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To cite this article: R Barimalala *et al* 2021 *Environ. Res. Lett.* **16** 044019

ENVIRONMENTAL RESEARCH
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OPEN ACCESS

RECEIVED
24 September 2020

REVISED
5 February 2021

ACCEPTED FOR PUBLICATION
2 March 2021

PUBLISHED
16 March 2021

LETTER

Potential impacts of 1.5 °C, 2 °C global warming levels on temperature and rainfall over Madagascar

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Keywords: CORDEX, CORDEX-Africa, Madagascar, global warming level

Supplementary material for this article is available online

Abstract

Outputs from 25 regional climate models within the coordinated regional downscaling experiments—Africa are used to assess the impacts of the 1.5 °C and 2 °C global warming levels (GWLs) over Madagascar. A robust increase in the annual mean temperature ranging from 0.9 °C to 1.2 °C (1.3 °C–1.8 °C) is projected in the 1.5 °C (2 °C) GWL. The west and southwestern parts of the island display the highest rise in temperature. On the other hand, the changes in rainfall signals depend on the location, the months within the rain season and the warming level with the models showing a large uncertainty in the signal of changes. During early summer, the west and southwest regions exhibit an increase in total rainfall accompanied with more wet spell days and excessive amounts of extreme rainfall. In contrast, the east and the north are characterized by a deficit in total rainfall and wet spell days while the maximum number of dry spells increase. The change signals are more pronounced in the 2 °C GWL. From January to April, an overall increase in total and extreme rainfall is projected over the island. The two warming levels agree on the delay in the rainfall onset and shortening of the rainfall season with the 2 °C GWL depicting more modest changes in the west and southern parts of the country compared to that of 1.5 °C GWL. These results have important implications not only for the development of the country but also for the endemic biodiversity which is already suffering from the impacts of climate change.

1. Introduction

The 2015 Paris agreement aims to hold the global average temperature rise well below 2 °C above pre-industrial levels and to make efforts to limit the temperature increase to 1.5 °C. Studies show that the impacts of such warming are not expected to be spatially or temporally uniform (e.g. Collins *et al* 2013, Déqué *et al* 2017, Lennard *et al* 2018). Land areas warm faster than the oceans while frequent and/or intense extreme events may increase in some regions (IPCC SR15).

Over the past decades, sub-Saharan Africa has already experienced more frequent and intense climate extremes than before (Paeth *et al* 2011, Taylor *et al* 2017). Recent findings confirm that at 1.5 °C–2 °C global warming levels (GWLs), the temperature increases in the continent are projected to be higher than that of the global mean, accompanied with frequent hot nights, heat waves, drought and flood periods (e.g. Pinto *et al* 2016, Kharin *et al* 2018, Nikulin *et al* 2018, Weber *et al* 2018). These results show the need to understand the potential impacts of these GWL at local and regional scales for better mitigation and adaptation plans.

With the efforts from the coordinated regional downscaling experiment (CORDEX, Jones *et al* 2011, Giorgi and Gutowski 2015, Gutowski *et al* 2016) and CORDEX-Africa communities, the effects of these GWLs on temperature and rainfall over different parts of Africa have been the focus of a number of recent studies (e.g. Klutse *et al* 2018, Maure *et al* 2018, Mba *et al* 2018, Nikulin *et al* 2018, Osima *et al* 2018, Gudoshava *et al* 2020). Although southern Africa has been a main focus for numerous works, only a few studies have been particularly done on the changes in temperature and rainfall over Madagascar. There is, in fact, a lack of scientific attention to the climate variability and change over the region (Macron *et al* 2016). By using station daily record from 1961 to 2000, Tadross *et al* (2008) found a consistent increase in both minimum and maximum annual temperatures over the island. These are accompanied by an overall decrease in annual rainfall over the eastern part of the country (Morishima and Akasaka 2010, Vincent *et al* 2011) whereas the south observes an increase (Tadross *et al* 2008). On the other hand, downscaled global circulation models (GCMs) within the Coupled Model Intercomparison Project phase 3 (CMIP3) under the A2 SRES scenario projected an overall increase in rainfall by 2050, except the southern half of the east coast of the country which is projected to be drier during July and September. These signals are accompanied by a consistent increase in temperature of 1.1 °C–2 °C throughout the island with moderate changes along the coastal areas and maximum changes over the south and southwest (Tadross *et al* 2008). The northern part of the island has a monsoonal climate. Sitting between the warm sea surface temperatures of the tropical southwest Indian Ocean and the Mozambique Channel near the Inter-Tropical Convergence Zone (ITCZ) in summer, Madagascar is also prone to tropical cyclones between November and May. About 11 cyclones form in this basin each season (Mavume *et al* 2010) and, although overall numbers are projected to decrease, the numbers of category 3–5 cyclones are expected to increase in the future (Malan *et al* 2013). In general, heavy rainfall associated with cyclones and other convective storms is likely to increase under increasing global warming (Senevirante *et al* 2012).

The possible impacts of the projected changes on the well-being of the country are significant and are compounded by its low adaptive capacity. For instance, in addition to loss of life, damages from intense tropical cyclones costs the island an average of USD 87 million annually (GFDRR 2016). Moreover, despite the excess of rain or flooding caused by the number of tropical cyclones hitting the island, water stress remains a major challenge in most areas given that the country also experiences very dry periods quite often, especially over the west and southwest often associated with El Niño events (Randriamahefasoa and Reason 2017). In fact, Madagascar is classified as one of the most stricken countries for water shortages (UNICEF 2018). Yet the economy of Madagascar still heavily relies on rain-fed agriculture and it expects most of its energy to be hydropower-sourced by 2030. Furthermore, one third of the worldwide human plague cases are reported to be in Madagascar and the number of cases is particularly high under warm and wet conditions (Kreppel *et al* 2014). The island is also considered as one of the world's top conservation priorities due to its exceptional biodiversity and high endemism rates (Goodman and Benstead 2005). However, changes in temperature and rainfall are projected to highly impact such biodiversity (Hannah *et al* 2008).

