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IX Encontro Sul Brasileiro de Meteorologia

Sensitivity of an unusual cyclone in South America to convective parameterization schemes in RegCM5

Sensibilidade de um ciclone incomum na América do Sul em diferentes esquemas de parametrização convectiva no RegCM5

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ABSTRACT

Raoni storm (2021) was a remarkable and unusual cyclone that developed on the Atlantic coast of southern South America. This study evaluates the performance of different parameterization schemes with the RegCM5 model in simulating the evolution of Raoni. Results show that the Tiedtke convective scheme has the best performance in representing the evolution of the cyclone in terms of position, intensity, and duration, though the maximum intensities are underestimated with respect to the ERA5 reanalysis. The cyclone's growth and its initial propagation are fairly well represented by the Emanuel scheme, but the cyclone dissipates too early. In the Grell scheme, the cyclone moved southeastward, and then a new cyclone developed along the coast of southern Brazil. The erroneous representation of the upper-level structure in the Grell scheme may have prevented the decrease of vertical wind shear, which is an important factor in the development of a low-level warm core, though this needs further exploration. In terms of precipitation, all the convective schemes show increased precipitation during the initial stages of the cyclone, followed by a rapid decrease. These findings would be helpful in choosing the more appropriate cumulus parameterization schemes for cyclone simulations over South America and in improving model predictions given the existence of model bias derived from imperfections in physical parameterizations.

Keywords: Raoni; Subtropical transition; Convection; Model simulations; RegCM5

RESUMO

A tempestade Raoni (2021) foi um ciclone notável e incomum que se desenvolveu sobre a costa do Atlântico Sul, próximo à América do Sul. Este estudo avalia o desempenho de diferentes esquemas de parametrização com o modelo RegCM5 na simulação da evolução do Raoni. Os resultados mostram que o esquema convectivo Tiedtke teve o melhor desempenho na representação da evolução do ciclone em termos de posição, intensidade e duração, embora as intensidades máximas foram subestimadas em relação à reanálise ERA5. O crescimento do ciclone e sua propagação inicial foram bem representados pelo esquema Emanuel, mas o ciclone se dissipa cedo demais. No esquema Grell, o ciclone se moveu para sudeste e depois um novo ciclone se desenvolveu ao longo da costa do Sul do Brasil. A representação errônea da estrutura em níveis superiores pelo esquema Grell pode ter impedido a diminuição do cisalhamento vertical do vento, que é um fator importante para o desenvolvimento de um núcleo quente em baixos níveis, embora isso precisa ainda ser investigado. Em termos de precipitação, todos os esquemas convectivos mostraram um aumento da precipitação durante a fase inicial do ciclone, seguido por uma rápida diminuição. Esses resultados são importantes para a escolha de esquemas de parametrização cumulus mais apropriados para simulações de ciclones sobre a América do Sul e na melhoria das previsões dos modelos numéricos, dada a existência de erros sistemáticos dos modelos decorrentes de imperfeições nas parametrizações físicas.

Palavras-chave: Raoni; Transição subtropical; Convecção; Simulações; RegCM5

1 INTRODUCTION

Subtropical cyclones are important synoptic-scale systems that can produce strong winds, then their skilful predictions are of great importance. Generally, regional climate models are used to simulate the cyclone characteristics such as track, intensity and structure, but the ability to do so depends on several factors, such as model resolution, physics parameterizations, and accuracy of the initial and lateral boundary conditions used to drive the model (Giorgi & Mearns, 1999). Regional climate models are typically initialized with data from global climate models or reanalysis data sets that provide information on the initial state of the atmosphere.

In large-scale atmospheric models, the behaviour of individual cumulus clouds is not explicitly simulated due to their small scale, except for convection-permitting models which are able to capture fine-scale processes that drive convection (Prein et al. 2015). However, convection-permitting models require high computational power which limits their usefulness for short-term predictions. The use of convective parameterizations offers a computationally cheaper alternative to represent the effects of sub-grid scale convective processes in numerical weather prediction and climate models. They are typically based on simplified representations of convective processes, and their accuracy can vary depending on the specific conditions being simulated (Rio et al. 2019).

Different convective parameterizations can lead to different treatment of convection and cloud microphysics, which can in turn affect the heat and moisture atmospheric fluxes and influence the development of cyclones (Villafuerte et al. 2021). Therefore, it is important to carefully evaluate and choose the most appropriate convective parameterization for the specific conditions being simulated, as well as to validate the results of their simulations against observational data to ensure their accuracy.

