Statistical evaluation of NEMO OGCM outputs based on multi-order statistics

and some other works related to scales
(downscaling and unresolved scales parameterization...)

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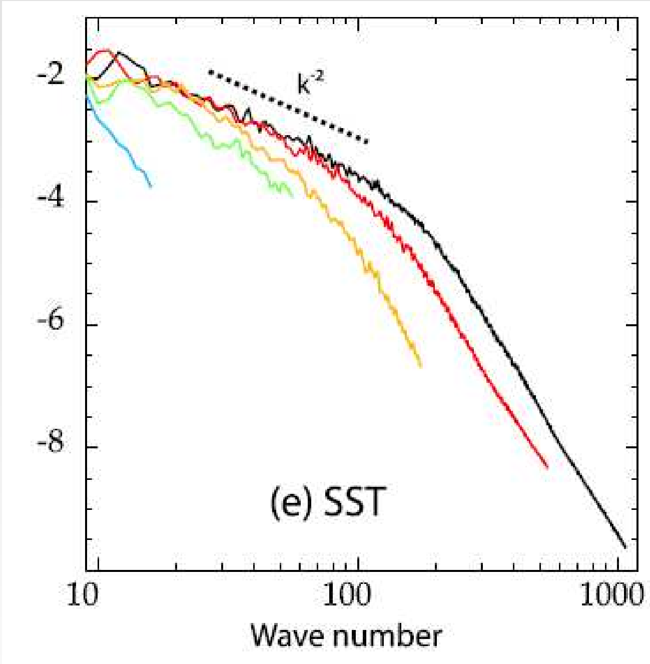
Post-doctoral work with M. Crépon, S. Thiria, J. Brajard (LOCEAN/UPMC) & M. Berrada (ENSAM Meknès)

Topics

- I) Multi-scale, multi-order statistical evaluation of NEMO OGCM
  - Idealized configurations
- II) From multi-order statistics to multifractal downscaling
  - Method based on properties identified in I)
  - Applicability : more general than OGCMs
- III) Controlling unknown diffusion parameters in NEMO
  - A variational approach

I) Statistical evaluation

- Geophysical flows are turbulent
- Scales related by remarkable symmetries
  - Energy/power spectra are scaling
- OGCM outputs should follow scaling statistics
  - Multi-scale evaluation tool
- Spectral tools are restrictive
  - Mono-order (quadratic)
  - Not the whole cdf



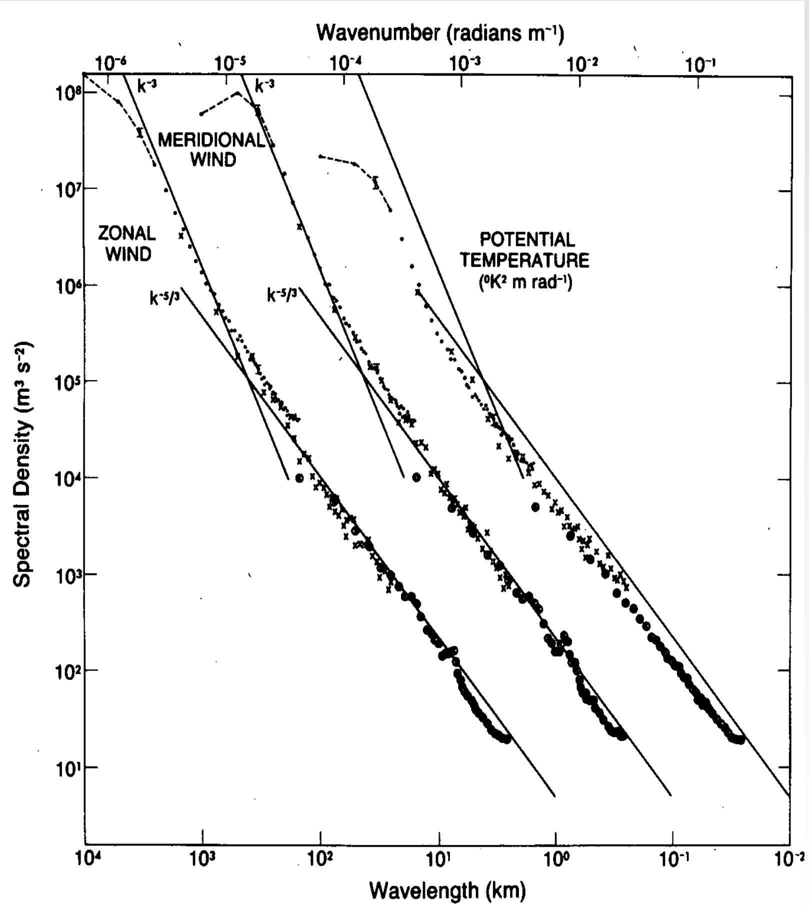
Example: NEMO-GYRE 1/54° spectrum (Lévy et al., 2012)

Suggestion: use multi-order statistics across different scales to generalize spectral analysis

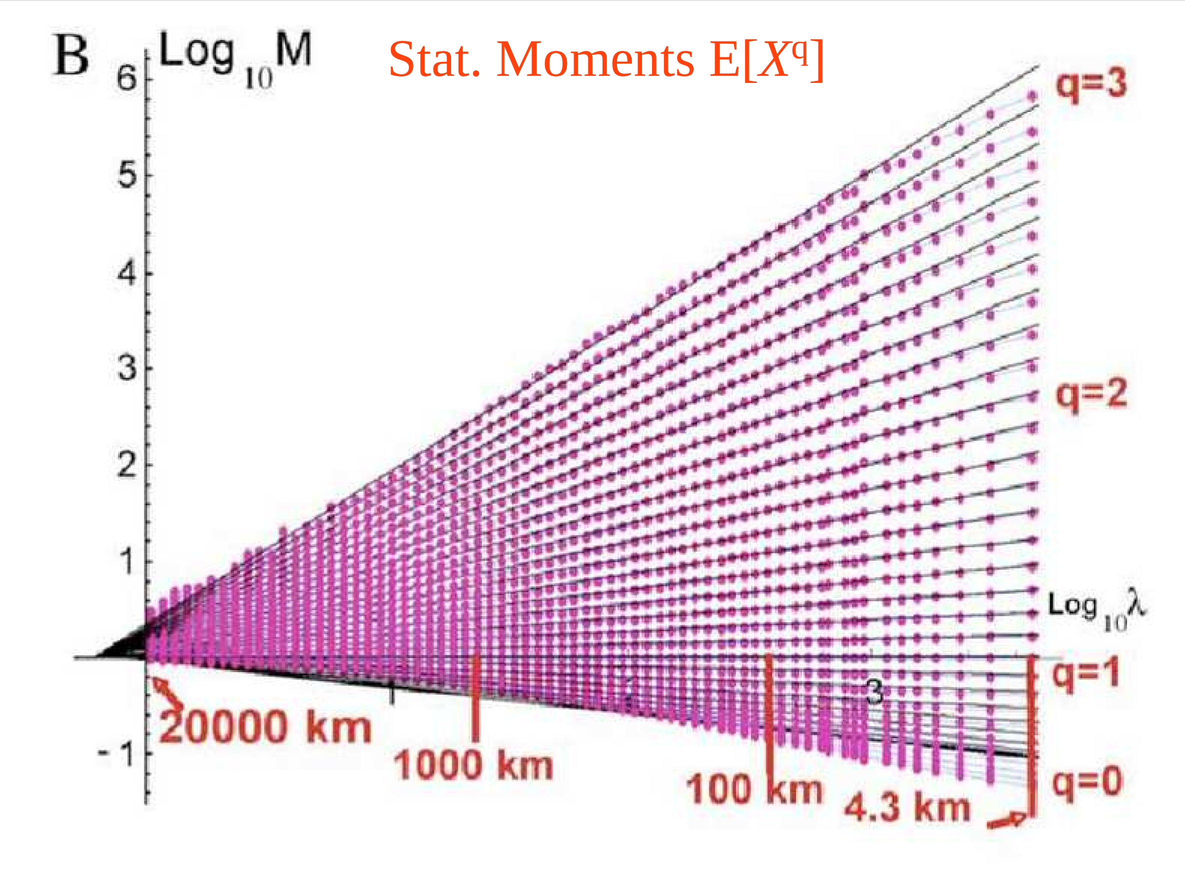
From mono- to multi-order scaling : atmospheric data

Spectra

« Multifractals » (Schertzer & Lovejoy, 1987)



Spectra GASP (Gage & Nastrom, 1985; Lilly, 1989)



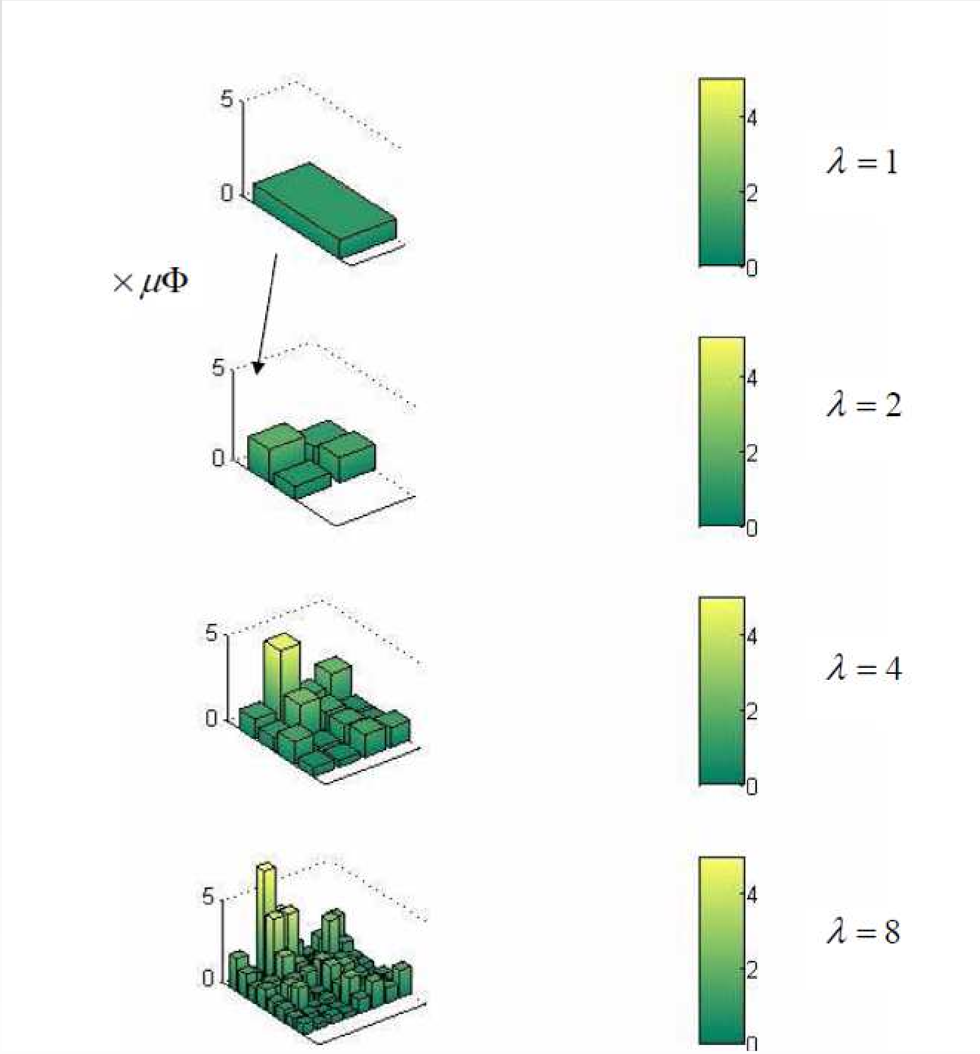
Stat. Moments of TRMM-PR reflectivities (Lovejoy et al., 2008)

Multiplicative cascades

- Multifractal fields are built by a stochastic iterative apparoach

--> cascade Φ

- Possibly add a (scaling) low-pass filter
  - State variable is related to the positive quantity Φ but is not Φ



Multiplicative cascade Φ: i.i.d. multiplicative increments

Statistical properties of multifractal fields

- Power-law energy spectrum

$$E(k) \approx k^{-\beta}$$

β = 1-*K*(2) (< 1)

- Statistical moments of order *q* vary as a power-law of resolution λ:

$$\langle \Phi_\lambda^q \rangle \approx \lambda^{K(q)}$$

q = statistics order (> 0, not necessarily integer)