Limiting the GWL to 1.5 °C–2 °C is therefore crucial for Madagascar in many ways. Nevertheless, it is also of a high importance to understand the local responses of these GWL, mainly in temperature and rainfall given that the consequences described above are mostly due to the changes in the intensity and frequency of extreme heat, rain and drought. Thus, the focus of this work is to investigate, for the first time, the potential impacts of the 1.5 °C–2 °C global warming levels on temperature and rainfall over Madagascar. Changes in mean and extremes are of a particular focus. These are important for the country's adaptation and mitigation plan while considering the Paris agreement.

2. Data and methodology

Simulated daily temperature and rainfall from CORDEX-Africa multi-model ensemble mean (Nikulin *et al* 2018) are used in this study. The ensemble consists of output from 25 regional circulation models (RCMs) downscaled from a set of 13 CMIP5 GCMs (for models list, see table 1 in Nikulin *et al* 2018). Simulation from historical runs and future climate under Representative Concentration Pathway RCP8.5 are analyzed. The choice of RCP8.5 is motivated by the fact that it contains the largest number of ensemble members. It is also considered as the most realistic business as usual scenario, given the current trajectory of greenhouse gases emissions.

The method from Nikulin *et al* (2018) is used to determine the timing of when the GWLs are reached. Briefly, the period of 1861–1890 is defined as pre-industrial (PI) period as it is available across all CMIP5 historical simulations. The timing of GWLs is then defined, for each GCM, as the first time the 30 year moving average of global temperature is above 1.5 °C or 2 °C compared to the PI mean. The resulting 30 year period is then extracted from the downscaling RCM for analysis using 1971–2000 as a control period. It is worth noting that the computed changes do not represent the total change induced by 1.5 °C–2 °C warming but rather the difference between the 20th century climate and that projected in a 1.5 °C–2 °C warmer world, considering that the CORDEX simulations are integrated from 1950 to 2100. A direct assessment of the projected changes relative to PI is therefore only appropriate for the CMIP5 GCMs simulations. For comparison purposes, analysis of the changes in the CMIP5 used

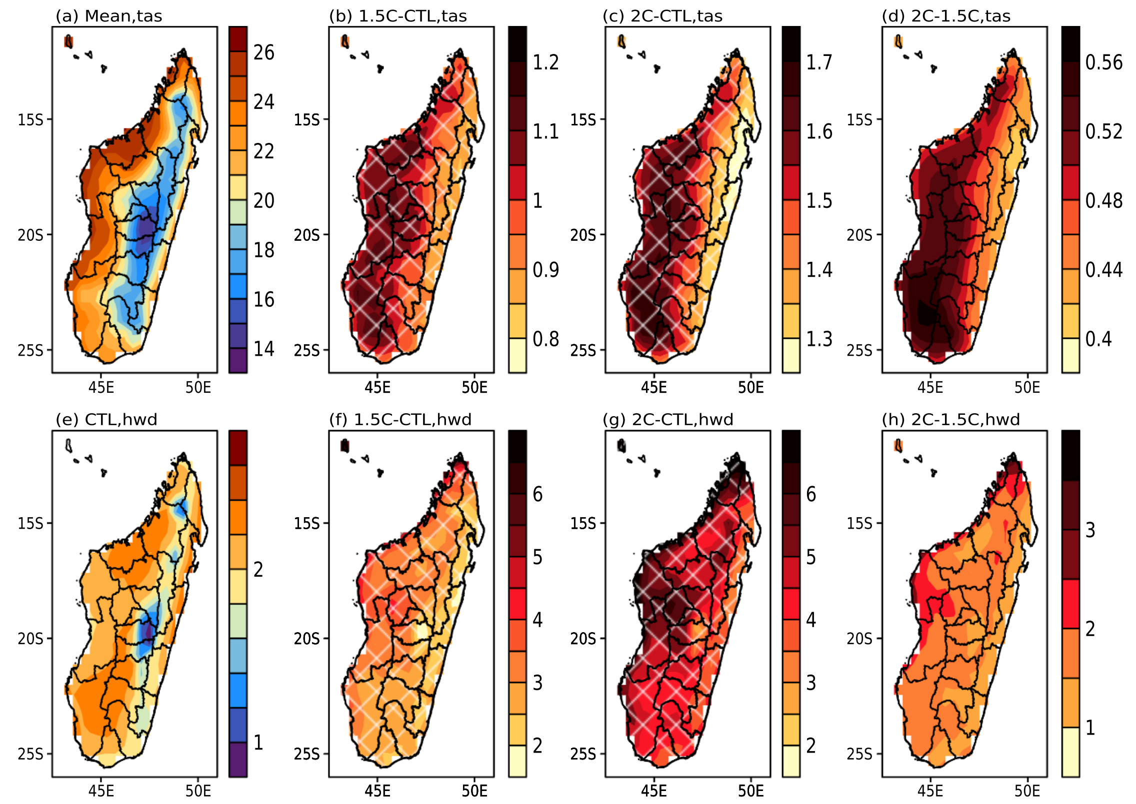

Figure 1. (a) Mean temperature in CTRL. (b) Changes in mean temperature at 1.5 °C GWL. (c) Changes in mean temperature at 2 °C GWL. (d) Temperature difference between 1.5 °C and 2 °C GWL. Figures (e)–(h) same as (a)–(d) but for heat wave days frequency.

to force the CORDEX RCM is also conducted for the changes in mean and extreme temperature and rainfall.

Extreme temperature and rainfall indices are calculated based on the definition from the Expert Team on Climate Change Detection and Indices (ETCCDI, Zhang *et al* 2011), whereas the definition from Liebmann *et al* (2012) is used for rainfall onset and cessation. Details on the indices used are described in the supplementary materials (SM is available online at stacks.iop.org/ERL/16/044019/mmedia). In the following, a climate change signal is robust if (a) more than 80% of model simulations agree on the sign of change (positive slope hatching in the figures) and (b) the signal to noise ratio i.e. ratio between mean and standard deviation of the ensemble is larger than one (negative slope hatching). The method used here has been applied in similar studies over Africa (e.g. Mba *et al* 2018, Nikulin *et al* 2018), although there are different methodologies to test the significance and robustness of a climate change signal (Collins *et al* 2013, Dosio and Fischer 2018).

