Africa Journal of Physical Sciences Vol. 4, pp. 98-114, June 2020
http://journals.uonbi.ac.ke/index.php/ajps/index
ISSN 2313-3317

Advancing understanding and modeling of climate processes for provision of deterministic climate information for sustainable development in Kenya and Eastern Africa

MUTEMI J. N.[1,*], MWANTHI A. M.[1], JAMES R.[2] and WASHINGTON R.[2]

[1]Department of Meteorology, School of Physical Sciences, College of Biological & Physical Sciences, University of Nairobi, P. O. Box 30197-00100 GPO, Nairobi-Kenya.

[2]School of Geography and the Environment, University of Oxford, Oxford, OX1 3QY, UK

*Corresponding author email: mnzau@uonbi.ac.ke

ARTICLE INFO

Article History:
Submitted:17 June 2019
Accepted: 30 April 2020
Available online: June 2020

Keywords:
Model evaluation
Moist thermodynamics
Droughts and floods
Moisture depth

ABSTRACT

The implications of climate variability and emerging climate change make East Africa particularly vulnerable region due to dependence of most socio-economic activities on highly variable climatic variables like rainfall which has relatively low predictability. Dynamical climate modelling for both operational climate information services like seasonal outlooks, and long-term projections has made notable improvements since 1990s. Models are the only tools for projecting the long-term future climate alongside provision of short-term information for planning and management of climate sensitive socio-economic activities like rain-fed agriculture and water resources. Using rainfall and moist circulation evaluation results, this study illustrates the "UM HadGEM-GC2" model give good indications of processes which quantify climate extremes namely floods and droughts over East Africa. Among the most important processes revealed in this study, vertically integrated moisture flux, which embraces both horizontal moisture transport into or out of East Africa with sufficient moist-air depth or dry atmospheric column are crucial mechanisms for occurrence of floods and droughts in Kenya and East Africa. Knowledge products like these can translate into mitigation and adaptation decisions in water resources, agriculture and food security. To model developers, processed based model evaluation outcomes like these reveals what physics and dynamics attributes to focus on in the formulation of next generation models and development of evaluation metrics.

ISSN 2313-3317

1. Introduction

In Kenya, East Africa, and over many parts of the world, the weather conditions and the state of the climate become issues of serious concern when (1) rainfall is insufficient or has totally failed to be sufficient during one or several successive wet seasons causing a severe drought or (2) there is too much rainfall during the wet season rainfall leading to catastrophic flooding as was witnessed in most of Kenya during March to May 2018. The adverse impacts of the March-May 2018 and many other floods episodes in Kenya serve as a good highlight that such conditions should be anticipated well in advance and the information availed to relevant agencies, the general public and strategic planners for informing of decisions and preparedness actions which protect lives and help communities build resilience to climate extremes. Good examples of applications of climate information on a wide range of sectors are discussed in [1].

Weather and climate information is crucial for socio-economic welfare and it is important in the planning and management of activities geared towards enhancement of food security, water resources utilization and therefore weather forecasting and climate prediction is a crucial information service done for the common good and welfare of societies. [2] provides an innovative means of using numerical weather prediction models to provide highly accurate weather forecasts in various parts of Africa using the super-ensemble approach of numerical weather prediction models [3]. The application of the technique to provide medium range weather forecasts over the Greater Horn of Africa has been in many studies including [4]. The use of dynamical models to provide information on the state of weather and climate must be extended to provide information for longer time scales from few months and several decades to long-term future projections. Although this is an extremely challenging problem in the science of weather and climate, [5] demonstrate that deterministic models if sufficiently formulated can resolve the mechanisms and processes which control the major climate patterns/features over various sub-regions of Africa. These are of great importance and interest in application of dynamical models to provide present and future climate information for decision support.

The problem of droughts in parts of Africa has been subject of intensive climate research and concern due to the adverse impacts of droughts such as the drying of water resources and withering of food crops. In particular, the subject of the Sahel droughts with indications of recovery, for example positive rainfall trends over the Sahel is notable [6]. East Africa droughts are also subject of many studies [7] and their impacts in form of famines are the focus of many governmental agencies and non-governmental organizations. On the other hand, prolonged periods of torrential rainfall cause extensive flooding which also afflicts communities through loss of life and destruction of property and infrastructure like roads and bridges. The focus of this study is to highlight the scientific basis and causes of floods and droughts in Kenya and East Africa, through dynamical model evaluation of the moist-thermodynamic processes and mechanisms which lead to these stressing climatic conditions.

Often, climate models and operational weather and climate service institutions including the Kenya Meteorological Department (KMD), and the regional climate outlook forums (RCOFS) provide forecast information on the likely climate conditions which are anticipated to prevail for the next 3 months. This is the typical climate prediction time scale and the major control mechanism is the oceanic influence of atmospheric circulation and how this air circulation distributes moisture to the various parts of the earth. Indeed, Indian Ocean is very important for East Africa rainfall [8]. The large-scale floods and droughts can be predicted by climate models with good accuracy over East Africa, especially when the phases of ENSO have persisted in the global climate system with indices above thresholds depending on the particular ENSO index with lead times of several months [9]. Climate scientists and information providers, educational institutions and researchers have to advance the capability to provide accurately longer lead climate information on time scales like 5-40 year time scales. The information should have quality attributes that can used for long-term planning and implementation of flood and drought management programs and activities, for example, the climate dimension in attainment of development goals like vision 2030 in Kenya [10].

In recent decades, there has been remarkable progress in climate modelling [11], [12], but with limited discernible improvement over Africa [11]. This is most frequently highlighted with reference to the Sahel, where many models fail to capture the magnitude of the 1970s-80s drought [13]. Other African regions also present demanding tests for climate models and indeed, the trend of decrease in rainfall in parts of East Africa during the season March-May has been highlighted in and referred to as the East Africa paradox [14]. Organized convection [15] and sharp pressure gradients are problematic given large grid-spacing. The presence of strong land-atmosphere interactions [16], large aerosol emission from arid regions [17], influences from global ocean basins [18], and prominent modes of interannual and interdecadal rainfall variability [19] exacerbates the challenge. Furthermore, some of these features and systems are poorly understood due to limited observations and research attention. Nevertheless, advanced climate modelling and prediction science is a crucial key to improving our capability to provide high accuracy climate information especially rainfall. This study highlights some scientific outputs from a climate model development research undertaken under the auspices of IMPALA project (Improving Model Processes for African cLimAte - https://futureclimateafrica.org/project/impala/) over East Africa.

