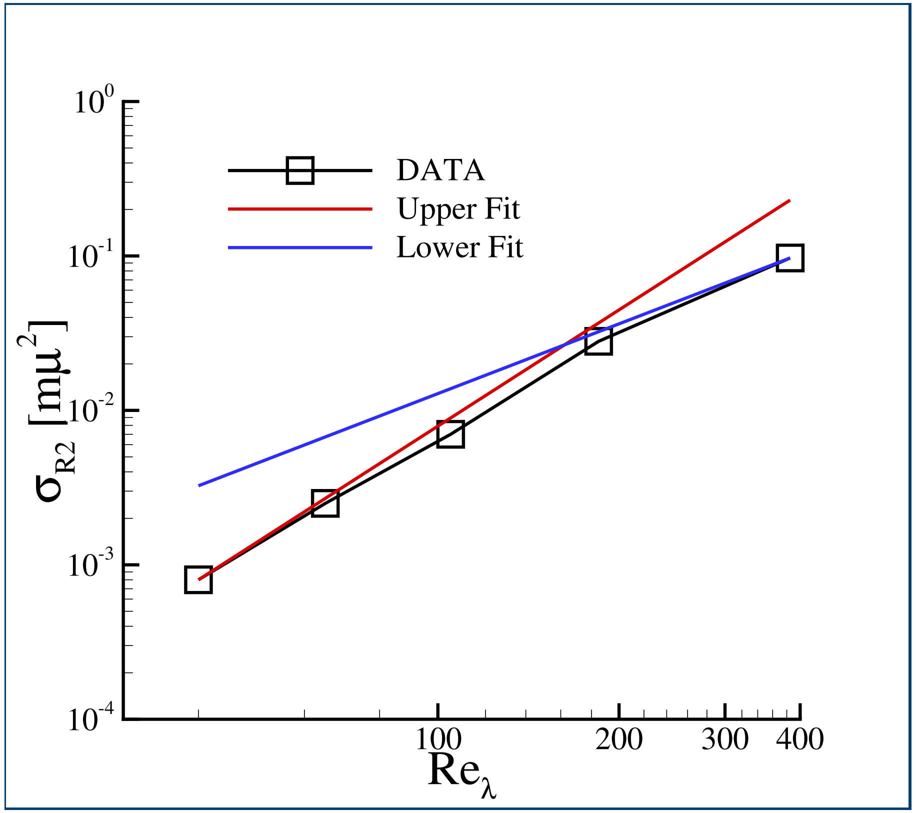
DNS with $1024^3$ grid point resolution corresponding to a domain length of 1.5 meters $10^9$ droplets evolved

First DNS with cloud size order meter

- Parameters
- Dissipation rate: $\varepsilon = 10^{-3} \quad m^2 s^{-3}$
- Kolmogorov scale: $\eta = 1 \quad mm$
- Kolmogorov time: $\tau_\eta = 0.1 \quad s$
- Velocity rms: $v_{rms} = 0.11 \quad m/s$
- Taylor Reynolds number: $Re_\lambda = 400$
- Initial Radius: $R_0 = 13 \quad \mu m$ Stokes number: $St_\eta = 0.0075$
- Phase relaxation time: $\tau_s = 2.5 \quad s$
- Integral time scale: $T_L = 13.6 \quad s \longrightarrow \quad T_L > \tau_s$

# New DNS Results




- State of the art of cloud DNS simulations
- Approaching lower limit regime and droplet spectra steady state since $T_L > \tau_s$
- Droplet spectra variance continues to increase with the cloud size (1.5 meters)
- Physics not different from previous small domain cases (0.7 meters)
- We need to grow with cloud sizes and Taylor Reynolds number→ Nowadays computationally impossible

