Dynamics methods for high resolution NWP modeling

Is the high resolution modeling really a limitation for spectral methods with SI SL?

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Issues to be discussed

Features of focus

- Transport scheme - SL advection
- Time scheme - SI
- Spectral techniques

Other issues of lesser interest for this talk

- Staggering
- Vertical coordinate
- Elastic vs. anelastic approximation
- Hydrostatic vs. non-hydrostatic
- ...

Dynamics is a system

- There are (as always) some rules/implications...
  - not much sense for semi-Lagrangian without SI (or RK)
  - elastic NH dynamics with explicit time stepping allows no homogeneous solution
  - any solution aiming at rather long and ’homogeneous’ (i.e. without splitting) time-steps requires a solver
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- Usually any change implies some consequences elsewhere (SI $\Rightarrow$ SL, ...)
- Better to improve a system by rather extending the existing solutions, unless there are some really blocking obstacles...

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$\Rightarrow$ **For two comparable schemes the one allowing longer timestep should be always preferable**

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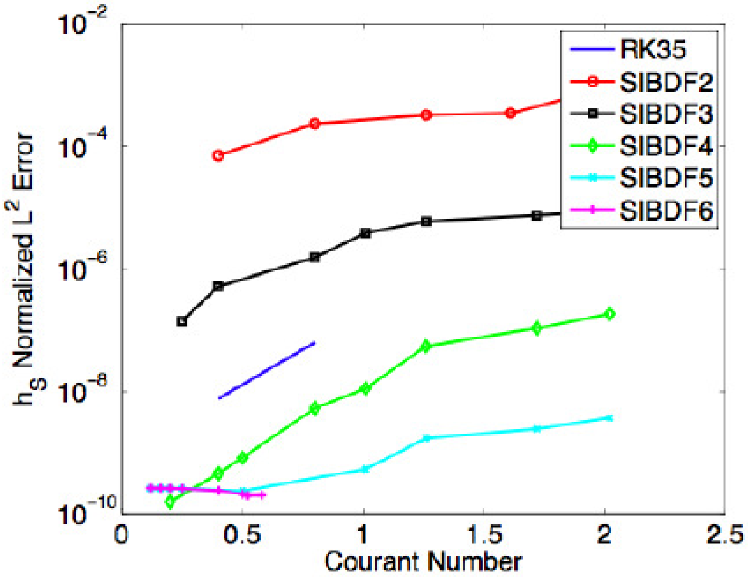
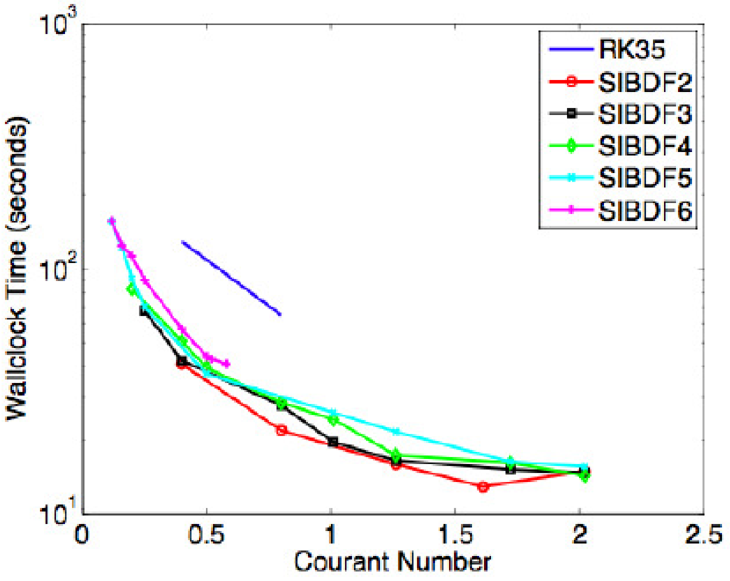


Accuracy



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- Further stabilization implies iterations

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- In spectral model the interpolation stencil offers natural (and efficient) entry point for 3D physics inclusion

What? Inherent diffusion is of any profit?!

FIG. 1. Potential temperature distribution at $t = 7$ min for an initially circular bubble with a diameter of 500 m and uniform potential temperature excess of 0.5°C over an isentropic environment.