Given that cumulus parameterizations are a key component of atmospheric models and considering that different schemes can produce widely varying results, the aim of this study is to evaluate the sensitivity of cumulus parameterizations in simulating an unusual cyclone, named as Raoni by the Brazilian Navy Hydrographic Center. The storm developed in late June 2021 along the coast of Uruguay and southern Brazil and during its mature stage exhibited a hybrid structure with a well-defined warm core at low-levels and a cold core aloft associated with a cut-off low pressure system (Reboita et al. 2022). It also exhibited a strong pressure gradient and strong winds near the surface, with maximum sustained winds of 46 knots (approximately 85 km/h). The simulations were produced with the fifth-generation version of the International Centre for Theoretical Physics (ICTP) regional climate model (RegCM5; Giorgi et al. 2023) with different convective schemes and evaluated against the ERA5 reanalysis.

The article is organized as follows: The data and methods used are described in Section 2; the results of the performance of the cumulus parameterization schemes in simulating the cyclone Raoni are in Section 3; and Section 4 concludes this study.

2 DATA AND METHODOLOGY

2.1 Model description and experiment design

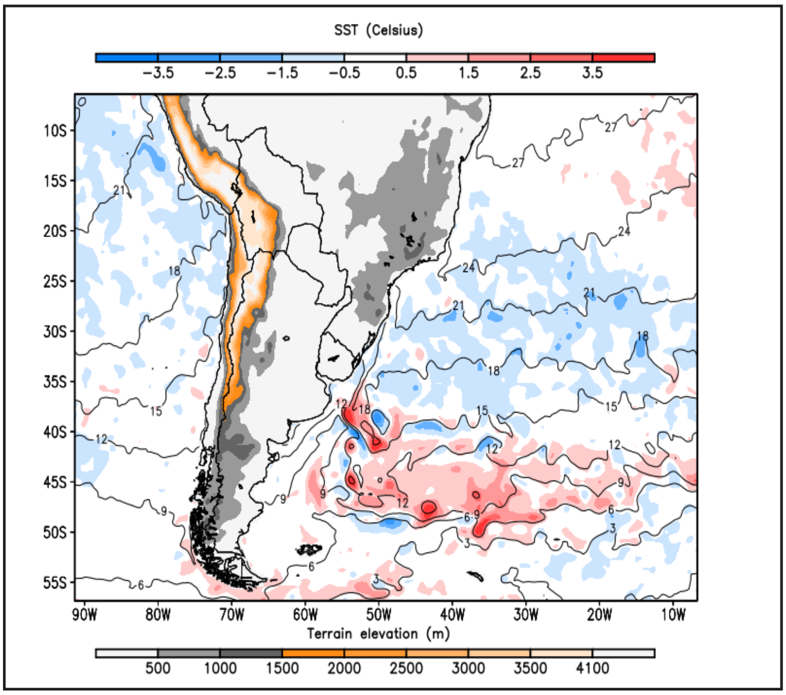
The fifth version of the RegCM non-hydrostatic limited area climate model (RegCM5; Giorgi et al. 2023), originally developed by Giorgi et al. (1993), is used to test the influence of cumulus parameterization schemes on the subtropical cyclone Raoni. Sensitivity experiments are performed using following mixed schemes: Grell over continent and Emanuel over ocean (Grell); Emanuel over continent and Grell over ocean (Emanuel); and Tiedtke over continent and Kain-Fritsch over ocean (Tiedtke). Simulations employing mixed convective parameterization schemes have been extensively used and have consistently demonstrated a high degree of agreement with observational data (Reboita et al. 2014; Raju et al. 2015). This may be attributed to variations in the dominant physical mechanisms driving convection over land and ocean regions (Yano et al. 2013).

The performance between different cumulus schemes often is a result of their representations of key physical processes within convective clouds. While the Emanuel scheme triggers convection when neutral buoyancy exceeds cloud base level (Emanuel & Živković-Rothman, 1999), the Grell and Tiedtke schemes are mass flux deep convection models, treating clouds as two steady-state circulations—an updraft and a downdraft. However, the Tiedtke scheme (Tiedtke, 1989) accounts for various cloud types and cumulus downdrafts, offering representation for deep, mid-level, and shallow convection.

We applied the same model options across all convective parameterization schemes, including planetary boundary layer (PBL), land surface, and radiative transfer components. Specifically, we employed the Holtslag PBL scheme (Holtslag et al. 1990), the Biosphere-Atmosphere Transfer Scheme (BATS) (Dickinson et al. 1993), and the RRTM radiative transfer scheme (Mlawer & Clough 1997).

