Projecting Changes in Tanzania Rainfall for the 21st century: Scenarios, Downscaling and Analysis

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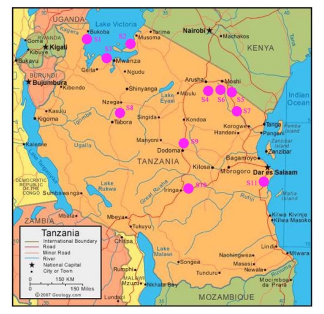
1. SUMMARY

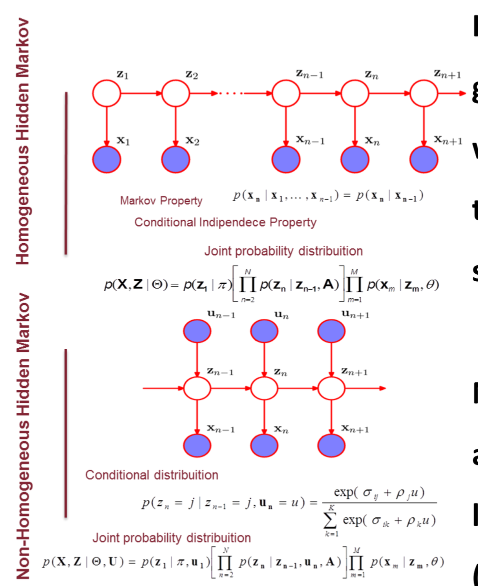
A Non-Homogeneous hidden Markov Model (NHMM) is developed using a 40-years record (1950-1990) of daily rainfall at eleven stations in Tanzania and re-analysis atmospheric fields of Temperature (T) at 1000 hPa, Geo Potential Height (GPH) at 1000 hPa, Meridional Winds (MW) and Zonal Winds (ZW) at 850 hPa, and Zonal Winds at the Equator(ZWE) from 10 to 1000 hPa. The NHMM is then used to predict future rainfall patterns under a global warming scenario (RCP8.5), using predictors from the CMCC-CMS simulations from 1950-2100. The model directly considers seasonality through changes in the driving variables thus addressing the question of how future changes in seasonality of precipitation can be modeled. The future downscaled simulations from NHMM, with predictors derived from the simulations of the CMCC-CMS CGM, in the worst conditions of global warming as simulated by RCP8.5 scenario, indicate that, Tanzania may be subjected to to a reduction of total annual rainfall; this reduction is concentrated in the wet seasons, OND, mainly as a consequence of decreasing of seasonal number of wet days. . Frequency and Intensity of extreme events don't show any evident trend during the 21 century.

2. DATA & METHODS

Type;	Daily Rainfall Spells
N. of Stations;	11
Time Period;	from 1950 to 1990
Dataset;	KNMI Climate Explorer



	ON MAP	CODE/NAME	LATITUDE	LONGITUDE
1	S1	TZ000063729 BUKOBA	-1.33N	31.82E
2	S2	TZ000063733 MUSOMA	-1.50N	33.80E
3	S3	TZ000063756 MWANZA	-2.47N	32.92E
4	S4	TZ000063789 ARUSHA	-3.33N	36.63E
5	S5	TZ000063790 MOSHI	-3.35N	37.33E
6	S6	TZ000063791 KILIMANJARO_AIRPORT	-3.42N	37.07E
7	S7	TZ000063816 SAME	-4.08N	37.72E
8	S8	TZ000063832 TABORA_AIRPORT	-5.08N	32.83E
9	S9	TZ000063862 DODOMA	-6.17N	35.77E
10	S10	TZ000063887 IRINGA	-7.63N	35.77E
11	S11	TZ000063894 DAR_ES_SALAAM_AIRPC	-6.87N	39.20E



$$p(\mathbf{x}_n \mid \mathbf{x}_1,\ldots,\mathbf{x}_{n-1}) = p(\mathbf{x}_n \mid \mathbf{x}_{n-1})$$

