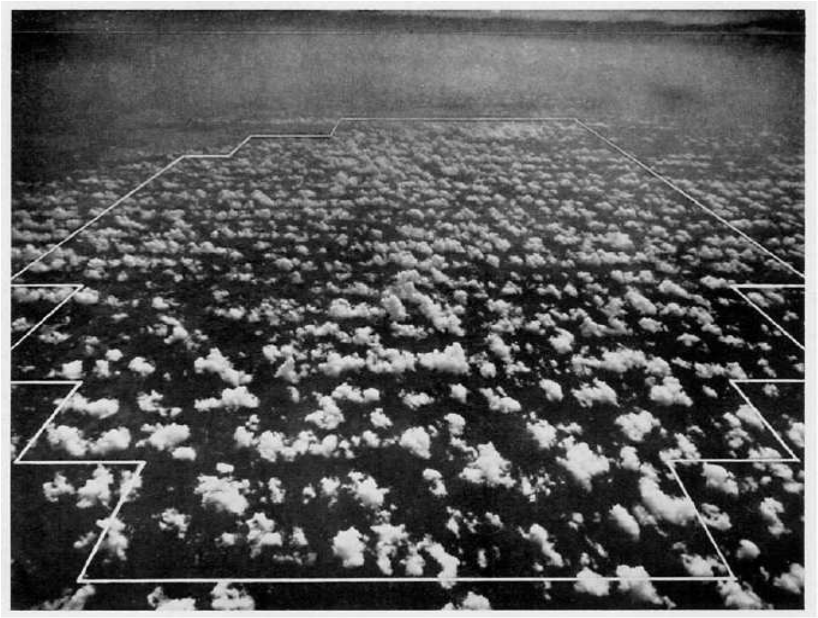
Towards scale-adaptivity and model unification in the representation of moist convection

Roel Neggers



Plank, J App Met, 1969

Contents

Entering the grey zone

Our computers are getting better and faster ⟶ Discretizations get finer

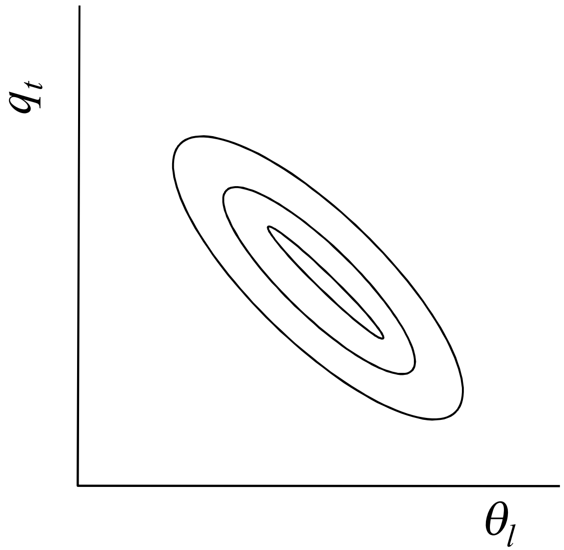
What does this imply for parameterizations of subgrid-scale processes?

For example:

* Previously unresolved processes get partially resolved
* PDFs of variability in nature get under-sampled in the gridbox
* How to deal with existing closures? Adapt, or discard and start from scratch?

Example: Boundary-layer schemes

Common goal:
To reproduce in some way the turbulent/convective PDF in temperature, humidity, vertical velocity, etc.



Various methods have been tried:
- Bulk
- Joint-PDF
- Multi-variate PDF
- Multi-parcel
- Higher-order closure techniques
- … combinations of the above

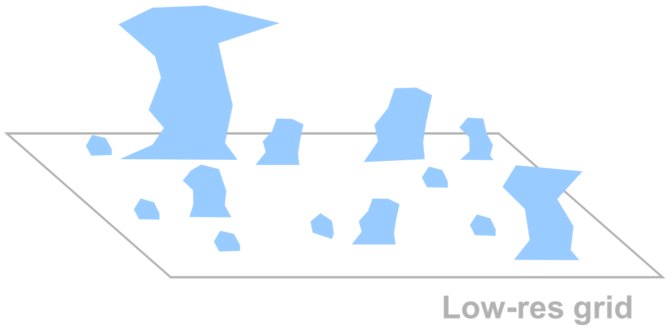
However, not many methods exist that express variability in terms of the scale / size of the processes behind it

This knowledge (or “scale-awareness”) is required to make parameterizations scale-adaptive

Scale-adaptivity

What do we mean by that?

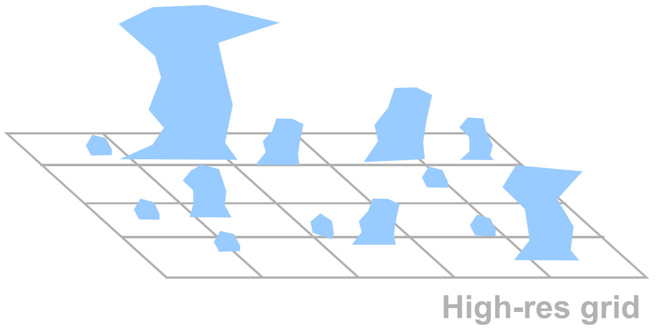
When a SGS parameterization is adaptive to the discretization-size of the 3D hostmodel in which it operates



Why do we care?

The question is what SGS parameterizations should represent

A finer horizontal discretization in a GCM means that smaller-scale processes become resolved

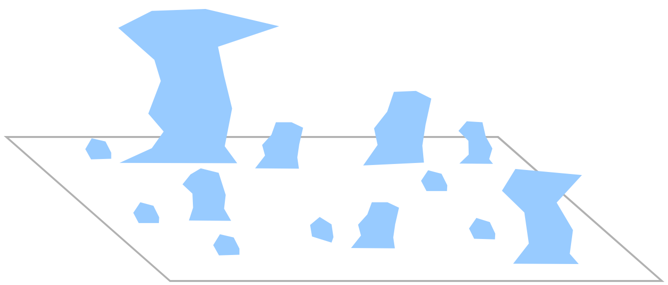


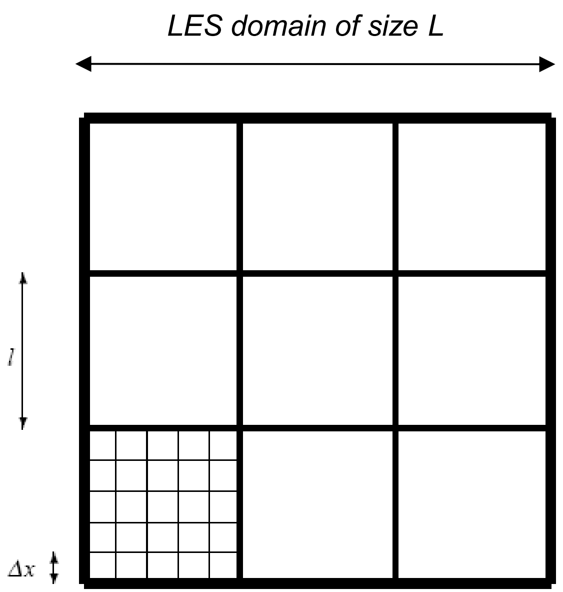
The work done by SGS parameterizations should adjust to this to avoid “double counting” and introduce stochastic effects

Exploring the grey zone with LES of shallow cu

Dorresteijn et al., TCFD 2012

Decomposition of the heat flux as a function of the size l of the sampling sub-domain within a 25x25km LES of shallow cumulus





$$\phi \in \{\theta_l, q_t\}.$$

$$\overline{w'\phi'}^{L} = K^{-1}\sum_k \overline{w'\phi'}^{l_k} + K^{-1}\sum_k (\overline{w}^{l_k} - \overline{w}^{L})(\overline{\phi}^{l_k} - \overline{\phi}^{L}),$$

