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Signature of present and projected climate change at an urban scale: The case of Addis Ababa

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A B S T R A C T

Understanding climate change and variability at an urban scale is essential for water resource management, land use planning, development of adaption plans, mitigation of air and water pollution. However, there are serious challenges to meet these goals due to unavailability of observed and/or simulated high resolution spatial and temporal climate data. The statistical downscaling of general circulation climate model, for instance, is usually driven by sparse observational data hindering the use of downscaled data to investigate urban scale climate variability and change in the past. Recently, these challenges are partly resolved by concerted international effort to produce global and high spatial resolution climate data. In this study, the 1 km^2 high resolution NIMR-HadGEM2-AO simulations for future projections under Representative Concentration Pathways (RCP4.5 and RCP8.5) scenarios and gridded observations provided by Worldclim data center are used to assess changes in rainfall, minimum and maximum temperature expected under the two scenarios over Addis Ababa city. The gridded 1 km^2 observational data set for the base period (1950–2000) is compared to observation from a meteorological station in the city in order to assess its quality for use as a reference (baseline) data. The comparison revealed that the data set has a very good quality. The rainfall anomalies under RCPs scenarios are wet in the 2030s (2020–2039), 2050s (2040–2069) and 2080s (2070–2099). Both minimum and maximum temperature anomalies under RCPs are successively getting warmer during these periods. Thus, the projected changes under RCPs scenarios show a general increase in rainfall and temperatures with strong variabilities in rainfall during rainy season implying level of difficulty in water resource use and management as well as land use planning and management.

1. Introduction

A demographic change is taking place at a significant rate across the developing countries that will be expected to see an additional two billion residents in urban areas in the next 20 years, with the urban populations of Africa doubling through this period (UNDESA, 2009). This will certainly exacerbate the emissions of greenhouse gases which are found to contribute to a rise in global average surface temperature by about 0.9 °C–1.3 °C for the period 2016 to 2035 (Revi et al., 2014; Brian, 2009). It is now widely accepted that climate change has already occurred and further climate variability and change are inevitable (Solomon et al., 2007). For example, one of the results from Intergovernmental Panel on Climate Change (IPCC) WG-I 5th Assessment Report (AR5) shows that the world average surface temperature raised by 0.85 °C between 1880 and 2012 (Revi et al., 2014). Climate related risks due to increased variations in climate and weather associated with extreme events have emerged as key natural hazards of the 21st century (Revi et al., 2014; Hayhoe and Gelca, 2013; Dastagir, 2015). Studies on both present climate variability and future climate change scenarios available today for assessing climate change impacts, vulnerability and adaptation have predominantly been derived from Global Circulation model (GCM) outputs. GCMs are the most multifaceted tools currently available for simulating the global climate system (Randall et al., 2007).

Various GCMs represent global climate in three dimensional-grids with horizontal resolution from 2.5° latitudes by 3.75° longitudes for atmospheric components to 1.25° Latitudes by 1.25° longitudes for oceanic components (Gordon et al., 2000). Recently, there is substantial improvements in the spatial resolution of GCMs despite computational costs and challenges in data storage. Yet, the information from GCMs may not be realistic for regional/national climate change impacts, adaptation and vulnerability assessments because of the high level of

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uncertainty in GCM simulations due to their coarse grid resolution and the possible misrepresentation of local and meso-scale climate and hydrological processes (Nimusiima et al., 2014). Previous studies have revealed that the model conformity with observations is the way to verify the quality of model (Houghton et al., 2001). Moreover, the quality of model as assessed from the present climate assures the reliability of climate change simulations (Coquard et al., 2004). Downscaling of GCMs is therefore essential and has been found to reduce the above and associated problems.

Statistical and dynamical downscaling are the two techniques normally used in climate research to obtain high resolution climate data. Dynamical downscaling involves nesting a Regional Climate Model (RCM) into a GCM which provides boundary as well as initial conditions (Christensen and Hewitson, 2007). Dynamical downscaling can simulate local feedback features which may not be captured by statistical methods, however, it requires strong computing resources. Statistical downscaling, on the other hand, involves finding statistical relationships between global scale features from GCMs and fine scale climate for a particular location which requires less computing resources and may be used to supplement intermediate dynamical downscaling (Mahmood and Babel, 2014).

As a result, these resource intensive GCMs simulations are produced by various international research centers through coordination with IPCC and made available to researchers. For example, the IPCC produced and encapsulated forty emission scenarios of regional and global path, based on different theory for processes such as growth of population, social and economic development, technology and energy development, land use change and agricultural development in 2000 (IPCC, 2000). The Special Report on Emission Scenarios (SRES) have been assessed critically in relation to the natural resource availability, use of economic parameters and production expectations in future in a number of studies that followed (IPCC, 2007; Parry et al., 2007). For instance, the 4th assessment report of IPCC (AR4) used Special Report on Emission Scenarios (SRES) for the coupled model Inter-comparison project three (CMIP3) (Solomon et al., 2007). However, the uncertainties in socioeconomic processes under SRES scenarios motivated the development of Representative Concentration Pathway (RCPs) scenarios that use greenhouse gases (GHGs) and radiative forcing. The RCPs give projections of indicators of climate and green house gas emissions, before starting from projections of socioeconomic processes or emission scenarios (Thoeun, 2015). An indicator of climate employed in RCPs comprises of greenhouse gases (GHGs) concentrations and radiative forcing in watts per square meter. The inclusion of adaptation, mitigations and climate policies in RCP makes the assessment of climate impacts potentially clearer (Van-Vuuren et al., 2011; Kumar et al., 2012).