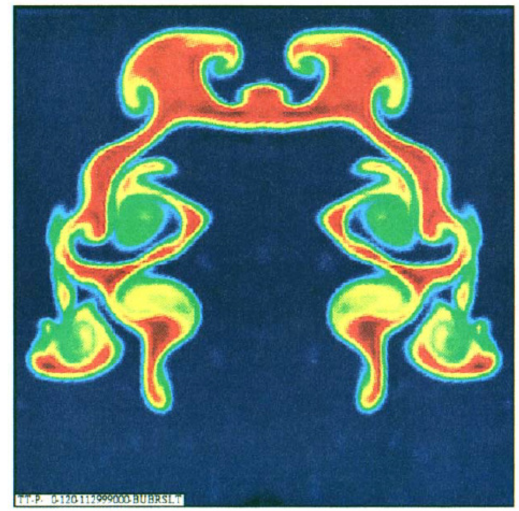

FIG. 2. Same as Fig. 1 but at $t = 10$ min.

”... The results of Smolarkiewicz and Grabowski (= anelastic Eulerian model) are noisy. This is not the case with the proposed model in spite of the fact that it did not use any explicit time filter or diffusion.”

A. Robert (Bubble Convection Experiments with a Semi-implicit Formulation of the Euler Equations, J.A.S., 1993)

Semi-Lagrangian scheme - II.

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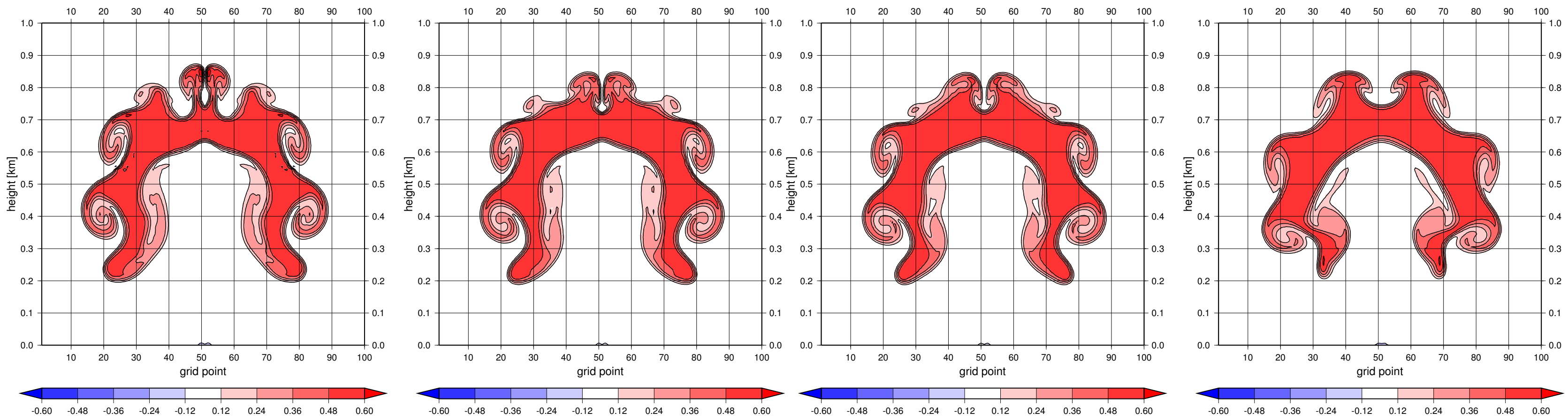
General interpolator of Aladin

$(\kappa = -2)$ $(\kappa = 0)$ $(\kappa = 1)$ $(\kappa = 6)$



$\Rightarrow$ decreased diffusivity of SL interpolator needs to be compensated by increased horizontal and vertical diffusion. Lagrangian cubic seems to perform extremely well for the real atmosphere.

Semi-Lagrangian scheme - III.

Limitations

- Trajectory research
  - still some ways to improve within the current code
  - higher order iterative methods in spirit of RK

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  - higher order iterative methods in spirit of RK
- Mass conservation
  - conservative cascade remapping (Nair, Lauritzen, Ullrich, Shashkin, Tolstykh, Zerroukat,...)
    - better than 2^{nd} order convergence
    - one order of magnitude more accurate than Eulerian finite-volume transport schemes
    - the method based on piecewise parabolic distribution of cell averaged density resembles much more expensive PPM (piecewise parabolic methods)

Semi-Lagrangian scheme - III.

Limitations - cont.