3. Changes in mean temperature and number of heat wave days

The annual mean temperatures of Madagascar are distributed longitudinally and strongly related to its topographical features, with the lowest temperatures displayed over the central highland areas and the west coast being the warmest region (figure 1(a)). An overall robust increase in mean temperature, also distributed zonally, is projected in both 1.5 °C and 2 °C GWL with the latter showing warmer responses ranging from 0.4 °C to 0.6 °C above the 1.5 °C GWL (figures 1(b)–(d)). The intensity of change is particularly higher in the western part of the country (west of 46° E) reaching up to 1.3 °C (1.8 °C) in the 1.5 °C (2 °C) GWL. A monthly breakdown of the changes indicates that increases are more pronounced during austral summer season (not shown). As expected, by using the CMIP5 GCMs, projected changes in mean temperature over the region with respect to the PI period are larger compared to the changes in late 20th century (figures S1(a) and (d)). This indicates that if regional changes were also compared to PI, the signals would be very likely larger.

Figure 1(e) shows the number of annual heat wave days (HWD) events during 1971–2000. Overall the country experiences between 1 (over the central highland) to 3 (in coastal areas) HWD annually. High frequencies are particularly displayed in the northwestern regions of Sofia and Boeny (around 15° S) as well as over the central south (south of 20° S, Matsiatra Ambony, Ihorombe, Atsimo Andrefana). Both 1.5 °C and 2 °C GWL indicate robust increases in heat wave events, respectively up to 100% and 200%, compared to that of the reference period (figures 1(f)–(h)).

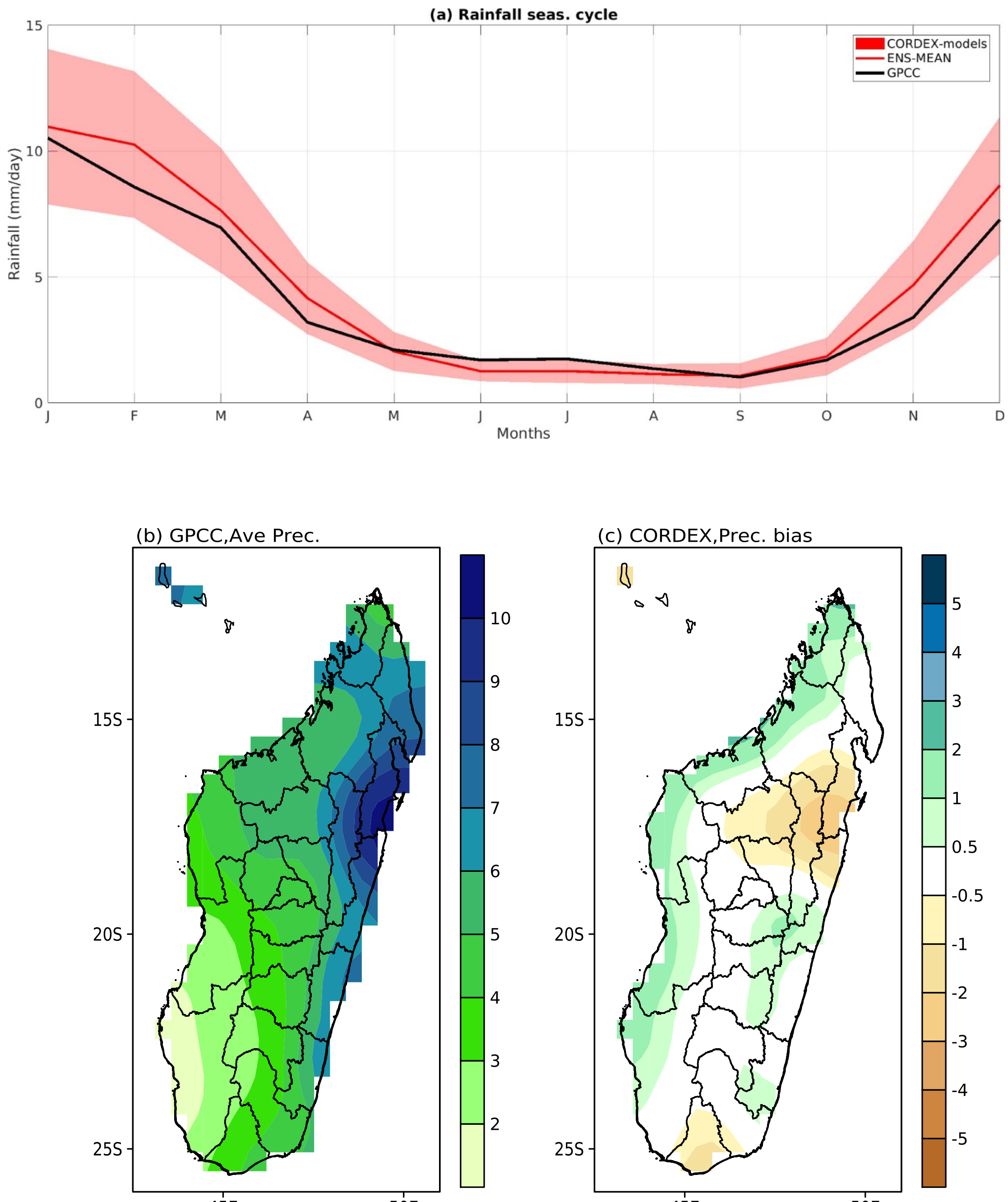

Figure 2. (a) Rainfall seasonal cycle in the CORDEX-models (shading), the ensemble mean (red solid line) and GPCC (black solid line). (b) Spatial distribution in annual rainfall from GPCC (in mm d^{-1}). (c) Rainfall biases in the CORDEX-ensemble mean (mm d^{-1}).

The central west shows the highest frequency in the projected HWD events. Compared to PI period, the GCM ensemble shows a substantial increase in the HWD higher than that of the late 20th century, with the maximum changes focused on the southwestern part of the island (figures S1(e) and (h)).