2. The Model, Data and Methods

The UK Met office Unified model (UM) has been used in this work. It is a continually developing dynamical model system for use in day to day weather predictions, medium range weather predictions whose time scale is three days to two weeks, climate forecasts which stretch out to three months, and also it is used for long term climate change projections [20], [21]. The model outputs of meteorological variables used in this work are from the model version named HadGEM3-GC2 [22]. The simulation runs of HadGEM3-GC2 are driven with historical natural and anthropogenic forcing for the long-term future projection of the climate. Model data in this study is presented for the 35- year period 1979-2013 for current climate and future projections are out to the 2070s. The field variables used are precipitation at the surface and in the atmospheric levels the variables used are wind and specific humidity at various levels in a domain covering all of East Africa. The observational data sets used are the GPCP monthly precipitation [23], [24], and the ERA-Interim [25] for derivation of the observational attributes of the dynamics used in the results discussed in the next section.

3. Results and Discussion

The typical climate normal tropical east Africa is the bimodal rainfall distribution, namely 2-wet seasons during the calendar year, occurring during the months of March – May (MAM), also called the long rainfall season, and the October-December (OND) period, also called the short rainfall season. Figure 1 left panel shows the model and observed rainfall over East Africa domain during the March-May season are shown on the right hand side panel. Both model and observations are consistent in East Africa, generally wet conditions everywhere within East Africa. As evident from Figure 1, the model (left panel) and observed rainfall (right panel) magnitudes are quite comparable, nearly 300mm within the area centred over Kenya (area enclosed by blue rectangle). The pattern during the October-December (OND) season is shown in Figure 2. Comparing the model and observations (left and right panels in Figure 2), the model rainfall is nearly 600mm against observation of 300mm. This is an overestimation and it is most notable over most of Kenya and stretches westwards across Uganda to central Africa.

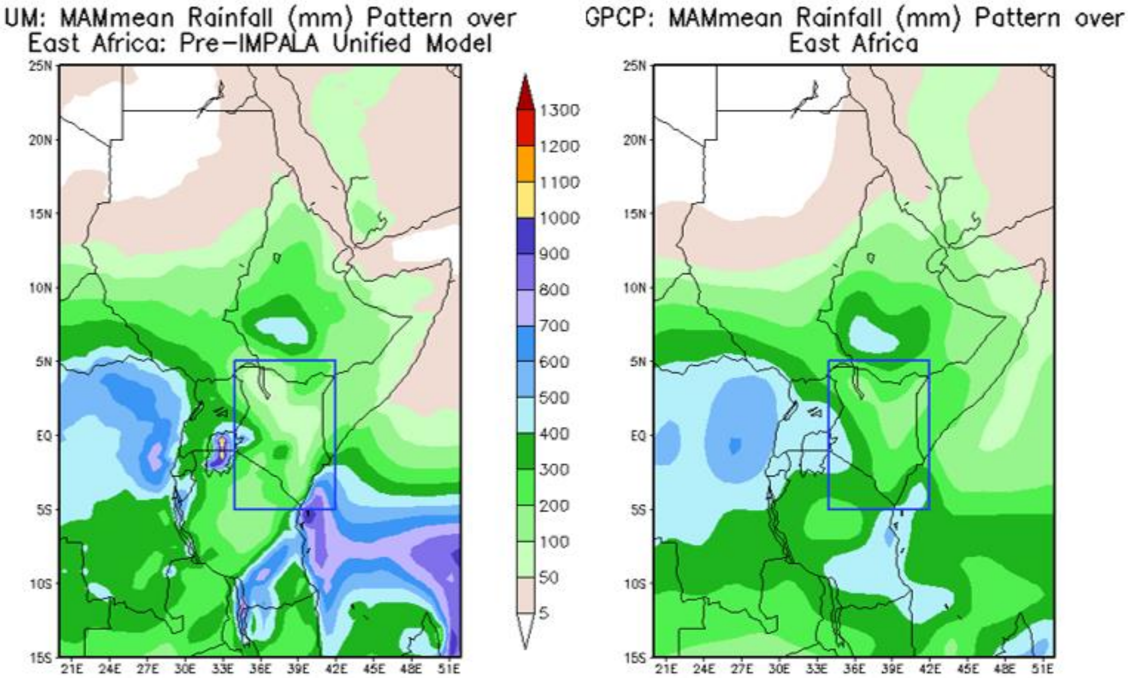

Figure 1: Model (left panel) and observed climatology/ baseline (right panel) of East Africa rainfall during the March-May (MAM) season.

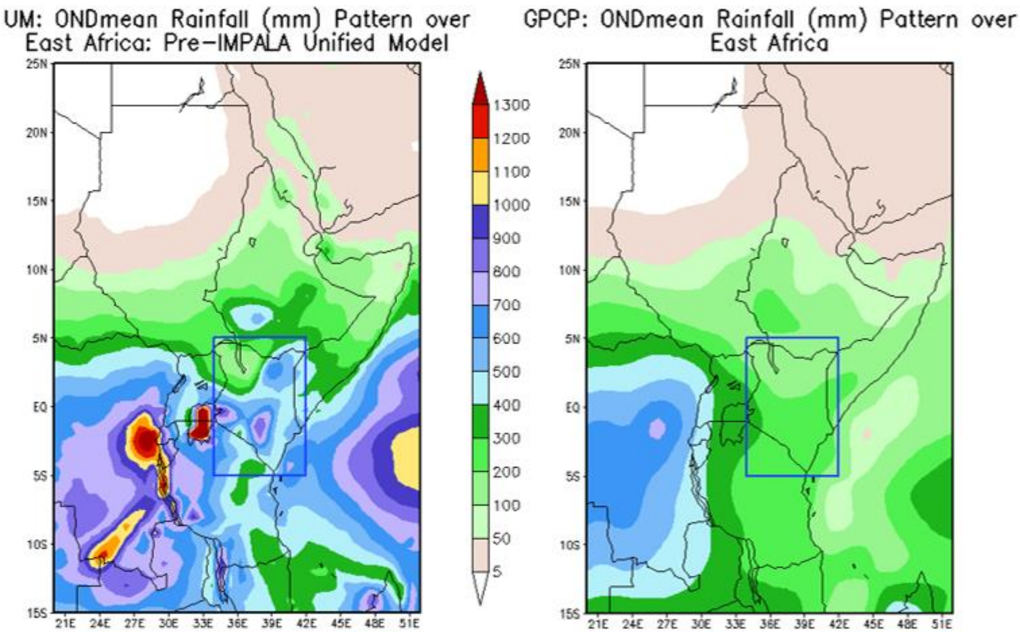

Figure 2: Model (left panel) and observed climatology/ baseline (right panel) of East Africa rainfall during the October-December (OND) season in East Africa.