K(*q*) = moment scaling function

- Filtered version : Additional fractional integration (multiply by k^{-H} in Fourier space)
  - Pente spectrale β = 1-*K*(2)+2*H*

MU/FIF parameterization

- Universal multifractals (Schertzer & Lovejoy, 1987)
  - Moment scaling function described by two parameters:

$$K(q) = \frac{C_1}{\alpha - 1}\left(q^{\alpha} - q\right)$$

α = multifractality parameter $0 < \alpha < 2$

C_1 = inhomogeneity parameter (for « mean » intensities) $0 < C_1 < D$

- FIF (Fractionnally Integrated Flux)

Φ is fractionnally integrated (at order H), providing the FIF field X:

  - Increments follow a scaling law:

$$\Delta X_{\lambda} = \Phi_{\lambda} \lambda^{-H}$$

(in distribution)

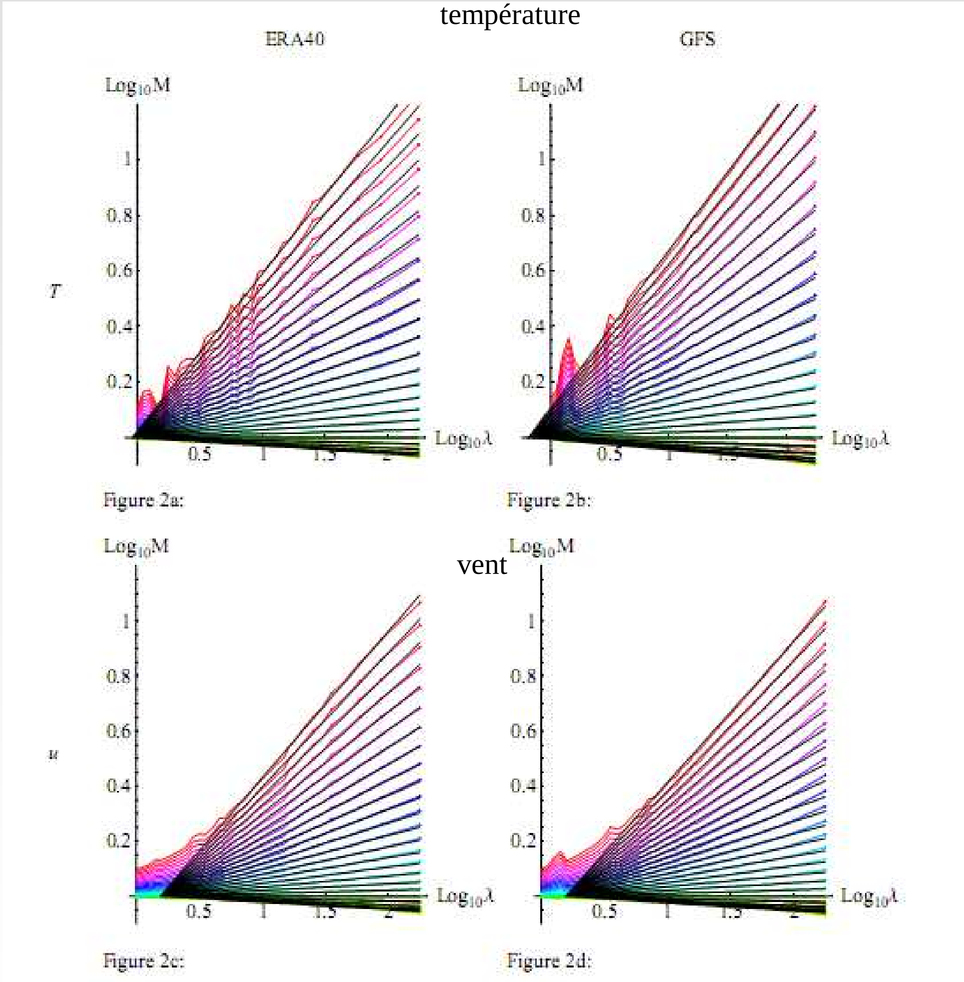
  - Analogous to Kolmogorov scaling law:

$$\Delta v_{\lambda} = \varepsilon_{\lambda}^{1/3} \Delta x^{-1/3}$$

Φ analoguous to energy/variance dissipation

Multifractals and AGCM?

- Stolle et al. (2009) and Lovejoy et al. (2011):
  - ERA-40 and forecast AGCM
- Multifractal laws were found from planetary scales to ~ 1°
- Needs to be done for OGCM outputs …



Multifractals and ocean?

What appears from satellite data (de Montera, Verrier, et al., 2011)

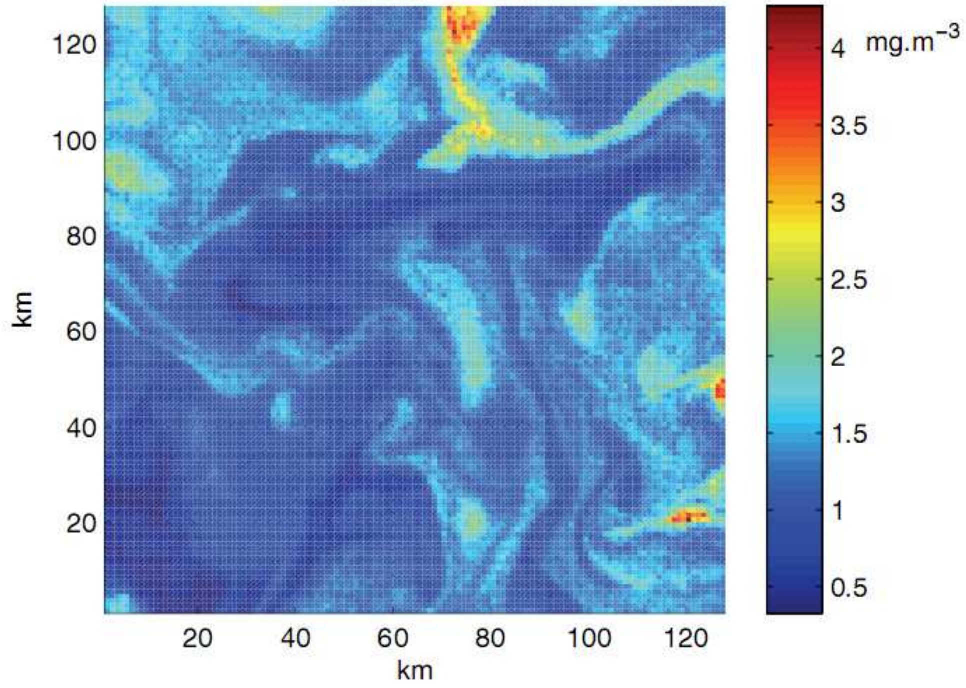


Fig. 2. Example of a 128 km^2 horizontal chlorophyll map (resolution 1 km^2) extracted from the SeaWiFS local L2 product.

Multifractals and ocean?

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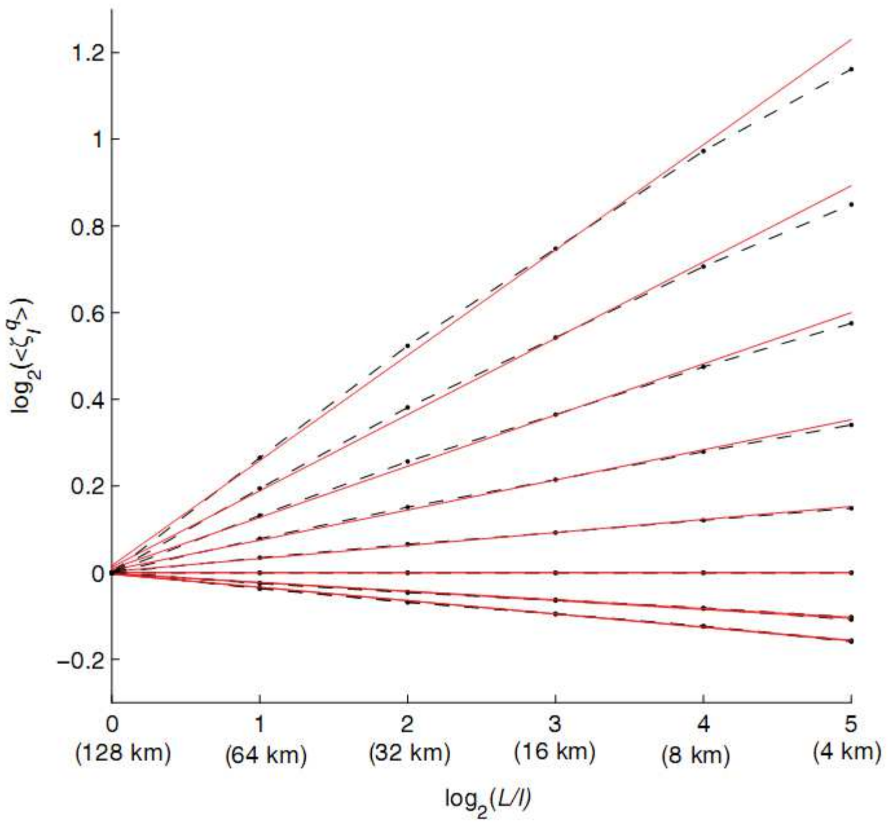


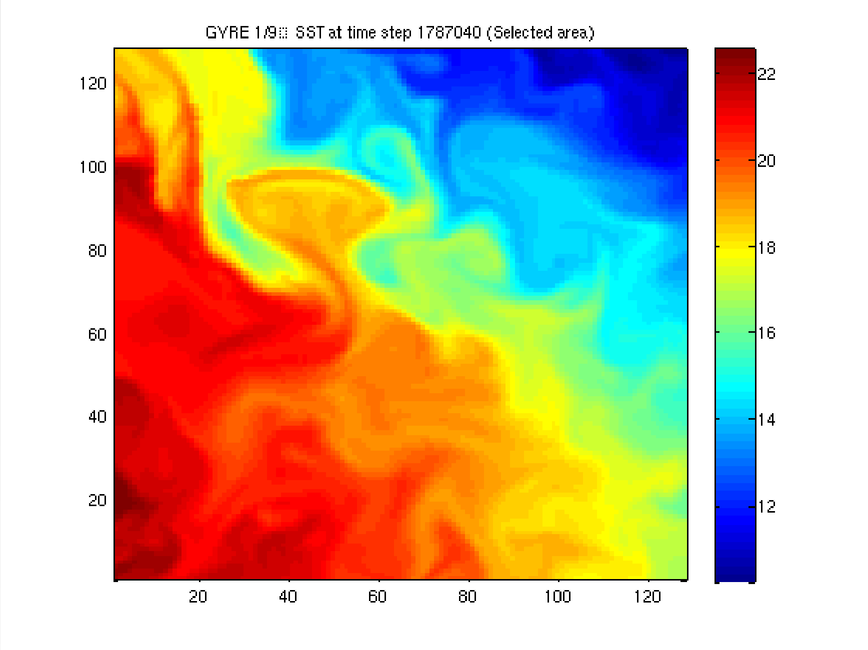
Fig. 5. Scaling of the statistical moments of the flux ζ for the orders q=0, 0.1, 0.2, ..., 2, with corresponding theoretical fits. Here, L corresponds to the largest scale of the SeaWiFS chlorophyll maps, i.e. 128 km. For each map, the flux was normalized to a mean value of 1.

