High resolution experiments with the ALADIN NH dynamics

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1 Motivation

Since introducing the option LGWADV=.TRUE., hereafter referred as LGWADV (i.e. hybrid prognostic variable based on vertical wind w staggered on half levels used in explicit model while a linear model is designed with a vertical divergence d based prognostic variable, see section 3.2) it is known that this model settings offers superior performance for the famous (and difficult) two bubbles experiment introduced by Robert (1993).

The original implementation of this hybrid option allowed only to be used for the iterative ICI time scheme offering the most robust setting for the NH dynamics. With the introduction of the second (so called acoustic) temperature to the linear model (Bénard, 2004), the SETTLS extrapolation (Hortal, 2002) with simple SI scheme starts to offer stable performance safely exceeding the stability of the model physics. As the SI scheme represents also at least 30% reduction of the whole model cost with respect to the ICI scheme it should not be surprising that all the current operational non-hydrostatic (NH) model applications are based on the SI scheme.

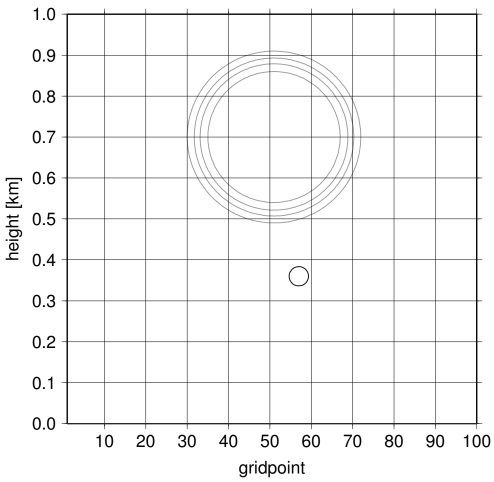

Figure 1: Initial profile of potential temperature for two bubbles experiment.

Aiming the good qualities of the LGWADV scheme with ICI time stepping there was naturally an interest to adapt this specific option also for the SI time scheme. The relevant implementation was done during the stay of K. Yessad at ECMWF in 2008. Unfortunately the resulting code was found unstable for the IFS and thus not really advertised within the international community sharing the same model dynamics (IAAAH). The knowledge that this option is available in the code remained unknown. No surprise then that the similar interest to have LGWADV with SI (hereafter referred as LGWADV+SETTLS[1]) in the model was reflected in the RC LACE scientific plan for 2011.

This paper summarizes the results obtained during a study done within the coordinated RC LACE research in 2011 at CHMI. The primary motivation for it was a check of an availability for the LGWADV+SETTLS option in the code. A specific focus of this study was however devoted to suitability of the current NH dynamics to serve as a safe dynamics kernel for future operational implementations at very high resolution, the scales where the non-hydrostatic effects play no longer a negligible role.

2 Experimental setup

As already mentioned the sensitive experiment demonstrating the LGWADV option superiority is the two bubbles experiment of Robert (1993). This experiment was used as the main diagnostic tool in this study.

[1]This can be a bit misleading as the SETTLS discretization can be used also in the ICI scheme. In this text however this will refer the LGWADW=.TRUE., LSETLLS=.TRUE. within the simple SI time-stepping, unless explicitly specified something else.

It was introduced into the 2D version of (adiabatic) model with 100 points in y-direction ($\Delta y = 10$ m) and 130 model levels with roughly lowest 100 levels spaced with $\Delta z = 10$ m bellow 1 km and remaining 30 levels leaved to maintain boundary condition with active sponge (`NSPONGE=2`).

The initial profile of temperature is demonstrated by the figure 1 showing the perturbation of potential temperature from the background value of 300 K with the contour interval 0.12 K. The maximum resolved departure of the warm bubble is 0.1485 K, the minimum resolved departure of the cold bubble is -0.5 K. The initial flow fields is set to zero maintaining also the hydrostatic balance $p = \pi$. The simulation is launched with Δt=5 s up to 10 minutes (120 time steps). The figures 2 and 3 illustrate the reference result for the potential temperature perturbation (with the same contour interval as the original profile) and the vertical velocity (with contour interval 0.09355 m/s) as it was obtained with the LGWADV and the ICI time-stepping after 7 minutes and 10 minutes (84 and 120 timesteps) of the simulation.

