How Physical Parameterizations Can Modulate Internal Variability in a Regional Climate Model

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ABSTRACT

The authors analyze to what extent the internal variability simulated by a regional climate model is sensitive to its physical parameterizations. The influence of two convection schemes is quantified over southern Africa, where convective rainfall predominates. Internal variability is much larger with the Kain–Fritsch scheme than for the Grell–Dévényi scheme at the seasonal, intraseasonal, and daily time scales, and from the regional to the local (grid point) spatial scales. Phenomenological analyses reveal that the core (periphery) of the rain-bearing systems tends to be highly (weakly) reproducible, showing that it is their morphological features that induce the largest internal variability in the model. In addition to the domain settings and the lateral forcing conditions extensively analyzed in the literature, the physical package appears thus as a key factor that modulates the reproducible and irreproducible components of regional climate variability.

1. Introduction

Internal variability (IV) has been increasingly investigated in recent years, especially within the regional climate modeling community. It results from chaotic processes intrinsic to the atmosphere and corresponds to the irreproducible component of climate variability in a multimember ensemble simulation (e.g., Giorgi and Bi 2000; Separovic et al. 2008). IV has been shown to vary according to the considered geophysical variable (Alexandru et al. 2007), the synoptic conditions (Lucas-Picher et al. 2008) and the season (Caya and Biner 2004), the domain size (Leduc and Laprise 2009), and location (Rinke et al. 2004).

Fewer studies have analyzed IV in the tropics, where lateral control is weaker and rainfall, mainly convective in nature, is more predominantly controlled by local-scale processes. Vanvyve et al. (2008) found that the large-scale features of the West African climate (i.e., those involving the longer periods or larger areas) are more reproducible than high-frequency or local-scale variability. Over southern Africa (SA), Kgatuke et al. (2008) found a strong (weak) reproducibility of the number (timing) of rain spells and suggested that ensemble simulations are not necessary at the seasonal scale. Over the same region, Crétat et al. (2011a) found that the number (intensity) of simulated rainy days is strongly (weakly) reproducible. Rainfall day-to-day variability was more (less) reproducible near the inflow boundary (outflow boundary and center) of their regional domain.

Although many studies depicted the strong sensitivity of the simulated regional climate to the model physical schemes [see, e.g., Heikkilä et al. 2010; Awan et al. 2011; Flaounas et al. 2011; Vigaud et al. 2011; see also Crétat et al. (2011b) and Pohl et al. 2011, who provide more exhaustive citations], it has never been attempted to analyze to what extent IV may be modulated by the model physical package. How the retained schemes affect the reproducible and irreproducible fractions of climate variability remains poorly documented. This is a gap that the present work proposes to fill. We compare here rainfall IV through two multimember ensemble simulations parameterized with two distinct cumulus schemes over SA, a region placed under the influence of both tropical and temperate systems.

2. Data and experimental setup

SA (and more particularly South Africa) is covered by a dense network of rain gauge measurements, which
makes this region particularly relevant to evaluate the capability of regional climate models (RCMs) over an area where convective rainfall is strongly predominant. Following Crétat et al. (2011a,b), analyses are conducted on the December–February (DJF) 1993/94 austral summer rainy season, representative of the South African rainfall climatology. Rain gauge measurements were obtained from the Water Research Commission (WRC) database (Lynch 2003). We extracted here 5352 stations over the northeastern part of South Africa, where a tropical rainfall regime prevails.

All experiments are performed using the nonhydrostatic Advanced Research Weather Research and Forecasting (WRF) model version 3.1.1 (Skamarock et al. 2008). The regional domain covers SA, from 46° to 5°S and from 3° to 56°E, with a 35-km horizontal resolution and 28 sigma levels. Lateral forcings are provided every 6 h by 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40) data (Uppala et al. 2005). SST is prescribed every 24 h after a linear interpolation of monthly ERA-40 SST. Integrations are initialized on 17 November 1993 and data are archived from 1 December 1993 to 28 February 1994 (i.e., after a 15-day spinup). Ensemble simulations are performed by perturbing the only atmospheric initial conditions, obtained from the ERA-40 fields of the 17 November of every year of the 1971–2000 period. Surface fields (such as soil moisture and temperature) are not perturbed in order to avoid artificial feedbacks with the surface.

