How do we handle the small stuff?

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NCAR & CMMAP

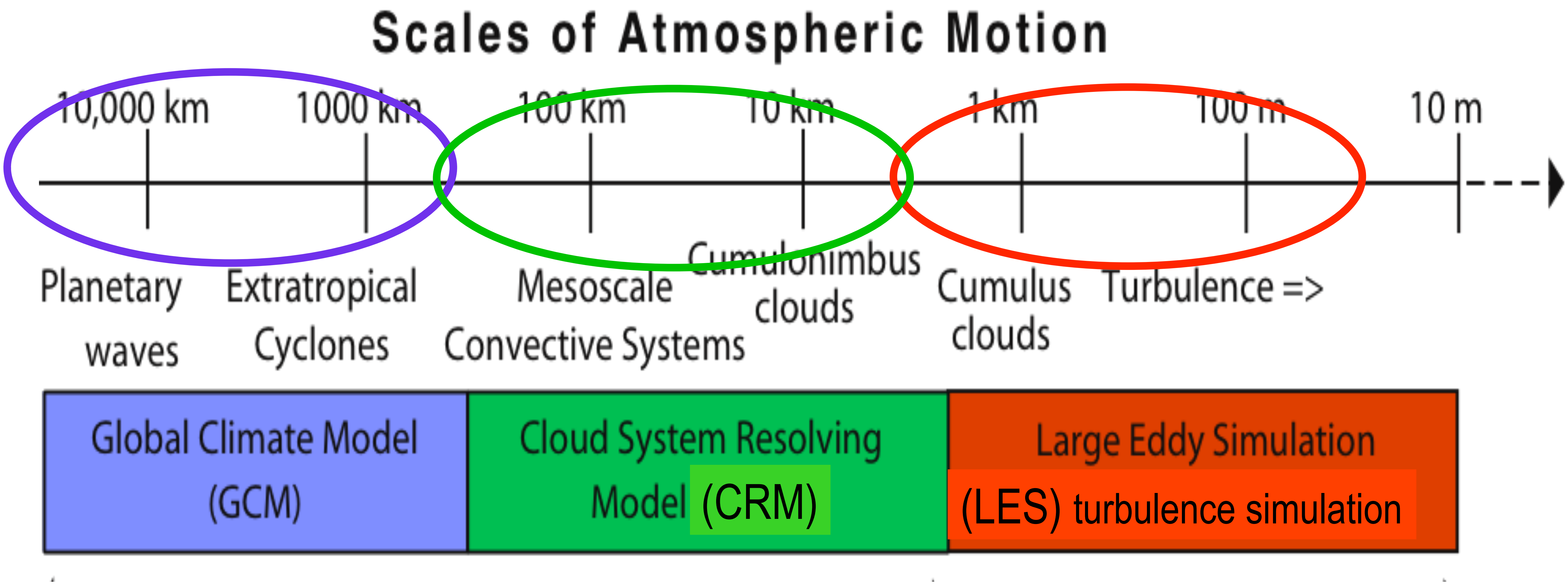
CMMAP meeting, Aug. 2010

NCAR & CMMAP are sponsored by the National Science Foundation

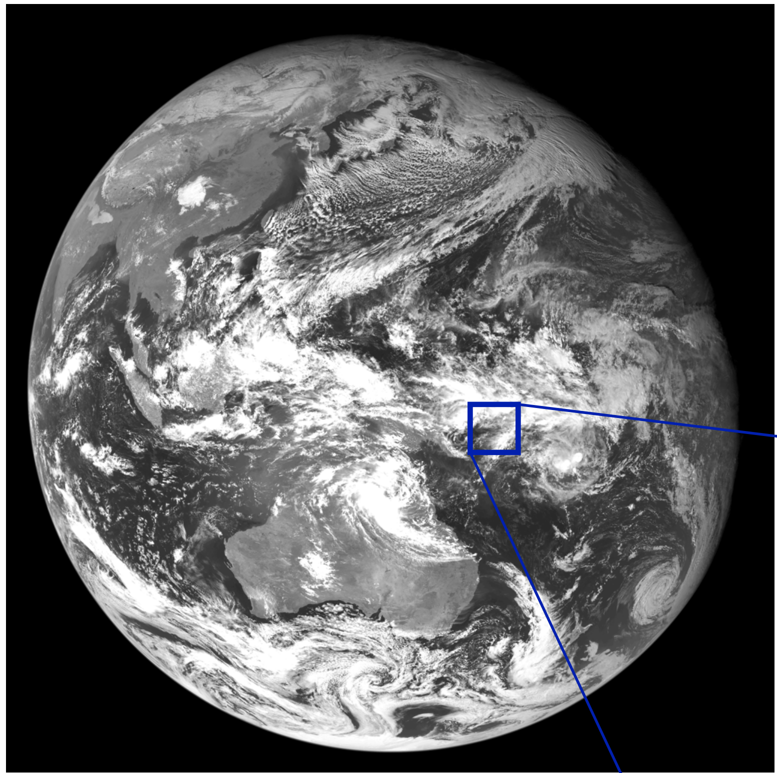
OUTLINE

1. What are the GCM, CRM, and LES models?
2. How do we study the small stuff (Subgrid-Scale SGS) in CRMs?
3. A SGS scheme to represent the transport of the small stuff in CRMs .

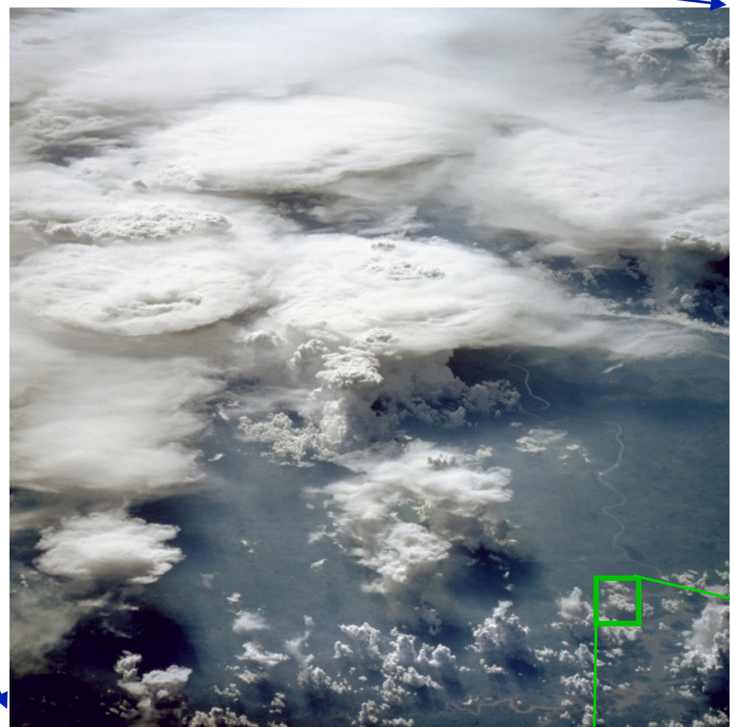
“*Conventional*” GCM, CRM and LES models



- **Solve different governing equations**
- **Study different physical phenomena**



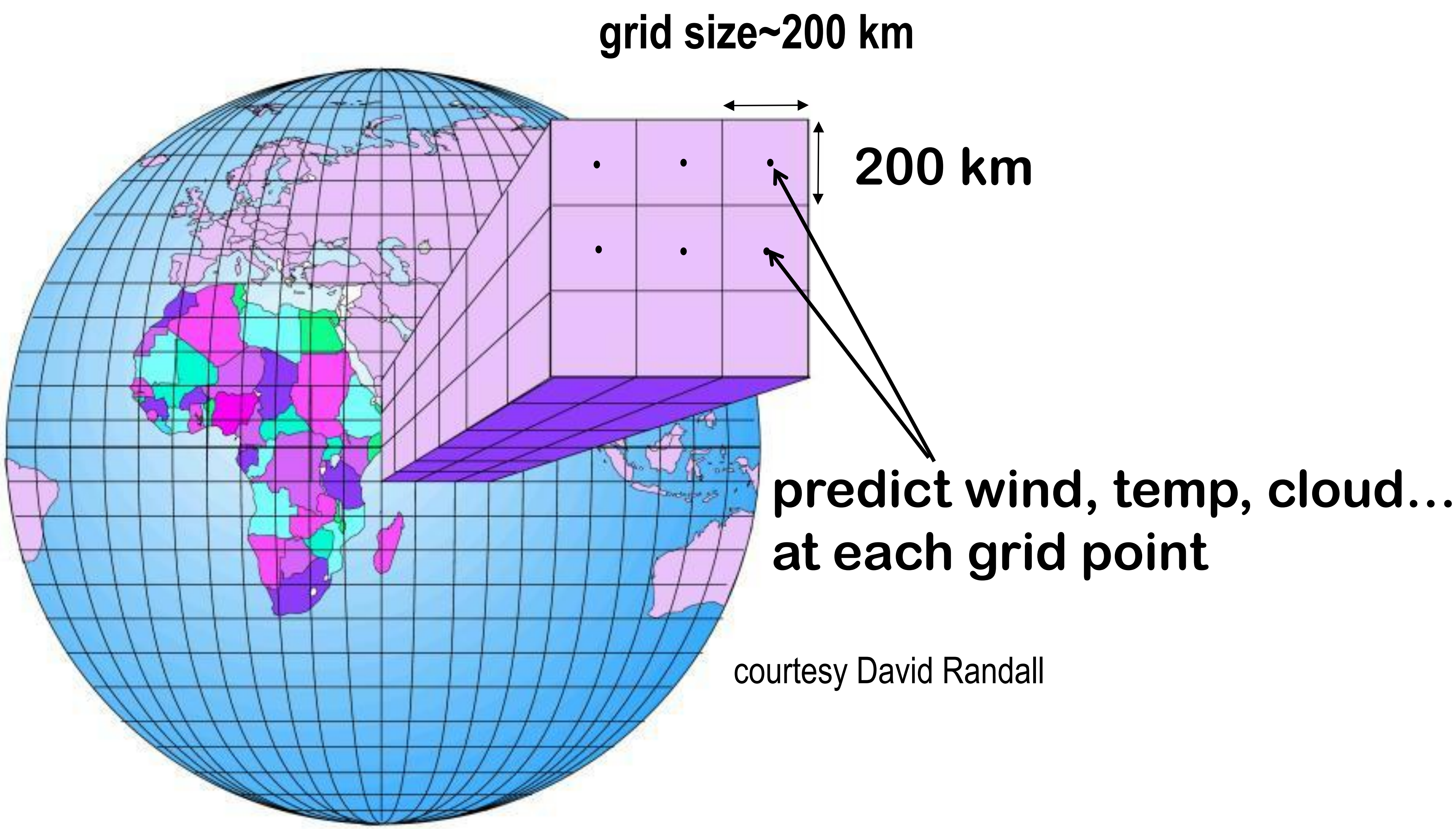
“Conventional” GCM;
grid box ~ O(100 km)
~ size of a small state



“Conventional” CRM;
grid box ~ O(few km)
~ a small city

“Conventional” LES;
grid box~ O(100m)
~ a football stadium

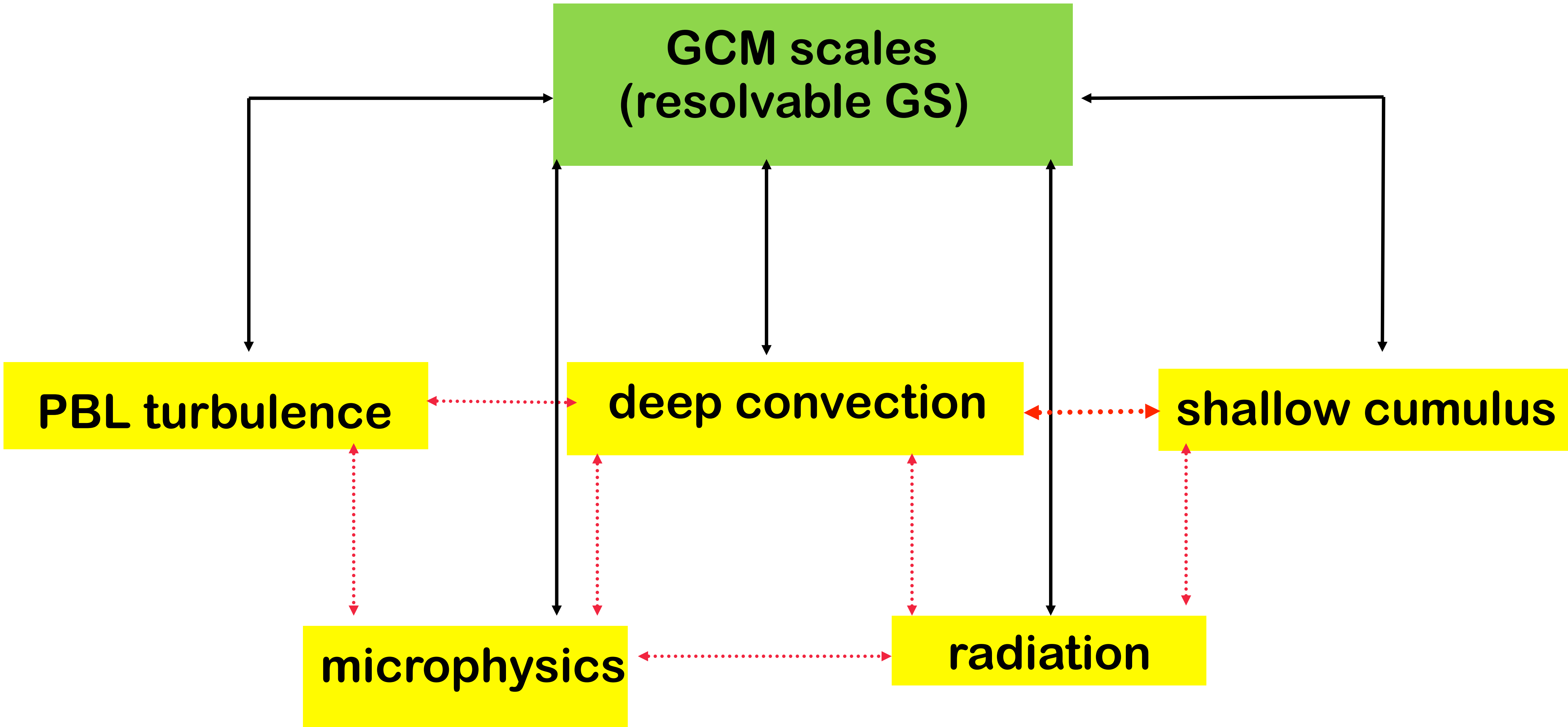
GCM : Solving discretized eqs. on a discretized globe



- **Scales > grid resolution: ‘resolvable scales GS’**
- **Scales < grid resolution: ‘subgrid-scale SGS’**

SGS processes are crudely represented
by simple theories (“parameterizations”).