# *Large Eddy Simulation/ Large-scale DNS*

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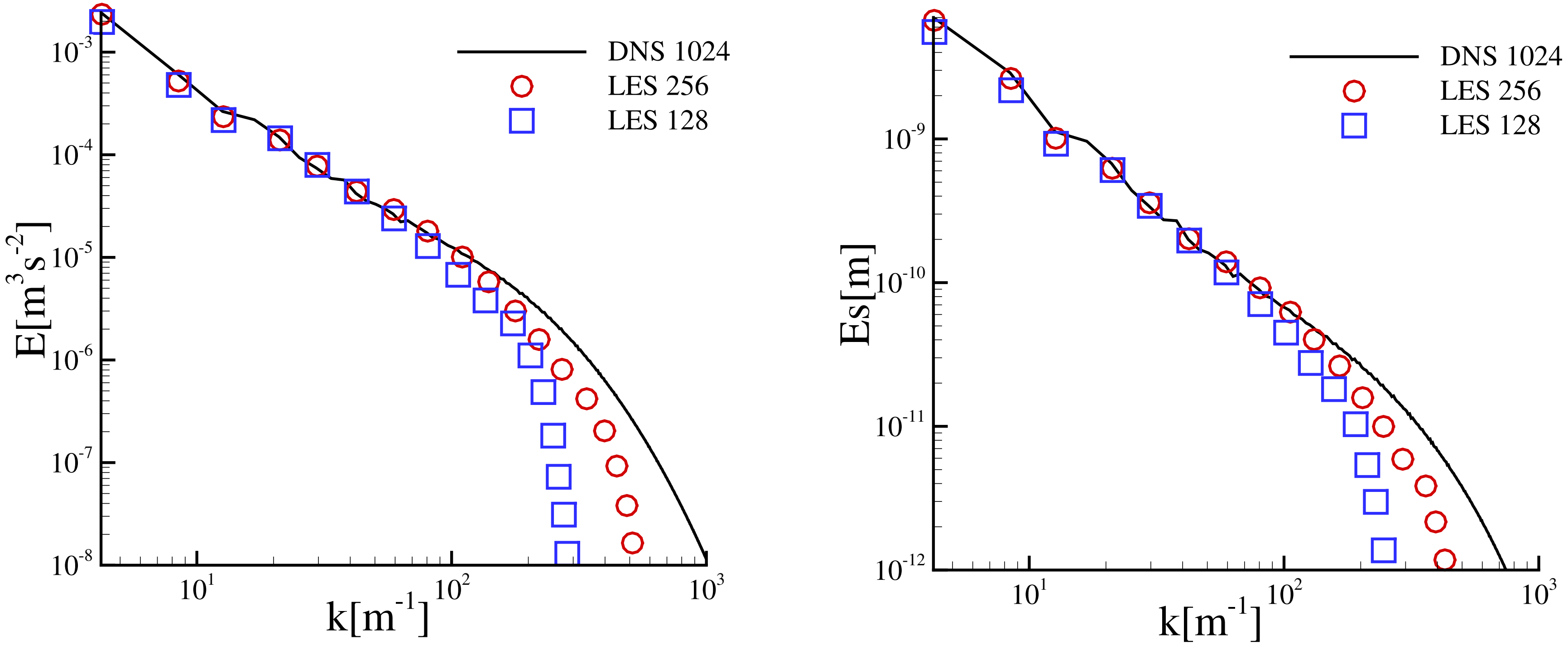
- We want to see the effects of the large scale on droplet condensation
- Maximum cloud size in homogeneous conditions order 100 meters
- Classic Smagorinsky model for the fluid velocity and supersaturation field
- Droplet number: order $10^{15}$ → unfeaseable→ use of renormalization as described in Lanotte et al., 2009
- Parameters $\varepsilon = 10^{-3} \quad m^2 s^{-3}$