$$p(\mathbf{X},\mathbf{Z}\mid\Theta) = p(\mathbf{z}_1\mid\pi)\left[\prod_{n=2}^{N} p(\mathbf{z}_n\mid\mathbf{z}_{n-1},\mathbf{A})\right]\prod_{m=1}^{M} p(\mathbf{x}_m\mid\mathbf{z}_m,\theta)$$

$$p(z_n = j \mid z_{n-1} = j, \mathbf{u}_n = u) = \frac{\exp(\sigma_{ij} + \rho_j u)}{\sum_{k=1}^{K}\exp(\sigma_{ik} + \rho_k u)}$$

$$p(\mathbf{X},\mathbf{Z}\mid\Theta,\mathbf{U}) = p(\mathbf{z}_1\mid\pi,\mathbf{u}_1)\left[\prod_{n=2}^{N} p(\mathbf{z}_n\mid\mathbf{z}_{n-1},\mathbf{u}_n,\mathbf{A})\right]\prod_{m=1}^{M} p(\mathbf{x}_m\mid\mathbf{z}_m,\theta)$$

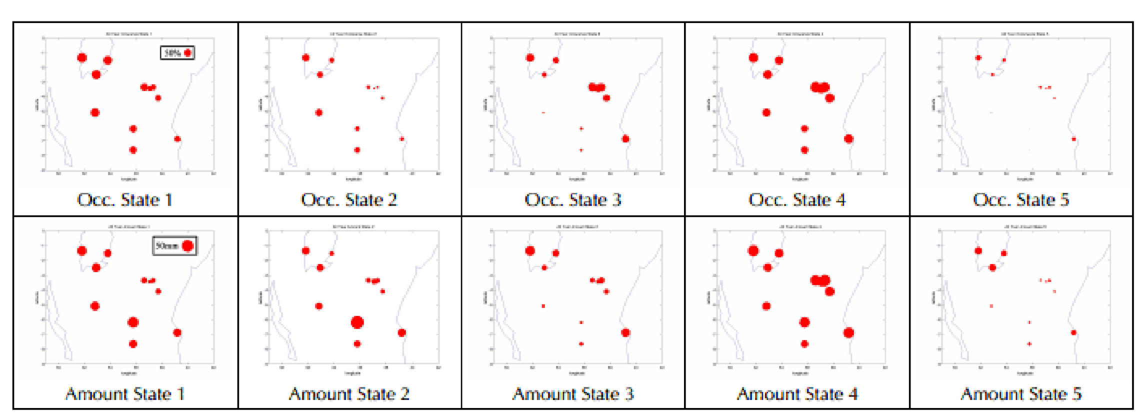
HMM = Rainfall occurrence and amount is governed by a few discrete hidden states, with Markovian daily transitions between them (Hughes and Guttorp, 1994 , Robertson et al., 2004,2006).

NHMM: HMM transition probabilities are allowed to vary with time, as a function of large scale atmospheric variables. (Abedalrazq et al. 2010, Kwon et al. 2009)

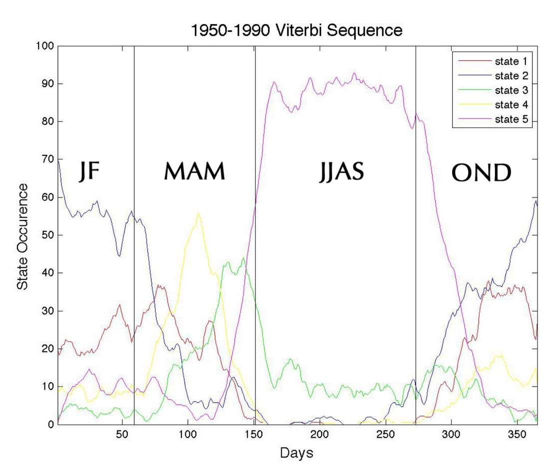
3. HIDDEN STATES OF DAILY RAINFALL OCCURRENCE AND AMOUNT

1. HMM is used to identify a number of hidden states of daily rainfall occurrence using observations of the 11 stations previously described in paragraph 2, for 1950 to 1990
2. NHMM is applied to relate hidden states to daily large scale predictors extracted from the NCAR-NCEP reanalysis dataset. Calibration (1950-1980) and validation (1981-1990) tests are carried out in order to select the best combinations of predictors and to construct a reliable predictive tool able to link the statistics of local daily rainfalls in Tanzania to large-scale atmospheric patterns.