The domain used in the simulations covers part of South America and neighbouring oceans (Figure 1). Simulations are performed with a 25-km horizontal grid resolution (305 × 235 points) and 23 vertical levels for the period from 00 UTC June 15th to 18 UTC July 5th, 2021. Initial and boundary conditions are derived from the ERA5 reanalysis (Hersbach & Dee, 2016) data for temperature, zonal and meridional wind components, geopotential, specific humidity and mean sea level pressure (MSLP). Additionally, RegCM5 is driven by ERA5 SST. Figure 1 shows the SST anomalies observed in the southwestern Atlantic Ocean surrounding South America from June 25 to June 30, 2021. Notably, this period exhibited pronounced SST gradients in the Brazil-Malvinas confluence region, potentially intensifying air-sea heat fluxes during the cyclone development.

Figure 1 – Model domain, topography (m), sea surface temperature (SST, contour) and SST anomalies (shaded) for the period from June 25 to June 30, 2021. SST units are Celsius, SST anomalies (shaded) are calculated considering the climatological period from 1979 to 2015



Source: Authors (2023)

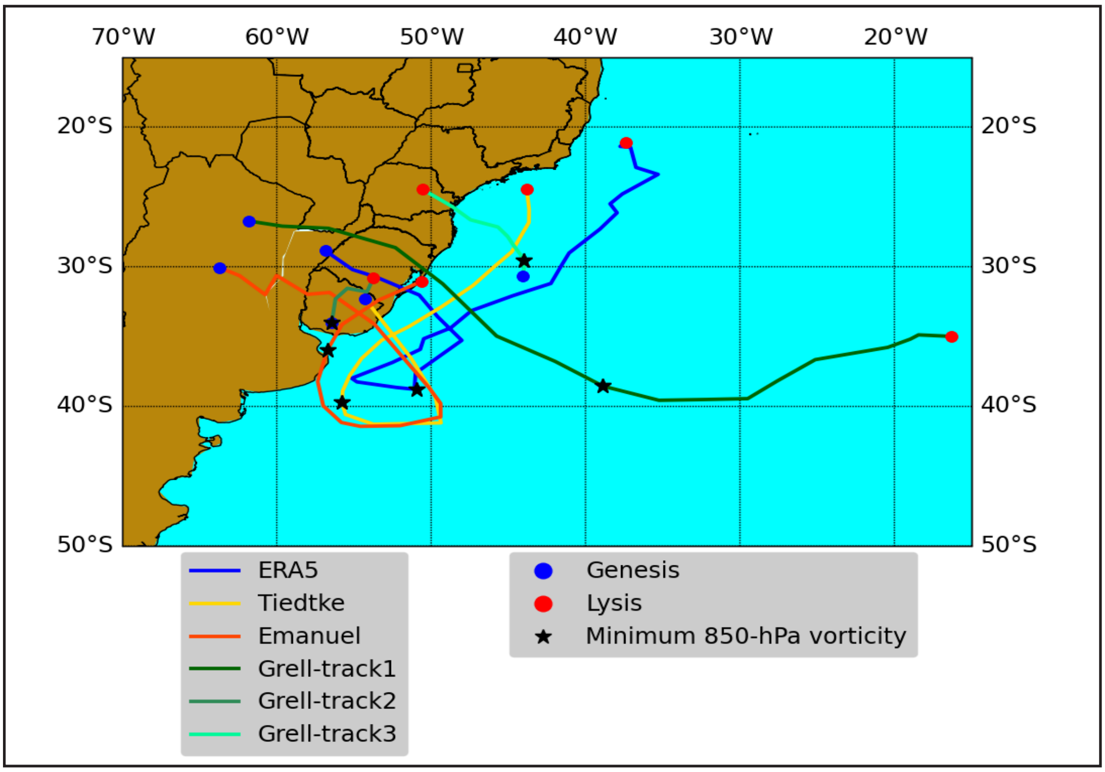
2.2 Identification and tracking of cyclone Raoni

Cyclone Raoni is identified and tracked with the tracking algorithm developed by Hodges (1995), as applied for reanalysis and model outputs. The tracking is performed using 6-hourly relative vorticity at 850 hPa () where the data are first truncated using a triangular truncation 42 (T42) as vorticity can be very noisy in high-resolution data. Vorticity has been found to be a preferable field as it allows the system to be identified before the formation of a closed pressure centre. The performance of individual parameterizations schemes in simulating the temporal evolution of cyclone Raoni is evaluated using area-averaged precipitation and minimum and MSLP, where the search is performed over a 5° spherical cap region centred on the storm centre for each point along the track.