$$T_L = 150 \quad s \qquad v_{rms} = 0.7 \quad m/s$$

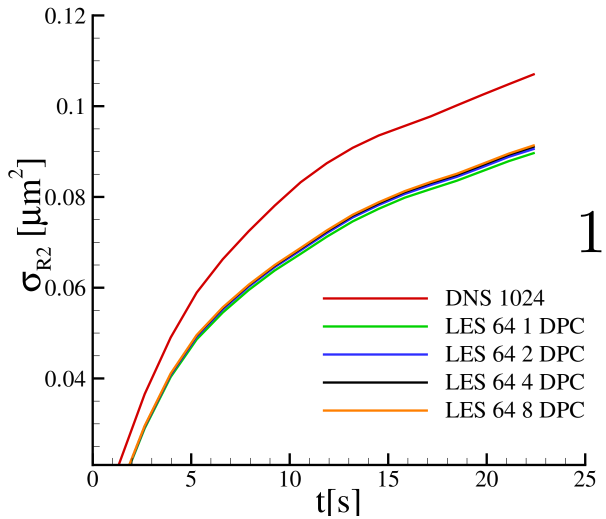
$$Re_\lambda = 5000$$

# LES VALIDATION/1

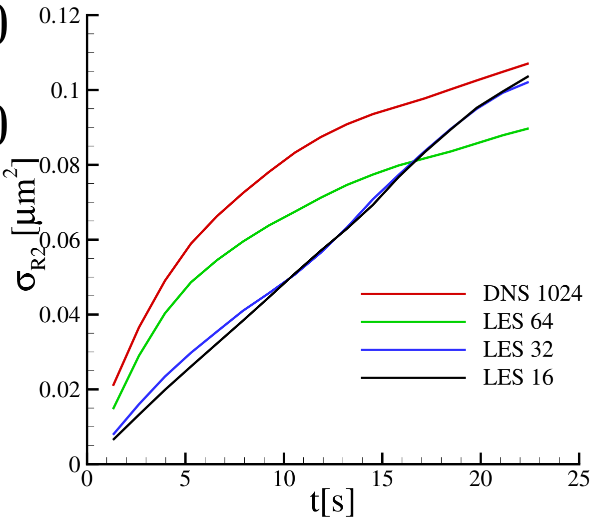


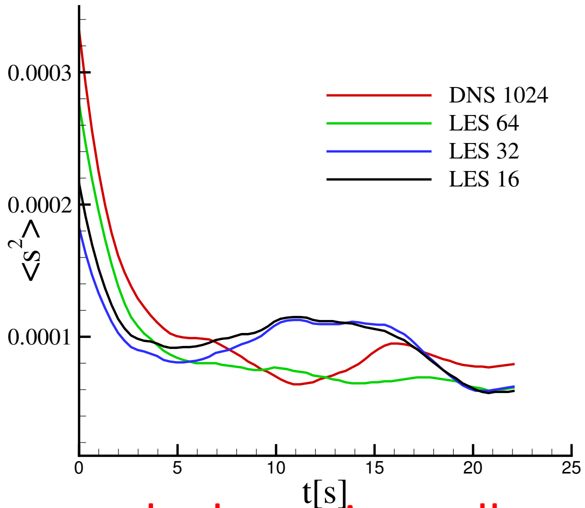

- Validation against our resolved DNS
- Smagorinsky model is enough to accurately capture large scale dynamics for both fluid velocity and supersaturation

# LES VALIDATION/2




$$64^3 \longrightarrow \Delta/\eta \simeq 25$$
$$32^3 \longrightarrow \Delta/\eta \simeq 50$$
$$16^3 \longrightarrow \Delta/\eta \simeq 100$$