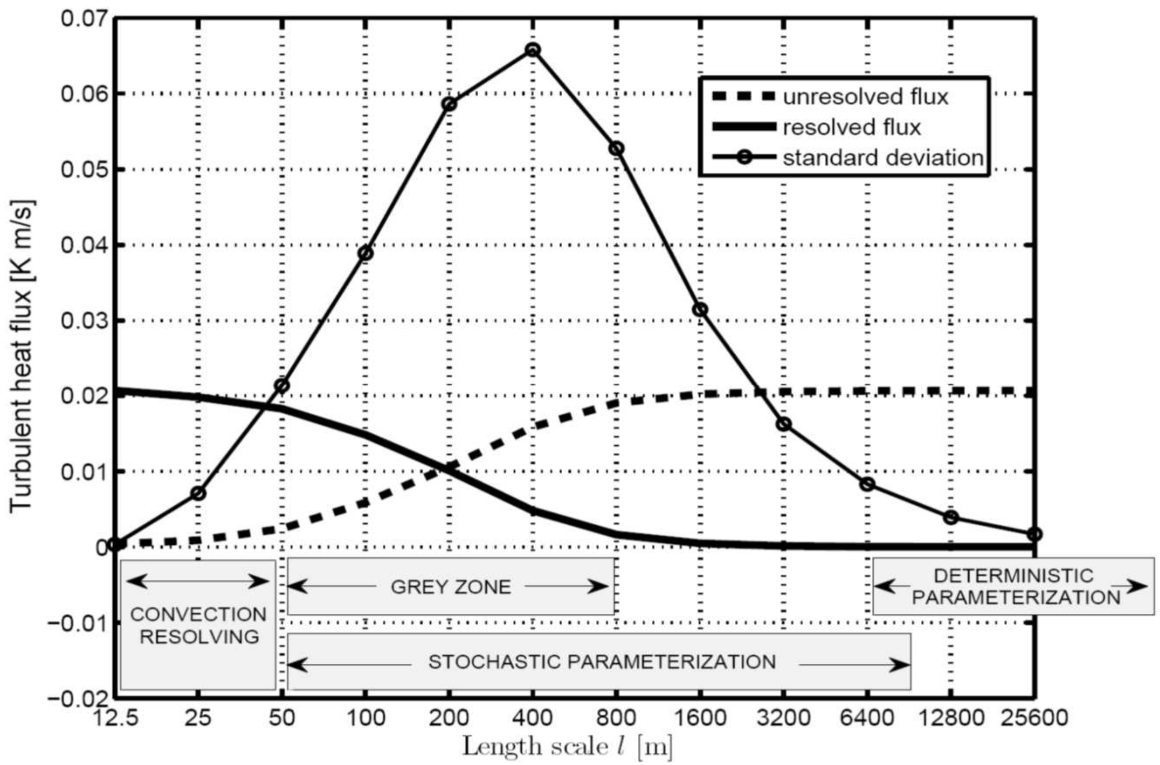
Flux by fluctuations within sub-domains

Flux by fluctuations of sub-domain means relative to mean of the total domain

Visualizing the grey zone

Defined here as the range of scales where the resolved and unresolved contributions are of the same order

Dorresteijn et al., TCFD 2012



A summary of the problem

Current SGS parameterizations in GCMs are not scale-adaptive:

* Formulated in age (1970-present) when all types of convection were still totally unresolved
* Parameterizations do not “know” about the size of the process they are representing

However, the discretizations in operational GCMs are ever increasing:
We are getting in the danger-zone or “grey zone”

The challenge:
We have to stretch ourselves to make SGS models scale-adaptive, and thus “bridge the gap” between scales

Population dynamics

Lotka-Volterra equations

Alfred J Lotka & Vito Volterra,
1910-1926

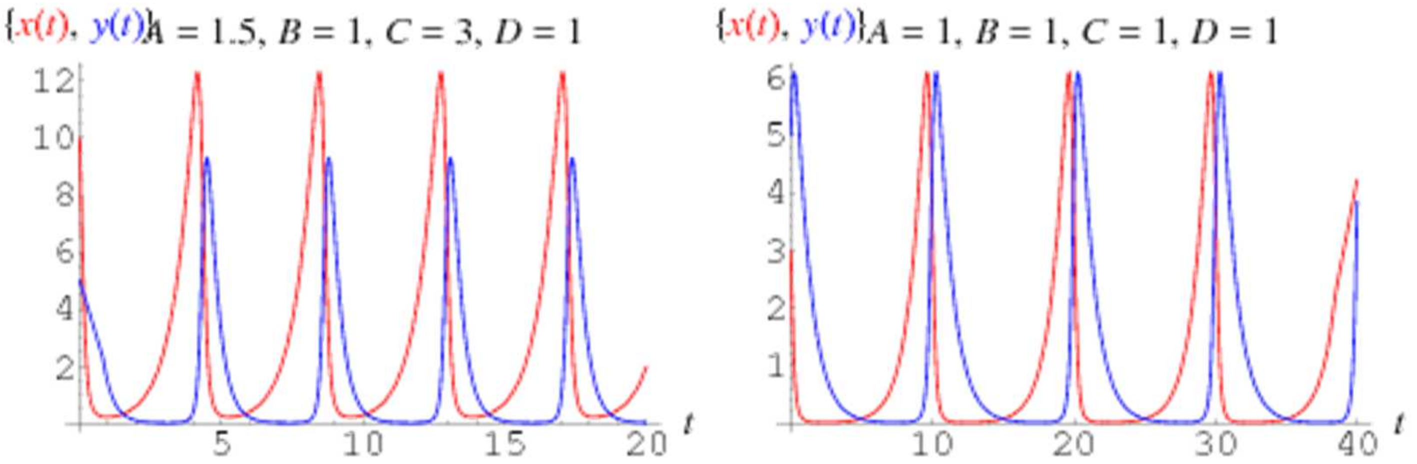
$$\frac{\partial x}{\partial t} = Ax - Bxy$$

$$\frac{\partial y}{\partial t} = -Cy + Dxy$$

x: Number of prey
y: Number of predators

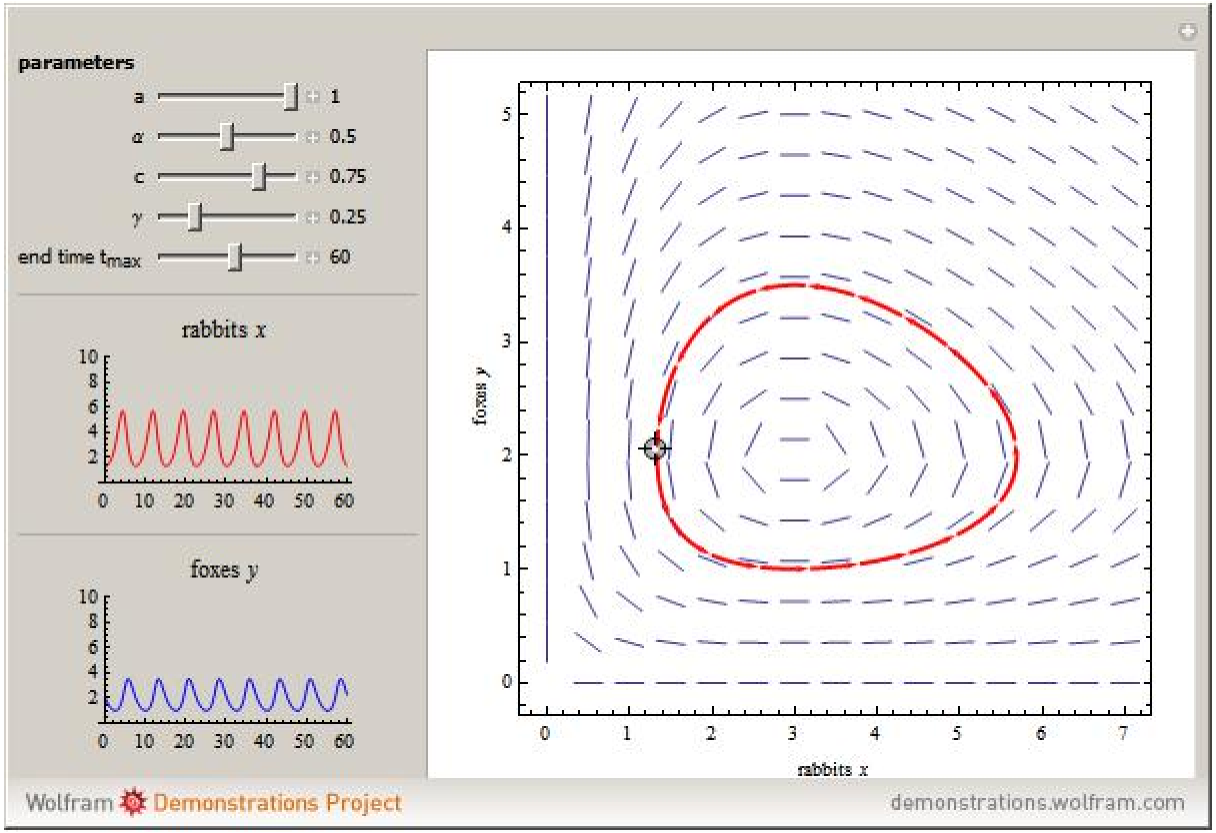
A: The growth rate of prey (exponential)
B: The rate at which predators destroy prey
C: The death rate of predators (exponential)
D: The rate at which predators increase by consuming prey