During the same season, over the same domain and using the same model, Crétat et al. (2011b) investigated seasonal and intraseasonal rainfall biases of 27 configurations corresponding to all combinations of three cumulus, three planetary boundary layer (PBL), and three microphysics schemes. They found that the rainfall field is predominantly sensitive to cumulus parameterizations and identified some configurations producing realistic rainfall. Among them, we retain here two satisfactory configurations, corresponding to the combination of two cumulus schemes, namely the Kain–Fritsch (KF; Kain 2004) and Grell–Dévényi (GD; Grell and Dévényi 2002) schemes, with the Yonsei University PBL (Hong et al. 2006), Morrison et al. (2009) microphysics, Rapid Radiative Transfer Model (RRTM; Mlawer et al. 1997) and Dudhia (1989) schemes for longwave and shortwave radiation, a Monin–Obukhov surface layer, and the Noah land surface model (LSM) (Niu et al. 2011). We perform two series of 30-member ensemble simulations, using respectively KF and GD cumulus and keeping the other schemes constant.

GD is a one-dimensional mass flux scheme that consists of a single updraft–downdraft couplet. Mixing between the updraft and downdraft, and between the convective system and the surrounding environment, takes place both at the top and bottom of the cloud and laterally. GD simulations result from 144 ensemble members, where 48 dynamic and trigger closures are applied with three different downdraft types. Closure assumption is based on convective available potential energy (CAPE), low-level vertical velocity, or moisture convergence for which a quasi-equilibrium is applied for the available buoyant energy (large-scale changes and changes due to convection are almost equal). Trigger mechanisms and thresholds permitting convection vary for each member. Convective precipitation is proportional to the integral of the moisture advected by updraft. The total amount of cloud water due to condensation is removed by rainfall leaving no residual.

KF is a more complex mass flux scheme. Its closure assumption depends on the CAPE removal for an entraining parcel. Its trigger function is based on checking the parcel for buoyancy at the calculated lifting condensation level, starting with the lowest 50-hPa layer and repeating the same procedure up to 600–700 hPa. Triggering occurs when a parcel within a grid column overcomes negative buoyancy in order to rise. Then, rearrangement of mass takes place by updraft, downdraft, and entrainment calculations until 90% of the CAPE is saved. Entrainment is explicitly calculated between the environment and the cloud and varies according to the low-level convergence. Empirical limitations are imposed because of unrealistic precipitation in earlier versions of the scheme. Deep convection is triggered when a certain cloud depth is reached. In the case of a nonbuoyant parcel, shallow convection is permitted, based on turbulent kinetic energy for mass flux.

3. Results

a. Seasonal time scale

This section investigates the differences of rainfall IV associated with the two experiments over the entire regional domain at the seasonal time scale. Figure 1 shows the seasonal mean daily rainfall, number of rainy days, and associated intensity, and Fig. 2 shows their IV. The latter is defined as the intermember coefficient of variation (CV; i.e., the ratio of the intermember standard deviation to the ensemble mean), which allows us to compare variability structures around differing mean states. This metric takes thus into account the systematic differences between the KF and GD solutions.

The main differences between the two ensemble simulations are located over the Drakensberg mountains (southeastern part of South Africa) and more clearly within the intertropical convergence zone (ITCZ), located at
this time of the year over the northern part of the domain (i.e., Angola, Zambia, northern Mozambique/southern Tanzania, and Madagascar) (Figs. 1a,d,g; Waliser and Gautier 1993). KF tends to produce wetter conditions, mostly related to more frequent rainy days over the Drakensberg (Fig. 1h), and both more frequent (Fig. 1h) and wetter (Fig. 1i) rainy days in the eastern side of Madagascar.

