Spatial and temporal evolution of deep moist convective processes: the role of microphysics

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Second Split Workshop in Atmospheric Physics and Oceanography, Brac, 27 may 2010

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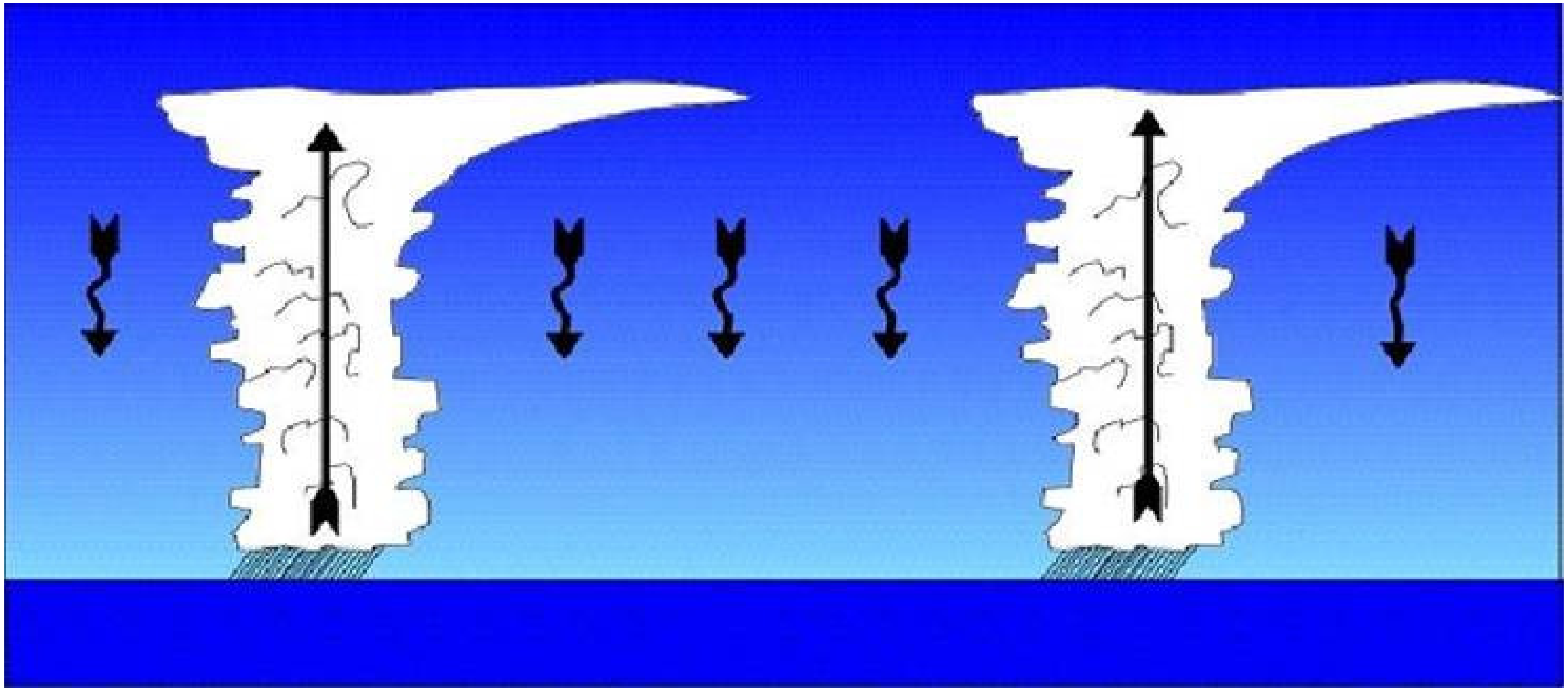
"True" dynamics:
turbulent, moist, non-Boussinesq, precipitating convection



Can we find a simplified dynamical model ?

Which is the key process/parameter in deep moist convection?

Which are the implications for statistical downscaling?

Background (1)

Cloud and water vapour processes affect radiative transfer and the earth's climate in several ways:

• by coupling dynamical and microphysical processes in the atmosphere through the heat of condensation and evaporation and through redistributions of sensible and latent heat and momentum;

• by coupling radiative and dynamical–microphysical processes in the atmosphere through the reflection, absorption, and emission of radiation;

• by influencing hydrological process in the ground through precipitation;

• by influencing the couplings between the atmosphere and oceans (or ground) through modifications of radiation and planetary boundary layer (PBL) processes.

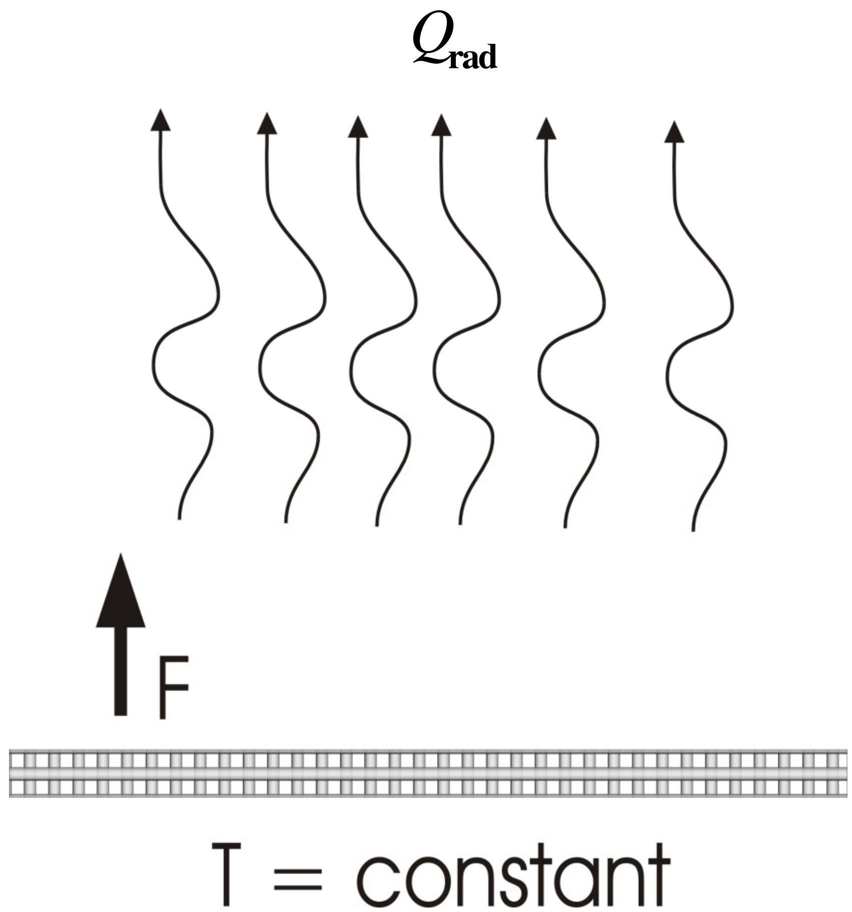
Background (2)

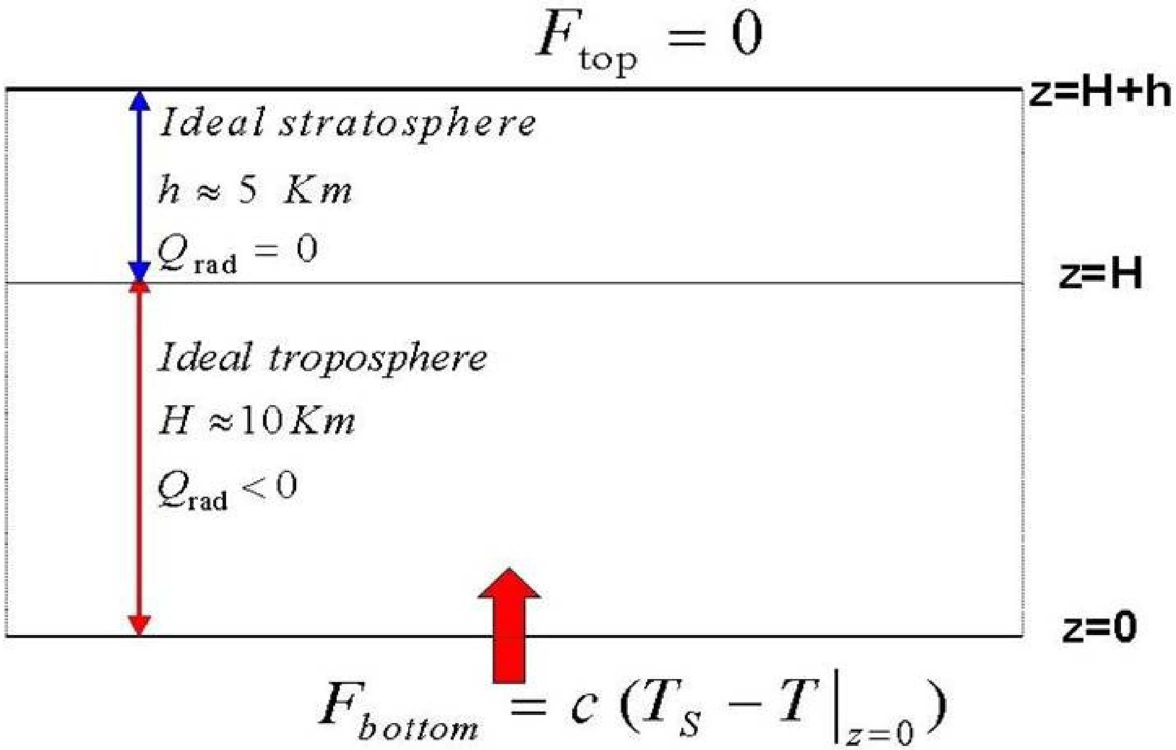
It has been well documented that the extent to which GCMs (Global Circulation Models) can be used as reliable tools to study climate dynamics and change crucially depends on how adequately tropical convection and related water vapour processes can be represented in these models.

