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On the need for regional climate information over Africa under varying levels of global warming

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Abstract

The Paris Agreement of COP21 set a goal of holding global average temperature increases to below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C. This is particularly relevant for the African context where temperatures are likely to warm faster than the global average and where the magnitude of change will be regionally heterogeneous. Additionally, many biogeophysical and socioeconomic systems are particularly vulnerable to change in both means and extremes. In this paper we contextualise the lack of regional climate information over Africa at global warming levels (GWLs) of 1.5 and 2 °C above pre-industrial levels through a short review of the literature. We show most studies that provide information over Africa under specific GWLs have used data from global models, however global models poorly resolve local scale forcing (e.g. topography) nor the internal climate variability of a region. Although downscaling using regional climate models can address these issues we find only one paper that has used downscaled data for GWL studies over Africa. Articles in this focus collection use data from global climate models and the co-ordinated regional downscaling experiment to elucidate the regional and local scale climate responses to various warming levels. This may provide information that contributes meaningfully to the UNFCCC negotiation process and also for the development of adaptation and mitigation policies.

1. Introduction

The changing nature of climate variability over Africa as a result of greenhouse gas warming has seen changes in regional means of temperature and precipitation as well as an increase in the frequency and intensity of extreme events (Easterling *et al* 2000, New *et al* 2006, Shongwe *et al* 2011, Engelbrecht *et al* 2015, 2013, Zwiers *et al* 2013, Sylla *et al* 2015b, Pinto *et al* 2016). This poses a notable threat to sustainable development on the continent where an increased exposure to climate stressors may push systems beyond their coping capacities, especially in vulnerable systems (Field *et al* 2014). This is because many systems, biogeophysical, socio-economic and others, have climate-sensitive thresholds which if crossed have deleterious impacts. For example, if crops experience an excess of killing degree-days at worst they fail or at

best produce reduced yield (Butler and Huybers 2015); crossing heat stress thresholds in vegetation, animals and humans lead to ill health or mortality (Anderegg *et al* 2012, Amegah *et al* 2016); at hot, high altitude airports take-off weight restrictions of aircraft may negatively impact the airline industry should temperatures reach a certain threshold (Coffel *et al* 2015). Understanding these climate-sensitive thresholds and the potential impact of climate change on these requires climate information that is defensible and scale relevant (in space and time) in order to develop adaptation and policy responses (Hewitson *et al* 2014).

The IPCC fifth assessment report (IPCC 2013) reported that under the assumptions of the greenhouse gas concentration-driven representative concentration pathways or RCPs (see section 2), end-of-century mean global surface temperatures relative to 1986–2005 are *likely* to increase by between 0.3 °C–1.7 °C

following the RCP2.6 pathway, 1.1 °C–2.6 °C following the RCP4.5 pathway, 1.4 °C–3.1 °C following the RCP6.0 pathway and 2.6 °C–4.8 °C following the RCP8 pathway. Following the release of the AR5, the 2015 Paris Agreement of the 21st Conference of the Parties of the United Nations Framework Convention on Climate Change developed the following statement as a goal: ‘Holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C’⁶. Although these targets are the subject of some debate (Hulme 2016, Raftery *et al* 2017), it is essential to understand what the regional climate response to these targets over Africa might be as rates and magnitudes of warming across the continent as a result of greenhouse gas emissions are likely to be faster than the global average (Diffenbaugh and Scherer 2011, Hawkins and Sutton 2012, Joshi *et al* 2011, Mahlstein *et al* 2013, Sanderson *et al* 2011, Niang *et al* 2014). Furthermore, understanding how risk and impact may differ regionally under different degrees of global warming is important to identify regions where the development of adaptation options is most urgent and for climate policy discussions (Rogelj and Knutti 2016).

Compounding this, the IPCC special report on managing the risks of extreme events and disasters to advance climate change adaptation shows the effect of this warming will initially be seen in the characteristics of extremes such as heat waves, increasing maximum temperatures, fewer cold extremes and more heavy rainfall events (Field 2012). Projected changes and consequent climate impacts will not be evenly distributed across the globe and local capacities to adapt to or cope with these impacts differs among regions (Orlowsky and Seneviratne 2012). This is especially relevant over Africa where agriculture, food insecurity and social development are vulnerable to the effect of climate (Thornton *et al* 2011, Chen *et al* 2015, McDowell *et al* 2016). Of particular concern in Africa are heat waves and rainfall extremes because of the devastating impact they have across natural and socioeconomic systems. There has been an increase in the number, spatial extent and duration of heat waves in recent decades (Russo *et al* 2016, Ceccherini *et al* 2017) and downscaled projections suggest that by the end of the century heat waves may become extremely long (more than 60 consecutive days) and frequent (once every two years) in large areas of central Africa, the Sahel, the Horn of Africa, and the Arabian Peninsula (Dosio 2017) and that unusual heat wave conditions today will occur regularly by 2040 under the RCP 8.5 scenario (Russo *et al* 2016). Although there is more uncertainty about the sign and magnitude of projected regional rainfall changes, there is robust model evidence to suggest changes in

