Challenges for future upper-air parameterisation work.

J.-F. Geleyn

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'Brac-HR' workshop

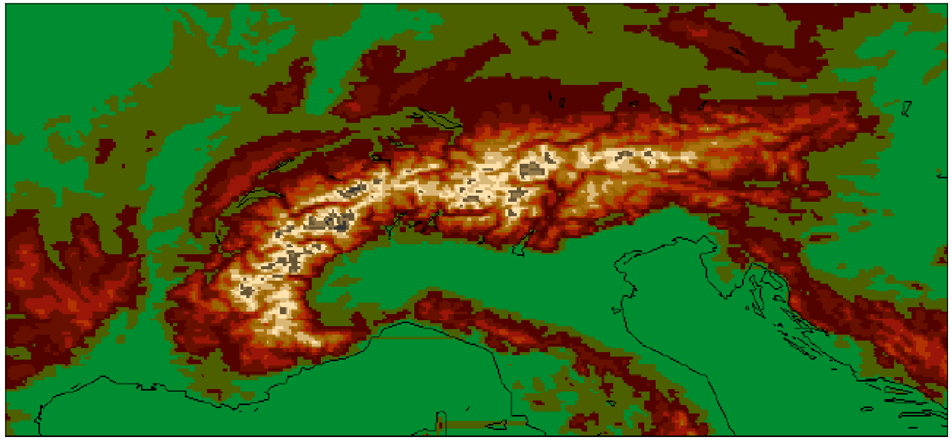
17/5/10, Supetar, Island of Brač, Croatia

What can be expected when going to higher and higher resolution?

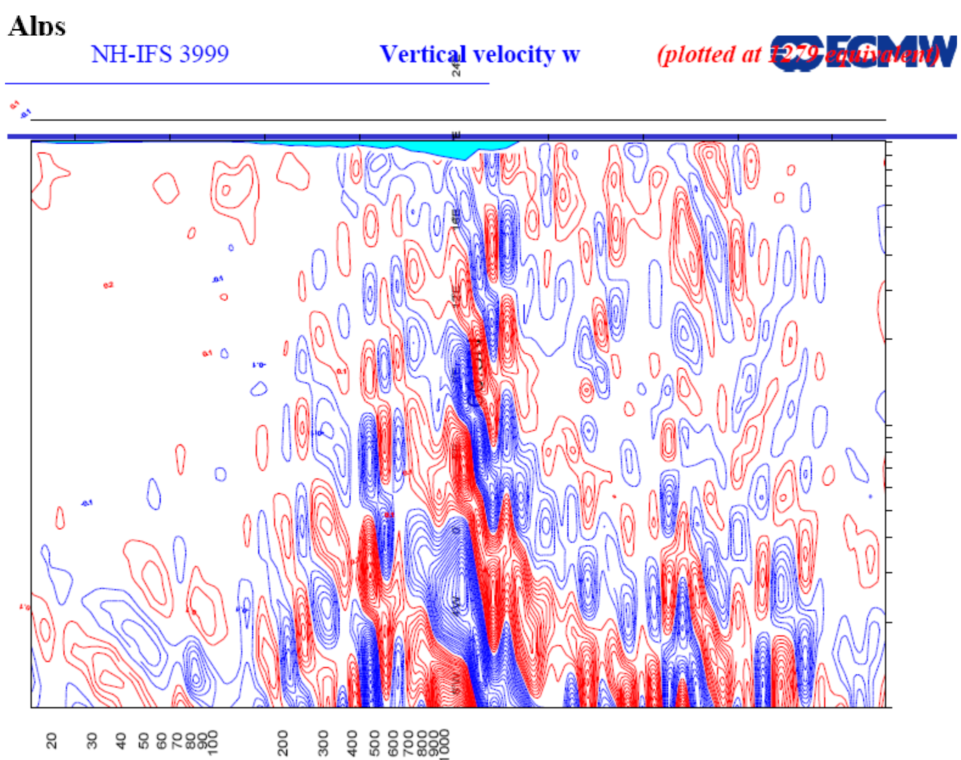
- A lot of problems with predictability
- More dilemmas about computing constraints
- A more complex scale-interaction handling with respect to 'global' forcings
- Less problems as 'resolution' plays the 'doctor' ?
- An easier selection of the processes really needed in the parameterisation trade ?
- A better description of the influence of surface conditions (including orography) ?

Orography - T3999

Max altitude = 7185m



(Thanks to P. Bechtold)



Results plotted at three times less resolution than the computation

About a better selection of the limits between parameterised processes

- It is true that we learn more and more how to separate, on the paper, the 'processes' (radiation + microphysics, **R** & **M**, basically) from the 'transport', **T**, ***BUT***:
  - We shall see later that the correct definition of the latter is not at all trivial;
  - Clouds are still playing an ambiguous role in this 'clearer' partition:
    - Geometry effects in **R** and in **M** become paramount at high resolution and they are heavily '**T**-linked'; **no time to show this today, alas!**
    - The whole axis from dry unorganised turbulence to precipitating deep convection cannot (***yet?***) be taken under one single hat.
- We shall organise this presentation by starting from the last issue and trying to go back to simpler things. In fact I already warn you that this amounts to open a Pandora box!
- So let us start with the issues of FP-MT and then 'shallow convection', as classically called.

Full-Prognostic Microphysics-Transport (FP-MT); a possible long-term solution (proposed by J.-M. Piriou) to all 'partition' problems?