In this framework, one of the main factors limiting our understanding of cloud dynamics and water vapour control by deep convection is the lack of a correct scaling for velocity and buoyancy in moist convection, even though there have been several studies of this topic (Renno et al, 1994; Emanuel and Bister, 1996; Grabowski, 2003; Robe and Emanuel, 1996, 2001; Xu and Randall, 1998; Wu, 2002).

A simplified dynamical model?

The canonical problem of radiative-dry convective equilibrium was first developed by Prandtl (1910, 1942). This problem *is the simplest model that captures some of the essential aspects of atmospheric convection*.





$$\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \nabla \boldsymbol{u} = -\frac{1}{\rho} \nabla p + \boldsymbol{g} \frac{\rho}{\rho_0} + \nu \nabla^2 \boldsymbol{u}$$

$$\frac{\partial T}{\partial t} + \boldsymbol{u} \cdot \nabla T = \kappa \nabla^2 T - \frac{Q_{\text{rad}}}{c_p}$$

$$\nabla \cdot \boldsymbol{u} = 0$$

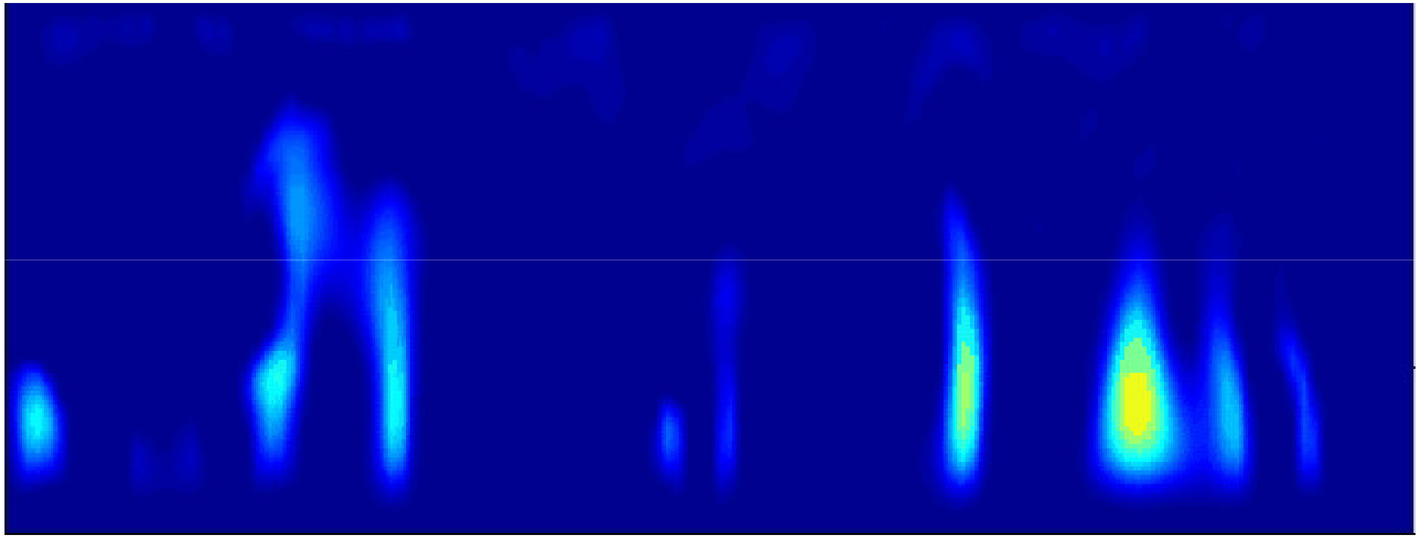
$$\tilde{x} = x/H$$
$$\tilde{t} = Ut/H$$
$$\tilde{u} = u/U$$
$$\tilde{p} = p/\rho_0 U^2$$
$$\tilde{T} = (T - T_{\text{s}})/\Delta T$$

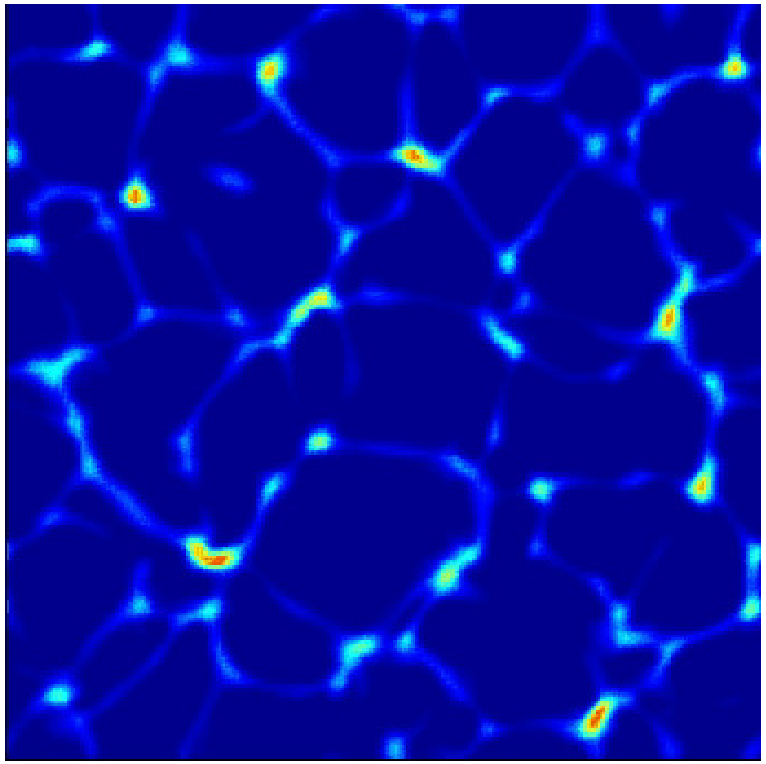
$$U = \left(\frac{g Q_0 H^2}{c_p T_{\text{s}}}\right)^{\frac{1}{3}}$$

$$\Delta T = \frac{U^2 T_{\text{s}}}{g H}.$$

Parodi, Emanuel, and Provenzale
(New Journal of Physics 2003)

$$H_t^+ = \langle w\theta \rangle_{++} \quad \textbf{with} \quad w > 0\,,\ \theta > 0$$





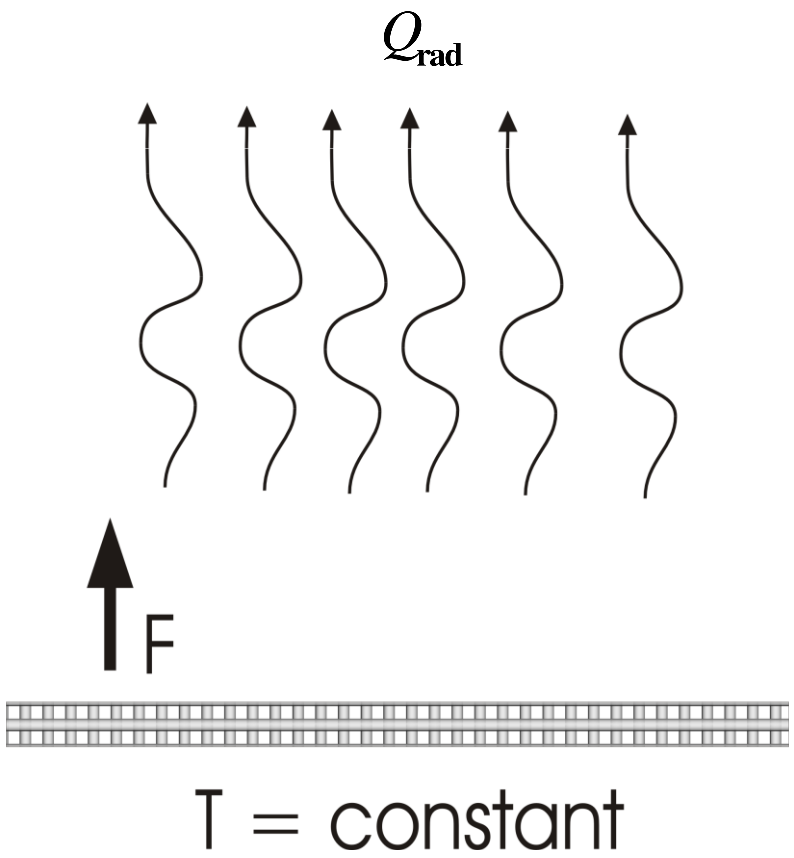
Key process/parameter in deep moist convection: buoyancy and velocity scales