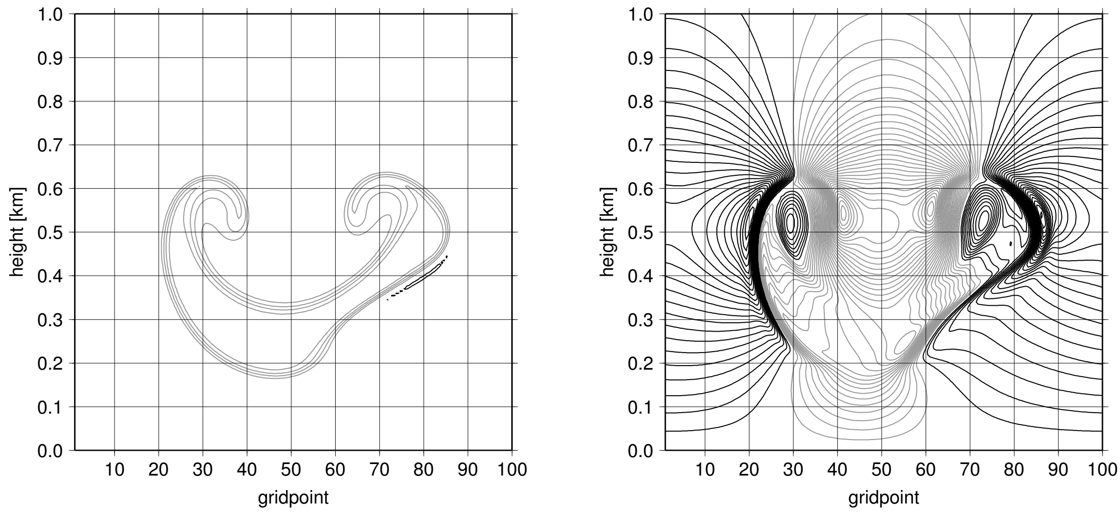

Figure 2: Potential temperature profile and vertical velocity (w) from the two bubbles experiment at the 7th minute of simulation (after 84 timesteps).

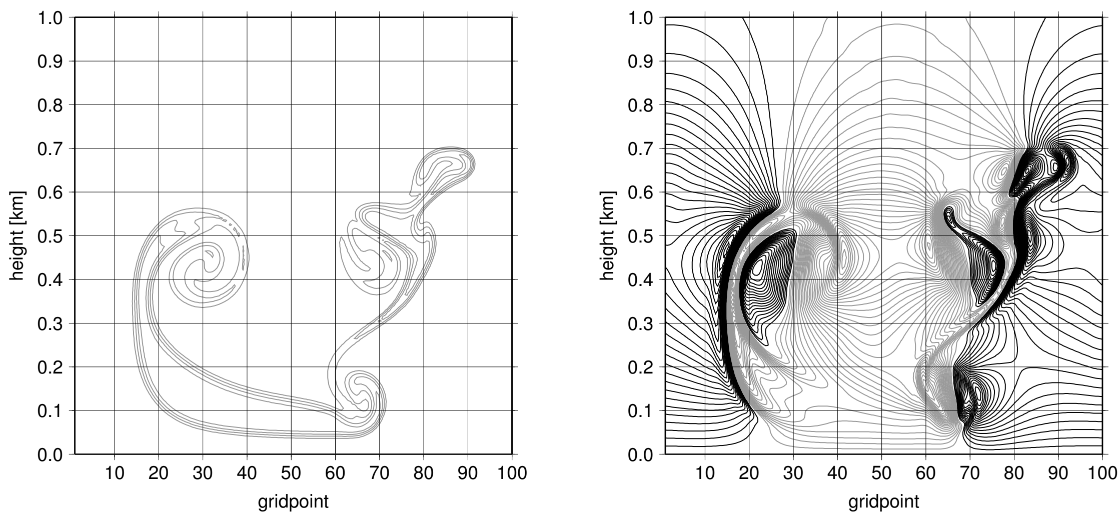

Figure 3: The same as on figure 2 at the end of 10 minutes simulation (after 120 timesteps).