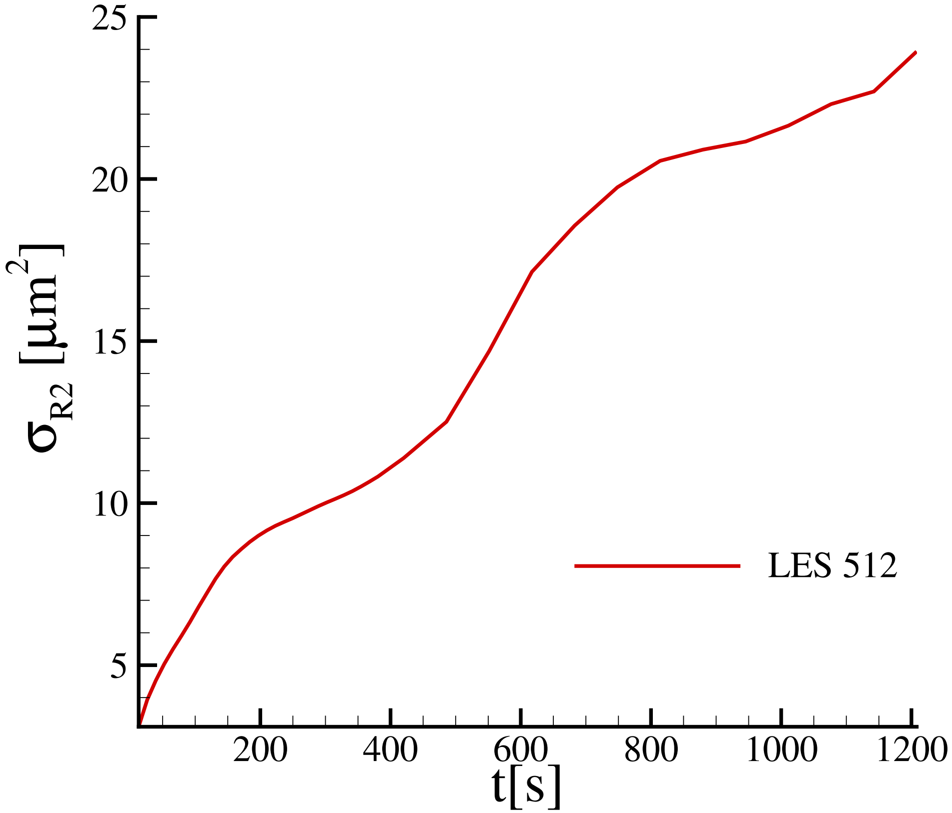



Large scale dynamics well resolved
as shown in the plot for supersaturation
variance

- Renormalization with 1/2 droplets per cell is sufficient
- Coarsest LES simulations overestimate droplet radius variance for long times→ lack of saturation
- Supersaturation is driven by large scale and droplets are outside equilibrium

# Cloud size 100 meters




- Resolution $512^3$
- Grid space $\Delta = 20 \quad cm$
  $\Delta/\eta = 200$
- Simulation time up to 20 minutes→ rain formation time
- After 1 integral time scale, 150 s, $\sigma_{R^2} \simeq 8\mu m^2$ same order found in large scale DNS Lanotte et al. 2009
