Parallel version for the BRAMS with Runge-Kutta dynamical core

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Abstract

BRAMS (Brazilian developments on the Regional Atmospheric Modeling System) is a mesoscale model for weather predition. In the Center of Weather Predition and Climate Studied (CPTEC), a division of the National Institute for Space Research (INPE), BRAMS was also adapted to be used as an environmental prediction model. The CPTEC-INPE has employed the BRAMS as an operational tool to provide the forecasting to the pollutant gases, including chemical reaction, over the Brazilian region. Recently, an effort to apply the third order Runge-Kutta (RK3) as a new dynamical core for the BRAMS model version 5.2. In this paper, the development of the parallel version of the RK3 is described. The new dynamical core for the BRAMS is evaluated simulating events under strong rain-fall in different regions of the Brazil.

Keywords: BRAMS mesoscale model, Runge-Kutta time integration, weather and environmental prediction.

1. Introduction

The CPTEC-INPE (Centro de Previso do Tempo e Estudos Climáticos / Instituto Nacional de Pesquisas Espaciais) is responsable to provide the numerical weather and seasonal climate prediction to the Brazil. The Center uses the BRAMS (Brazilian developments on Regional Atmospheric Modeling System) as a limited area model on high resolution for environmental prediction. Model forecasting is able to antecipate the field of meteorological variables a period of time ahead. Precipitation is one of the most important meteorological variables of the climate system and directly affects human acivities.

Precipitation prediction provides important information for the population. However, quantitative precipitation forecasting, especially on tropical

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and subtropical regions in summertime, is particularly challenging – including over amazon region. with intense convective process

In a regional model, the temporal and spatial scales are reduced compared with global circulation models. The models have difficulty in developing and organizing convection at the correct location and time [7]. The characteristics of precipitation forecasts are often directly affected by the assumptions used to develop the model parameterization schemes for convection and other processes [11].

A permanent issue in NWP is to develop or evaluating methods for numerical integration of the partial differential equations. A third (3rd) order Runge-Kutta (RK3) scheme for time integration is applied to the BRAMS. The goal of this paper is to do a comparison of two time integration methods: leapforg (LF) and RK3 (Hoffman, 1993). Both schemes are evaluated during a strong convective process in a SACZ (South Atlantic Convergence Zone) event (January 14-16, 2017). The parallel version for the RK3 was implemented and evaluated using a cluster with 280-cores.

2. The BRAMS Model

The BRAMS model is a joint project of several Brazilian institutions [3, 8], including the CPTEC-INPE, and was initially funded by FINEP[2] – a Brazilian funding agency. BRAMS is based on the Regional Atmospheric Modeling System (RAMS) [13], with several new functionalities and parameterizations. BRAMS is a numerical model developed to simulate atmospheric circulations on many scales. It solves the time-split compressible nonhydrostatic equations [2]. Physical parameterizations in BRAMS are appropriate for simulating processes such as surface-air exchange, turbulence, convection, radiation and cloud micro-physics [3]. The BRAMS model includes an ensemble version of a deep and shallow cumulus scheme based on the mass flux approach (the GD scheme) [10].

2.1 Time integration procedures

The mathematical system representing the atmospheric dynamics can be expressed as a non-linear mathematical equation:

$$\frac{\partial\phi(\vec{r},t}{\partial t} + R(\phi,t) = F(t) \tag{1}$$

where $\phi(r,t)$ is a state vector, grouping the meteorological variables: T temperature, (u,v,w) wind components, pressure p, density ρ, moisture

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q, and $F(t)$ is a forcing term. The general operator R can be split in two other operators: $R(\phi, t) = L(\phi, t) + N(\phi, t)$, expressing linear and non-linear operators in our atmospheric model.

2.1.1 Time integration: Leapfrog

Models for the NWP are mathematical computer framework, where Eq. (1) needs to be integrated by some numerical procedure. A famous scheme for time integration is the Leapfrog (LF) method. The algorithm for the method can be outlined as:

$$(a) \quad \phi_n \equiv \phi(t_n) \tag{2}$$

$$(b) \quad \phi_{n+1} = \phi_{n-1} + 2\,\Delta t\,[F(t_n) - R(\phi_n\,,\ t_n)]\ . \tag{3}$$