rainfall variability larger than current natural variability over tropical Africa by mid-century (Chadwick *et al* 2016), a delay in the onset of the West African Monsoon with increased intensity but decreased frequency of very wet events (Sylla *et al* 2015a), and an increase in extreme rainfall and extreme rainfall variability over southern Africa (Pinto *et al* 2016) and East Africa (Ongoma *et al* 2018).

Even though the projected regional rainfall changes are more uncertain than regional temperature changes, it is important for policy makers to understand the individual and cumulative risks associated with both variables. Climate and climate impact information at regional and local scales is therefore critical to (a) improve our understanding of the regional climate response at different global warming levels in terms of means and extremes, (b) assess the regional impact of climate change on regional natural and human systems, (c) provide a robust foundation for policy discussions and (d) to develop regional adaptation options and mitigation policies.

In this focus collection we investigate the potential changes in means and extremes of regional African climates under different global warming levels (GWLs). The regional focus is the target of solicited papers and each paper will have specific information in terms of seasonality and extremes under different GWLs. Below we provide a short literature review that contextualises the need for climate information under different GWLs, especially within the African context (section 3 and 4). Thereafter we introduce the Coordinated Regional Downscaling Experiment (CORDEX) and the potential benefits of using downscaled data from a common climate modelling framework like CORDEX for addressing GWL questions (section 5). Here we also introduce the CORDEX-Africa initiative, members of whom have written the solicited papers of this focus collection. Finally we list the objectives of the focus collection and briefly introduce the solicited papers (section 6).

2. A note on representative concentration pathways and baselines in GWL studies

Representative Concentration Pathways are a set of scenarios that represent pathways of radiative forcing based on socio-economic and technological development (Van Vuuren *et al* 2011). Four scenarios were developed that lead to top-of-atmosphere radiative forcing levels of 8.5, 6, 4.5 and 2.6 W m⁻² by the end of the century. General circulation models (GCMs) running transient simulations forced with these RCP scenarios have contributed to the 5th phase of the Climate Model Intercomparison Project (CMIP5) to produce long term simulations that typically span the historical climate from 1850 to the twenty-first century and beyond (Taylor *et al* 2012). These simulations are generally forced with observed greenhouse gas

⁶ <https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf>.

(GHG) concentrations until 2006 and with equivalent GHG concentrations to facilitate each RCP from 2006 onward.

The historical period of a transient GCM simulation can be used in GWL studies to establish a baseline departure period from which GWLs are calculated. For each GCM that has performed a transient run e.g. 1850–2100, the year in which the 1.5 and 2 degrees GWL is reached under each RCP can be approximated relative to the particular baseline period used. However, the process is not without caveats. There are different methods employed to reach this approximation (e.g. Mora *et al* (2013), Hawkins *et al* (2014), Maule *et al* (2017)) and the time a GWL is reached can vary up to a decade using the same model and methodology depending on which reference period is chosen (Hawkins and Sutton 2016). Furthermore, the RCP scenarios were not designed to address threshold concerns, nor to analyze difference between the effects of 1.5° and 2 °C of global warming (James *et al* 2017). The RCP scenarios also diverged from observations in 2005 and since then the global GHG emissions have been closer to RCP8.5 than any other scenario (Le Quéré *et al* 2016) so a new divergence point is also necessary for updated analysis.

Despite these concerns, within a large model ensemble context like CMIP computing the timing a GWL is reached under a particular RCP scenario relative to a baseline period is still the most widely available option to researchers. This fundamental idea is used for the production of the results reported by the solicited papers in this focus collection.

3. Regional climate information—a global modelling perspective

Much of our understanding about regional climates under GWLs of 1.5, 2 °C or more have been based on data from GCMs. Using CMIP3 GCMs, James and Washington (2013) show precipitation changes in Africa are insignificant at 1 °C above preindustrial levels, but anomalies become larger at 2 °C which increase in magnitude and spatial extent at 3 and 4 degrees of global warming. The changes they report include a wetting signal in East Africa and a drying signal in southern Africa, the Guinea coast and the Sahelian coast with a delay in the rainy season. Lehner *et al* (2017) show that although a two-degree increase in global temperature results in only a small change in drought risk over the US Southwest and Central Plains compared to present day, drought risk over the Mediterranean, central Europe, the Amazon and southern Africa increases significantly for both 1.5 °C and 2 °C warming levels, and the additional 0.5 °C from a 1.5 °C–2 °C climate leads to significantly higher drought risk here. Schleussner *et al* (2016) report increased risk to corals under 1.5 and 2 degrees of global warming and that there are benefits to corals in the former scenario

