The X-term treatment for the vertical motion variable in the ICI time scheme of the ACCORD system

Report from the stay
at CHMI, Prague, 04.11-29.11.2024

Natalia Szopa, Petra Smolíková

April 15, 2025

1 Introduction

We consider the non-hydrostatic fully compressible dynamical core with the two-time level ICI time scheme available in the ACCORD system.

- There are several available variables in the ACCORD system for vertical motion chosen with the key NVDVAR=3, 4, 5.
- We focus on NVDVAR=4. The definition of the vertical motion variable is in this case

$$\mathbb{d} = \hat{d} + \mathbb{X} \tag{1}$$

$$\hat{d} = -g \frac{p}{mR_d T} \frac{\partial w}{\partial \eta} \tag{2}$$

$$\mathbb{X} = \frac{p}{mRT} \nabla \phi \cdot \frac{\partial \mathbf{V}}{\partial \eta} \tag{3}$$

- The key LGWADV=T allows for the usage of vertical divergence $\mathbb{d}$ in the linear model and vertical velocity w in the non-linear model with the transformation between them utilizing (2).
- After the implicit part being realized in the spectral space, the vertical divergence $\mathbb{d}$ is transformed into the grid-point space together with the $\mathbb{X}$-term. Then the true vertical divergence $\hat{d}$ is being calculated as $\hat{d} = \mathbb{d} - \mathbb{X}$ and w is calculated from $\hat{d}$. This value is available as w^0 in predictor and as $w^{(k)}$ in the $(k+1)$-th iteration (corrector). Then the new value $w^{(k+1)}$ comes from

$$\frac{w_F^{(k+1)} - w^0_{O(k+1)}}{\Delta t} = \frac{\mathrm{RHS}[w]^0_{O(k+1)} + \mathrm{RHS}[w]^{(k)}_F}{2} \tag{4}$$

- This new value is being transformed to $\hat{d}$ and $\mathbb{d}$ and enters the spectral space for implicit calculations for the next iteration or the next time step together with the newly calculated $\mathbb{X}$-term.

- The horizontal derivatives of the $\mathbb{X}$-term are not needed in this case anywhere in the time marching scheme. For option L3DTURB or other attempts to include horizontal features of the turbulence, horizontal derivatives of w may be needed, which would call for availability of horizontal derivatives of $\mathbb{X}$. In that case they may be calculated using the SL-halo with finite difference method instead of through the transformation to the spectral space.

- Under ND4SYS=0 the $\mathbb{X}$-term transformed from spectral space is not used, instead $\mathbb{X}$ is calculated at the beginning of the time step or the time scheme iteration from available model variables. In this case the transformation of the $\mathbb{X}$-term to and from spectral space may be avoided resulting in the reduced usage of the CPU time.

- The options ND4SYS=0 and ND4SYS=3 were recently being developed by Fabrice Voitus. The previously implemented options ND4SYS=1 and ND4SYS=2 are using a different approach where the time evolution of $\mathbb{d}$ is being solved by

$$\frac{d\,\mathbb{d}}{dt} = \mathrm{RHS}[\mathbb{d}] + \frac{d\mathbb{X}}{dt}. \tag{5}$$

  Then $\frac{d\mathbb{X}}{dt}$ is discretized in the following way:

$$\frac{d\mathbb{X}}{dt} = \frac{\mathbb{X}^0_F - \mathbb{X}^0_{O(k+1)}}{\Delta t} \qquad \text{for ND4SYS=1} \tag{6}$$

$$\frac{d\mathbb{X}}{dt} = \frac{\mathbb{X}^{(last)}_F - \mathbb{X}^0_F}{\Delta t} + \frac{\mathbb{X}^0_F - \mathbb{X}^0_{O(k+1)}}{\Delta t} \qquad \text{for ND4SYS=2,} \tag{7}$$

  where the first term in (7) is evaluated only in the last iteration and the second term of (7) is the same as in (6). It was shown that the fully explicit treatment of $\mathbb{X}$ under ND4SYS=1 results in a solution oscillating in time. See Fig. 4 for an illustration. It would be possible to handle this solution without the transformation of $\mathbb{X}$ into the spectral space. On the other hand, for ND4SYS=2, the term $\mathbb{X}^0_F$ is being saved through the transformation to spectral space for the next iteration to become $\mathbb{X}^0_{O(k+1)}$ after interpolation to the origin point and this step may not be avoided with the current data structures.