4. Mean rainfall in the models

The monthly climatological rainfall averaged over Madagascar is presented in figure 2(a). Overall, the highest rains are depicted during austral summer, starting from around November to April. The observed seasonal cycle is reasonably captured by the CORDEX ensemble mean despite a large spread in the individual models. The spatial distribution of the observed total rainfall indicates that highest rainfall occurs over the highland areas, the north and the east (more than 10 mm d^{-1}, figure 2(b)). These patterns are mainly caused by the southward shift of the ITCZ during austral summer as well as heavy rain from tropical cyclones while rainfall over the east is also enhanced by the moisture transported from the tropical Indian Ocean impacting on the mountains

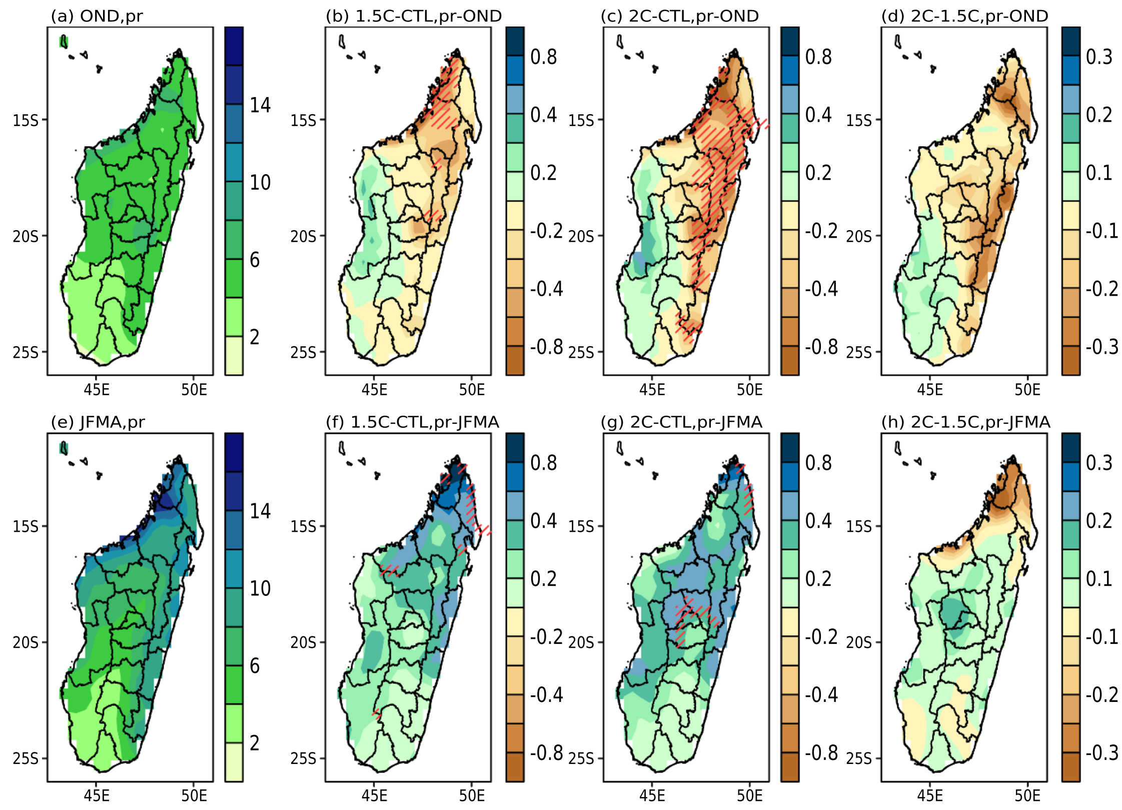

Figure 3. (a) October–November (OND) mean rainfall in CTRL. (b) Changes in OND mean rainfall at 1.5 °C GWL. (c) Changes in OND mean rainfall at 2 °C GWL. (d) Rainfall difference between 1.5 °C and 2 °C GWL. Figures (e)–(h) same as (a)–(d) but January–April.

which extend the length of the island. In contrast, the semi-arid region in the southwest receives only up to 400 mm of rain per year (~1 mm d^{-1}, figure 2(b)), at least partly due to the rain shadow effect of the mountains on the prevailing easterly winds.

In general, the CORDEX ensemble represents the rainfall spatial distribution well, regardless of the dry biases in the south and high plateau regions and wet biases along the western coastal areas (figure 2(c)). Based on the rainfall seasonality, analysis of potential changes due to 1.5 °C and 2 °C warming in rainfall will be focused on the months of October–April with the early (October–December, OND) and late (January–April, JFMA, when most rain falls) responses investigated separately, given the observed consistent decrease (increase) in the monthly mean rainfall during OND (JFMA) over the region (not shown).

5. Changes in mean rainfall, onset and length of rainy season

In the control runs, Madagascar receives more rainfall during JFMA compared to OND (figures 3(a) and (e)) with heavy rain (up to 16 mm d^{-1}) displayed in the far north. In both 1.5 °C and 2 °C GWL, the model ensemble median projects a dipole-like pattern of rainfall changes during OND, where the east and central parts of the island are characterized by rainfall deficit of up to 1 mm d^{-1} (~10% of that of the control) whereas an increase is displayed over the west, south of 15° S. The intensity of the rainfall deficit in the east and the excess over the central west and southwest are much stronger in the 2 °C GWL. An overall decrease in mean rainfall relative to both PI and the control periods is displayed in the GCMs (figures S2(a) and (d)) with the east and northern parts of the island show a stronger decrease compared to the west and the south. The discrepancies between CORDEX and CMIPs over the south could be due to the lower horizontal resolution thus smoothed topography in the GCMs. However, it is to be noted that the south is also characterized by a large uncertainty in the regional models (figures 3(b) and (c)), which could further emphasize the disagreement in the signs. Both regional and global models agree that the eastern part of the island is projected to be drier.