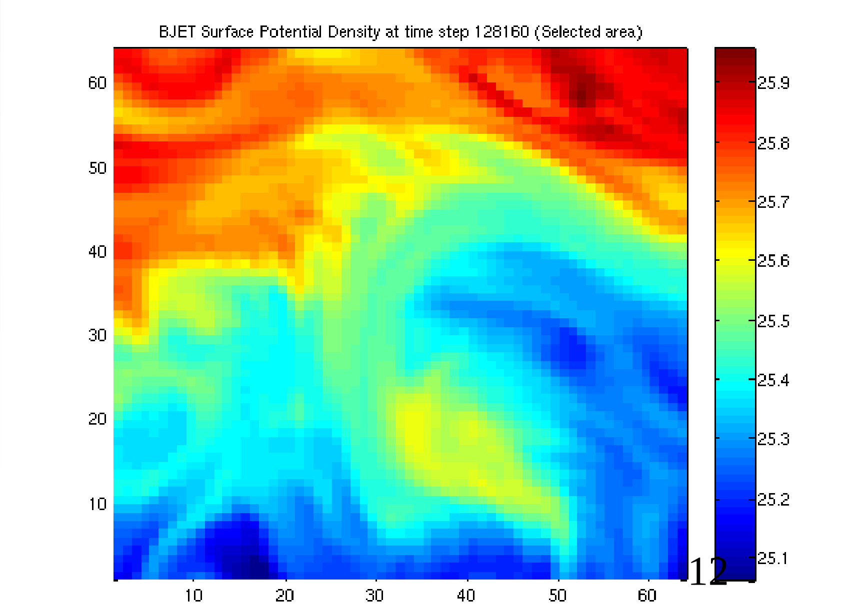
I) NEMO multi-order evaluation

- 1) Idealized simulations of NEMO
- 2) Determination of filtering exponent H , deconvolution provides Φ
- 3) Study of Φ moments for several positive orders, providing an estimate of α et C1

NEMO simulation

- GYRE 1/9°
  - Spinup 50Y + study window 1Y
  - Surface data are considered
- BJET 5km
  - Zonal jet + baroclinic perturbation
  - Zonally periodic domain (~EEL)
  - Spinup 1Y + study 1Y





Estimation of filtering parameter H

- Scaling of 1st order Kolmogorov structure functions :

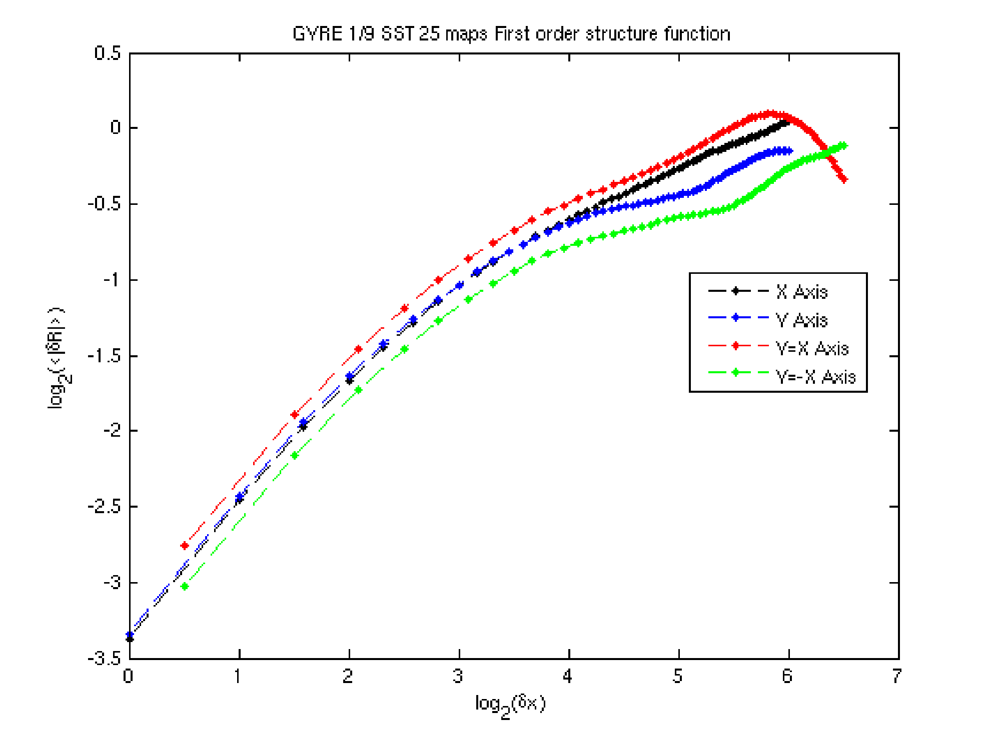
$$<|SST(x+\delta x) - SST(x)|> = <\Phi> \delta x^H$$

$$\beta \sim 1 + 2H$$

- Piecewise scaling :
  - H ~ 0.4 for δx > 10 x gridstep
  - H ~ 0.75 for δx < 10 x gridstep

- Smoother variability at small scales, confirmed for other fields

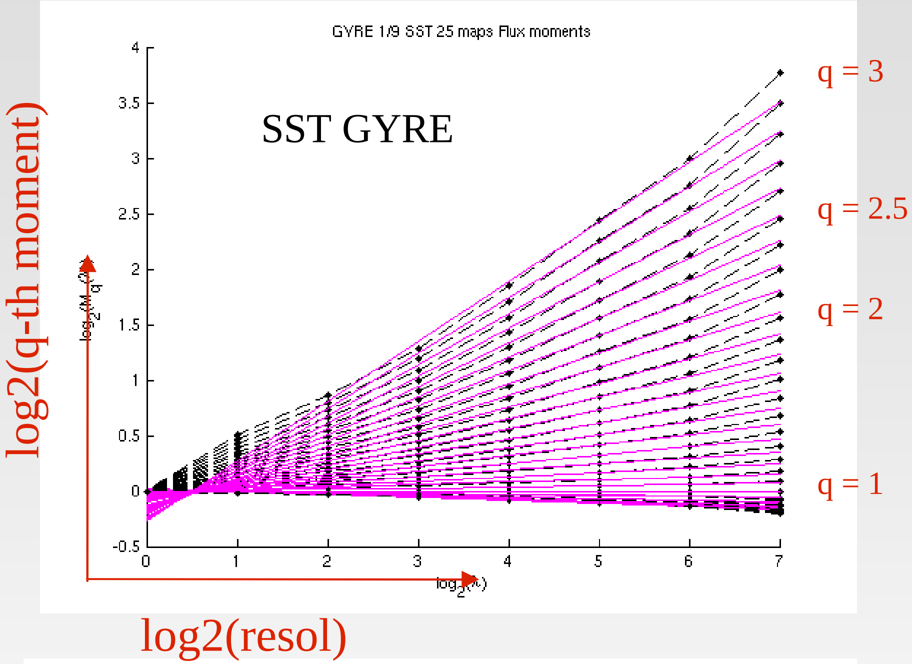
- Physical regime ? Effective resolution problem ?

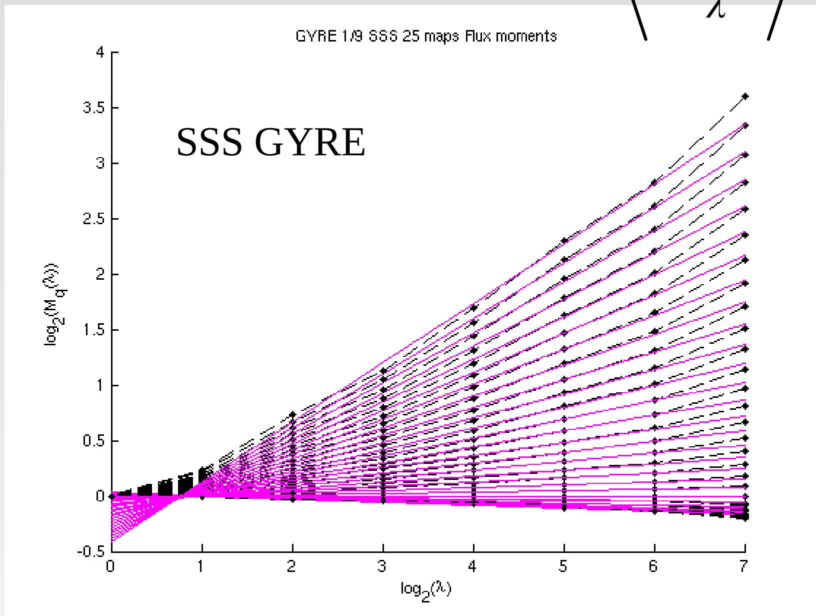


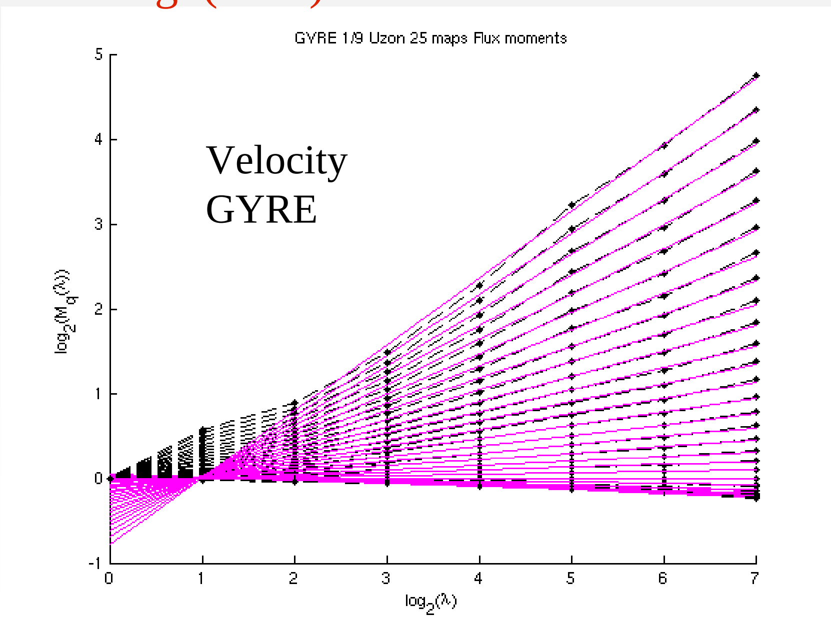
Absolute SST increments for the GYRE simulation, as a function of lag

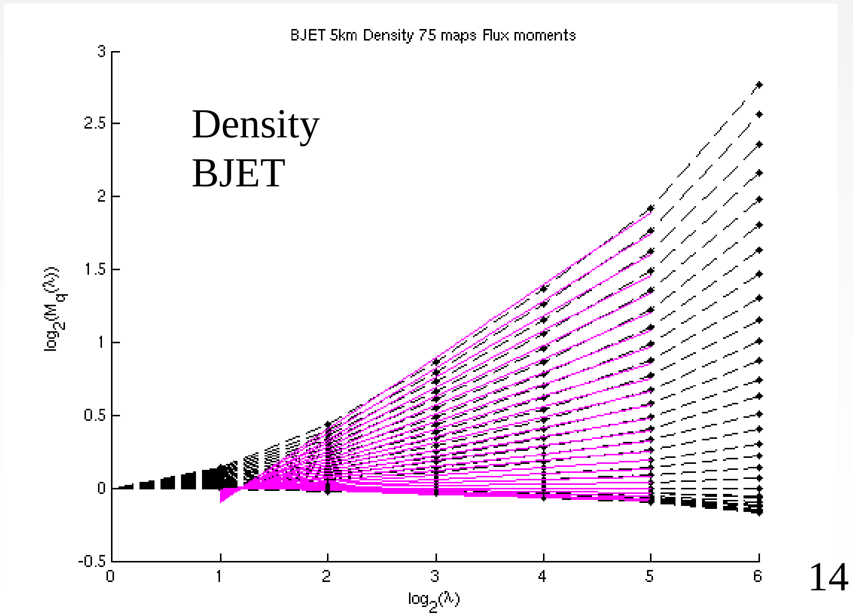
Moments of Φ (log-log)

$$\left\langle \Phi_{\lambda}{}^{q} \right\rangle \approx \lambda^{K(q)}$$









Scaling exponents K(q)