Figure 3 presents the month by month (also called annual cycle) rainfall evolution in various areas East Africa represented by few stations. The stations shown in this study are four, namely Wajir in Northern Kenya (top left panel), Entebbe in Uganda (to right panel) representing Lake Victoria Basin, Kigali in Rwanda (left bottom panel) representing the western highland parts of East Africa, and Same in northern Tanzania (right bottom panel). These curves reveal that the model (red-curve) resolves the two wet seasons MAM and OND well. The MAM season is centred on the month of April, while the OND season is centred on the month of November. For the MAM season, the model rainfall (red curve) is slightly lower than the station and GPCP observations. For the OND season, the pattern is simply the opposite, with the model typically overestimating the rainfall magnitudes. An over estimation or underestimation can be adjusted for in practical usage of the model since it is a systematic attribute. These results indicate that the model provides realistic and useful information on regional rainfall. The model is therefore a good tool for generation climate information in the region for a wide range of socio-economic applications. For advancement of modeling science, it is important to establish the processes and mechanisms leading to the most extreme East Africa rainfall conditions, especially the floods and droughts alongside understanding the causes of model performance results like overestimation.

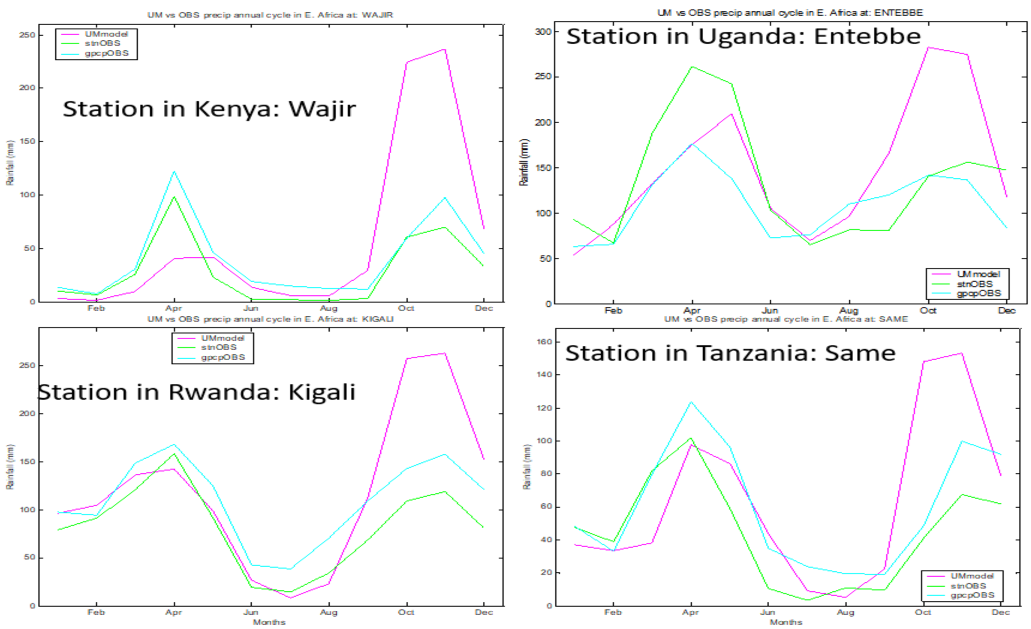

Figure 3: Point wise model and observed annual cycle of rainfall at various stations in East Africa as indicated on each panel. Notably, UM overestimates the October-December rainfall systematically across East Africa.

The cause-effect processes and driving mechanisms, especially circulation in relation to moisture source and distribution are the core target of this model evaluation. When using dynamical models, there is always the need to understand details of the model performance. For example, in Figures 4 and 5, the basic controls of weather and climate in East Africa, namely, the atmospheric signatures of the sub-tropical high-pressure systems are in their proper positions as indicated by the red circles in Figures 4 and 5. However, the modelled circulation details within the region can have deficiencies. For example, in Figure 5, it may be noted that during the October-December season, the model simulates "easterlies over the tropical Indian Ocean" while in the observations "the circulation is actually westerly". While these details are the subject of dynamics improvement in deterministic modelling, it is good to note that the easterlies are from the Indian Ocean. This is a moist-thermodynamic process of Equatorial Indian-Ocean-East Africa sub-region within the atmospheric depth from low levels (such as 850mb) to medium levels including 700mb. Circulation attributes like this is a necessary mechanism which leads to widespread torrential rainfall in East Africa during October-December (OND) season.

The model is found to be quite realistic in the production of the wettest and driest conditions (the heavy rainfall and dry conditions which afflict East Africa), for example during the OND season, with remarkable details as presented in Figure 6. In Figure 6, the top panel on the left shows the model simulated wet conditions and top right panel are the observations. From these two, it may be noted that the model is wetter than observations, but the signals are consistent. In Figure 6, the bottom left panel is the simulated dry conditions and the bottom right panel is observed dry conditions. Again, there is good consistency in the model and observations.

From Figure 3 results discussion above, it should be recalled that the model overestimates rainfall over most of equatorial East Africa during the October to December season. The vertically integrated moisture shown in Figure 5 reveals the physical basis of this result. The vertically integrated moisture flux is stronger and convergent in the model over the interior East Africa. With respect to the oceans, it is strongly easterly with respect to the Indian Ocean and strongly westerly with respect to the Atlantic and Congo Basin (Congo-airmass) to the west of East Africa. This is valid moist dynamics and consequence is enhanced rainfall by the model during the OND season. Therefore, results in Figure 5 reveals the validity of OND rainfall results in Figure 3 and also the overestimation of the OND rainfall pattern shown in Figure 2 discussed earlier.