On the other hand, an overall increase in rainfall is projected for JFMA in both warming levels (figures 3(f) and (g)). Maximum changes, up to 1 mm d^{-1} (~10% of the reference climatological values), are seen in the far north, northeast and the eastern parts of the island. Similar response is displayed in the GCMs if compared to the PI period (figures S2(e) and (f)), while a weak decrease in mean rainfall is shown over the northeast areas relative to control period. The difference between the changes from 2 °C

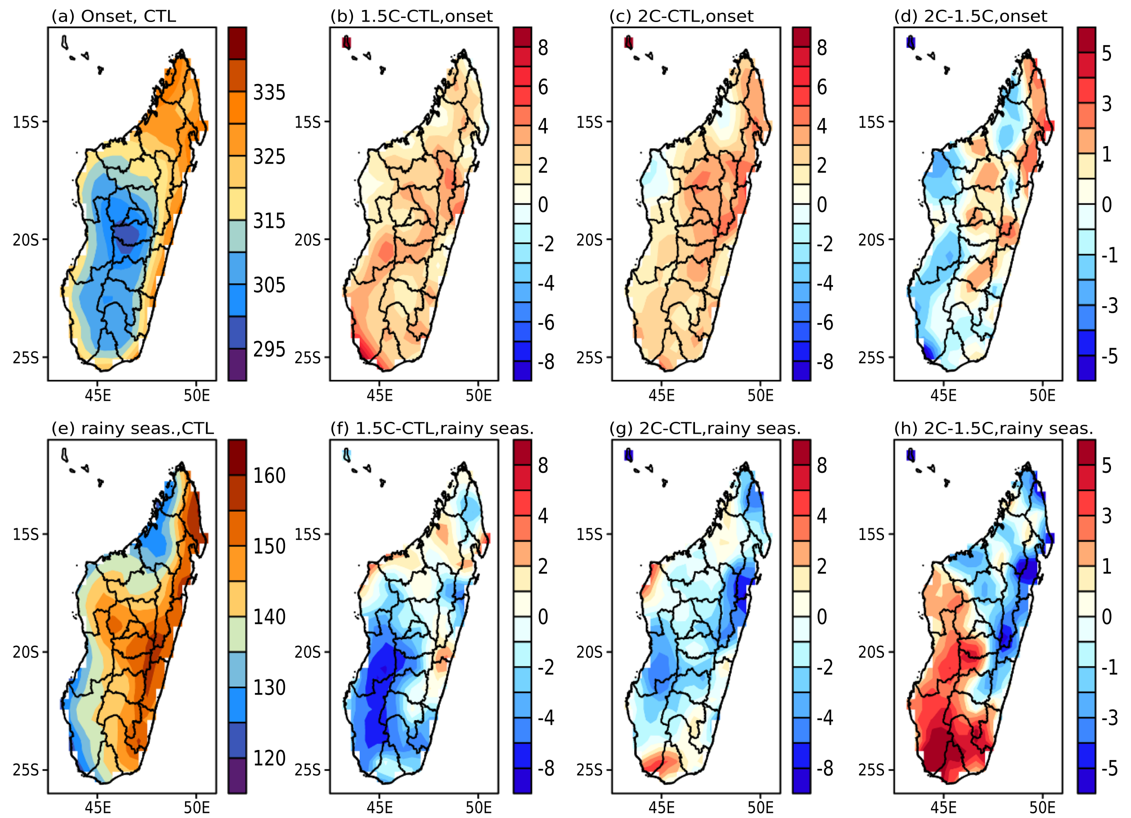

Figure 4. (a) Rainfall onset in CTRL (day of the year). (b) Changes in onset at 1.5 °C GWL (day). (c) Changes in onset at 2 °C GWL (day). (d) Onset day difference between 1.5 °C and 2 °C GWL (day). Figures (e)–(h) same as (a)–(d) but for length of rainy season. No areas meet the robustness criteria.

and 1.5 °C GWL shows that at higher GWL, the far north and some areas in the south receive less rainfall while the opposite is projected for the highland area (between 15° and 22° S).

Figures 4(a) and (e) show the spatial distribution of the median of rainfall onset and length of the rainy season during the reference period. Overall, no area meets the robustness criteria, suggesting a large uncertainty in the models. The high plateau areas are the first to receive rainfall around day 290 (17 October) and the season lasts up to 5 months long. By early November, a shorter rain season (4 months) starts over the west and the south while the rain period begins much later in the year (after the middle of November) and lasts for more than 5 months along the eastern coast. In both GWLs, projected changes in rainfall onset indicate a delay of a few days up to a week, mainly in the east and the northern parts of the island (figures 4(b) and (c)). The difference between the two GWLs shows that the west and southwestern areas tend to have a longer delay in the 1.5 °C GWL whereas the opposite is projected over the northeast (figure 4(d)).

The spatial distribution of the changes in the length of the rainy season differs in the two warming levels. In the 1.5 °C case, changes are mainly seen over the southwest and the southern regions where a decrease in the length of the season by a week is indicated, as opposed to a slight increase over the southern tip of the island in the 2 °C GWL (figures 4(f) and (g)). These are also confirmed by the difference between 2 °C and 1.5 °C GWL (figure 4(h)) in which the south and western parts of the country tend to have longer rainy seasons in the 2 °C GWL compared to the 1.5 °C (figure 4(h)). This may contribute to the slight increase in OND rainfall in these areas (figure 3(d)). Over southwestern Madagascar, the latter onset of rainy season in the 1.5 °C GWL (figure 4(d)) shortens the season up to 5 d compared to the 2 °C GWL (figure 4(h)).

In these results, it is important to note the large uncertainty on the changes in the models where less than 80% of the models agree on the sign and the inter-model variability is greater than the signal. Thus, while these results are indicative of possible changes, more work is needed to assess the reliability of these signals given the large model inconsistency in the derived rainfall responses to the GWL.

6. Changes in wet and dry spells

During OND, the eastern coastal and central areas of Madagascar are characterized by a relatively low CDD (3 d maximum) while the far north and south show much higher numbers (more than 10 CDD, figure 5(a)). The two warming levels present