compared to the latter. They also demonstrate projected local yield reductions, particularly for wheat and maize agriculture, in tropical regions of West Africa, South-East Asia, Central and northern South America. Seneviratne *et al* (2016) scale regional extremes in temperature and rainfall with changes in the global mean temperature and find significant changes in extreme temperature characteristics in the Mediterranean, central Brazil, contiguous USA and Arctic. Mora *et al* (2013) show that tropical regions are likely to warm much faster than mid-latitude regions with deleterious consequences on tropical biodiversity. Although Hawkins *et al* (2014) dispute the methodology of Mora *et al* (2013), they also demonstrate that the time of emergence (ToE) of a new temperature climate regime in many African regions occurs earlier than most other regions of the world. Even though Mora *et al* (2014) defend their position in response to Hawkins *et al* (2014) this argument does not detract from the fact that most regions in Africa are projected to warm at a rate faster than that of the global average. In fact, Chadwick *et al* (2016) demonstrate changes in tropics to occur by mid-century which is earlier than in Mora *et al* (2014) and also show that despite uncertainty in the location of future rainfall shifts, GCMs consistently project large rainfall changes over tropical Africa during the twenty-first century.

4. Regional climate information—a regional modelling perspective

However, as a result of their relatively coarse horizontal grid resolution, GCMs do not adequately capture locally forced responses from e.g. topography, coastlines, land surface heterogeneity and smaller scale mesoscale process nor are extremes well accounted for (Giorgi and Mearns 1999, Frei *et al* 2006). One solution to this is to dynamically downscale the global models using regional climate models. A regional climate model (RCM) is usually nested in a coarse resolution global data set (e.g. reanalysis or a GCM) over some region of interest and driven at the boundaries by the coarse resolution data. The RCM simulates the climate system in the nested domain taking into account the finer scale regional and local forcings. Regional modelling often adds value to the raw GCM results as the finer horizontal grid resolution allows for the simulation of local scale forcing and processes (Laprise *et al* 2013, Crétat *et al* 2014, Giorgi *et al* 2014, Diallo *et al* 2015, Dosio *et al* 2015). However, downscaling may sometimes increase the uncertainty range particularly in the precipitation field where trends signs between the driving GCM and the RCM may be opposite (Dosio and Panitz 2016). This is because a RCM generates its own internal climate variability within the nested domain, which may differ from that of the driving GCM over the same region and lead to different projections of e.g. precipitation changes, especially over

topographically complex regions. Furthermore, the internal variability of a GCM-RCM combined ensemble over a solely GCM ensemble (where both ensembles have the same number of GCMs) is likely to be higher as a result of this. Although this is an extremely challenging problem, it is desirable for the climate modelling community to understand the physical and numerical reasons for the opposing signals (see e.g. Saeed *et al* 2013, Teichmann *et al* 2013, Mariotti *et al* 2014, Dosio and Panitz 2016) and for the VIA and policy making communities to consider the effect the opposing signals have on impact modelling results and the subsequent implications for adaptation and mitigation policy.

Relatively fewer numbers of studies use climate data from RCMs to address regional GWL questions. However, there are three coordinated European projects that do in fact consider downscaled data within an impacts framework. The Inter-sectoral Impact Model Intercomparison Project (ISI-MIP) addresses sectoral impacts of warming at each GWL over Europe and other regions of the world (Warszawski *et al* 2014). In a 'fast track' phase data from CMIP5 GCMs were used by impacts models so that the research could be considered in the IPCC fifth assessment report but in the second phase (ISIMIP2A) downscaled data from CORDEX (see section 5) are also being used. The latest phase (ISIMIP2B) is designed specifically to address the impacts of 1.5 °C of global warming and related low-emission pathways in many sectors including hydrology, vegetation, ecosystems, infrastructure and others (Frieler *et al* 2017). The second large coordinated project is the IMPACT2C project (Jacob and Solman 2017) that investigates the impacts of 2 degrees of global warming over Europe on winter tourism (Damm *et al* 2017a), electricity demand (Damm *et al* 2017b), agricultural resilience to drought (Williges *et al* 2017), primary production and soil carbon storage (Sakalli *et al* 2017) and health (Hunt *et al* 2017). Within the project there is also focus on tropical Africa (Déqué *et al* 2017) and over Bangladesh (Zaman *et al* 2017). The third project is the High-End Climate Impacts and Extremes (HELIX) project that examines climate change impacts and adaptation at global warming levels of 1.5, 2, 4 and 6 °C. The project investigates the impacts and implications of these GWLs in multiple sectors over Europe, Sub-Saharan Africa in the Northern Hemisphere and the north-East Indian sub-continent using both global and downscaled data. Examples using downscaled data include Mohammed *et al* (2017) who show over Bangladesh using CORDEX data an increased likelihood of flooding and higher flood magnitudes in the Brahmaputra River at a GWL of two degrees warming as opposed to that of 1.5 degrees; Chang *et al* (2017) force an ecosystem model with downscaled GCM data to show significant projected phylogenetic shifts in European grassland, and also find a grassland soil carbon sink under warming levels of 1.5 and 2 °C that satu-

rates to gradually become a carbon source when the warming level reaches 3.5 °C.