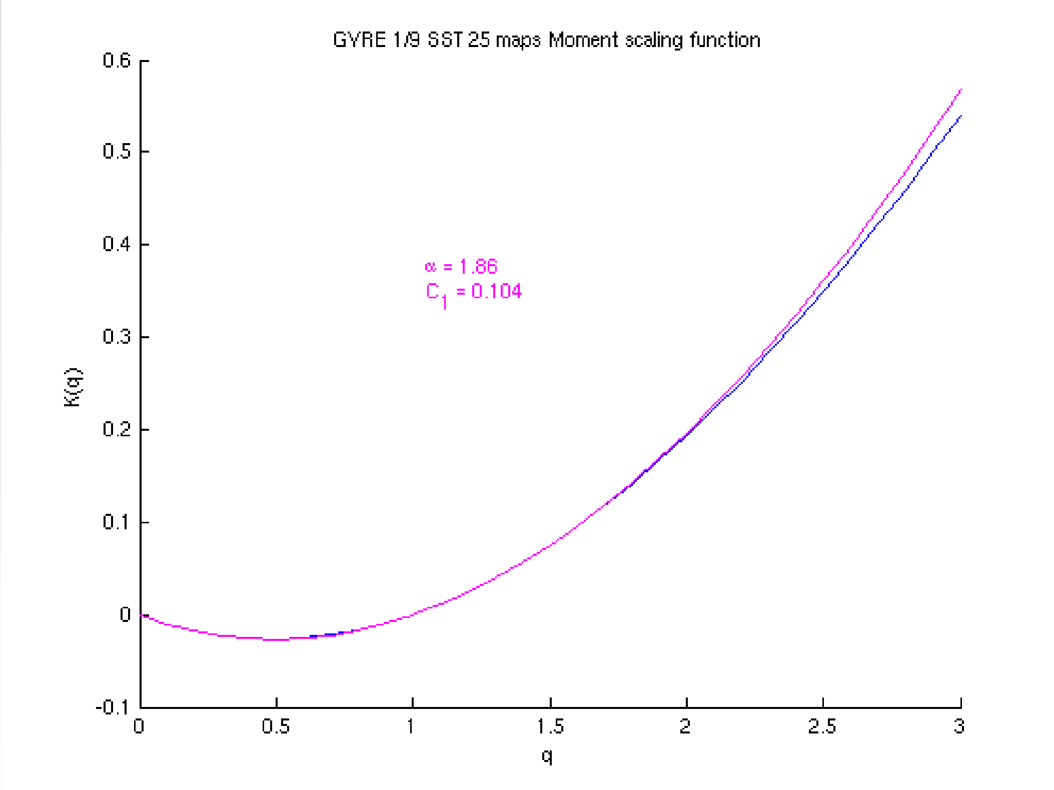
- Better scaling of Φ statistics, down to O(2) x the gridstep
- Scaling is better for GYRE than for BJET
- Scaling exponents $K(q)$ such that :

$$\left\langle \Phi_\lambda{}^q \right\rangle \approx \lambda^{K(q)}$$

- $K(q)$ accurately described by Schertzer-Lovejoy (universal) parameterization :

$$K(q) \sim C_1/(\alpha-1)\ (q^\alpha - q)$$

- Parameter values are coherent with oceanic empirical values



Values of $K(q)$ for NEMO simulation and best-fit universal parameterization in the range $0<q<2$

II) Downscaling

- Purpose : determining a description of unresolved variability that can convert low-resolution GCM outputs into higher-resolutions variables

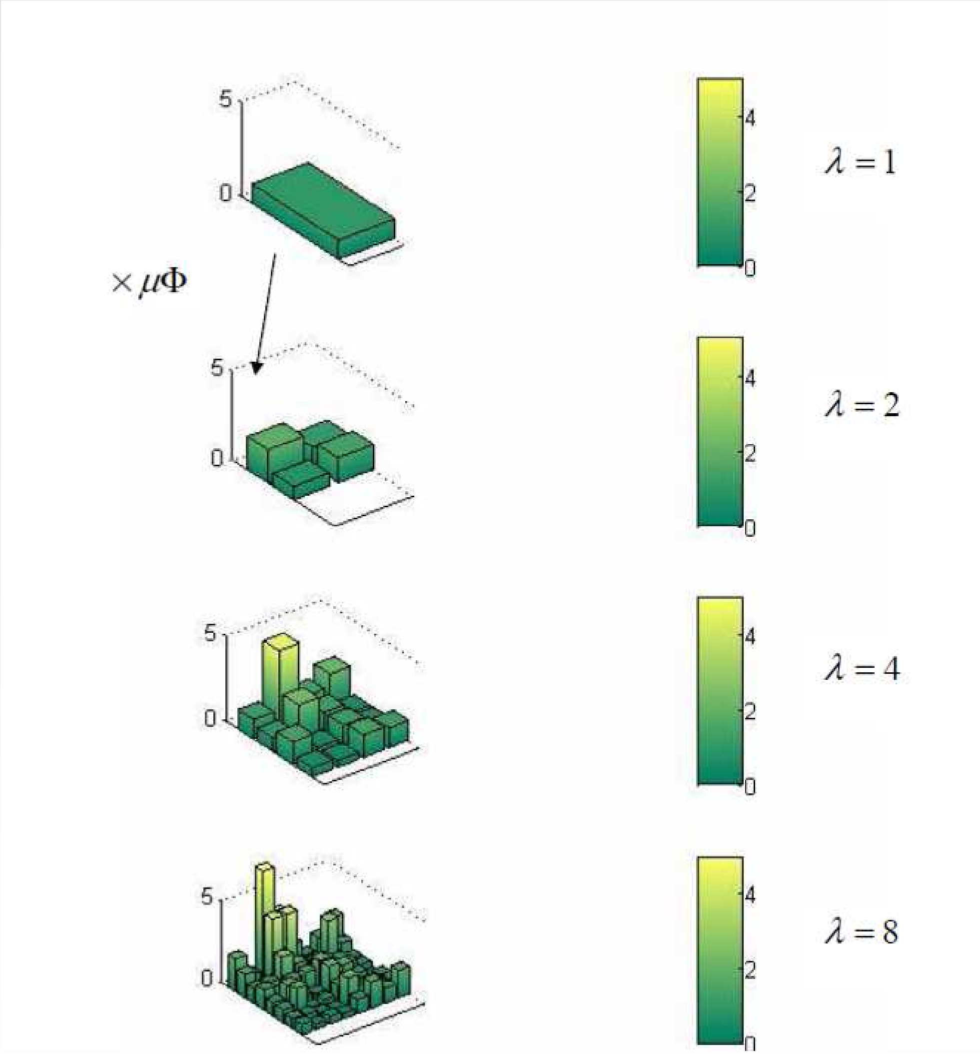
- Needed for important applications:
  - Impacts of climate change (e.g., impact models need high-resolution precipitation inputs)
  - Downscaling atmospheric forcings used in high-resolution oceanic models
  - Helps to improve comparison between model outputs and data (satellite, in-situ/pointwise...) with different resolution

Downscaling strategy

- Dynamical (regional GCM) vs statistical approaches
  - Dyn : correct location of extrema is expected, but computationnally demanding
  - Stat : correct probability distributions, error bars, higher gain in resolution ...
- Most existing statistical downscaling methods lack of physical justification
  - If correctly calibrated, it should work for converting a CDF from one specific scale to another
  - Representation of intermediate scales ? Fields structure ? Scaling symmetries?
- Emerging approach : use multifractal cascades to simulate subpixel variability
  - By construction, scaling symmetries are respected

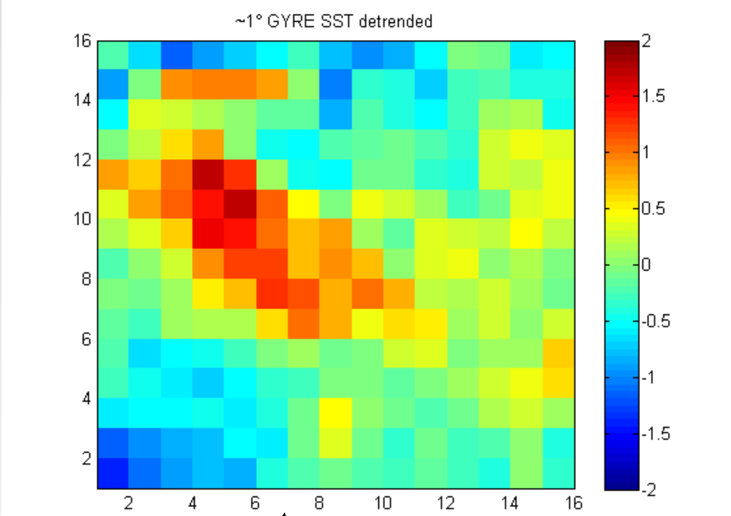
Multiplicative cascades (2)

- Direct multiplicative cascades : downscale the multifractal flux Φ
- When *H* > 0 : add a power-law filter
- Relatively inexpensive computationnally
- Well-suited for the simulation of an ensemble of high-resolution realizations

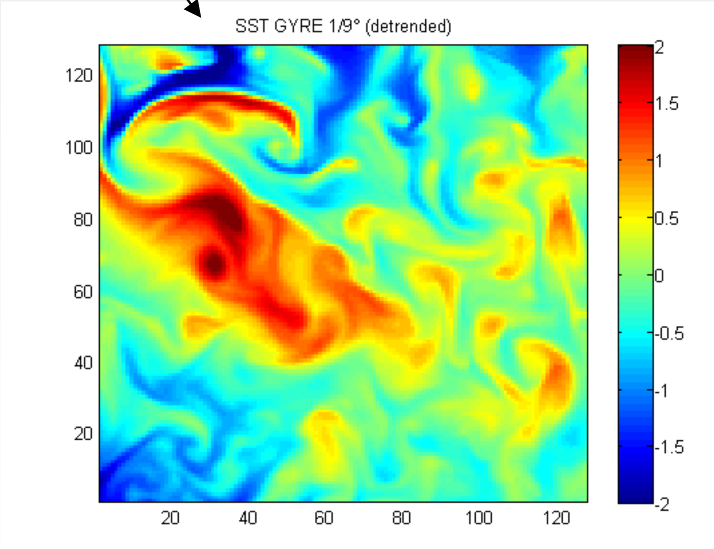


Multiplicative cascade Φ: i.i.d. multiplicative increments

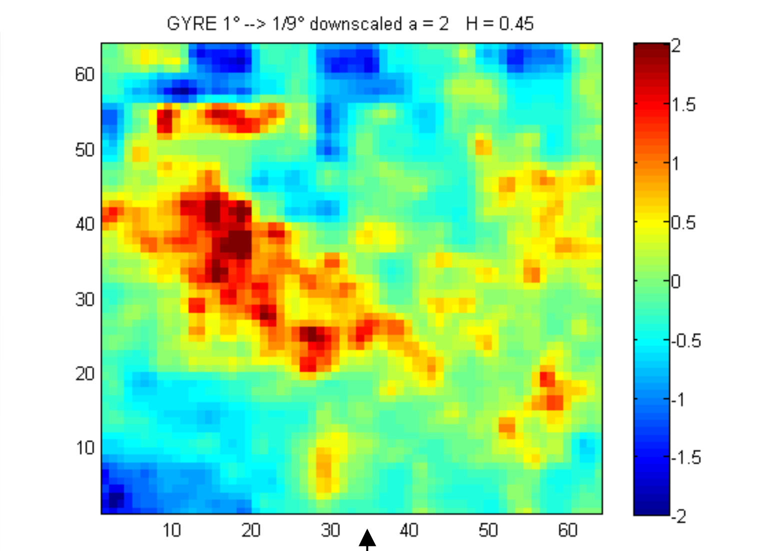
An oceanic example (in progress)



1) GYRE 1/9°
Detrended SST



2) Aggregated
detrended SST at 1°



3) Downscaled data at 1/9°

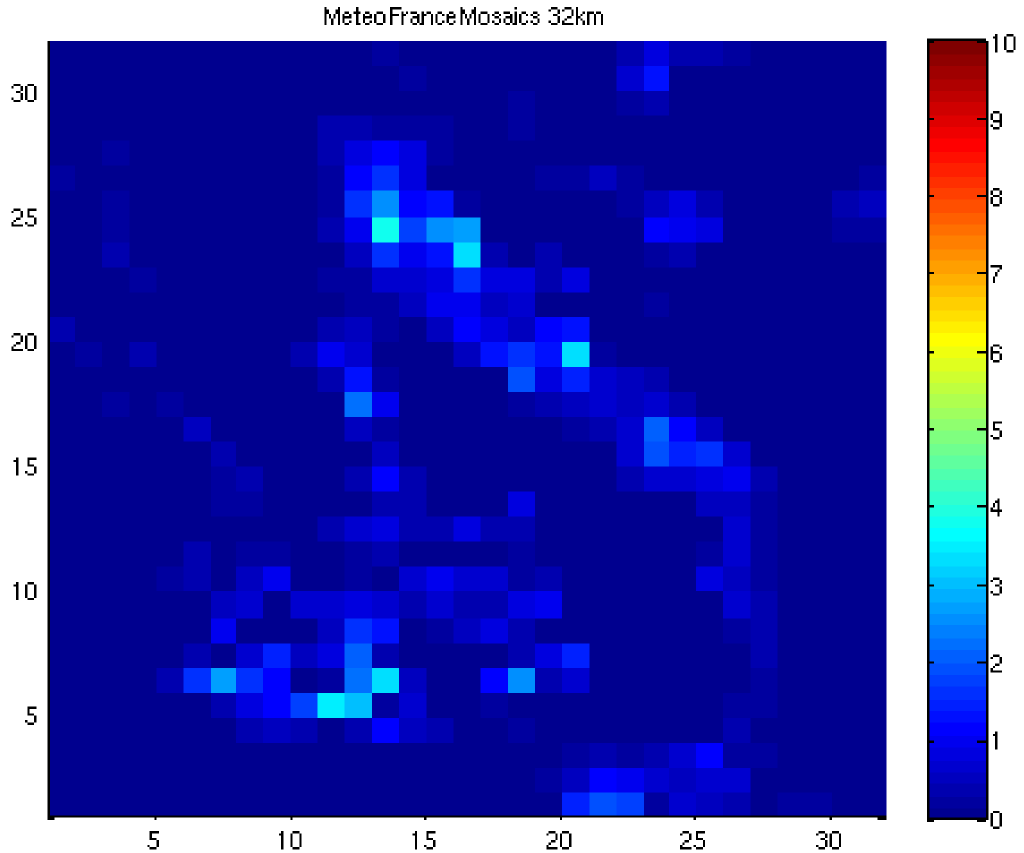
A more developed example on rainfall data