- As seen before, variance does not saturate at longer times→ possible LES artifact

# *DNS vs LES*

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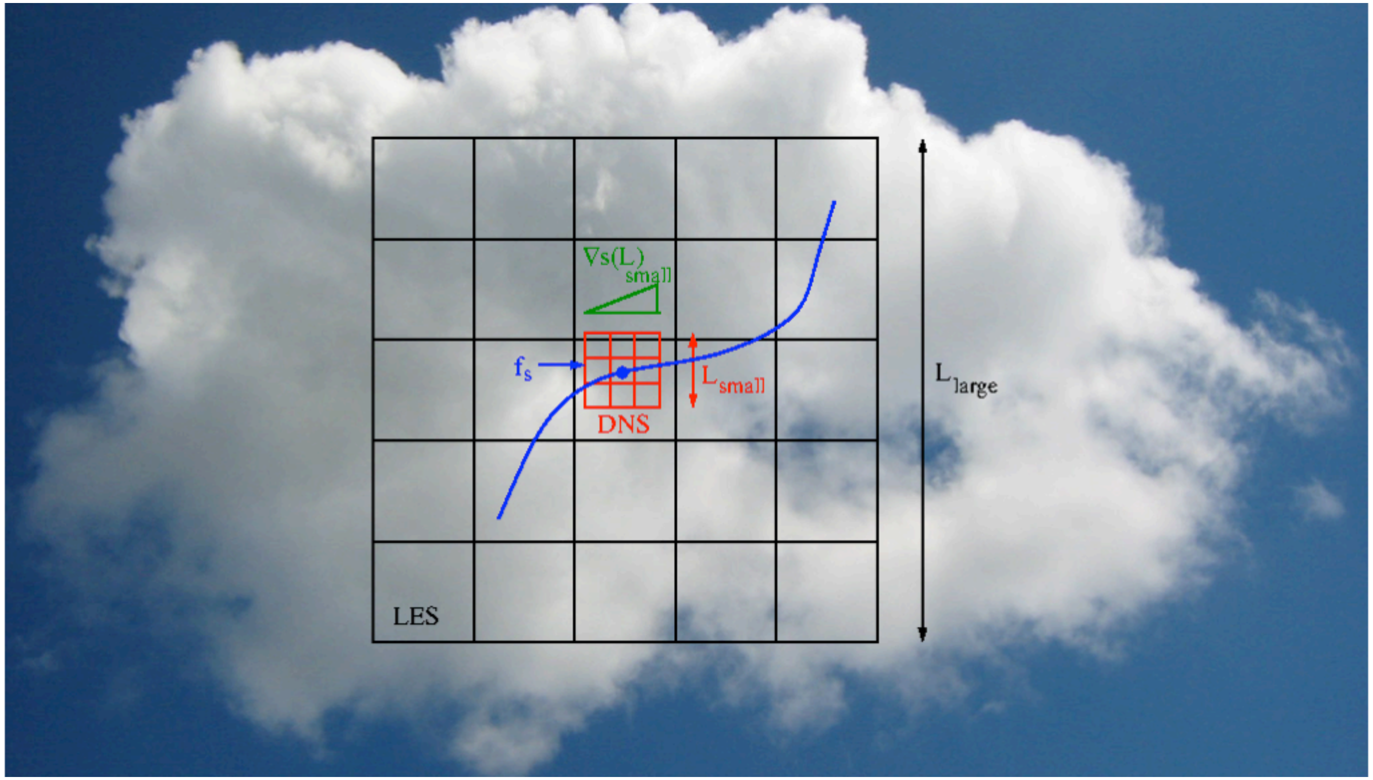
| DNS | LES |
|---|---|
| • No models | • Small scales are modelled |
| • Realistic simulation of small scale turbulence dynamics | • Good simulation of large scale turbulence dynamics |
| • Disadvantages: huge computational time→impossibility to simulate clouds more than 1 meter size | • Disadvantages: Droplets radius distribution seems to be affected by the model at large scale separation and long times $\Delta/\eta > 50$ |