There are of course other studies outside these coordinated projects. For example, Vautard *et al* (2014) use regional models from the ENSEMBLES project (van der Linden and Mitchell 2009) to show spatially heterogeneous, higher than global average warming under two degrees of warming over Europe. Grillakis *et al* (2016) developed a Tourism Climatic Index for the Mediterranean and using data from the ENSEMBLES project showed that under a two degree warming tourism will be negatively affected during the hot summer months but positively affected in the early and late summer seasons. The hydrological impact of different GWLs was examined over Europe using CORDEX model data to drive five hydrological models and indicated a robust increase in projected discharges over Scandinavia and decreased runoff in Portugal and coastal regions of the Iberian Peninsula, Balkans and France (Donnelly *et al* 2017). Dosio and Fischer (2017) examine the benefits of limiting global warming to 1.5 °C compared to 2 °C over Europe using CORDEX data and show robust change in minimum summer temperature indices between the two GWLs over most of Europe and over a smaller area for maximum temperature indices. Regional warming is not only a function of space but also of time—some regions are warming at a faster rate than others. Grillakis *et al* (2016) also show the two degree change should occur between 2031 and 2060 and suggest that these shifts in the climate favourability of Mediterranean countries require early adaptation strategies.

The short review above indicates there are relatively few GWL studies using downscaled data compared to those using GCM data. However, the regional added value downscaling provides behaves analyses of downscaled data and to this end CORDEX provides tremendous potential for such activities.

5. The CORDEX-Africa initiative

CORDEX was implemented by the World Climate Research Programme with a vision to advance and coordinate the science and application of regional climate downscaling (using both dynamical and statistical methods) through global partnerships (Giorgi and Gutowski 2015). Four overarching goals lie within this vision which are (1) to better understand relevant regional/local climate phenomena, and their variability and changes, through downscaling, (2) to evaluate and improve regional climate downscaling models and techniques, (3) to produce coordinated sets of regional downscaled projections worldwide and (4) to foster communication and knowledge exchange with users of regional climate information. Africa was identified as a priority region because of its low adaptive capacity and a general lack of RCMs studies targeting the

continent, and regional modelling centres were asked to provide downscaled data for the African domain in addition to their region of interest (Giorgi *et al* 2009). Following CORDEX experimental and data output protocols⁷ 12 RCMs have downscaled the Era Interim Reanalysis (Dee *et al* 2011) and 15 CMIP5 GCMs to a horizontal grid resolution of 0.44 degrees over the African domain. The 15 CMIP5 models are a subsample of the CMIP5 ensemble and include three RCPs (2.6, 4.5 and 8.5). More information about the CORDEX GCM-RCM matrix for Africa is presented in the Nikulin *et al* (2018) paper of this focus collection.

Although no African climate group has contributed to the production of this ensemble (computational resources in terms of hardware, software and support are generally not available at African research institutions for these types of simulations), the CORDEX data are publically available through the Earth System Grid Federation. To this end, the CORDEX-Africa initiative was developed which brings together climate and vulnerability-impact-adaptation (VIA) scientists to analyze the CORDEX data available for the African domain⁸. The initiative has developed regional, trans-disciplinary teams within sub-Saharan Africa to identify and address key climate vulnerabilities and analyze climate and impacts data appropriately in an effort to distill actionable information from climate data. The cohort has to date published over 30 papers that have evaluated the downscaling models, analyzed projected rainfall and temperature changes as well as the impacts of projected change on hydrological and agricultural systems (see the Publications list on the CORDEX-Africa website).

However, this cohort has not published on the theme of GWLs and in fact we have found only one publication using downscaled data over Africa that does. Déqué *et al* (2017) use an ensemble of 12 CORDEX models and find that under two degrees of global warming the tropical African region warms faster than the global mean, shows an increase in the frequency of heat waves, a decrease in the number of rain days and an increase in rain intensity, a later onset of the rainy season and less (more) precipitation in the early (late) summer. There are therefore, to our knowledge, no studies that investigate the regional effects of different GWLs over Africa using an ensemble of downscaled climate data nor information on regions outside the Déqué *et al* (2017) study. The CORDEX-Africa ensemble therefore provides a most comprehensive dataset to be exploited for addressing regional GWL questions over the continent.