$$
\begin{cases}
\left(\frac{\partial \sigma_i \overline{\rho}^i}{\partial t}\right)_\varphi = \sum_{j\neq i}(E_{ij} - D_{ij}) - \frac{\partial}{\partial z}\sigma_i \overline{\rho}^i \overline{w}^i \\
\left(\frac{\partial \sigma_i \overline{\rho}^i \overline{q_v}^i}{\partial t}\right)_\varphi = \sigma_i \overline{\rho}^i(-\overline{C}^i + \overline{E_C}^i + \overline{E_P}^i) + \sum_{j\neq i}(E_{ij}\overline{q_v}^j - D_{ij}\overline{q_v}^i) - \frac{\partial}{\partial z}\sigma_i \overline{\rho}^i \overline{w}^i \overline{q_v}^i \\
\left(\frac{\partial \sigma_i \overline{\rho}^i \overline{q_l}^i}{\partial t}\right)_\varphi = \sigma_i \overline{\rho}^i(\overline{C}^i - \overline{E_C}^i - \overline{A}^i) + \sum_{j\neq i}(E_{ij}\overline{q_l}^j - D_{ij}\overline{q_l}^i) - \frac{\partial}{\partial z}\sigma_i \overline{\rho}^i \overline{w}^i \overline{q_l}^i \\
\left(\frac{\partial \sigma_i \overline{\rho}^i \overline{q_r}^i}{\partial t}\right)_\varphi = \sigma_i \overline{\rho}^i(\overline{A}^i - \overline{E_P}^i) + \sum_{j\neq i}(E_{ij}\overline{q_r}^j - D_{ij}\overline{q_r}^i) - \frac{\partial}{\partial z}\sigma_i \overline{\rho}^i (\overline{w_s}^i + \overline{w}^i)\overline{q_r}^i \\
\left(\frac{\partial \sigma_i \overline{\rho}^i \overline{s}^i}{\partial t}\right)_\varphi = \sigma_i \overline{\rho}^i(\overline{LC}^i - \overline{LE_C}^i - \overline{LE_P}^i + \overline{H}^i) + \sum_{j\neq i}(E_{ij}\overline{s}^j - D_{ij}\overline{s}^i) - \frac{\partial}{\partial z}\sigma_i \overline{\rho}^i \overline{w}^i \overline{s}^i \\
\left(\frac{\partial \sigma_i \overline{\rho}^i \overline{u}^i}{\partial t}\right)_\varphi = \sigma_i \overline{\rho}^i \overline{S_u}^i + \sum_{j\neq i}(E_{ij}\overline{u}^j - D_{ij}\overline{u}^i) - \frac{\partial}{\partial z}\sigma_i \overline{\rho}^i \overline{w}^i \overline{u}^i \\
\left(\frac{\partial \sigma_i \overline{\rho}^i \overline{w}^i}{\partial t}\right)_\varphi = \sigma_i \overline{\rho}^i \overline{S_w}^i + \sum_{j\neq i}(E_{ij}\overline{w}^j - D_{ij}\overline{w}^i) - \frac{\partial}{\partial z}\sigma_i \overline{\rho}^i \overline{w}^i \overline{w}^i
\end{cases}
$$

The index 'i' runs over 'n' modes (randomly positionned vertical slices of the grid-mesh). The physics' problem is **basically** reduced to 'n-times' Radiation and Microphysics computations and, **key ingredients**, the vertical velocity prognostic equations plus the parametrisation of 'one mode to one mode' Entrainment(-Detrainment) terms.

The open issue is of course « what beyond the above 'basically'? »

Towards a Unified Description of Turbulence and Shallow Convection (D. Mirovov)

Quoting Arakawa (2004, The Cumulus Parameterization Problem: Past, Present, and Future. *J. Climate*, **17**, 2493-2525), where, among other things, "Major practical and conceptual problems in the conventional approach of cumulus parameterization, which include artificial separations of processes and scales, are discussed."

"It is rather obvious that for future climate models the scope of the problem must be drastically expanded from "cumulus parameterization" to "unified cloud parameterization" or even to "unified model physics". This is an extremely challenging task, both intellectually and computationally, and the use of multiple approaches is crucial even for a moderate success."

The tasks of developing a "unified cloud parameterization" and eventually a "unified model physics" seem to be too ambitious, at least at the moment.

However, a unified description of boundary-layer turbulence and shallow convection seems to be feasible. There are several ways to do so, but it is not a priory clear which way should be preferred.

Towards a Unified Description of Turbulence and Shallow Convection (D. Mirovov)

• ***Extended mass-flux schemes*** built around the top-hat updraught-downdraught representation of fluctuating quantities. Missing components, namely, parameterisations of the sub-plume scale fluxes, of the pressure terms, and, to some extent, of the dissipation terms, are borrowed from the ensemble-mean second-order modelling framework. (ADHOC, Lappen and Randall 2001)

• ***Hybrid schemes*** where the mass-flux closure ideas and the ensemble-mean second-order closure ideas have roughly equal standing. (EDMF, Soares et al. 2004, Siebesma and Teixeira 2000)

• ***Non-local second-order closure schemes*** with skewness-dependent parameterisations of the third-order transport moments in the second-moment equations. Such parameterisations are simply the mass-flux formulations recast in terms of the ensemble-mean quantities!

We shall now see a recent result that gives a bit added credibility to the last of the three choices (the one 'entirely' in the turbulent framework)

The problem of the 'ideal' moist potential temperature (1/5)

- Transport terms are of two kinds:
  - **Advective** ('conservation' = the Lagrangian derivative is zero);
  - **Diffusive** ('conservation' = the 'intensity' of the average is equal to the average of the 'intensities').
- In the definition of so-called 'potential temperatures', this creates a problem. Generally speaking when one of the properties is verified, the other one is not!
- Contrary to general belief, this starts already with 'dry' $\boldsymbol{\theta}$ expressions like:

$$\theta_a = T.(\frac{p_0}{p})^{[R(q_d,q_v)/(C_p(q_d,q_v,q_l,q_i)]} \quad vs. \quad \theta_d = T.(\frac{p_0}{p})^{[R_d/C_{pd}]}$$

∀ $\boldsymbol{\theta_a}$ is a 'Lagrangian' quantity ($\boldsymbol{R/C_p}$ remaining constant in displacements) but not an 'intensive' quantity (one cannot average the exponents between differing air parcels).

- The situation is obviously the reverse for $\boldsymbol{\theta_d}$!

The problem of the ‘ideal’ moist potential temperature (2/5)

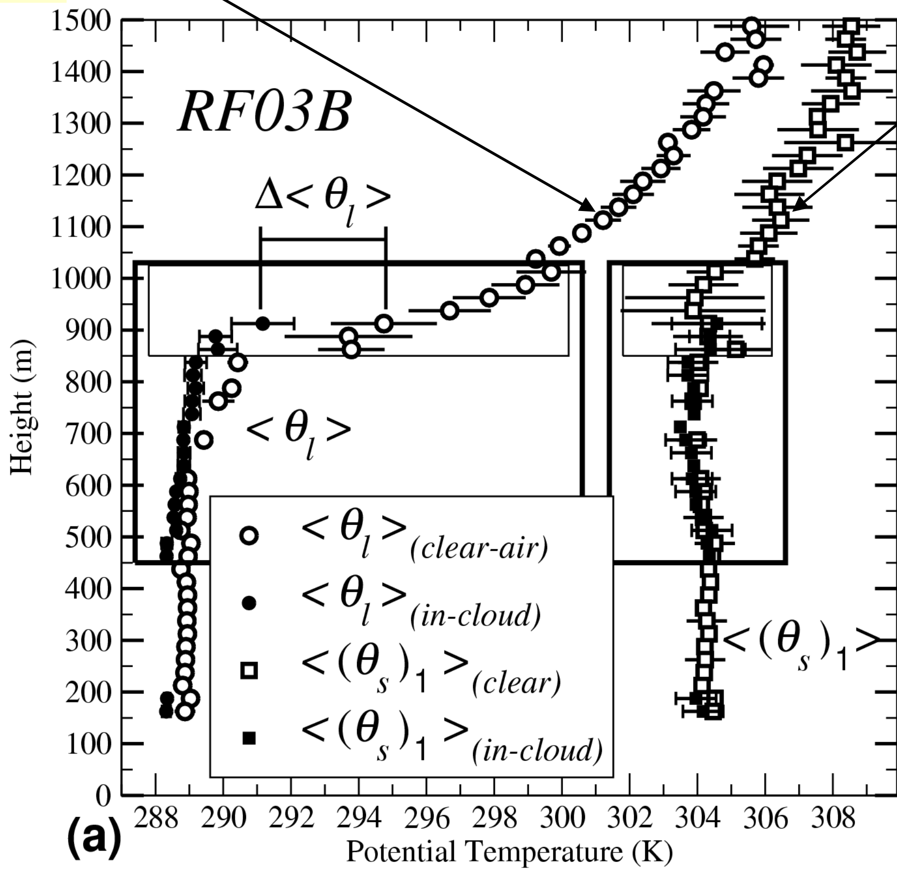
- When introducing phase changes, the situation becomes even more complicated. The associated heat sources/sinks of course diminish the resistance to buoyant fluctuations. For consistency, one has to also take into account the variations of the latent heats with temperature.
- All this makes it far more difficult to define ‘moist potential temperatures’ both with good ‘Lagrangian’ and with good ‘intensive’ conservation properties. The literature is nevertheless full of proposals!
- Even if the goal of a full multi-use formula is not yet completely reached, there is a significant progress in spe, with a (soon-to-be-published) proposal of P. Marquet.