To confirm the validity of results obtained within the academic environment the same settings of dynamics were in parallel checked for a real case simulation with the full LAM using the Alaro physics at two different resolutions and domains: 4.7 km (432 x 540 points) with Δt = 360 s and 2.3 km (600 x 720 points) with Δt = 60 s, both sharing the same 87 model levels distribution and tuning for model physics as used in the CHMI operational model. The aim was to use the 4.7 km results as a reference (from the scales where the NH effects still play rather a negligible role) to be compared with the 2.3 km results, i.e. scales where the NH starts to depart the hydrostatic assumption. For even higher simulation runs we are at the moment missing an appropriate physics (convection with full control between resolved and yet not resolved components, anisotropic turbulence with horizontal components and mainly sophisticated surface description with tiles). Naturally any such test would be possibly affected by this deficiency. For the moment one has to only rely to academic tests at those scales. The starting date was randomly chosen to be the 30/9/2010 00 UTC and the forecast range was 48 hours. Boundary conditions were driven by Arpege global model being in hydrostatic balance.

3 Implementation notes

This section serves as a basic reference for the subsequent argumentation. In the following the algorithmic aspects are reduced to those relevant to the discussed issues. This simplistic approach is hoped to ease an understanding for the described aspects. On the other hand this then should not be considered as a sort of model documentation. The real code is much more complex. Reader is kindly asked to see the specific NH-documentation (Bénard and Mašek, 2010) or the code documentation of relevant parts maintained by K. Yessad for features like decentering, treatment of the so called X-term, various sets of NH variables, vertical discretization etc.

3.1 SETTLS versus NESC discretization

Discretized in time the prognostic equation for variable X

$$\frac{dX}{dt} = MX$$

with the neglected physics and horizontal diffusion term (having both only little relevance to the studied advection effects) one would arrive in the 2TL SL formalism to:

$$\frac{X_F^+ - X_O^0}{\Delta t} = MX_M^{t+\frac{\Delta t}{2}} \quad . \tag{1}$$

In the previous the subscripts O, M and F are respectively used for origin, medium and final points of a SL trajectory. The appropriate time levels are denoted by usual superscripts 0, $t+\frac{\Delta t}{2}$ and $+$ representing given state at time t, $t+\frac{\Delta t}{2}$ and $t+\Delta t$ respectively. The key factor here is to express the right hand side. Despite it is valid at the time $t+\frac{\Delta t}{2}$ being beyond the known time level t it is also favorable to avoid an interpolation to the medium point by replacing it by a average of the same quantity along the SL trajectory (as for example advocated in Tanguay et al., 1992).

The most successful approach (in terms of being used in all operational installations among various services) implemented in the model is using the semi-implicit discretization and the SETTLS technique for the extrapolation of the non-linear residual ($(M-L)X_M^{t+\frac{\Delta t}{2}}$). In this formalism the (1) can be rewritten to:

$$\left(1 - \frac{\Delta t}{2}L\right) X_F^+ = X_O^0 + \frac{\Delta t}{2}[2MX_O^0 - MX_O^-] - \frac{\Delta t}{2}[LX_O^0 - LX_O^-] + \frac{\Delta t}{2}MX_F^0 - \frac{\Delta t}{2}LX_F^0 \quad . \tag{2}$$

To maintain the second order accuracy, quantities from the previous (third) time level $t-\Delta t$ (denoted by the superscript $-$) have to be used to complete (2). This specific treatment consequently makes it only to be quasi-two-time-level scheme. The above discretization given by (2) is hereafter referred as SETTLS (or SETTLS-SI).

Staying strictly within the two-time-level scheme the (1) can be also discretized with off centered first order accuracy treatment for the non-linear residual term:

$$\left(1 - \frac{\Delta t}{2}L\right) X_F^+ = X_O^0 + \frac{\Delta t}{2}MX_O^0 + \frac{\Delta t}{2}MX_F^0 - \frac{\Delta t}{2}LX_F^0 \quad . \tag{3}$$

Note the cancellation of linear terms leading to only need of MX quantity to be interpolated to the origin point (making it specially attractive for the LGWADV option as discussed bellow). The accuracy of (3) can be further increased to a second order by applying an iteration. In such a case the previous can be extended by corrector(s) step(s) defining the ICI (iterative centered implicit) scheme with at least one additional iteration i:

$$
\begin{aligned}
\left(1-\frac{\Delta t}{2}L\right)X_F^{+(0)} &= X_{O^{(0)}}^0 + \frac{\Delta t}{2}MX_{O^{(0)}}^0 + \frac{\Delta t}{2}MX_F^0 - \frac{\Delta t}{2}LX_F^0 \\
\left(1-\frac{\Delta t}{2}L\right)X_F^{+(i)} &= X_{O^{(i)}}^0 + \frac{\Delta t}{2}MX_{O^{(i)}}^0 + \frac{\Delta t}{2}MX_F^{+(i-1)} - \frac{\Delta t}{2}LX_F^{+(i-1)} \quad .
\end{aligned} \tag{4}
$$

Here the quantity $X_F^{+(i-1)}$ denotes the resulting value of X at final point after the previous iteration is completed. The discretization given by (3) and (4) will be hereafter referred as NESC-SI and NESC-ICI respectively.

