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Babutunde J. Abiodun
University of Cape Town

William Gutowski
Iowa State University, gutowski@iastate.edu

Abayomi Abatan
Iowa State University, abatanaa@iastate.edu

Joseph Prusa
Teraflux Corporation

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CAM-EULAG: A Non-Hydrostatic Atmospheric Climate Model with Grid Stretching

Babatunde J. ABIODUN¹, William J. GUTOWSKI²
Abayomi A. ABATAN², and Joseph M. PRUSA³

¹Department of Environmental and Geographical Sciences, University of Cape Town, South Africa; e-mail: babiodun@csag.uct.ac.za (corresponding author)

²Department of Geological and Atmospheric Sciences, Iowa State University, Ames, USA; e-mails: gutowski@iastate.edu, abatanaa@iastate.edu

³Teraflux Corporation, Boca Raton, FL, USA; e-mail: jprusa@bellsouth.net

Abstract

This study evaluates the capability of a non-hydrostatic global climate model with grid stretching (CEU) that uses NCAR Community Atmospheric Model (CAM) physics and EULAG dynamics. We compare CEU rainfall with that produced by CAM using finite volume dynamics (CFV). Both models simulated climate from 1996 to 2000, using the same parameterization schemes.

CEU and CFV both simulate well the observed global rainfall pattern. However, with same grid, CEU performs better than CFV in simulating the annual cycles of precipitation over our target region of West Africa. The reason is that it simulates African easterly jet and monsoon circulations better than CFV. CEU simulations with horizontal grid stretching to 0.5° are markedly better than those using CAM's standard $2.0^\circ \times 2.5^\circ$ grid.

Key words: global climate model, stretched grid, non-hydrostatic dynamics.

1. INTRODUCTION

Historically, global climate models have used hydrostatic governing equations to simulate circulation dynamics. A goal of climate simulation is to increase

spatial resolution as computing power increases. However, as resolution increases, non-hydrostatic behavior emerges, even for resolutions as coarse as 50 km (Prusa and Gutowski 2006). There is thus a growing need to represent well non-hydrostatic dynamic processes in global climate simulation. In addition, climate study often needs to target specific regions at relatively high resolution for assessing impacts of climate change, for analysis of regionally important climatic processes and to study potential upscale interactions in which regional phenomena may influence global-scale climate.

In this paper we demonstrate some of the capabilities of an atmospheric global climate model CAM-EULAG (CEU) constructed using the EULAG dynamics (Prusa *et al.* 2008) and the Community Atmospheric Model (CAM; Collins *et al.* 2004, 2006) physics, developed by the U.S. National Center for Atmospheric Research (NCAR). CEU simulates non-hydrostatic climate dynamics in a formulation that allows grid stretching. We can thus target higher resolution to select regions and elicit non-hydrostatic dynamics as appropriate for the resolution. We compare CEU results with those from a standard version of CAM that uses the finite-volume, hydrostatic dynamics (CFV; Collins *et al.* 2004, 2006). This is useful for determining which features of the simulated climate are due to the parameterizations of atmosphere and land processes in CAM and which are due to the choice of dynamics core. This study focuses on West Africa, because previous studies (*e.g.*, Sylla *et al.* 2010b) have shown that many GCMs fail to simulate correctly the West Africa monsoon system. We demonstrate below that CEU gives a more realistic simulation of the monsoon system than CFV.

2. MODEL DESCRIPTION

EULAG is a non-hydrostatic, parallel computational model for all-scale geophysical flows. Its “all-scale” capability has allowed successful application of EULAG to simulations of dynamics on scales as fine as those governing cloud microphysics (\sim cm; Andrejczuk *et al.* 2004) and as large as those governing the magneto-hydrodynamics of the solar sphere (Elliott and Smolarkiewicz 2002). In the formulation used here and in previous global applications, non-hydrostatic behavior is obtained through the anelastic approximation. Experimental versions of EULAG are under development that use the fully compressible equations as well as other sound-proof approximations permitting non-hydrostatic flow, such as the Durran equations (Durran 2008, Smolarkiewicz and Dörnbrack 2008). Future development will consider implementation of these formulations in CEU. For the present, we continue with the dynamics equations used in our previous development of CEU.