Climate projections for Ethiopia have been reported based on the CMIP3 models but with limited scope (NMA, 2007). Since then the improved set of emission scenarios (i.e., RCPs) are developed by the scientific community (Revi et al., 2014). To our knowledge, there is no work based on the new scenarios with similar scope as the report based on SRES scenarios. Therefore, this study employed statistically downscaled NIMR-HadGEM2-AO model data to study current and future climate change and variabilities at an urban scale for the city of Addis Ababa (Fig. 1). The downscaled and bias corrected NIMR-HadGEM2-AO model outputs for both present and future periods under RCP4.5 and RCP8.5 scenarios are constructed based on WorldClim reference climatology, which itself is constructed from observations, GPCC rainfall and CRU temperature. Worldclim is used for downscaling whereas GPCC rainfall and CRU temperature are used for bias correction. The WorldClim reference climatology is a high spatial resolution (about 1 km^2) global climate set consisting of layers which are suitable to assess the climate of urban areas (Hijmans et al., 2005). This spatial resolution is critically important as the Addis Ababa city is located in the highlands of Ethiopia which is very ragged and exhibits altitude variation from 2000 m in the south to over 3000 m in the north of the city (Fig. 1).

The two (of the four) RCP scenarios used in this study are RCP4.5 and RCP8.5 as they represent optimal and extreme scenarios respectively. RCP4.5 is one of the modest scenarios in which radiative forcing becomes stabilized before 2100. RCP8.5 assumes the worst case scenario under which there will be least amount of effort in emissions reduction.

The paper is organized as follows. Descriptions of observational data, delta change method and NIMR-HadGEM2-AO model are given Section 2. A brief evolution of NIMR-HadGEM2-AO and its suitability for this study are also briefly described in Section 2. In Section 3 results and discussions on various aspect of historical and projected climate variability and change of the city are given. Finally, conclusions are presented in Section 4.

2. Data and methodology

2.1. Data

Observed daily and monthly historical data for rainfall, maximum temperature (Tmax) and minimum temperature (Tmin) at Addis Ababa Observatory station (9.01 °N, 38.74 °E) in the city were used. The NIMR-HadGEM2-AO model data for historical and projections under RCP 4.5 and RCP 8.5 are obtained from CMIP5 data server and then statistically downscaled using delta method. The data sets are selected because of their availability. Moreover, NIMR-HadGEM2-AO was developed by incorporating processes in the troposphere, land surface and hydrology, aerosols, ocean and sea ice in the course of several development phases. This version of the model is improved by including several changes and additions to the representation of aerosol. These include changes to existing aerosol species, such as sulphate and biomass-burning aerosols, and representation of additional species, such as mineral dust, fossil-fuel organic carbon, and secondary organic aerosol (The HadGEM2 Development Team: Martin and Coauthors, 2011). These changes improved the agreement in aerosol optical depth between model and observations (Bellouin et al., 2007). The NIMR-HadGEM2-AO model also incorporates land use change applying Land-use Harmonization (LUH) (Hunt and Watkiss, 2011).

The gridded 1 km^2 resolution observed data set from Worldclim is used as a reference climatology for downscaling NIMR-HadGEM2-AO after validating it with station observation.

2.2. Methodologies

It is rather inappropriate to use spatial resolution of a GCM to provide features that are important to study climate impact at regional and local scale. To avoid such restriction, it is common to use downscaled data from GCMs (Parry et al., 2007). There are two techniques used in downscaling: dynamical and statistical. Statistical downscaling techniques develop relation between observed variable of local climate and GCM predictors. These relations are then used in the projections of future GCM to local climate variables (Samadi et al., 2012). The delta method is used to downscale projections under RCP 4.5 and RCP 8.5 scenarios from NIMR-HadGEM2-AO model which are made available in the frame work of IPCC AR5. The gridded observations, also available at Worldclim data archive (Hijmans et al., 2005), are used as a reference climatology in the statistical downscaling of the projections. The GCM data is first interpolated to the spatial scale of reference climatology using the thin-plate smoothing spline so that the reference monthly climatology is used at individual grid. The downscaled data sets have been subjected to bias correction using GPCC rainfall and CRU temperature.

The delta change method, which assumes that GCMs simulate relative changes more reliably than absolute values (Hay et al. (2000); Tryhorn and DeGaetano (2011) and references therein), for temperature and precipitation are respectively given by