To complete previous, it is also possible to introduce iterative version of the SETTLS discretization. In the model the hybrid version of such approach is only made available using the SETTLS discretization for the predictor step following the equation (2) while the corrector(s) steps strictly shares the discretization of NESC given by (4). This inconsistent treatment saves CPUs and, as it will be discussed later, it also leads to more stable solution. Still, to use the SETTLS discretization with the ICI scheme has not much sense (already second order accuracy scheme is iterated to obtain again only second order accuracy results) and remains in the code mainly for testing purposes.

3.2 LGWADV option

The use of d as a prognostic variable instead of the vertical velocity w leads to difficulties for the computation of the explicitly-treated non-linear part of the system (see Bénard et al. 2010 for details). In order to avoid potential problems related to the use of this variable, a formulation using w as a prognostic variable for the explicit system was designed to be activated by the model key `LGWADV` = .T. This specific option (referred as LGWADV here) then mixes the use of a "native" prognostic variable d in linear model with its transformed form into the w variable in the explicit system. As a consequence the LX terms can't be mixed with MX terms for this hybrid prognostic variable before a conversion from w to d is applied to the explicit model MX. This special treatment makes just little difficulty for the NESC discretization, as there only MX terms require to be interpolated. When the SETTLS is however activated liner model and full model tendencies of d/w, both interpolated to the origin point, have to be treated separately. For some consistently reason the same separation of MX from LX terms is applied to the other prognostic variables where this specific trick is not required.

4 Results

As already mentioned, there is no way to achieve similar results for the convective bubbles test without the LGWADV option. All pure d runs become unstable and blow up before reaching the end of the 10 minutes simulations, unless a rather strong smoothing by horizontal diffusion is introduced. As illustrated by results from 7th minute displayed on figure 4 the vertical velocity field is subjected by noise already by that stage of simulation.

The configuration LGWADV+SETTLS performs quite well in terms it reaches the end of simulation and the potential temperature profile is only little distorted (not shown). On the other hand the results are affected by a noise visible mainly in the w field. To some surprise the first order accurate NESC-SI scheme (with LGWADV) was offering noise free results being then very close to the NESC-ICI reference, see figure 5. This indicates either a problem in the SETTLS implementation for LGWADV or a general problem related to this kind of discretization being not adequate for such tough tests at very high resolutions.

