NH modelling with AROME

(and some properties of Quasi-Elastic systems)

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8-10 November 2010 - Reading

AROME

- Almost 2 years of AROME operations
- Some results with AROME model

Quasi-Elastic systems (Arakawa and Konor, 2009)

- QE systems as an alternative to EE systems ?
- Normal modes of the QE system
- The dark face of the QE system

Almost 2 years of AROME operations

- Part of the IFS/ARPEGE/ALADIN/AROME/HARMONIE galaxy
- EE system, Cartesian, hybrid "η" "mass" coord. (Laprise)
- 2-TL SL SI
- Spectral (horiz.) and FD (vertic.)
- Physics adapted form mesoscale research model Meso-NH
- 3D-VAR RUC (3h)
- Inclusion of mesoscale observations (radars, AIREPS, AMSU-A,...)

(see : Bénard et al., QJRMS, 2010; Seity et al., MWR, 2011)

Almost 2 years of AROME operations (cont'd)

Operational suit : 4 runs/day to 30 h forecasts

First version (on Nec SX8, in ops. on 18th Dec. 2008):

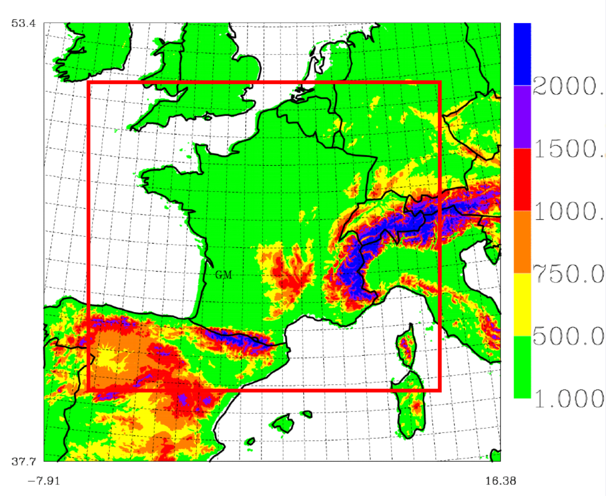
- 600x500 pts, (Δx"= 2.5 km), 41 levels, Δt=60s
- Coupled to ALADIN (9.5km) itself coupled to ARPEGE (15km)

Second version (on Nec SX9, in operation from 6th Apr. 2010):

- 60 levels, and coupled to ARPEGE (10 km)

Third version (Nec SX9, in ops. on Nov. 19th 2010 ?):

- New domain 750x720 pts
- Six condensate species (adding hail)
- More mesoscale observation data (7 additional radars; more IAREPS, IASI)



- inner (in red): current domain (600x500)
- outer : new domain (750x720)

Almost 2 years of AROME operations (cont'd)