- Buoyancy and velocity scales for dry convection in statistical equilibrium were derived long ago by Prandtl (1910, 1925):

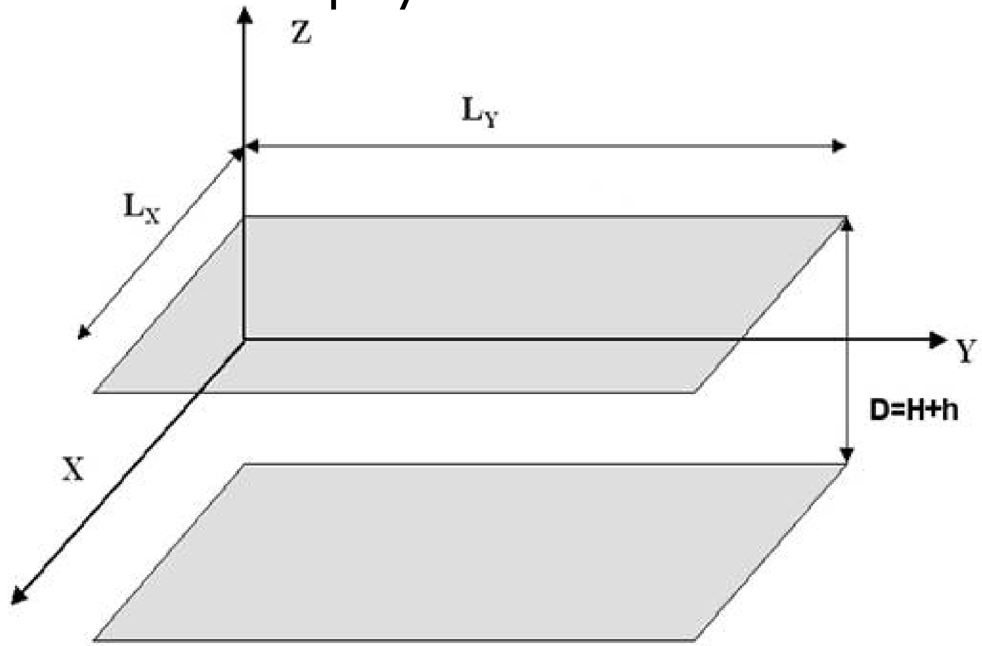
  for this problem the turbulence kinetic energy scales as $(Fz)^{2/3}$, where z is the altitude above the surface, while the unstable stratification decreases as $z^{-4/3}$

- But the question of convective velocity and buoyancy scales, as well as the topic of fractional area coverage of convective clouds, are unresolved in moist convection (in radiative convective equilibrium) (Emanuel and Bister, 1996; Grabowski, 2003; Robe and Emanuel, 1996, 2001; Xu and Randall, 1998; Wu, 2001)

The precipitating radiative-convective equilibrium

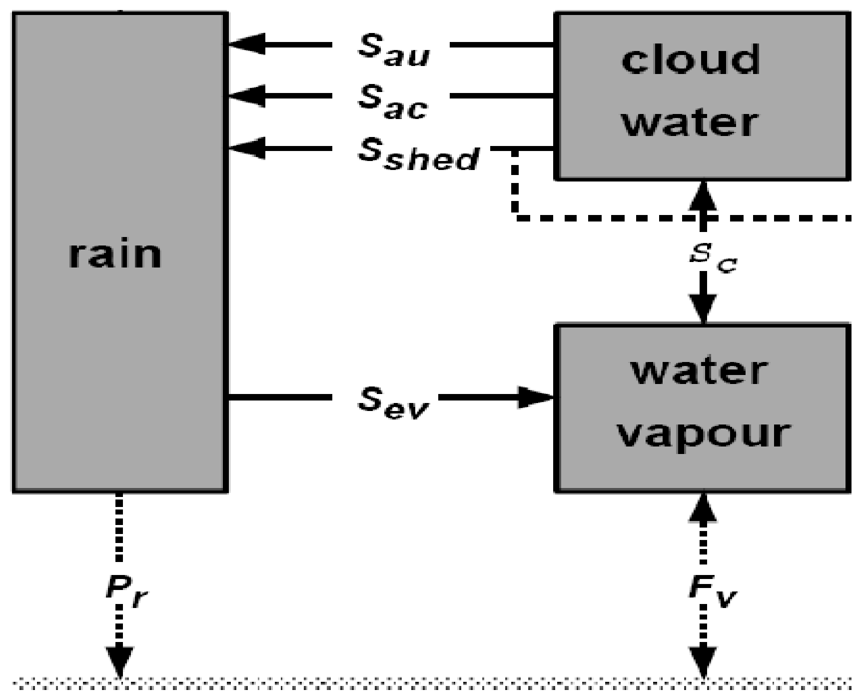


- WRF model
- Doubly periodic domain, $\Delta x = \Delta y = 2$ km
- Costant cooling rate Q_{rad} over the full height of the troposphere
- LES-type turbulence parameterization
- Kessler microphysics



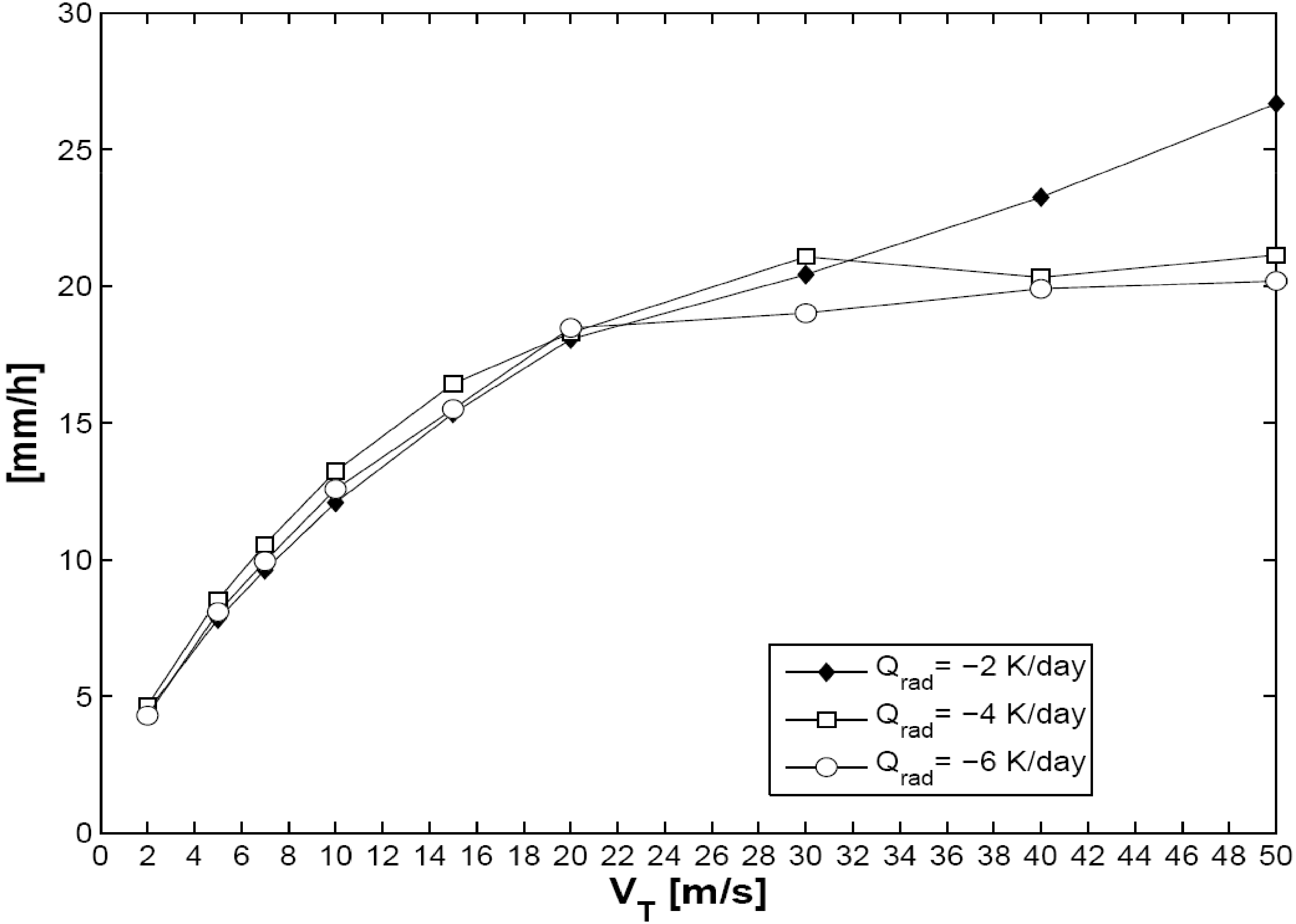
- **The underlying hypothesis of the work is that <u>convective updraft velocities and rainfall intensity scale with the terminal velocity of raindrops;</u>**