A signature feature of EULAG is its formulation in generalized, time-dependent curvilinear coordinates. The code uses continuous mappings from

a physical space where the problem is posed to a transform space where the problem is solved numerically. The mappings allow us to implement grid stretching in which the grid may appear non-uniform in physical space but uniform in the computational transform space. The mappings allow dynamic (time-dependent) grid stretching, though we report here results that use only static stretching. Further details appear in Prusa and Gutowski (2006), Abiodun *et al.* (2008), and Prusa *et al.* (2008).

The CAM provides the physics parameterization used in CEU. The results here use CAM Version 3 (Collins *et al.* 2004). CAM3 has a clear separation between dynamics and physics parameterizations, which allows relatively straightforward coupling of CAM and EULAG. The physics packages in CAM3 consist of moist (precipitation) processes, cloud and radiation calculations, ocean-surface and terrestrial models and turbulent mixing processes. Collins *et al.* (2004) give detailed descriptions of the parameterizations, and Abiodun *et al.* (2008) describe how CAM and EULAG are coupled.

3. SIMULATIONS

We report here results of two simulations using CEU: one that used CAM's standard 2.0° (lat.) \times 2.5° (long.) grid for the entire globe (CEU-UNI), and one that

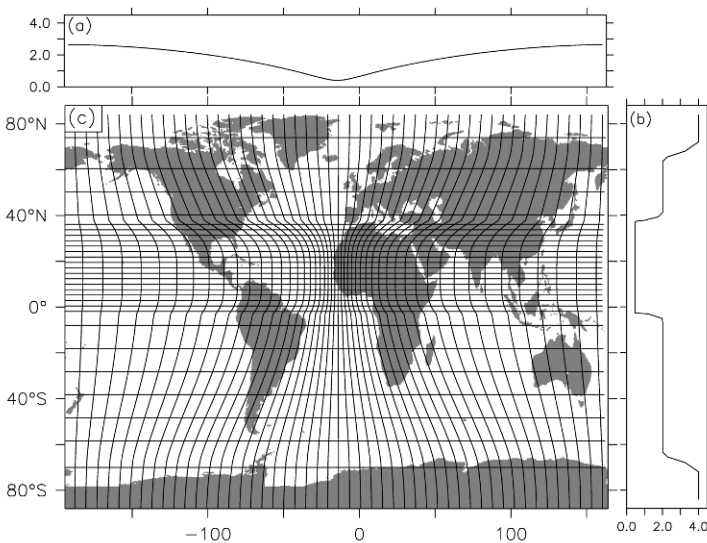


Fig. 1. Horizontal grid resolution for CEU-SG simulation. Panel (a) shows the zonal distribution for the grid points along 18°N (line). Panel (b) shows the double nested distribution used for the meridional grid points. Panel (c) shows the combined effect of meridional and zonal mappings for the grid. Only 20% of the grid points are shown for clarity.

stretched the grid (CEU-SG) to have 0.5° (lat.) \times 0.5° (long.) resolution over West Africa while transitioning smoothly to a coarser grid elsewhere (Fig. 1). For comparison, we performed a corresponding simulation using CAM3 with its finite volume (CFV) dynamical core using CAM standard resolution. All the simulations started at 1 January 1995 and ran for six years. Observed sea surface temperatures and sea ice distributions used in the simulation came from the standard CAM package. We discarded the first year for spin up.

We compare simulations to gridded precipitation observations produced by the Global Precipitation Climatology Project (GPCP; Huffman *et al.* 2001), by the Climatic Research Unit (CRU; Mitchell and Jones 2005), and by the Tropical Rainfall Measurement Mission (TRMM; Simpson *et al.* 1996) and to atmospheric circulation features in the ECMWF Interim Reanalysis (ERA-Interim; Berrisford *et al.* 2009).

4. RESULTS

4.1 Global and regional rainfall pattern in summer

Figure 2 shows that the models give a realistic simulation of the global rainfall pattern in boreal summer (June-August, hereafter, JJA). In GPCP, the rainfall pattern features a zone of maximum rainfall in the tropics, corresponding to the Inter-Tropical Convergence Zone (ITCZ), the upward branch of the Hadley cell. The zone is captured in the models, except that the models produce higher precipitation than GPCP does. Another important feature is a zone of maximum rainfall at $\sim 40^\circ\text{S}$ in the models and GPCP, showing the mid-latitude storm tracks. The third important feature is the sub-tropical dry zones, which mark the downward arm of the Ferrell and Hadley cells, centered around 30°N and 20°S in models and GPCP. Hence, the global rainfall pattern – a signature of large-scale circulation – shows that the models capture essential global circulation features. However, regional (or mesoscale) circulation features interact with these large-scale features and alter the rainfall pattern at the regional scale. These interactions pose a challenge to many GCMs in simulating the regional rainfall correctly, especially over West Africa.