- Communication (MPP)

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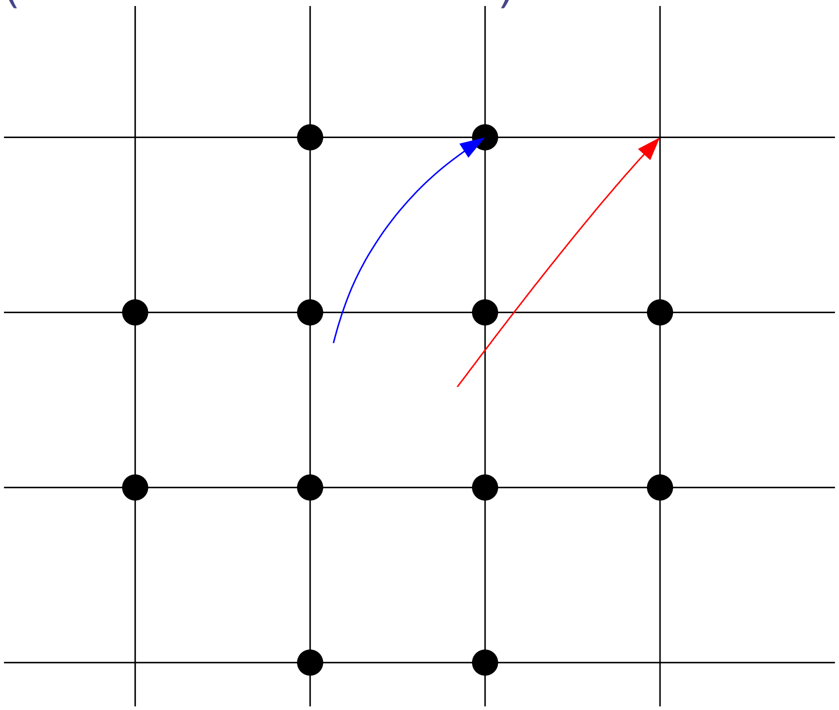
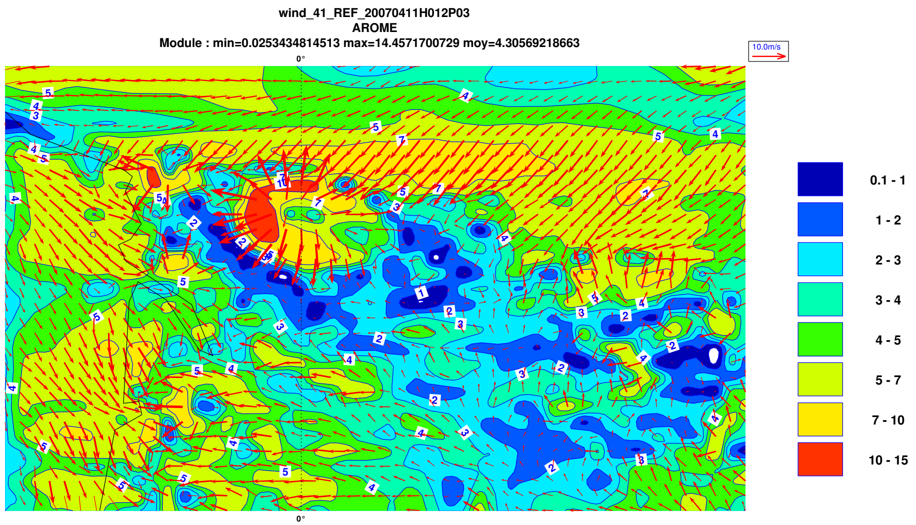


Semi-Lagrangian scheme - III.