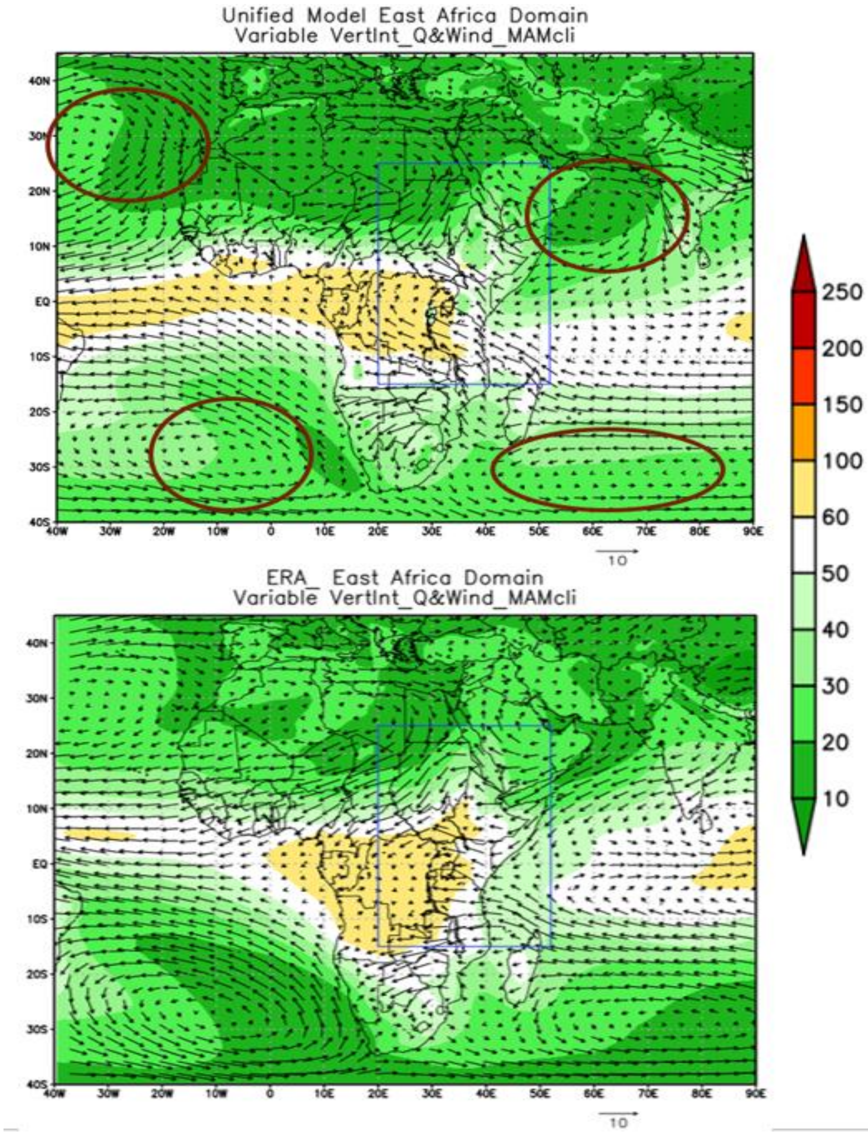

Figure 4: Unified model (UM – top) and observed circulation from ERA-interim reanalysis data sets (bottom) indicated by vectors and vertically integrated moisture flux within the atmospheric column 850-600mb for the long rainfall season March-May (MAM) mean patterns.

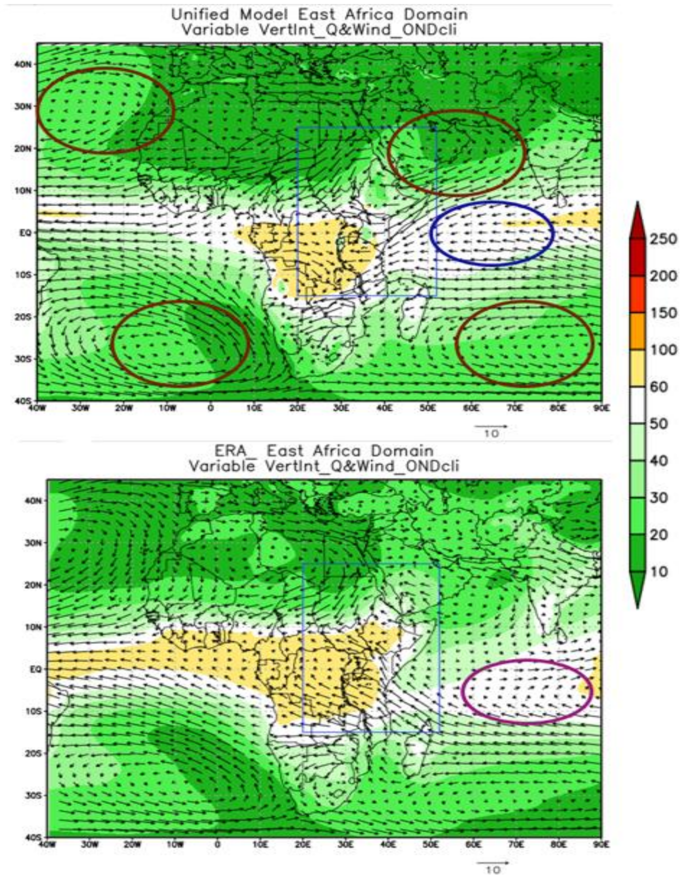

Figure 5: Unified model (UM – top panel) and observed circulation from ERA-interim reanalysis data sets (bottom panel) indicated by vectors and vertically integrated moisture flux within the atmospheric column 850-600mb for the second wet season in East Africa, the short rainfall season October-December (OND) mean patterns.

The capability of dynamical models to resolve the rainfall extremes in form of floods and droughts is most important. To illustrate this clearly, rainfall biases are used rather than total amounts. Figure 6 shows the model and observed biases during the OND season for floods and droughts. The floods and droughts constitute the extremes cases of greatest research and socio-economic interest. Comparing the top panels in Figure 6, it is noticed that the indications of the floods is present in both model and observations. The bottom panels reveal the droughts also. There are notable details of scientific interest. For example, from the top panels in Figure 6, the structure of flood conditions is within East Africa extends towards the Indian Ocean in both model and observations. In the drought case shown by the bottom panels, the model biases are greater than observations. The resolution of both wet and dry extremes by the model are quite consistent. Attention is now turned to what additional dynamical processes can help us formulate these extremes.