Time-dependent solutions



http://demonstrations.wolfram.com/PredatorPreyModel/

Plotting solutions in {x,y}-space:



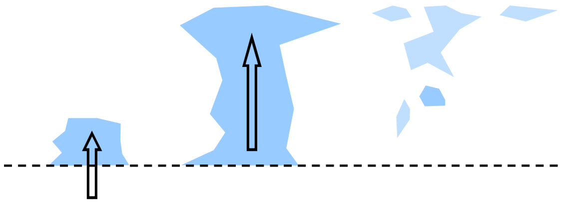
http://demonstrations.wolfram.com/PredatorPreyModel/

Idea: Application of LV to cloud populations

Nober and Graf, 2005
Wagner and Graf, 2011

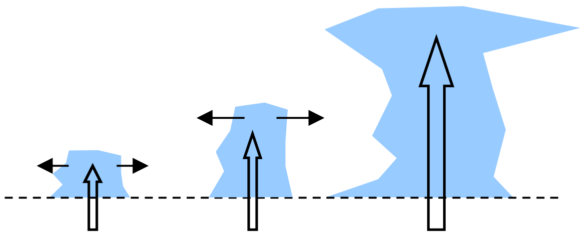
See each cloud size as a different species

Interactions between clouds of different size:

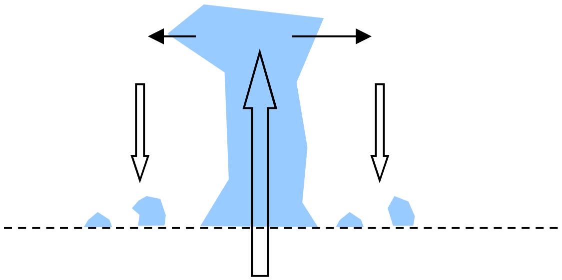


* Big clouds die and break apart into smaller ones (energy cascade)

* Smaller clouds feed bigger ones by 'preparing the ground' for their existence (pulsating growth)

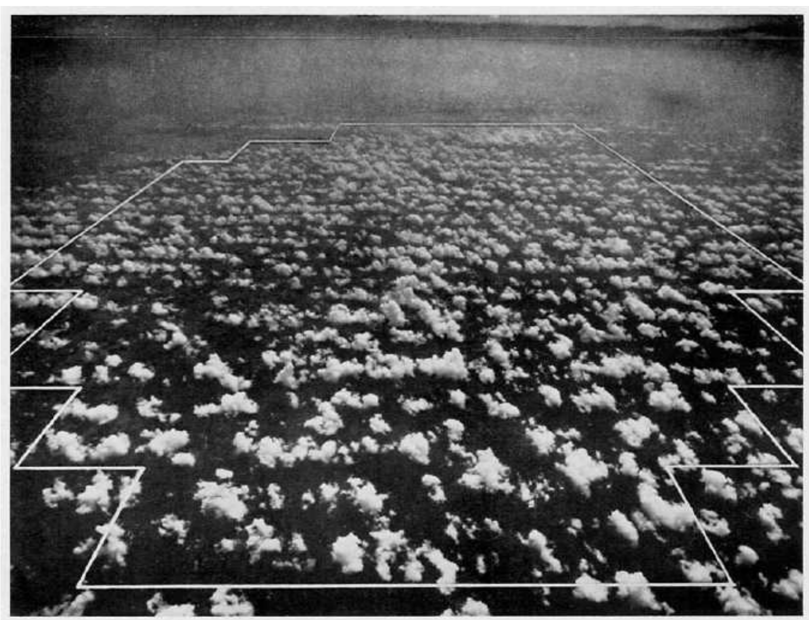


* Bigger clouds prey on smaller clouds, by suppressing them through their compensating subsidence field

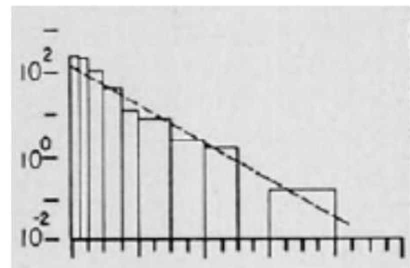


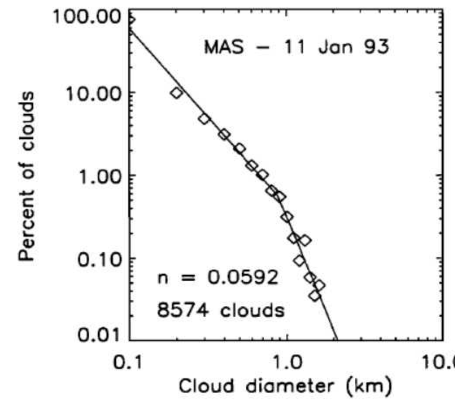
Cloud size statistics

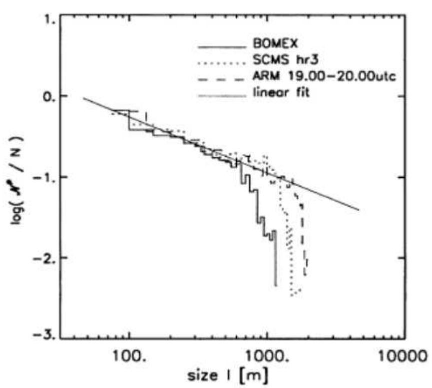
Pretty well known from observations and LES

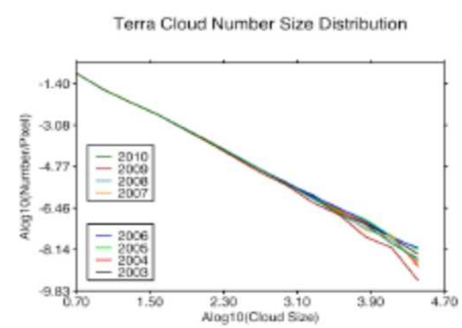


Plank, J App Met, 1969









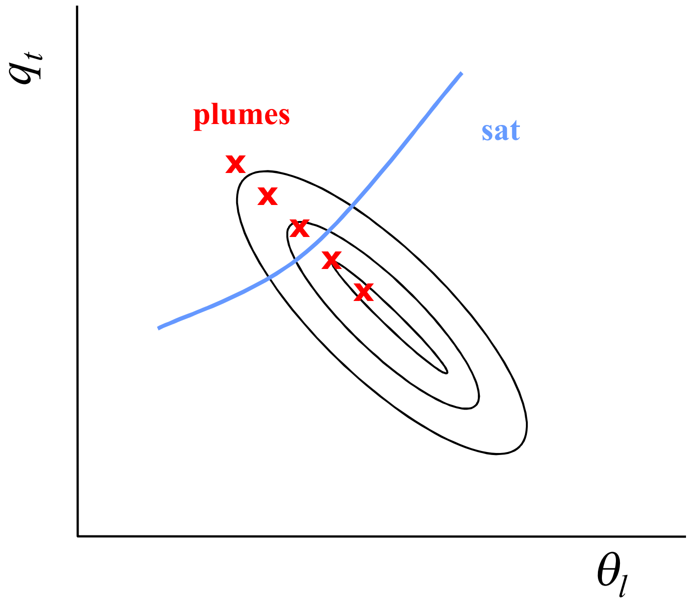
Start from scratch: Reformulating EDMF

The Eddy Diffusivity – Mass Flux (EDMF) approach

Combining the best of both transport models

$$\overline{w'\phi'} = -K\frac{\partial\overline{\phi}}{\partial z} + \sum_{i=1}^{I} M_i\left(\phi_i - \overline{\phi}\right)$$