2 Code modifications

The ACCORD code modification was done based on the operational version of CY46t1 available in Prague on lada:/home2/mma010/build/CY46/NMPI2260NFC400/mma010_CY46t1mp_op2/ and may be found on lada:/mnt/backup/lx/kazi1l_2025-02-21/mma277/cy46/build/CY46t1mp_op2_nhxhypc_w5only.

We introduced a new logical key $LSPNHX$ and replaced $LNHX$ in some subroutines with this new switch. As introduced in Arp/module/yomdyna.F90, when $LSPNHX = .T.$, the $\mathbb{X}$-term is transformed from grid-point to spectral space and back and when $LSPNHX = .F.$ no transformation happens. In Arp/setup/sudyna.F90 we set:

$LNHX = LNHDYN.AND.(NVDVAR == 4.OR.NVDVAR == 5)$
$LSPNHX = LNHX.AND.(ND4SYS == 2.OR.ND4SYS == 3)$
$LNHXDER = LSPNHX$

All modified subroutines can be found in Appendix A.

3 Results

The experiment was performed for the 24 hours forecast from 19 August 2022 00 UTC. The resolution used was 200 m with 87 vertical levels and a time step of 8s. We use Czech operational setting with one iteration of the ICI time scheme (predictor and one corrector step), SLHD applied and physics parametrizations 3MT, TOUCANS and ACRANEB2 of the ALARO CMC.

A development of unrealistic patterns in the wind field above the mountain range have been observed under the options ND4SYS=1 and ND4SYS=2. Those spurious so-called chimneys over orographic obstacles may be a consequence of interactions between kinematic BBC, “d” prognostic variable and the SL algorithm [3].

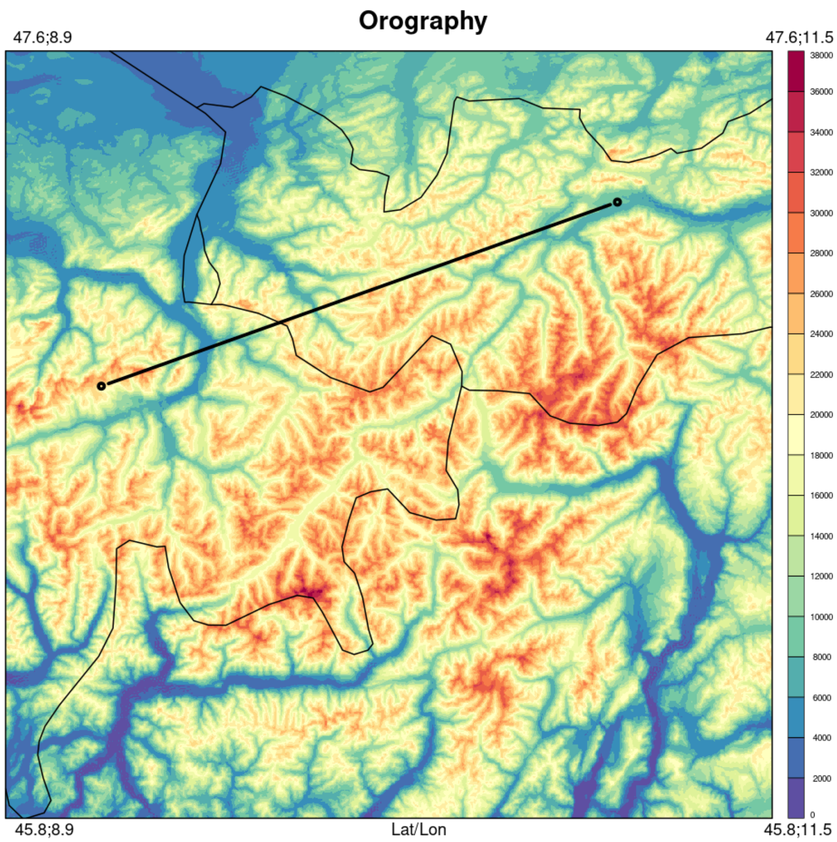


Figure 1: The cross section line over orography.