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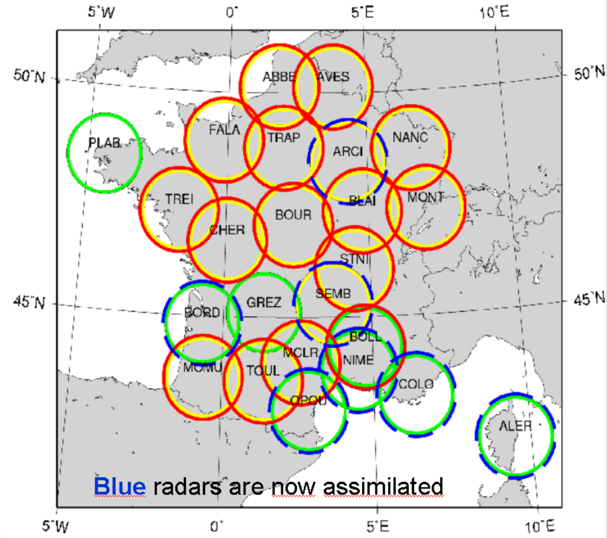
5°W
0°
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10°E
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ABBE
AVES
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FALA
TRAP
ARCI
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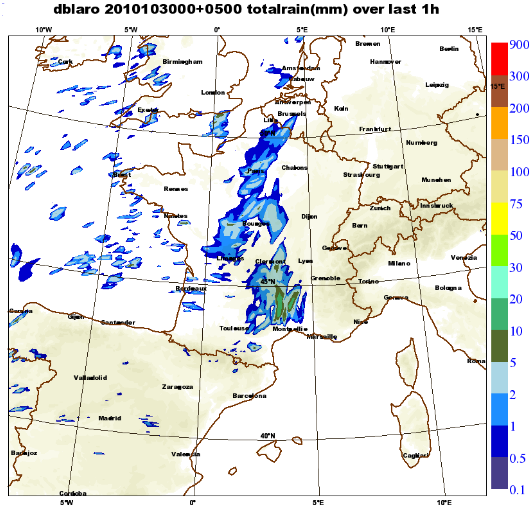
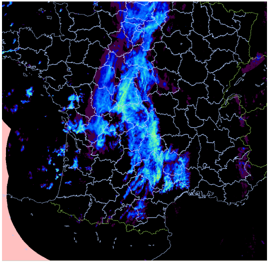
TREI
BLAI
MONT
BOUR
CHER
STNI
SEMB
BORD
GREZ
BOLL
MCLR
NIME
MOMU
TOUL
COLO
OPOU
ALER
Blue radars are now assimilated

Almost 2 years of AROME operations (cont'd)

Some results with AROME :
- "Cevenol" flood case (2010/10/30)
- Xynthia storm case (2010/02/27)
- AROME evaluated by forecasters
- Availability on two years

"Cevenol" Flood case of 2010/10/30





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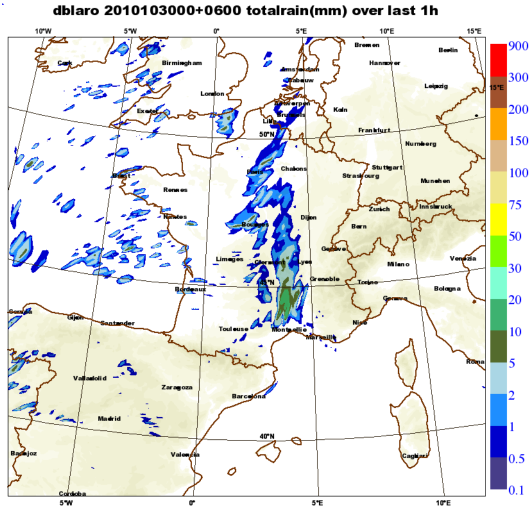

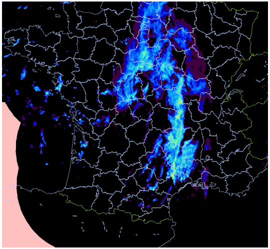

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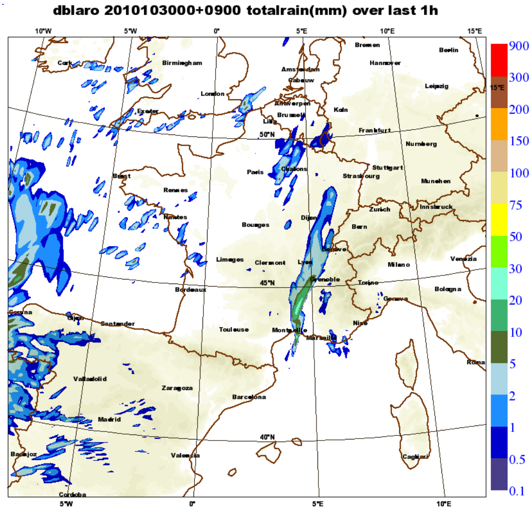