CEU-SG simulates fine scale features in West African rainfall, similar to those seen in the high resolution observational datasets: CRU and TRMM (Fig. 2). These features are absent in CFV and CEU-UNI because of the models' low resolution. Furthermore, CEU-SG better simulates the regional features in West Africa compared to GPCP, CRU, and TRMM (Figs. 2 and 3). The improved simulation in CEU-SG may arise from the stretched grid capability that allows the model to increase its horizontal resolution locally and better resolve the interaction between the large and regional scales.

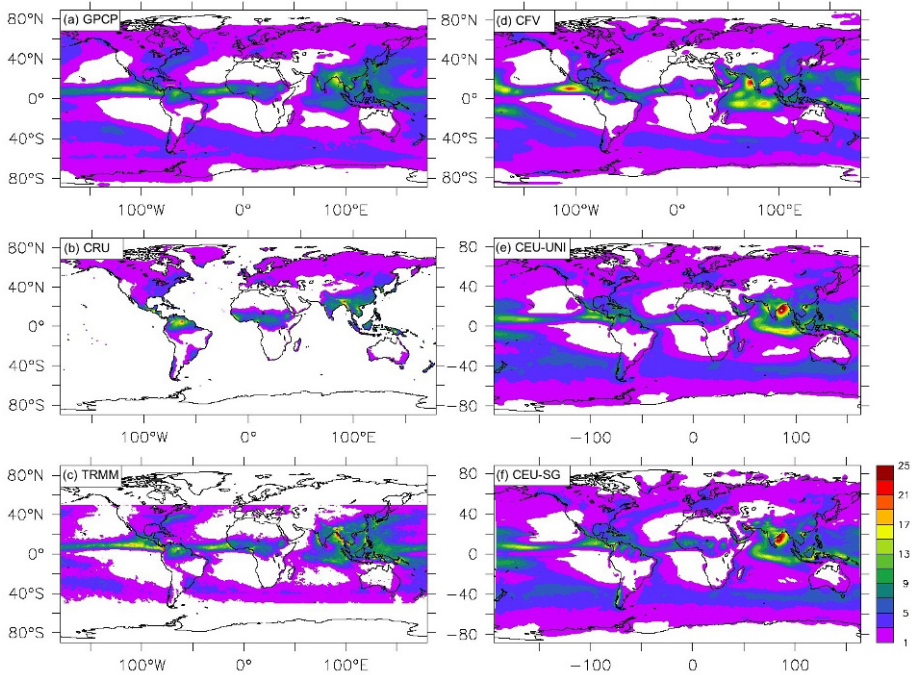


Fig. 2. Mean JJA precipitation (mm day^{-1}) for: (a) GPCP, (b) CRU, (c) TRMM, (d) CFV, (e) CEU-UNI, and (f) CEU-SG. Note that CRU has no data over the oceans and TRMM has no data poleward of 50°N and 50°S .

4.2 The West Africa monsoon system and rainfall

Figure 3 shows that the West African rainfall exhibits three distinct phases: the onset, the peak, and the retreat of the rainfall, in agreement with previous studies (*e.g.*, Le Barbé *et al.* 2002). The onset period, characterized by the northward extension of the rain belt from the coast to about 6°N , is from March to June in GPCP, CEU-UNI, and CEU-SG, but from March to May in CFV (Fig. 3). The peak period, characterized by a northward jump of the rain-belt to 10° – 14° and the termination of rainfall south of 6°N , occurs from June to September in GPCP and the models. However, CFV fails to capture the rainfall maximum at the peak of the monsoon. CEU-SG captures the rainfall maximum, but the duration is four months instead of two months as in GPCP. The southward retreat of the rainbelt starts in September in the models and GPCP. The seasonal variation of the rainfall closely follows the latitudinal position of the Inter-Tropical Discontinuity (ITD) and the African Easterly Jet (AEJ), in agreement with previous studies (Le Barbé *et al.* 2002, Omotosho and Abiodun 2007, Sylla *et al.* 2010a). The models underestimate the strength of the AEJ,