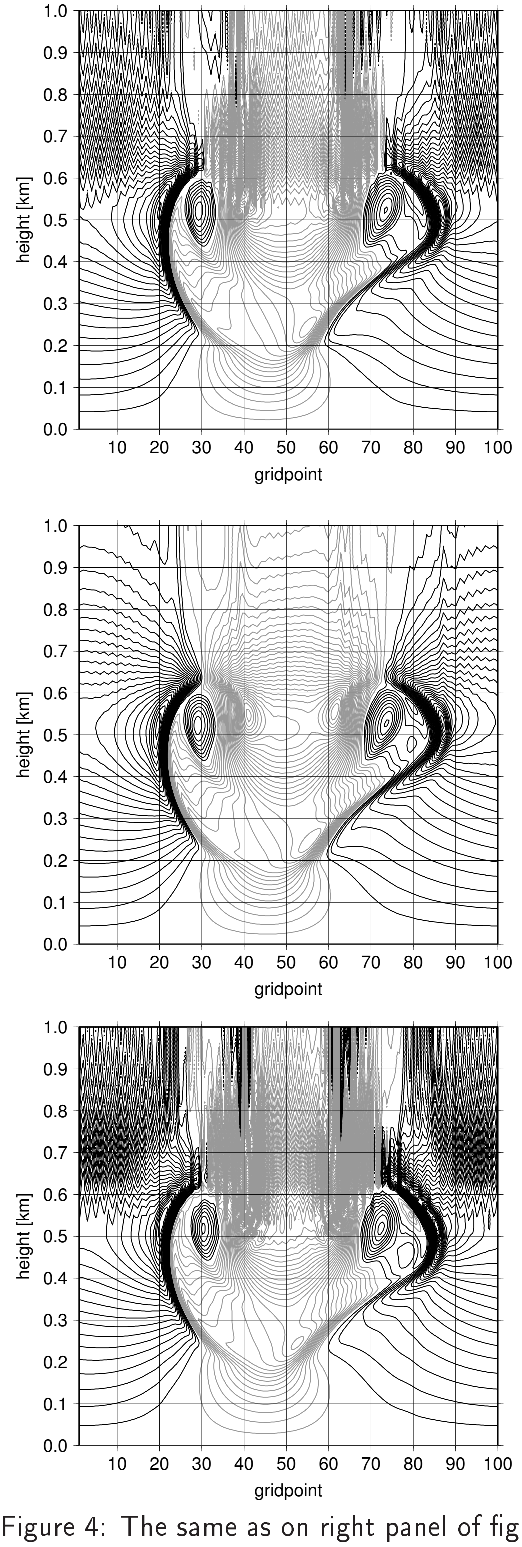

Figure 4: The same as on right panel of figure 2 as it was obtained with pure d_4 prognostic variable (from top to bottom): SETTLS-SI, NESC-ICI and SETTLS-ICI.

To ensure the LGWADV+SETTLS is not affected by an implementation bug, adequate buffers within this configuration were filled by quantities appropriate to the LGWADV+NESC-SI scheme keeping the remaining data-flow unchanged. (The quantities in the square brackets in (2) were replaced by MX^0_O and zeroes respectively.) By obtaining the desired results similar to the NESC-SI it was rather ensured that the code works as supposed. Hence a possibility of wrong SETTLS option design in the model could be likely excluded.

The remaining question to explain is why the SETTLS discretization was outperformed by simpler and less accurate NESC-SI scheme. Summing up the absolute values of w in every model level it was possible to compare difference in the time evolution of those quantities for the two compared discretization simulations. It was hoped by this to spot a first occurrence of the two runs difference, in case it starts in one area. Luckily this was really the case. The first deviation between the two runs was detected around the height of 800 meters (level 50), i.e. in the area above the simulated event, see figure 6 showing the time evolution of differences summed over the entire level from the NESC-SI and SETTLS-SI experiments. By closer inspection of a single point temporal evolution from this level (in the middle of the domain) a spurious $2\Delta t$ behavior of model tendencies of mainly temperature and NH variables was detected. It should not be then surprising that the extrapolation based on consecutive timesteps (as it is the case in SETTLS) is not performing very well with respect to the NESC scheme, especially when amplitude of those waves exceeds the value of a tendency itself. As can be seen from figure 7 although the SETTLS method significantly reduces the oscillations for both full and linear model tendencies, the resulting explicit model tendency (i.e. all the right hand side terms of equations (2) and (3) except the very first one) is drifted with respect to the reference as illustrated by figure 8. Even the total value of the appropriate tendency for the investigated point is very small its almost 3 times amplifications in case of the SETTLS discretization clearly exhibit a problem there. Apparently the extrapolation technique of the SETTLS scheme adds some computational mode to the balanced model state.

Naturally to make SETTLS performing comparable to the NESC requires to get rid of the $2\Delta t$ noise. Various approaches to that were tested like applying decentering, tuning the SI reference profiles or summing up tendencies in different order before the interpolation is performed (to exclude computational mode). None of those however displayed any significant impact to the wavy behavior except amplification or reduction of the wave amplitude[2].

[2]The most notable impact from those tests was observed for the acoustic temperature T^*_a (SITRA) of the linear model having ability with increased value to damp amplitude of the waves.