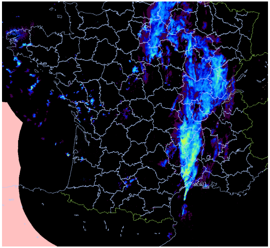

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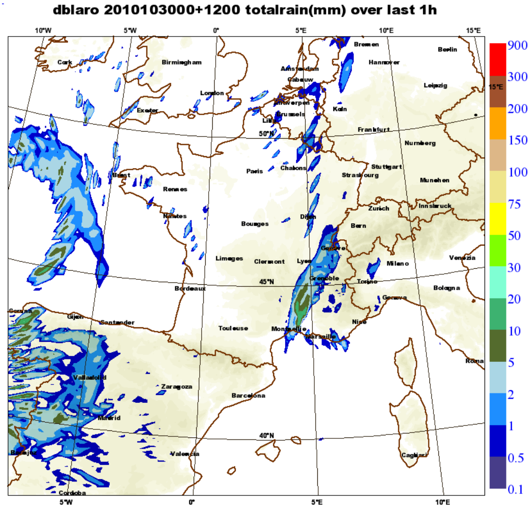

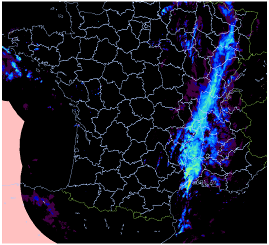

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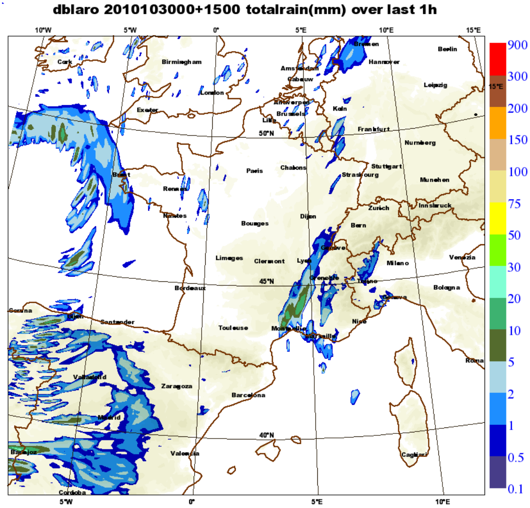

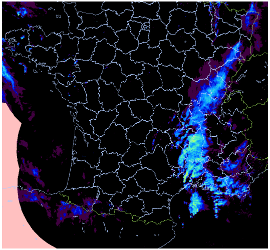

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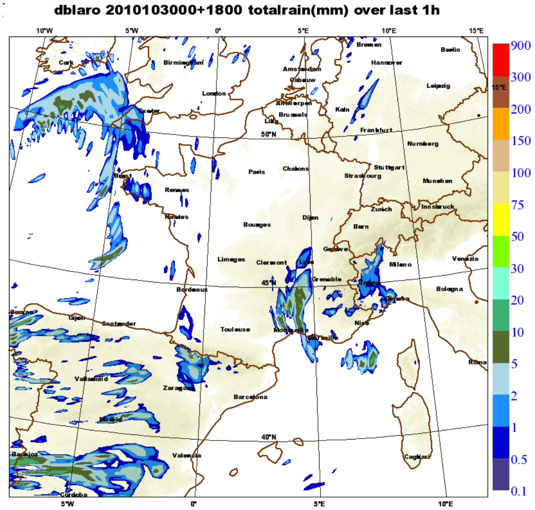

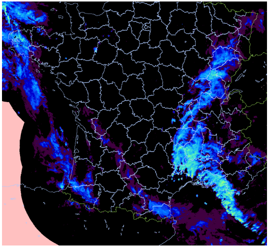

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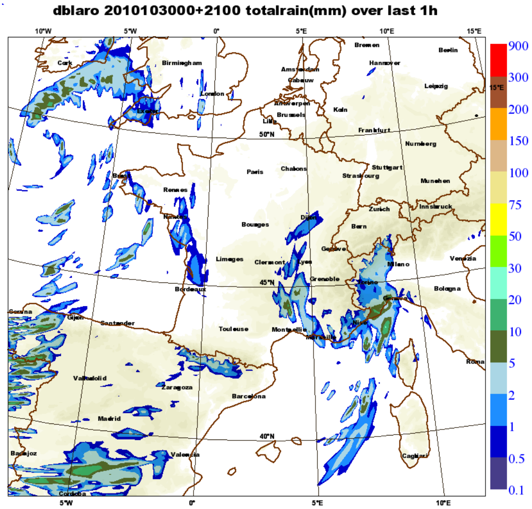