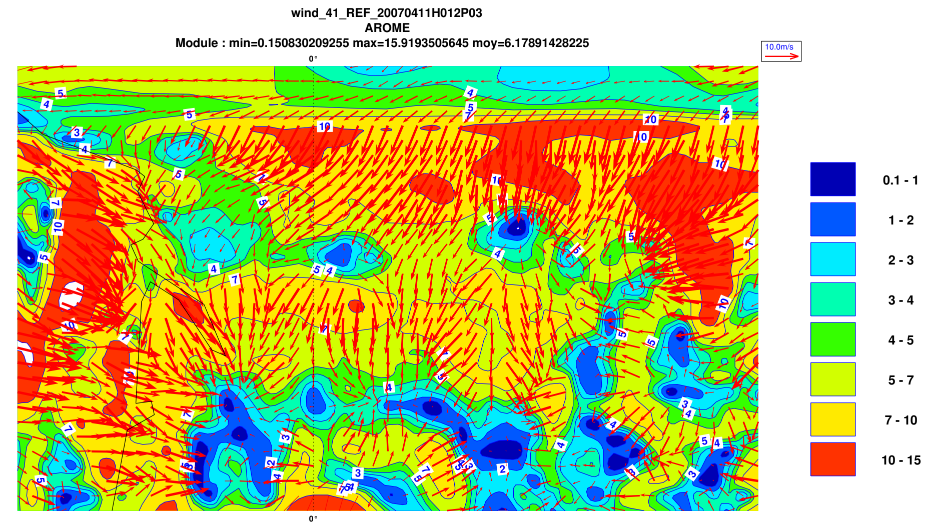
Limitations - cont.

- Communication (MPP)
- Memory conflicts (vector architectures)
- Long timesteps has better chance to destabilize model fields

  Spectral HD is proportional to the field itself (it doesn't care about any atmospheric balance)



full HD

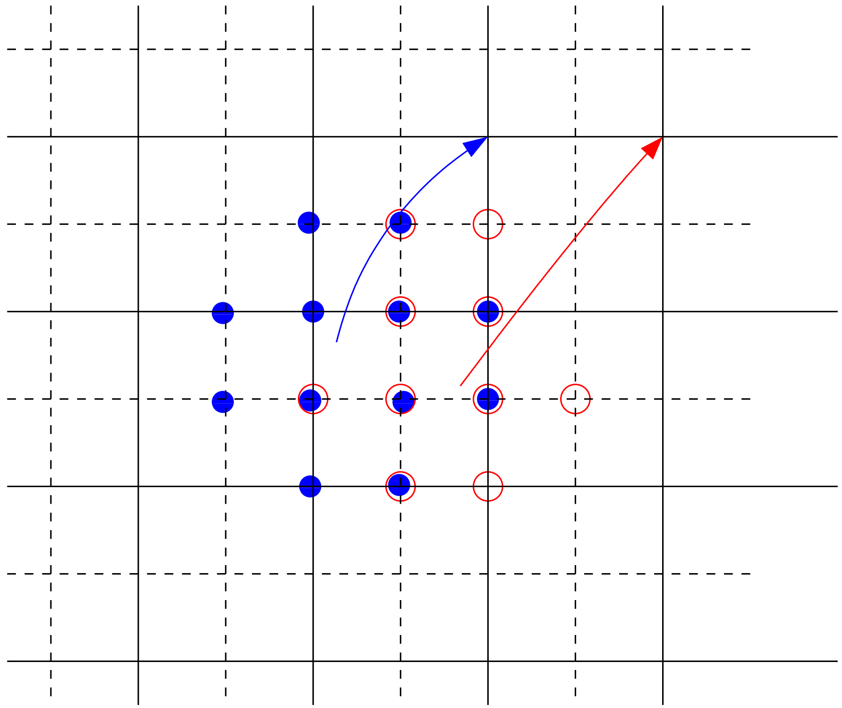


reduced HD

Semi-Lagrangian scheme - III.

P-refinement - a solution for memory conflicts?

Vector machines: memory is not an issue, FFT^{-1} is cheap



Aladin/CE, NEC SX9:

- FFT^{-1} performed to double resolution (+5%)
- memory conflicts reduction by $\approx$ 60-70% (-5%)
- SL comms reduced by up to 50%