In global warming scenarios, seasonal shifts due to large scale atmospheric circulation changes have to be considered. The NHMM is consequently applied to the daily data for the full year without seasonality assumptions. "Seasonality" is identified by the variables that determine the atmospheric circulation patterns and their rainfall implications.



Occurrence and the mean amounts of daily rainfall for each of the 5 hidden states identified by HMM



Seasonality of the daily frequency of the hidden states (averaged over 1950-1990)

State 1 : *wet homogeneous*. Dominant in the current Winter / early Spring, from November to April. Disappears currently from June to September.

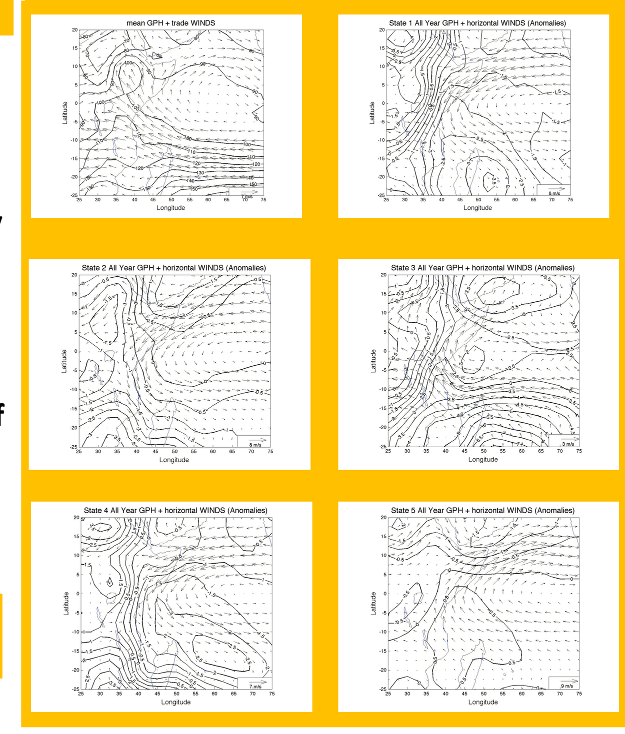
State 2 : *wet inhomogeneous*; occurrence probabilities are generally very low for all the stations, but occurrence is higher for the stations far from the coast. This state significantly persists in winter and completely disappears from June to September.

State 3 : *wet inhomogeneous*. It has a higher rainfall occurrence for the stations close to the coast. It is absent in the current Winter and its occurrence probability peaks in May. It is the only wet state occurring in the dry season from June to September.

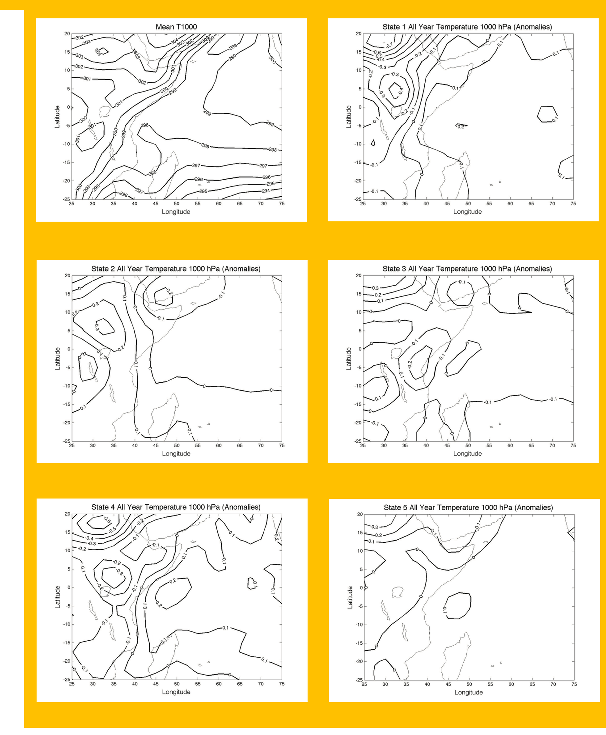
State 4 : *Very wet homogeneous* . Its occurence probability reaches a maximum (up to 50%) in April, disappears from June to September and it has a minor intense peak in November.

