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REGIONAL CLIMATE PROJECTIONS AND ASSOCIATED CLIMATE SERVICES IN THE SOUTHWEST INDIAN OCEAN BASIN

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1. The BRIO project

This research work was motivated by the lack of quality climate data specifically designed for the anticipation of climate change in the Southwest Indian Ocean (SWIO) basin that stretches from 30 to 90 degrees East. This region is prone to tropical cyclone activity with an average of 9.7 tropical systems developing each year, among which 4.8 systems go on to become TCs that are equivalent to a hurricane or a typhoon (Leroux et al. 2018). The SWIO region is also characterized by many small-size islands with peculiar high-orography. In the former Cordex program, regional climate models were run over Africa and only covered the western part of the South Indian Ocean at a coarse 50-km resolution (Dosio et al. 2015) while a 12-km resolution was used for Europe. A 50-km resolution is insufficient for island territories as small and steep as those in the Indian Ocean and the restriction of the domain to the western part of the basin could not represent the climatology of SWIO tropical systems, which is crucial for representing precipitation patterns.

Yet this area is especially vulnerable to natural catastrophes related to the effects of climate change; It is the third region in the world most affected by extreme climatic events. The need for climate services over that populated area has now become a critical issue.

Through the framework of the "Adapt'action" program, the Agence Française de Développement (AFD), the Indian Ocean Commission (IOC) and Météo-France have defined a cooperation agreement to finance the BRIO (Building Resilience in the Indian Ocean) project aiming at supplying IOC member countries with regional climate simulations over the 2018-2021 period. One of the project's final objective is to provide a set of 21^{st} century high quality climate-related data on a free-access online regional portal as well as climate services. Another goal is to train national experts to climate data mining in each of the IOC member countries: Madagascar, Reunion, Mauritius, as well as the Comoros and Seychelles archipelagos.

The numerical and statistical tools used for this regional climate study as well as some results are illustrated here for the southwest Indian ocean basin as well as for some islands of the region.

2. Regional climate simulations

Dynamical downscaling from a few ongoing CMIP6 simulations (historical and ScenarioMIP, O'Neill et al. 2016) was used to obtain regional climate information on a large area of the southwest Indian Ocean that includes most of the inhabited countries from the coasts of Mozambique (33°E) to 74°E as well as the

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main area of tropical cyclone genesis [2-28°S]; the domain is visible in Figure 4. The ALADIN limited area model was implemented in its most recent 6.3 climate version (Daniel et al. 2019; Nabat et al. 2020) with a horizontal resolution of 12 km and 91 vertical levels. It is based on a bi-spectral, semi-implicit, semi-Lagrangian advection scheme and will be called ALADIN63 hereafter. The first simulations were driven by one of the CMIP6 Earth System coupled models named CNRM-ESM2-1 (Séférian et al. 2019), providing atmospheric lateral boundary forcing at 6-h frequency with a horizontal resolution of about 150 km (T127) and 91 vertical levels. Historical simulations were run over the 1979-2014 period while projections were obtained for the ssp126, ssp245 and ssp585 scenarios (O'Neill et al. 2016) over the 2015-2100 period. The acronym "sspXYY" indicates the shared socioeconomic pathways (ssp) based on a development pathway X (i.e., 1, 2, 3, 4, or 5) reaching a net radiative Y. Y by 2100.

a. *Benefits from high resolution modeling*

The 12-km resolution of ALADIN63 allows small islands such as the Seychelles and Comoros archipelagos to be depicted as earth pixels (e.g., Fig. 1). The refined topography (e.g., Fig. 1) allows refined precipitation over all the steep islands of the region as illustrated in Fig. 2 for Madagascar.

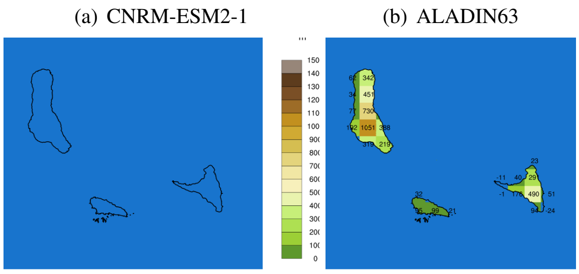

FIG. 1. Model orography (m) over the Comoros archipelago in (a) CNRM-ESM2-1 and (b) ALADIN63.

b. *Evolution of tropical systems and their intensity*

The climatology of tropical systems in ALADIN63 is close to the best-track data of RSMC La Réunion over the historical period 1981-2014, albeit a positive bias in tropical system intensity and a poleward bias in tropical systems' tracks (not shown). After an intensity calibration of the model, differences between future and past frequencies of maximum intensity show a most likely decrease of the total number of tropical systems over the region, a constant or slight increase in the number of intense to very intense TCs (Fig. 3), and a likely increase of their maximum intensity (not shown).