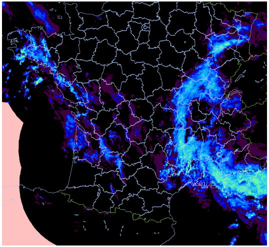

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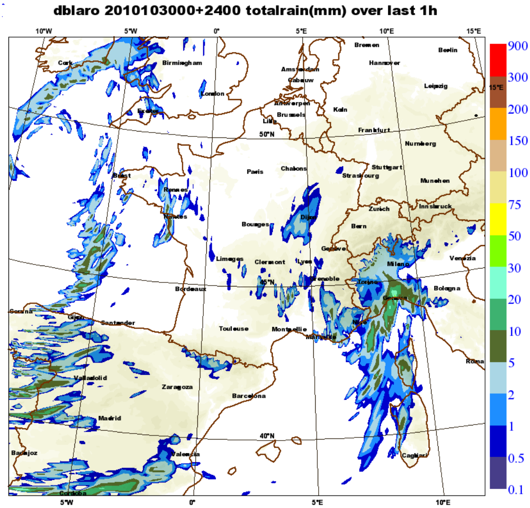
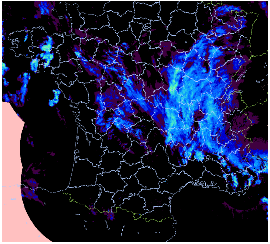
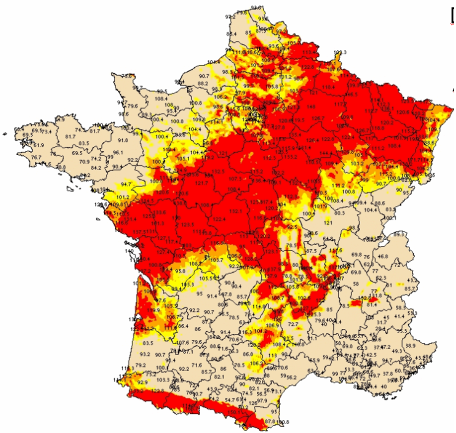




"Xynthia Storm (2010/02/27)



Max gust velocity for 2010/02/27-28:

Yellow : max gust > 95 km/h

Orange : max gust > 100 km/h

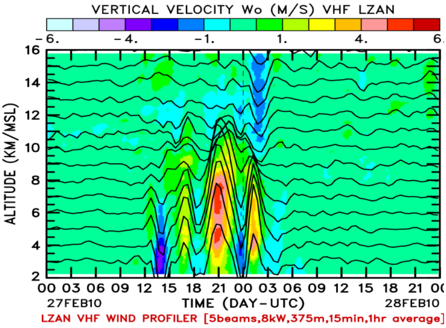
Red : max gust > 105 km/h

1) Strong sea flood on Atlantic coast (30 deads)

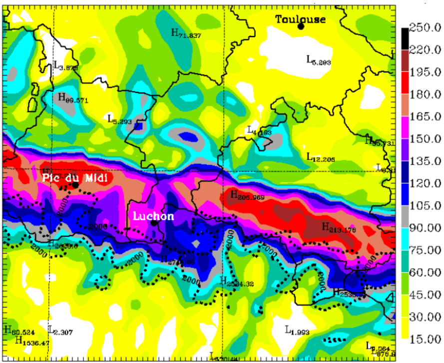
2) Strong winds in Pyrenees mountains (1 dead)

Second point quite challenging for dynamics (quite rare, downslope winds, calm areas...)