The problem of the 'ideal' moist potential temperature (3/5)

Bett's 'moist conservative' $\boldsymbol{\theta_l}$

New proposal $\boldsymbol{(\theta_s)_1}$

More homogeneity between cloudy and clear air parts in the new case



Cloud layer

The 'top of PBL discontinuity' practically disappears when using the new quantity

The problem of the 'ideal' moist potential temperature (4/5)

The result is quite robust from one FIRE flight to the other ones

Here only the horizontally averaged values are plotted.

The problem of the 'ideal' moist potential temperature (5/5)

- We shall now have a moist potential temperature truly conservative for reversible and adiabatic processes, including all those linked to phase changes.
- If the applicability to other type of clouds is confirmed (and there is no reason why it should not be) this has far-reaching implications for the treatment of 'moist turbulent motions'.
- Indeed (a) the cloud to clear-air horizontal homogeneity and (b) the vertical continuity, clearly point towards the definition of a $(N^2_s)_1$ generalised BV-frequency that could be used together with $(\theta_s)_1$ for:
  - Defining the overall turbulent activity (via a measure of stability);
  - Getting better conservation of energy in the diffusive transport;
  - Uniquely defining the split of the heat flux between its sensible and latent parts.
- Currently the simultaneous solution of these three problems calls for using information computed outside the turbulent parameterisation. **It would not anymore be necessarily the case!** => ***Back to non local closure schemes, with the perspective of an 'homogeneous' treatment of moist second-order and third-order terms …***

Skewness-Dependent Parameterisation of Third-Order Transport (D. Mironov)

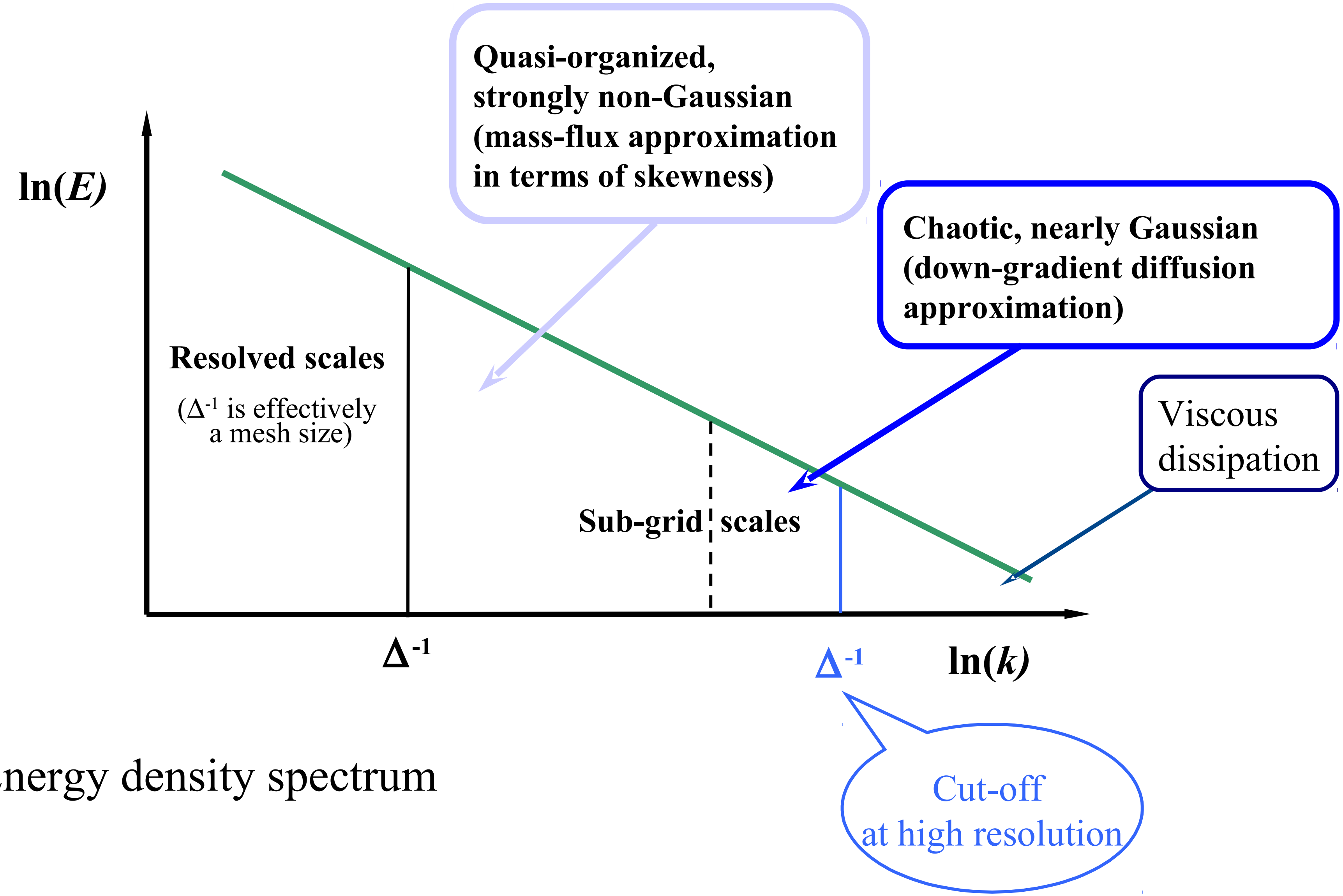
$$\overline{u_i'\theta'^2} = -K\frac{\partial\overline{\theta'^2}}{\partial x_i} + S_\theta\overline{\theta'^2}^{1/2}\,\overline{u_i'\theta'}, \qquad S_\theta = \frac{\overline{\theta'^3}}{\overline{\theta'^2}^{3/2}}$$

Down-gradient term (diffusion)

Non-gradient term (advection)

Accounts for non-local transport due to coherent structures (convective plumes or rolls) – mass-flux ideas!