The subtropical latitudes and the South Indian convergence zone (Cook 2000), elongated from SA toward the Mozambique Chanel and the southwest Indian Ocean (SWIO; Figs. 1a,d), concentrate largest IV and IV differences (Fig. 2). There, KF is not only wetter than GD (Fig. 1), but it also generates larger IV (Figs. 2a,d,g). In both experiments, IV patterns are thus relatively similar, showing weak reproducibility of seasonal rainfall
(Figs. 1a,d) between the southern periphery of ITCZ and the Drakensberg. Such IV patterns are mostly due to the intensity of rainy days (Figs. 1c,f,i) rather than their number (Figs. 1b,e,h).

b. Daily time scale

Figure 3 refines these analyses to the day-to-day variability. Following Créat et al. (2011a), the fraction $f$ of in-phase (i.e., reproducible) signals among the overall simulated variability in an ensemble simulation $X$ can be given by $f = \left(\frac{\sigma^2[X(t)]}{\lambda^2[X(t)]}\right) \times 100$, where $X(t)$ is the daily variability of a given geophysical field (e.g., rainfall) in all members, $\bar{X}(t)$ is their corresponding ensemble mean, and $\sigma^2$ is their daily variance. Also, $f$ is interpreted as a signal-to-noise ratio that quantifies the consistency between the members: if a given climate signal is perfectly reproducible (irreproducible) by all members, $f$ will tend toward 100 (0). This ratio is not biased by systematic differences between the two experiments.

**FIG. 2.** As in Fig. 1, but for the intermember coefficient of variation (%); in (g)–(i) units are percentage points (pp) and contour interval is 5 pp.
In both cases, IV is stronger near the domain center and its outflow boundaries (i.e., the western boundary in the midlatitudes, where westerly fluxes prevail, and the eastern boundary in the tropics; Figs. 3a,b). Day-to-day rainfall variability is once again much more reproducible in GD. The most pronounced differences (Fig. 3c) concern the hinterlands of SA, the neighboring of Madagascar, and the SWIO, where convective rainfall predominates (Crétat et al. 2011b). They reach up to 40%–50% points [percentage points (pp)] at the subtropical latitudes. In tropical South Africa, the spatial average of the reproducibility is roughly 11.5 pp weaker in KF (Fig. 3).

As for seasonal rainfall, the main differences between GD and KF experiments basically involve the raw reproducibility values, but associated spatial distributions are barely modified (Figs. 3a,b). We conclude thus that the “spatial spinup” of the model (i.e., the characteristic distance that the large-scale fluxes need to cover before developing small-scale features; Leduc and Laprise 2009) does not seem to be sensitive to its physics. The regions strongly constrained by the lateral forcings are thus primarily determined by the modulus and direction of the forcing fluxes, while the distance needed by the model to simulate its own variability is not drastically modified by its physics.

c. South African rainfall

A South African rainfall index is next computed over the area shown in Fig. 3, for which high-density rain gauge measurements are available (section 2). The analysis of the model biases being the scope of a previous study (Crétat et al. 2011b), our aim here is only to compare the respective behavior of the GD and KF schemes.

The fraction $f$ of the index reproducibility is 80% and 65% in GD and KF, respectively (Figs. 4a,b). Compared with the average reproducibility of the grid points embedded in the South African domain (51% and 40%; Figs. 3a,b), the reproducibility of a spatially averaged index is thus larger than the average reproducibility of the corresponding grids. This shows that, in agreement with Vanwyve et al. (2008), the large-scale features of the rainfall field are more reproducible than its local-scale variability. These relatively large reproducibility

![Fig. 3. (a) Daily rainfall reproducibility (%), see text for details) for the GD experiment. The average reproducibility of the grid points located in the South African domain (white contour) is labeled on the figure. (b) As in (a), but for the KF experiment. (c) Difference (pp) between the GD and KF experiments.](image-url)
values may be due to the strong orographic forcing of the Drakensberg (Blamey and Reason 2009).