warm rain scheme



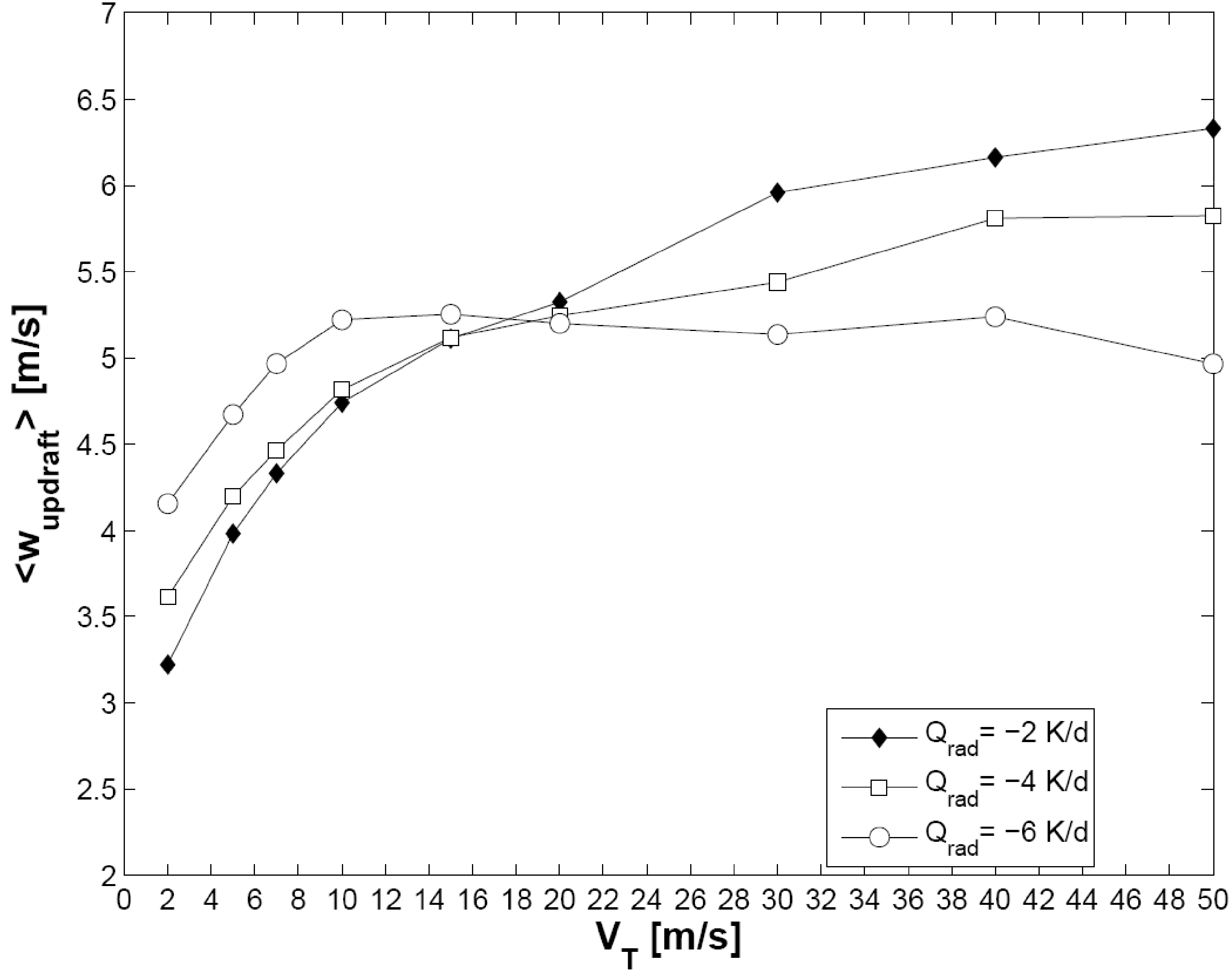
- For prescribed cooling rate Q_{rad}, a set of simulations with different raindrop terminal velocities V_T (range: 2-50 m/s) is performed and the results are compared

Radiative convective equilibrium statistics: Rainfall intensity scaling

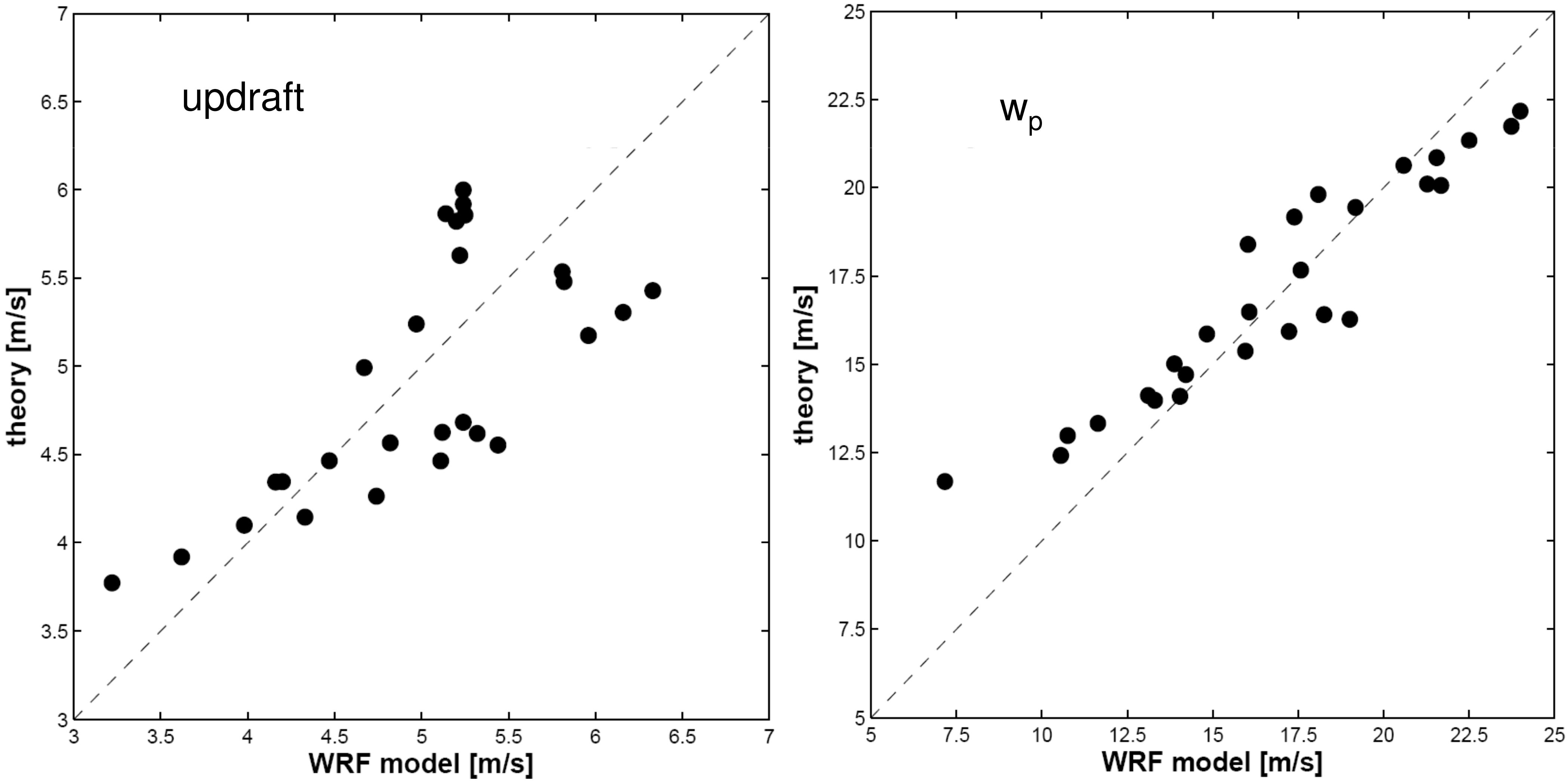


Parodi and Emanuel (JAS, 2009)

Radiative convective equilibrium statistics: Updraft velocity



A theory for buoyancy and velocity scales in deep moist convection



Which are the implications for statistical downscaling?