- Rainfall is piecewise multifractal with specific parameters
- Real data: Radar mosaics are considered (1000x1000 km at 1km resolution)
- Scaling ranges 32-8km et 8-1km

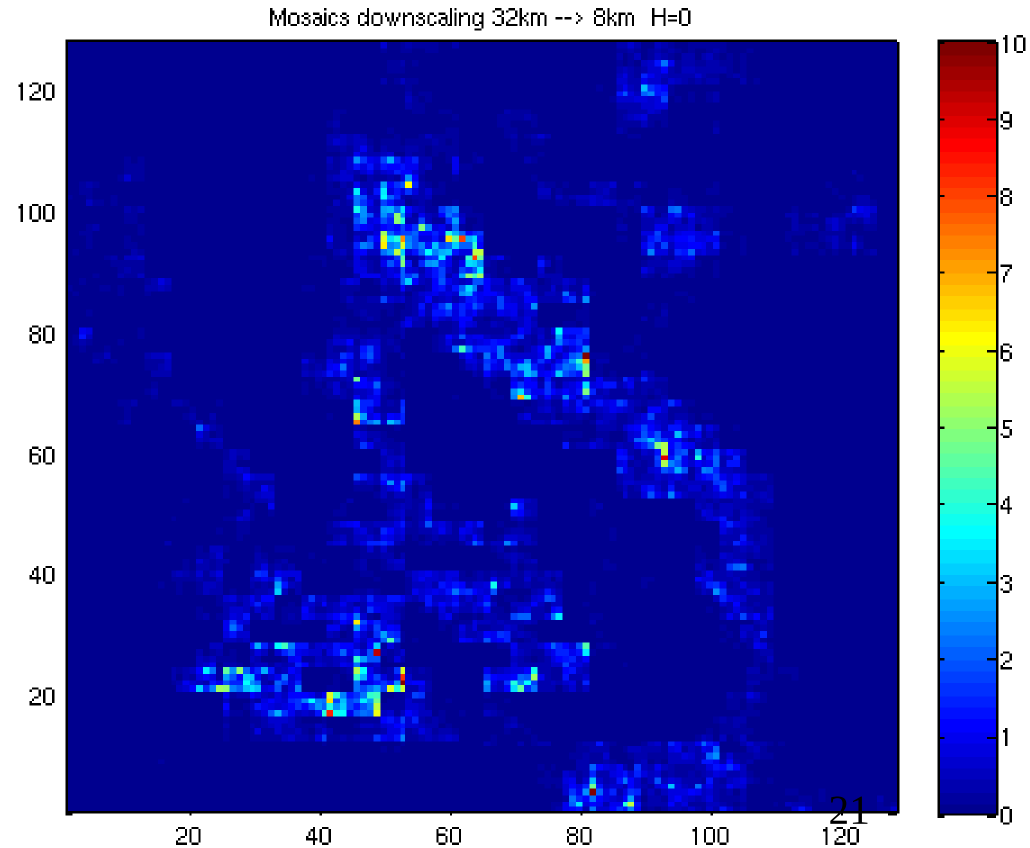
Inferring sub-pixel variability

- Possibility to simulate stochastic sub-pixel variability by extrapolating multifractal scaling laws…
- By construction, accurate retrievement of the CDF at multiple scales

Rainfall composite data aggregated at 32 km scale

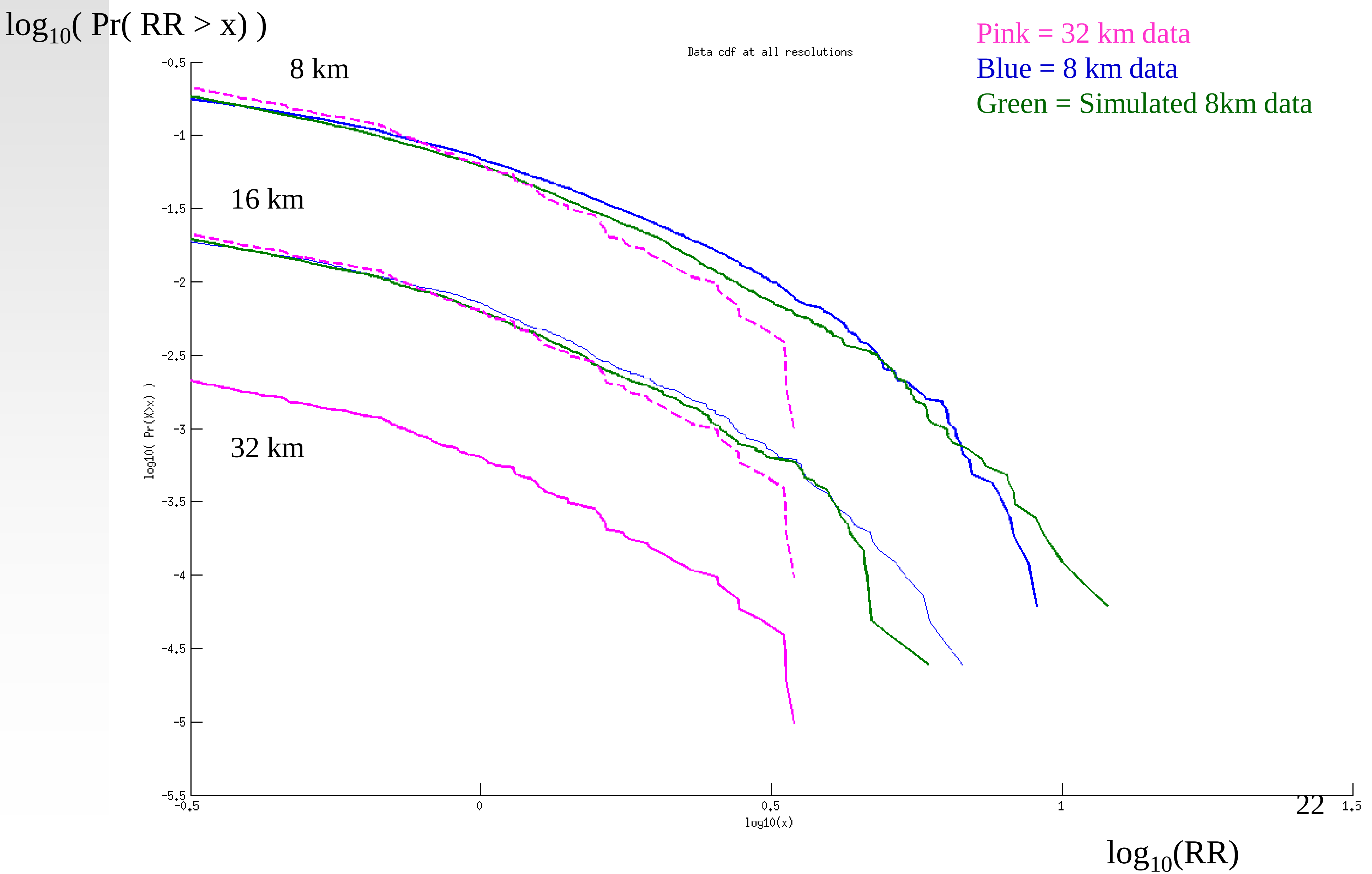


Rainfall composite data disaggregated at 8 km scale



MeteoFrance Mosaics rain rate (26/03/2008)

Multifractal downscaling 32-8 km (example on 1 map)