"Xynthia Storm (2010/02/27)



Lannemezan vertical profiler (Vert. Velocity *w*, in m/s)



10m gust wind 21:00 h (213 km/h AROME, 209 km/h obs)

"Xynthia Storm (2010/02/27)

Good forecast on the Pyrenees with AROME :
wind storm on the downwind slope
winds on peaks but also in valleys
Correct structure of trapped lee-waves
More accurate than Aladin (hydrostatic)

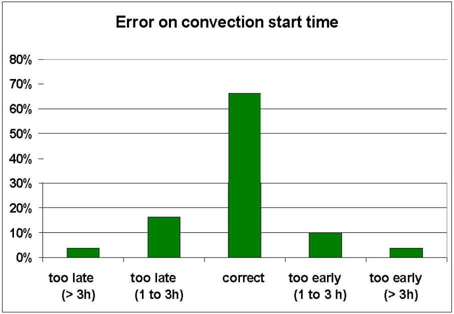
AROME seen by forecasters

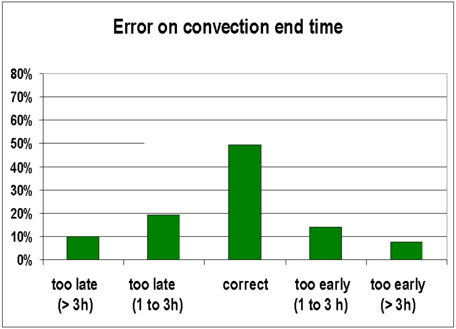
Goal 1 : evaluate AROME on a less subjective basis
Goal 2: compare merits of both LAMs in operational use.

"Objective" evaluation in challenging situations.
Forecaster decides to open a "challenge" event;
Specifies the type of challenge (wind, precip, snow, fog,...)
Before event : fills a forecast form with indications of competitors models (Aladin, AROME)
After event : gives a "note" to the forecast" made with both competitors

AROME seen by forecasters

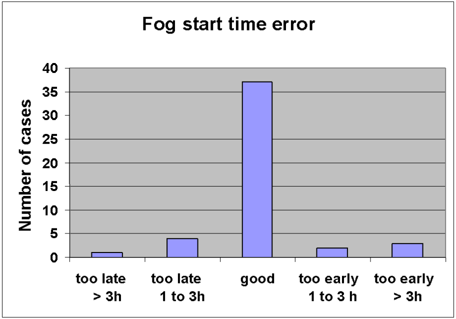
Evaluation of AROME for convection

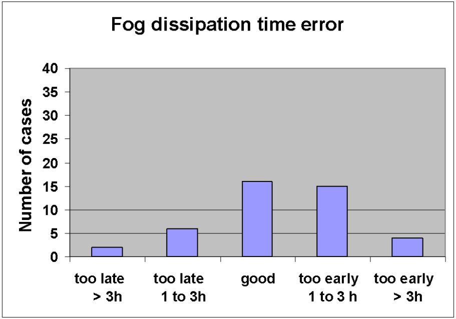




AROME seen by forecasters

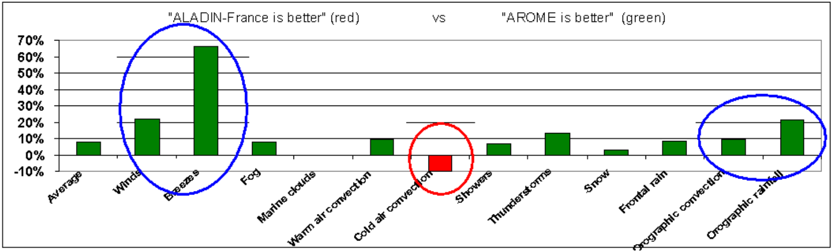
Evaluation of AROME for fog



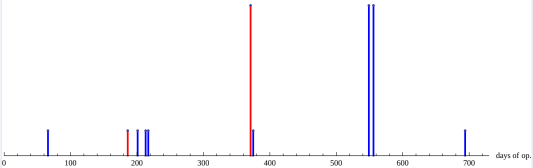


AROME seen by forecasters

Evaluation of AROME vs. Aladin:



Availability of AROME



Blue = Forecasts available
Red = Not all forecasts avail.

small bars = external problem (scheduler, computer)

tall bars = model problem (assim, forecast)

10 problems in about 700 days
Small : Mainly files problem in scheduler process ; forecasts from an older analysis or dynamical adaptation.
Tall.1 : problem in SL (too strong winds at top, cured by spectral coupling at top)
Tall.2 : problem in σ_b for grid-point q (cured by going back to spectral σ_b)

Conclusion about AROME

AROME does a fairly good operational job (availability and score)

Some weaknesses (exotic "d4" variable, no Vertical Finite Elements,...)