⁷ www.cordex.org.

⁸ www.csag.uct.ac.za/cordex-africa.

6. Objectives of this focus collection

Given the review above and the lack of GWL literature over Africa, the concerns raised by Sutton *et al* (2015) (local climate variability and responses to global warming), Orłowsky and Seneviratne (2012) (lack of regional seasonal analyses) and James *et al* (2017) (methodological concerns and uncertainty in regional responses) and the goals of the COP21 Paris Agreement, it becomes apparent that much work is needed to enhance our understanding of regional African responses of climate and climate related impacts to 1.5 degrees or more of global warming. The CORDEX-Africa cohort has begun to engage with some of these concerns through an analysis of CORDEX data to address amongst others, the following questions:

1. What are the regional expressions of seasonal mean rainfall and temperature over Africa under various GWLs?
2. What are the regional expressions of seasonal extreme rainfall and temperature characteristics across Africa under various GWLs?
3. How well do models agree on these changes?
4. What difference does 0.5 °C make in regional rainfall and temperature fields?
5. What might the implications of these regionally nuanced climate changes be on climate sensitive systems?

This focus collection was initiated by the CORDEX-Africa community and opened to other authors concerned with GWL questions over Africa. The solicited papers produced by the CORDEX-Africa cohort include a methodological discussion on the assessment approach used in all the papers (Nikulin *et al* 2018), and more focused regional analyses for west, east, central and southern Africa presented respectively in Klutse *et al* (2018), Osima *et al* (2018), Pokam Mba *et al* (2018) and Maúre *et al* (2018).

It should be noted that these are preliminary assessments of the CORDEX scenario ensemble in a GWL context and further detailed analyses are planned within the framework of CORDEX-Africa as funding facilitates.

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The solicited papers in this focus collection are a contribution of the CORDEX-Africa programme to address critically important questions about the effects and impacts different degrees of global warming may have on the African continent. These papers would not have been written without the financial support from the Swedish Government through the Swedish