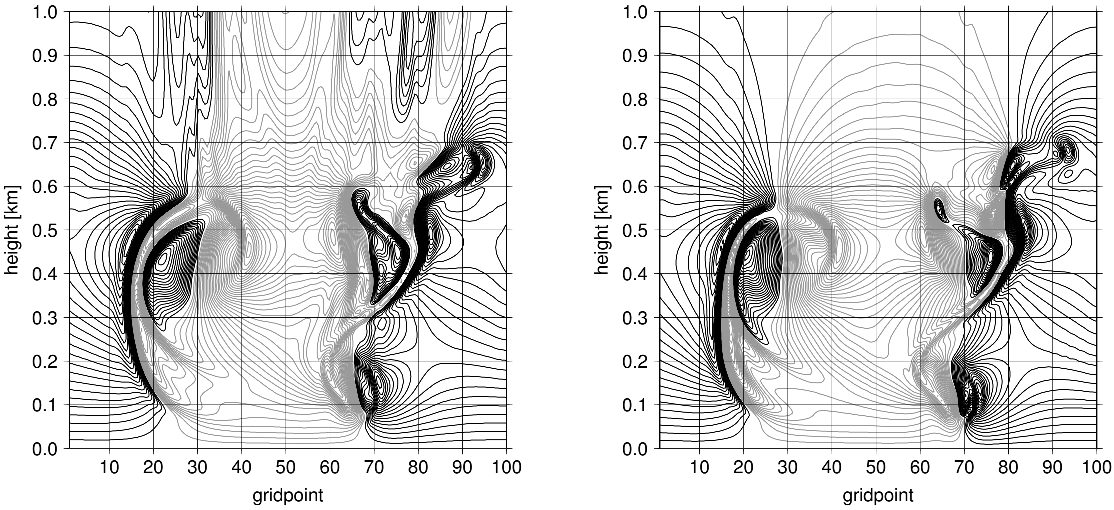

Figure 5: The same as on right panel of figure 3 as resulted from LGWADV simulations with SETTLS-SI and NESC-SI respectively.

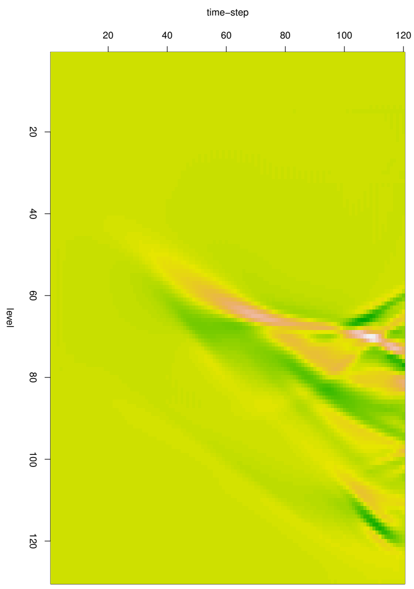

Figure 6: Time evolution of summed w for every model level differences between the SETTLS-SI and NESC-SI runs. When the two runs have comparable results differences are yellow-green. The areas with dark green or orange color denotes significant differences with positive or negative sign. Model levels are ordered in agreement with the model, i.e. from top to bottom.

It seems at the moment there is no cure withing the present model dynamics to damp those short time variation. The same wavy feature was detected also for the neighboring points keeping even the same phase. Thus it seems like the whole model is subjected by those organized oscillations. This can be illustrated by time evolution of the average model temperature (figure 9) obtained with NESC-SI. Even there the $2\Delta t$ mode is cleanly visible. This confirms that the mentioned problem is certainly not a problem of one single point. In the light of this sort of non-local or perhaps global behavior, the SI scheme naturally becomes the most suspected one for generating those oscillations. The mechanism responsible for it is however still to be discovered.

Although the source of those model oscillation is unknown at the moment the NESC discretization apparently handles it very well. Any use of information from two time levels seems to be less favorable for this kind of model behavior (unless it maintains level-to-level model balance). Naturally an extrapolation in this case drifts a tendency opposite way than should be the balanced one. Moreover as the SETTLS extrapolation is performed independently to every prognostic model variable, the model balance is not ensured at the end of explicit timestep. It is then rather questionable whether a SI correction (and horizontal diffusion) are sufficient to ensure the model stability. To confirm this assumption the iterative scheme can be activated with the SETTLS scheme. When the code was adapted to the way that predictor and corrector keep the SETTLS discretization, the test blows up quickly (after few timesteps) for one and even three iterations. Evidently it doesn't converge. With the SETTLS ICI scheme used as implemented in the model (i.e. predictor keeps