State 5 : *very dry homogeneous*. It is representative of the of dry season in Tanzania: from June to September is the dominant state

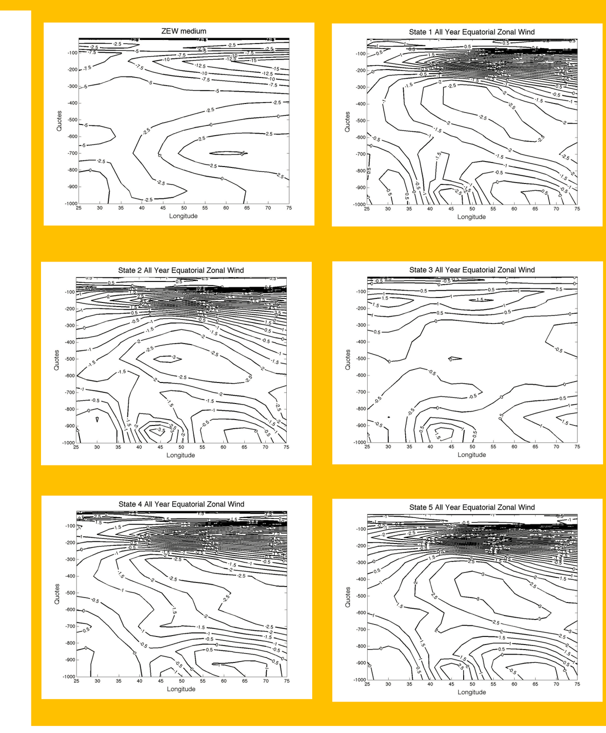
4. HIDDEN STATES PHYSICAL INTERPRETATION & SELECTION OF PREDICTORS



GEO-POTENTIAL HEIGHT at 1000 hPa and Vector WIND at 850 hPa (Reanalysis data from IRI Library – NOAA-NCAR)



TEMPERATURE at 1000 hPa (Reanalysis data from IRI Library – NOAA-NCAR)



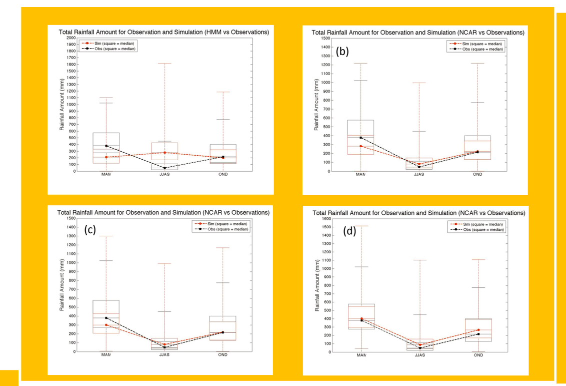
ZONAL WINDS from 10 to 1000 hPa captured at 27N Latitude (Reanalysis data from IRI Library –NOAA-NCAR)