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References

- Amegah A K, Rezza G and Jaakkola J J 2016 Temperature-related morbidity and mortality in Sub-Saharan Africa: a systematic review of the empirical evidence *Environ. Int.* **91** 133–49
- Anderegg W R L, Kane J M and Anderegg L D L 2012 Consequences of widespread tree mortality triggered by drought and temperature stress *Nat. Clim. Change* **3** 30–6
- Butler E E and Huybers P 2015 Variations in the sensitivity of US maize yield to extreme temperatures by region and growth phase *Environ. Res. Lett.* **10** 34009
- Ceccherini G, Russo S, Amezttoy I, Marchese A F and Carmona-Moreno C 2017 Heat waves in Africa 1981–2015, observations and reanalysis *Nat. Hazards Earth Syst. Sci.* **17** 115–25
- Chadwick R, Good P, Martin G and Rowell D P 2016 Large rainfall changes consistently projected over substantial areas of tropical land *Nat. Clim. Change* **6** 177–81
- Chang J, Ciais P, Viovy N, Soussana J-F, Klumpp K and Sultan B 2017 Future productivity and phenology changes in European grasslands for different warming levels: implications for grassland management and carbon balance *Carbon Balance Manage.* **12** 11
- Chen C, Noble I, Hellmann J, Coffee J, Murillo M and Chawla N 2015 *University of Notre Dame Global Adaptation Index Country Index Technical Report* (IN, USA: ND-GAIN South Bend)
- Coffel E, Horton R, Coffel E and Horton R 2015 Climate change and the impact of extreme temperatures on aviation *Weather Clim. Soc.* **7** 94–102
- Crétat J, Vizio E K and Cook K H 2014 How well are daily intense rainfall events captured by current climate models over Africa? *Clim. Dyn.* **42** 2691–711
- Damm A, Greuell W, Landgren O and Prettenhaler F 2017a Impacts of +2 °C global warming on winter tourism demand in Europe *Clim. Serv.* **7** 31–46
- Damm A, Köberl J, Prettenhaler F, Rogler N and Töglhofer C 2017b Impacts of +2 °C global warming on electricity demand in Europe *Clim. Serv.* **7** 12–30
- Dee D P *et al* 2011 The ERA-Interim reanalysis: Configuration and performance of the data assimilation system *Q. J. R. Meteorol. Soc.* **137** 553–97
- Déqué M, Calmanti S, Christensen O B, Aquila A D, Maule C F, Haensler A, Nikulin G and Teichmann C 2017 A multi-model climate response over tropical Africa at +2 °C *Clim. Serv.* **7** 87–95
- Diallo I, Giorgi F, Sukumaran S, Stordal F and Giuliani G 2015 Evaluation of RegCM4 driven by CAM4 over Southern Africa: mean climatology, interannual variability and daily extremes of wet season temperature and precipitation *Theor. Appl. Climatol.* **121** 749–66
- Diffenbaugh N S and Scherer M 2011 Observational and model evidence of global emergence of permanent, unprecedented heat in the 20th and 21st centuries *Clim. Change* **107** 615–24
- Donnelly C, Greuell W, Andersson J, Gerten D, Pisacane G, Roudier P and Ludwig F 2017 Impacts of climate change on European hydrology at 1.5, 2 and 3 degrees mean global warming above preindustrial level *Clim. Change* **143** 13–26
- Dosio A 2017 Projection of temperature and heat waves for Africa with an ensemble of CORDEX Regional Climate Models *Clim. Dyn.* **49** 493–519
- Dosio A and Fischer E M 2017 Will half a degree make a difference? Robust projections of indices of mean and extreme climate in Europe under 1.5 °C, 2 °C, and 3 °C global warming *Geophys. Res. Lett.* **45** 935–44
- Dosio A, Panitz H-J, Schubert-Frisius M and Lüthi D 2015 Dynamical downscaling of CMIP5 global circulation models over CORDEX-Africa with COSMO-CLM: evaluation over the present climate and analysis of the added value *Clim. Dyn.* **44** 2637–61
- Dosio A and Panitz H J 2016 Climate change projections for CORDEX-Africa with COSMO-CLM regional climate model and differences with the driving global climate models *Clim. Dyn.* **46** 1599–625
- Easterling D R *et al* 2000 Observed variability and trends in extreme climate events: a brief review *Bull. Am. Meteorol. Soc.* **81** 417–25
- Engelbrecht C J, Engelbrecht F A and Dyson L L 2013 High-resolution model-projected changes in mid-tropospheric closed-lows and extreme rainfall events over southern Africa *Int. J. Climatol.* **33** 173–87
- Engelbrecht F *et al* 2015 Projections of rapidly rising surface temperatures over Africa under low mitigation *Environ. Res. Lett.* **10** 85004
- Field C B 2012 *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special Report of the Intergovernmental Panel on Climate Change* (Cambridge: Cambridge University Press)
- Field C B, Barros V R, Mach K and Mastrandrea M 2014 *Climate Change 2014: Impacts, Adaptation, and Vulnerability* vol 1 (Cambridge: Cambridge University Press)
- Frei C, Schöll R, Fukutome S, Schmidli J and Vidale P L 2006 Future change of precipitation extremes in Europe: intercomparison of scenarios from regional climate models *J. Geophys. Res. Atmos.* **111** D06105
- Frieler K *et al* 2017 Assessing the impacts of 1.5 °C global warming—simulation protocol of the inter-sectoral impact model intercomparison project (ISIMIP2b) *Geosci. Model Dev.* **10** 4321–45
- Giorgi F, Coppola E, Raffaele F, Diro G T, Fuentes-Franco R, Giuliani G, Mangani A, Llopert M P, Mariotti L and Torma C 2014 Changes in extremes and hydroclimatic regimes in the CREMA ensemble projections *Clim. Change* **125** 39–51
- Giorgi F and Gutowski W J 2015 Regional dynamical downscaling and the CORDEX initiative *Annu. Rev. Environ. Resour.* **40** 467–90
- Giorgi F, Jones C and Asrar G R 2009 Addressing climate information needs at the regional level: the CORDEX framework *WMO Bull.* **58** 175
- Giorgi F and Mearns L O 1999 Introduction to special section: regional climate modeling revisited *J. Geophys. Res.* **104** 6335–52