better handling of imbalances

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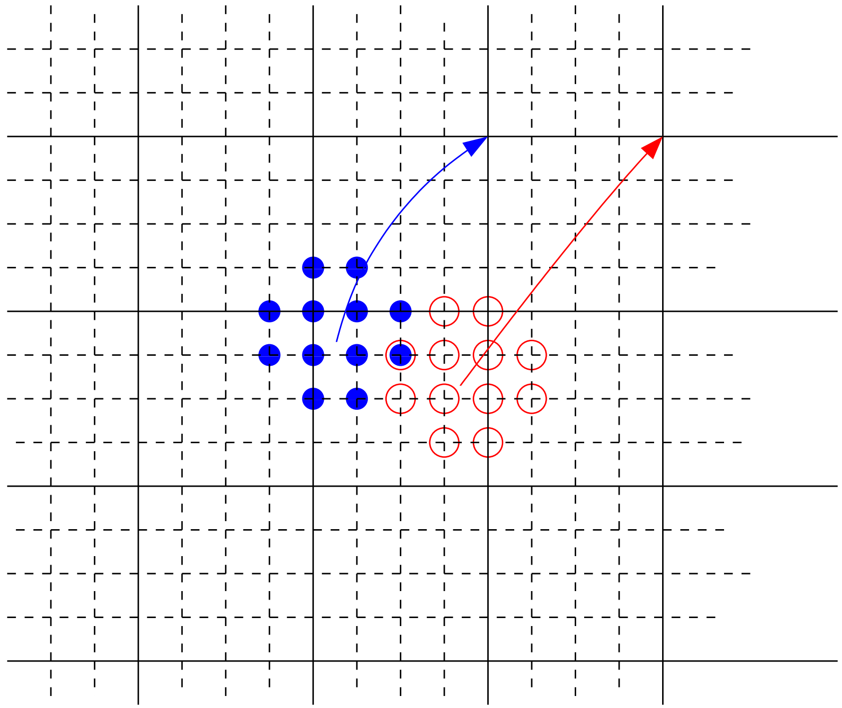

Aladin/CE, NEC SX9:

- FFT^{-1} performed to four times higher resolution (+15%)
- nearly no memory conflicts (-8%)
- SL comms reduced by up to 75%

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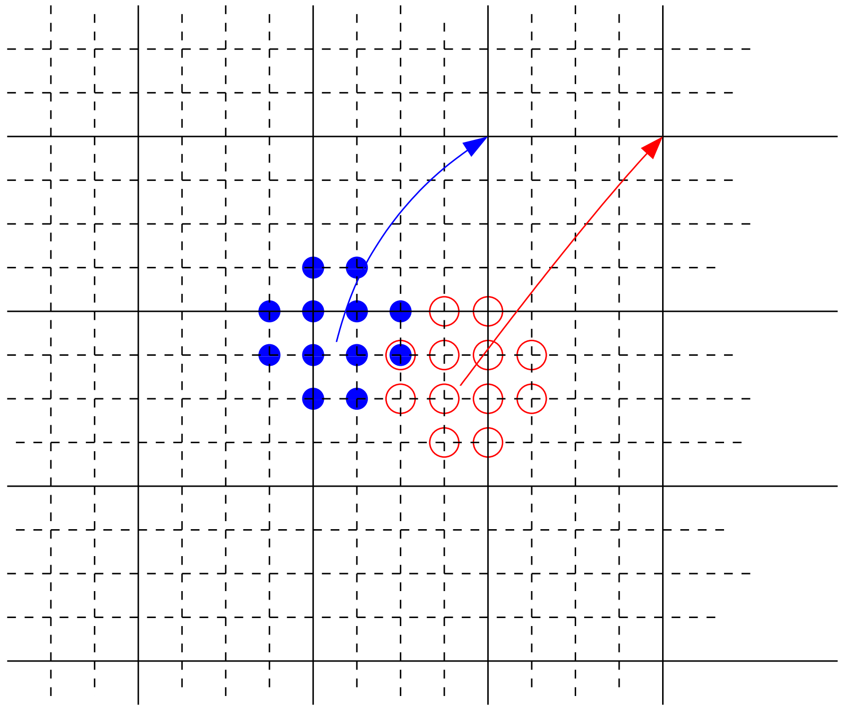

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no gain for SX9 (without MPI), but there's a potential...

Spectral methods

Advantages

- Very accurate (until certain extent)
- Efficient SI and spectral HD
- Reduced memory conflicts, easier decomposition along horizontal
- Offers a nice tool for sub-grid modeling of turbulence
- SSDFI

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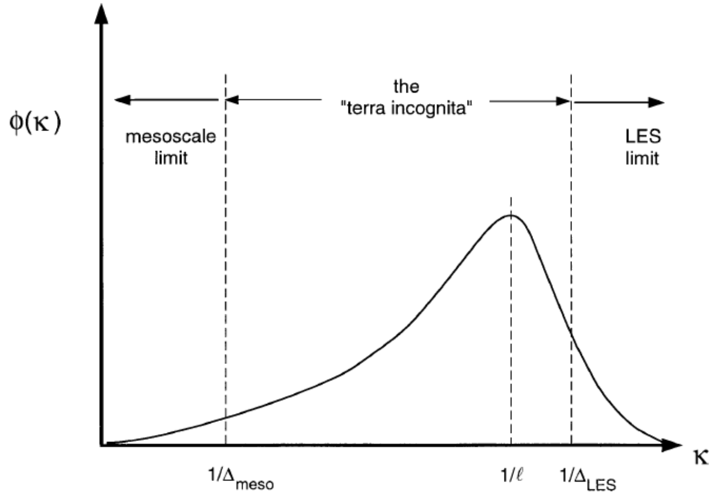
Limitations