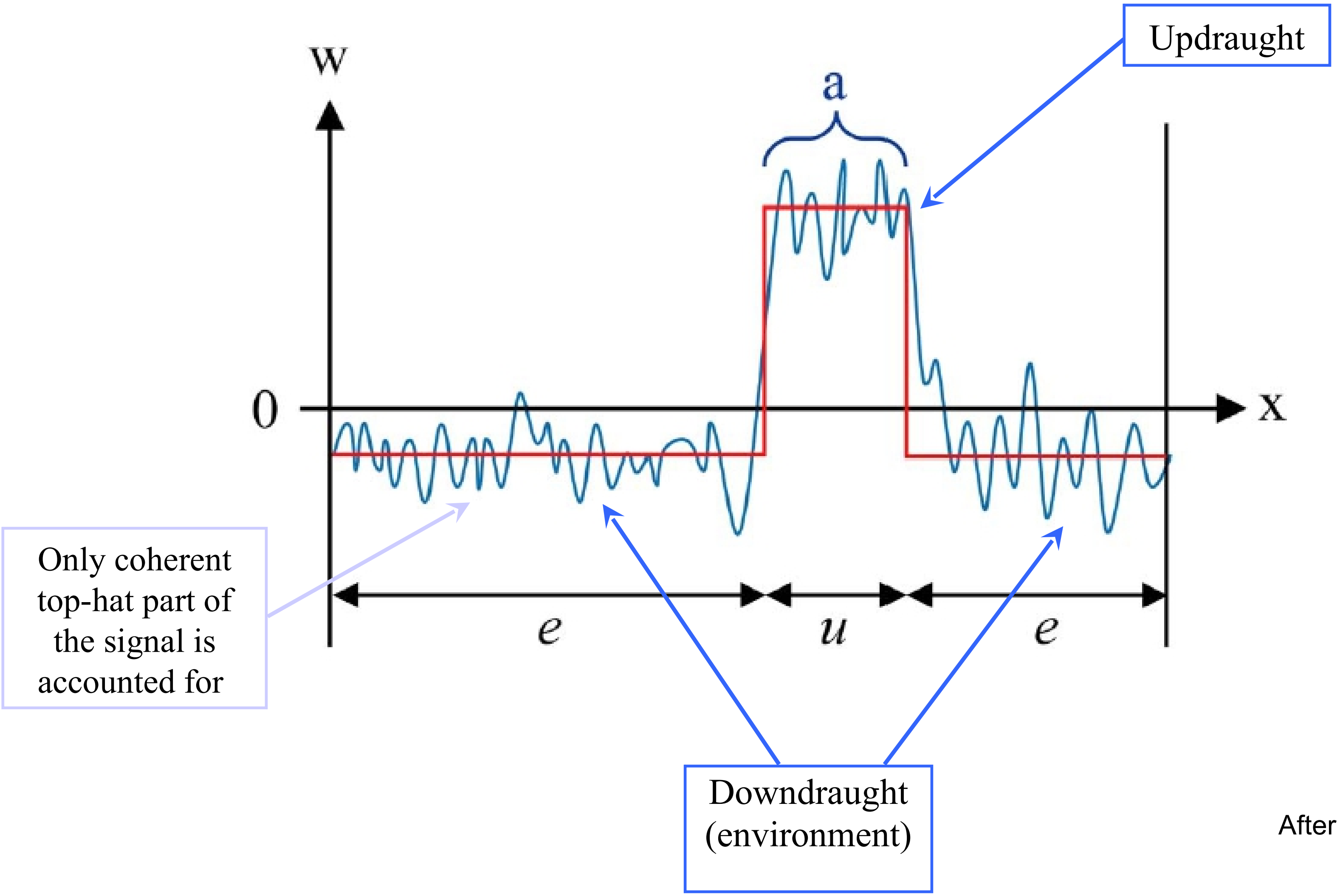
Relation to Scale: Separation Ideas (D. Mironov)



Energy density spectrum

Analogies to Mass-Flux Approach (D. Mironov)

A top-hat representation of a fluctuating quantity



After M. Köhler (2005)

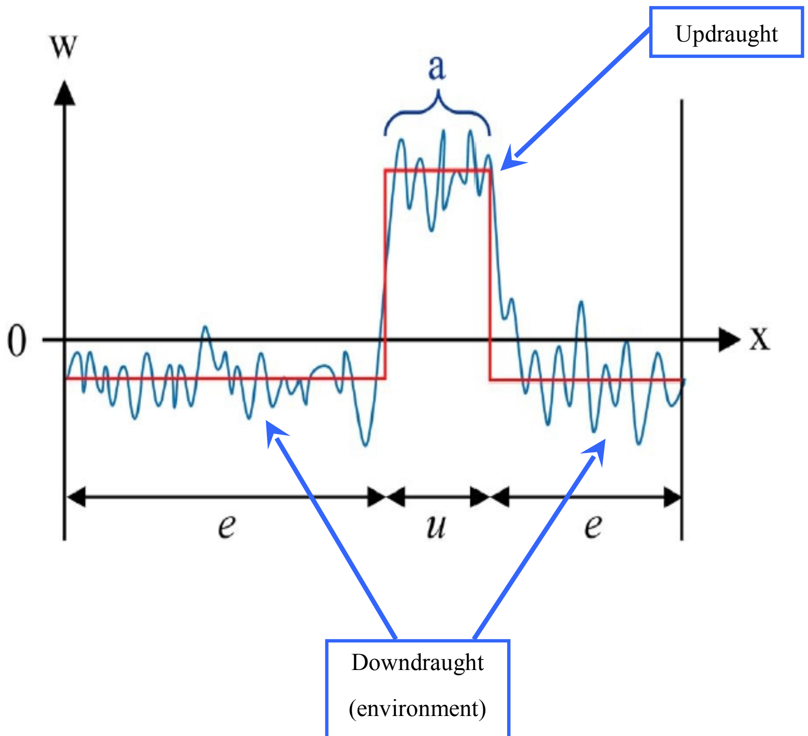
But what if the convection is 'precipitating' ?