3 RESULTS

Figure 2 shows the track of the subtropical cyclone Raoni along its life cycle as simulated by the RegCM5 model in different cumulus convection schemes compared to the track observed in the ERA5 reanalysis. Genesis and lysis indicate the first and last track points identified by the algorithm, respectively, which do not necessarily represent the first and last observed closed isobars in the MSLP charts, as discussed above. According to ERA5, the cyclone presented an unusual trajectory as it initially propagated southeastward, remained semi-stationary and then moved northeastward until its dissipation near the coast of Southeast Brazil. It is obvious that the Tiedtke scheme provides the best performance in simulating the track and intensity of the cyclone Raoni. This can be seen in Table 1 which allows a comparison of the cyclone Raoni's evolution across the three convective schemes during distinct development stages. The simulation produced with the Emanuel scheme reasonably represents the cyclone trajectory, although the system dissipates too early. However, unlike the previous schemes described above, the model performs poorly with the Grell scheme that shows a cyclone moving southeastward into the ocean, as represented by the first simulated trajectory (referred to as Grell-track1). The simulation with Grell shows other cyclogenetic processes occurring between Uruguay and southern tip of Brazil (Grell-track2) and later further north over the Atlantic Ocean (Grell-track3). A discussion of the cyclone lifecycle in terms of MSLP, vorticity and precipitation will be presented later.

Figure 2 – Raoni track as observed in reanalysis and simulated in the model



Source: Authors (2023)

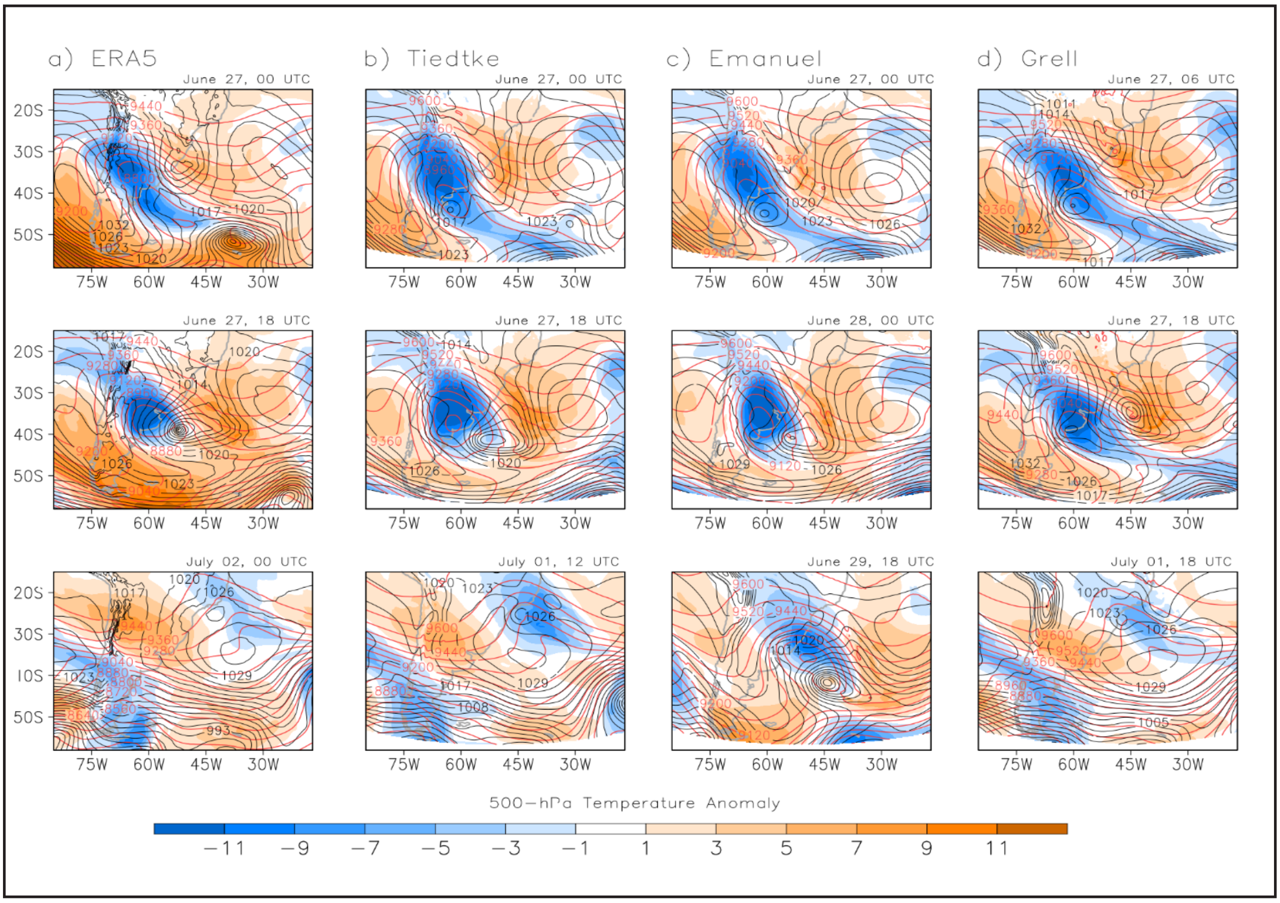
Caption: Parameterization cumulus schemes are: Tiedtke (yellow), Emanuel (red) and Grell (green). Blue line indicates the observed track in the ERA5 reanalysis. The start and end of the storm are indicated in blue and red points, respectively. The symbol star denotes the position of the cyclone minimum 850-hPa relative vorticity