SGS in a “conventional” GCM



SGS “parameterization”--- called separately

cloud-scale interactions missing in most GCMs.

However, cloud-scale interactions are many and crucial:

- cloud/rain ⟷ landscape/forest...
- cloud circulation ⟷ rain/snow drop sizes
- cloud shadow ⟷ radiation
- ....

As computer power grows, global models are using finer and finer grid meshes, e.g.,

- Fine-grid Numerical Weather Prediction
- Multi-scale Modeling Framework (MMF)
- Global Cloud Resolving Model (GCRM)

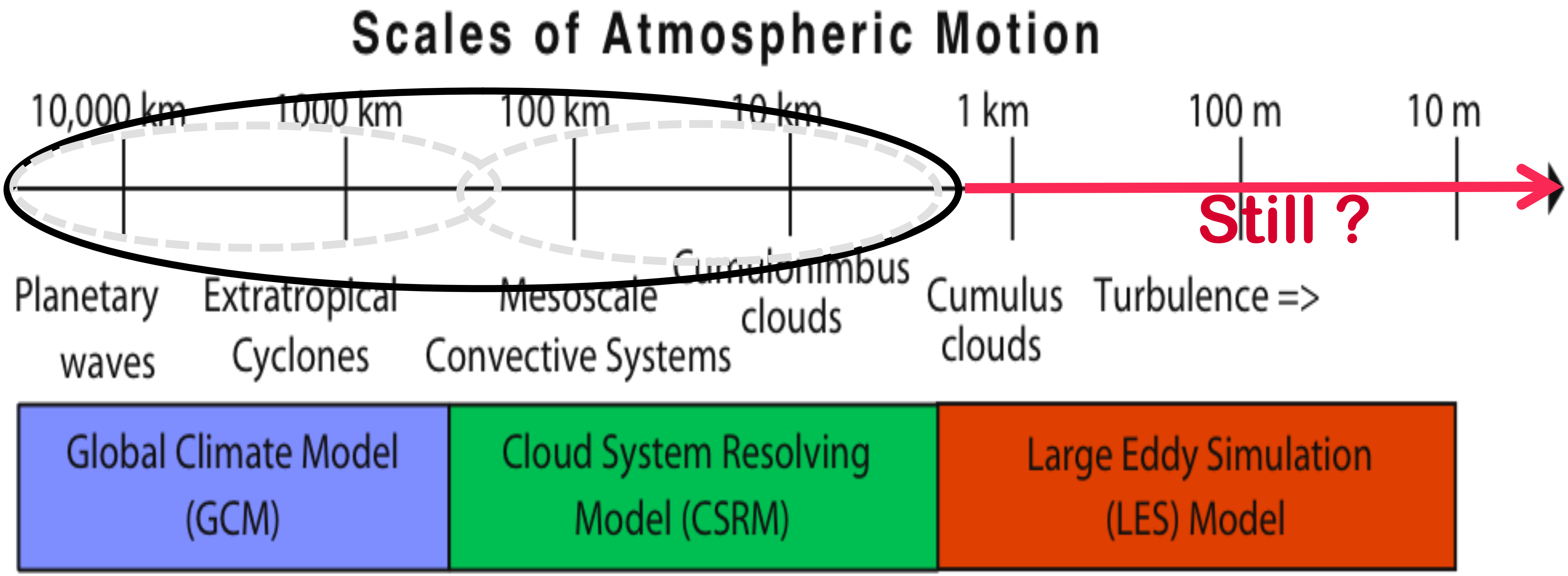
to explicitly calculate cloud-system scales.

Thus, allow for many cloud-scale interactions on the model grid meshes.

CMMAP

Reach for the sky.

Fine-grid NWP, MMF or GCRM



Dynamical-Framework Team

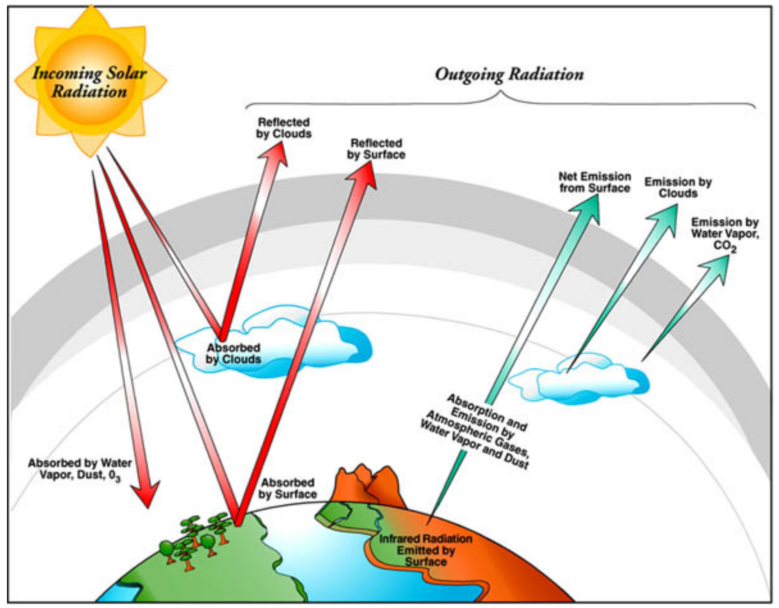
Physical-Process Team

SGS processes in CRMs or GCRMs are many…

low-level stratocumulus

cloud droplets/rain/snow…

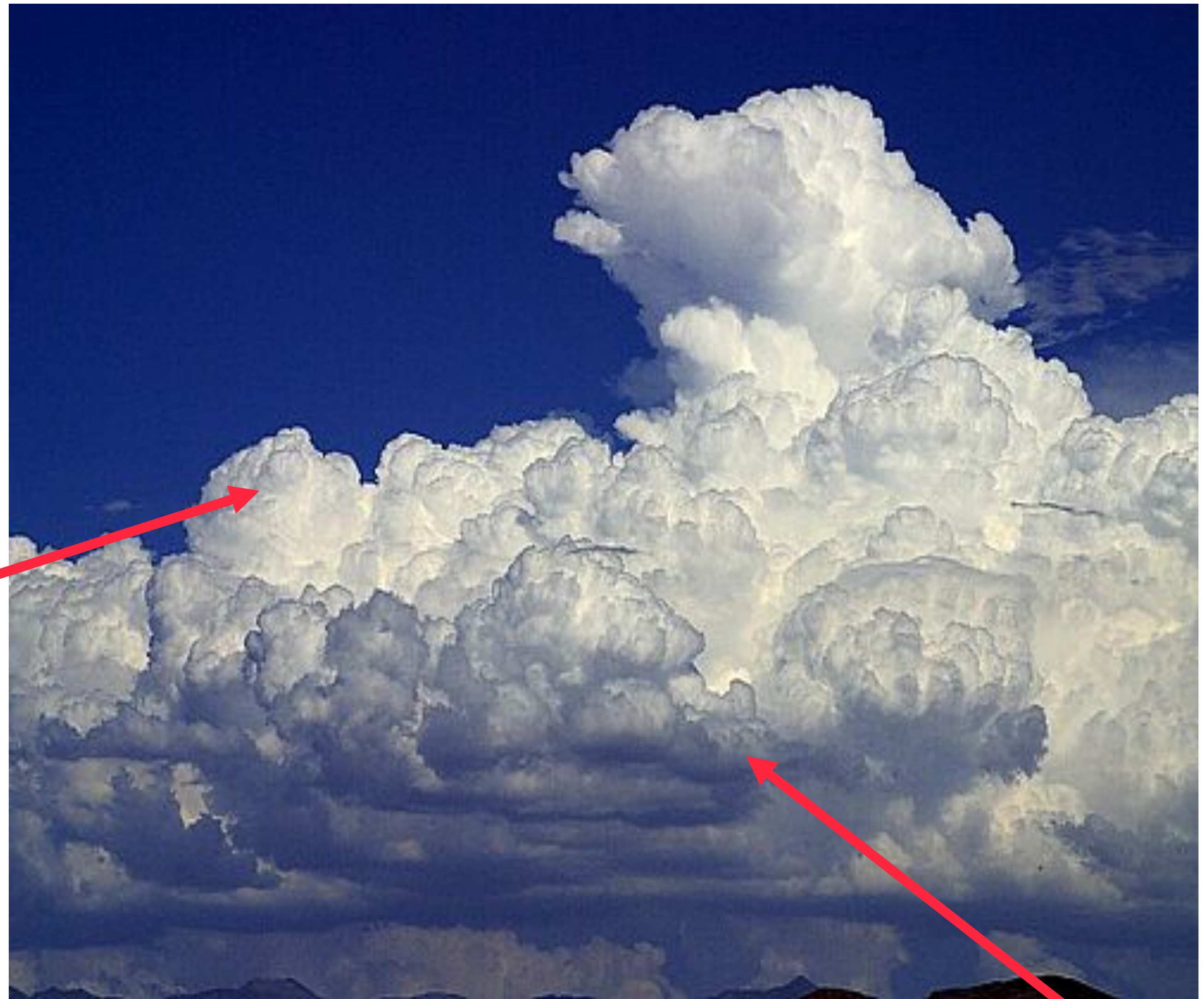
fair-weather cumulus



solar and long-wave radiation

And…

…heat, moisture, momentum transport by motions < a city size.



turbulent motions

small, shallow clouds

They transport heat, moisture,…
& are crucial to cloud system development.

My research topic:

To improve the representation of SGS fluxes inside CRMs or GCRMs.

Models with a grid spacing of about a small city size.

