A non-hydrostatic SI dynamical core : current-state, limitations and perspectives

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(Thanks to: F. Voitus, S. Caluwaerts, Ch. Colavolpe, Y. Seity, ...)

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INTRODUCTION

Galaxy

We speak about the dynamical core of the following "galaxy" :
IFS(ECMWF) / ARPEGE (MF) / ALADIN (Int'l) / HARMONIE (Int'l)

The dynamical core of these models share many parts in common, developed jointly, code cooperation

History (dynamical core)

- IFS+ARPEGE (Global HPE) .... oper
- ALADIN (LAM HPE) .... oper
- ALADIN NH (LAM NH) – HARMONIE, AROME... .. oper
- ARPEGE NH and IFS NH (Global NH) .... exper

INTRODUCTION

Three talks are dealing more or less with the same dynamical core (or research avenues) :

- N. Wedi
- P. Bénard (time)
- M. Hortal (space)

INTRODUCTION

OUTLINE of the talk

- Current status of AROME model
- Limitations (mainly from SI point of view)
- Perspectives

CURRENT STATUS of AROME

What is AROME ?

- AROME: High resol LAM model NH (Euler Equations) operational at Meteo-France (also in some other countries)
- Dyn core IFS/ARP/ALA-NH (common concept, spectral SI SL)
- "Meso-scale" physics from 90-00's research world (column-wise)
- 3D-VAR Data Assimilation with 3h cycle
- Many mesoscale observations assimilated (Radar reflectivities, Doppler wind, thiner Sat radiances...)

Current oper configuration of AROME

- $\Delta x = 2.5$ km, 60 levels, 750*720 points
- $\Delta t = 60$s (30h forecasts)
- limited overcost with respect to HPE version

CURRENT STATUS of AROME

Experimental version (1)

- $\Delta x = 1.3$ km, 90 levels, $\Delta t = 45$ s
- Prototype for next oper version
- smaller domain, dynamical adaptation (no Data Assim)
- Has run routinely at 00UTC $\rightarrow$ 30h for one year
- robust, positive impact, nice results

Experimental version (2)

- $\Delta x = 0.5$ km, $\sim$100 levels, Δt 10-15s
- Only isolated test cases (in dynamical adaptation)
- $\rightarrow$ robustness OK (but small sample)

Next operational configuration of AROME

Characteristics

- $\Delta x = 1.3$ km, 90 levels, 1536*1440 points
- $\Delta t = 45$s (still 30h forecasts)

CPU overcost to current version

Δx + Dom	Δz	Δt	SI $\rightarrow$ ICI	Other	Total
$\times 4.1$	$\times 1.5$	$\times 1.33$	$\times 1.1$	$\times 1.1$	$\times 10$

Maximum slope : $23^\circ \rightarrow 38^\circ$ hence "SI $\rightarrow$ ICI" .

On new Bull machine ∼25000 cores (∼1000 nodes) ∼500 tflops
$\Rightarrow$ new AROME ($\Delta x = 1.3$ km) in operations at summer 2014.

Limitations of the current system

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Indentified concerns

- Scalability (mainly at high granularity)
- Ability to manage severe high-resolution flows and slopes
- Compatibility with new developments (e.g. change progn. var., Vertical Finite Elements,...)

Possible modifications (of time-scheme) for solutions

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- give-up implicitness and use filtered system → Explicit Quasi-Elastic

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Retained option for mid-term: improve SI scheme

Original spirit of SI Schemes

System to solve (e.g. in Leap-Frog)

$$\frac{\partial X}{\partial t} = M(X) \quad \rightarrow \quad \frac{X^{+} - X^{-}}{2\Delta t} = RHS$$

Two limiting-case of centered time schemes

- Explicit : $\frac{X^{+}-X^{-}}{2\Delta t} = M(X^{0})$
  $\rightarrow$ easy, bad stability (wave-CFL)
- Crank-Nicolson: $\frac{X^{+}-X^{-}}{2\Delta t} = M\left(\frac{X^{+}+X^{-}}{2}\right)$
  $\rightarrow$ very good stability, but very difficult to attain

Original spirit of SI Schemes

Original SI scheme (1970s)

Choose a simple stationary fixed state X_*
Define the linear operator L_* as $L_* = \frac{\partial M}{\partial X}\Big|_{X_*}$
Then SI scheme:

$$\frac{X^+ - X^-}{2\Delta t} = [M - L_*]\,(X^0) + L_* \left(\frac{X^+ + X^-}{2} \right)$$

$$X^+ = (I - \Delta t L_*)^{-1} \left\{ X^- + \Delta t \left[2M(X^0) + (L_* X^- - 2 L_* X^0) \right] \right\}$$

Stability depends on what is in $[M - L_*]$
and may lead to bad surprises...