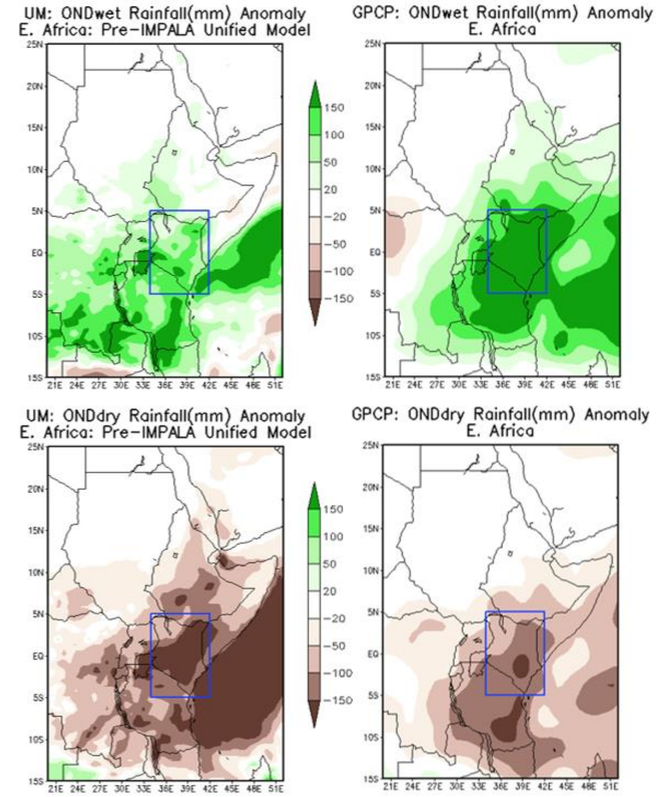

Figure 6: The Unified model resolution of rainfall extremes of greatest concern in East Africa, the wet and dry conditions for October-December (OND) season, shown as biases in the model (UM) and observations. Top panels wet cases: Left panel is model and right panel is observation: Bottom panels dry cases: Left model and right panel observation.

The importance of the thermodynamic role of the Indian and Atlantic oceans including the Congo air-mass and vertical extent of the moist depth are crucial mechanisms in understanding these results. Figure 7 shows the specific humidity (shaded) alongside the east-west wind (contours) for the floods and droughts during the MAM season. The bolded green and blue arrows illustrate the easterly and westerly flows with respect to East Africa, which may be taken as centred within 20^{o}E to 40^{o}E degree longitudes in this vertical-zonal cross section. The levels of significant moisture in the air can be noted to extend to above 400mb in both model and observations. This can be seen from panels “a” and “b” on Figure 7. The convergence of Indian Ocean easterlies and Atlantic / Congo-airmass westerlies is evidently a very important mechanism for the flooding conditions during MAM season. Corresponding vertical profiles for drought conditions are shown in panels “c” and “d”. In both model and observations, the atmosphere is too dry at all levels. The easterlies and westerlies are also reversed. These conditions are necessary for the failure of seasonal rainfall within East Africa, hence the droughts, just the way the opposite conditions are sufficient and necessary for the floods. The model rainfall extremes as shown in Figure 8 can now be better understood in view of these deterministic processes. Figures 7 and 8 are for the MAM season. We briefly show for the OND season to point out some major dynamical differences which can inform modeling advancement.

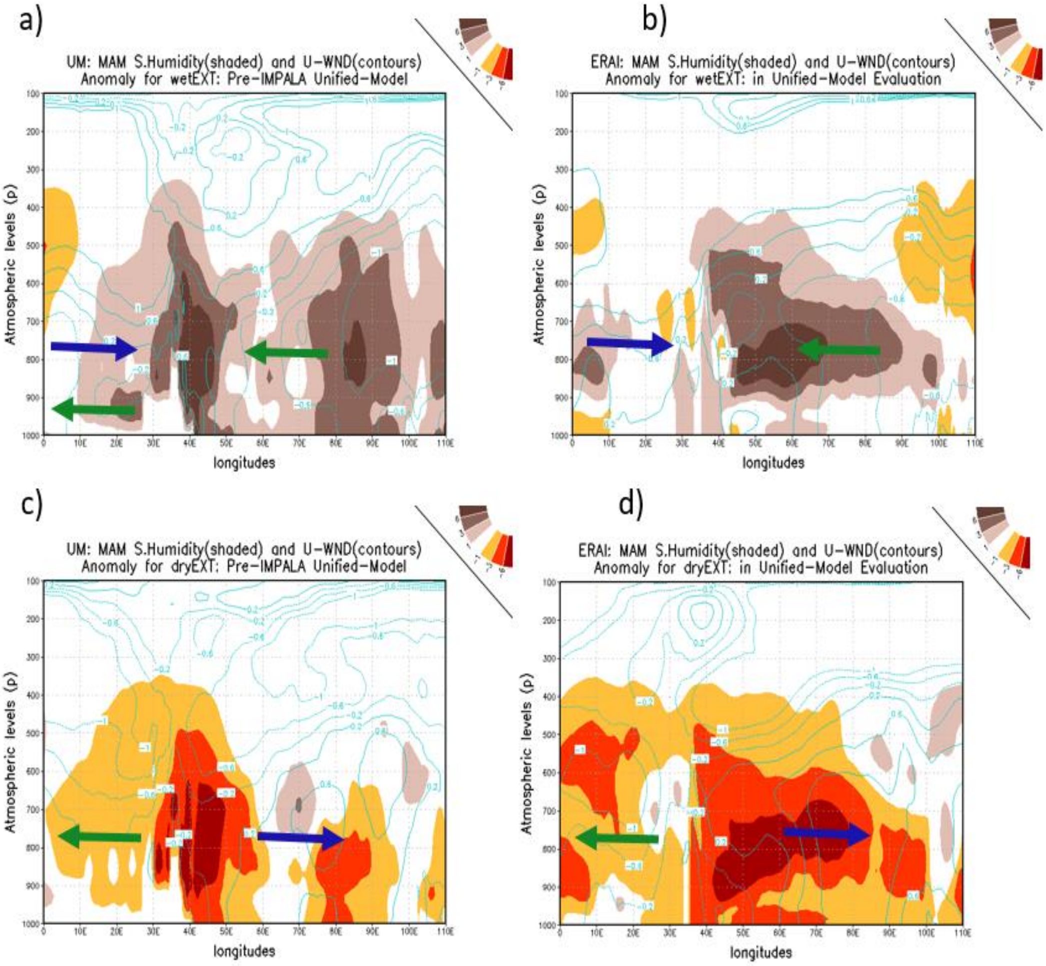

Figure 7: March-May (MAM) Vertical-zonal cross section (ZX-transects) of moisture depth (shaded brown-red) and zonal wind (contours) along the equator from 0°E to 110°E. East Africa is approximately within the longitudes 20°E to 50°E. Top panels illustrate the wet cases, and bottom panels the dry cases. In the ZX-transects, note the circulation and atmospheric validity in the model (UM) and Observations (ERI) with respect to wet/dry conditions within the area centred at 35°E, which is the position of East Africa. Green arrows indicate easterly flow and blue arrows indicate westerly flow.