We propose a new numerical simulation technique able to mimic the advantages of both DNS and LES at a reasonable computational cost.

We name the new methodology as "Chinese Box Simulation"

# Chinese Box Simulation




- 1) Cloud Large scales solved by LES in a volume size $L_{large}$
- 2) Portion of the cloud with detailed dynamics of small scales solved by DNS $L_{small}$
- 3) need of a forcing at DNS larger scale
- 4) forcing proportional to LES large scale quantities calculated by following different tracers trajectories $\propto \nabla s(L_{small})$

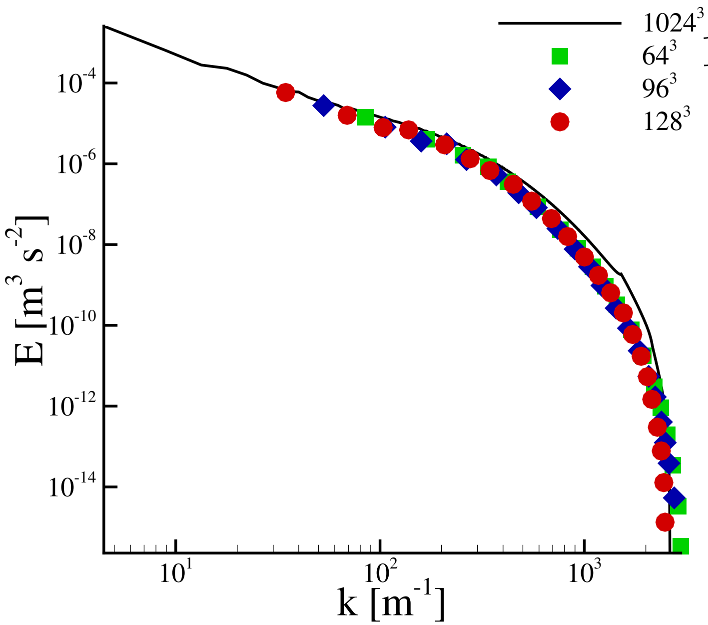
# Forcing of supersaturation field

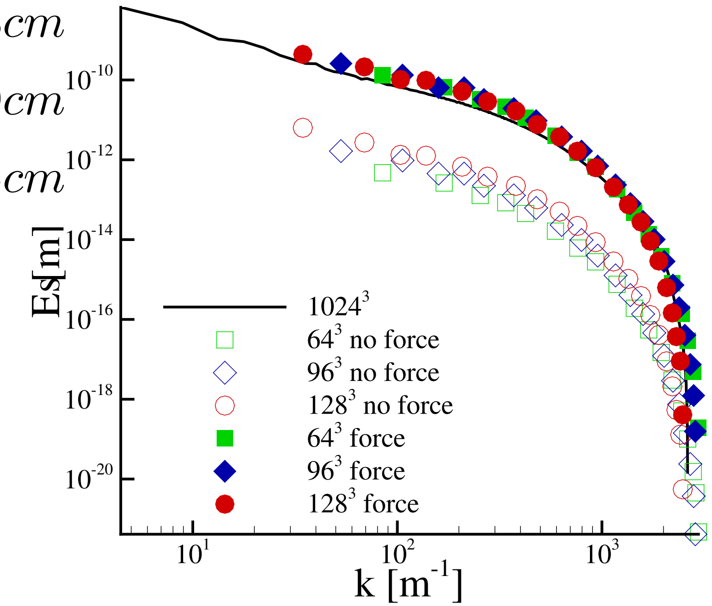
$$1024^3 \longrightarrow L_{large} = 1.5m$$

$$128^3 \longrightarrow L_{small} = 18cm$$

$$96^3 \longrightarrow L_{small} = 9cm$$

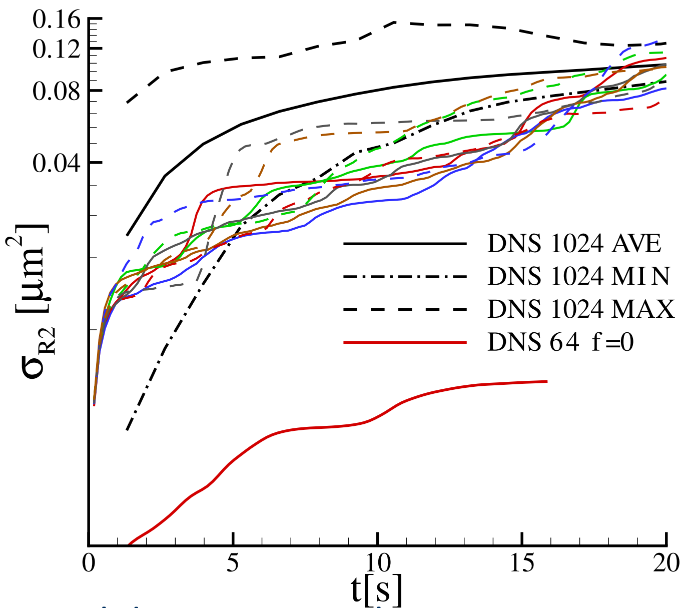
$$64^3 \longrightarrow L_{small} = 4.5cm$$



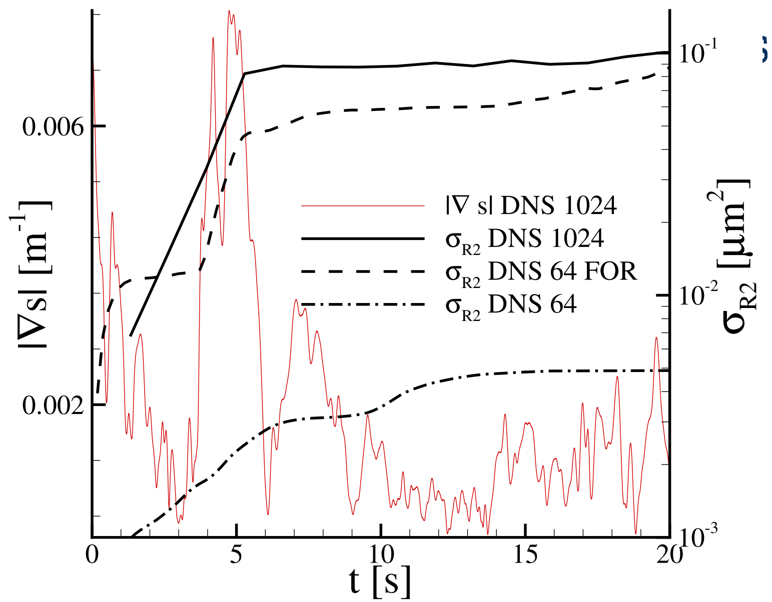




- Usual large scale forcing for the fluid velocity field is enough to correctly take in account turbulent kinetic energy cascade
- $f_s = 0$ no effects of the large scale supersaturation production towards the small scales
- Our model $f_s = (u\nabla s(L_{small}), k = k_{L_{small}})$
- Model well reproduce the small scale dynamics of the supersaturation field of the largest domain simulation. The forcing amplitude is not arbitrary as in Pauli & Sharif 2009
- New methodology →counterpart of LES→ small scales resolved while large scale modeled