Both experiments fairly reproduce the day-to-day variability of the observed South African rainfall index (Fig. 4). The temporal succession of wet and dry periods generally matches the observations, in spite of some timing errors (e.g., days 25–30 in GD) or unrealistic rainfall amounts (e.g., the same days in KF). In addition to a clear tendency for KF to furnish wetter conditions (Figs. 1, 3, and 4), the main differences between the experiments concern their simulated IV. The latter is larger in KF during almost all days of the season (Fig. 4c), whatever metrics are used (coefficient of variation or standard deviation). Although key phases of the season tend to concentrate peaks of IV in both experiments (e.g., days 20–30 and 50–70), other periods show sharp differences. This is, for instance, the case for days 10–20, during which rainfall is strongly (weakly) reproducible in GD (KF). In particular, the abnormally strong IV values (referred to as IV peaks henceforth, and defined as the local maximum of the intermember CV of the South African rainfall index, for a sequence of 5 days during which the 50% value is reached at least once) generally differ between the experiments (Fig. 4c). The relationships between lateral, synoptic-scale forcing conditions and IV within the domain, such as investigated in Crétat et al. (2011a), are therefore partly modulated by the model physics. Figure 4 indeed suggests that, even if given forcing conditions are associated with relatively similar regional IV between GD and KF experiments, other configurations may produce more uncertain effects.

d. IV peak case studies

The regional IV peaks (identified in Fig. 4c) are next analyzed at the whole domain scale in order to discuss the large-scale meteorological contexts that may favor such irreproducible events over South Africa. Note that our definition of IV peaks (section 3c) enables us to discuss different synoptic conditions, two successive peaks being separated by at least 6 days. The retained case studies correspond thus to the five most irreproducible days in GD and KF (Figs. 5 and 6, respectively).

Among these five days, only two (days 1 and 84) are common to both experiments. Yet, GD and KF IV peaks involve the same rain-bearing systems: (i) the ITCZ in the tropics [days 38 and 84 (GD) and days 39, 63, and 84 (KF)] with moisture advections from the Mozambique channel or the Indian Ocean (Washington and Preston 2006), the tropical Atlantic Ocean (Vigaud et al. 2007, 2009), and the Congo basin; (ii) tropical–temperate troughs [TTTs; Harrison 1984; Fauchereau et al. 2009; days 1 and 30 (GD) and days 1 and 39 (KF)] materializing as northwest-to-southeast rainbands extending between South Africa and the SWIO, and associated with a strong poleward export of momentum in the lee of their locations (Todd and Washington 1999; Todd et al. 2004); and (iii) TTT-like structures also associated with strong cyclonic moisture fluxes over the southern part of the Mozambique channel [days 69 (GD) and 58 (KF)].

In both experiments and for all IV peaks, the cores of the rain-bearing systems are strongly reproducible, while their peripheries concentrate the largest CV values. This is particularly true in the subtropical latitudes, where IV is strongest at both seasonal and daily time scales (Figs. 2 and 3). Hence, it is concluded that the genesis and development of the rain-bearing systems (tropical–temperate interactions or tropical storms embedded within the ITCZ), which are simulated by all members and are thus strongly reproducible, are predominantly due to large-scale mechanisms (that is to say, structures of larger size than our
FIG. 5. For each IV peak shown in Fig. 4c (see text for details), (left) daily ensemble mean rainfall amount, (middle) intermember CV, and (right) vertically integrated moisture fluxes in the GD experiment. The ensemble mean rainfall amount and CV computed over the South African rainfall index are labeled on the figure.
Day 1: 1/12/1993 ($\Sigma=2.14$ CV=117.99)

Day 39: 8/1/1994 ($\Sigma=1.81$ CV=54.76)

Day 58: 27/1/1994 ($\Sigma=1.59$ CV=113.68)

Day 63: 1/2/1994 ($\Sigma=1.82$ CV=93.63)

Day 84: 22/2/1994 ($\Sigma=0.47$ CV=55.68)

Fig. 6. As in Fig. 5, but for the KF experiment.
domain). The morphological features of such systems (size, location, and propagation speed) are in contrast highly variable from one member to another and relate therefore to the chaotic behavior of the atmosphere at the regional and local scales. This conclusion is particularly true for TTT events, in agreement with Créta et al. 2011a (who extensively analyzed a case study corresponding to day 30 of the GD experiment).