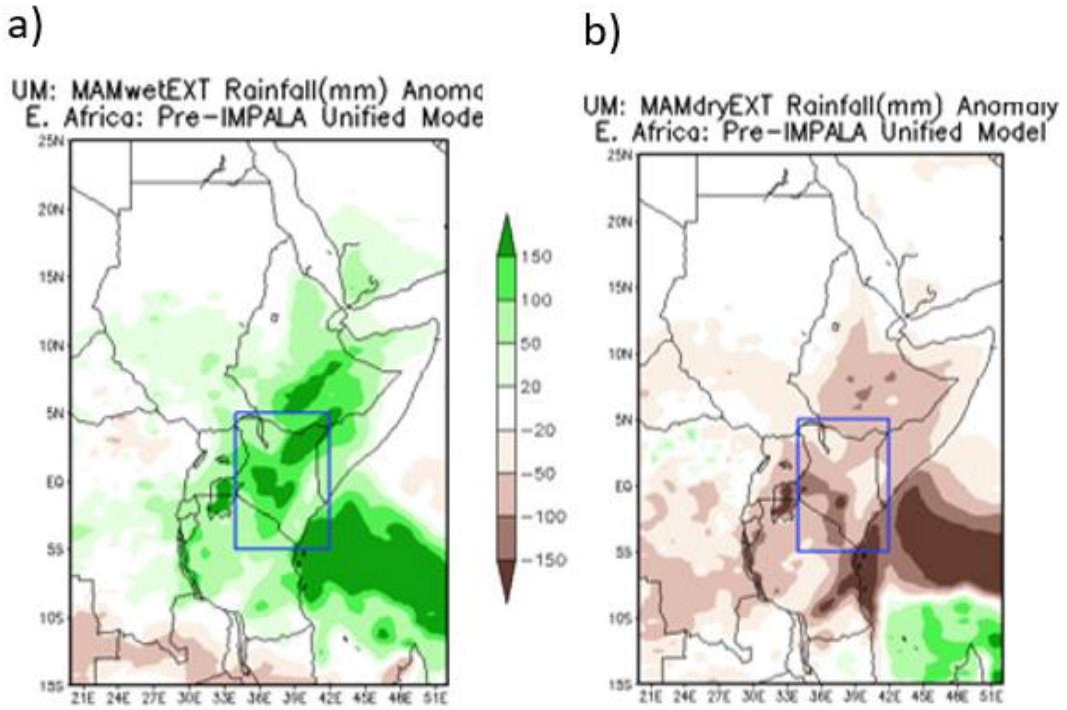

Figure 8: The rainfall biases for floods and droughts in the model during March-May (MAM). Wet (left) and dry (right) corresponding to vertical profiles of moist air and east-west circulation attributes shown in Figure 7.

Figures 9 and 10 show results similar to Figures 7 and 8, but for the Short rainfall season October – December (OND). Even though the results have similar attributes to those discussed above for MAM season, during the OND season, there is a huge depth of dry air over the Indian Ocean extending westwards to East Africa up to 55^{o}E. There is also a column of dry atmosphere westwards of 20^{o}E. The vertical column of moist air within East Africa is confined with longitude range 25^{o}E to 50^{o}E in the model as seen from panel “a” in Figure 9. In the observations, the moist depth has very wide longitudinal range and quite deep as seen in panel “b” Figure 9. For drought conditions, the location of dry and moist air vertical columns are reversed as revealed panel “c” in Figure 9. Similar to the MAM cases, the convergence of easterlies and westerlies is sufficient for the occurrence of floods and the reversed circulation is sufficient for the failure of the season rainfall.