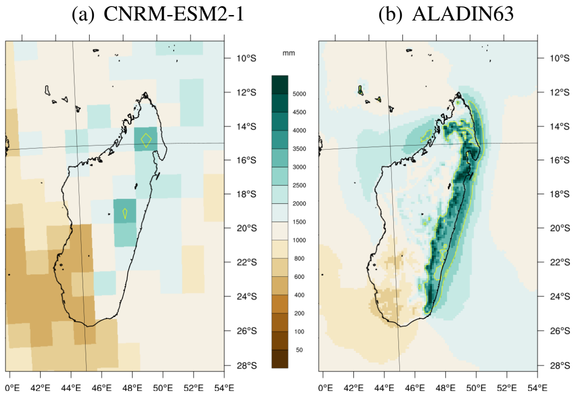

FIG. 2. Average annual precipitation (mm) over Madagascar for the 1981-2010 period in (a) CNRM-ESM2-1 compared to that in (b) ALADIN63. Yellow contours delineate 3000-mm annual precipitation.

c. *Future temperature anomalies expected over the region*

According to ALADIN63, temperatures over the SWIO region are projected to increase by $+1$°C to $+2.2$°C under the ssp126 scenario at the end of the century (Fig. 4). Increases of about $+3$°C to $+5.6$°C are projected under the ssp585 scenario (Fig. 4). Large continental masses such as Madagascar and the African continent will be prone to the greatest temperature increases (above $+5.0$°C over 2071-2100 under the ssp585 scenario), while small islands will be affected by lower yet substantial amounts of warming (about $+4.0$°C over 2071-2100 under the ssp585 scenario). It is worth noting that projected rates of regional warming are stable throughout the century under the lower case scenario considered here (ssp126) while they are accelerating at the end of the century under the high emission scenario (ssp585).

d. *Bias correction*

Observations over the islands of Madagascar, Reunion, Seychelles, Comoros, Mayotte, Mauritius, Rodrigues, Agalega and St Brandon during the 1981-2014 period were used for model bias correction on daily temperature and precipitation variables. The quantile delta mapping bias correction algorithm (Cannon et al. 2015) was chosen as it explicitly preserves relative changes in the model quantiles. We used 30-year moving time-slices over 3-month windows centered on the month to correct. The final resolution after bias correction depends on the observational data and ranges from

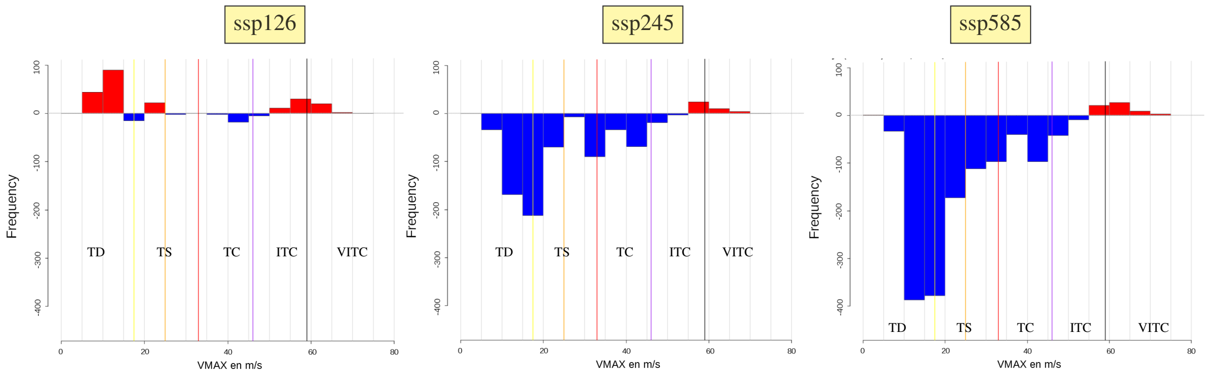

FIG. 3. Evolution (blue for a decrease, red for an increase) of ALADIN63 6-hr tropical system counts per 5-m/s bins of maximum intensity (Vmax) in the southwest Indian Ocean by the end of the century (2066-2099) compared to that of the historical period 1981-2014 under ssp126, ssp245 and ssp585 scenarios. Letters indicate intensity categories: Tropical Depression (TD), Tropical Storm (TS), Tropical Cyclone (TC), Intense Tropical Cyclone (ITC), Very Intense Tropical Cyclone (VITC).