These results are of importance for operational weather forecasts. They demonstrate that even if the large-scale meteorological context outside the domain is perfectly predicted, the chaotic behavior of the atmosphere over the region is responsible for nonnegligible uncertainties in the morphology and location of such recurrent, well-known rain-bearing systems. TTT events are notably known to contribute to 30%–60% of South African summer rainfall (Todd et al. 2004), and a sizeable part of rainfall interannual variability in South Africa relates to their preferential longitudinal locations during the austral summer season (i.e., over the subcontinent of SA or over the Mozambique Channel; Fauchereau et al. 2009). The typical error in the location of the rainband can reach up to 1000 km longitudinally. These values illustrate the magnitude of the limitations that one can expect from weather forecasting in SA and the usefulness of ensemble simulations.

4. Summary and main conclusions

Figure 7 summarizes the main differences between both experiments, in terms of spatial and temporal variability of the South African rainfall field. The most obvious differences are found for the spatial and temporal standard deviations, which are larger (and overestimated) for KF. This denotes stronger variability in KF from one grid point to another (Fig. 7a) and from one day to another (Fig. 7b). Parts of these results are related to the fact that KF simulates wetter conditions, leading to an overestimation of South African rainfall and hence to a slight increase of the spatial and temporal root-mean-square error (Fig. 7). This is likely not the only reason. Previous analyses, based on the coefficient of variation (Figs. 2 and 4) and signal-to-noise ratio (Fig. 3), showed that KF simulates much more variable rainfall than GD, even when the effects of associated amounts are removed.

Spatially (Fig. 7a), the correlation coefficients between rain gauge measurements and WRF grids vary between 0.7 and 0.8 in both experiments, highlighting the capability of the model to reproduce the geography of South African rainfall. WRF improves upon the forcing reanalyses ($r \approx 0.6$). IV appears as moderate and little dependent on the physics. Temporally (Fig. 7b), correlations are weaker and less constant (between 0.3 and 0.7). They remain weaker than in ERA-40 ($r = 0.8$) because of the absence of data assimilation. Although correlations are more variable and slightly weaker in KF (ranking from 0.32 to 0.66 vs 0.4 to 0.67 for GD), it is not possible to conclude than one schemes behaves significantly better than the other.

This result differs from Flaounas et al. (2011), who found that day-to-day variability simulated by KF over West Africa is more realistic than GD, in spite of stronger biases. Their results, however, were not
obtained through ensemble simulations. The strong IV found in this study (particularly for KF experiment), which generates inconstancy in our daily correlation coefficients, questions the robustness of their conclusions. Our results also highlight the usefulness of a mixed-physics ensemble simulation when working at the daily time scale (Figs. 3 and 4) and even, to a lesser extent, on seasonal fields (Figs. 1 and 2).

5. Discussion

Analyzing IV in a regional climate model is a complex issue because it is a multidimensional problem that varies according to many factors. In addition to those already pointed out in the literature, we show here that the model’s physical schemes are likely to strongly modulate the irreproducible component of climate variability. The simulation of tropical and subtropical rainfall IV, in particular, appears as highly sensitive to the parameterization schemes of atmospheric convection. Rainfall variability simulated with KF systematically appears as less reproducible (i.e., with less consistency between ensemble members) than that obtained with GD, from the seasonal to the daily time scale, and from the regional to the local scale. These results are probably related to the ensemble approach of convective precipitation used in the GD scheme. The combination of 144 ensemble members used in its trigger function is hypothesized to smooth out simulated fields and reduce associated IV.

The choice of the convective scheme for tropical and subtropical rainfall analysis was known to strongly affect the model mean state. In addition, we show here that it impacts the relative weight of both reproducible and irreproducible components of climate variability. Of course, other physical parameterizations (such as the PBL, the LSM, or the radiation) may also modulate simulated IV, an issue that could be focused on in future work.

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