Then there exist several micro-physics-related positive feed-backs that do not allow a full equivalent with a turbulent treatment, even of the mixed type. What to do? Two solutions:

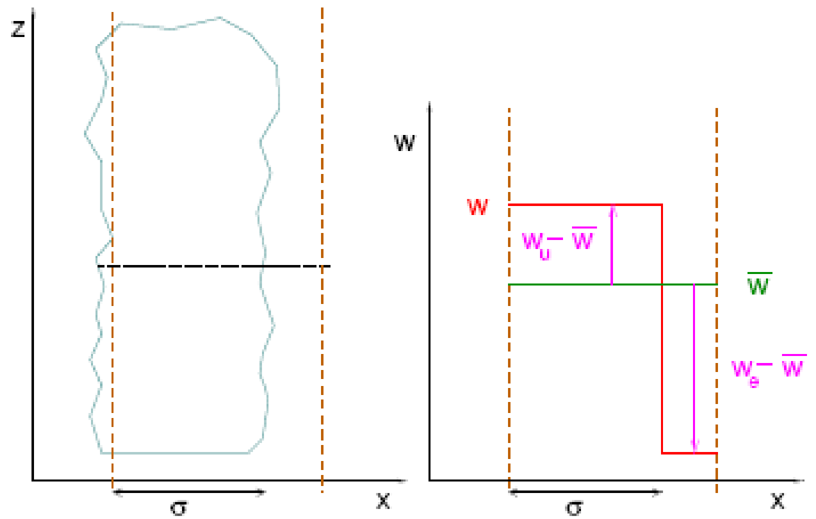
- Ignore the problem, counting on the 'resoved micro-physics' to explicitely simulate the natural phenomenon (<u>jump over the 'grey-zone' approach</u>).

- Consider a mass-flux + microphysics approach where what is parameterised is not the total effect but only its <u>fluctuating part</u> around the 'resolved' computation:

  - ***no more scale issue*** (it gets by-passed);
  - because the relevant pseudo-updraft fractional area can get rather big, theory shows that ***one must treat it prognostically***.



Subgrid updraught contribution concept



Virtual Unresolved Cloud :

- condenses with $\sigma_u(\omega_u - \overline{\omega})$
- Transports with $\sigma_u(\omega_u - \omega_e)$
- Entrains with $\sigma_u(\omega_u - \omega_e)$
- Rises with ω_u

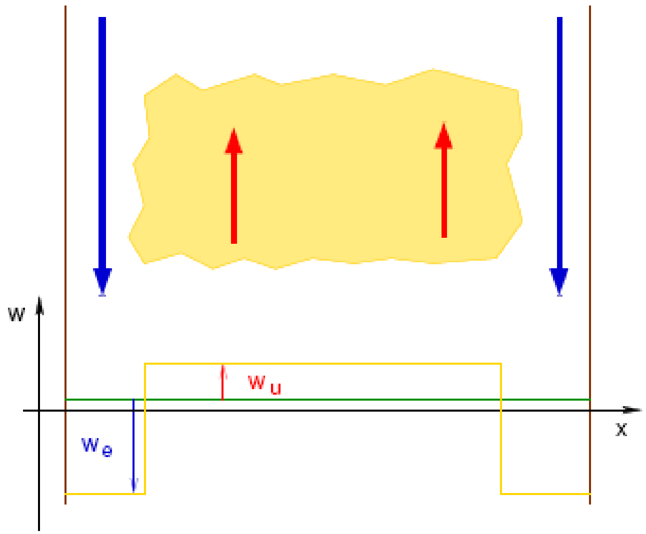
Newton law formulation
no more 'apparent mass coefficient'

$$\frac{d\left[\sigma_u(\omega_u - \overline{\omega})\right]}{dt} - \frac{d\left[(1-\sigma_u)(\omega_e - \overline{\omega})\right]}{dt} = (\mathbf{F}_\mathrm{b} + \mathrm{drag})$$

$$2\frac{d\left[\sigma_u \omega_u^\diamond\right]}{dt} = (\mathbf{F}_\mathrm{b} + \mathrm{drag})$$

$$\boxed{\omega_u^\diamond = \omega_u - \overline{\omega}}$$

Subgrid updraught : confinement concept



Bjerknes (1938), Asai and Kasahara (1967)

$$\frac{\partial T_u}{\partial t} \approx -w_u \frac{g}{c_p}\frac{\partial h}{\partial \phi} \qquad \leq 0$$

$$\frac{\partial T_e}{\partial t} \approx -w_e \frac{g}{c_p}\frac{\partial s}{\partial \phi} \qquad \geq 0$$

$$T_{vu} - \overline{T_v}^{+} \approx (T_{vu} - \overline{T_v})\left[1 - \sigma_u \underbrace{(1 - \frac{\triangle s}{\triangle h})}_{b \geq 1}\right]$$