Table 1 – Date, longitude, latitude and intensity for the 850-hPa vorticity (scale by 10^{-5} s^{-1}) and MSLP (hPa) for the cyclone Raoni's track identified in both reanalysis and model data. Genesis and lysis represent the first and last track points identified by the algorithm, respectively; maturity is the time of maximum intensity in the 850-hPa vorticity

		Genesis	**Maturity**	**Lysis**
ERA5	Date	June 25, 18 UTC	June 27, 18 UTC	July 03, 06 UTC
	Longitude	303.1	308.9	322.6
	Latitude	-28.8	-38.5	-21.1
	Vorticity	-6.4	-144.6	-5.9
	MSLP	1013.0	986.2	1022.1
Tiedke	Date	June 27, 00 UTC	June 27, 18 UTC	July 01, 18 UTC
	Longitude	305.7	310.6	316.1
	Latitude	-32.3	-41.1	-24.4
	Vorticity	-11.3	-77.6	-39.3
	MSLP	1010.2	999.6	1020.2
Emanuel	Date	June 27, 18 UTC	June 28, 00 UTC	June 30, 06 UTC
	Longitude	296.2	310.6	309.3
	Latitude	-30.0	-40.7	-31.0
	Vorticity	-5.7	-140.5	-14.5
	MSLP	1012.5	1007.8	1020.6
Grell-track1	Date	June 26, 12 UTC	June 27, 18 UTC	June 30, 12 UTC
	Longitude	298.1	314.2	343.7
	Latitude	-26.7	-34.9	-34.9
	Vorticity	-30.9	-84.1	-5.4
	MSLP	1010.1	996.7	1015.1
Grell-track2	Date	June 28, 18 UTC	June 28, 18 UTC	June 29, 18 UTC
	Longitude	303.5	303.5	306.2
	Latitude	-34.0	-34.0	-30.8
	Vorticity	-90.8	-90.8	-24.2
	MSLP	1014.6	1014.6	1026.7
Grell-track3	Date	June 30, 00 UTC	June 30, 06 UTC	July 02, 06 UTC
	Longitude	315.9	316.0	309.4
	Latitude	-30.6	-30.0	-24.4
	Vorticity	-84.4	-94.6	-14.6
	MSLP	1012.3	1010.6	1023.2

Figure 3 shows the synoptic pattern in three key stages in the cyclone's life cycle: formation, marked by the first observed closed isobar and cold-core extratropical development; maturity, representing the peak intensity (850-hPa vorticity) and a potential subtropical transition; and the system weakening and further dissipation. A comprehensive examination of the cyclone Raoni's thermal structure can be found in Reboita et al. (2022).

Figure 3 – Simulated atmospheric fields in different parameterization cumulus schemes



Source: Authors (2023)