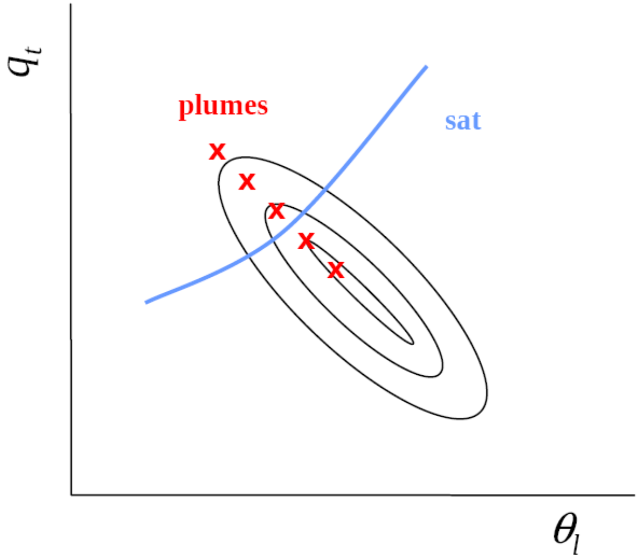
The multiple mass flux formulation can be used to reconstruct the joint-PDF, by letting each model-plume represent a separate point in its tail



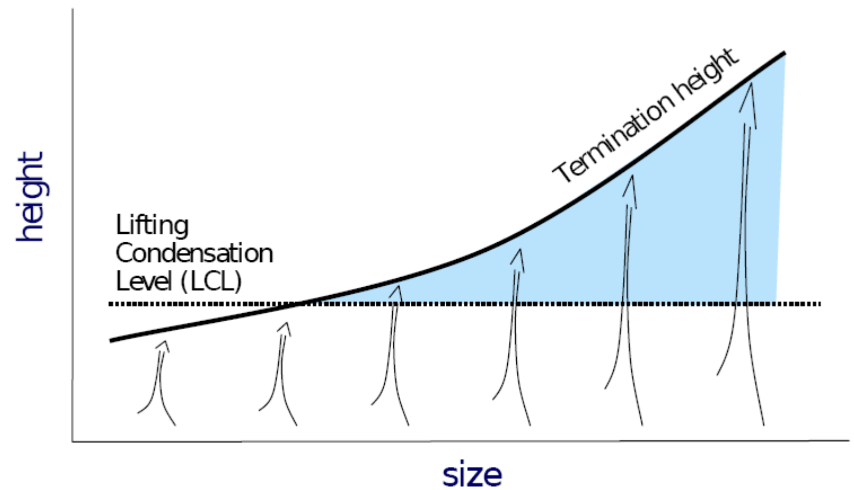
Each plume will have its own unique vertical profile, yielding a PDF that is resolved and that is changing with height

Introducing scale-awareness in EDMF …

Instead of defining multiple plumes in conserved variable space …



… we now define them in "size-space":



Model formulation – Step I

Foundation: the number density as a function of size

$$N = \int_l \mathcal{N}(l)\, dl$$

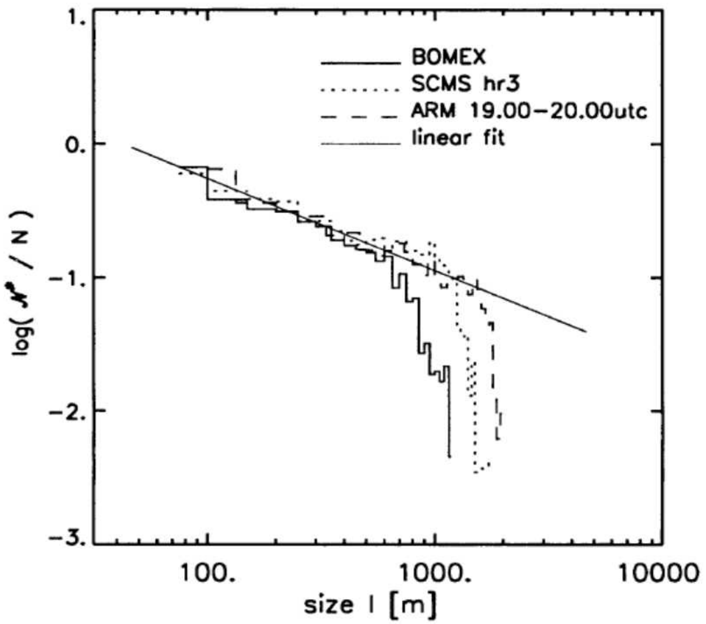
l : size
N : total nr

Adopted shape: power-law , potentially including scale-break

$$\mathcal{N}(l) = a\, l^{\,b}$$

Observations suggest:

$$b \approx \begin{cases} -1.9 & \text{for} \quad l < l_{break} \\ -3 & \text{for} \quad l \geq l_{break} \end{cases}$$



Model formulation – Step II

Related: the size density of area fraction

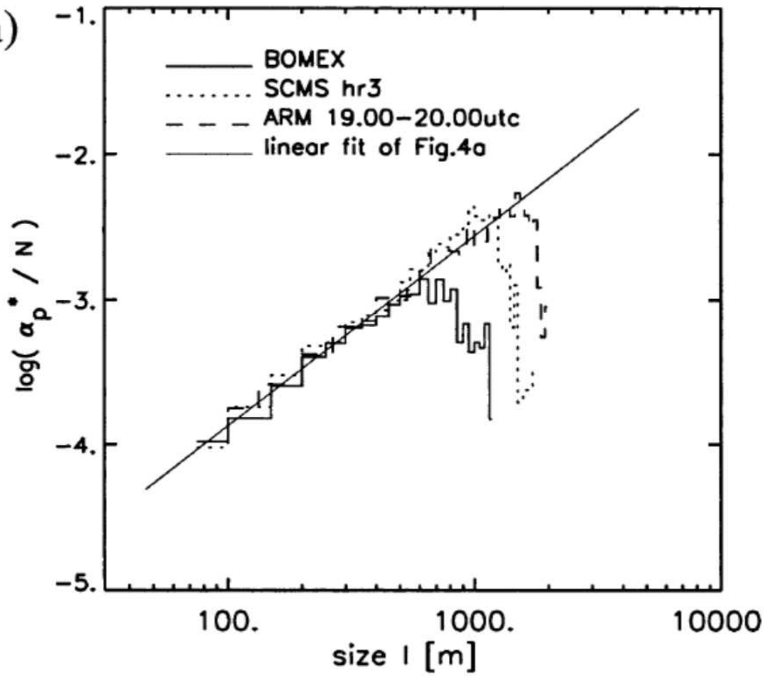
$$a_{MF} = \int_l \mathcal{A}(l)\, dl$$

$$= \frac{1}{A} \int_l \mathcal{N}(l)\, l^2\, dl$$

Basic EDMF:

$$a_{MF} = 10\%$$

a)



Model formulation – Step III

Expand to fluxes , introduce dependence on height (z):

$$a_{MF}\,\overline{w'\phi'}^{MF}(z) = \int_l \underbrace{\mathcal{A}(l,z)\,w(l,z)}_{\mathcal{M}(l,z)}\,\left[\phi(l,z)-\bar{\phi}(z)\right] dl$$