Bjeknes buoyancy-reduction coefficient $b \geq 1$

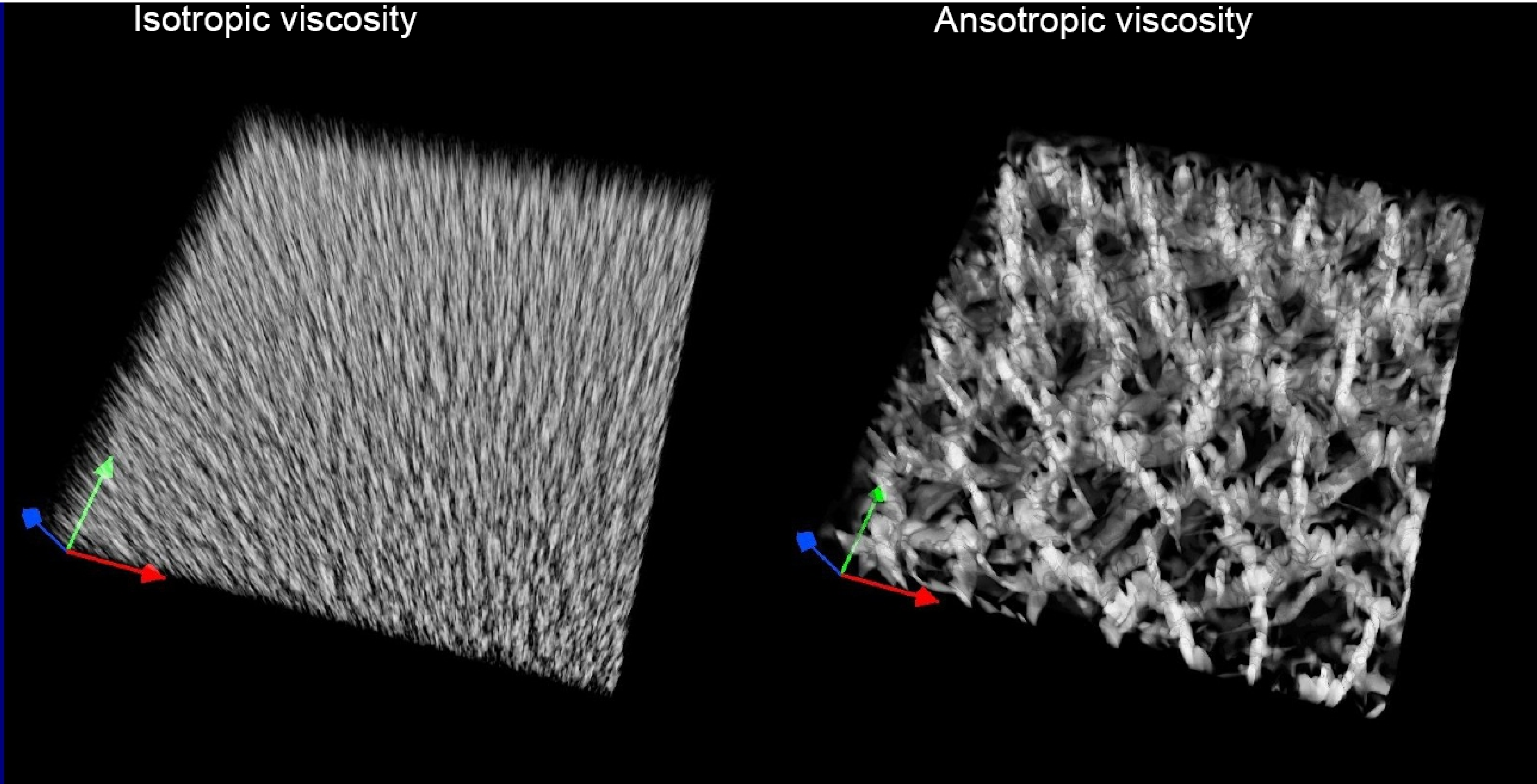
L. Gerard, March 2010

Such a step is needed to close the mass-budget for the parameterisation step. But, in nature, the ‘return current’ originates from far more ascents than the one(s) within the grid box. It is the reason why:

-one cannot say that the convective forcing looses its ‘statistical character’ when the updraft is mainly resolved; the need of a sub-grid treatment goes deeper than that;

-when parameterising, we anyhow need a trick to solve the problem ‘locally’.

The Piotrowski et al. ‘surprise’: the shape of “numerical viscosity” **matters a lot**



Structure of thermal convection over heated plate. Vertical velocities after 6h of simulated time are shown within the PBL depth. Bright and dark volumes denote updrafts and downdrafts, respectively. The only difference between the two solutions is the value of viscosity in horizontal entries of the stress tensor, $\nu_h = 2.5$ and $\nu_h = 70\ m^2s^{-1}$, while constant vertical entry is $\nu_v = 2.5\ m^2s^{-1}$

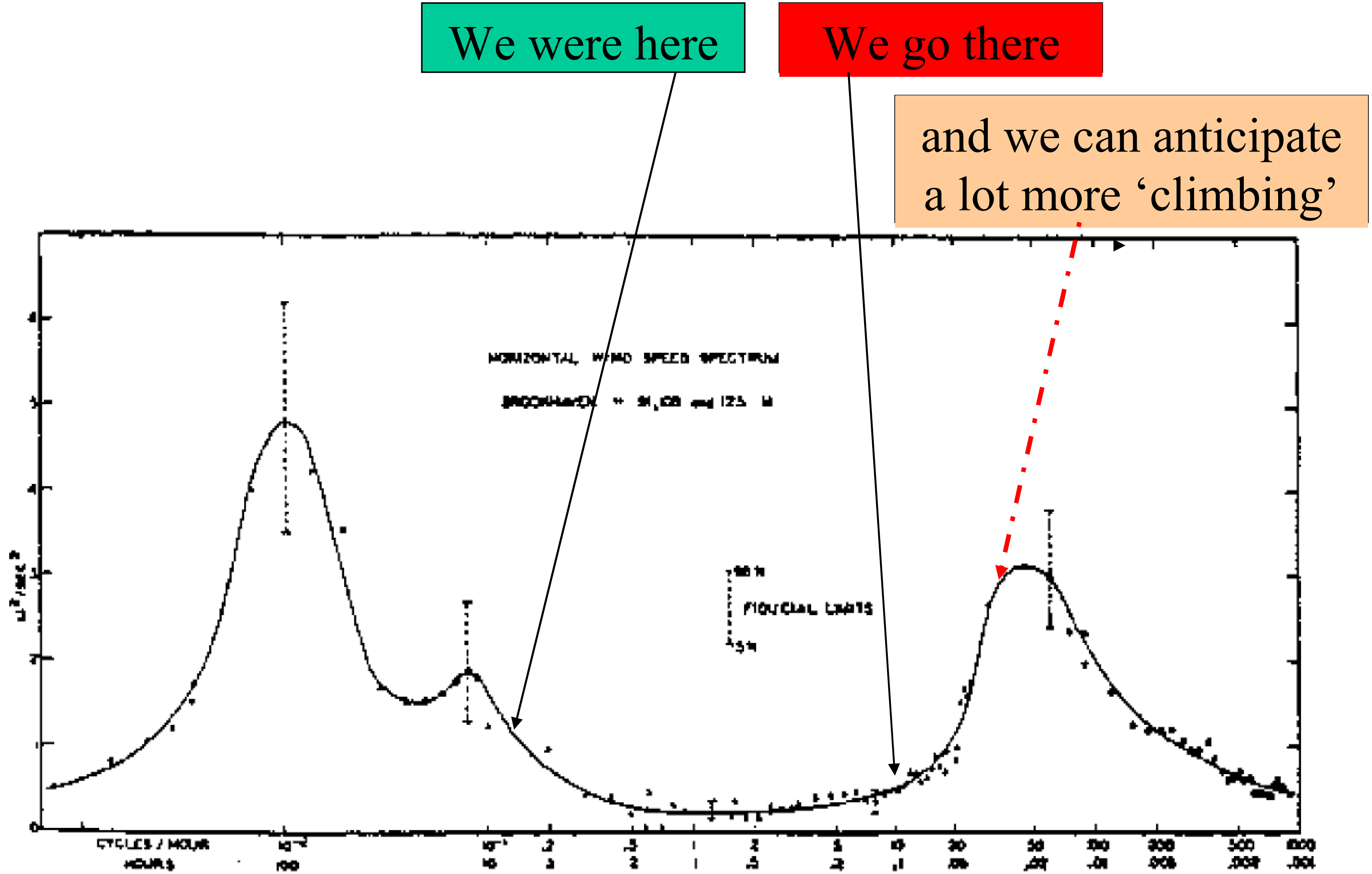
The Piotrowski et al. 'surprise': the main reason, model ≠ nature !