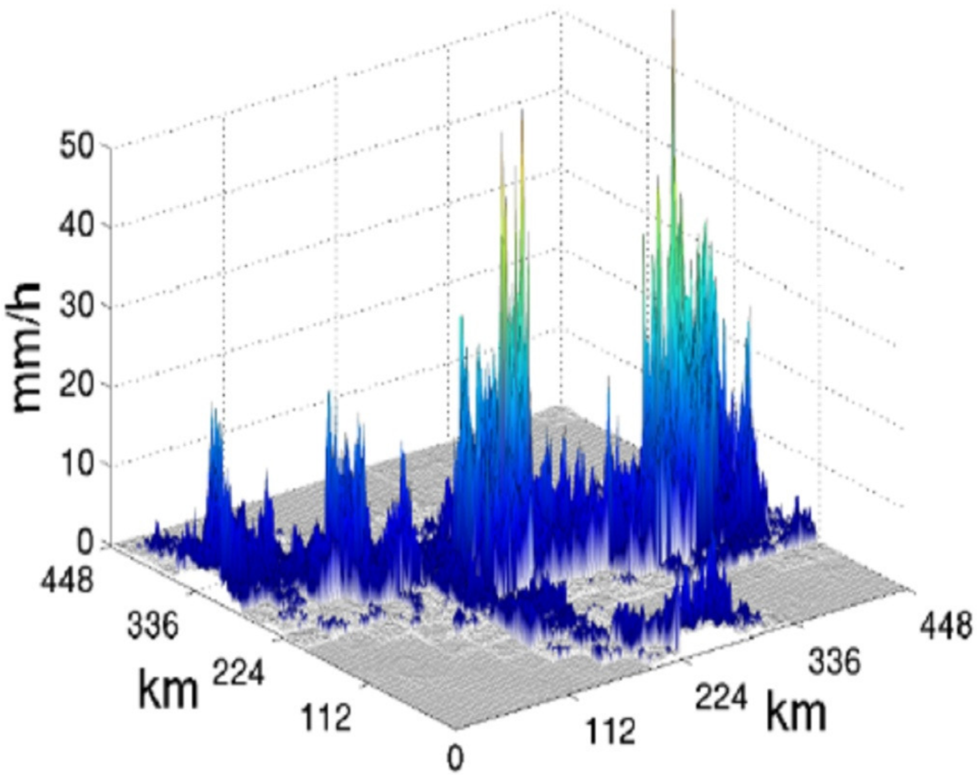
Stochastic downscaling (or disaggregation) techniques are important in order to:

• allow to derive Higher Resolution Stochastic Ensembles (HRSE) of precipitation fields from a single (measured or forecasted) precipitation field with limited spatial and temporal resolution (does not provide the future of the system);

• reproduce in a statistical sense the small scale properties of rainfall derived from the properties of a (measured or forecasted) precipitation fields defined on large scales;

• conserve the large-scale features of the precipitation fields

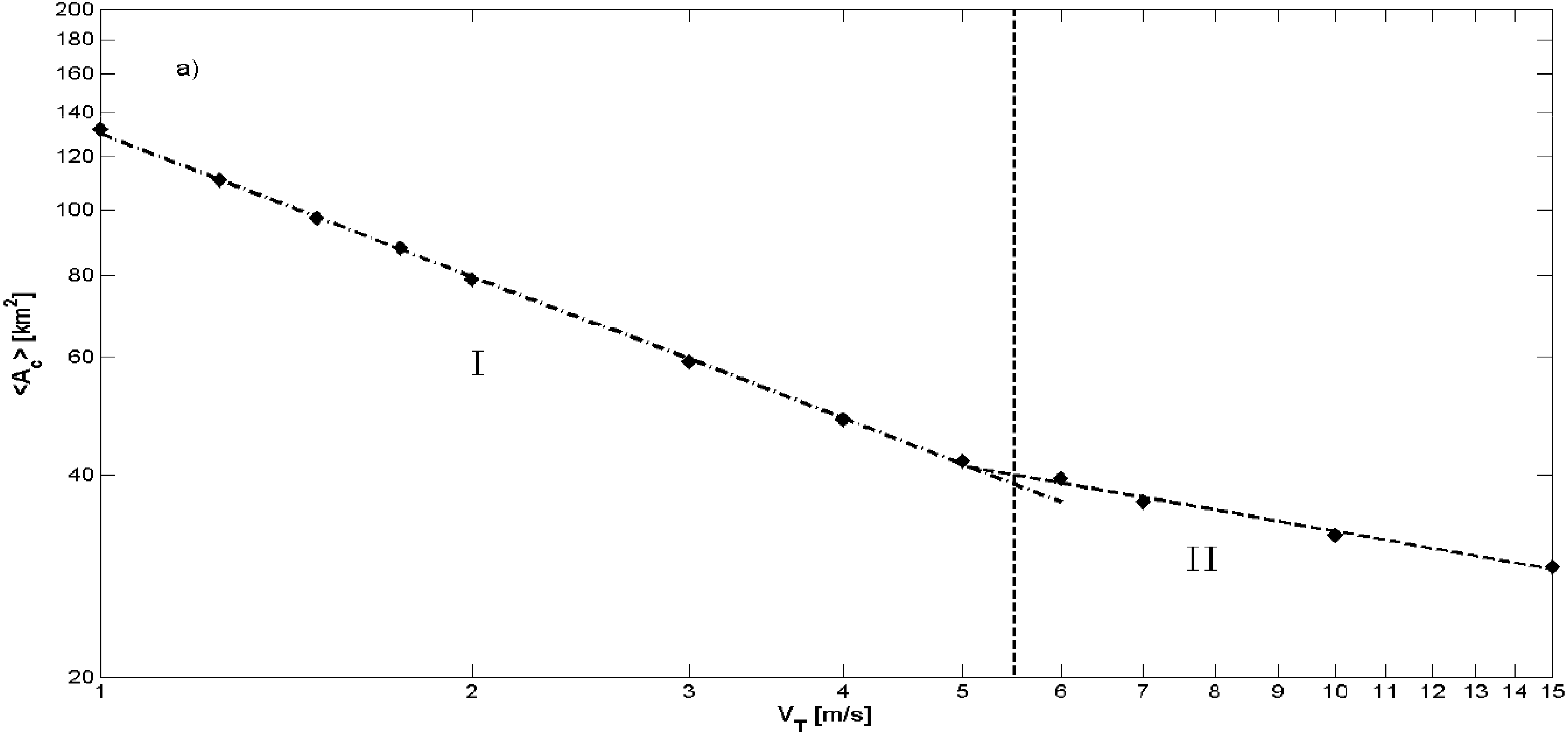
BUT....



- In statistical downscaling schemes, a remaining challenge *is that of relating the statistical parameters of the downscaling scheme to physical observables which can be used as predictors in real-time downscaling applications*;

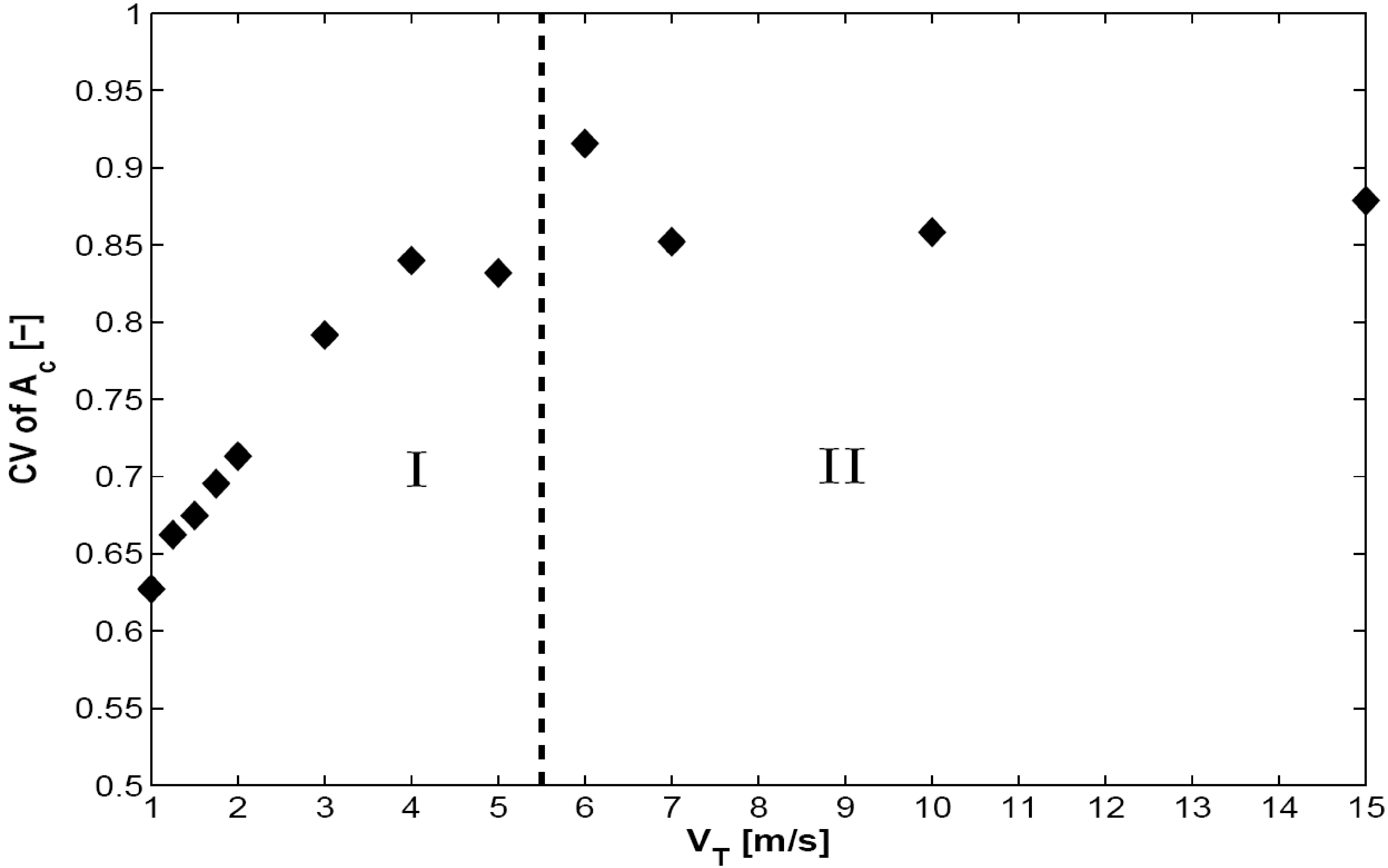
- Previous studies, based on limited observations, have suggested that the statistical scaling structure of rainfall can be parameterized in terms of thermodynamical descriptors of the storm environment and such dependence has been successfully implemented in downscaling applications (Perica and Foufoula-Georgiu, 1996);