2.1.2 Time integration: Runge-Kutta 3rd order

The 3rd order Runge-Kutta approach is also famous method for time integration. The algorithm can be summarized as following:

$$(a) \quad \phi_n \equiv \phi(t_n) \tag{4}$$

$$(b) \quad \phi_{n+1} = \phi_n + (\Delta t/6)\,[k_1 + 4k_2 + k_3] \tag{5}$$

where:

$$(c) \quad k_1 = [F(t_n) - R(\phi_n\,,\ t_n)]$$

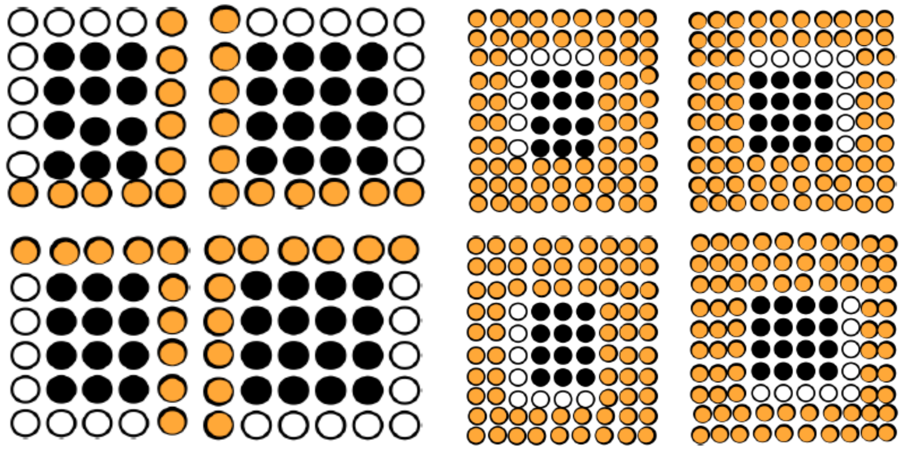
$$(d) \quad k_2 = [F(t_n + \Delta t/2) - R(\phi_n + \Delta t\, k_1/2\,,\ t_n + \Delta t/2)]$$

$$(e) \quad k_3 = [F(t_n + \Delta t) - R(\phi_n - \Delta t\, k_1 + 2\Delta t\, k_2\,,\ t_n + \Delta t)]\ .$$

2.2 Parallel version for the RK3 dynamical core

For the current BRAMS version, the parallel framework follows the Message Passage Interface (MPI) standard. For the horizontal (2D) space variables, the domain decomposition approach is adopted as the parallel strategy, where each sub-domain is addressed for different processor to carry out an independent processing – there is no partition on vertical direction. Up dated values need to be provided on the interface for each sub-domain. The MPI procedures feed the up dated values for different sub-domains from a zone around the sub-domain – the *ghost zone*.

For the time integration with LF, the ghost zone length has only one computational cell linked to each cell in the sub-domain, sharing the storaged values. For higher order time integration schemes, the size of the ghost zone needs to be enhanced, changing the data structure in the computer code. The ghost zones for Leapfrog (LF) and Runge-Kutta 3rd order (RK3) are illustrated for four processors in Figure 1a and 1b, respectively. The parallel



(a) (b)

Figure 1: Ghost zones for domain decomposition to the BRAMS, illustrated with four processors: (a) LF, (b) RK3.

code adaptation for the RK3 implies to redifine the vectors/matrices, as well as the loop limits.

3. Numerical Experiments

The BRAMS version 5.3 was used to simulate precipitation over South America region – see Figure 2. The model was run for a forecast length of 48 h, at January 14th and 15th (2017), initialized at 12:00 UTC. The following configuration was used: model grid with $\Delta x = \Delta y = 20$ km with 100 m for the first vertical level. The vertical resolution varied telescopically with higher resolution at the surface with a ratio of 1.1 up to a maximum vertical grid cell of 950 m, and the top of the model at approximately 19 km – total of 40 vertical levels. For initial and boundary conditions, CPTEC/INPE Atmospheric General Circulation Model (AGCM) was used with T126L28 resolution.

The precipitation data is from the CPTEC/INPE, using a technique called MERGE [9]. The authors combine data from the Tropical Rainfall Measuring Mission (TRMM) satellite precipitation estimates [6] with rain gauge observations over South America. Figure 2 shows the space domain defined for the simulation.