The main stream of research in geophysical and astrophysical convection falls in the regime of large Rayleigh numbers. Rapid progress in computational technology already enables large- and global-scale simulations of convective fields at unprecedented meso-scale resolutions. This enables calculations free of convection parameterizations (viz. phenomenological models), in the spirit of LES.

Ironically, the simulated convection can be largely under-resolved, making numerical solutions sensitive to ad hoc filtering present in some form in all computational models.

The latter shifts the virtual reality of convection toward moderate and low Rayleigh number regimes, rich in intriguing and attractive forms of the structural organization, yet unrealistic for the specified external parameter range.

The Piotrowski et al. ‘surprise’: why do we see it only now ?

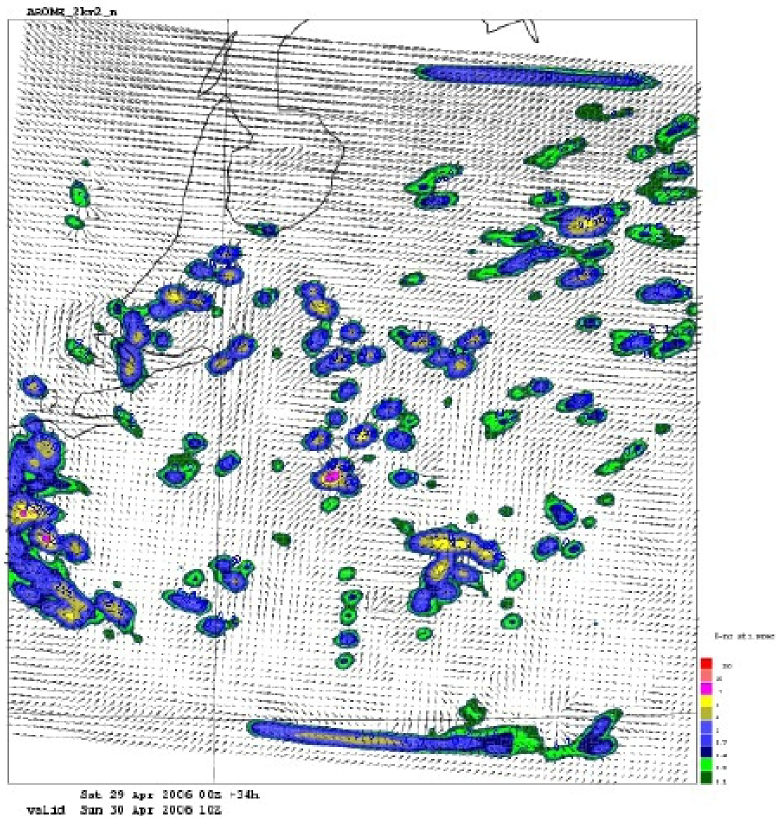


The task to reconciliate model & nature won’t get easier when going to higher resolution

The Piotrowski et al. ‘surprise’: a possible general track for progress

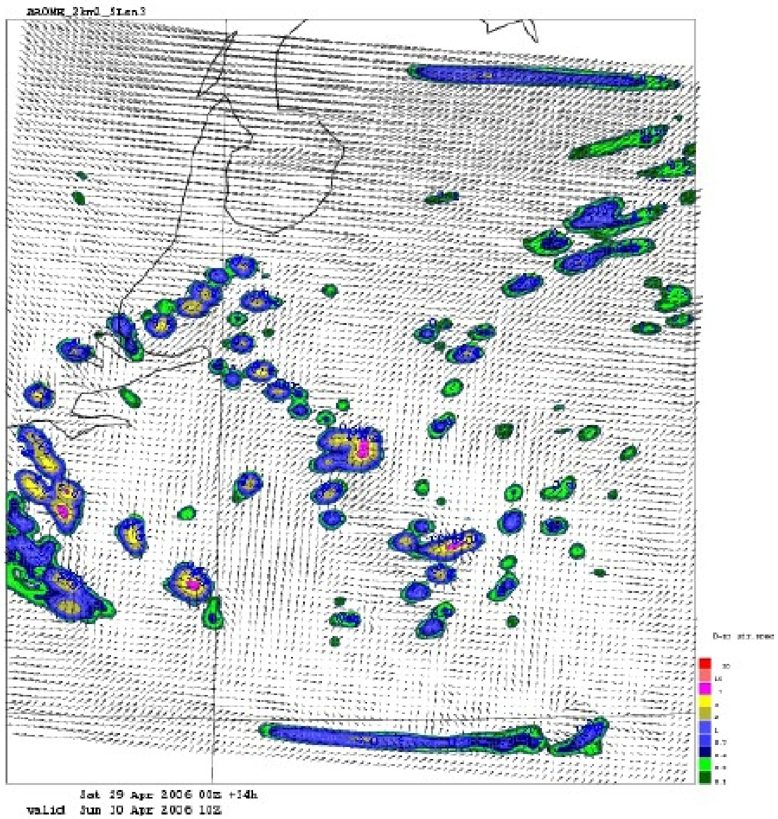
- Rather than considering separately ‘dynamics’ and ‘physics’, start thinking of ‘reversible’ vs. ‘irreversible’ parts of the model time step, seen as a whole.
- Of course, this brings in first the issue of lateral diffusion (assuming we master more or less the vertical one).
- Even if it was surely not invented to anticipate this need, SLHD is certainly a step that brings us nearer to this kind of new paradigm!
- And indeed, there is a lot (too much ?) sentivity to it => up to us to make **a true asset** from what people sometimes consider as **a big annoyance** …
- ***COST ES0905*** action’s main opinion on the way forward for high-resolution:
  - Rather call it ‘**new resolution**’ (a psychological step);
  - Consider as main tools for regaining better control, (i) ***laterality*** (see above), (ii) push of ***prognostic*** character, (iii) ***stochasticity***.

Influence of the lateral diffusion set-up on precipitations at δx=2km (courtesy of L. Bengtsson)



AROME set-up of ‘hdiff’

(weak, linear)



ALARO set-up of ‘hdiff’

(medium, non-linear [SLHD])