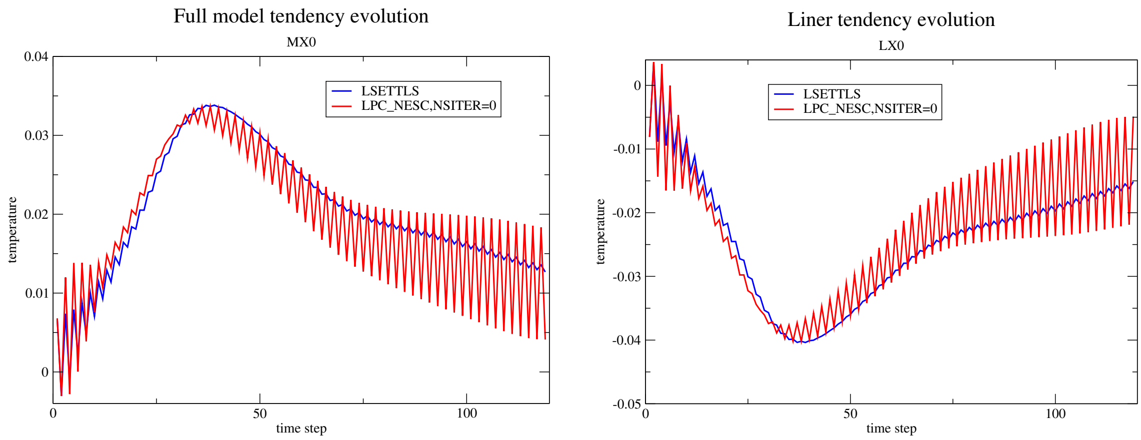

Figure 7: Time evolution of temperature tendencies of full model sum (left) and sum of linear model from explicit part (right) from single point (around 80 m above the surface) as obtained with SETTLS-SI and NESC-SI schemes.

SETTLS while correctors are using NESC) already one iteration helps to restore correct solution very similar to the one obtained with NESC-ICI.

Evidently the SETTLS extrapolation scheme was designed under the assumption that a model evolution is not subjected by any short time oscillation. This is not the case for very high resolution NH simulations with the current model dynamics. Aiming the increasingly dominating non-linear regimes over the linear one at high resolution and the fact that the full NH approach allows extra degrees of freedom over the hydrostatic balance, general numerical techniques imposing less assumption to the model evolution should be prioritized for those scales. This fact then cleanly favors the NESC-ICI scheme over the SETTLS.

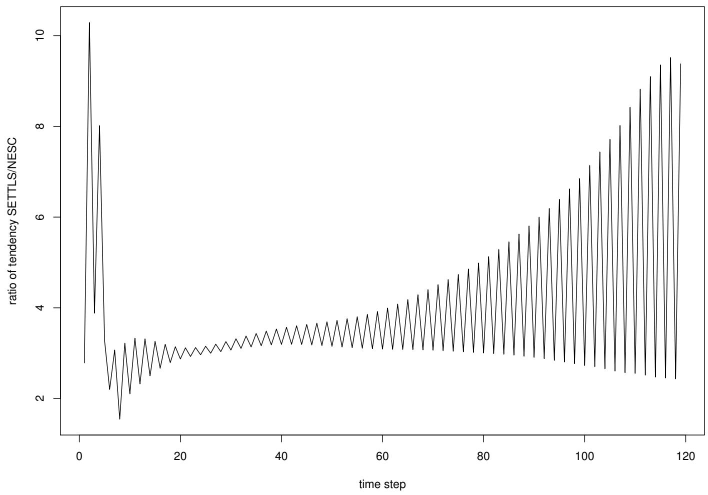

Figure 8: Time evolution of total tendency of temperature from the explicit dynamics with SETTLS-SI divided by the same from NESC-SI for the same single point as in figure 7.

To check how those conclusions are relevant to the current operational scales following model configuration were launched with the real atmosphere for both 4.7km and 2.3 km resolutions:

- pure d_4, NESC-ICI
- LGWADV, NESC-ICI
- LGWADV, SETTLS-ICI
- LGWADV, SETTLS-SI
- pure d_4, SETTLS-ICI
- pure d_4, SETTLS-SI

"Unfortunately" all those configurations were delivering stable and meteorologically sound results. When the timestep was pushed it usually crushed in physics at around 3 time longer timesteps than the appropriate (i.e. around 150-200 s for 2.3 km). Obviously to decide the superior configuration at those scales could be only possible by a standard model verification. The good new from those tests is the fact that the SETTLS and pure d_4 are offering equivalent results with the other configurations, i.e. both are still reliable for the tested scales. This is indeed not a surprise knowing that this setting is the default one for the Arome being computed with resolutions between 2-2.5 km at various services.

5 Conclusions

The primary task to make available or re-check the LGWADV+SETTLS configurations in the model seems to be trivially fulfilled. The mentioned configuration works without apparent implementation problems. It can be also illustrated by the experience from DHMZ (Croatia) running daily a quasi-operational application based on this settings. So far after over 4 months of tests they don't report any stability problem. This configuration however still can be coded more efficiently. There is for example no reason for separation of linear model tendencies from those of the full model. There are also some traps allowed through the setup (for example if an obsolete value of `ND4SYS`=3 is used, model doesn't complain and even allow some computation which is not comparable to neither of the allowed option defined by values 1 and 2). Those inconsistencies hopefully might be covered by the ongoing rationalization of code within the OOPS project.