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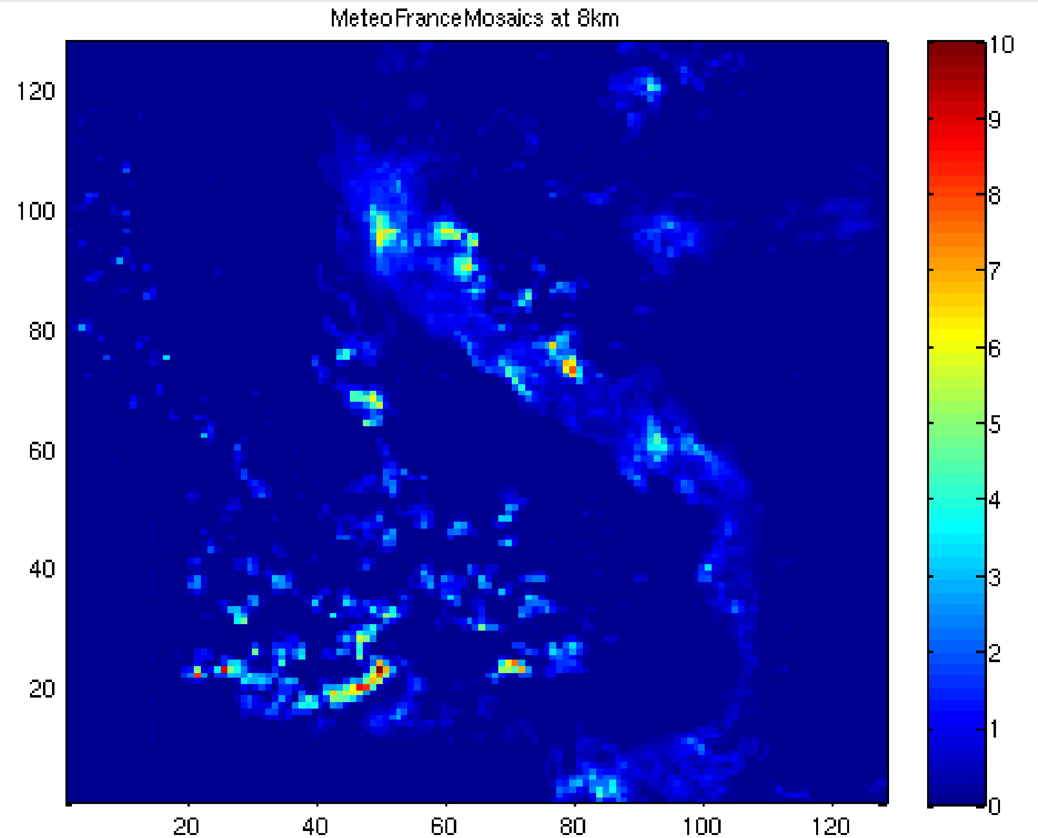
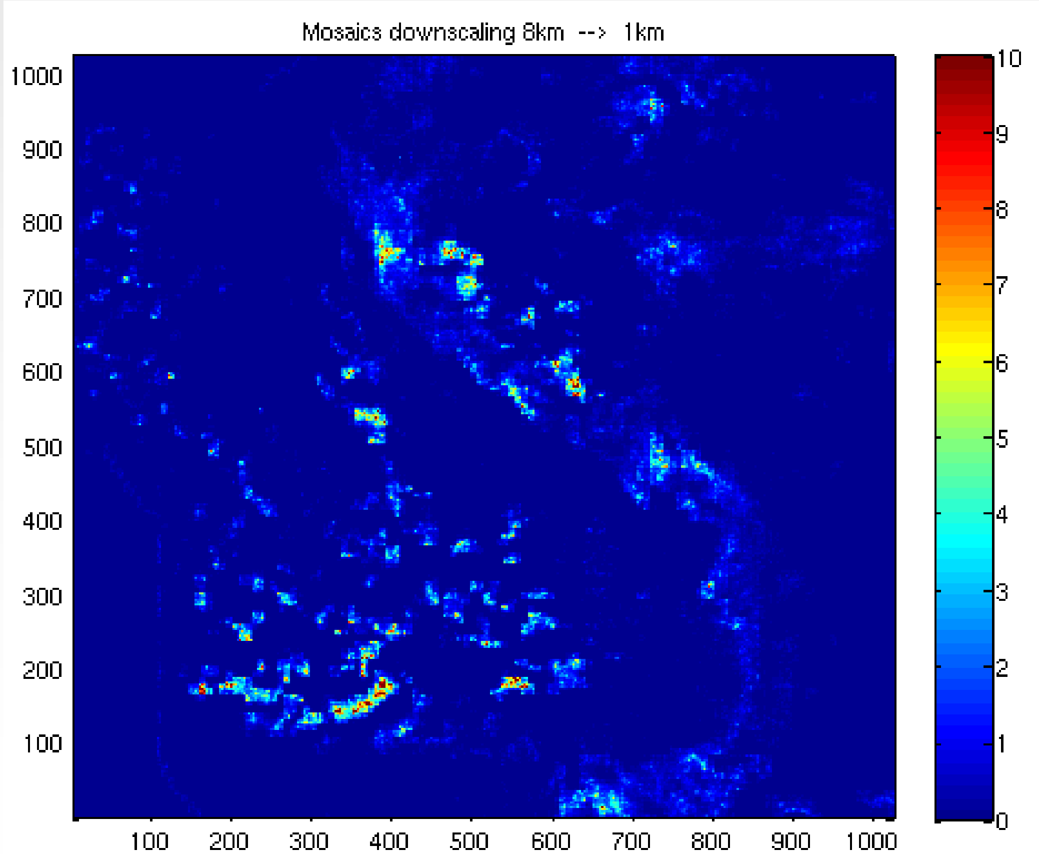
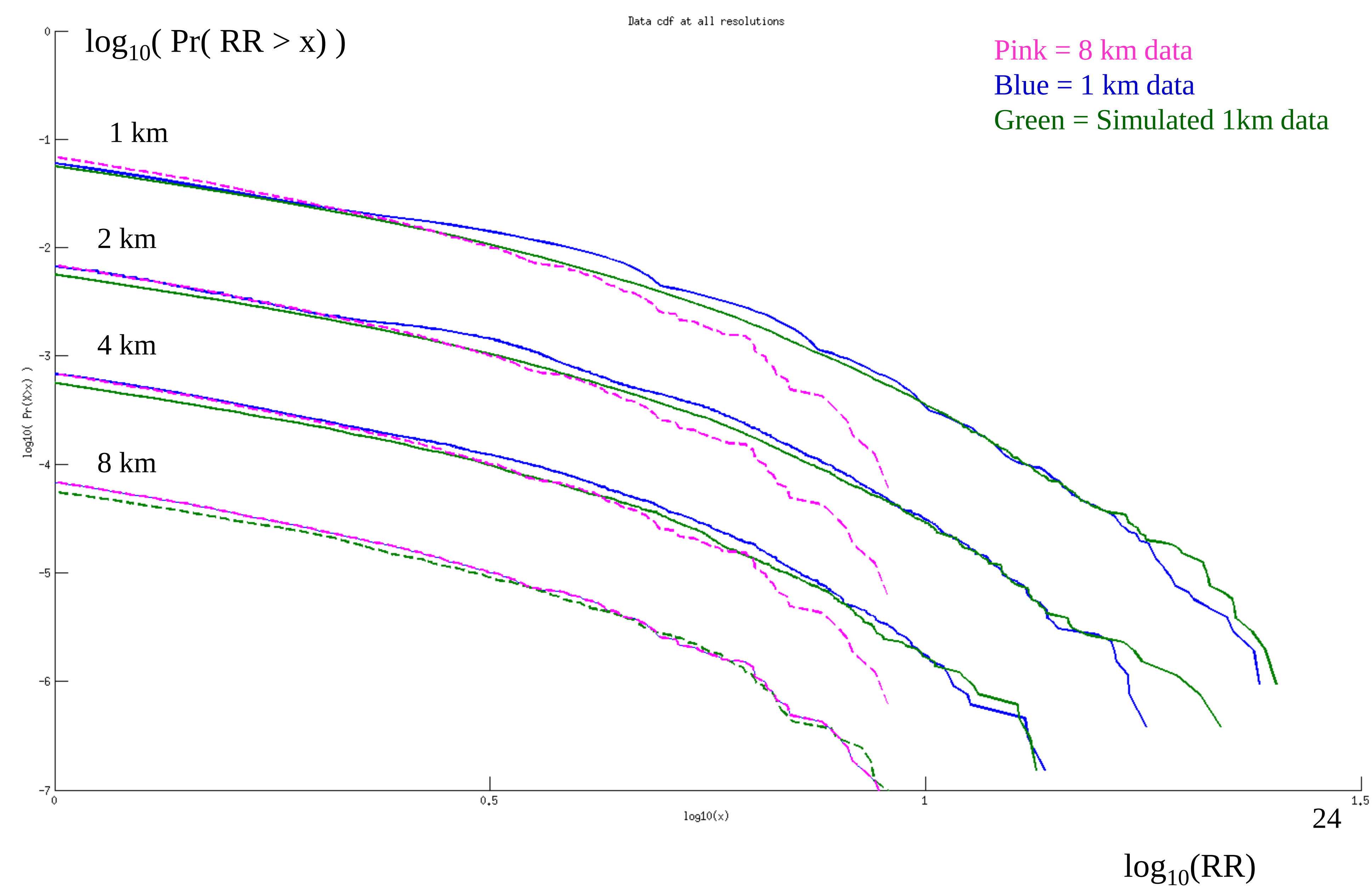


MeteoFrance Mosaics rain rate (26/03/2008)

Rainfall composite data disaggregated at 1 km scale



Multifractal downscaling 8-1 km (example on 1 map)



III) Variational control of diffusion parameters in NEMO

- Variational approach
- Twin experiments (obs = other simulation)
- Two trajectories with different resolutions
  - High resolution trajectory provides « observations”
  - Low resolution trajectory : viscosity and diffusivity are controlled as function of space point f(x,y,z)
- Purpose : study the link between eddy viscosity and local properties of the flow

YAO

- Software dedicated to variational data assimilation
- Modular description of a numerical model
- Automatic computation of the adjoint model from elementary jacobians

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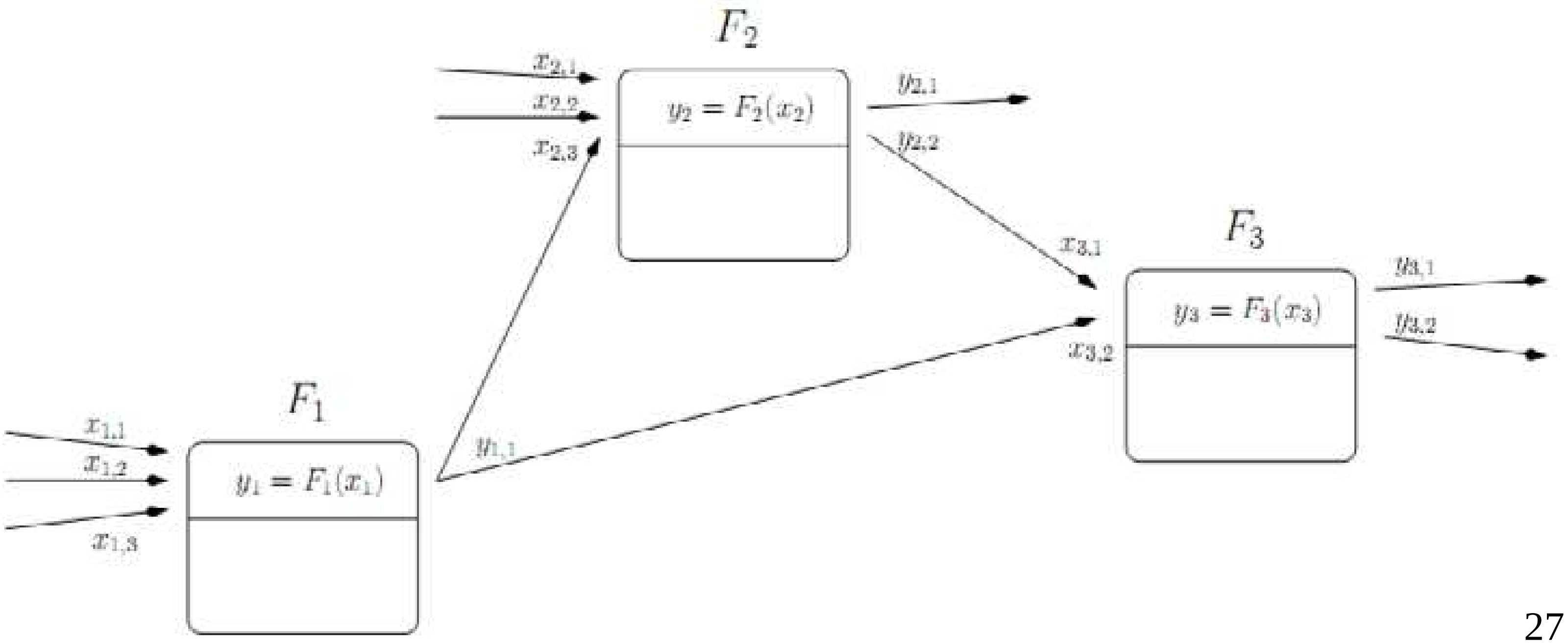
YAO

Direct model

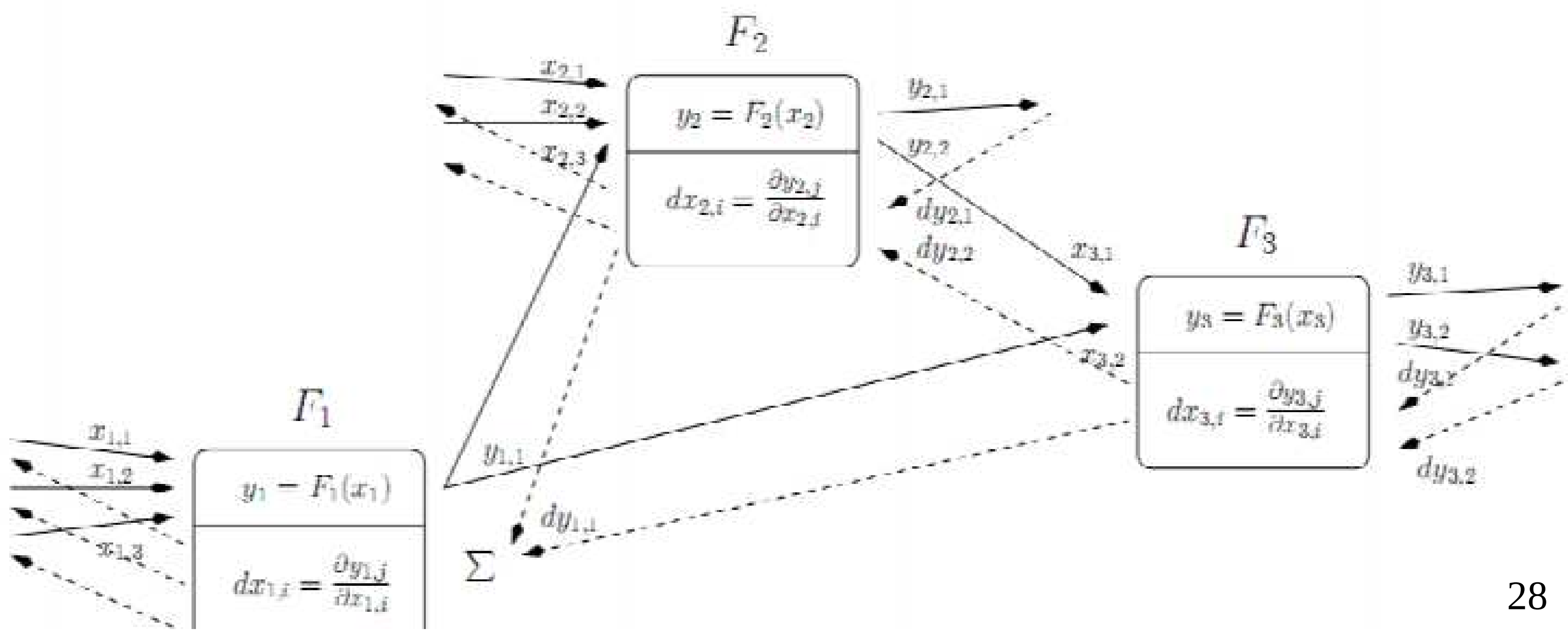
Passing through the graph in a topological order we calculate the direct model : forward algorithm



YAO

Adjoint model

Passing through the graph in a reverse topological order we calculate the adjoint model : backward algorithm



NEMO-YAO configuration

- Version of NEMO coded within YAO assimilation software
- “Translation” of GYRE idealized configuration
  - Available resolutions : 1°, 1/2° et 1/4°
  - 4th order diffusive scheme (2^{nd} order also available)
- Trajectories initialized by a 30Y GYRE (fortran) spinup