What about the limits of SL and spectral technics (slope, scalability...)

Still need of some prospective

QE systems, an alternative to Euler Eqs ?

Quasi-Elastic systems (Arakawa and Konor, 2009): The "minimal" modification of EE system that allows elastic wave filtering.

One less prognostic variable (pressure)

Diagnostic relationship for pressure.

But these are not anelastic systems.

QE systems, an alternative ... (cont'd)

All is in the continuity equations:

Euler Equations (EE):

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \mathbf{V}) = 0$$

Anelastic:

$$\nabla(\overline{\rho}\, \mathbf{V}) = 0 \quad \text{with} \quad \overline{\rho} = \overline{\rho}(z)$$

Pseudo-Incompr. (PI):

$$-\left(\frac{\overline{\rho}}{\overline{\theta}}\right) \frac{\partial \theta}{\partial t} + \nabla(\overline{\rho}\, \mathbf{V}) = 0 \quad \text{with} \quad \overline{\theta} = \overline{\theta}(z)$$

Quasi-Elastic (QE):

$$\frac{\partial \rho_h}{\partial t} + \nabla(\rho_h \mathbf{V}) = 0$$

(where ρ_h is "an" hydrostatic density)

QE systems, an alternative ... (cont'd)

Typically :

$$\frac{\partial p}{\partial z} = -\rho g \qquad \longleftrightarrow \qquad \frac{\partial p_h}{\partial z} = -\rho_h g$$

$\Longrightarrow$ The QE continuity equation is "very close" to the EE one.

QE systems, an alternative ... (cont'd)

$$\text{EE :} \qquad \frac{\partial \rho}{\partial t} + \nabla(\rho \mathbf{V}) = 0$$

$$\text{QE :} \qquad \frac{\partial \rho_h}{\partial t} + \nabla(\rho_h \mathbf{V}) = 0$$

Unlike Anelast. and PI, there is no $\overline{\rho}$

$\Longrightarrow$ In the limit of hydrostatic regime, the QE system becomes exact (in whatever region of the globe...).

$\Longrightarrow$ the first classical objection against anelastic systems falls.

Normal modes of the QE system

Dispersion relations for an isothermal f-plane state:

$$\mathrm{EE}: -(\nu^2-f^2)(N^2-\nu^2)-k^2c^2(\nu^2-N^2)-c^2(m^2+\mu^2)(\nu^2-f^2))=0$$

$$\mathrm{PI}: -k^2c^2(\nu^2-N^2)-c^2(m^2+\mu^2)(\nu^2-f^2))=0$$

$$\mathrm{QE}: -(\nu^2-f^2)(N^2) -k^2c^2(\nu^2-N^2)-c^2(m^2+\mu^2)(\nu^2-f^2))=0$$

Classical notations : $(k, m) =$ (horiz, vert) wave number, ν frequency

$N^2 =$ BV freq., $c^2 =$ speed of sound , $f =$ Coriolis param.