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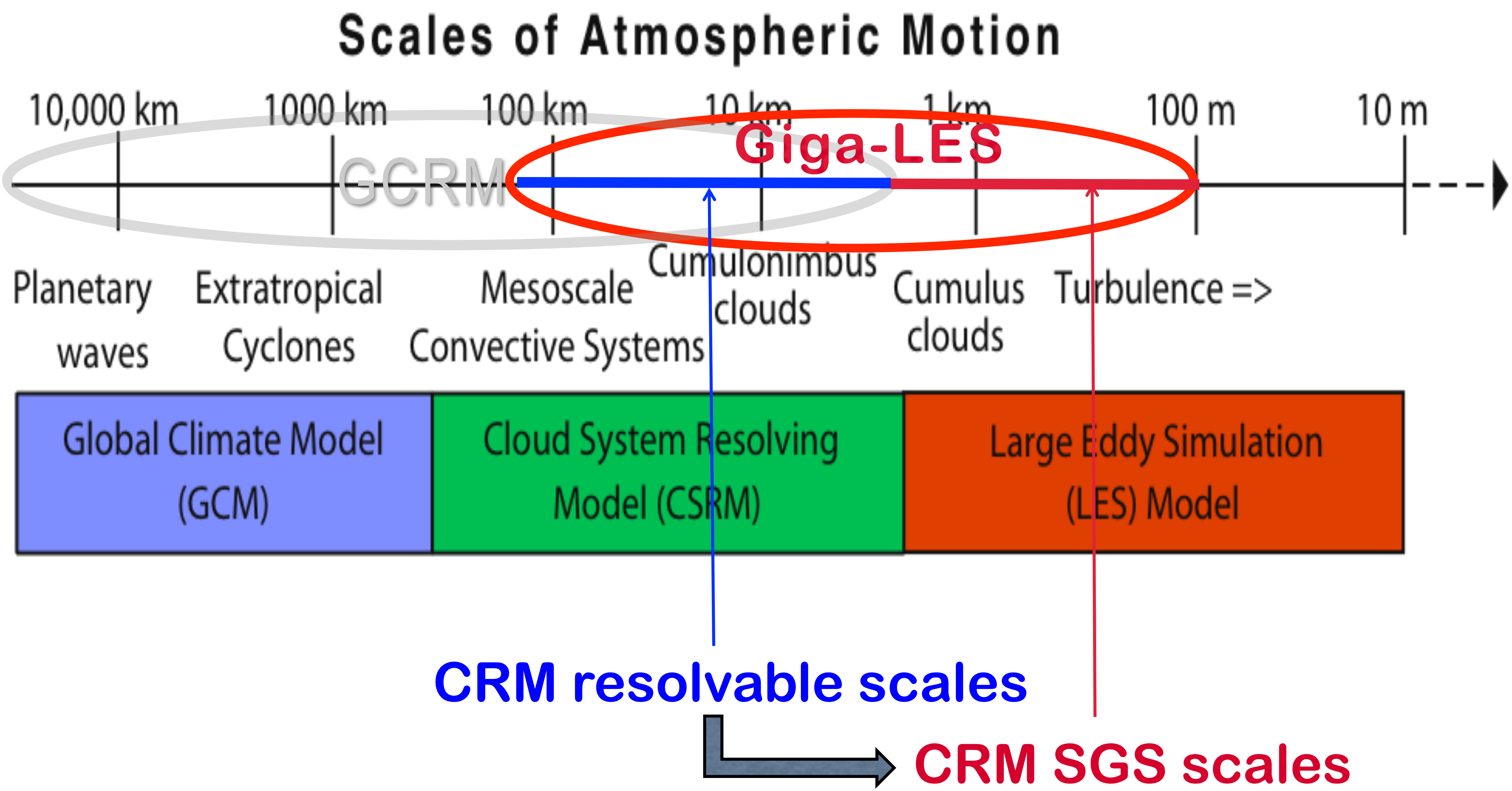
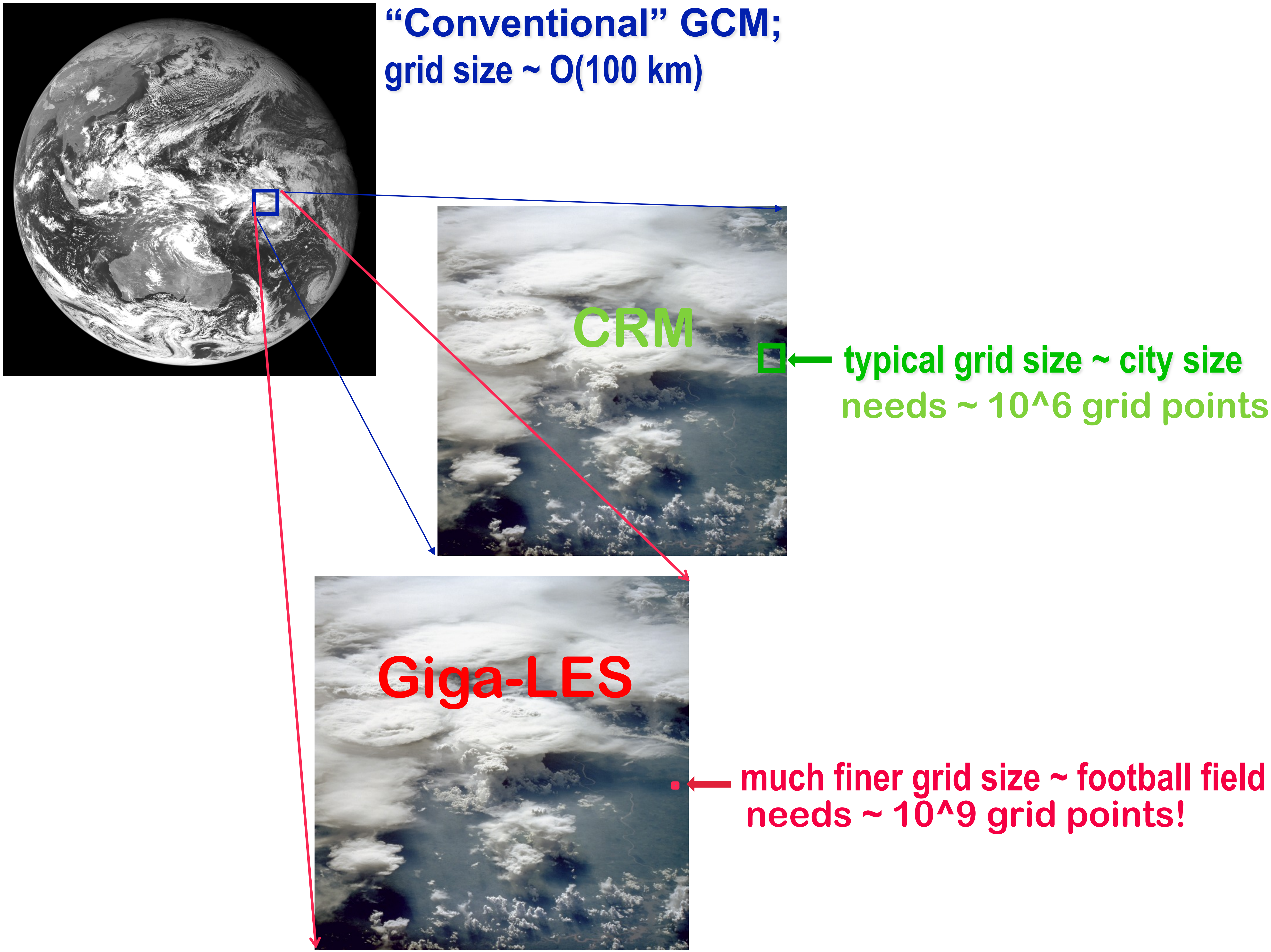
Our research tool: Giga-LES



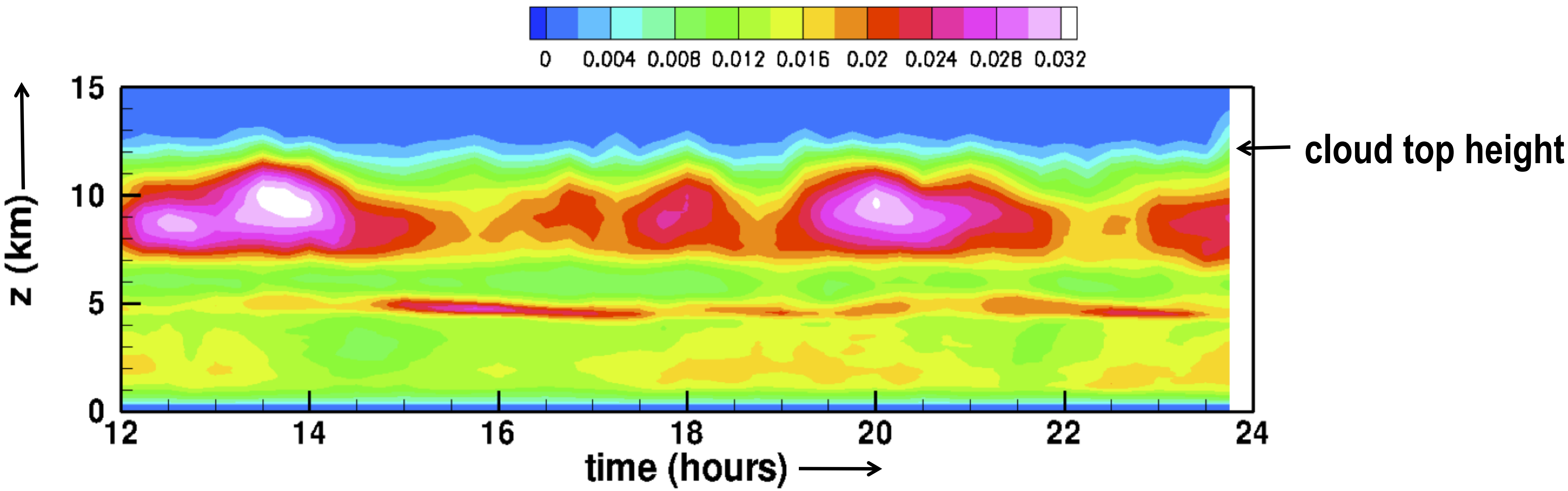

"Conventional" GCM;
grid size ~ O(100 km)
CRM
typical grid size ~ city size
needs ~ 10^6 grid points
Giga-LES
much finer grid size ~ football field
needs ~ 10^9 grid points!

Take advantage of ever-increasing massive-parallel-computer power and a skillful modeler

Marat consumed ~ 400,000 hours (~ 46 years!) of a supercomputer time; completed the run in just two weeks; used 2048 MPI processors simultaneously.

It's the finest-grid simulation of a tropical deep convection system ever performed.

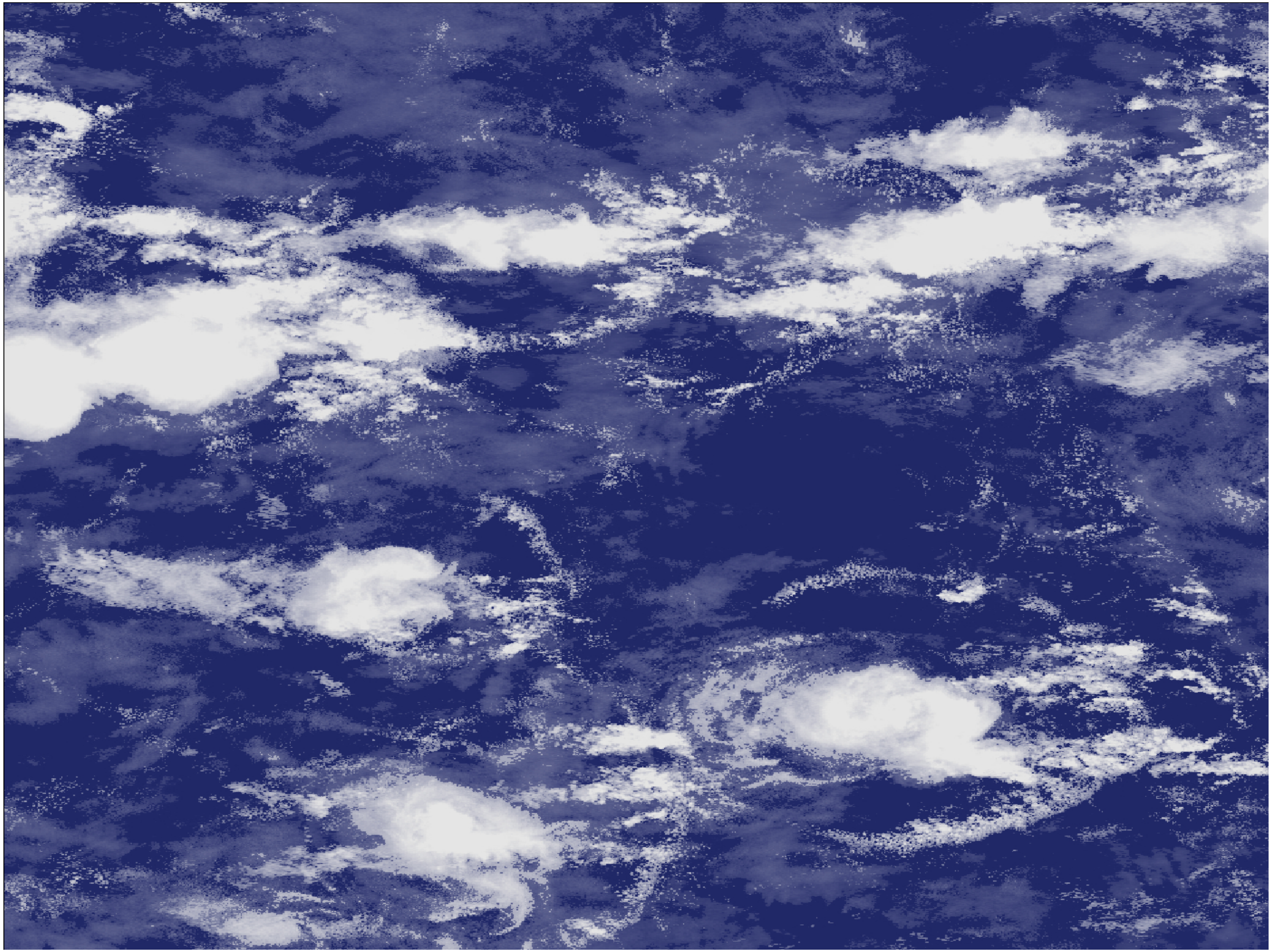
Vertical cross-section of the Giga-LES cloud field



horizontally averaged cloud field
during the last 12 hours of simulation

Khairoutdinov et al 2009; JAMES

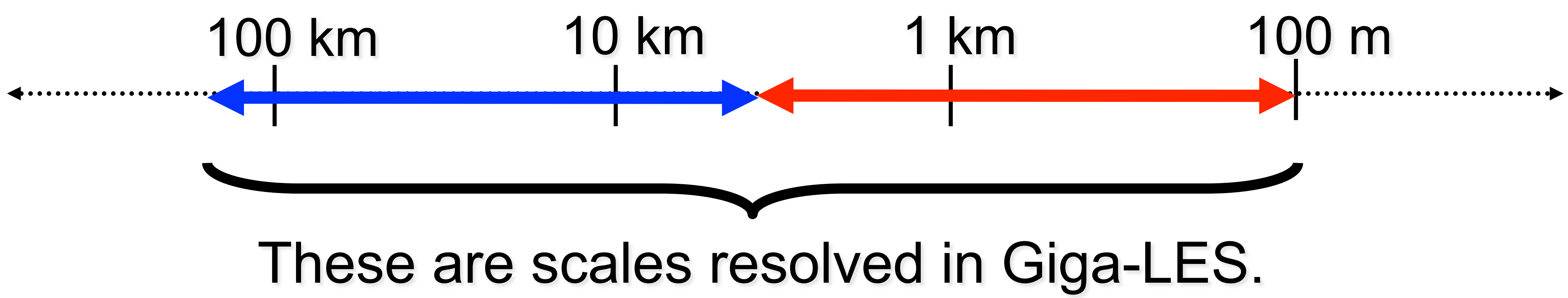
Horizontal view: “satellite” image



205 km (~ a GCM grid cell)