Two-resolution experiment

¼°

Init from spinup GYRE ¼°

Constant viscosities & diffusivities (~1e +11 m4/s)

t = t0

tf = t0 + 2 day

Obs = final SST aggregated at ½°

½°

Init from spinup (aggregation at ½°)

Constant background visc. & diff. (-1e+12 m4/s)

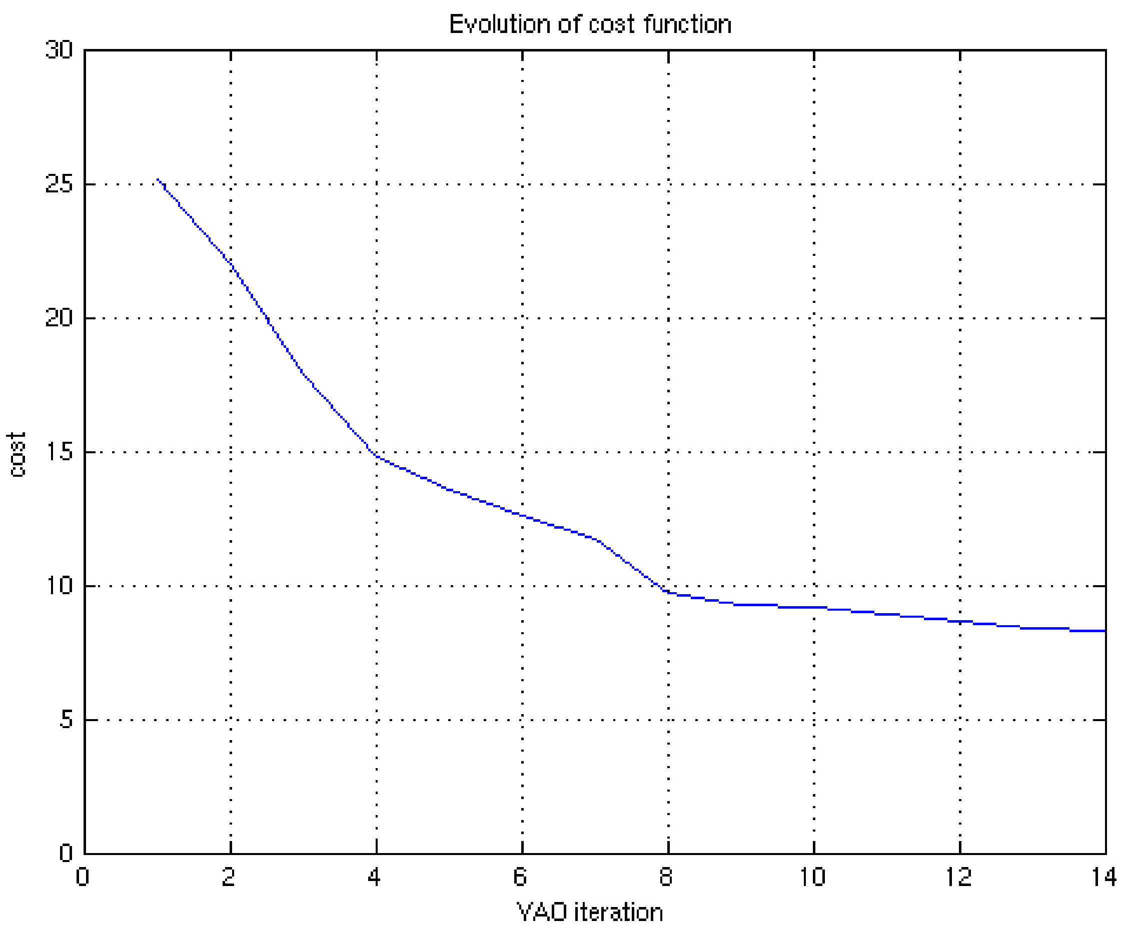
t = t0

tf = t0 + 2 day

Cost function minimization (YAO)

Control parameters = spatial fields of bilapacian viscosities & diffusivities

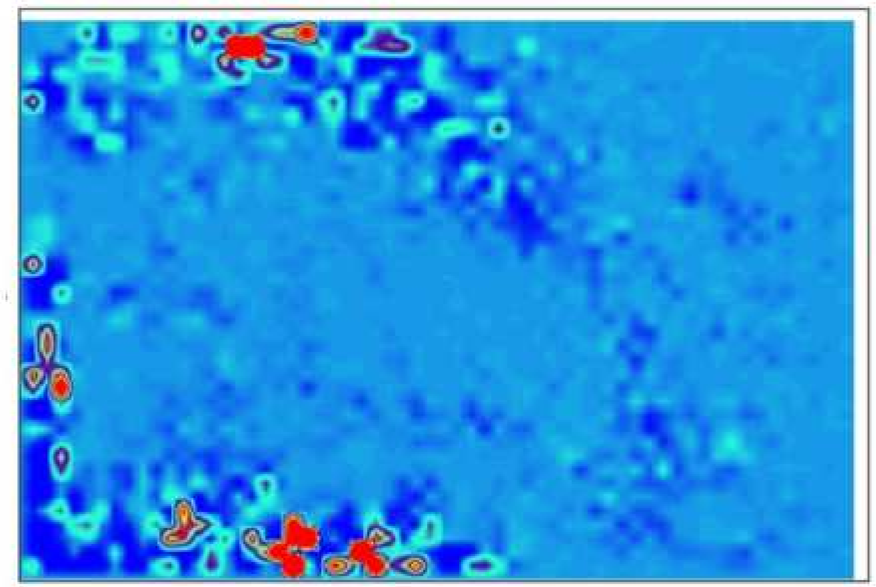
Minimisation of J(diffusivity, viscosity)



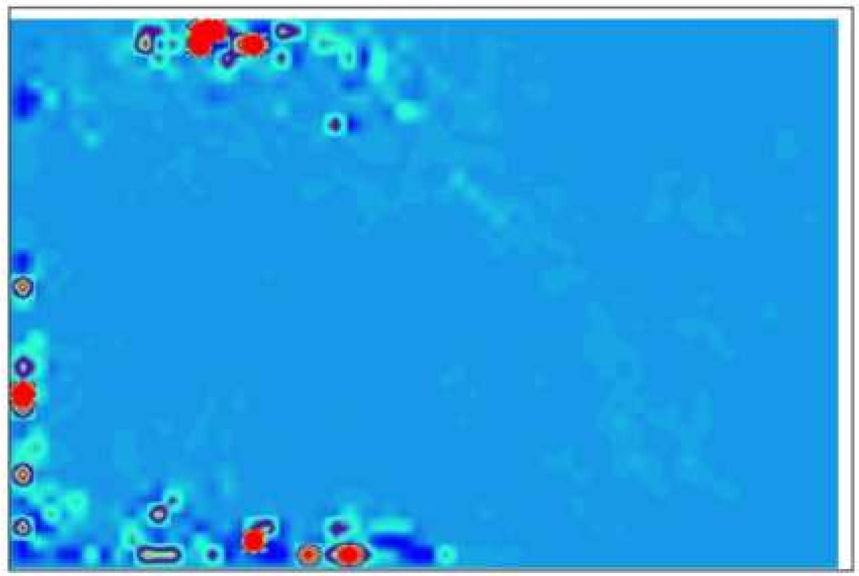
Gain of a factor 3 by controlling 3D diffusive coefficients only
(future improvements expected by adding control of initial conditions)

Surface diffusive coefficients

|Surface Diffusivity|



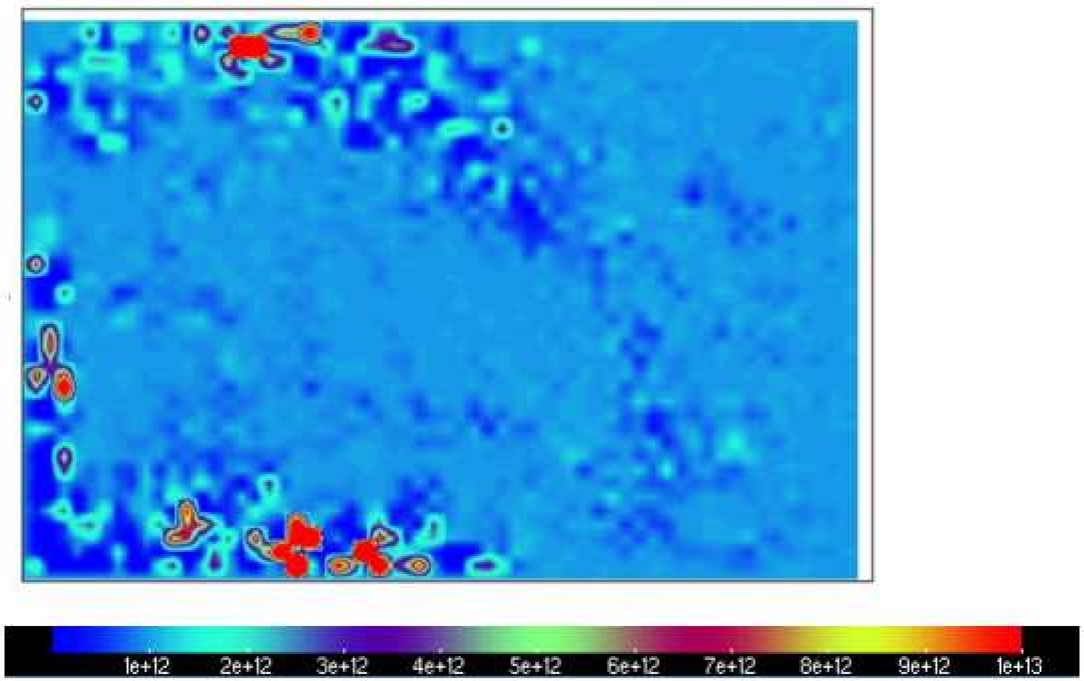
|Surface Viscosity|



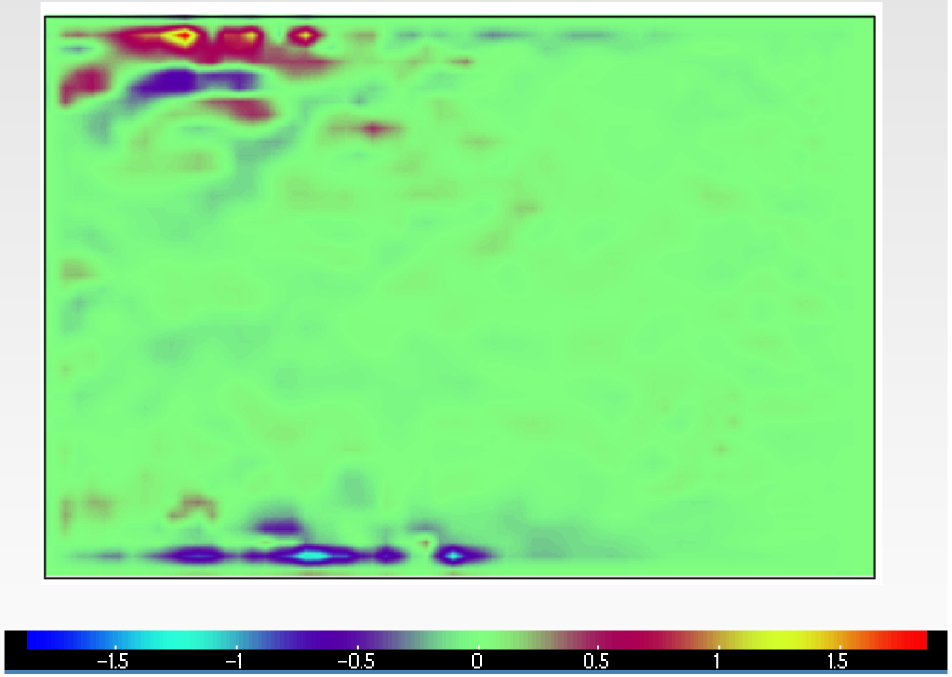
Background value = 1.0e +12 m4/s (background color)