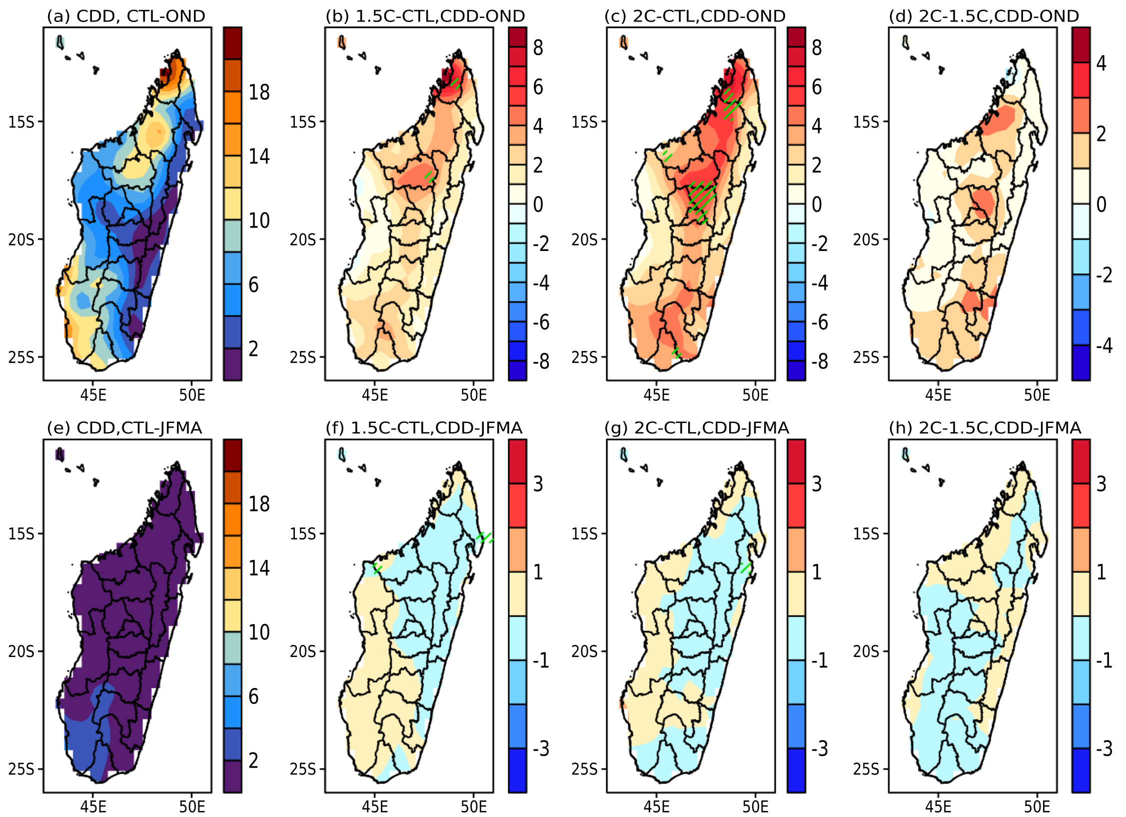

Figure 5. (a) Maximum number in consecutive dry days (CDD) during OND in CTRL. (b) OND changes CDD at 1.5 °C GWL. (c) OND changes in CDD at 2 °C GWL. (d) Difference in CDD between 1.5 °C and 2 °C GWL. Figures (e)–(h) same as (a)–(d) but for January–April.

a consistent increase in the maximum number of dry spell days reaching up to more than 50% of that of the reference period (figures 5(b) and (c)). The most pronounced signals are extended latitudinally over the highland areas with the 2 °C GWL showing more CDD than the 1.5 C (figure 5(d)).

On the other hand, during JFMA, the maximum number of CDD throughout the reference period divides the island into two regions in which dry spells only exist in the far south, up to 4 d long (figure 5(e)). The changes are very marginal in both GWLs (figures 5(f) and (g)). Overall the north and the east show a weak decrease and the southwest is characterized by an increase in CDD with the 2 °C GWL shows less dry spell than the 1.5 °C.

Figures 6(a) and (e) represent the maximum number of CWD during 1970–2000. For early summer, the northern and southwestern tips of the island get between 25 to 50 wet spell days while the rest of the country shows up to 80 d (figure 6(a)). Randriamahefasoa and Reason (2017) show that wet spells in the south and southwest mostly occur between October and March and are associated with La Niña events when tropical-extratropical cloudbands are more likely to occur there than over the mainland (Hart *et al* 2013, 2018).

For the two warming levels, the projected changes are mostly confined towards the east, with a decrease in wet spell days of up to 10%. In addition, an increase in CWD is also depicted over the southwest (figures 6(b) and (c)). The difference between 2 °C and 1.5 °C GWLs indicates that the southwest areas are projected to experience more wet spell days in the higher warming level.

During JFMA, the whole island experiences more than 50 CWD with the lowest number seen in the southwestern areas. Changes in the maximum number of CWD are smaller compared to that of the early summer. The two GWLs also show very inconsistent patterns with a decrease in CWD of up to 3 d mostly in the central west and the south and an increase in the northeast.

7. Changes in extreme rainfall (rx5day)

The northwest of Madagascar experiences very heavy rainfall of up to 120 mm d^{-1} during the summer season (figures 7(a) and (e)). The amount of rain gradually decreases toward the south with the coastal areas receiving more rain than the interior. Heavy rains in the northwestern part of island are associated with a surge in the monsoon northwesterlies and upper tropical easterlies (Nassor *et al* 1997), whereas the southwest areas are more likely to receive heavy rainfall when the Southern Annular Mode (SAM) is at its positive phase (Randriamahefasoa and Reason 2017).