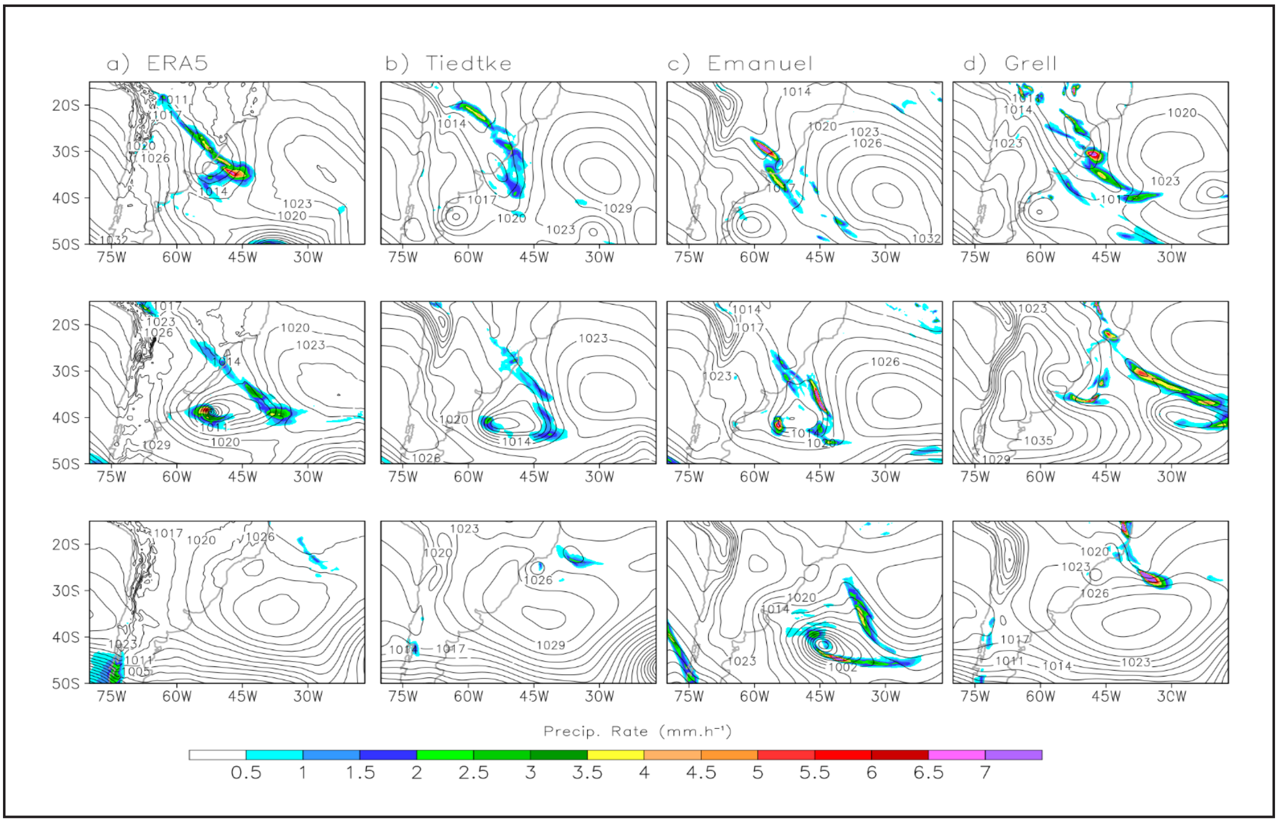
Caption: MSLP (hPa, black contour), 500-hPa geopotential height (gpm, red contour) and 500-hPa zonal mean temperature anomaly (Celsius, colour) for a) ERA5 reanalysis and RegCM5 model with the cumulus parameterization schemes b) Tiedtke, c) Emanuel and d) Grell. Upper, middle and lower panels denote the formation, maturity and dissipation stages of the cyclone life cycle, respectively

We first analyse the synoptic conditions observed in the ERA5 (Figure 3a). The cyclone formed near the coast of Uruguay and southern Brazil at 00 UTC June 27 when an upper-level trough moved northeastward from the South Pacific to Argentina and South Atlantic. Note that the cyclone formation, indicated by the first isobar centre, occurs after the algorithm initiates the tracking, as previously discussed (see Figure 2). At that moment, a significant cold core in the middle troposphere over the north-central Argentina (anomaly below -10ºC) and another one near the South Atlantic coast associated with a cyclonic vortex are observed. Then the cyclone rapidly intensifies and reaches a minimum MSLP of 984 hPa at 18 UTC June 27. Simultaneously, an upper-level ridge amplifies over the southern South America, exhibiting a dipole blocking pattern. This atmospheric pattern contributed to the detachment of the mid and upper cold core and to the slow westward movement of the surface cyclone that looped around itself and then moved northeastward until its dissipation near the coast of southeast Brazil on July 2.

The model simulations (Figure 3, upper panel) show a similar synoptic pattern to that observed in the reanalysis for the formation phase of the cyclone. The model roughly captures the cyclone formation, but there are differences in its location and intensity compared to reanalysis. In the simulations, a surface cyclone forms off the coast of Argentina, south of where the cyclone Raoni forms, in contrast to a trough observed in the ERA5 reanalysis. These differences could carry important implications for simulating the cyclone development.