Dependence of some basis statistics of convective rainfall cells (mean cell area and CV of cell area) on the raindrop terminal velocity VT



Mean cell area versus the raindrop terminal velocity V_T on log-log axes (threshold 2 mm/h).

Parodi, Foufoula-Georgiou and Emanuel
(2010, JGR-Atmospheres, under review)

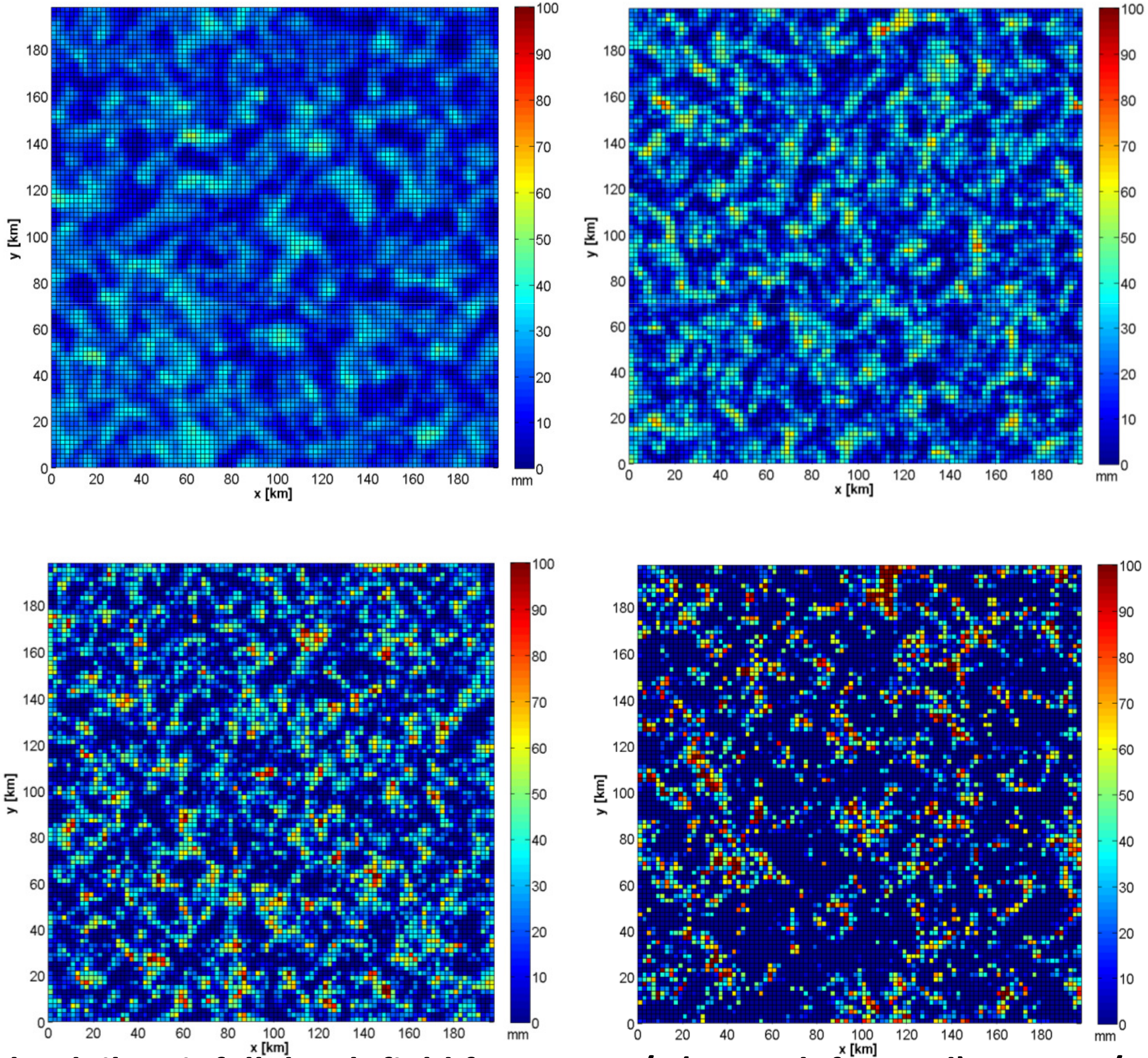


The log-log linear scaling of the first and second moment (not shown here) of the cell area with V_T and the CV dependence on V_T, for V_T up to 5-6 m/sec but not for larger values, **suggest that the dependence of cell statistics on V_T is simple scaling for large velocities and multi-scaling for small velocities**: for small V_T the standard deviation of the cell areas grows slower than the mean cell area for V_T <5 m/s while it grows at the same rate for larger V_T.