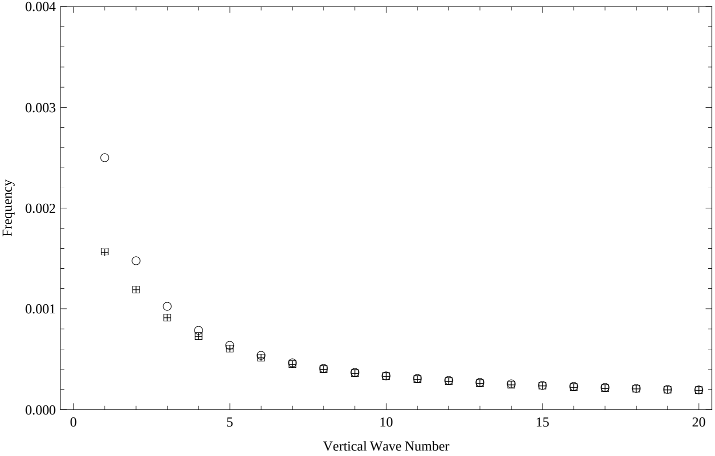
Normal modes of the QE system

Dispersion relations for an isothermal state, f-plane:

$$\mathrm{EE}: -(\nu^2 - f^2)(N^2 - \nu^2) - k^2c^2(\nu^2 - N^2) - c^2(m^2 + \mu^2)(\nu^2 - f^2)) = 0$$
$$\mathrm{PI}: \qquad -k^2c^2(\nu^2 - N^2) - c^2(m^2 + \mu^2)(\nu^2 - f^2)) = 0$$
$$\mathrm{QE}: -(\nu^2 - f^2)N^2 \qquad -k^2c^2(\nu^2 - N^2) - c^2(m^2 + \mu^2)(\nu^2 - f^2)) = 0$$

Leading term in red : $10^{[-4/-6]} \times 10^{-4}$, is present in QE relation.

$\Longrightarrow$ The frequency of GW are numerically equal in QE and EE systems



The frequency of internal gravity modes of horizontal scale 1000 km.
(squares : EE, + : QE, circles : Pseudo-Incompressible).

Normal modes of the QE system

The frequency of GW are numerically equal in QE and EE systems.
The height scale of normal modes ($\exp(-z/2H - \kappa/H)$) is exactly captured in QE system (not in anelastic ones).
The projection on kinetic, thermobaric and elastic component is exact also (not in anelastic systems).
These results extend to β-plane case (Davies et al. 2003, Thuburn et al. 2002)
Consequence : there is **no distortion** of any type of wave (including Rossby)

$\Longrightarrow$ the second classical objection against anelastic systems falls.

Normal modes of the QE system

Properties of the QE system:

- Filters Elastic waves
- Does not possesses the weaknesses of anelastic or PI systems
- Smoothly lends itself to various formulations (mass coord., SI,...)
- Potentially simpler than EE system

$\Longrightarrow$ QE is a promising system

The dark side of QE systems

HOWEVER ...

The dark side of QE systems

Dark side of QE : formulation and solution of the pressure diagnostic equation ...

Principle identical to anelastic models :
Substitute the $(\partial V/\partial t)$ and $(\partial w/\partial t)$ equations in $(\partial/\partial t)$ of the continuity equation.
Basically (and simplifying):

$$\begin{aligned}
\frac{\partial V}{\partial t} &= \mathrm{RHS}(\nabla p, ...) \\
\frac{\partial w}{\partial t} &= \mathrm{RHS}(\partial p/\partial z, ...) \\
\frac{\partial}{\partial t}\left(\nabla V + \frac{\partial w}{\partial z}\right) &= ...
\end{aligned}$$

The dark side of QE systems

In QE systems, this writes:

$$
\begin{aligned}
\frac{\partial V}{\partial t} &= \mathrm{RHS}(\nabla p, ...) \\
\frac{\partial w}{\partial t} &= \mathrm{RHS}(\partial p/\partial z, ...) \\
\frac{\partial \rho_h}{\partial t} &= f(V, \nabla V) \\
\frac{\partial}{\partial t}\left(f(V, \nabla V) + \nabla V + \frac{\partial w}{\partial z} \right) &= ...
\end{aligned}
$$