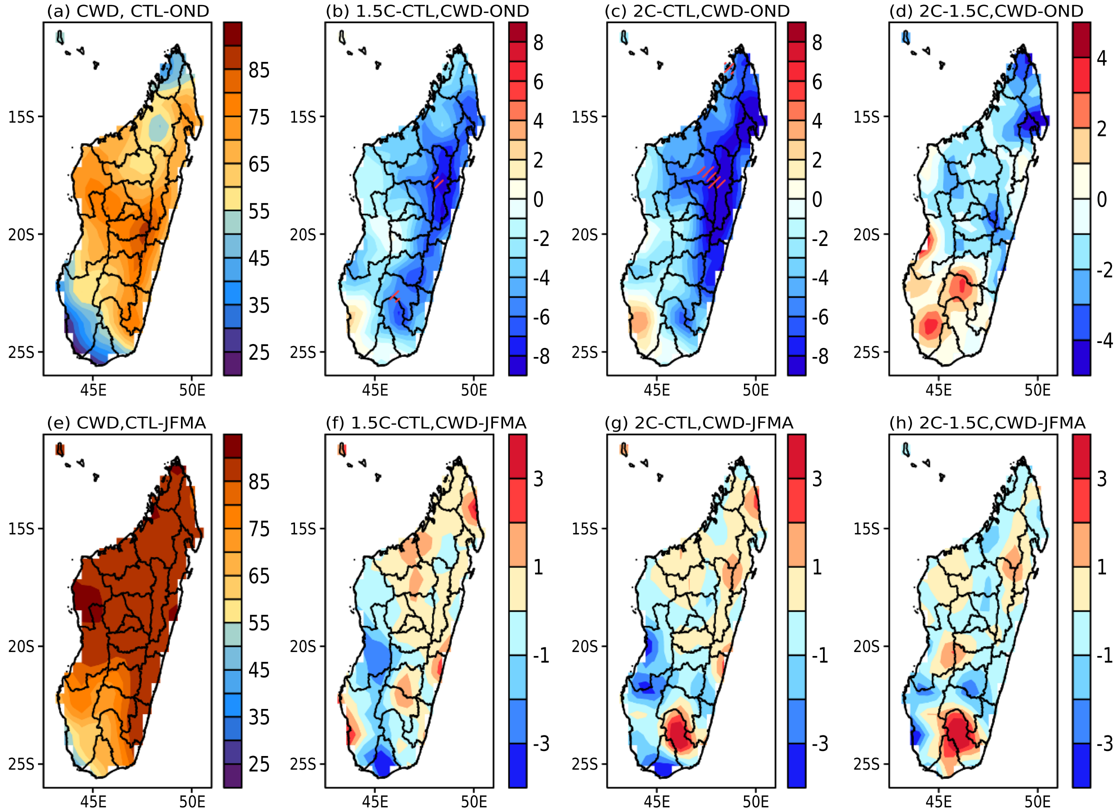

Figure 6. Same as figure 5 but for consecutive wet days (CWD).

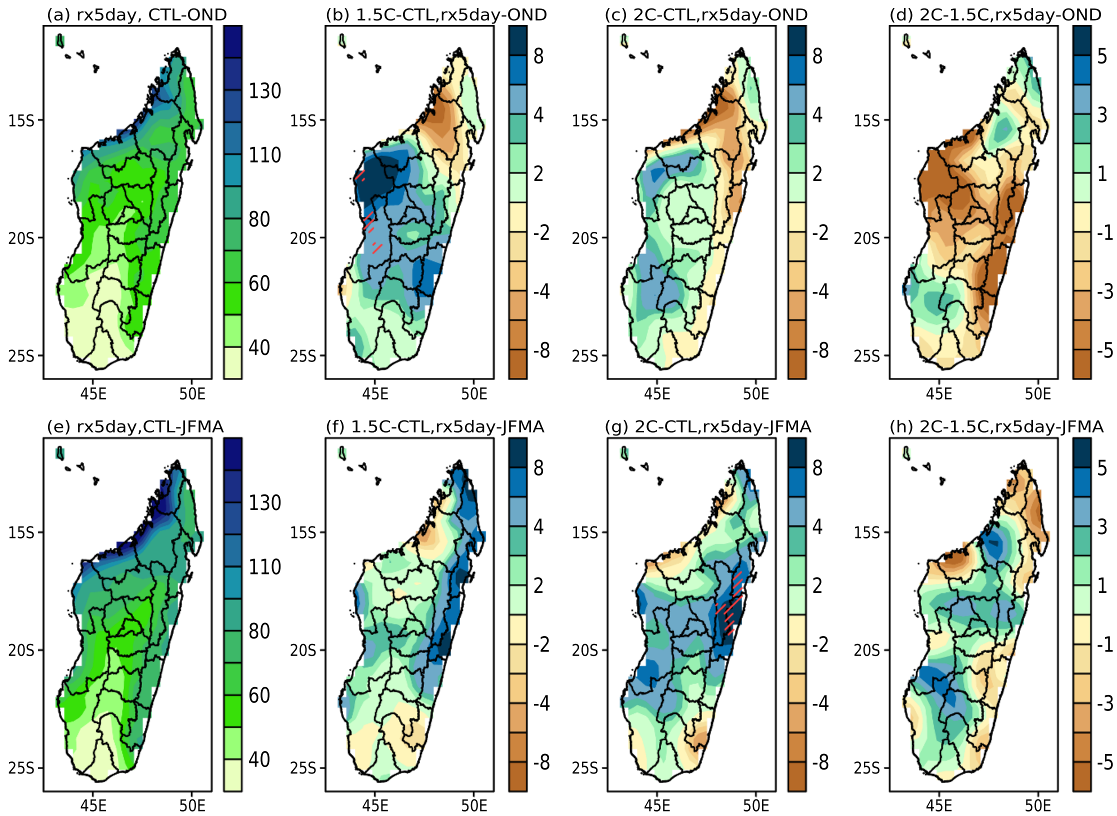

Figure 7. Same as figure 3 but for extreme rainfall (rx5day).

Tropical cyclones, also, often bring heavy rainfall over the island.

During OND, a consistent deficit in rx5day (see SM) is projected north of 16° S, especially in the region of Sofia (figures 7(b) and (c)). Such a deficit is also extended along the eastern coast in the 2 °C GWL. In contrast, the central and western parts of the island, south of 16° S are characterized by increased rx5day which is particularly high in the west and extended further to the east in the 1.5 C GWL. Overall, the 2 °C warming level shows less amount of rain from extreme compared to the 1.5 °C except over the north in the region of Sofia and in the south region of Atsimo Andrefana (figure 7(d)).

For JFMA, the maximum increase in rx5day is broadly projected along the eastern regions north of 22° S (figures 7(f) and (g)). Similarly, the central and western parts of the island are also characterized by an increase in rx5day. In contrast, areas of lower extreme rains than the reference period are displayed around the northwestern coasts as well as in the south (Atsimo-Atsinanana, Anosy and part of Atsimo-Andrefana). Interestingly, these areas coincide with areas of slightly higher CWD during JFMA (figures 6(f) and (g)). The changes are consistent in both warming levels with the 2 °C GWL depicting higher intensity in the central and western parts of the island (figure 7(h)).

Overall, relative to PI, the GCMs show an agreement with the changes in rx5day from CORDEX during summer season but with an intensity of up to 3 times larger compared to that during the control period (figure S3).