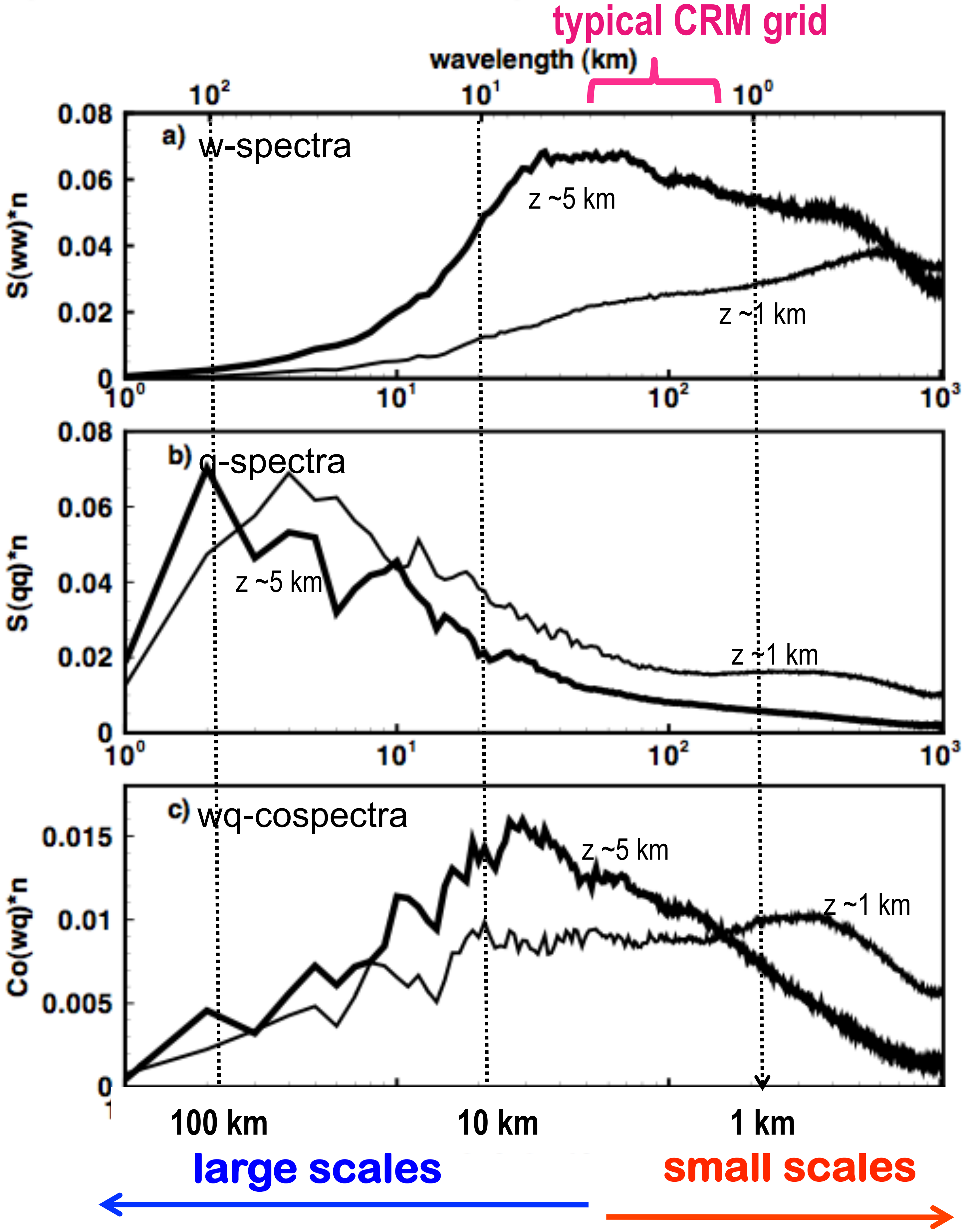
from Marat Khairoutdinov

Giga-LES resolves a broad range of motions:
mesoscale organization, large clouds,
small clouds, and turbulence…



As a benchmark to learn the relationship between
small conv. & turbulence (small stuff)
and
scales resolvable by CRMs.

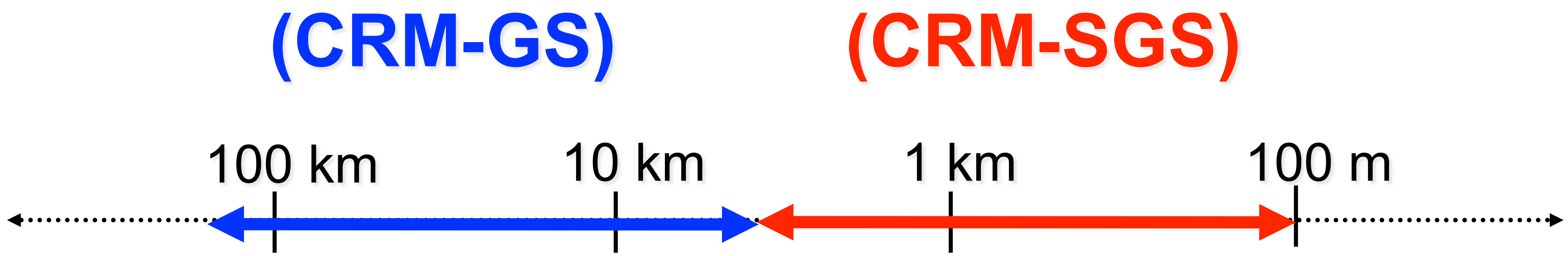
Spectra and co-spectrum of vertical wind and moisture



1. convective motions are continuous in scales
2. w-fluctuating levels peak ~ CRM grid size
3. lots of moisture flux carried by motions below CRM grid size

Split scales of Giga-LES

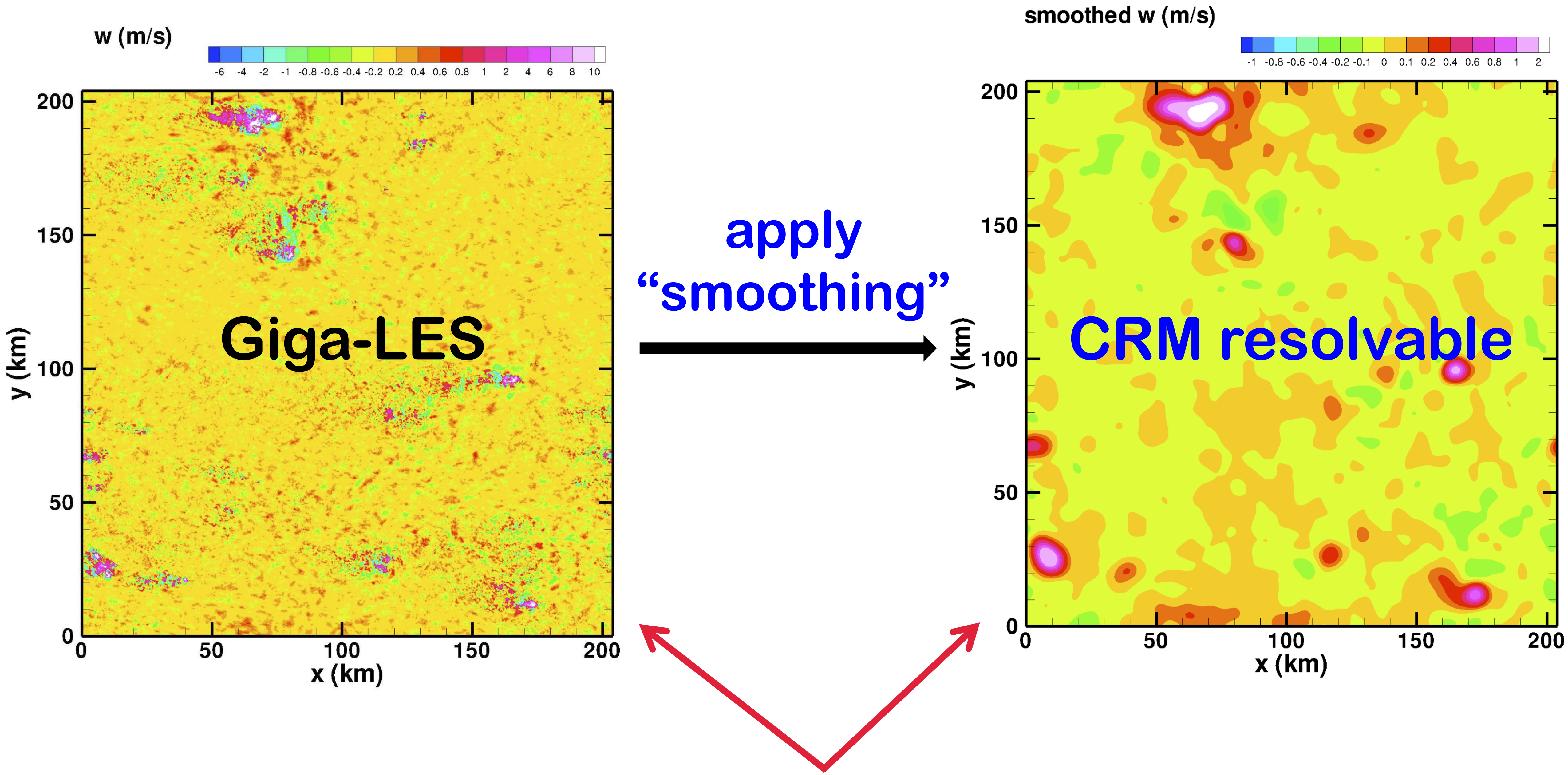
into large scales & small conv./turbulence



Using a smoothing function G:

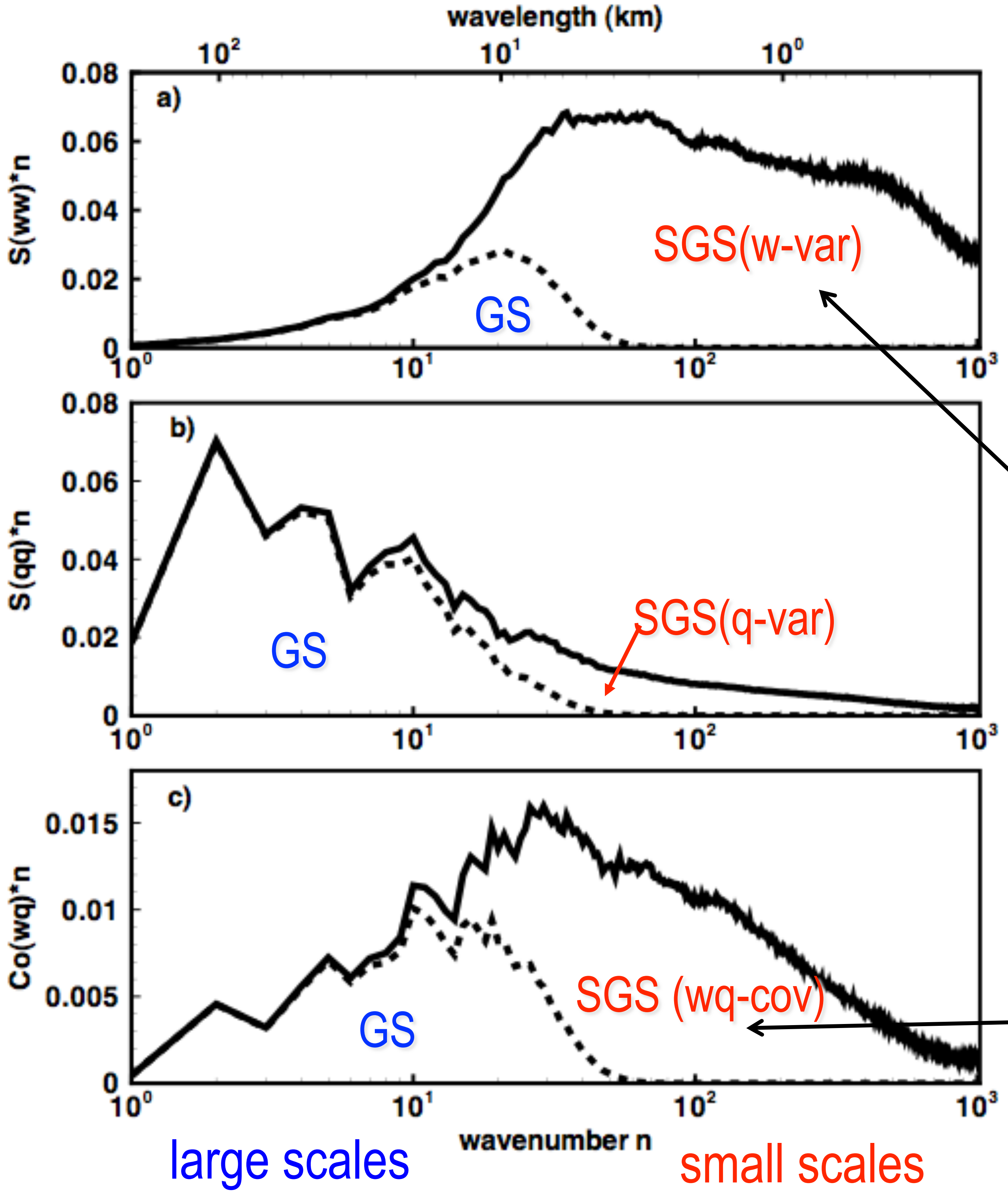
$$w = \underbrace{\overline{w}}_{\text{GS}} + \underbrace{w'}_{\text{SGS}} \quad \text{where} \quad \overline{w} \equiv \iint G w \, dx \, dy$$

Split the LES flow into: "resolvable" grid-scale (GS) & "unresolved" scale (SGS)



SGS is the difference.