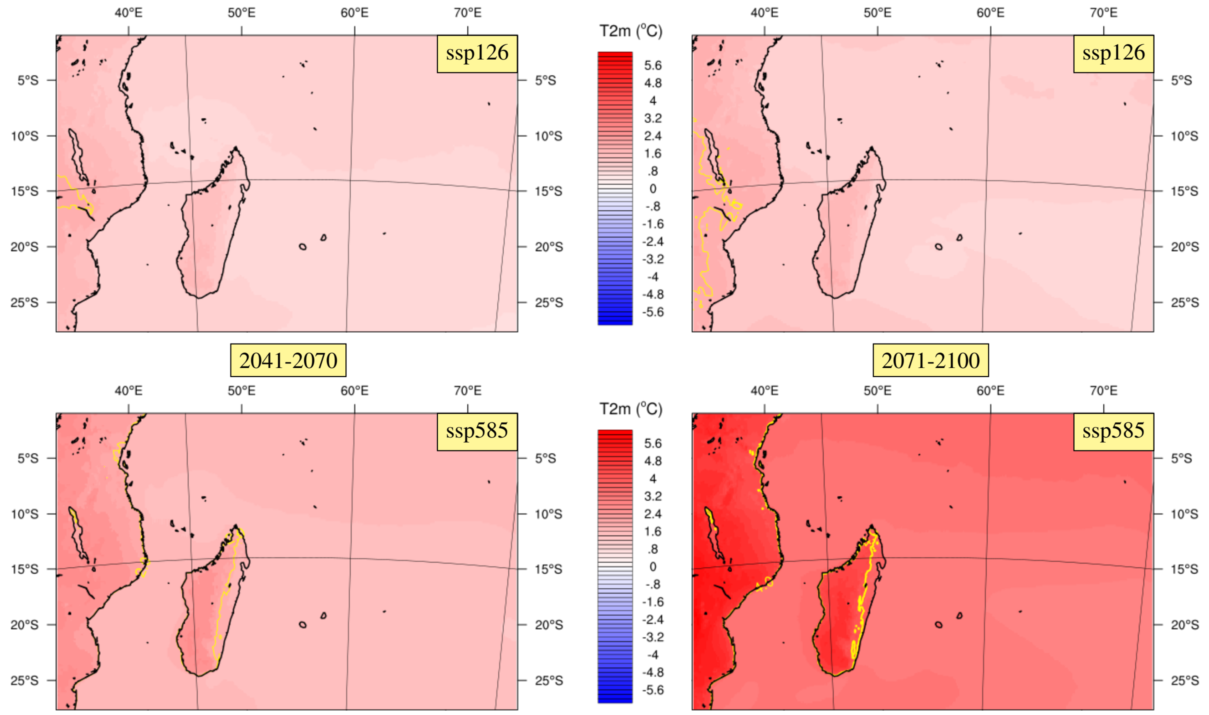

FIG. 4. Annual average differences relative to 1981-2010 of ALADIN63 mean 2-m air temperature (°C, shaded) over the southwest Indian ocean under the ssp126 and ssp585 scenarios and over two future periods (2041-2070 and 2071-2100). Yellow contours delineate $+4^{\circ}$C temperature anomalies.

4 km (Madagascar, Mauritius) to 6 km (Reunion) for gridded data. Station-scale bias correction was applied on the smallest islands (Seychelles, Comoros, Mayotte, Rodrigues, Agalega and St Brandon). An example is given in Figure 5 for Reunion island. It indicates that annual water deficits could rise up to 20% at the end of the century under the worst-case scenario (it will be illustrated in the next section that ALADIN63 has inherited from the rather dried signal of its driving model over the SWIO region).