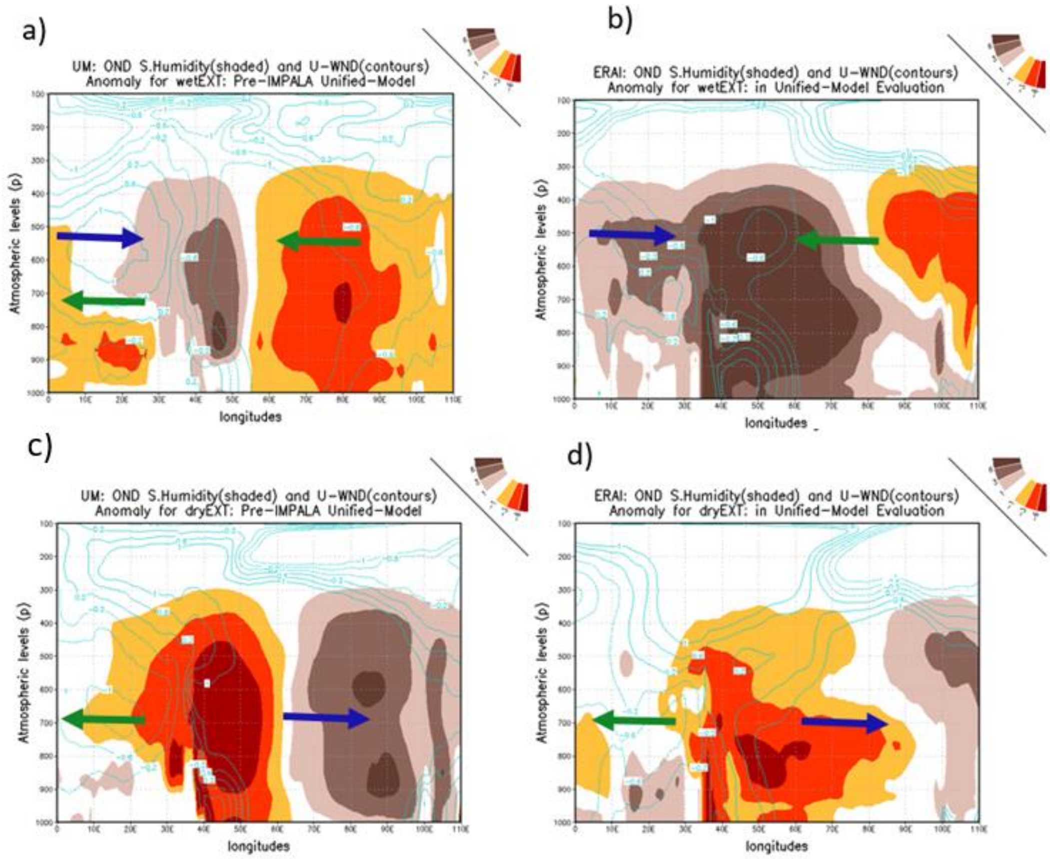

Figure 9: October-December (OND) Vertical-zonal cross section (zx-transects) of moisture depth (shaded-brown-red) and zonal wind (contours) along the equator from 0°E to 110°E. East Africa is approximately within the longitudes 20°E to 50°E. Top panels illustrate the wet cases, and bottom panels the dry cases. In the ZX-transects, notice the circulation and atmospheric validity in the model (UM) and Observations (ERI) with respect to wet/dry conditions within the area centred at 35oE, which is the position of East Africa.

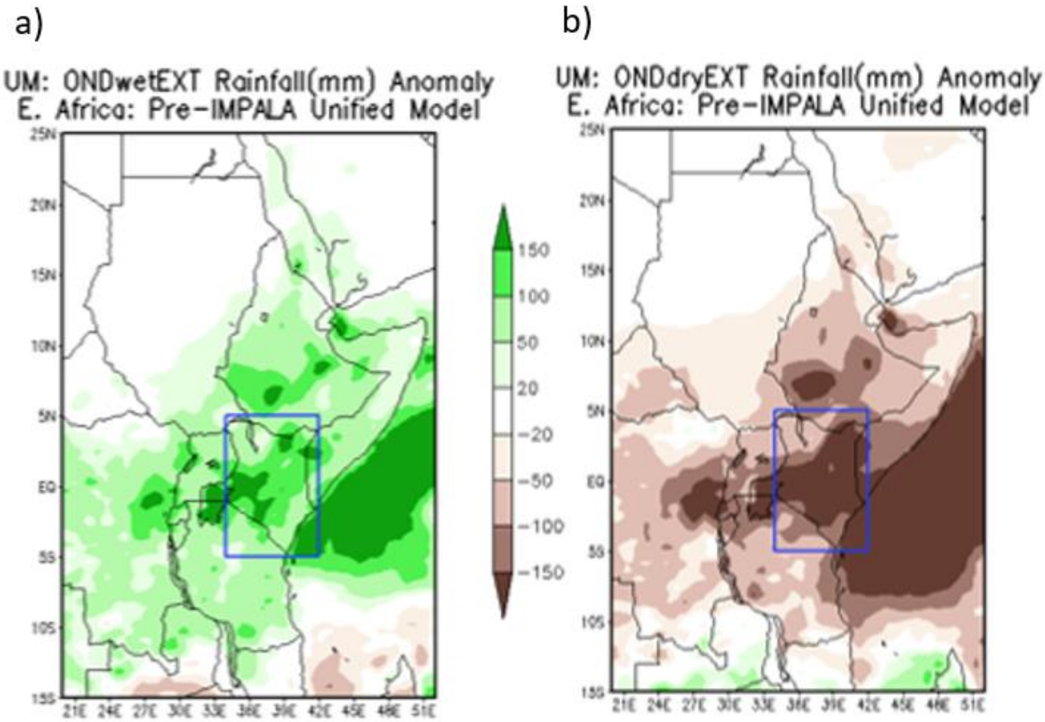

Figure 10: The rainfall biases for floods and droughts in the model during October-December (OND) wet (left) and dry (right) corresponding to vertical moisture and east-west circulations shown in Figure 9.

From Figures 7 and 9, the UM is somewhat a bit dry in the low levels within East Africa, unlike the observations. Moist air in the atmospheric column and its vertical extent is most crucial for condensation and heavy rainfall be widespread. From Figure 7(b) and 9(b) for wet extremes in East Africa during the two seasons, it is evident that the moisture in the lows from and medium levels of the atmosphere is enforced by easterlies from the east (green arrow) and westerlies from the west (blue arrow). The consequence is a sustained moist convergence and vertical ascent. This process is well resolved by the model as shown in Figures 7(a) and 9(a). It can also be noted from panels “a” in Figure 7 and 9 that the model has low level easterlies and medium level westerlies (see the green and blue arrows within 10^{o}E to 20^{o}E). This implies a wind shear which can have important thermodynamic implications on the in advancing understanding and driving mechanisms of East Africa rainfall extremes. The mechanism of moist air inflow with corresponding increase in depth of moist in the interior East Africa explains why wettest conditions in the region are confined more towards the eastern areas of the region (Figures 8b and 10b) for the two seasons. The model has appropriate physics for resolution of moist attributes, and can be relied upon as tool to generate near-term and long-term climate evolution information for strategic decision making. Information products like these are the major inputs required to address the socio-economic challenges posed by floods (extremely heavy rainfall) and drought (rainfall failure) over Kenya and East Africa in general.

4. Conclusions

The Unified model (UM) version used in this study has shown good capability in representation and resolution of the most important rainfall attributes across east Africa. It reveals with scientifically valid details the processes and mechanisms which underlie both droughts and floods in Eastern Africa. It shows that during the March-May season (MAM), thermodynamic processes involving both the Indian and Atlantic oceans are equally important, while during October-December (OND) season, Indian Ocean is the most important. Not only does the model resolve realistically the rainfall baselines, but it also resolves well the extremes, namely the floods and droughts in East Africa seasonal rainfall. These extremes adversely impact on livelihoods, especially on food and water resources. These impacts retard socio-economic development. Model results like these are good sources of information for supporting planning and decisions towards preparedness, mitigation and adaption to climate extremes and change. Following the outcomes of these East Africa evaluation results of the UM model HadGEM3-GC2, the future model advancement is focused on improvement of precipitation schemes, while model users work on a suit of evaluation diagnostics for more efficient use of dynamical models across Africa in general.

Acknowledgements

Results reported in this study are part of the larger project conducted under funding by the UK Natural Environment Research Council (NERC)–Department for International Development (DFID): "Improving Model Processes for African Climate (IMPALA), Grant NE/M017206/1, as part of the Future Climate for Africa (FCFA) program (futureclimateafrica.org/project/impala)”. Authors are grateful to their affiliate Institutions, the University of Nairobi-Kenya and University of Oxford-UK for enabling excellent scholarly collaborations.