Steps

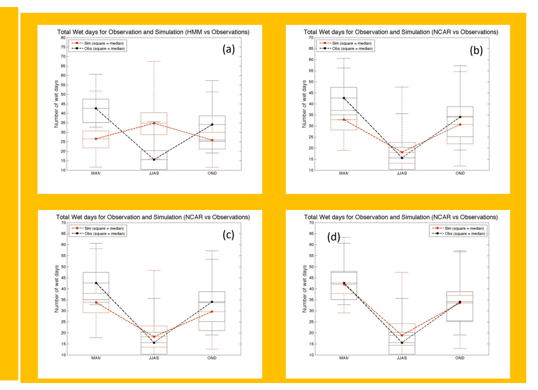
- Predictor domain for atmospheric variables: latitude (25S to 25N) and longitude (25E to 75N).
- Predictors considered: Temperature (T) at 1000 hPa, Geo Potential Height (GPH) at 1000 hPa, Meridional Winds (MW) and Zonal Winds (ZW) at 850 hPa, and Zonal Winds along the equator (ZWE) from 10 to 1000 hPa.
- Calculation of the averaged composite of each variables, from the daily fields corresponding to a particular state of the HMM "Viterbi" sequence. These fields were obtained from NCEP/NCAR Reanalysis data (http://iridl.ldeo.columbia.edu/).
- Comparative analysis of the composite fields for each hidden state for meaningful physical interpretation.
- Dimension reduction for each field using Principal Component Analysis (PCA).

5. HMM & NHMM VALIDATION

Data refer to the average value on all the stations, (a) HMM; (b) NHMM with PCAs from geo-potential height composite fields; (c) NHMM with PCAs from geo-potential height and temperature composite fields; (d) NHMM with PCAs from composite fields of geo-potential height, temperature and zonal and meridional winds (validation period 1981-1990)

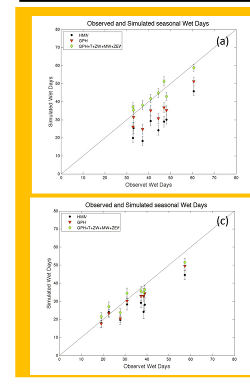


Total Seasonal Rainfall Amount

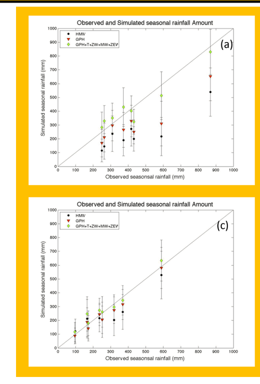


Total Seasonal Wet Days

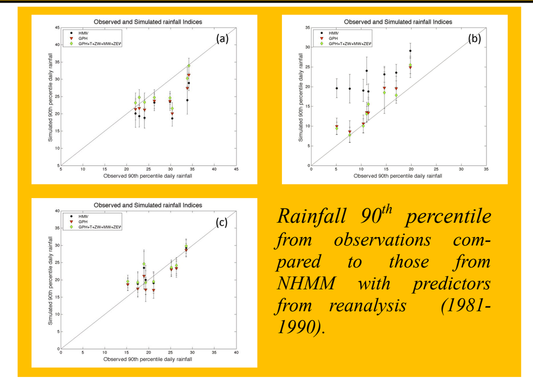
Data refer to single stations, (a) MAM; (b) JJAS; (c) OND



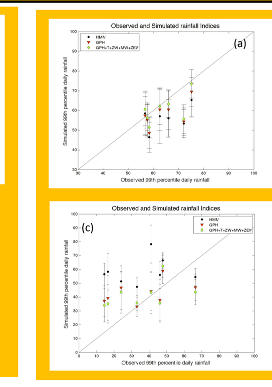
Seasonal Wet Days from observations compared to those from NHMM with predictors from reanalysis (1981 -1990)



Seasonal Total Amount from observations compared to those from NHMM with predictors from reanalysis (1981-1990).



Rainfall 90th percentile from observations compared to those from NHMM with predictors from reanalysis (1981-1990).



Rainfall 99th percentile from observations compared to those from NHMM with predictors from reanalysis (1981-1990).

The calibration (1950-1980) and validation (1981-1990) tests, for different predictor combinations, reveal the effectiveness of the NHMM for the conditional simulation of the rainfall occurrence and amount statistics including the extreme values

6. PROJECTING CHANGES IN TANZANIA RAINFALL FOR THE 21ST CENTURY

In order to use NHMM to predict future rainfall patterns for Tanzania using 21st century global warming scenarios we apply:

1. a selection criteria to choose between different GCMs from CMIP5 (Coupled Model Inter-comparison Project Phase 5). (Karl et al, 2009).