"General pedagogy" about SI Schemes

- Stable explicit schemes are conditionally stable (in terms of Δt), CFL...

Analysis for simple flows :

SI schemes may be unconditionally stable (in terms of Δt)
e.g. handbooks : "... SI-SL unconditionally stable ... "

Ignoring SI overcost

"I'm going to add a SI scheme in my model,
putting some implicitness in the scheme cannot hurt..."

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This is wrong !

- SI schemes may be unconditionally unstable (in terms of Δt)
- 'unstable' SI schemes are unconditionally unstable (in terms of Δt)

"SI Schemes

Robustness of simple SI schemes becomes poorer and poorer when the stiffness of the system increases:
SW $\rightarrow$ HPE $\rightarrow$ EE $\rightarrow$ EE + High Resolution

If SI kept, need to improve it (from the original idea)

Two main ways:

"TL-SI" Schemes

Improving the content of L_*

If we define $X_* = X^0$ (X at current time-step)
The linear operator L_* is then $L_0 = \frac{\partial M}{\partial X}\Big|_{X_0}$ (same TL as in 4D-VAR)
Then SI scheme:

$$\frac{X^+ - X^-}{2\Delta t} = [M - L_0]\,(X^0) + L_0\left(\frac{X^+ + X^-}{2}\right)$$

Very close to Crank-Nicolson, need to invert L_0 ($I - \Delta t L_0$, indeed)
But L_0 is large 3D, non-sparse, time-dependant, and ill-conditioned
solution approached by iterative solver operator of the size of X
Not very realistic (4D-VAR uses TL, but does not try to invert it)
Practical approach : drop as much as possible terms or dependencies in L_0 while trying to remain stable
Instability usually occur by lack of convergence toward the aimed scheme in the iterative solver.

"ICI" Schemes

Improve by iterating L_*

Define a time-independant linear operator L_*
Then use iterative scheme (with iterator index k):

$$\frac{X^{+(k)} - X^-}{2\Delta t} = M(\frac{X^{+(k-1)} + X^-}{2}) + L_* \left(\frac{X^{+(k)} - X^{+(k-1)}}{2} \right)$$

Initialize by a simple extrapolated estimate: $X^{+(0)} = (2X^0 - X^-)$
$k = 1 \rightarrow$ classical SI scheme

$$\frac{X^+ - X^-}{2\Delta t} = M \left[\frac{(2X^0 - X^-) + X^-}{2} \right] + L_* \left[\frac{X^+ - (2X^0 - X^-)}{2} \right]$$

then $k = 2$, $k = 3$, ... $\rightarrow$ ICI scheme
If converging, converges toward Crank-Nicolson scheme
Pre-inversion $\Rightarrow$ still relatively cheap (if $k_{\max}$ small)
If L_* too simple, will not lead to a convergent system

TL-LI and ICI Schemes

These are not the same

$$\frac{X^+ - X^-}{2\Delta t} = [M - L_*]\,(X^0) + L_*\left(\frac{X^+ + X^-}{2}\right)$$

- TL-SI tries to minimize $L_* - L_{X_0}$
  (to treat explicitely only the NL part of M)
- ICI tries to approach Crank-Nicolson globally
  (to treat explicitely nothing)
- Both can always be combined

Limitations of the current AROME SI scheme

- Spectral: very efficient SI (direct solver), but:
- Spectral SI ⇒ Constant Coefficients SI (CCSI)
  coefficients of L_* must not depend on space
  otherwise no longer (direct) solution of SI problem
  Example SW:

$$(I - \Delta t^2 \phi_* \nabla^2)\phi^+ = \mathrm{RHS}$$

$$(I - \Delta t^2 \phi_*(x) \nabla^2)\phi^+ = \mathrm{RHS}$$

- Slopes increase with resolution → CCSI not robust enough:
  $\Delta x = 2.5$ km: CCSI robust with $\Delta t = 60$ s
  $\Delta x = 1.3$ km: CCSI not fully robust with $\Delta t = 30$ s
  $\Delta x = 1.3$ km: CC ICI robust with $\Delta t = 45$ s (one iteration $k = 2$)