Under the options ND4SYS=0 and ND4SYS=3 some of the chimneys above slopes disappeared, while the meteorological results remained unchanged. Moreover, the CPU time decreased by 7.5% when using the option ND4SYS=0 and LSPNHX=F, and by 4.5% when using ND4SYS=3.

The results are illustrated in Figures 2-7. Figure 1 shows the line along which cross section of vertical wind velocity was made and presented in Figure 2. Figures 3-6 illustrate vertical wind velocity at heights 1000m and 5000m over the Alpine region with the spurious chimneys indicated by pink circles. As pictured in 7, experiments with all the options are stable. Norms under the options ND4SYS=0 and ND4SYS=3 are smooth, while for ND4SYS=1 and ND4SYS=2 the norms are oscillating in time.

4 Conclusions

The results show that setting the options to ND4SYS=0 or ND4SYS=3 can be a preferable choice, since using one of these options in the ALARO model leads to similar outcomes. This indicates that transformation of the $\mathbb{X}$-term to and from spectral space may not be necessary. By avoiding the transformation, we are able to save computational resources. As shown in this report, using the diagnostic $\mathbb{X}$-term calculated at the beginning of each step of the grid-point calculations we are able to lower CPU usage by up to 7.5%.

In order to further verify the results, it is required to conduct testing on different domains, using forecasts from various dates and times. The CPU time savings achieved by avoiding the transformation of the isolated $\mathbb{X}$-term are likely to become greater with the experiment conducted on larger domains. This is because the efficiency improvements might scale more effectively as the domain size increases.

In recent years, there has been a growing interest in increasing resolution of models with the goal of the implementation of hectometric scale meteorological models. However, as highlighted in [4], these developments are intrinsically linked to higher computational costs. The approach proposed in this report could be one of the steps contributing to the mitigation of the computational efficiency challenges associated with higher-resolution meteorological models, including hectometric-scale systems, while maintaining numerical stability.

References

[1] Pierre Bénard, Ján Mašek, 2011: *Scientific Documentation for ALADIN-NH Dynamical Kernel*, Météo-France, CHMI.

[2] Karim Yessad, 2018: *Semi-Lagrangian Computations in the cycle 46T1 of ARPEGE/IFS*, METEO-FRANCE/CNRM/GMAP/ALGO.

[3] Jozef Vivoda, 2018: *New vertical motion variables in the non-hydrostatic dynamical core of the ALADIN system*, SHMI, RC LACE stay in Prague.

[4] Humphrey W Lean, Natalie E Theeuwes, Michael Baldauf, Jan Barkmeijer, Geoffrey Bessardon, Lewis Blunn, Jelena Bojarova, Ian A Boutle, Peter A Clark, Matthias Demuzere, Peter Dueben, Inger-Lise Frogner, Siebren de Haan, Dawn Harrison, Chiel van Heerwaarden, Rachel Honnert, Adrian Lock, Chiara Marsigli, Valéry Masson, Anne Mccabe, Maarten van Reeuwijk, Nigel Roberts, Pier Siebesma, Petra Smolíková, Xiaohua Yang, 2024: *The hectometric modelling challenge: Gaps in the current state of the art and ways forward towards the implementation of 100-m scale weather and climate models*, Quarterly Journal of the Royal Meteorological Society: Volume 150, Issue 765.

Appendix A

List of modified subroutines.