In the mature stage (Figure 3, middle panel) some discrepancies are observed between simulations and reanalysis, particularly with respect to the Grell scheme that shows a westward tilted-trough and a surface cyclone far away from the continent. This pattern indicates an unfavorable condition for weakening vertical wind shear and coupling between upper- and lower-level disturbances, an important factor for the development of a warm core seclusion (Guishard et al. 2009). In contrast, simulations with Tiedtke and Emanuel schemes show a similar barotropic structure to that observed in ERA5. However, the cyclone dissipates prematurely in the Emanuel simulation due to the development of a secondary system that “absorbed” the primary pre-existing cyclone, as shown in Figure 3c (lower panel).

Figure 4 – Simulated precipitation in different parameterization cumulus schemes

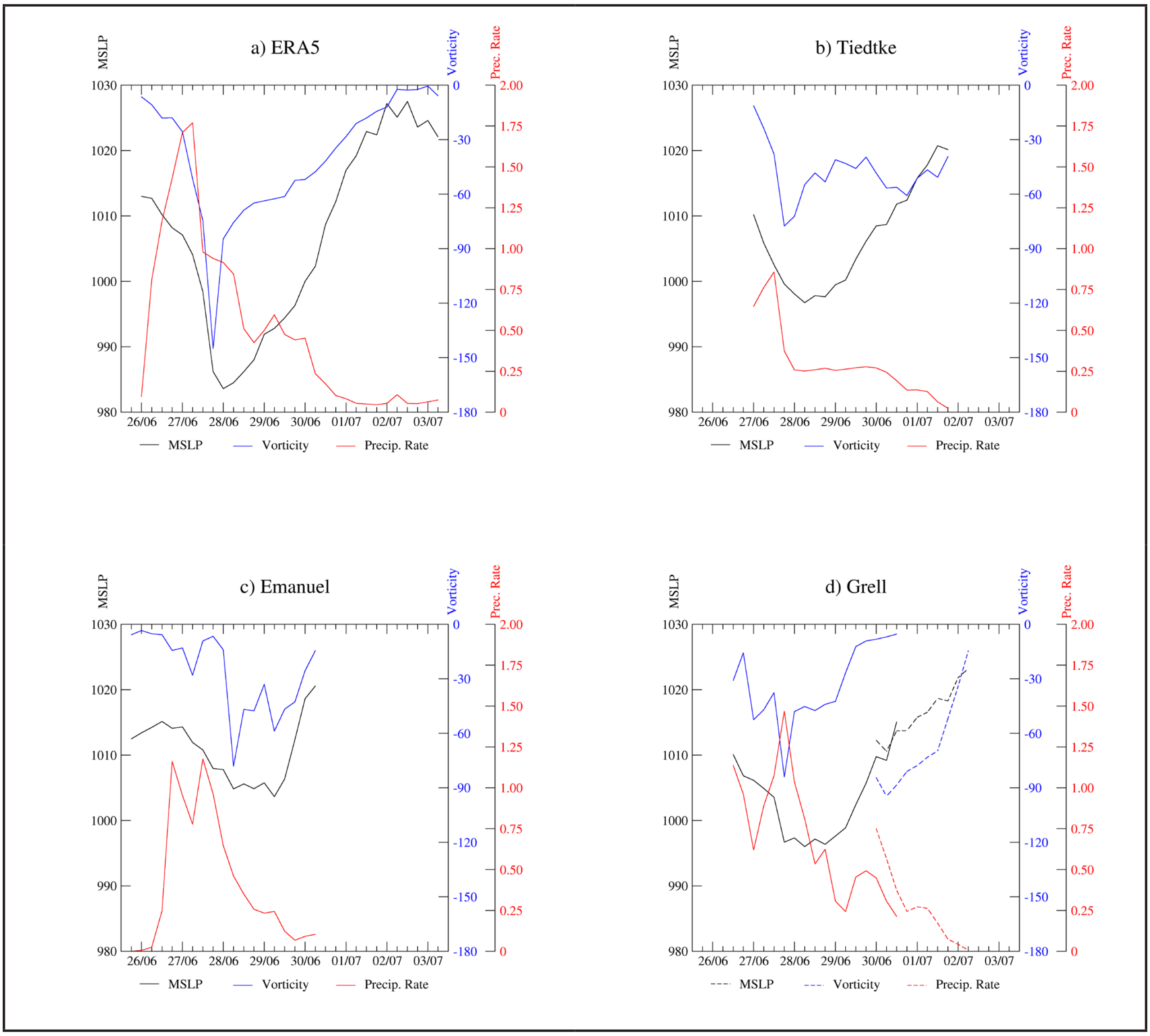


Source: Authors (2023)

Caption: MSLP (hPa, black contour) and 6-hour mean precipitation rate (mm.h^{-1}, colour) for a) ERA5 reanalysis and RegCM5 model with the cumulus parameterization schemes b) Tiedtke, c) Emanuel and d) Grell. Upper, middle and lower panels denote the formation, maturity and dissipation stages of the cyclone life cycle, respectively