Mass flux

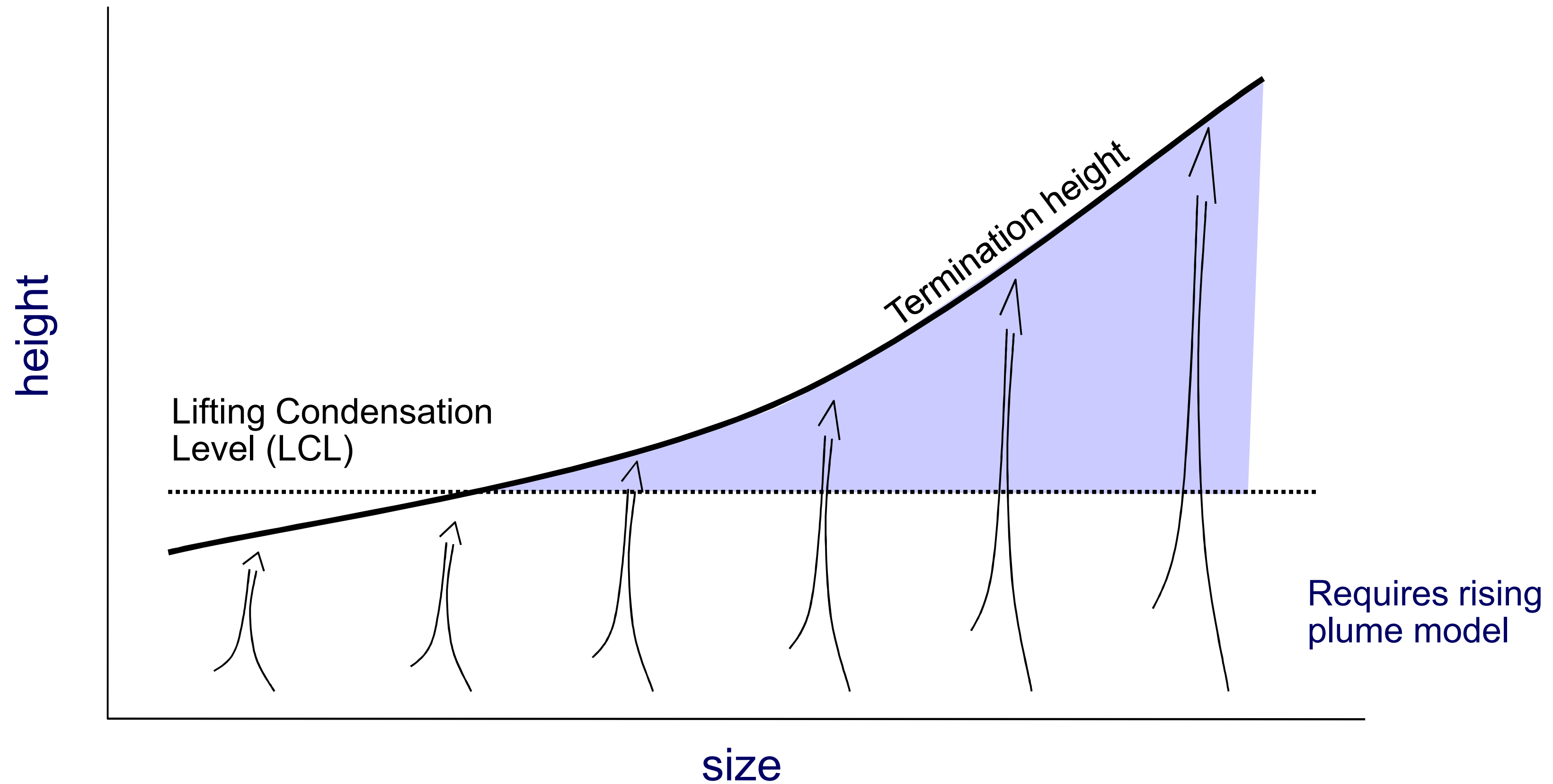
$$= \frac{1}{A}\int_l \overbrace{\mathcal{N}(l,z)\;l^2\;w(l,z)}\;\left[\phi(l,z)-\bar{\phi}(z)\right] dl$$

A spectral mass flux scheme (e.g. Arakawa & Schubert,1974)

To do: come up with a method to produce (l, z) fields

Model formulation – Step IV

Resolve (l, z) fields using a limited number of plumes:



Some consequences

- Integral becomes discrete:

$$\int_{l} (\ldots) dl \rightarrow \sum_{n=1}^{N} (\ldots) \Delta l$$

What N gives good performance?

- Introduce dependence on size in plume model components:
  - i) initialization
  - ii) entrainment
  - iii) microphysics
  - iv) …

  This requires more research

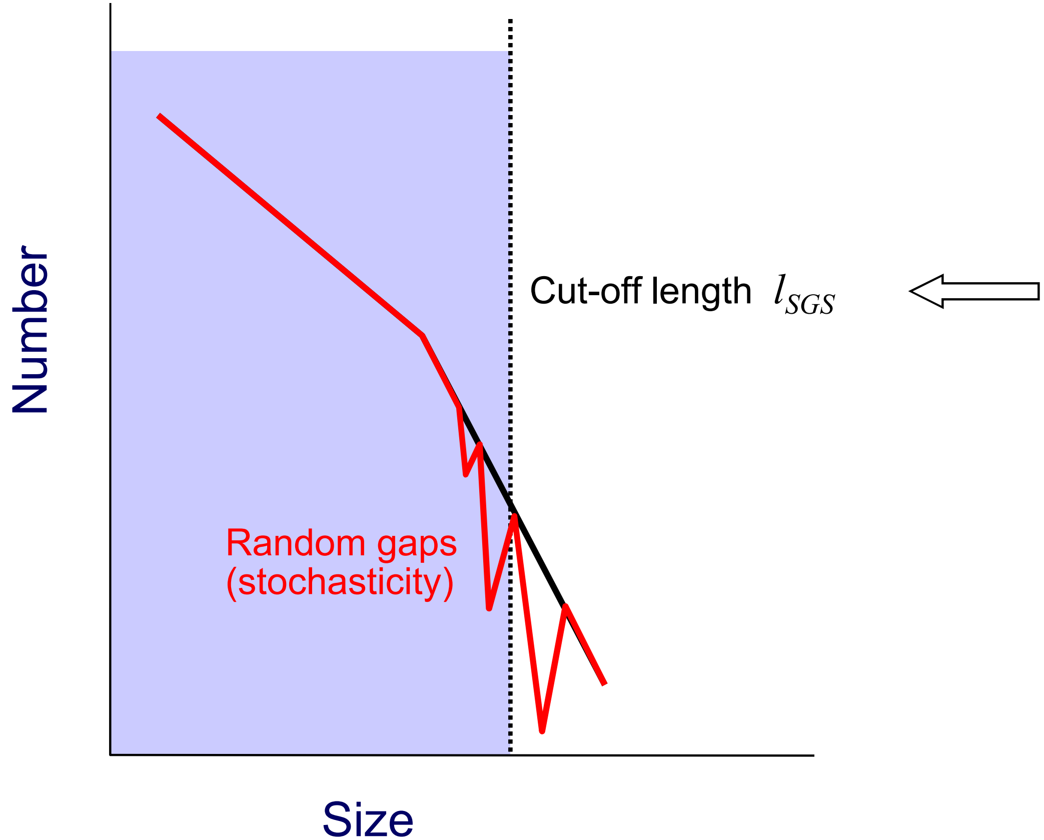
- Explicit closure no longer needed for
  - i) cloud base mass flux
  - ii) vertical structure of mass flux
  - iii) other buoyancy sorting effects
  - iv) cloud & condensate associated with cumulus updrafts

  Can be read from resolved size density

  → EDMF formulation becomes much simpler

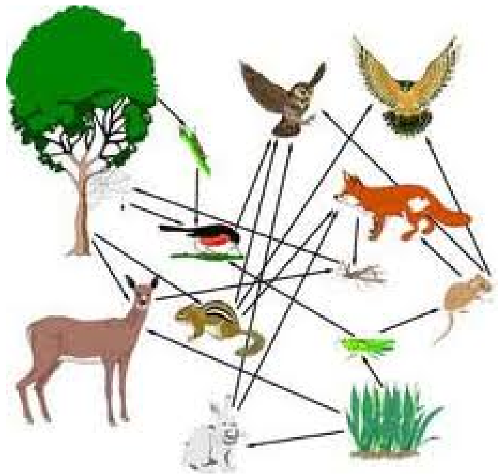
Practical benefit: Allows low-pass filtering on size

Transport is known as a function of size!
Integrate size-densities up to the desired cut-off length, reflecting the sub-grid scale (SGS) of the host model



Scale-awareness!

Step V   Closure of the number density



A multi-species version of the LV equations:

N plumes, N equations

$$\frac{\partial E_i}{\partial t} = P_i - \sum_{j=\{1,N\}\setminus\{i\}} T_{ij} + \sum_{k=\{1,N\}\setminus\{i\}} T_{ki} + D_i$$

E_i : Total energy of all plumes of size l_i
P_i : Buoyancy-flux production by plumes of size l_i (the cloud "work-function")
D_i : Viscous dissipation at size l_i
T_{ij} : Energy transfer from size l_i to size l_j