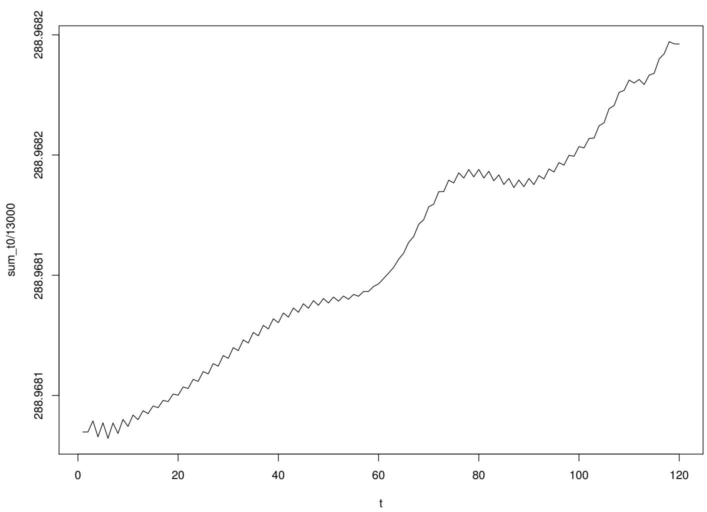

Figure 9: Time evolution of average model temperature as obtained by NESC-SI scheme.

A careful reader can still ask what was the reason for the mentioned instability of LGWADV+SETTLS in IFS. This is indeed hard to explain as the relevant listings from the tests are not available. However even excluding any possible problems in model setup there are several differences between the IFS and the Aladin possibly responsible for the different experience with this settings in model dynamics. (The operational configuration of Arome is also not delivering sufficient stability for the IFS, by the way.) Those are namely different time-step organization and different physics (with a prognostic treatment of physical quantities - like it is the case of Alaro physics using actually 11 such advectable quantities and two more keeping only history - significant stabilization of the model has been reported). It can be also due to the simplification of the original fully Lagrangian averaging in SETTLS which was according Hortal (2002) simplified to the current treatment mainly to ease the assimilation. Perhaps above steep mountains the previous timestep quantities should be rather treated in their appropriate departure point from the time $t - \Delta t$.

From the very high resolution tests $\Delta x = 10$ m with resolved convection an evidence for LGWADV superiority over the pure d option was demonstrated. With the same test the pure two-time-level scheme using the NESC-ICI cleanly outperformed the SETTLS-SI time-stepping theoretically being of the same accuracy. Those conclusions are however still difficult to apply for present operational scales being around 2 km of horizontal mesh. There the SETTLS-SI discretization performs well by offering attractive saving by avoiding the iteration. Still the NESC-ICI scheme holds a potential for the scales where the SETTLS discretization will be limited by inability to keep the model in balance. In this light it is worth to keep maintaining also the NESC-ICI data-flow including promotion of all the novelties. In addition to this, there's only little point to spend much effort with the SETTLS-ICI scheme.

The mentioned ultimate accent to the model balance by avoiding any extrapolation of extremely non-linear tendencies puts also in question the eventual second order coupling of physics and dynamics within the Aladin time-step organization. The current inclusion of physics in Aladin family of models appropriate to a origin point at the time t doesn't seem to offer other choice for second order accurate physics dynamics interface (when one wishes to avoid the extrapolation from previous time-level similar to the one of SETTLS) than to call physics second time at the end of iterative procedure. A way to this direction seems to be the current phys-dyn coupling of IFS, which is however storing the tendency derived from previous timestep model state to compute physics only once per a given timestep. This simplification offers perhaps attractive and more consistent coupling appropriate to the NESC-ICI discretization ensuring no extrapolation for the extremely non-linear physics. Still if even this way of interface would not be consistent enough, than perhaps the best way to couple physics and avoid double call of it during one timestep is to accept only a first order accuracy coupling of physics to dynamics. In such a case the present time-step organization in Aladin seems to be the more appropriate solution with respect to the model stability.

Author would like to acknowledge fruitful and inspiring discussions with his CHMI colleagues mainly to Ján Mašek and Radmila Brožková. The extensive e-mail exchange of information with Karim Yessad (Météo-France) was also found extremely helpful and profitable for this work.

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