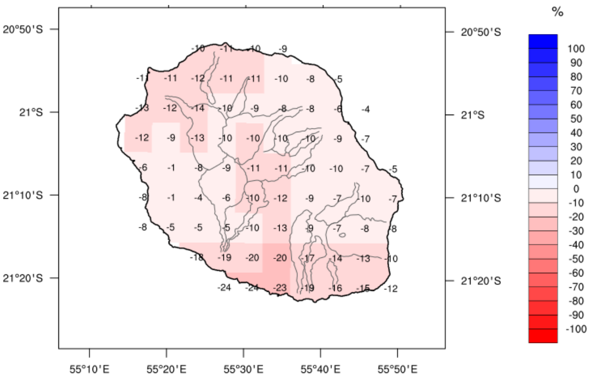

FIG. 5. Annual precipitation (%) anomalies over Reunion simulated by ALADIN63 over the 2071-2100 period under the ssp585 scenario. The percentage anomalies are computed against the average annual precipitation of the 1981 – 2010 reference period.

Note that bias correction is currently being computed at 3-km resolution over Reunion island for the precipitation, temperature, humidity, wind and solar radiation reference parameters in order to correct the model daily evapotranspiration (ETP) computed using the FAO-56 formula (Allan et al. 1998).

3. Climate uncertainty sampling

The precipitation and temperature variables from a pool of global climate models available from the CMIP6 archive (`https://esgf-node.llnl.gov/search/cmip6/`), including CNRM-ESM2-1, were examined over the SWIO region. An annual decrease in precipitation over the entire SWIO region is expected by most models under the ssp585 scenario (Fig. 6). An examination of the seasonal trends show that the January-February-March trimester will actually be wetter while the second semester of the year will be much drier than the reference period (not shown). This is due to more extreme events in the future such as tropical cyclones with increased intensity, floods and droughts (not shown) but also longer periods of droughts (illustrated in the next section for Reunion island).

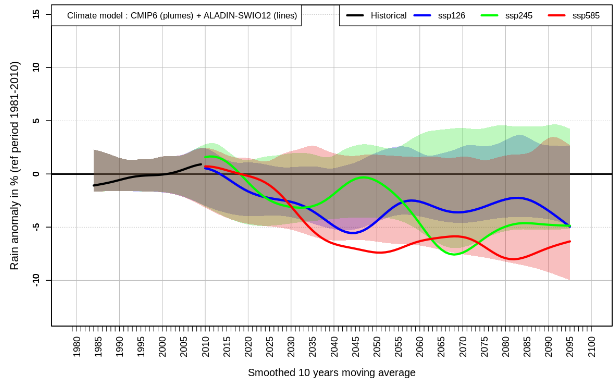

FIG. 6. Annual precipitation anomalies (%) between future and historical periods for eighteen of the CMIP6 models (colored plumes or envelopes) and for ALADIN63 (solid lines) under ssp126, ssp245 and ssp585 scenarios. The percentage anomalies are computed against the average annual precipitation of the 1981 – 2010 reference period. The eighteen CMIP6 models are named in Fig. 7.

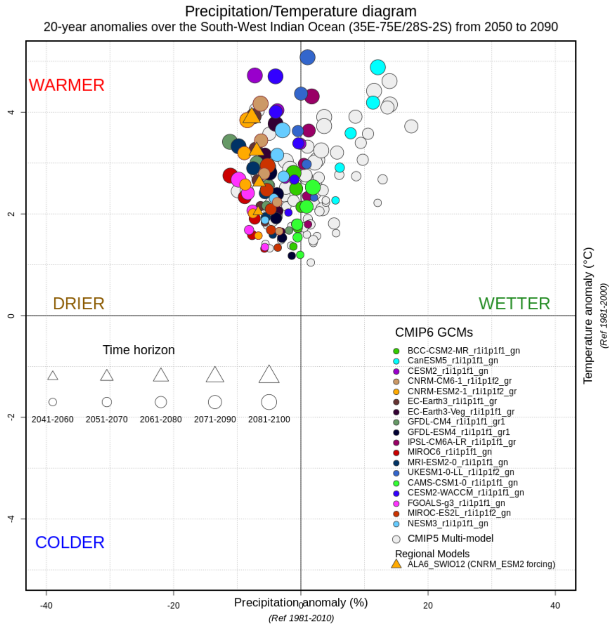

FIG. 7. The annual precipitation (x, %) and 2-m mean temperature (y, °C) 20-year anomalies over the SWIO region from 2050 to 2090 under the ssp585 scenario. The reference period is 1981 – 2010 for the precipitation and 1981 – 2000 for the temperature. Data are displayed for eighteen of the CMIP6 models (colored dots with CNRM-ESM2-1 in orange), for CMIP5 models (grey dots), and for the ALADIN63 regional model (orange triangles). Dots or triangles sizes increase with time horizon.