- Global character, FFTs are expensive for MPP with poor network
- Limitations for the SI background profiles
- More difficult handling of sharp features
- Orography representation needs some special care
- With locally conservative schemes, an extra care is required to derivatives computations

3D turbulence

- Entering the scales of turbulence ($L \approx dx$) we are appearing with our models in the "terra incognita" of turbulence modeling



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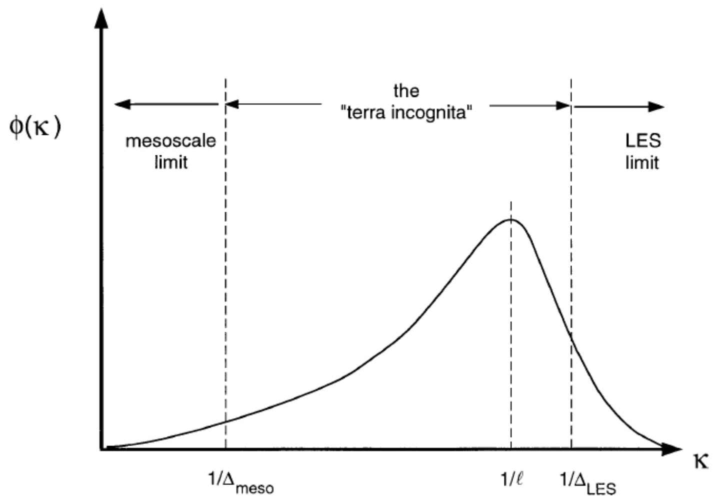

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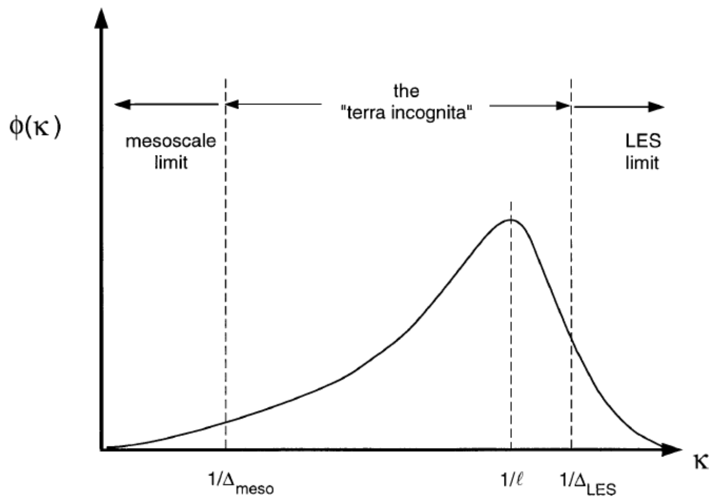

- The 3D interactions of turbulence should be no longer neglected
- Problem how to do it in the most optimal way (with respect to the forecast quality and also the cost)

3D turbulence in ALADIN

Options to be considered for horizontal components

(from short till a long-term range)

- Retuned SLHD

  $\Rightarrow$ *SL*

- Extension of TOUCANS based on QNSE

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- Previous combined with (Lagrangian-averaged) dynamic model

  $\Rightarrow$ *spectral methods, SL*

- Full (Lagrangian-averaged) dynamic model

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⇒ Trajectory computations and spectral methods are becoming increasingly popular in turbulence modeling.