Apply "smoothing" with a width of 4 km



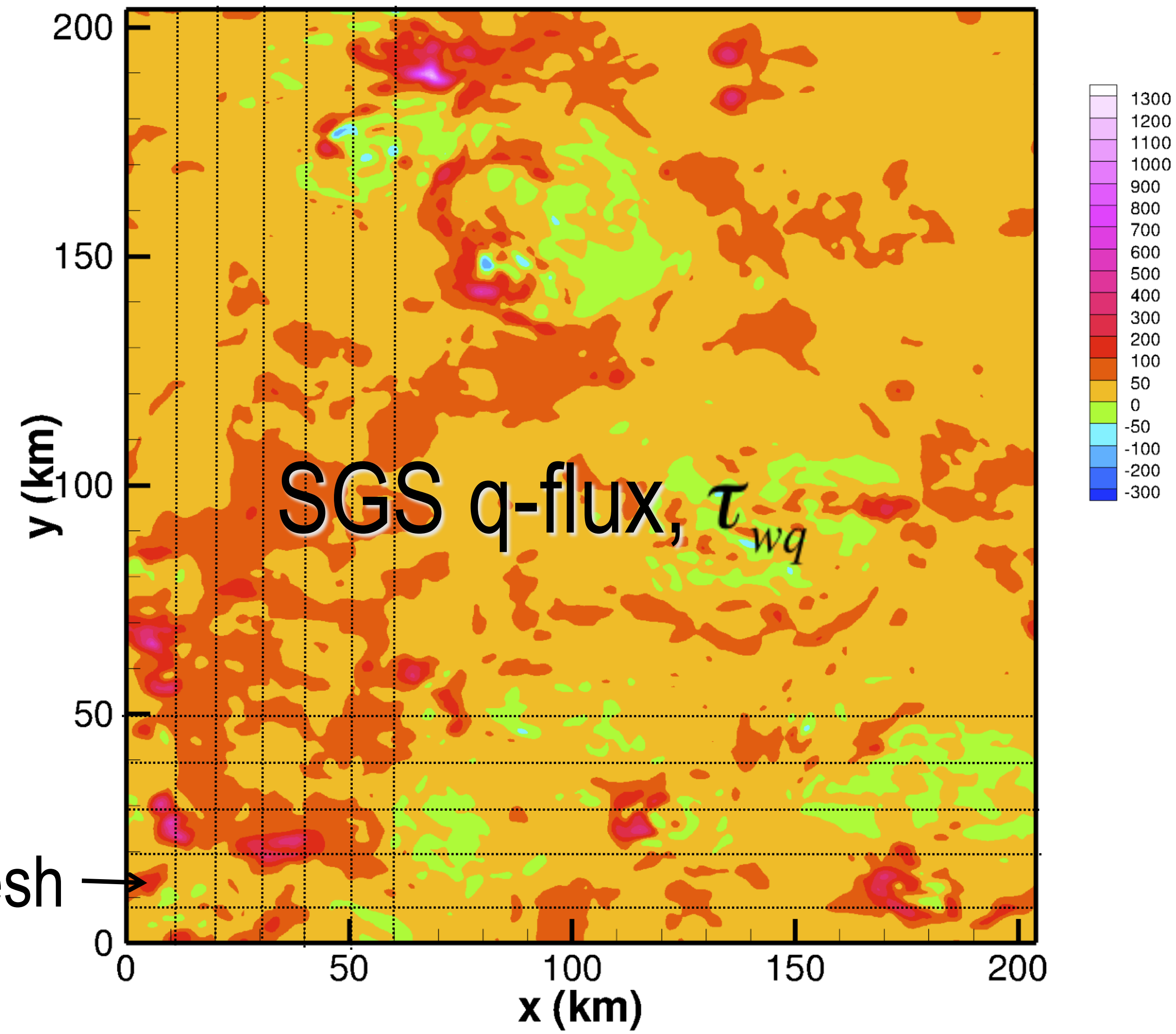
GS: CRM-grid scales

SGS: CRM-SGS

most of w-kinetic energy in SGS

~ half of moisture flux in SGS

What's needed in CRMs are SGS fluxes---at every CRM grid points.



CRM grid mesh

SGS q-flux retrieved from Giga-LES at z ~ 5km
smoothing width =10 km

Our task is to find an expression for τ_{wq} in terms of CRM resolvable variables---at each grid point.

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The SGS fluxes

$$\tau_{wc} \equiv \overline{wc} - \overline{w}\,\overline{c}$$

using $w = \overline{w} + w'$ and $c = \overline{c} + c'$

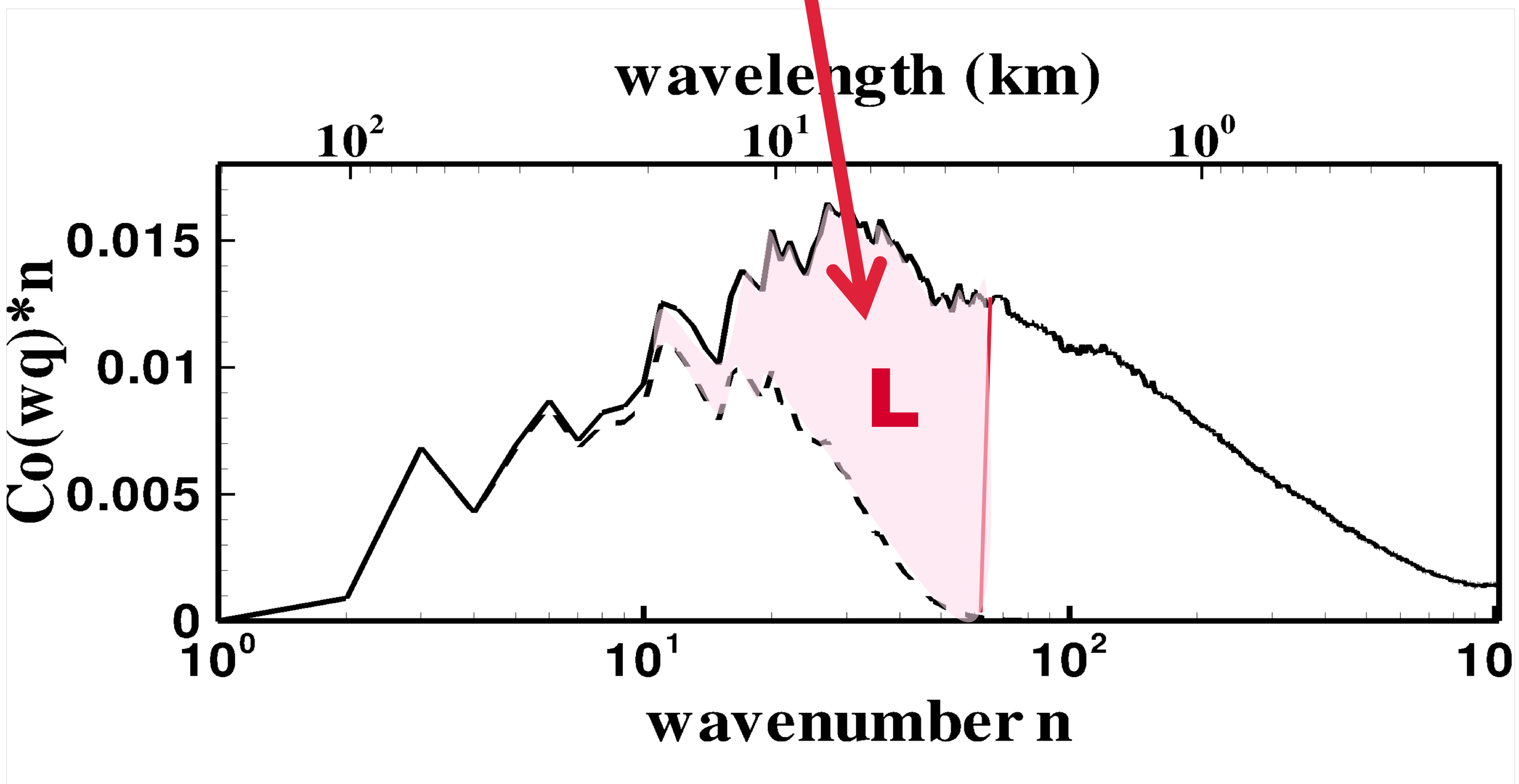
$$\tau_{wc} \equiv [\overline{\overline{w}\,\overline{c}} - \overline{\overline{w}}\,\overline{\overline{c}}] + [\overline{\overline{w}c'} + \overline{w'\overline{c}} - \overline{\overline{w}}\,\overline{c'} - \overline{w'}\,\overline{\overline{c}}] + [\overline{w'c'} - \overline{w'}]$$

Leonard term   cross term   Reynolds term

❖The L term contains only the bar variables, GS, thus representing the largest SGS eddies.

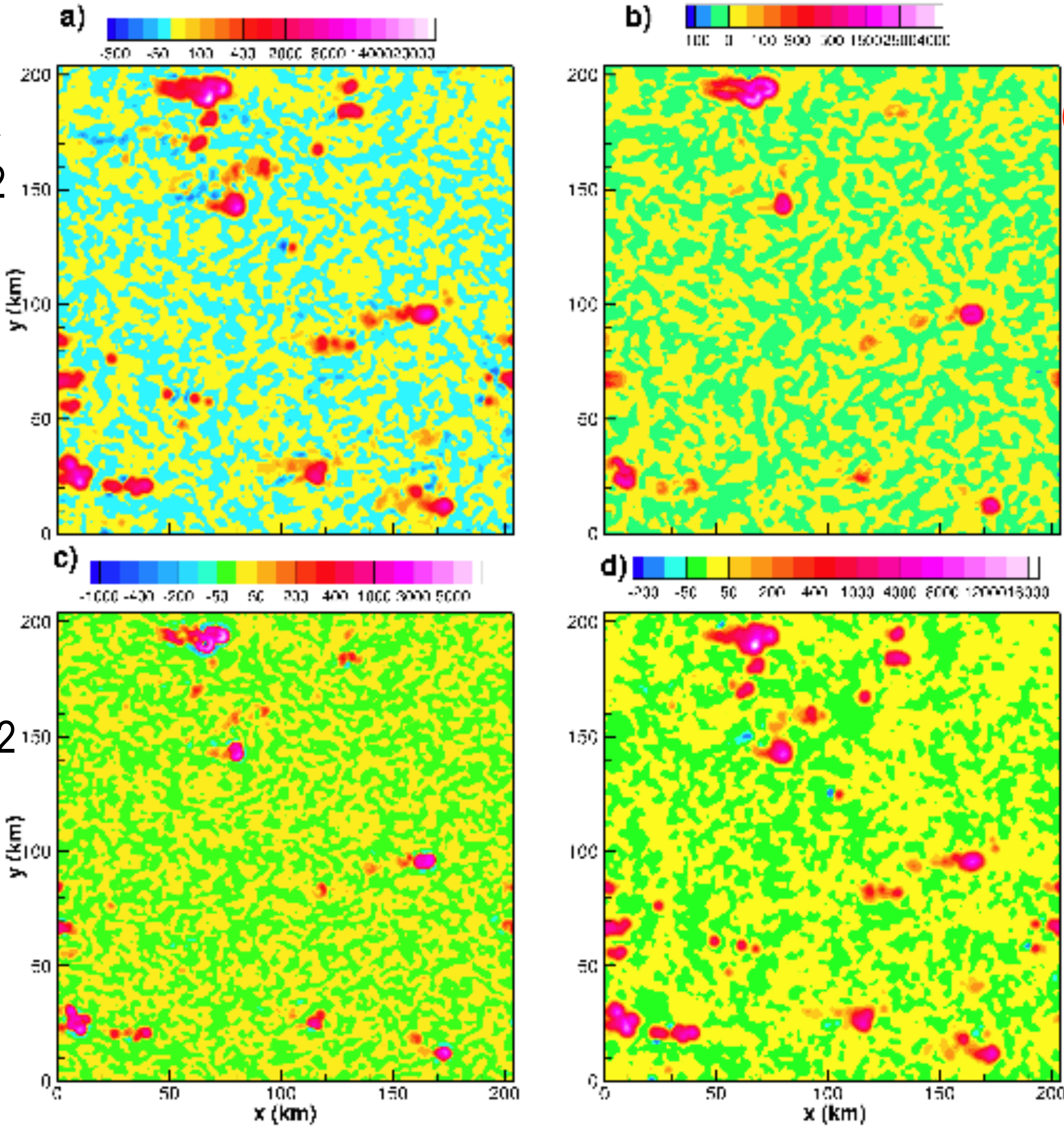
After Germano (1986), Leonard (1974)

The L term represents contribution from the largest SGS eddies.