Still OK (with ICI) – even 30% cheaper – but indicates danger

CHALLENGES for AROME

Prioritizing identified concerns

- Scalability:
  We think we can survive at mid-term (FLT,...)
- Compatibility with new developments:
  We have now good hope to manage implementing VFEs
- Severe flows and slopes:
  Is prioritized as the main concern at mid-term

PERSPECTIVES for our dynamical core

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Postulates

- Assume the current SI scheme is operational-proof at $\Delta x \sim 500$m
  (accuracy of the response, ability to include progesses, scalability)
- Assume (or show) that future potential problems first originate
  from the orographic forcing

- Concentrate on including orographic forcing terms in the SI scheme (only)
- Try to keep the time-independant SI inversion problem pre-computed

PERSPECTIVES for our dynamical core

Include the orographic forcing into the SI treated terms

- SI problem remains time-independant by nature
- SI problem no longer homogeneous linear, non-separable
  $\rightarrow$ requires a 3D non-direct solver
- Strong identity required between space operators used in explicit RHS and in implicit LHS (to be inverted).

$$(u^{+} + \Delta t \partial_x) T^{+} = ... + \Delta t \partial_x (2T^0 - T^{-})$$

- Non-possible choice: spectral computation of derivatives in explicit terms and grid-point operators in the matrix of the implicit scheme
- Matrix form of spectral ∂_x possible but $\rightarrow$ many full blocks non-sparse 3D SI problem, not realistic (although time-independant)
- Non-spectral model / local horizontal operators only (preserve sparsity).
  $\Rightarrow$ Horizontal: high-order FE

PERSPECTIVES for our dynamical core

Consequences of non-spectral model

- Make the use of the solver compatible with efficiency/scalability
  Choose solver which exploits sparse matrix property
- Which variables and staggering for horizontal FE ? (next slide)
- For global model, which grid geometry for horizontal FE (next slide)
- Preserve pre-computation SI operator ???

PERSPECTIVES for our dynamical core

Which variables and staggering for horizontal FE ?

- Deals with short gravity waves propagation, geostrophic adjustment and computational modes
- Advantages of non-staggered grids:
  - Approach valid on any grid-geometry (i.e. problem of discretisation disconnected from the one of the geometry)
  - Preserve (u+v):p d.o.f. ratio for no spurious computational modes (ratio 2:1 ensures only 2 gravity modes for one Rossby mode)
- Examine non-staggered grid with Vor-Div variables:
  - correct propagation of short gravity waves
  - needs transform $(VOR, DIV) \rightarrow (u, v)$ (Poisson Equation)
  - non-locality reappears, however standard and 2D problem ...
- PhD work by S. Caluwaerts (IRM - Brussels)

PERSPECTIVES for our dynamical core

Which grid-geometry for global horizontal FE ?

Deals with spurious evolution of Rossby waves

Reduced lat-lon grids

- Reported drawback: distorted Rossby waves propagation with spurious meridional transport
  ... but this is only only for 40 years-old configurations
  ... with 2nd-order FD schemes, with very low resolutions
  ... and drastic grid-reduction
- Preserves simple geometry along each parallel circle
  $(\partial/\partial\lambda)$: trivial 1D uniform spacing
  $(\partial/\partial\varphi)$: uniform spacing
- Preserves existing model architecture

PERSPECTIVES for our dynamical core

Further perspectives (not discussed)

- explore horizontally explicit schemes (HEVI) for EE
  coupled with time-splitting technique
  use with a pre-computed vertical SI scheme
  sensitivity to the choice of the variable
  (Phd work by Ch. Colavolpe)
- explore non-terrain-following coordinate with ‘step-orography’ for very high resolution (‘kick’ response at orography-steps become evanescent?)

CONCLUSIONS

CONCLUSIONS

- Current SI scheme may reach its viability limits at some mid-term
- However still very competitive $\Rightarrow$ mid-term-strategy :
  change space-discretization (FE) and keep (improved) SI scheme
- Try to keep unmodified the deepest architectural nucleus of the model's kernel: grid A + lat-lon (reduced)
- This step is compatible with longer-term programs (HEVI,...)