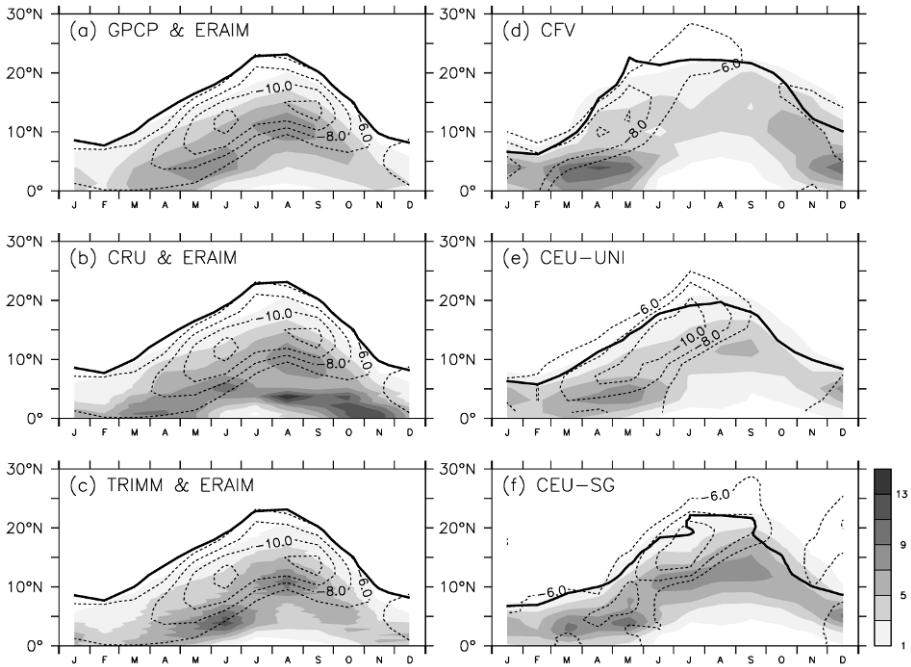


Fig. 3. Time-latitude cross section of monthly mean rainfall (mm day^{-1} ; shaded), averaged over 10°W – 10°E . Panels are: (a) GPCP, (b) CRU, (c) TRMM, (d) CFV, (e) CEU-UNI, and (f) CEU-SG. Panels (a)–(c) use ERA-Interim wind data. The location of the ITD (the contour of zero meridional wind at the surface) is indicated by the black solid lines, and the cores of AEJ (at 600 hPa in ERAIM and 650 for the models, see Fig. 4) are indicate with dashed contours lines.

although CEU-UNI and CEU-SG better simulate the magnitude (-10 m s^{-1} in CEU, -8 m s^{-1} in CFV, and -12 m s^{-1} in ERA-Interim). The models reproduce only approximately the southward retreat of AEJ after September.

Figure 4 shows that CEU-UNI and CEU-SG simulate the vertical structure of the monsoon system better than CFV does. With the zonal winds, ERA-Interim (Fig. 4a) shows the monsoon flow (4 m s^{-1}) at low levels (below 800 hPa) south of 22°N , the AEJ (-11 m s^{-1}) at middle levels (600 hPa) around 16°N and the Tropical Easterly Jet (TEJ, -18 m s^{-1}) in upper atmosphere (200 hPa) at 6°N . Although, all the models simulate stronger monsoon flows than ERA-Interim does and put the peaks farther north, CEU-UNI (8 m s^{-1} at 11°N) and CEU-SG (8 m s^{-1} at 12°N) capture the monsoon somewhat better than CFV (12 m s^{-1} at 14°N). Also note that CEU-UNI and CEU-SG simulate the AEJ at a lower level (650 hPa) and $\sim 3^{\circ}$ north of the ERA-Interim position. The simulation of AEJ 3° north of the location in ERA-Interim could also