Surface patterns localization

|Surface Diffusivity|



Velocity (u component) snapshot



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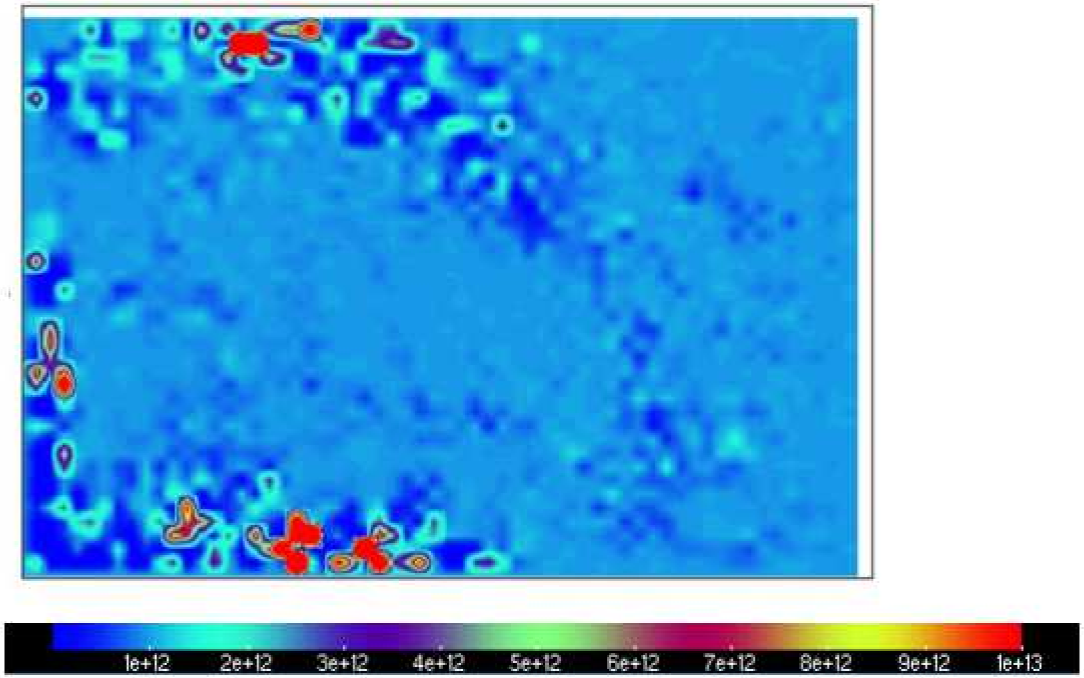
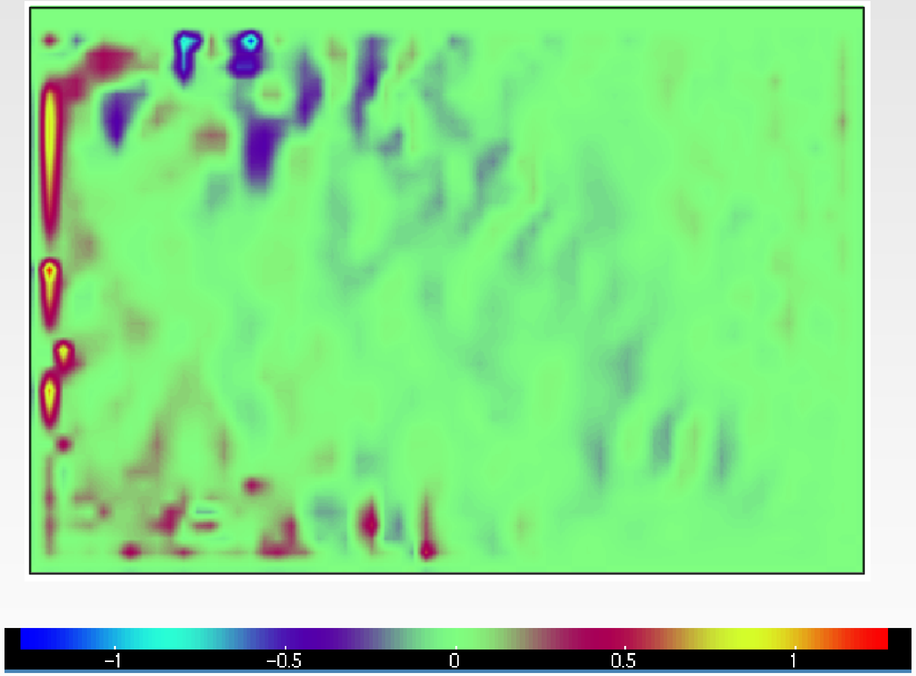


Velocity (v component) snapshot



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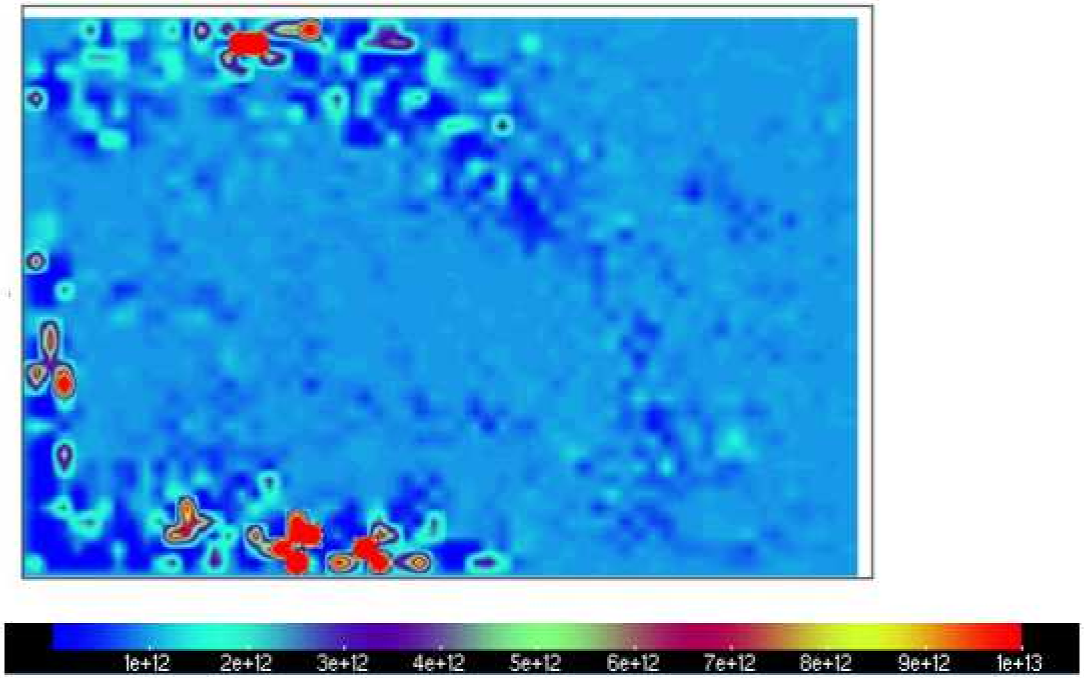
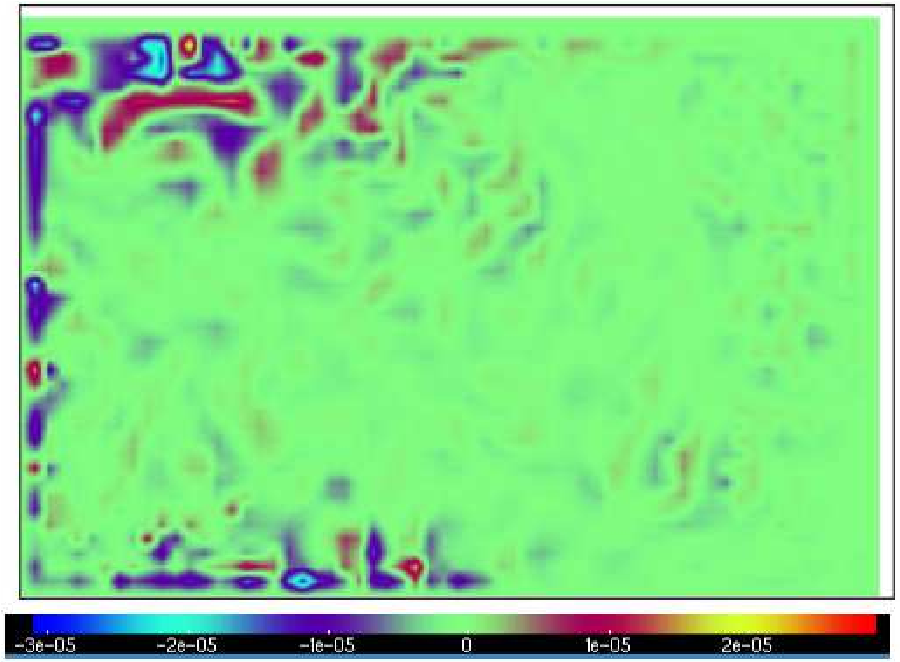


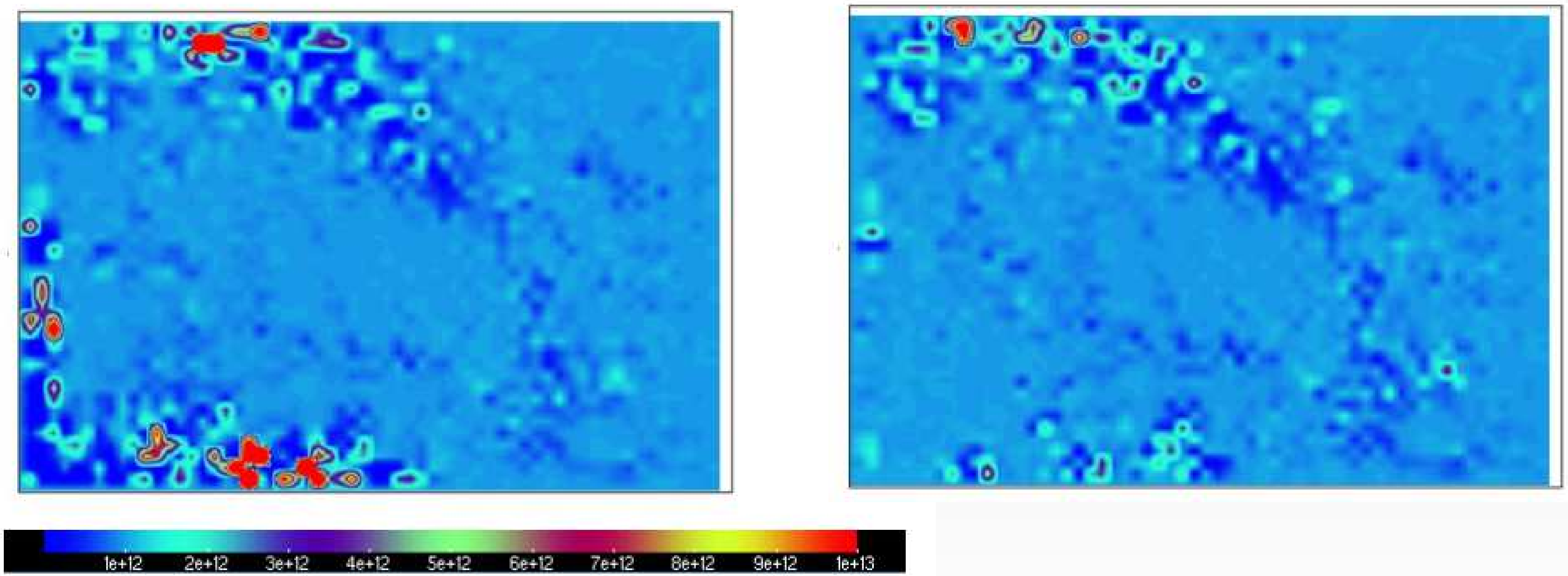
Vorticity snapshot



Vertical coherence of patterns

|Surface diffusivity| k=0

|Diffusivity| at level k=5 (60 m depth)



Significant patterns even at level k = 10 (135 m)
Note that only SST data have been assimilated

Conclusions

- Multifractal scaling properties:
  - A statistical tool for OGCM/AGCM evaluation
  - Multi-order = generalizes spectral tools

- Downscaling:
  - Multifractal properties provide information on CDF transformations when changing resolution
  - Relatively inexpensive method, parameterizable
  - Respects fundamental symmetries of the flow

- NEMO-YAO:
  - Feasibility study for controlling diffusive parameters and comparing with local properties of the flow

Perspectives

- Multifractal scaling properties:
  - To be validated in available higher-resolution NEMO simulations (1/54°)
  - Comparison with ROMS
- Downscaling:
  - Modifications needed for simulating accurate filamentary structures
  - Method not specific to SST or rainfall, could be adapted for downscaling wind forcings
- NEMO-YAO:
  - Larger assimilation window, higher resolutions
  - More complex diffusive schemes

Questions?

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