Change of the key from LNHX to LSPNHX:
- Ald/transform/etransinv_mdl.F90
- Ald/transform/etransdir_nhconv.F90
- Arp/adiab/spchor.F90
- Arp/dfi/dfi2.F90
- Arp/module/gmv_subs_mod.F90
- Arp/module/iospeca_mod.F90
- Arp/module/yemlbc_fields.F90
- Arp/module/yemlbc_init.F90
- Arp/module/yemlbc_model.F90
- Arp/module/yomdyna.F90
- Arp/parallel/trmtos.F90
- Arp/parallel/trstom.F90
- Arp/setup/sudyna.F90
- Arp/transform/transdir_nhconv.F90
- Arp/transform/transinv_mdl.F90

Other changes:
- Arp/adiab/gpinislb.F90
- Arp/adiab/cpglag.F90

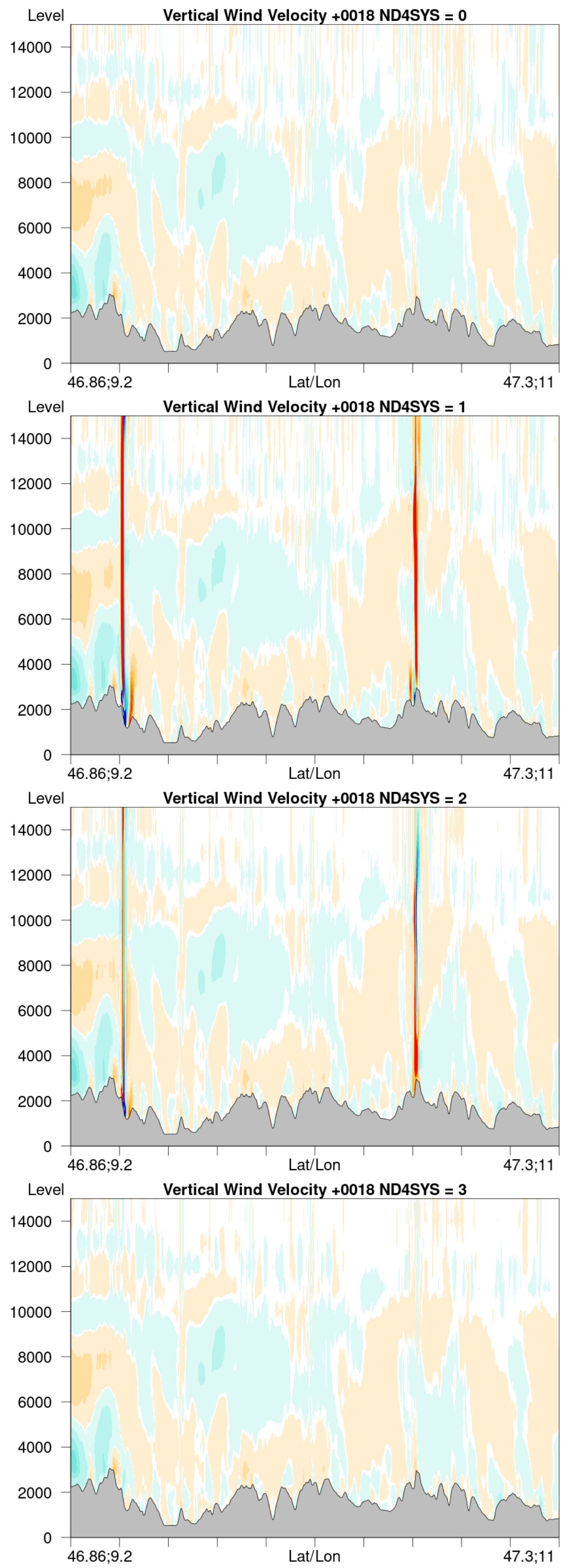
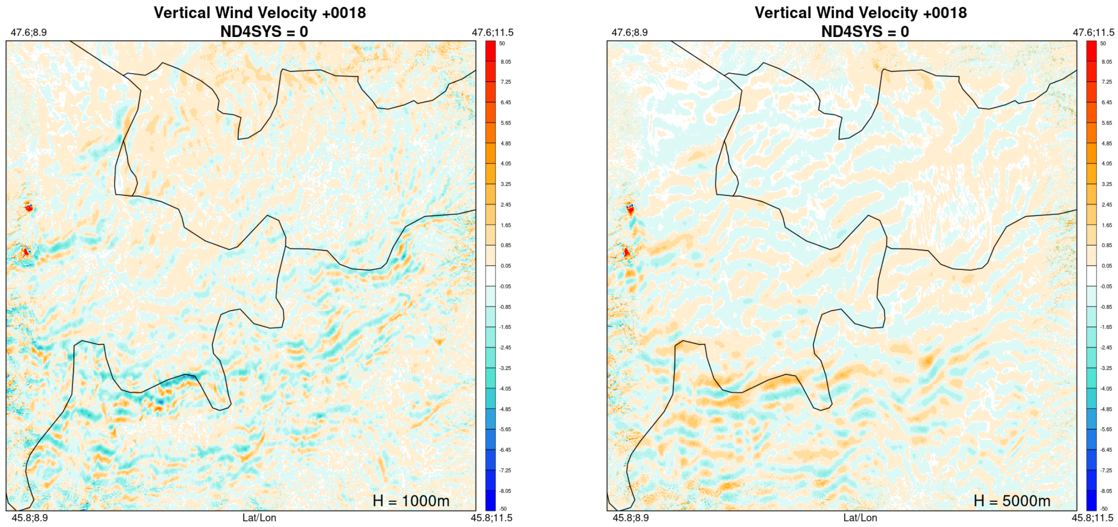
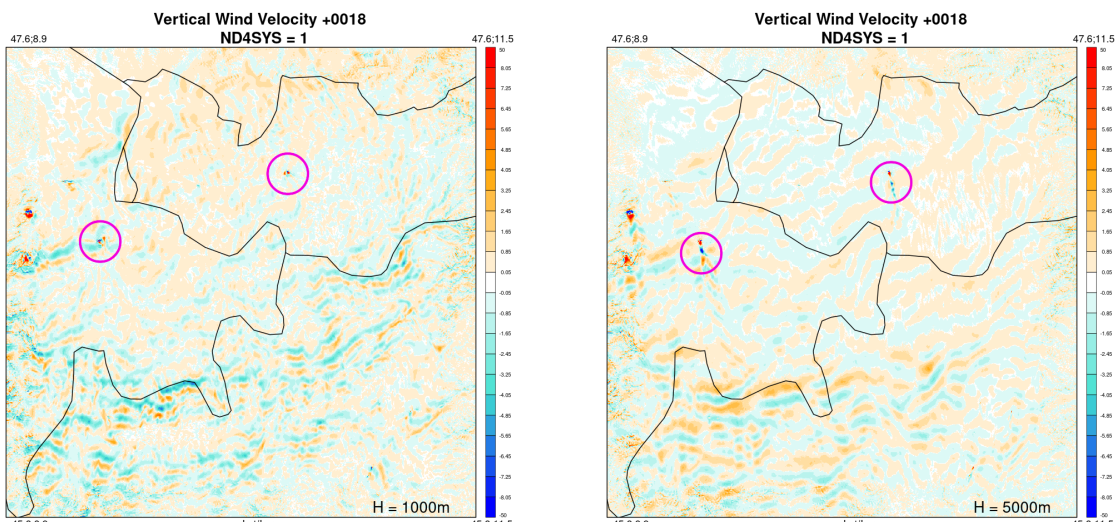


Figure 2: The vertical cross section of the vertical wind velocity through the line shown in Figure 1 under four ND4SYS options.