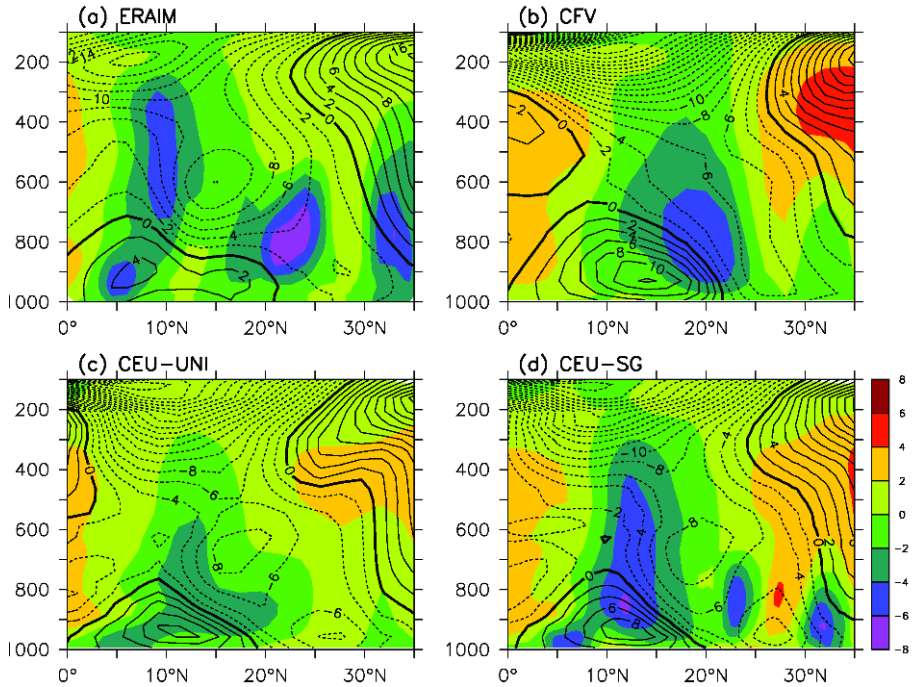


Fig. 4. Vertical structure of the monsoon system in August. Zonal wind (m s^{-1}) depicted in contours and the vertical wind (mb s^{-1}) in colour: (a) ERA-Interim, (b) CFV, (c) CEU-UNI, and (d) CEU-SG.

place the simulated rainfall peak northward of the observed rainfall. However, the CFV fails to simulate AEJ, which explains why the model could not reproduce the rainfall maximum of the monsoon (Fig. 2). The models put the TEJ at same altitude (~ 200 hPa) with that of ERA-Interim, but the location is $\sim 5^\circ$ north of the ERA-Interim location (ERA-Interim = 6°N , CFV = 11°N , CEU-UNI = 11°N , CEU-SG = 10°N), and the speed is stronger (ERA-Interim = -18 m s^{-1} , CFV = -34 m s^{-1} , CEU-UNI = -24 m s^{-1} , CEU-SG = -22 m s^{-1}). CEU-UNI and CEU-SG results are better than CFV regarding the TEJ speed, and CEU-SG is the best on all 3 measures. The difference between the simulated and ERA-Interim TEJ could contribute to the rainfall biases, as TEJ plays important roles in West African rainfall (Nicholson 2009, Jenkins *et al.* 2005, Sylla *et al.* 2010a).

With the vertical wind components, south of 30°N , ERA-Interim shows three local ascent extrema. The first is an ascent region centered at 22°N and below 600 hPa, corresponding to the ITD, and characterized by dry convection (Sylla *et al.* 2010a). The second is a shallower ascent region (below 800 hPa) at

5°N, at the interface of the Gulf of Guinea and the West African coast. The third is a deep ascent region between 700 and 200 hPa at 10°N, corresponding to the ITCZ. CFV fails to capture these three extrema, but instead simulates a single deep ascent (between the surface and 300 hPa) centered at 20°N. CEU-UNI also simulates only a single extremum of ascent, but shows a three lobed structure suggestive of ERA-Interim's behavior. The best simulation comes from CEU-SG, which cleanly separates the three extrema, though the northernmost ascent is shallower (below 700 hPa) and weaker than that of ERA-Interim. This ascent better captured in CEU-SG could have led to the stronger and more realistic ITCZ in the spatial distribution of rainfall for the model.

5. CONCLUSIONS

The simulations show that relative to GPCP and ERA-Interim, CEU-SG and CEU-UNI tend to perform better over West Africa than CFV, even though the models are using the same physical parameterizations. The summer precipitation patterns in all three are similar to the patterns in the GPCP, though CEU-SG tends to have more intense precipitation, which agrees better with observations.

The improvement is most notable in August, when the monsoonal circulation extends farthest inland. Again, CEU-SG simulates more intense precipitation than CEU-UNI, in better agreement with observations. Contributing reasons for the better performance of the CEU versions is that they produce an African easterly jet and monsoon circulation that generally agree better with observations, as depicted by the ERA-Interim reanalysis.

Finally, previous studies (*e.g.*, Sylla *et al.* 2010b) have shown that many GCMs fail to simulate correctly these features in the vertical structure of the West Africa monsoon system (especially the AEJ). The present study shows that this may be more a problem of resolution of dynamics than parameterization.

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