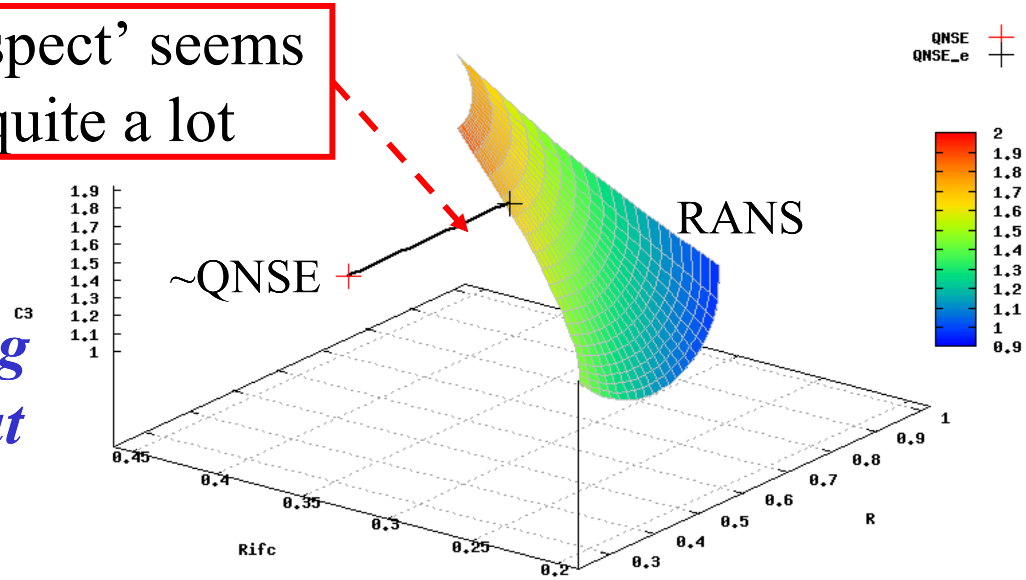
Return to the basic parameterisation of turbulence. The main issues at stake:

- Incorporating or not the effects of the flow's **anisotropy**?
- How to deal with the fact that it is now rather sure that there exists **no critical Richardson number** when going to high stability:
  - Artificially limiting $\boldsymbol{R_i}$ in order to avoid the collapse in case of 'old' schemes;
  - Finding a framework centered around the asymptotic behaviour at high stability;
  - Accepting the additional complexity and for instance giving up the 'separation' between the stability dependency functions (SDFs) for momentum and for heat.
- When having a prognostic treatment of TKE (Turbulent Kinetic Energy), what to do with the term representing the **conversion between TKE and TPE** (Turbulent Potential Energy)? Three schools:
  - COSMO: prognostic treatment of TPE;
  - ALARO: obtaining the SDFs for ∂TKE/∂t only, but via the filtering role of a conservation law for TKE+TPE;
  - AROME: having a direct parameterisation of the said term.
- How to deal with the arrival of an alternative to 'Reynolds averaging', i.e. the **QNSE theory** that introduces the 'wave aspect of turbulence' into the direct production of (separated and filtered-type) SDFs?

A way to assess the importance of the difference between QNSE and 'RANS'-methods (courtesy of I. Bastak)

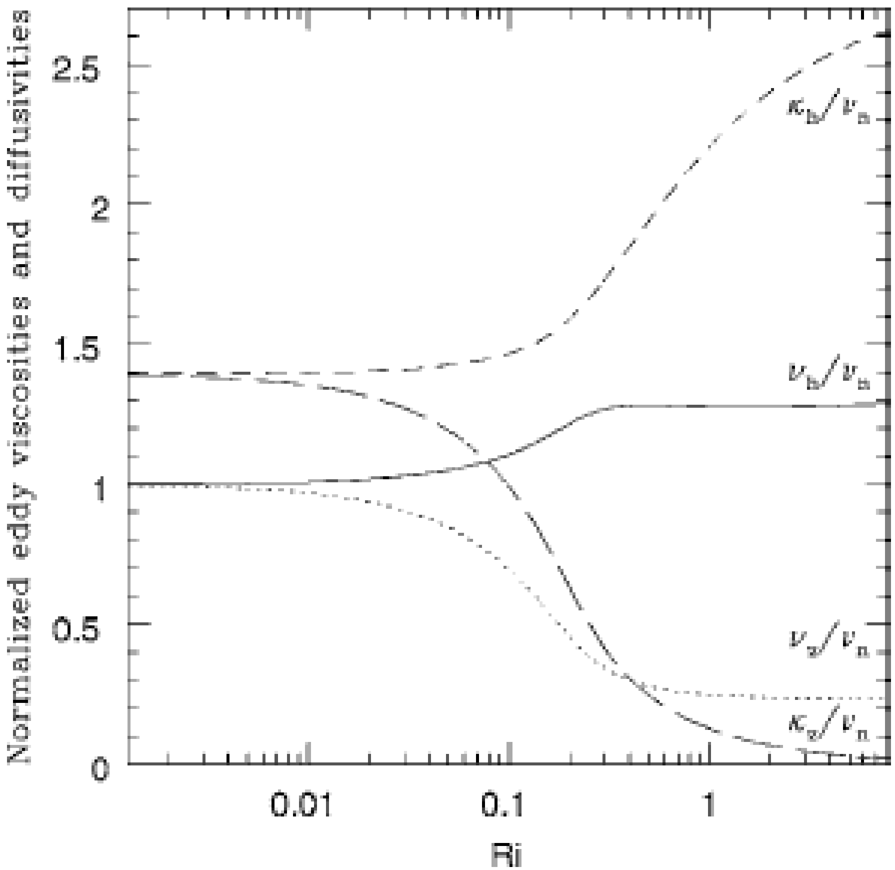
- Rewriting the result of a so-called 'NoRi(cr)' treatment of a complex RANS model (CCH02) into a system with three degrees of freedom:
  - ***C3***, inverse Prandtl number at neutrality;
  - $\boldsymbol{R_{ifc}}$, value for infinite stability of the flux-Richardson-number;
  - ***R***, value characterising the influence of anisotropy on the turbulence structure.
- Finding the best solution to fit the 'absolute' QNSE result in the [$\boldsymbol{C3}$,$\boldsymbol{R_{ifc}}$,$\boldsymbol{R}$] 'space'.
- Looking at what reduction of the space of solutions leads the classical RANS hypothesis that the ratio of the turbulent dissipation time scales for momentum and heat is 2TKE/TPE.

The 'wave aspect' seems to matter quite a lot



Question: can we afford making choices for our basic issues that are QNSE-incompatible?

But QNSE, thanks to its full accounting of anisotropy, has another advantage …



Heat - Horizontal

Momentum - Horizontal

Momentum - Vertical

Heat - Vertical

It delivers information about the relative variations of horizontal mixing in dependency upon vertical stability => this offers a way to return to the question of laterality (cf. F. Vana's talk).

Conclusions

- Let us try to anticipate problems, not just waiting for the increases in resolution to reveal them.
- There are many tools available, all more or less redefining the limit between where the solution is known (provided you have enough CPU) and where it is not.
- This is not to say that the interfacing between the two parts should be taken as a side-issue, it still deserves attention!
- The ‘upstream’ work is sometimes where one expects it less …

Left-over important items

- The geometry aspects of micro-physics and radiation. Also the consequences on intermittent approaches for heavy computations.
- The necessity of ‘conservation laws’ and of consistency in the ‘phys-dyn’ interfacing treatment.
- The various ways to introduce stochasticity and in particular the ‘cellular automatons’, for simulating self-organised criticality.