- Grillakis M G, Koutroulis A G, Seiradakis K D and Tsanis I K 2016 Implications of 2 °C global warming in European summer tourism *Clim. Serv.* **1** 30–8
- Hawkins E *et al* 2014 Uncertainties in the timing of unprecedented climates *Nature* **511** E3–5
- Hawkins E and Sutton R 2016 Connecting climate model projections of global temperature change with the real world *Bull. Am. Meteorol. Soc.* **97** 963–80
- Hawkins E and Sutton R 2012 Time of emergence of climate signals *Geophys. Res. Lett.* **39** 1–6
- Hewitson B C, Janetos A C, Carter T R, Giorgi F, Jones R G, Kwon W-T, Mearns L O, Schipper E L F and van Aalst M 2014 Regional context *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* ed V R Barros *et al* (Cambridge: Cambridge University Press) pp 1133–97
- Hulme M 2016 1.5 °C and climate research after the Paris Agreement *Nat. Clim. Change* **6** 222–4
- Hunt A, Ferguson J, Baccini M, Watkiss P and Vladimir K 2017 Climate and weather service provision: economic appraisal of adaptation to health impacts *Clim. Serv.* **7** 78–86
- IPCC 2013 Summary for Policymakers *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed T F Stocker, D Qin, G-K Plattner, M Tignor, S K Allen, J Boschung, A Nauels, Y Xia, V Bex and P M Midgley (Cambridge: Cambridge University Press) p 116
- Jacob D and Solman S 2017 IMPACT2C—an introduction *Clim. Serv.* **7** 1–2
- James R and Washington R 2013 Changes in African temperature and precipitation associated with degrees of global warming *Clim. Change* **117** 859–72
- James R, Washington R, Schleussner C F, Rogelj J and Conway D 2017 Characterizing half-a-degree difference: a review of methods for identifying regional climate responses to global warming targets *Wiley Interdiscip. Rev. Clim. Change* **8** 1–23
- Joshi M, Hawkins E, Sutton R, Lowe J and Frame D 2011 Projections of when temperature change will exceed 2 °C above pre-industrial levels *Nat. Clim. Change* **1** 407–12
- Klutse N A B *et al* 2018 Potential impact of 1.5 °C and 2 °C global warming on consecutive dry and wet days over West Africa *Environ. Res. Lett.* **13** 055013
- Laprise R, Hernández-Díaz L, Tete K, Sushama L, Šeparović L, Martynov A, Winger K and Valin M 2013 Climate projections over CORDEX Africa domain using the fifth-generation Canadian regional climate model (CRCM5) *Clim. Dyn.* **41** 3219–46
- Lehner F, Coats S, Stocker T F, Pendergrass A G, Sanderson B M, Raible C C and Smerdon J E 2017 Projected drought risk in 1.5 °C and 2 °C warmer climates *Geophys. Res. Lett.* **44** 7419–28
- Mahlstein I, Daniel J S and Solomon S 2013 Pace of shifts in climate regions increases with global temperature *Nat. Clim. Change* **3** 739–43
- Mariotti L, Diallo I, Coppola E and Giorgi F 2014 Seasonal and intraseasonal changes of African monsoon climates in 21st century CORDEX projections *Clim. Change* **125** 53–65
- Maule C F, Mendlik T and Christensen O B 2017 The effect of the pathway to a two degrees warmer world on the regional temperature change of Europe *Clim. Serv.* **7** 3–11
- Maure G *et al* 2018 The southern African climate under 1.5 °C and 2 °C of global warming as simulated by CORDEX regional climate models *Environ. Res. Lett.* **13** 065002
- McDowell G, Ford J and Jones J 2016 Community-level climate change vulnerability research: trends, progress, and future directions *Environ. Res. Lett.* **11** 33001
- Mohammed K, Islam A S, Islam G T, Alfieri L, Bala S K and Khan M J U 2017 Extreme flows and water availability of the Brahmaputra River under 1.5 and 2 °C global warming scenarios *Clim. Change* **145** 159–75
- Mora C *et al* 2014 Reply *Nature* **511** E5–6
- Mora C *et al* 2013 The projected timing of climate departure from recent variability *Nature* **502** 183–7
- New M *et al* 2006 Evidence of trends in daily climate extremes over southern and west Africa *J. Geophys. Res.* **111** D14102
- Niang I, Ruppel O, Abdrabo M, Essel A, Lennard C, Padgham J and Urquhart P 2014 *Africa* ed V R Barros *et al* (Cambridge: Cambridge University Press) pp 1199–265
- Nikulin G *et al* 2018 The effects of 1.5 and 2 degrees of global warming on Africa in the CORDEX ensemble *Environ. Res. Lett.* **13** 065003
- Ongoma V, Chen H, Gao C, Nyongesa A M and Polong F 2018 Future changes in climate extremes over Equatorial East Africa based on CMIP5 multimodel ensemble *Nat. Hazards* **90** 901–20
- Orlowsky B and Seneviratne S I 2012 Global changes in extreme events: regional and seasonal dimension *Clim. Change* **110** 669–96
- Osima S *et al* 2018 Projected climate over the Greater Horn of Africa under 1.5 °C and 2 °C global warming *Environ. Res. Lett.* **13** 065004
- Pinto I, Lennard C, Tadross M, Hewitson B, Dosio A, Nikulin G, Panitz H J and Shongwe M E 2016 Evaluation and projections of extreme precipitation over southern Africa from two CORDEX models *Clim. Change* **135** 655–68
- Pokam Mba *et al* 2018 Consequences of 1.5 °C and 2 °C global warming levels for temperature and precipitation changes over Central Africa *Environ. Res. Lett.* **13** 055011
- Le Quéré C, Andrew R M, Canadell J G, Sitch S, Korsbakken J I, Peters G P, Manning A C, Boden T A, Tans P P and Houghton R A 2016 Global carbon budget 2016 *Earth Syst. Sci. Data* **8** 605
- Raftery A E, Zimmer A, Frierson D M W, Startz R and Liu P 2017 Less than 2 °C warming by 2100 unlikely *Nat. Clim. Change* **7** 637–41
- Rogelj J and Knutti R 2016 Geosciences after Paris *Nat. Geosci.* **9** 187–9
- Russo S, Marchese A F, Sillmann J and Immé G 2016 When will unusual heat waves become normal in a warming Africa? *Environ. Res. Lett.* **11** 54016
- Saeed F, Haensler A, Weber T, Hagemann S and Jacob D 2013 Representation of extreme precipitation events leading to opposite climate change signals over the Congo Basin *Atmosphere (Basel)* **4** 254–71
- Sakalli A, Cescatti A, Dosio A and Güçela M U 2017 Impacts of 2 °C global warming on primary production and soil carbon storage capacity at pan-European level *Clim. Serv.* **7** 64–77
- Sanderson M G, Hemming D L and Betts R A 2011 Regional temperature and precipitation changes under high-end (≥ 4 °C) global warming *Phil. Trans. R Soc. London A Math. Phys. Eng. Sci.* **369** 85–98
- Schleussner C-F *et al* 2016 Differential climate impacts for policy-relevant limits to global warming: the case of 1.5 °C and 2 °C *Earth Syst. Dyn.* **7** 327–51
- Seneviratne S I, Donat M G, Pitman A J, Knutti R and Wilby R L 2016 Allowable CO2 emissions based on regional and impact-related climate targets *Nature* **529** 477–83
- Shongwe M E, van Oldenborgh G J, van den Hurk B and van Aalst M 2011 Projected changes in mean and extreme precipitation in africa under global warming. Part II: East Africa *J. Clim.* **24** 3718–33
- Sutton R, Suckling E and Hawkins E 2015 What does global mean temperature tell us about local climate? *Phil. Trans. R. Soc. A* **373** 20140426