8. Summary and discussion

In this study, the projected changes in temperature and rainfall under 1.5 °C and 2 °C GWL over Madagascar are analyzed for the first time. At both warming levels, the island is characterized by a robust warming, mostly confined over its west and southern parts with the changes in the 2 °C GWL more pronounced compared to that of 1.5 °C. Unlike most regions, the rate of warming over the island is slightly below that of the global scale. These results are consistent with Nikulin *et al* (2018) showing a weaker warming in many coastal regions due to the slower warming ocean. Nevertheless, such slow warming is associated with a significant increase of up to 100% (200%) in the frequency of heat wave days under the 1.5 °C (2 °C) GWL.

Rises in temperature over the island have been shown to lead to more heat related deaths and increase in the risk of vector-borne diseases with an expansion of the vectors to higher elevations (WMO 2015). Warmer and extreme high temperatures also, negatively impact the crop yields, and therefore on national food security and the overall economy.

Unlike for temperature, changes in rainfall show not only large uncertainty between the models but also different responses depending on the season, location and the warming level. For instance, the temperature increase in the west and southwest is reflected in an increase in extreme and total rainfall during both early and late summer seasons. In addition, only the southwest regions show a consistent increase in wet spell days during OND, which could contribute to the excess in total rainfall. With higher warming level, the magnitude of change is higher in these areas.

Apart from the west and southwest, there is a tendency towards an overall decrease in the total amount of rainfall during early summer (OND). This could be due to a combination of different changes in the rainfall characteristics such as the delay in rainfall onset, the increase in the maximum number of CDD (up to 50%) and the decrease in CWD along the central and eastern escarpment areas, although the 1.5 C warming level depicts an increase in extreme rainfall along the southeast coasts. The decrease in rx5day over the far north could also contribute to the deficit in total rainfall in the area during OND. In addition, less heavy rain events are depicted in the 2 °C GWL compared to that of 1.5 °C. This strengthens the decrease in total rainfall as the warming level goes higher. Similar changes using available station data from 1961 to 2008 are found by Vincent *et al* (2011) in which a decrease in total rainfall and increase in CDD characterizes the east of Madagascar while the total and extreme rains increase in the west.

The months of OND generally correspond to the planting season over the island. Thus, the overall rainfall deficit and increase in CDD in the east and the north, as well as the changes in extreme rainfall during this period would have implication in the decision-making of the start of the planting season. Over the south and southwest, although there is an increase in the mean rainfall, it appears to be mostly from extreme and more frequent CWD events. Such conditions are not very favorable for cultivation given that it requires consistency in the minimal amount of received rainfall (Usman and Reason 2004, Moron *et al* 2007). The changes in rainfall characteristics during OND throughout the island, therefore, could have significant implications on the agriculture and food production over the country. Moreover, with most of the hydropower plants installed in the eastern part of the island, the decrease in mean rainfall could also impact the hydroelectricity production.

On the other hand, Madagascar is projected to receive more rainfall during JFMA with no to minimal changes in the maximum number of wet and dry spells but a substantial increase in the amount of extreme rainfall except in the regions of Atsimo-Atsinanana, Anosy, Atsimo-Andrefana (in the south) and Sofia (in the north). These areas are characterized by an increase in the wet spell days and a decrease in the amount of rains from extreme events.

The island is thus projected to be warmer and wetter than normal throughout JFMA. With an appropriate mitigation plan, the increase in rainfall could be beneficial for the south and southwestern regions which have been experiencing prolonged drought. On the other hand, previous studies found that the warm and wet conditions have important biological implications, including extinction risk of some endemic species (Hannah *et al* 2008, Vieilledent *et al* 2013). Recently, Vieilledent *et al* (2016) showed that the projected climate change signals over Madagascar could also lead to a decrease in the tropical forest carbon stock in the country, hence enhanced emission of carbon into the atmosphere. In addition, a rise in the number of cases in human plague and vector-borne diseases such as malaria is likely to occur with the changes during JFMA.

However, the island shows almost no changes in rainfall when averaged over the summer half of the year due to the opposite signs in the early and late summer responses. Similar cases are also found over tropical Africa by Déqué *et al* (2016) where no significant responses in the overall summer rainfall is depicted due to fewer rain days with increased rainfall which mostly tend to occur during late summer. These results highlight that the availability of information at a shorter time scale, including extreme events, rather than annual mean is very crucial for the country to build its adaptation plan. Understanding the physical processes driving the change signals, which are omitted here, are also important and will be a focus of a future study. From previous observational studies, wet spells in the south are associated with tropical extratropical cloudbands (Hart *et al* 2013, 2018) and mostly with La Niña events (Randriamahefasoa and Reason 2017). On the other hand, tropical cyclones, northwesterly monsoonal flows, upper tropical easterlies, SAM and the position of the ITCZ are potentially responsible for heavy rainfall over the island (Nassor *et al* 1997, Randriamahefasoa and Reason 2017). Changes in these phenomena could therefore also lead to changes in the rainfall derivates.

In general, the changes in rainfall display large uncertainties among the models. These are expected given the already large rainfall uncertainties in the GCMs, especially over the tropical areas (Kent *et al* 2015). In addition, studies that use CORDEX output also lack the possible impacts of different GWL on regional sea level rise and ocean temperatures which are critical for coastal ecosystems and fisheries. Nevertheless, the unique characteristics of Madagascar, including the diversity in the vegetation, the highly varied topography, and regional air-sea interaction that drive the climate over the area could offer a useful test bed for models and downscaling analyses.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://cordex.org/data-access/esgf/.

Acknowledgments

This work was supported through the Climate Research for Development (CR4D) Postdoctoral Fellowship CR4D-19-13 implemented by the African Academy of Sciences (AAS) in partnership with the United Kingdom's Department for International Development (DfID) Weather and Climate Information Services for Africa (WISER) program and the African Climate Policy Center (ACPC) of the United Nations Economic Commission for Africa (UNECA). Statements made and views expressed in this work are solely the responsibility of the author(s).

Support for this study has also been provided by the University of Cape Town and the Climate System Analysis Group at the University of Cape Town. The CORDEX-Africa data used in this work were obtained from the Earth System Grid Federation server.

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