References

[1] Dutton, J. (2002) Opportunities and priorities in a new era for weather and climate services. Bull. Amer. Meteor. Soc., September 2002, BAMS 1303-1311.

[2] Mutemi, J. N., Ogallo, L.A., Krishnamurti, T. N., Mishra, A. K. and Vijaya, T.S.V. Kumar (2007) Multimodel based Superensemble Forecasts for Short and Medium Range NWP over Various Regions of Africa: Meteorol Atmos Phys 95, 87-113

[3] Ross, R.S. and Krishnamurti, T.N. (2005) Reduction of forecast error for global numerical weather prediction by the Florida State University (FSU) Superensemble. Meteorol 38, Atmos Phys 88: 215–235.

[4] Kipkogei, O., Bhardwaj, A., Kumar, V., Ogallo, L. A., Opijah, F. J., Mutemi, J. N. and Krishnamurti, T. N. (2015) Improving multimodel medium range forecasts over the Greater Horn of Africa using the FSU superensemble. Meteorol Atmos Phys. DOI 10.1007/s00703-015-0430-0

[5] James, R., Washington, R., Abiodun, B., Kay, G., Mutemi, J., Pokam, W., Hart, N. and Artan, G. (2018) Evaluating climate models with an Africa lens. BAMS, 313-336
[6] Biasutti, M. (2019) Rainfall trends in the African Sahel: Characteristics, processes, and causes. WIREs Clim Change. 2019;10:e591. wires.wiley.com/climatechange 1 of 22 https://doi.org/10.1002/wcc.591.
[7] Ntale, H.K. and Gan, T. Y. (2003) Drought indices and their application to East Africa. Int. J. Climatol. 23: 1335–1357 (2003) Published online in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/joc.931.
[8] Mutemi, J.N. (2019) Improving Seasonal Climate Forecasts over Various Regions of Africa Using the Multimodel Superensemble Approach. DOI: 10.4236/acs.2019.94038
[9] Deborah E.H., Bourassa, M. A., O'Brien, J. J., Smith, S.R. and Spade, E.R. (2003) A Quantitative evaluation of ENSO indices. J. Climate, 1249 – 1258
[10] Government of Kenya (2007) Kenya Vision 2020:
http://vision2030.go.ke/inc/uploads/2018/05/Vision-2030-Popular-Version.pdf
[11] Gates, W. L., Henderson-Sellers, A., Boer, G. J., Folland, C. K., Kitoh, A., McAvaney, B. J., Semazzi, F., Smith, N., Weaver, A. J. and Zeng, Q. (1995) Climate Models - Evaluation. Climate Change 1995: The Science of Climate Change. Contribution of WGI to the Second Assessment Report of the Intergovernmental Panel on Climate Change.
[12] Randall, D.A., Wood, R.A., Bony, S., Colman, R., Fichefet, T., Fyfe, J., Kattsov, V., Pitman, A., Shukla, J., Srinivasan, J., Stouffer, R.J., Sumi, A. and Taylor, K.E. (2007) Cilmate Models and Their Evaluation. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
[13] Watterson, I. G., Bathols, J. and Heady, C. (2015) What influences the skill of climate models over the continents? Bulletin of the American Meteorological Society, 95(5), 689–700. https://doi.org/10.1175/BAMS-D-12-00136.1
[14] Vellinga, M., Roberts, M., Vidale, P. L., Mizielinski, M. S., Demory, M., Schiemann, R., Strachan, J. and Bain, C. (2016) Sahel decadal rainfall variability and the role of model horizontal resolution. doi:10.1002/2015GL066690.1.
[15] Birch, C.E., Marsham, J.H., Parker, D.J. and Taylor, C.M. (2014) The scale dependence and structure of convergence fields preceding the initiation of deep convection. https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1002/2014GL060493
[16] Wainwright C.M., Marsham, J.H., Keane, R. J., Rowell, D. P., Finney, D L., Black, E. and Allan, R.P. (2019) Eastern African Paradox' rainfall decline due to shorter not less intense Long Rains. https://www.nature.com/articles/s41612-019-0091-7
[17] Taylor, C. M., Birch, C. E., Parker, D. J., Dixon, N., Guichard, F., Nikulin, G. and Lister, G. M. S. (2013) Modeling soil moisture-precipitation feedback in the Sahel: Importance of spatial scale versus convective parameterization. Geophys. Res. Lett., 40, 6213-6218, doi:10.1002/2013GL058511.
[18] Allen, C. J., Washington, R. and Engelstaedter, S. (2013) Dust emission and transport mechanisms in the central Sahara: Fennec ground-based observations from Bordj Badji Mokhtar, June 2011. Journal of Geophysical Research: Atmospheres, 118, 6212-6232.
[19] Rowell, D. P. (20130 Simulating SST Teleconnections to Africa: What is the State of the Art? J. Clim., 26, 5397-5418, doi:10.1175/JCLI-D-12-00761.1.
[20] Giannini, A., Biasutti, M., Held, I. M. and Sobel, A. H. (2008) A global perspective on African climate. Clim. Change, 90, 359-383, doi:10.1007/s10584-008-9396.

[21] Brown, A., Milton, S., Cullen, M., Golding, B., Mitchell, J. and Shelly, A. (2012) Unified modeling and prediction of weather and climate: A 25-year journey. Bull.Am.Meteorol.Soc., 93, 1865-1877.
[22] Waters, D. and co-authors (2017) The Met Office Unified Model Global Atmosphere 6.0/6.1 and JULES Global Land 6.0/6.1 configurations. Geosci. Model Dev., 10, 1487–1520, 2017. doi:10.5194/gmd-10-1487-2017.
[23] Williams, K., Harris, C., Bodas-Salcedo, A., Camp, J., Comer, R., Copsey, D., Fereday, D., Graham, T., Hill, R. and Hinton, T. (2015) The met office global coupled model 2.0 (GC2) configuration. Geoscientific Model Development, 8, 1509-1524.
[24] Adler R. F, Gu, G., Sapiano, M., Wang, J. J. and Huffman, G. J. (2017) Global Precipitation: Means, Variations and Trends During the Satellite Era (1979–2014). Surv Geophys (2017) 38:679–699. DOI 10.1007/s10712-017-9416-4
[25] Dee D. P. and co-authors (2011) The ERA-Interim reanalysis: configuration and performance of the data assimilation system. Quarterly Journal of the Royal Meteorological Society, vol. 137, issue 656, pp. 553-597