# *Validation*




$$L_{large} = 1.5m$$
$$L_{small} = 4.5cm$$




- Validation against largest DNS case
- 10 Lagrangian trajectories followed in the $1024^3$ DNS and supersaturation gradients time series
- In the 10 small DNS cases, the droplet radius variance well reproduces the behavior of the largest case in contrast with the not forced case
- Very good agreement by measuring the droplet variance in the largest DNS along a box of 4.5 cm centered in a Lagrangian trajectory (right plot)
- Huge droplet radius variance variation in correspondence of large supersaturation gradients--> forcing model reproduces a physical behavior

# Preliminary results 100 m cloud

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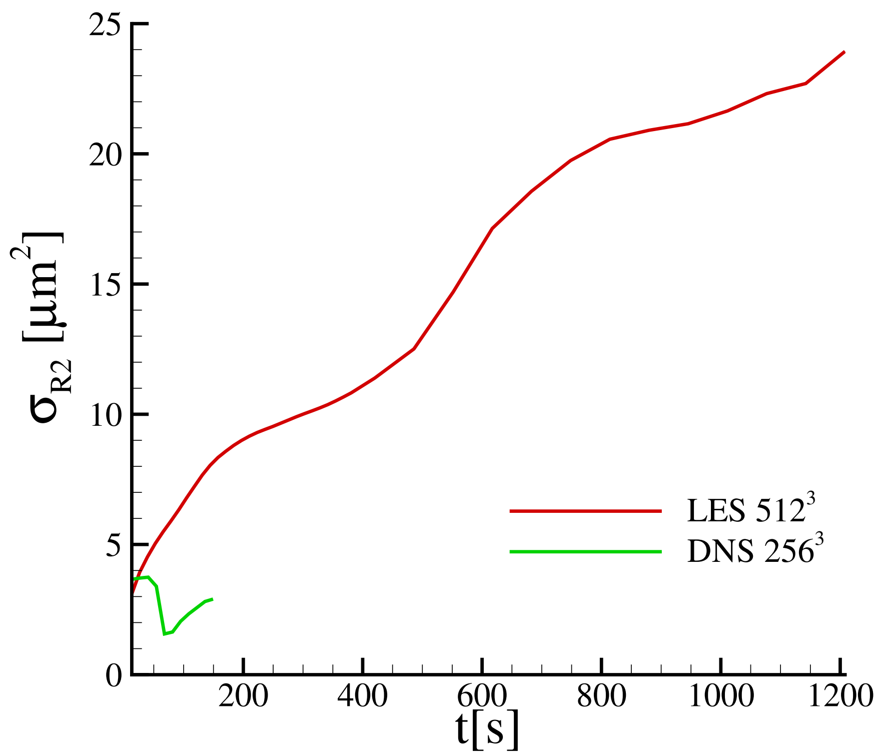


- Domain sizes:

$$L_{large} = 100m$$

$$L_{small} = 40cm \; 256^3$$

- LES supersaturation gradients on particle trajectories estimated as K41:

$$\nabla s(L_{small}) = \delta s/r \propto r^{-2/3}$$

- 10 small DNS boxes
- First impression: steady state regime and smaller variances in with respect to LES

# *Conclusions and perspectives*

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- New numerical method to study droplet condensation evaporation in large size warm clouds
- Full resolution of the small turbulent scales (DNS)/ large scales resolved by LES
- Importance of gradients of supersaturation field
- Export the method in nonhomogeneous and larger size clouds (Km) by using LES codes and quantify a more realistic droplet size distribution
- Implement in the model the growth by droplet/ droplet collisions induced by turbulence