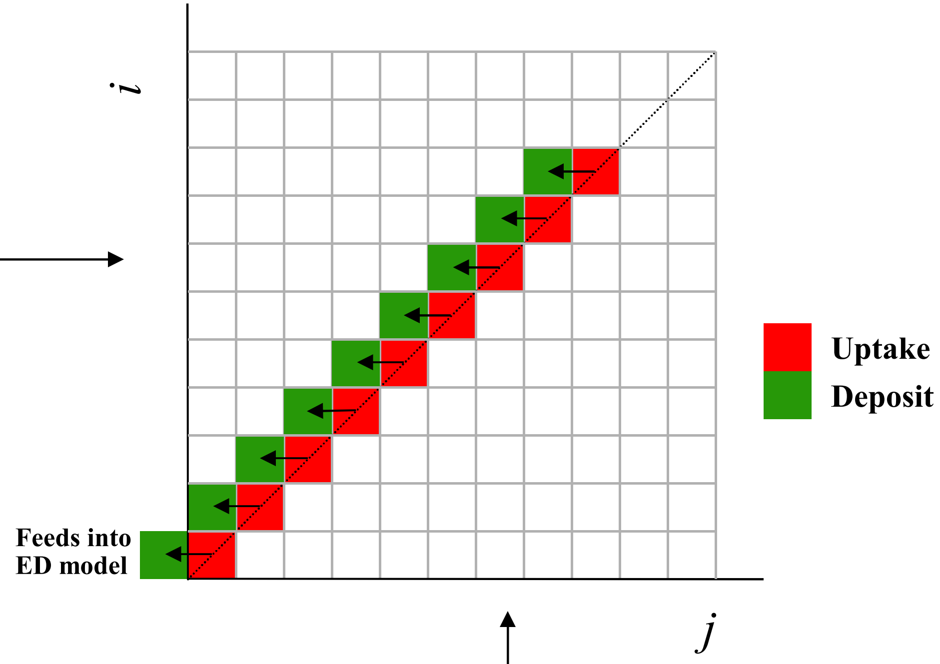
Matrix T_{ij} : describes interaction between sizes

Fingerprints of different processes

Energy cascade
(local, downscale)

Sink *at i:*
Integrate horizontally
(2^{nd} index)

$$\sum_{j=\{1,N\}\backslash\{i\}} T_{ij}$$



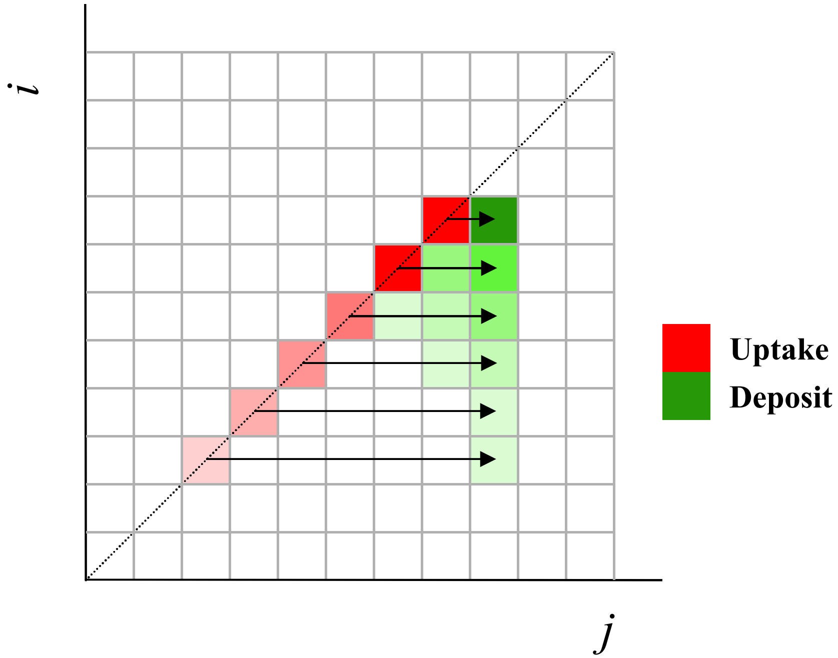
Source *at i:*
Integrate vertically
(1^{st} index)

$$\sum_{k=\{1,N\}\backslash\{i\}} T_{ki}$$

Matrix T_{ij}

Suppression of smaller clouds by largest clouds, through compensating subsidence

(broader band, up-scale)



Proof of principle

Preliminary results with the EDMF based on resolved size densities

Regional Atmospheric Climate Model (RACMO) : IFS physics cy33r2 + mods
Single Column Model

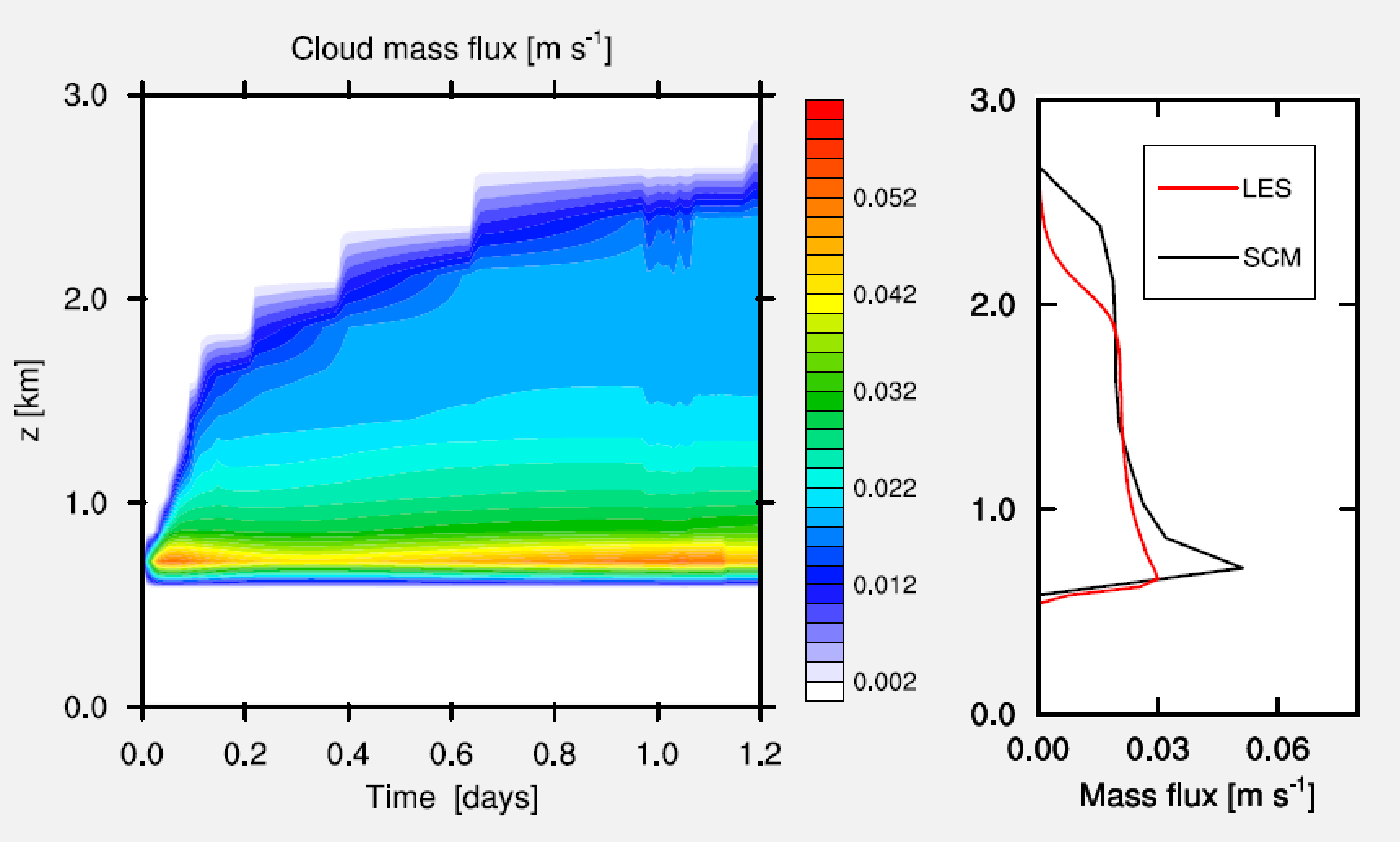
Rain in Cumulus over the Ocean (RICO) field-campaign
GCSS model inter-comparison case for SCM & GCM

Model settings:

- 10 resolved plumes
- Epsilon = 1 / size
- Plume initial excesses increase linearly with size
- No plume precipitation
- Energy cascade