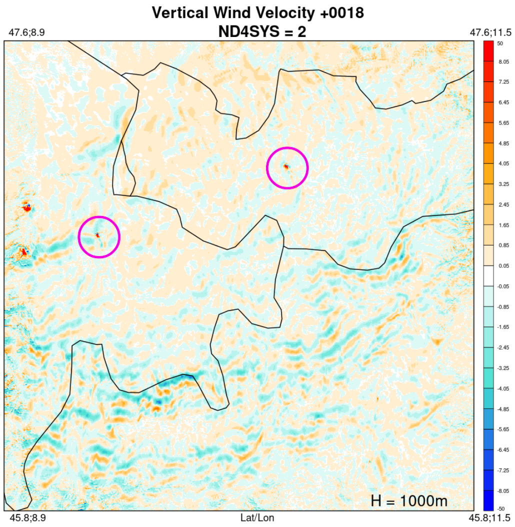
(a) (b)

Figure 3: The vertical wind velocity field at the height of 1000m (a) and of 5000m (b) under the option ND4SYS=0.

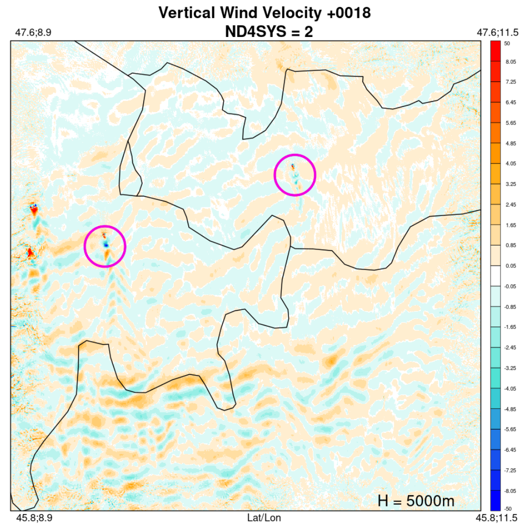


(a) (b)

Figure 4: The vertical wind velocity field at the height of 1000m (a) and of 5000m (b) under the option ND4SYS=1.

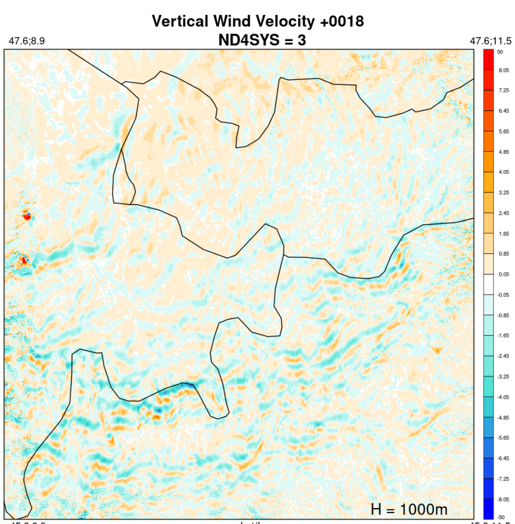


(a)

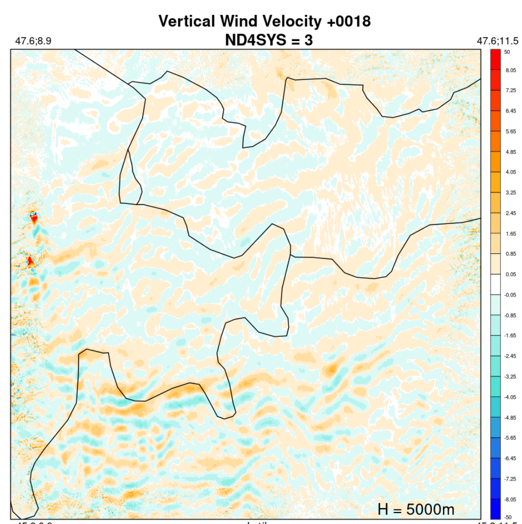


(b)

Figure 5: The vertical wind velocity field at the height of 1000m (a) and of 5000m (b) under the option ND4SYS=2.



(a)



(b)

Figure 6: The vertical wind velocity field at the height of 1000m (a) and of 5000m (b) under the option ND4SYS=3.