   Criteria: comparison of basic statistics (seasonal mean, variance, skew, variance and serial correlation) and the spatial pattern for the PCs from the two candidate GCMs for each variable in the NHMM developed with re-analysis atmospheric fields;
2. Variance correction of the PC's for the best GCM to match the scales of the corresponding PC's for the observations.

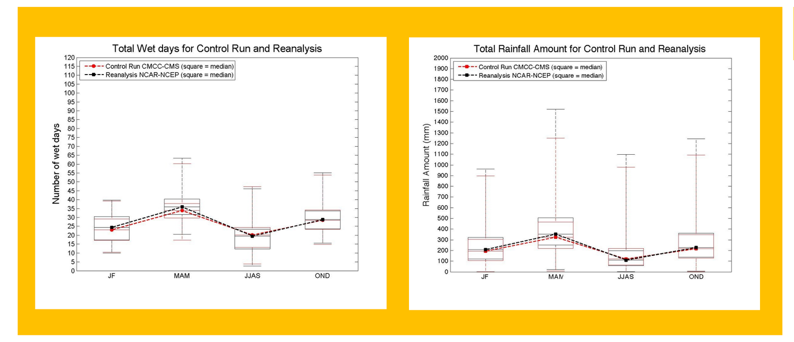
Variance correction of the best GCM's predictors

The CMCC-CMS model best matches the main features - temporal trend and the spatial pattern- of the main meteorological variables which have been used in the NHMM application.

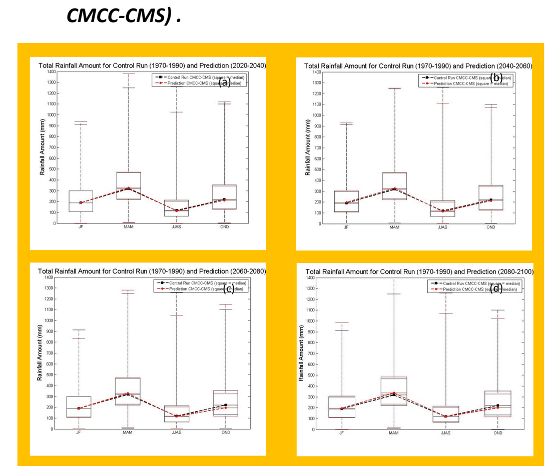
Let PC_{jt}^{M20} represent the time series of the j[th] predictor considered for the NHMM, and PC_{jt}^{O20} represent the corresponding time series for the observations, over the 20th century control run of CMCC-CMS.

Then the 21st century corrected predictor for the NHMM is:

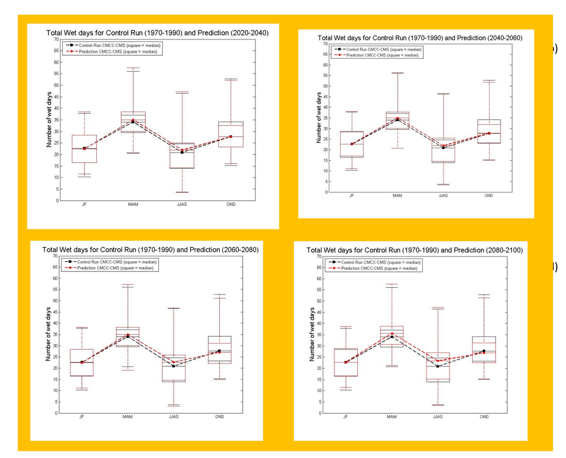
$$PC_{jt}^{M1'} = PC_{jt}^{M21} * s(PC_{jt}^{O20}) / s(PC_{jt}^{M20})$$



Comparison , for 1950-1990, between the Seasonal Total Rain Amount and Wet days as obtained by using predictors from Reanalysis (NCAR-NCEP) and from Control Historical Run (CMCC-CMS) .