Preliminary results: bulk statistics

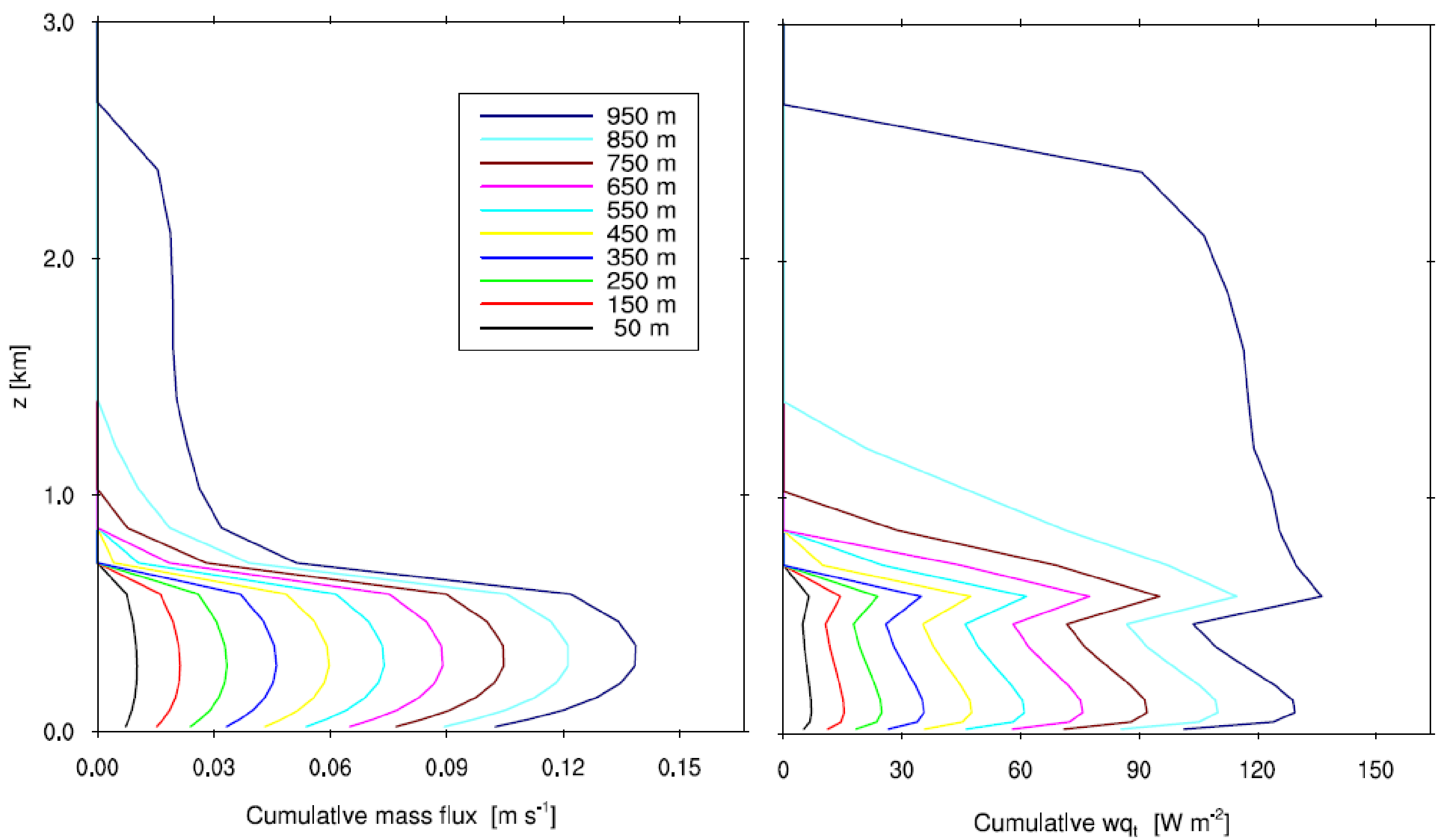
A numerically stable solution is obtained
Realistic vertical structure of mass flux:
- Humidity-convection feedbacks among plumes



Preliminary results: scale-awareness!

Turbulent flux is known as a function of size

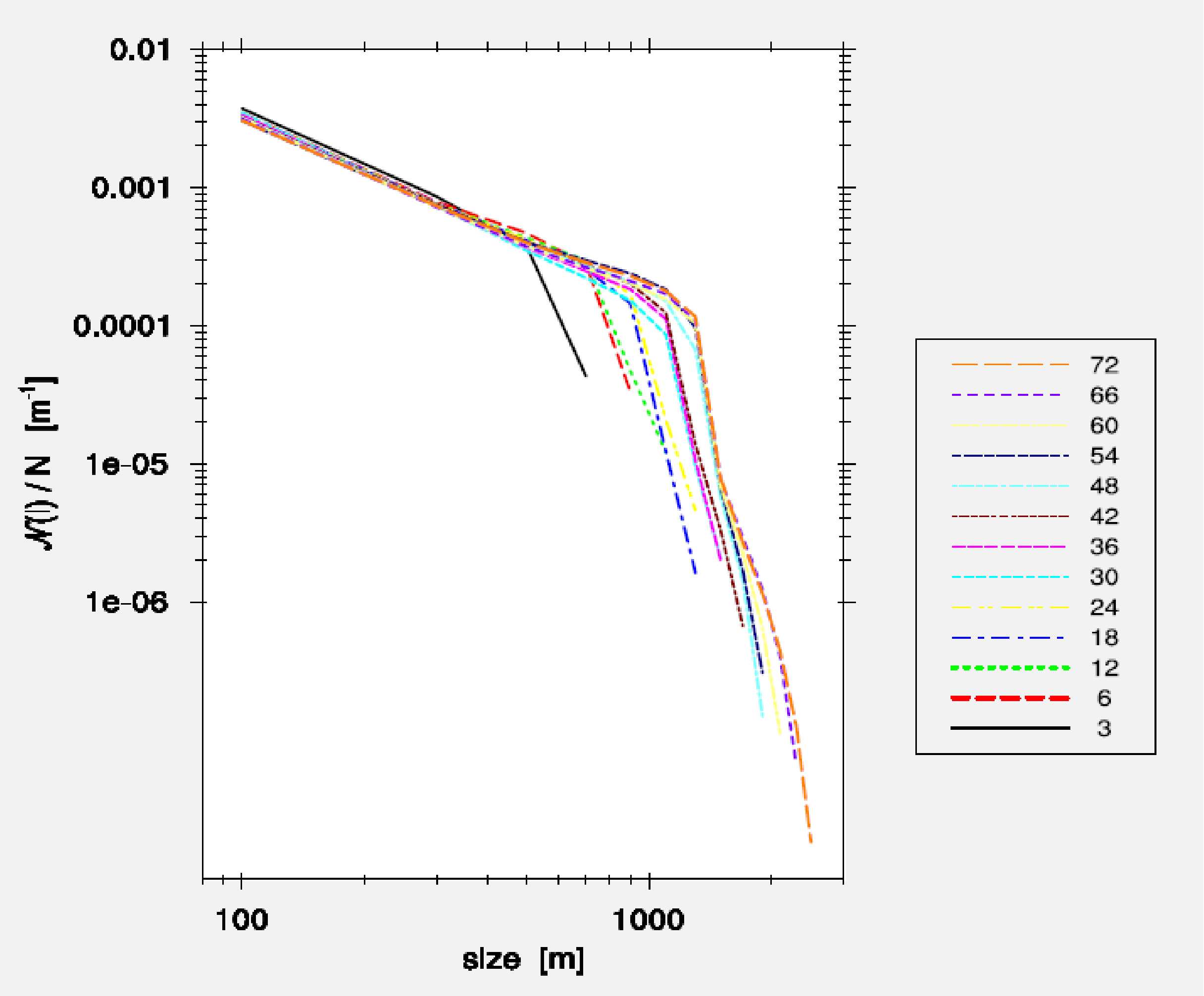
Contributions by different sizes to mass flux and total specific humidity flux



Preliminary results: population statistics

Power-law scaling is reproduced:

Why?



Power law scaling

* Energy is transferred from a larger size to a smaller size

* But individual plumes of smaller size carry less energy than big ones

* As a result, the same energy can be shared by more plumes, yielding a higher number

Why a scale break?