Figure 3 displays results for time integration using RK3 with $\Delta t = 45$ s and $\Delta t = 60$ s (3a and 3b, respectively). Figure 3c shows the precipitation

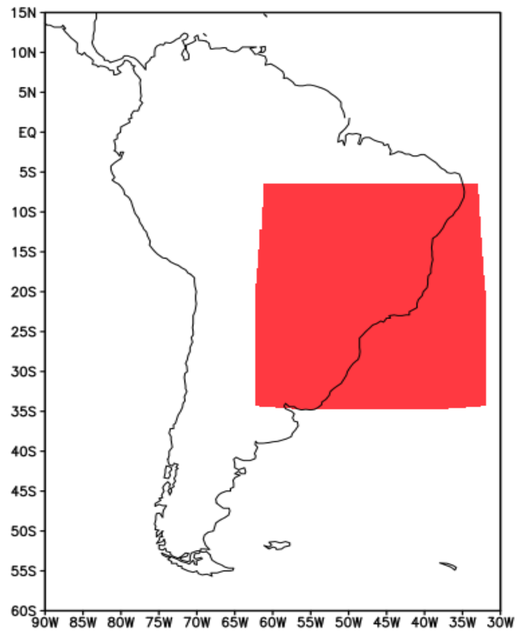


Figure 2: Domain for the BRAMS 5.3 simulation – red region.

field with the LF scheme ($\Delta t = 45$ s) – simulation with $\Delta t = 60$ s. can not be performed, because the time discretization is out of stability zone for the LF, i.e., the method is out of the CFL criteria. Finally, the precipitation field measured by TRMM with MERGE correction is shown in Figure 3d.

The parallel performance for the RK3 was evaluated in a machine ranging from 10 up to 280 processing cores. Table 1 presents the results in terms of CPU-time and efficiency related to the number of cores used. We want to pointed out two results: with 40-cores and 80-cores, presenting a very good performance (superlinear) and a poorest performance, respectively. The parallel version remains stable during all tests executed.

4. Final Remarks

Results for Runge-Kutta 3rd order (RK3) as a new dynamical core for the BRAMS meteorological simulator was presented. BRAMS can be used for regional numerical weather prediction and environmental forecasting. The evaluation of new time integration method for the BRAMS was carried out on two scenarios: simulating an event of strong convection regime placed on the South Atlantic Convergence Zone (in Portuguese: Zona de Convergência

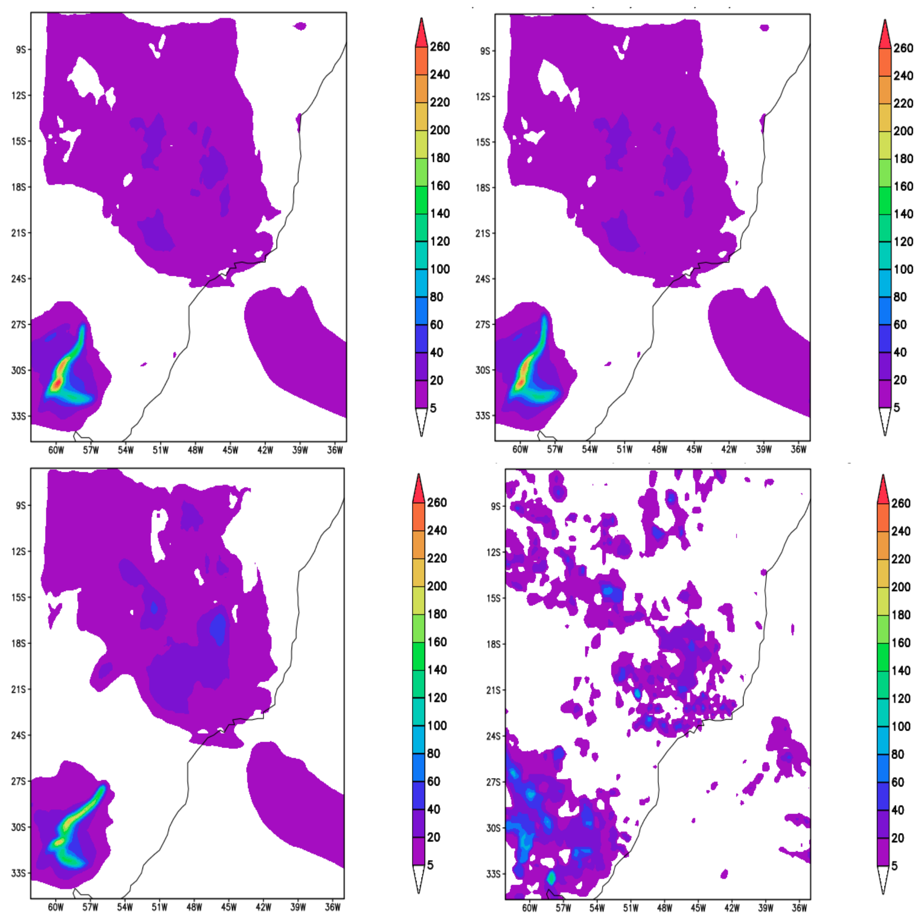


Figure 3: BRAMS simulation for precipitation fields at January 15th (2017), with: (a) RK3: $\Delta t = 60$ s, (b) RK3: $\Delta t = 45$ s, (c) LF: $\Delta t = 45$ s, (d) observation.