The dark side of QE systems

Formulation and solution of the pressure diagnostic equation

In σ coordinate (for conciseness):

$$
\begin{aligned}
\frac{\partial V}{\partial t} &= -\partial^* \widehat{p} \nabla \phi + \partial^* \phi \nabla \widehat{p} + Adv \\
\frac{\partial w}{\partial t} &= g(\partial^* \widehat{p} - 1) + Adv \\
\frac{\partial \rho_h}{\partial t} &= [V.\nabla \widehat{Q} - \mathbf{S}(\nabla V) - \mathbf{S}(\nabla \widehat{Q}.V)]
\end{aligned}
$$

with

$$
\begin{aligned}
\widehat{p} &= \ln p, \qquad \widehat{Q} = \ln p_{0s} \\
\partial^* &= \sigma \frac{\partial}{\partial \sigma}, \qquad \mathbf{S}(X) = \frac{1}{\sigma} \int_0^\sigma X d\sigma'
\end{aligned}
$$

The dark side of QE systems

Then :

$$
\begin{aligned}
&\left[(1-\kappa)\nabla\widehat{Q} - (\partial^* + 1)\frac{\nabla\phi}{\partial^*\phi}\right]\left(\partial^{*2}\phi\nabla\widehat{p} + \partial^*\phi\partial^*\nabla\widehat{p} - \partial^*\nabla\phi\partial\widehat{p} - \nabla\phi\partial^{*2}\widehat{p}\right) \\
&\quad - \left(\frac{\nabla\phi}{\partial^*\phi}\right)\Big(2\partial^*\phi\partial^{*2}\nabla\widehat{p} + 2\partial^{*2}\phi\partial^*\nabla\widehat{p} + \partial^{*2}\phi\nabla\widehat{p} + \partial^*\phi\partial^*\nabla\widehat{p} \\
&\qquad - \partial^{*2}\nabla\phi\partial^*\widehat{p} - 2\partial^*\nabla\phi\partial^{*2}\widehat{p} - \nabla\phi\partial^{*3}\widehat{p} - \partial^*\nabla\phi\partial^*\widehat{p} - \nabla\phi\partial^{*2}\widehat{p}\Big) \\
&\qquad + \kappa\left(\partial^*\nabla\phi\nabla\widehat{p} + \partial^*\phi\nabla^2\widehat{p} - \nabla^2\phi\partial^*\widehat{p} - \nabla\phi\partial^*\nabla\widehat{p}\right) \\
&+ \left(\partial^{*2}\nabla\phi\nabla\widehat{p} + \partial^{*2}\phi\nabla^2\widehat{p} + \partial^*\phi\partial^*\nabla^2\widehat{p} - \partial^*\nabla^2\phi\partial^*\widehat{p} - \partial^{*2}\nabla^2\widehat{p} - \nabla\phi\partial^{*2}\nabla\widehat{p}\right) \\
&\qquad - g^2(\partial^* + 1)\left(\frac{1}{\partial^*\phi}\right)\partial^{*2}\widehat{p} + \left(\frac{g^2}{\partial^*\phi}\right)\left(\partial^{*2}\widehat{p} + \partial^*\widehat{p}\right) \quad = \quad \mathrm{RHS}
\end{aligned}
$$

The dark side of QE systems

... with : "RHS" twice bigger than LHS (... or more, but does not really matter)

Results in a full 3D non-separable PDE with
almost the full zoology of up to third-order operators:

$$1,\ \partial^*,\ \partial^{*2},\ \partial^{*3}, \nabla,\ \partial^*\nabla,\ \partial^{*2}\nabla,\ \nabla^2\partial^*$$

For η coordinate, all the stuff would be twice bigger or so...

The dark side of QE systems

Solutions :

- Full solution (always possible but cost...)
- Trade-off 1 : keep $(\partial^2 \rho_h / \partial t^2)$ as a diagnostic
  e.g. $(\rho_h^{n+1} - 2\rho_h^n + \rho_h^{n-1})/\Delta t^2$
  This is the solution proposed by Arakawa and Konor 2009.
- Trade-off 2 : neglect some terms ? (replacing $\widehat{p}$ by the hydrostatic value)

Apparently no fully satisfying solution

Conclusion

Conclusion :

- QE system attractive from many points of view
- probably difficult to implement
- Difficult to establish practical viability without trying