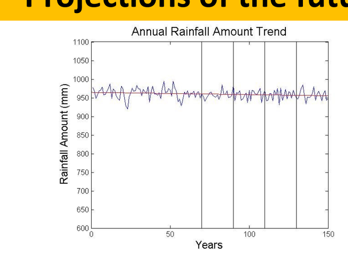


Comparison between the Total Seasonal Rainfall Amount for the period (1970-1990) and for the different twenties(2020-2040),(2040-2060),(2060-2080),(2080-2100).

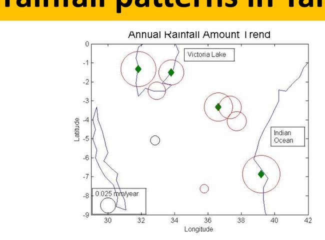


Comparison between the Seasonal Wet Days for the period (1986-2006) and for the different twenties(2020-2040),(2040-2060),(2060-2080),(2080-2100).

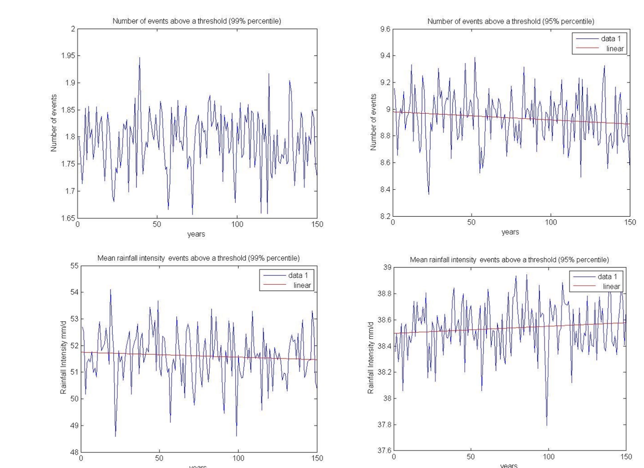
Projections of the future rainfall patterns in Tanzania under global warming scenario RCP8.5 as simulated by CMCC-CMS CGM



Annual Rainfall Amount Trend for the ensemble of stations



Annual Rainfall Amount Trend for each station: black circle = positive; red circle = negative; diamond = significant trend at 5%



Number and intensity of extreme events above a threshold (99th and 95 percentile)

No significant trends can be detected for extremes of precipitations

Diagnosis

The Inter-tropical Convergence Zone (ITCZ), together with Indian Ocean Dipole (IDO) have been identified as the most important circulation factors affecting the Tanzania hydro-climate. Rainfall seasonality is tied to the movement of the Inter-tropical Convergence Zone (ITCZ) which moves north and south during the year. (Chris Jack, 2008). The IOD contributes to the movement of moisture along the Indian ocean (precisely from-and-to the Arabian sea and the eastern Indian Ocean south of Indonesia). (N. H. Saji, 1999). This variation in IOD, coupled with ITCZ movement, cause different winds circulation patterns. In fact, when the western Indian Ocean sea surface temperature is warmer than the east one, the easterly wind anomalies across the Indian Ocean are strongly directed against east Africa with all moisture associated more rain in East Africa, less rain over Southern Australia), while cooler temperatures in the Western Indian Ocean relative to the East are related to westerly winds (more rain in Southern Australia, less rain over East Africa).(Caroline C. Ummenhofer, 2008).

Results

The averaged composite fields associated with each hidden state from HMM capture the main seasonal characteristics of large scale climatology affecting Tanzania. The role of seasonal movement of ITCZ and IOD is highlighted.

Under the RCP8.5 scenario , the NHMM downscaled future projections for Tanzania show :

(1) An slight increase in the number of wet days and total rainfall in MAM and JJAS, except OND; globally a reduction of annual total rainfall amount;

(2) The frequency and intensity of extreme rainfall events don't show significant trends

References

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