SGS-wq τ_{wq} components retrieved from Giga-LES

at z~ 5 km



total SGS q-flx
-300 ~ 20000 W/m2

L-term
-100 ~ 4000 W/m2

C-term
-1000 ~ 5000 W/m2

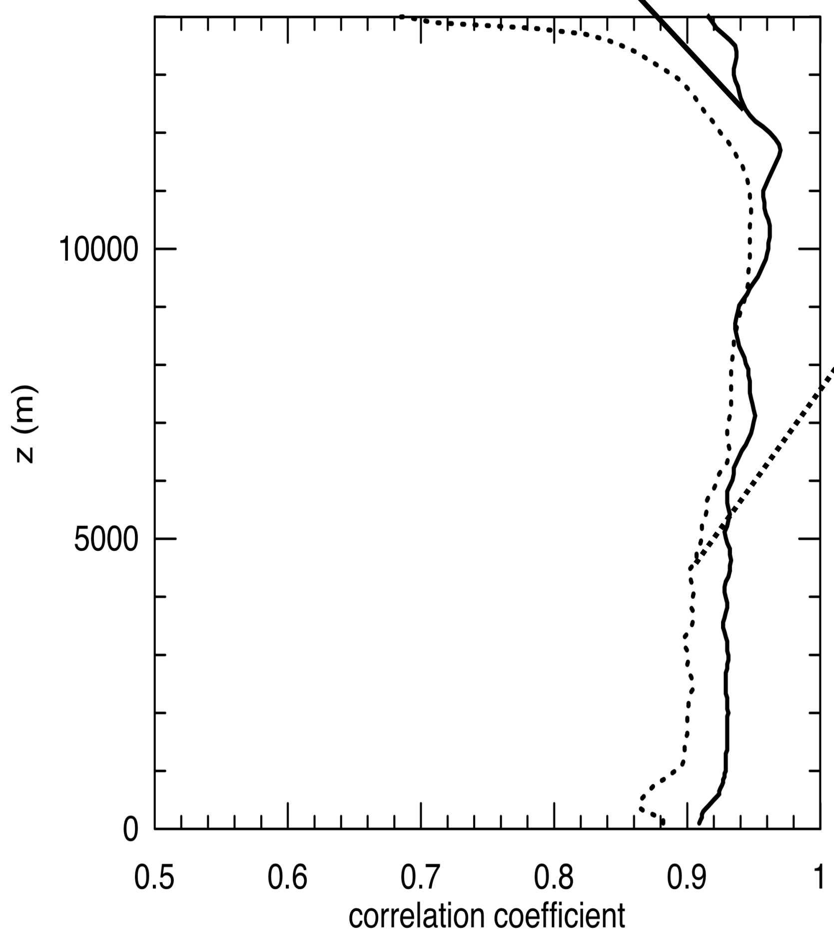
R-term
-200 ~ 16000 W/m2

filter width=4 km

Approximation for the L term
(using Taylor series expansion)

$$L \equiv \overline{\overline{w}\,\overline{c}} - \overline{\overline{w}}\,\overline{\overline{c}} \overset{?}{\approx} \left(\frac{\Delta_f^{\,2}}{12}\right)\left[\frac{\partial \overline{w}}{\partial x}\frac{\partial \overline{c}}{\partial x} + \frac{\partial \overline{w}}{\partial y}\frac{\partial \overline{c}}{\partial y}\right]$$

following Leonard (1974) and Clark et al (1979)

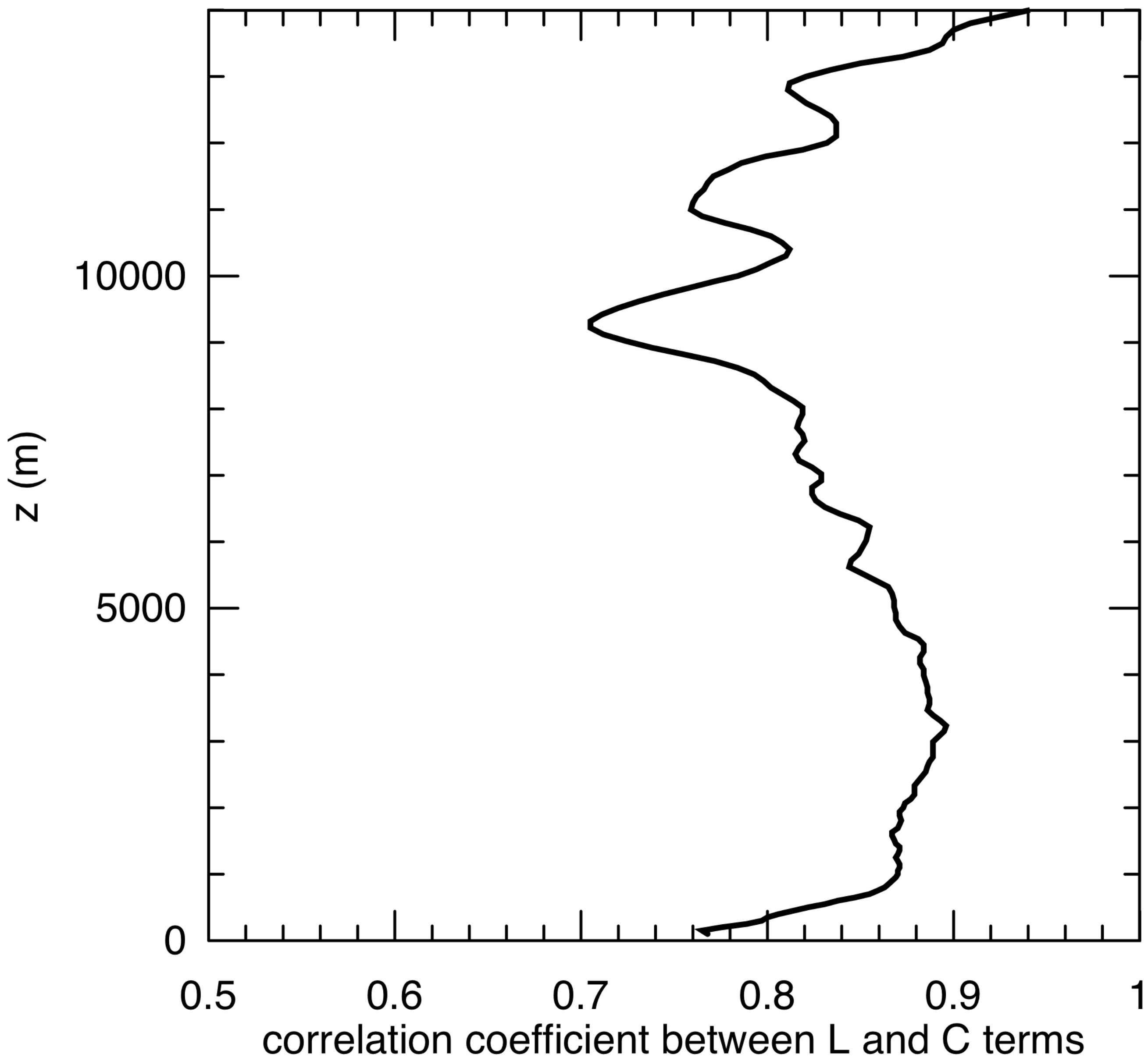


Computed from Giga-LES

RHS:

- good approximation for L-term;
- in terms of the bar variables;
- easy to compute in CRMs;
- no closure assumptions.

Does the C-term correlate well with the L-term?



It is reasonable to set C ~ L.

A mixed scheme for SGS fluxes in CRMs

Assume C = L.

$$\tau_{wc} = -K_h \frac{\partial \overline{c}}{\partial z} + 2\left(\frac{\Delta_f^2}{12}\right)\left[\frac{\partial \overline{w}}{\partial x}\frac{\partial \overline{c}}{\partial x} + \frac{\partial \overline{w}}{\partial y}\frac{\partial \overline{c}}{\partial y}\right]$$

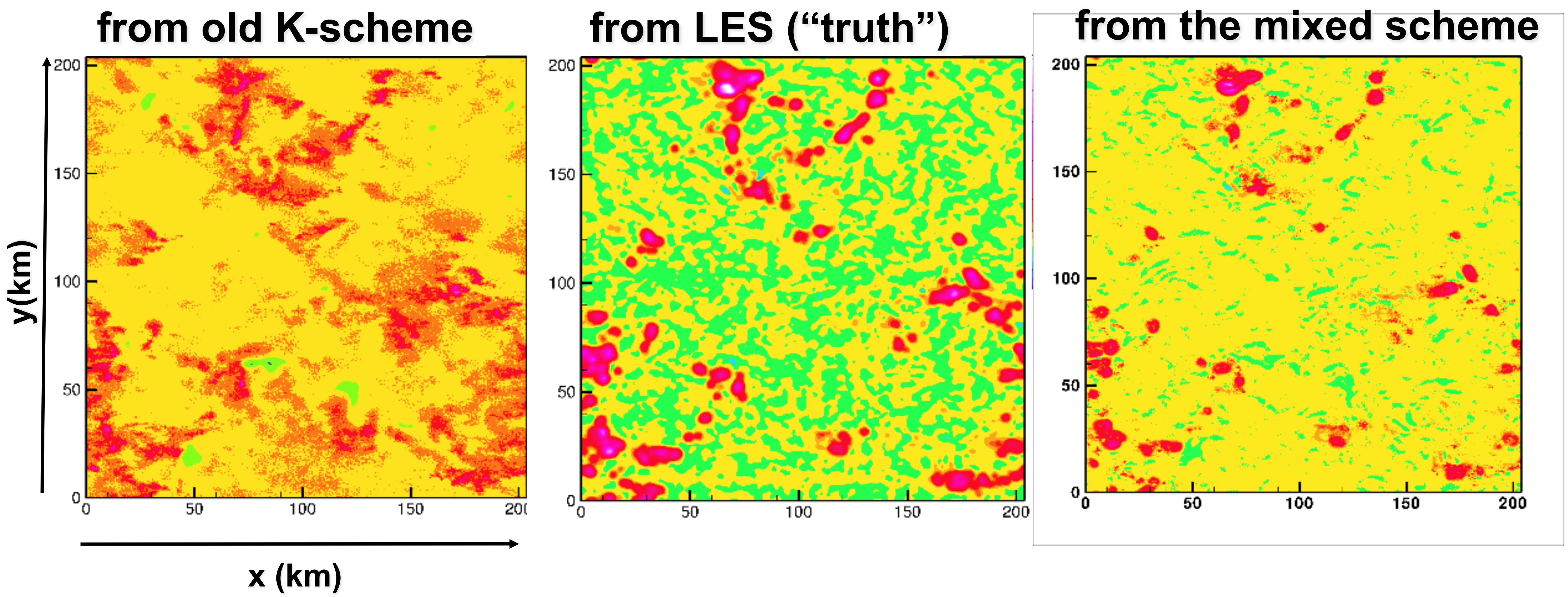
where $\overline{w}$ & $\overline{c}$ are CRM resolvable-scale variables.