* Latent heat release by the larger plumes significantly boosts their kinetic energy

* As a result, fewer big clouds are necessary to compose a given amount of energy

Outlook

Conceptual models describing population dynamics can be applied to make SGS parameterizations scale-aware and scale-adaptive

The development of such models for operational GCMs is in progress, but most implementations are still in testing-phase

Observations and high-resolution modelling results are needed to properly constrain this new type of scale-aware parameterization

Field campaigns

Measurements of the properties of cloud populations in nature

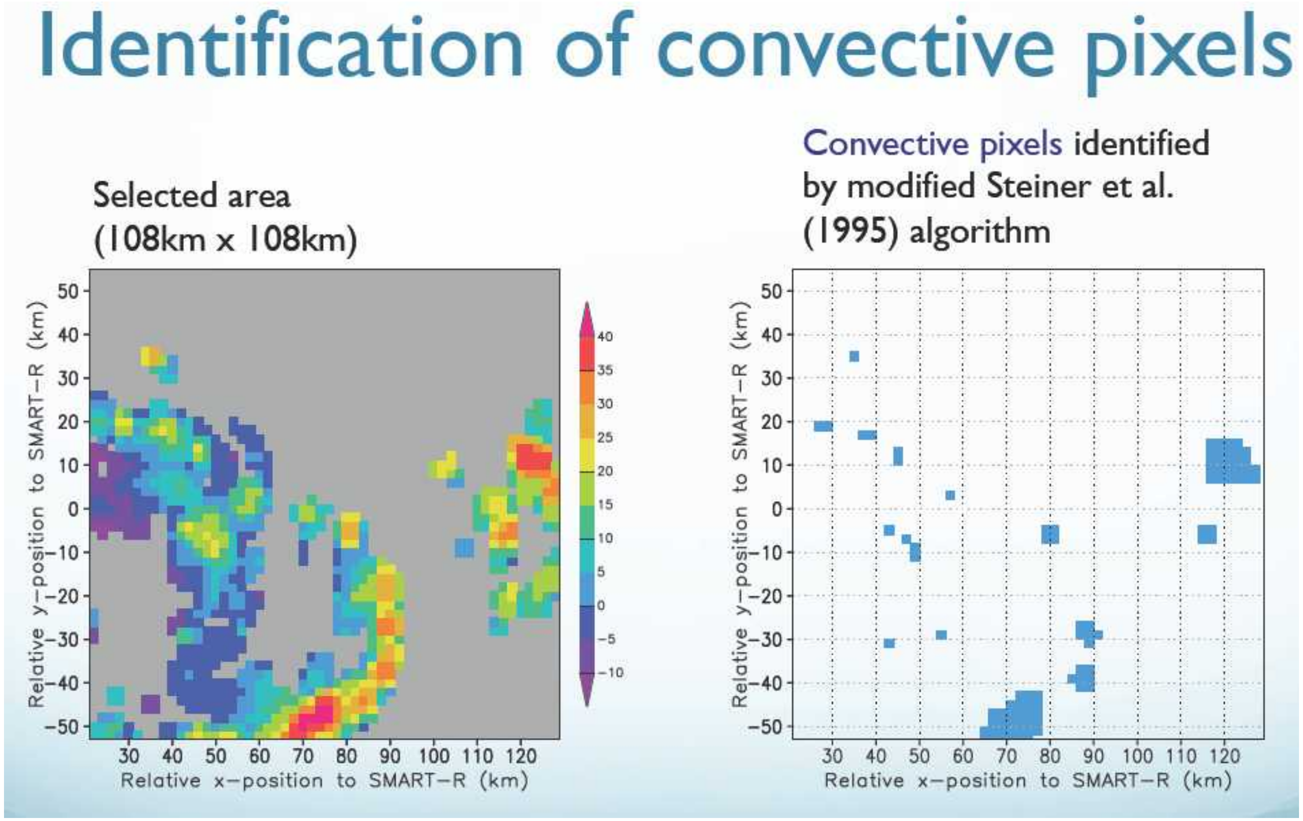
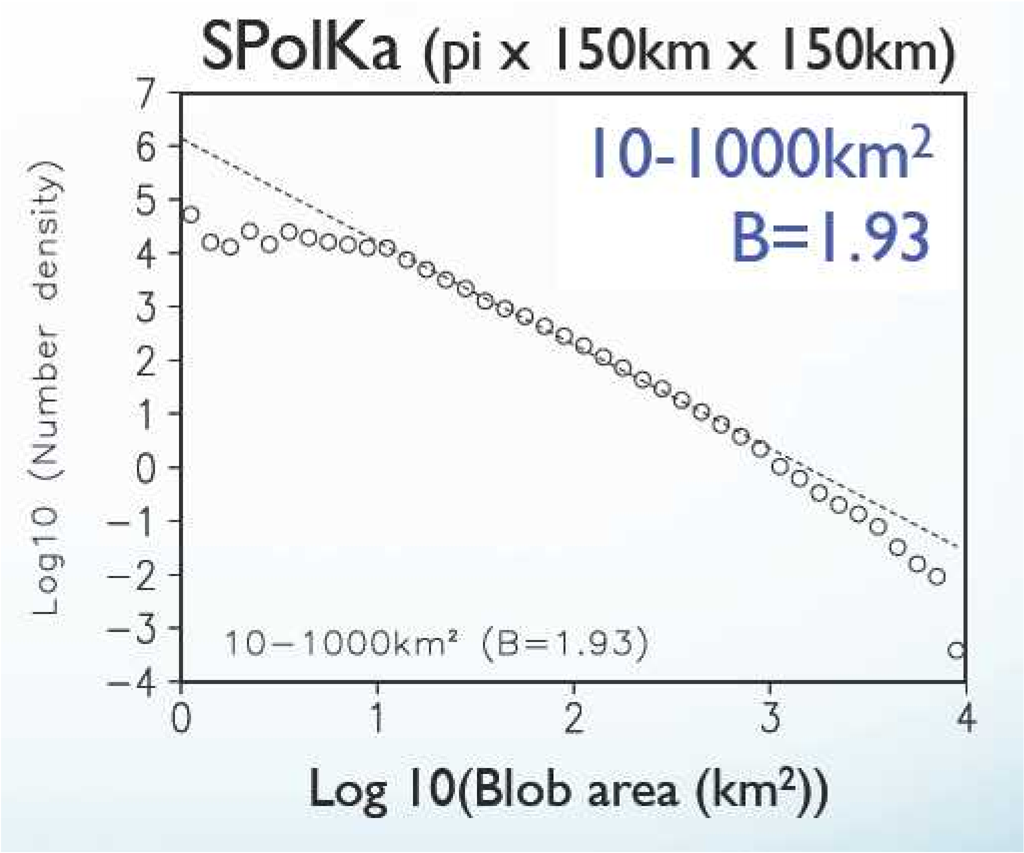


Figure courtesy of
Daeyhun Kim, Columbia Univ

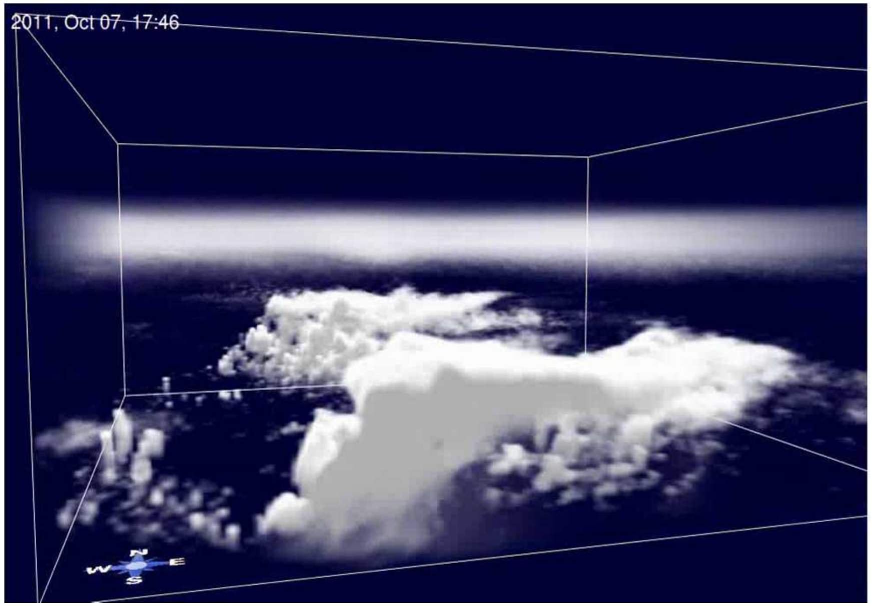
Field campaigns



Power Law $n(a) \propto a^{-B}$

Figure courtesy of
Daeyhun Kim, Columbia Univ

Large-eddy simulation (LES)



GPU-based LES, run daily in forecast-mode at Cabauw
(Jerome Schalkwijk, TU Delft)

3D fields of cloud, condensate, kinematic & thermodynamic state can be archived

Perfect for evaluating cloud size densities!