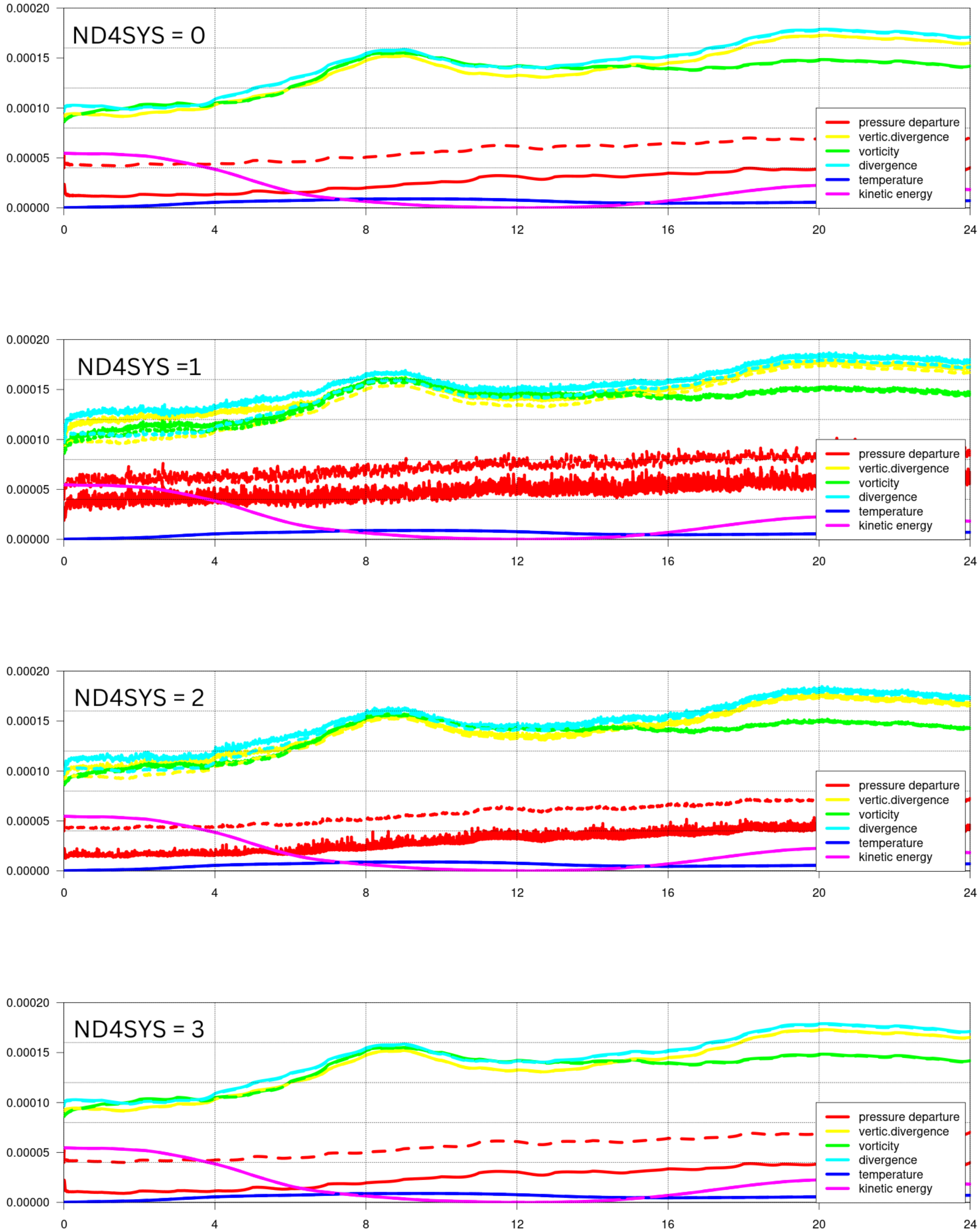


Figure 7: The evolution of model variables spectral norms under four ND4SYS options.