commonly-used K model

new term representing the large SGS eddies

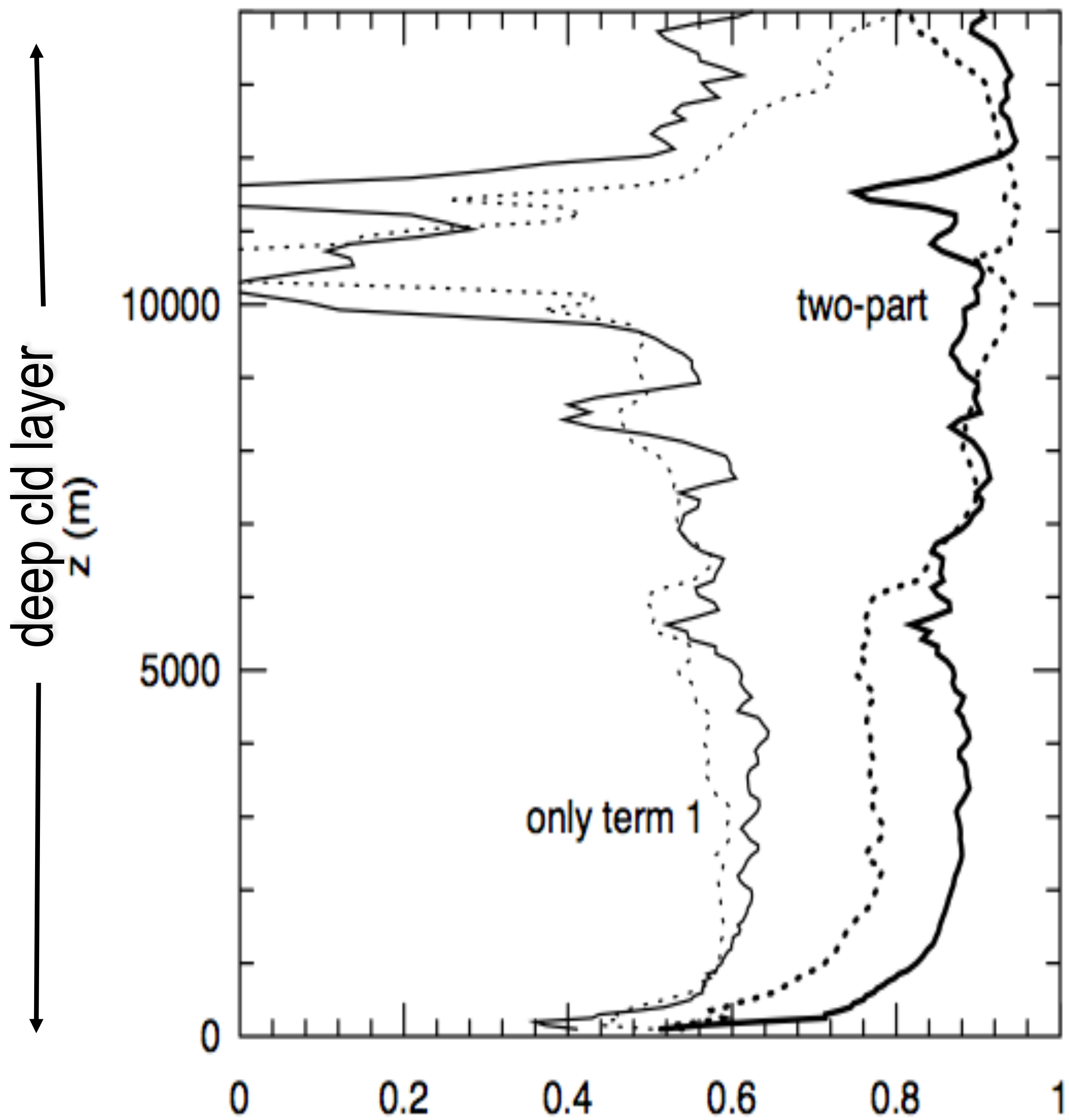
How does the mixed SGS scheme perform?

Horizontal distributions of vertical q-flux at z ~ 1.5 km

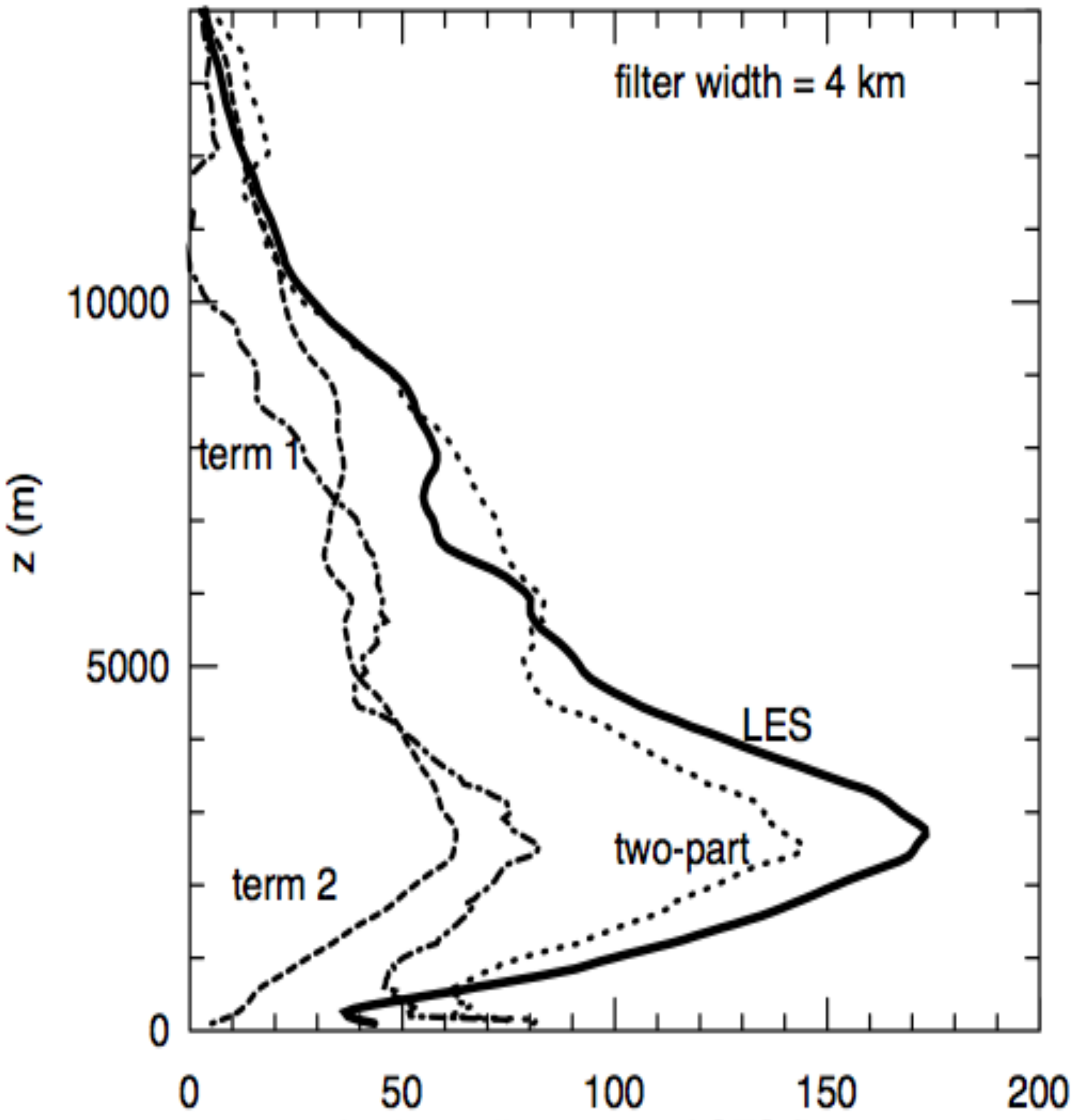


How well do they correlated? ➔

The model significantly improves the estimation of the vertical SGS flux of q.



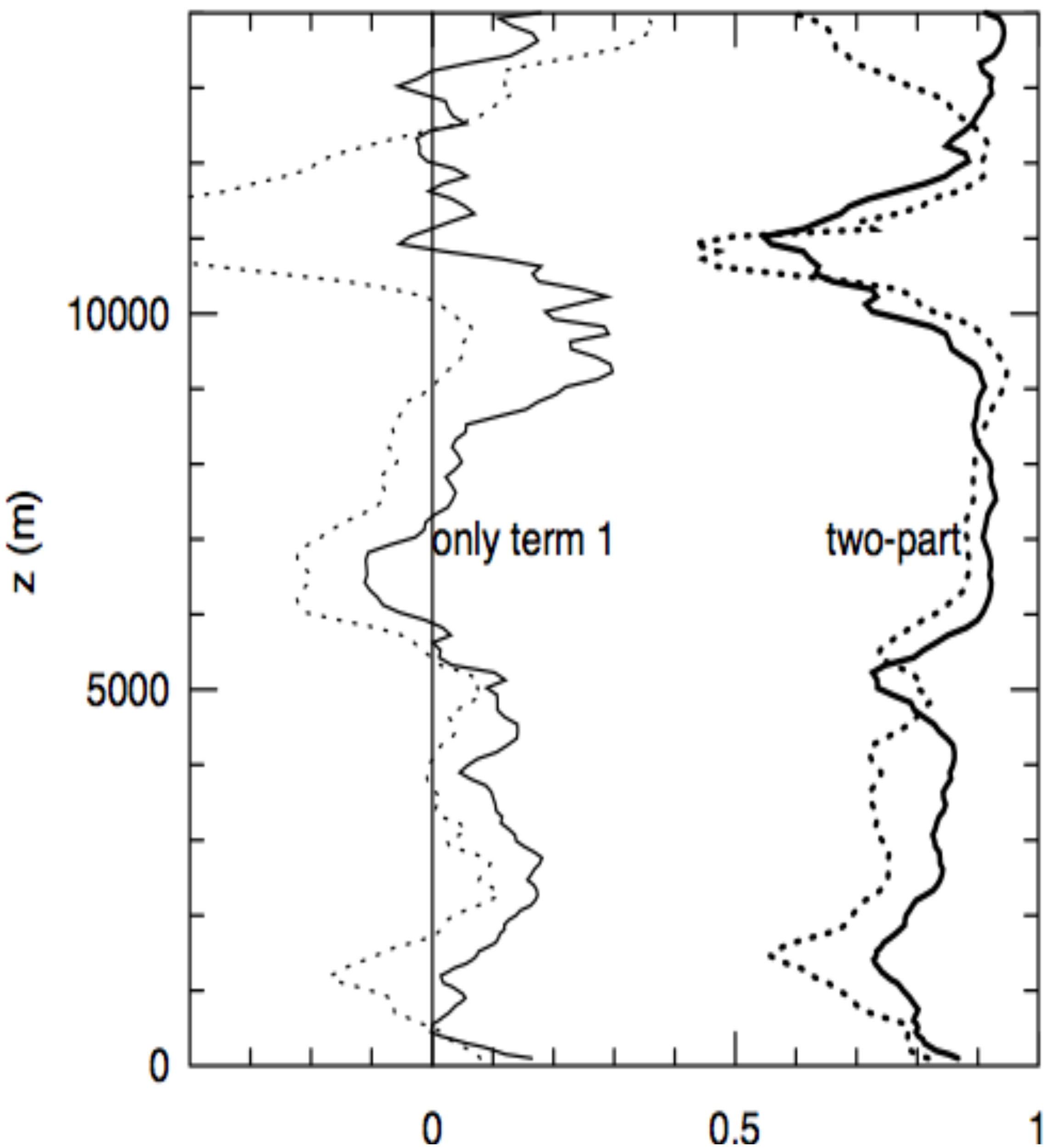
Spatial correlation coefficients with the LES-retrieved SGS-wq



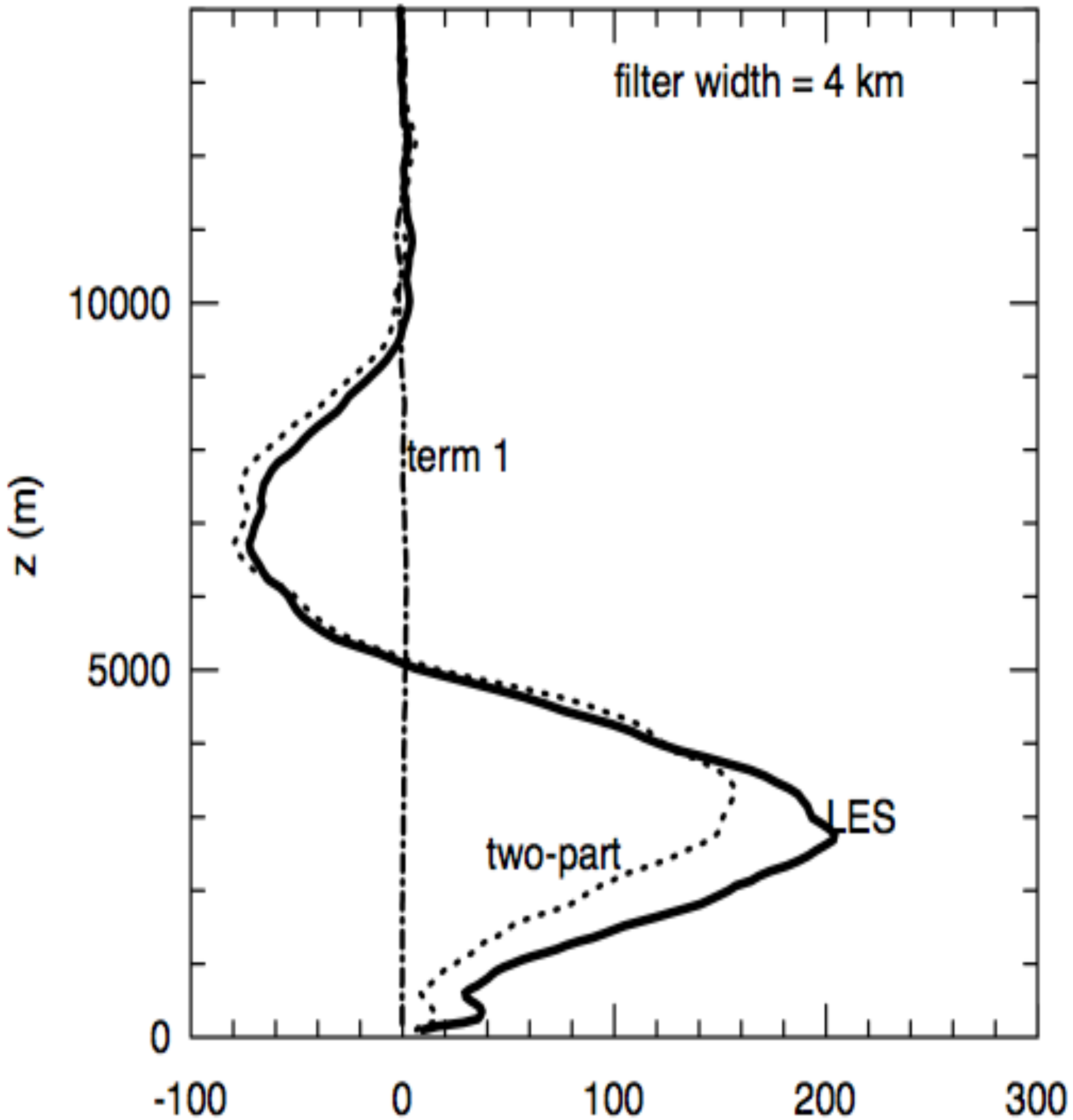
Contributions to the horizontally averaged SGS-wq

solid curves: filter width = 4 km
dotted curves: filter width = 10 km

How about horizontal fluxes of scalars?