SLHD

Discretized 2TL SI SL equation for Ψ^+ reads:

$$\Psi_F^+ = \left(1 - \frac{\Delta t}{2}\mathcal{L}\right)^{-1} \left[\underbrace{\left(1 + \frac{\Delta t}{2}\mathcal{L}\right)\Psi_O^0 + \Delta t \mathcal{F}_O^0}_{I} + \underbrace{\frac{\Delta t}{2}\mathcal{N}_O^*}_{I_L} + \frac{\Delta t}{2}\mathcal{N}_F^* \right]$$

The high order interpolator I weights are evaluated as:

$$\begin{pmatrix} \tilde{w}_1 \\ \tilde{w}_2 \\ \tilde{w}_3 \end{pmatrix} = \begin{pmatrix} 1-2\varepsilon & \varepsilon & 0 \\ \varepsilon & 1-2\varepsilon & 0 \\ 0 & \varepsilon & 1 \end{pmatrix} \cdot \begin{pmatrix} w_{lag,1} + \kappa(w_{quad,1} - w_{lag,1}) \\ w_{lag,2} + \kappa(w_{quad,2} - w_{lag,2}) \\ w_{lag,3} + \kappa(w_{quad,3} - w_{lag,3}) \end{pmatrix},$$

SLHD is introduced when κ and ε are defined as:

$$\kappa = \kappa_{min} + (\kappa_{max} - \kappa_{min}) \frac{\Delta t F(d, D_2)}{1 + \Delta t F(d, D_2)}, \qquad \varepsilon = \varepsilon_{H,V} \frac{\Delta t F(d, D_2)}{1 + \Delta t F(d, D_2)}$$

3D extension of TOUCANS

$$\frac{\partial \Psi}{\partial t} + ... = \boxed{-K_H \frac{\partial^2 \Psi}{\partial x^2} - K_H \frac{\partial^2 \Psi}{\partial y^2}} - \frac{\partial}{\partial z}\left(K_V \frac{\partial \Psi}{\partial z}\right) - K_{Num}\mathcal{D}(\Psi)$$

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where

- $K_H = K_H(x, y, z, t)$ but we assume $\nabla_H K_H \cdot \nabla_H \Psi = 0$
- $\nabla_H^2 \Psi$ is evaluated by the GP Laplacian of SLHD
- $K_V \neq K_H$
- K_V and K_H are derived in a consistent way with TOUCANS (emulating QNSE):

$$\begin{aligned} K_{m,V} &= L_K C_K \sqrt{e}\chi_3(Ri) \\ K_{h,V} &= L_K C_K C_3 \sqrt{e}\phi_3(Ri) \end{aligned} \Rightarrow \begin{aligned} K_{m,H} &= L_K^H C_K \sqrt{e}\chi_H(Ri) \\ K_{h,H} &= L_K^H C_K C_3 \sqrt{e}\phi_H(Ri) \end{aligned}$$

Dynamic model - an introduction

Germano identity

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- Additional test-filtering operation is introduced at scales $\alpha\Delta x$ with $\alpha > 1$, denoted by a convolution $G_{\alpha\Delta x} * q = \widehat{q}$.
- The Germano identity than simply reads:

$$\widehat{\overline{\mathcal{N}(q)}} - \mathcal{N}(\widehat{\overline{q}}) = \left[\widehat{\overline{\mathcal{N}(q)}} - \widehat{\mathcal{N}(\overline{q})}\right] + \left[\widehat{\mathcal{N}(\overline{q})} - \mathcal{N}(\widehat{\overline{q}})\right].$$

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- Previous applied to TOUCANS-3D leads (for example) to:

$$T_i = L_K^{\alpha H} C_K \chi(\widehat{Ri}) \sqrt{\widehat{e}} \widehat{\frac{\partial u_i}{\partial x_i}}, \quad \tau_i = L_K^H C_K \chi(Ri) \sqrt{e} \frac{\partial u_i}{\partial x_i}$$

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- Optionally $\widehat{\tau_i}$ can be evaluated in the SL stencil (to ease dataflow and to save some CPU)

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- Evaluating the $\hat{\tau}$ by spectral space, one would have a full freedom to evaluate any $\frac{\partial \tau_{ij}}{\partial x_i}$ at the same time.
  $\Rightarrow$ Full LES sophistication starts to be available.

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- What is the optimal solution with respect to the future computers? Going to o(10^5) is the only one side of the problem. There are other relatively seldom discussed views: Cray's new GEMINI switch, SW features like SHMEM (shared memory access library) or UPC (Unified Parallel C). In contrary, NWP people are frequently mentioning the potential of GPU. But to profit form it would require to the solve the problem of data transfer in/out to GPU.

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- There has been much work on constructing high-order spatial discretization methods but not as much effort has been spent on implicit time-integration. There might be a potential to obtain high-accuracy yet efficient time-integrators.