Table 1: BRAMS parallel execution evaluation to the RK3.

Cores	CPU-time (sec)	efficiency
10	27080	—
20	15661	72,91%
40	7257	115,81%
80	6895	5,25%
120	4936	79,38%
160	4150	56,82%
200	3746	43,14%
240	3330	62,46%
280	3166	31,08%

do Atlântico Sul – ZCAS), and the perfomance on a parallel machine.

For comparison, the intense rainfall during the ZCAS event at January 14 (2017) was simulated using LeapFrog (LF) and Runge-Kutta 3rd order. Both time integration methods are able to identify the zone of instability associated with SACZ, as well as a close zone with strong convective nuclei of instability place at South from the SACZ. However, the RK3 method maintains the model stability with greater time discretization than LF scheme. For the adopted space resolution, the RK3 with $\Delta t = 60$ s has similar results as RK3 $\Delta t = 45$ s, but BRAMS is unstable for LF with Δt greater than 45 s – for the space resolution employed. Therefore, the use of RK3 allows to perform a forecasting with a longer time discretization, reducing the requested CPU time.

The performance of the parallel version for the RK3 presented good results. As already mentioned, more investigation is necessary to explain the performance with 40-cores (superlinear) and 80-cores (poor).

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References

[1] BRAMS: `http://brams.cptec.inpe.br/`

[2] Cotton, W. R., Stephens, M.A., Nehrkorn, T., Tripoli, G. J.: The Colorado State University three-dimensional cloud/mesoscale model –

part II: an ice phase parameterization. *Journal de Recherches Atmospheriques*, 16(4), 295-320, 1982.

[3] Freitas, S. R., et al.: The Coupled Aerosol and Tracer Transport model to the Brazilian developments on the Regional Atmospheric Modeling System (CATT-BRAMS) – Part 1: Model description and evaluation, *Atmospheric Chemistry and Physics*, 9, 2843-2861, 2009.

[4] Freitas, S. R. et al. (2017): The Brazilian developments on the Regional Atmospheric Modeling System (BRAMS 5.2): an integrated environmental model tuned for tropical areas, *Geophysical Model Development*, 10(1), 189-222, 2017.

[5] Hofmann, J. D.: *Numerical Methods for Enginneres and Scientists.* McGraw-Hill, 1993.

[6] Huffman, G. J., Adler, R. F., Bolvin, D. T., Gu, G., Nelkin, E. J., Bowman, K. P., Hong, Y., Stocker, E. F., Wolff, D. B.: The TRMM multisatellite precipitation analysis (TMPA): quasi-global, multiyear, combined sensor precipitation estimates at fine scales, *Journal of Hydrometeorology*, 8, 38-55, 2007.

[7] Kain, J. S., Fritsch, J. M. : The role of the Convective Trigger Function in numerical forecasts of mesoscale convective systems. *Meteorol. Atmos. Phys.*, 49, 93-106, 1992.

[8] Longo, K. M., et al.: The coupled aerosol and Ttacer transportmodel to the Brazilian developments on the regional atmospheric modeling system (CATTBRAMS) – Part 2: Model sensitivity to the biomass burning inventories. *Atmospheric Chemistry and Physics*, 10, 2843-2861, 2010.

[9] Rozante, J. R., Moreira, D. S., de Goncalves, L. G. G., Vila, D. A.: Combining TRMM and Surface Observations of Precipitation: Technique and Validation over South America, *Weather Forecasting*, 25, 885-894, 2010.

[10] Santos, A. F., Freitas, S. R., Mattos, J. G. Z., Campos Velho, H. F., Gan, M. A., Luz, E. F. P., Grell, G. A.: Using the Firefly optimization method to weight an ensemble of rainfall forecasts from the Brazilian developments on the Regional Atmospheric Modeling System (BRAMS).*Advances in Geosciences*, 35, 123-136, 2013.

[11] Stensrud, D. J., Bao, J.-W., Warner, T. T.: Using initial condition and model physics perturbations in short-range ensemble simulations of mesoscale convective systems. *Mon. Weather Rev.*, 128, 2077-2107, 2000.

[12] Tripoli, G. J. and Cotton, W. R.: The Colorado State University three-dimensional cloud/mesoscale model, Part I: General theoretical framework and sensitivity experiments. *Journal de Recherches Atmospheriques*, 16(3): 185-219, 1982.

[13] Walko, R. L., et al.: Coupled atmosphere-biophysics-hydrology models for environmental modeling.]it Journal of Applied Meteorology, 39, 931-944, 2000.