- Sylla M B, Giorgi F, Pal J S, Gibba P, Kebe I and Nikiema M 2015a Projected changes in the annual cycle of high-intensity precipitation events over West Africa for the late twenty-first century *J. Clim.* **28** 6475–88
- Sylla M B *et al* 2015b Projected changes in the annual cycle of high-intensity precipitation events over West Africa for the late twenty-first century *J. Clim.* **28** 6475–88
- Taylor K E, Stouffer R J, Meehl G A, Taylor K E, Stouffer R J and Meehl G A 2012 An overview of CMIP5 and the experiment design *Bull. Am. Meteorol. Soc.* **93** 485–98
- Teichmann C *et al* 2013 How does a regional climate model modify the projected climate change signal of the driving GCM: a study over different CORDEX regions using REMO *Atmosphere (Basel)* **4** 214–36
- Thornton P K, Jones P G, Ericksen P J and Challinor A J 2011 Agriculture and food systems in sub-Saharan Africa in a 4 C+ world *Phil. Trans. Math. Phys. Eng. Sci.* **369** 117–36
- Vautard R *et al* 2014 The European climate under a 2 °C global warming *Environ. Res. Lett.* **9** 34006
- van der Linden P and Mitchell J F B 2009 *ENSEMBLES: Climate Change and its Impacts: Summary of Research and Results from the ENSEMBLES Project* (Exeter: Met Office) p 160
- van Vuuren D P, Edmonds J, Kainuma M, Riahi K, Thomson A, Hibbard K, Hurtt G C, Kram T, Krey V and Lamarque J-F 2011 The representative concentration pathways: an overview *Clim. Change* **109** 5–31
- Warszawski L, Frieler K, Huber V, Piontek F, Serdeczny O and Schewe J 2014 The inter-sectoral impact model intercomparison project (ISI-MIP): project framework *Proc. Natl Acad. Sci. USA* **111** 3228–32
- Williges K, Mechler R, Bowyer P and Balkovic J 2017 Towards an assessment of adaptive capacity of the European agricultural sector to droughts *Clim. Serv.* **7** 47–63
- Zaman A M, Molla M K, Pervin I A, Rahman S M M, Haider A S, Ludwig F and Franssen W 2017 Impacts on river systems under 2 °C warming: Bangladesh case study *Clim. Serv.* **7** 96–114
- Zwiers F W, Alexander L V, Hegerl G C, Knutson T R, Kossin J P, Naveau P, Nicholls N, Schär C, Seneviratne S I and Zhang X 2013 Climate extremes: challenges in estimating and understanding recent changes in the frequency and intensity of extreme climate and weather events *Climate Science for Serving Society* (Dordrecht: Springer) pp 339–89