The precipitation-temperature diagram drawn for the same pool of CMIP6 models but also for the CMIP5 models shows that there seem to be a shift towards drier trends from CMIP6 to CMIP5 models over the SWIO region under the ssp585 scenario (Fig. 7). This diagram shall be completed as soon as all CMIP6 models are published. Fig. 7 also illustrates that the CNRM-ESM2-1 and ALADIN63 models fall within the lowest range of precipitation anomalies simulated over the region.

This diagram is also used to choose global climate models to drive other ALADIN63 simulations and complete the dynamical downscaling in order to better sample climate model uncertainty. The IPSL-CM6A-LR model (red-purple dots in Fig. 7) and UKESM1-0-LL model (grey-blue dots in Fig. 7) are good candidates as their precipitation and temperature trends vary from that of CNRM-ESM2-1. The two models predict a neutral precipitation anomaly trend over the SWIO region and the UKESM1-0-LL model predicts the highest temperature anomalies by the end of the century.

Statistical downscaling from CMIP6 simulations is under progress to provide further quantification of climate uncertainty over the IOC member countries where observational data is available (not shown). The downscaling method is being tested on Reunion island using ERA-Interim data.

4. Portal and climate services for end-users

The BRIO project aims at supporting the IOC member countries in the implementation of their adaptation policies with respect to climate change (regarding water resources, health and other issues). Many end-users are already using the BRIO data in impact models (agriculture, biodiversity, and health for mosquito-borne diseases such as dengue fever). The BRIO data shall be publicly available for download on the regional portal by the end of the 2021 year.

A number of climate indices were also derived over the main IOC islands, such as TX90p, the percentage of days when daily maximum temperature exceeds its 90^{th} percentile; WSDI, the warm spell duration index; DTR, the daily temperature range (monthly mean difference between TX and TN); DEXHT, the number of days of extreme heat where both daily minimum temperature and daily maximum temperature exceed their respective 97.5^{th} percentile; Rnnmm, the annual count of days when the precipitation exceeds nnmm with various nn thresholds ranging from 10 to 100 mm; Rnnp, the annual count of days when the precipitation exceeds the nn^{th} percentile with various nn thresholds ranging from 75 to 99; RnnpTOT, the annual total precipitation when daily precipitation is greater than the nn^{th} percentile; CDD, the maximum length of dry spell (Fig. 8); Rx1day, the monthly maximum 1-day precipitation; Rx5day, the monthly maximum 5-day precipitation, among others. According to Figure 8, the length of droughts over Reunion island should increase in the future, especially under the ssp585 scenario for which the maximum decrease in annual total precipitation should occur (Fig. 5).

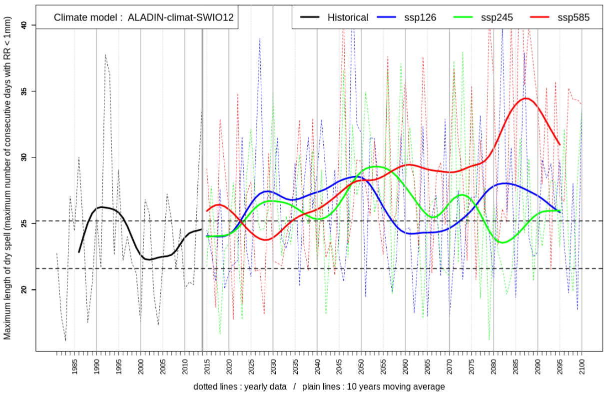

FIG. 8. Evolution of the maximum length of dry spell (i.e. the annual maximum number of consecutive days with daily precipitation lower than 1 mm) derived from ALADIN63 outputs over Reunion island from 1981 to 2100 under ssp126, ssp245 and ssp585 scenarios. Dotted lines are yearly data, solid lines are 10-year moving averages.

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