The same cumulus parameterization schemes are used to assess the performance of the model in simulating the precipitation associated with the cyclone. According to ERA5, a typical precipitation pattern of a wave-frontal cyclogenesis can be seen for the formation stage (Figure 4a, upper panel). High rainfall rates occur east of the cyclone and a homogeneous region extends into the continent, associated with a cold front positioned on the northern edge of the transient anticyclone. In the maturity stage (Figure 4a, middle panel) the precipitation associated with the frontal system detaches from the main cyclone. This feature follows the characteristics described in the conceptual model by Shapiro and Keyser (1990), also discussed in Reboita et al. (2022). The dissipation stage (Figure 4a, lower panel) shows the transient anticyclone over the South Atlantic and the cyclone dissipating over its northern edge. The complete life cycle of the cyclone is approximately represented only in the simulation with the Tiedtke scheme that shows a similar pattern to that observed in reanalysis, whereas other schemes do not reproduce well the observed precipitation.

Figure 5 – Temporal Evolution of cyclone Raoni



Source: Authors (2023)

Caption: Fields are area-averaged precipitation (mm.h^{-1}, red), and minima of MSLP (hPa, black) and (10^{-5} s^{-1}, blue) for ERA5 and RegCM5 with the parameterization cumulus schemes Tiedtke, Emanuel and Grell. Values are computed over a 5º spherical cap region centred on the storm centre for each point along the track identified by the algorithm. Dashed lines represent a secondary cyclone development simulated with the Grell scheme.

Figure 5 shows the temporal evolution of the cyclone in terms of area-averaged precipitation, and minima of MSLP and 850-hPa relative vorticity () for model simulations compared to ERA5. According to ERA5 the system shows a rapid intensification and reaches the minimum (cyclones in the Southern Hemisphere are characterized by negative relative vorticity) at 18 UTC June 27. The cyclone intensification is accompanied by a deepening cyclone that reaches 984 hPa at 00Z 28 June. At that moment the cyclone receives the name of Raoni by the Brazilian Navy. The area-averaged precipitation rate increases rapidly after the cyclone formation and reaches its maximum value (1.8 $mm.h^{-1}$) just before the time of maximum intensity, followed by a rapid weakening.

Among the model simulations, Tiedtke performs best in reproducing the temporal evolution of the cyclone-related variables, though it underestimates the maximum intensities. In general, model simulations accurately represent the precipitation cycle, with maximum precipitation rates occurring just before the maximum cyclone intensity, followed by a rapid decline. However, the simulations exhibit shorter life cycles compared to reanalysis, particularly with respect to Emanuel and Grell schemes.

4 CONCLUSIONS

This study evaluated the performance of three different cumulus convection schemes with the RegCM5 model in simulating the cyclone Raoni. The results showed that the model is sensitive to the parameterization scheme as they largely affect the simulated track, intensity and precipitation associated with the cyclone. The cyclone's life cycle was analysed in terms of MSLP, vorticity, and precipitation.

Model simulations exhibited a shorter life cycle compared to the reanalysis, particularly with the Emanuel and Grell schemes. This can be partially attributed to the underestimation of intensities, leading to the cyclone dissipating prematurely. Notably, the Tiedtke scheme outperformed the others in reproducing the cyclone evolution, though maximum intensities were underestimated. The model accurately captured the precipitation cycle, with peak rates occurring just before maximum cyclone intensity.

However, the Grell scheme failed to consistently reproduce the cyclone evolution, so that this cumulus scheme should be used carefully.

Understanding why some convection parameterization schemes perform better is challenging. Although it is difficult to identify the exact reasons for the superior performance of the Tiedtke scheme, especially compared to the Grell scheme, we can offer some insights. The Tiedtke scheme’s strengths lie in its capacity to account for entrainment, employing conditional instability triggering, and distinguishing between shallow and deep convection. These features make it a versatile and potentially more realistic representation of convective processes in a variety of conditions.

We recognize the complexity of the parameterization scheme behaviour, which can vary by region and conditions, thus a cumulus convective scheme that works well for a region or set of conditions may not work as well for another. The studied case is considered an unusual cyclone, so simulations with different convective parameterizations might yield contrasting results for cyclones closer to the typical pattern. Therefore, more studies including cyclones that conform to the expected pattern are needed. Our results provide important insights into the relative strengths and weaknesses of different parameterizations and can help to improve the accuracy of future atmospheric models.

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Contribution: Visualization

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