Raindrop terminal velocity and the daily rainfall depth pattern

V_T= 1 m/s

V_T= 2 m/s

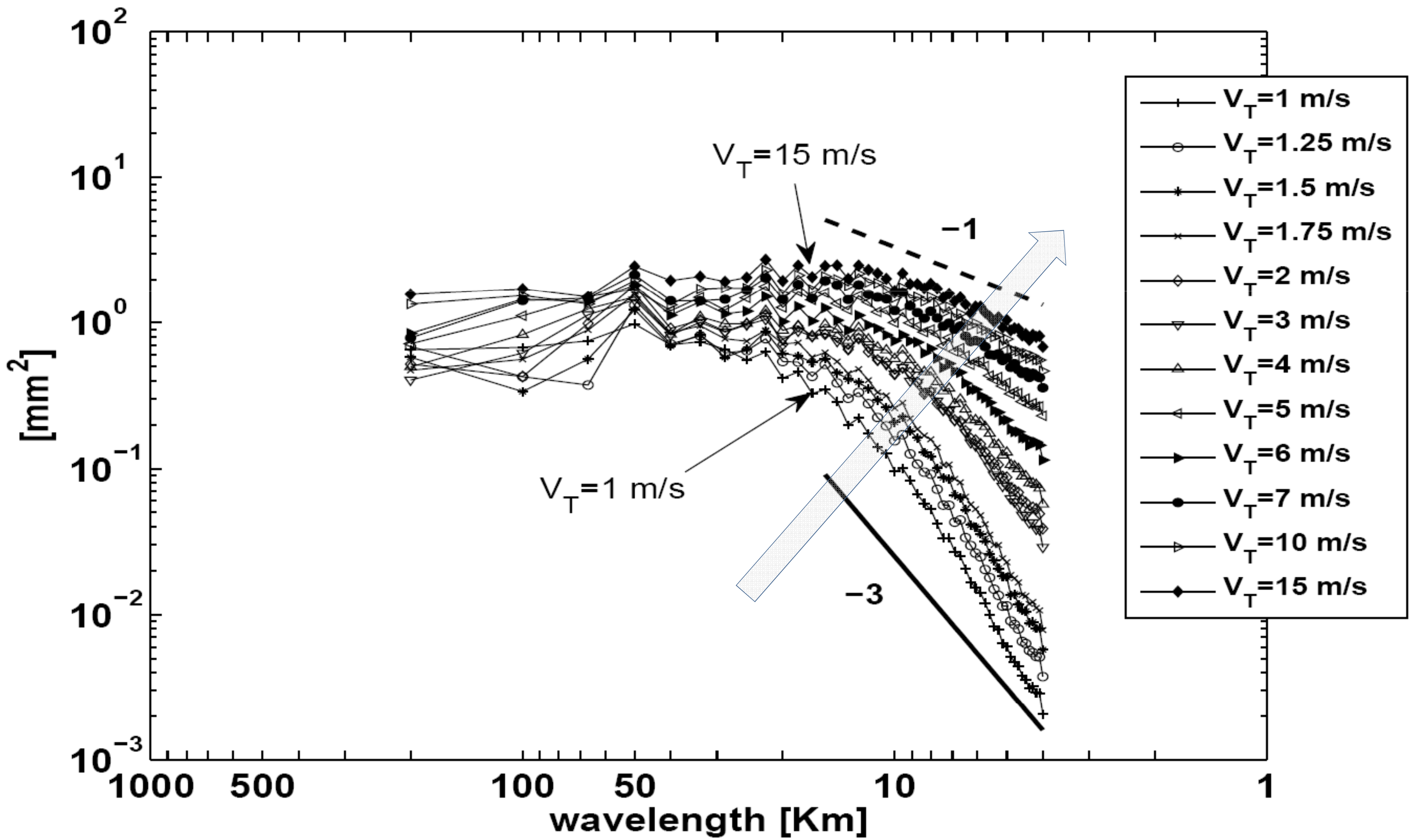


V_T= 5 m/s

V_T= 15 m/s

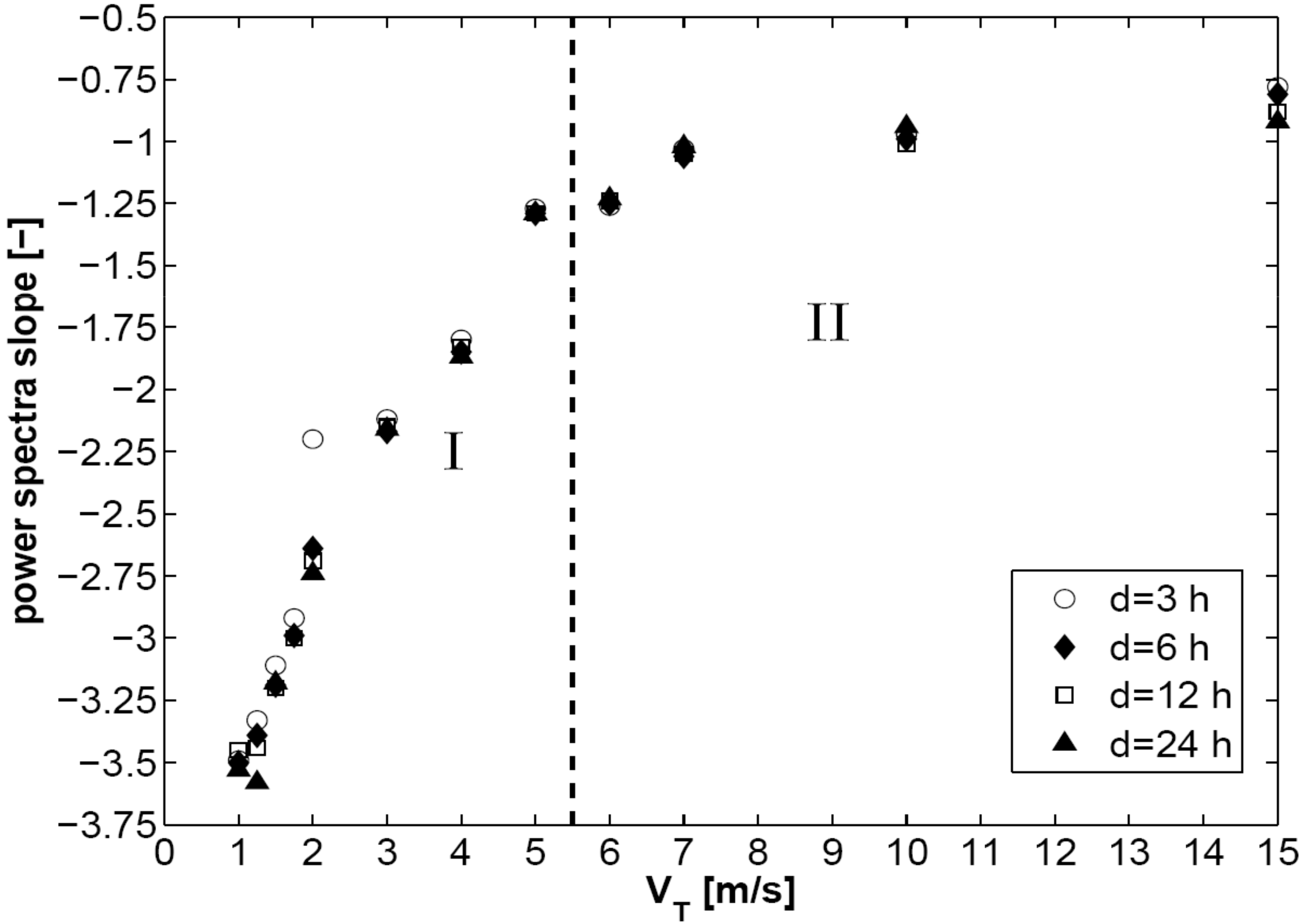
Generic frames of the daily rainfall depth field for V_T=1 m/s (upper left panel), V_T=2 m/s (upper right panel), V_T=5 m/s (lower left panel) and V_T=20 m/s (lower right panel). The cooling rate value is Q_{rad}=-4 K/day.

Power spectral analysis: three-hourly rainfall depth fields



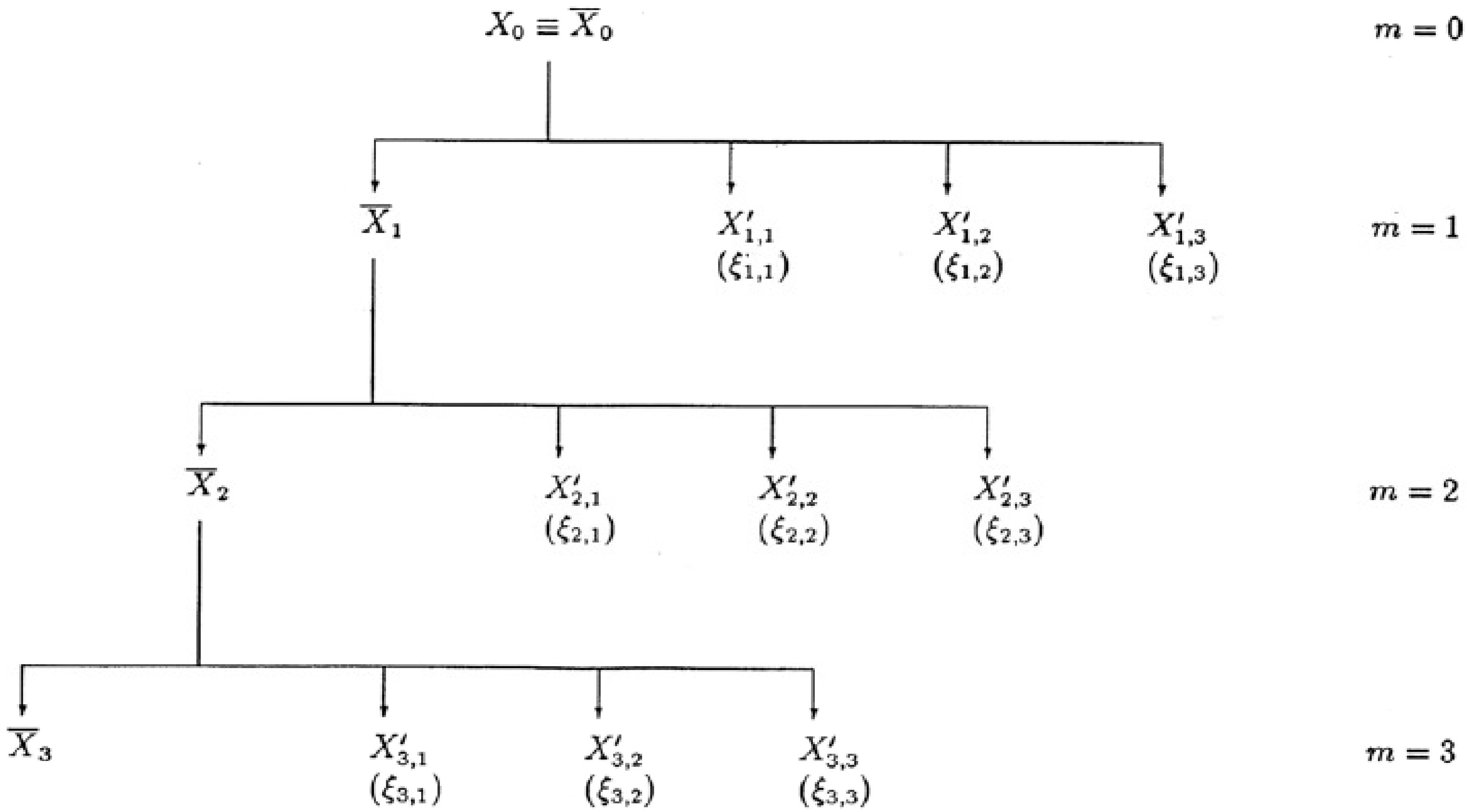
Power spectral analysis of the 3 hours rainfall depth field for V_T values in the range 1-15 m/s and Q_{rad}=-4 K/day. The spectral slope is higher for lower raindrop terminal velocity, meaning that the variability of the cells at those low velocities spreads over a smaller range of scales: the 3h rainfall depth field passes from anti-correlated for larger terminal velocities to more spatially correlated for lower velocities