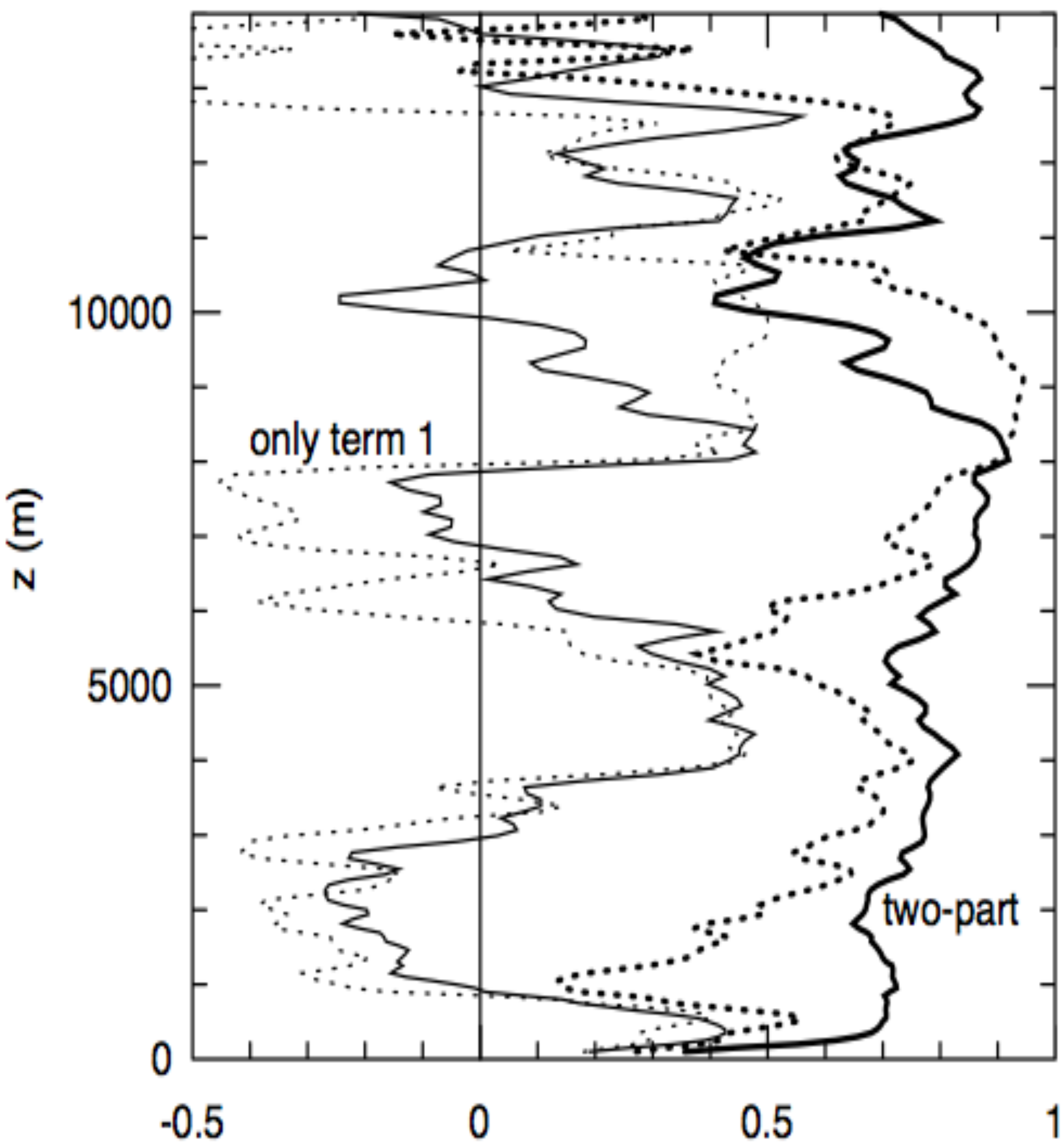


spatial correlation coefficients
with the LES-retrieved SGS-uq

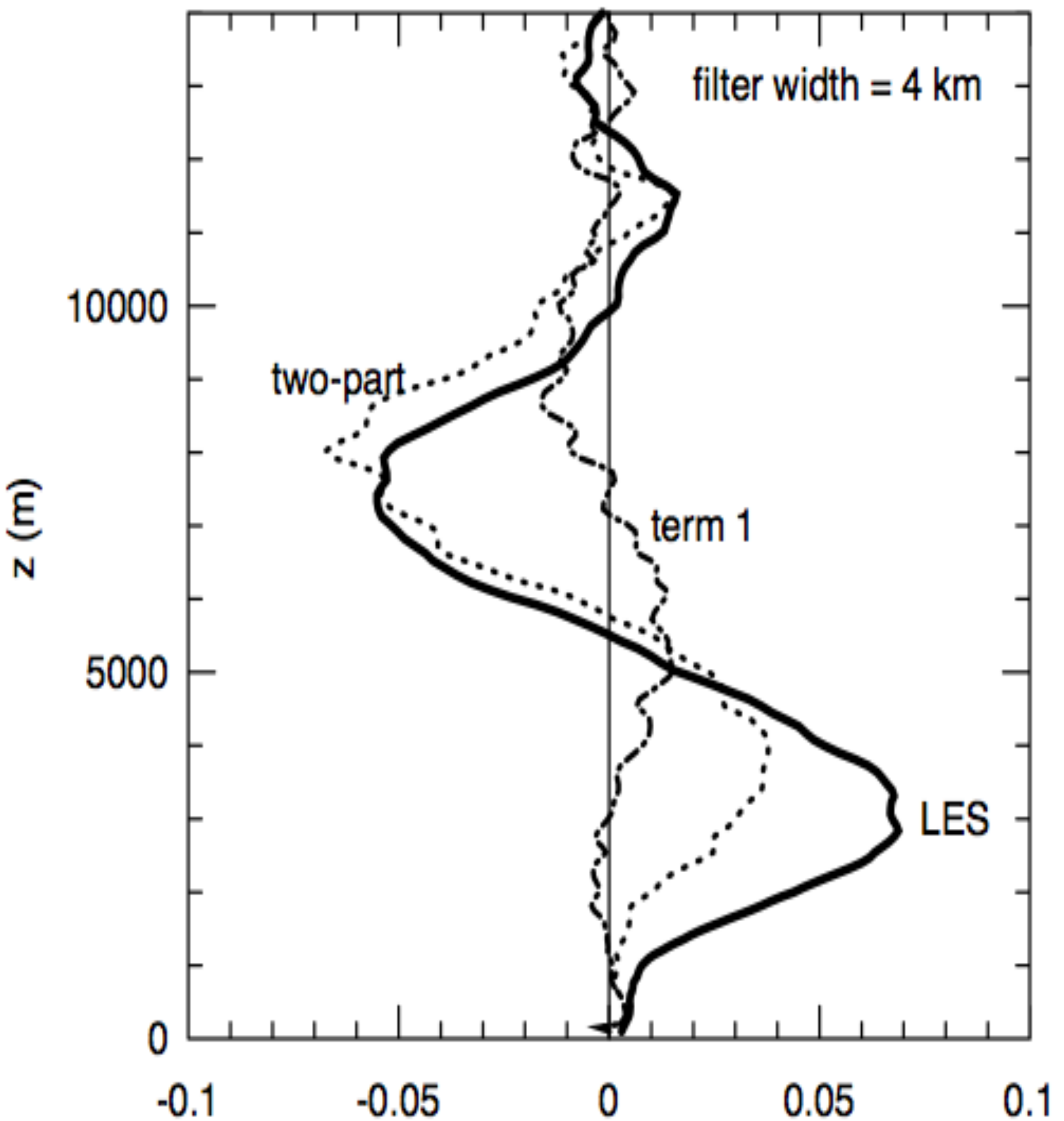


contributions to the horizontally
averaged SGS-uq

How about the momentum fluxes?



spatial correlation coefficients with the LES-retrieved SGS-uw

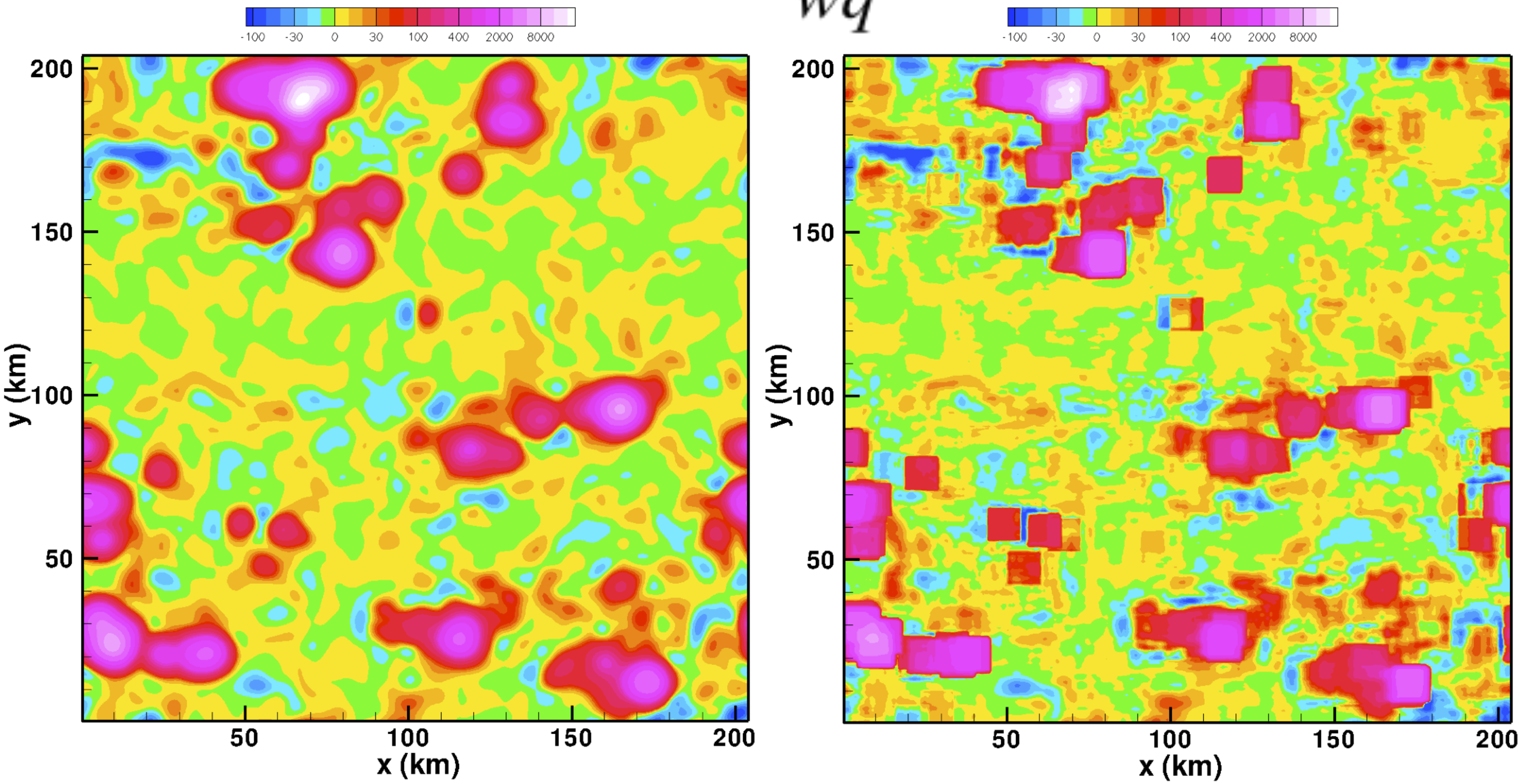


contributions to the horizontally averaged SGS-uw

solid curves: 4 km   dotted curves: 10 km

Depending on the smoothing function?

τ_{wq}



$$G = \frac{6}{\pi \Delta_f^2} e^{-6(x^2+y^2)/\Delta_f^2} \qquad \Delta_f = 10km$$

avg. over 10 km x 10 km area

❖ **Results are very similar.**

Giga-LES is a useful tool to study SGS transport for CRMs:

1. Motions in deep conv systems have continuous scales across “CRM resolvable” & “CRM-SGS”.

2. A significant amount of transport is carried by motions smaller than a typical CRM grid size. The small stuff is important.

3. The mixed SGS scheme looks promising.

4. Next: implement the SGS scheme into a CRM and perform full tests.