Power spectral analysis: spectral slope



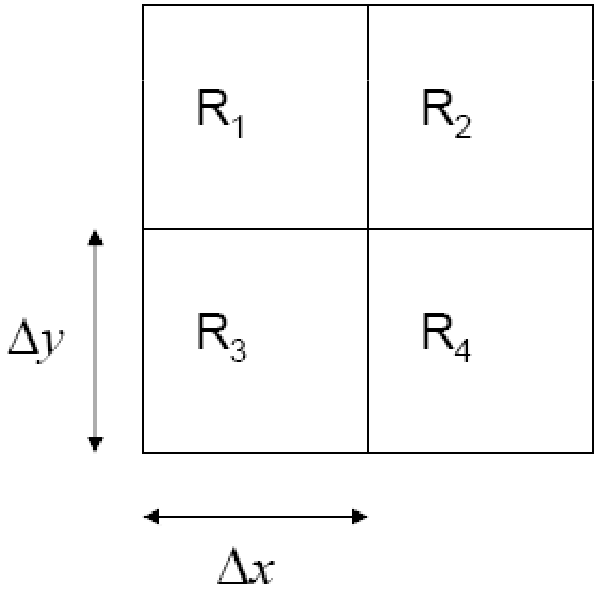
The comparison of the spectral slopes corresponding to duration d=3, 6, 12 and 24 h, suggests that all rainfall depth fields exhibit the same power spectral slopes and evolve from anti-correlated for larger terminal velocities to more spatially correlated for lower velocities. Furthermore doubling V_T reduces the spectral slope by a factor of 1.4-1.5 with the pertinent implications for scaling analysis

Multiscale analysis – 2D example



Perica and Foufoula-Georgiou, 1996

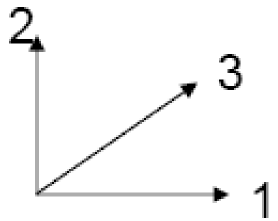
Interpretation of directional fluctuations (gradients)



$$X_1^{'} = \frac{1}{2}\left[\left(\frac{R_2 - R_1}{\Delta x}\right) + \left(\frac{R_4 - R_3}{\Delta x}\right)\right] \cong \frac{\partial R}{\partial x}$$

$$X_2^{'} = \frac{1}{2}\left[\left(\frac{R_4 - R_2}{\Delta y}\right) + \left(\frac{R_3 - R_1}{\Delta y}\right)\right] \cong \frac{\partial R}{\partial y}$$

$$X_3^{'} = \frac{1}{2}\left[\left(\frac{R_1 - R_4}{\Delta l}\right) + \left(\frac{R_2 - R_3}{\Delta l}\right)\right] \cong \frac{\partial^2 R}{\partial x \partial y}$$



$$\Delta l = \sqrt{\Delta x^2 + \Delta y^2}$$

R rainfall intensity field

(See Kumar and Foufoula-Georgiou, 1993)

(See Perica and Foufoula-Georgiou, 1996)

- ✓ Local rainfall gradients ($X'_{m,i=1,2,3}$) depend on local average rainfall intensities $\overline{X}_m$ and were hard to parameterize

- ✓ But, standardized fluctuations $\xi_{m,i=1,2,3} = \dfrac{X'_{m,i=1,2,3}}{\overline{X}_m}$

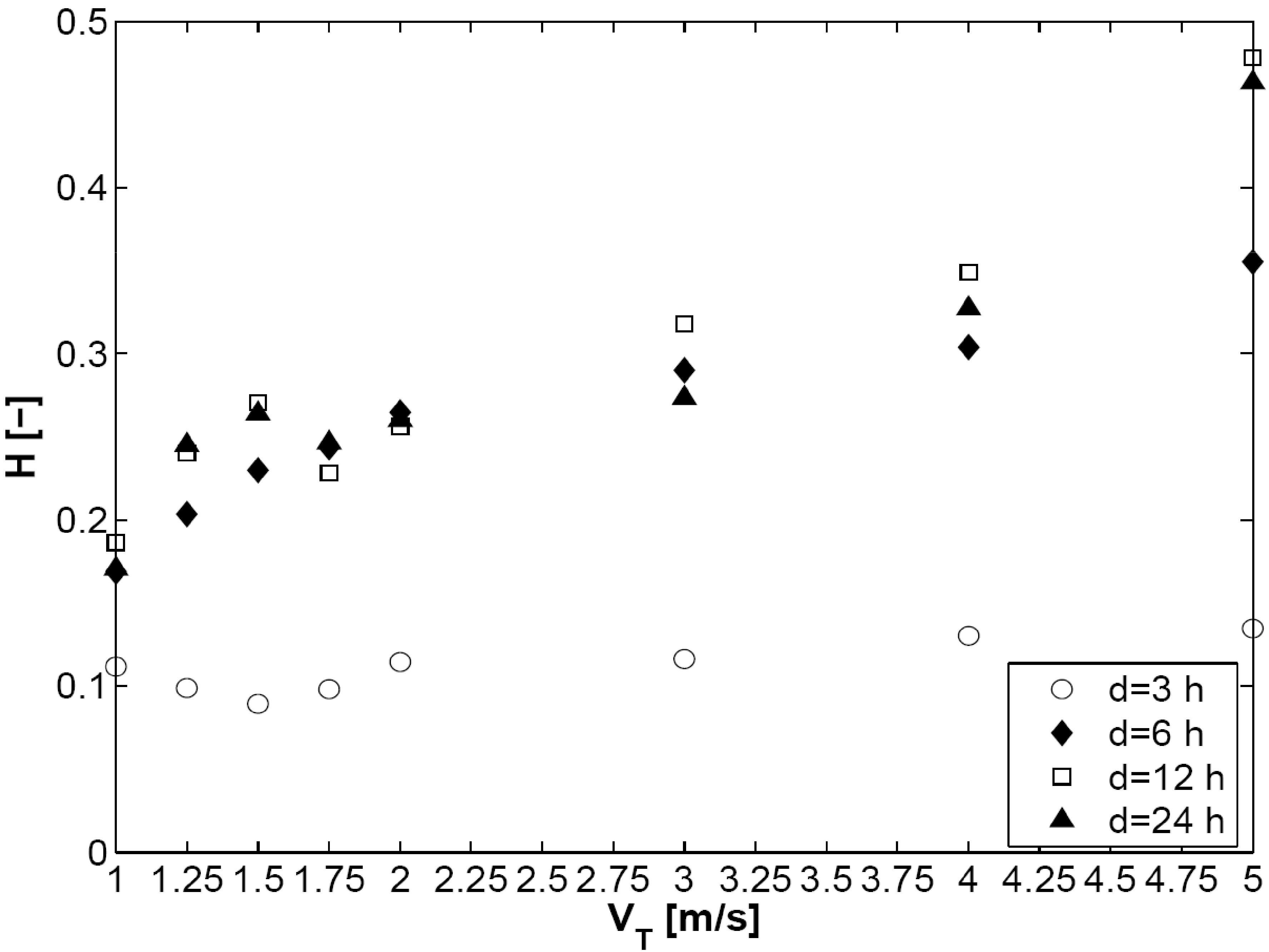
  - ➢ are approximately independent of local averages
  - ➢ obey approximately a Normal distribution centered around zero, i.e, have only 1 parameter to worry about in each direction

$$\text{At scale m:} \quad \sigma_{\xi_1}, \ \sigma_{\xi_2}, \ \sigma_{\xi_3}$$

$$\{X'_{m,i}\} \stackrel{d}{=} \{(2^{m-1})^{H_i} X'_{1,i}\} \qquad\qquad i = 1, 2, 3$$

where H_i are the scaling exponents and $\stackrel{d}{=}$ stands for equality in distribution.

Downscaling analysis



Conclusion

These findings provide a quite comprehensive picture about the role of raindrop terminal velocity in determining some important statistics of rainfall depth and convective flow field.

Potential evolution of the work for more realistic severe rainfall scenarios: this will require a classification of rainfall events and a quantification of their degree of predictability + microphysics features

Stay tuned on Cisneros talk!

Predictability and predictive ability for severe hydrometeorological events in the Mediterranean area