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Detection and forecast of the rainy seasons, application over Analamanga (-18S: -20S and 46E:48E)

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Abstract

Changes like decrease of the rainfall amount or late rainy seasons are observed over Madagascar nowadays due to the climate changes. To tackle the negative impacts of climate changes, this paper aims to detect rainy seasons period (onset dates and offset dates) in order to forecast rainy season and set calendar. Climate variables, from 1979 to 2021, such as the daily precipitations, the temperatures, the Dipole Index Mode and the Oceanic Niño Indexes) were used. The detection of the rainy seasons was done by the mean of the accumulation of the anomalies of the daily mean of the precipitations. Modelling and forecasting stages were made by using Fuzzy Logic with triangular membership functions. The skill scores were the Root Mean Squared Error (RMSE), the Mean Absolute Error (MAE), the RMSE and MAE scaled by the standard deviation and the average of the onset and demise dates of the rainy seasons. Findings show that the investigated region was subdivided into two regions: A, where the climatological wet spell starts between 25th October and 12th November, and B, where the climatological wet spell starts between November 16 and 20. The best forecasting models were observed with values of RMSE (MAE) between 0.52 and 0.80 (0.04 and 0.36). Moreover, scaled by the standard deviation (average), these skill scores are less than 1 (have values between 0.05% and 7.30%).

Keywords

Analamanga, Rainy seasons, Onset dates, Cessation dates, Forecasting, Modelling, Fuzzy Logic

1. Introduction

Whether in winter [1] or throughout the year, the crop yield relies on the precipitation. However, the climate change influences the wet spell, the rainfall frequencies and the amount of rain-day [2]. Moreover, [3] cited the developing countries as vulnerable to climate change. Not only does climate change has impacts on socio-economic and health [4] but it also generates negative impacts on agriculture and the crop yields [5, 6, 7, 8]. Changes regarding the wet spells and the amount of precipitations were projected over Madagascar [9]. Furthermore, decrease (increase) in annual rainfall are observed over the eastern(southern) part of the island [10, 11].

The knowledge of the onset dates and withdrawal dates of the rainy seasons play a significant role in developing countries where the economy relies on farming and breeding. According to [12] and [13], farming and agricultural sector of Madagascar use more than 70 % of the labor force and represent about 30 % of the Gross Domestic Products of the country. Previous works on precipitations and the rainy seasons over Madagascar were done. [14] and [15] tried to forecast the precipitations regarding the temperatures and the wind speed. [16] concluded that the wind at the 700hPa and 850hPa air pressure levels behave like the precipitation of the austral summers of Madagascar. [17] found that the Indian Ocean Dipole and the El Niño phenomena have links with the rainfall of the Indian Monsoon over the South-East part of Africa. [18] demonstrated that the rainfall over Madagascar is connected to the sea surface temperature of the Indian Ocean. According to [19] and [20], the phenomenon ENSO has an impact on the precipitations of Madagascar. Moreover, the same phenomenon plays a role on the length of the rainy seasons of the Island [21]. However, the climate change has effects on these climatic variables, this leads to the huge variations and changes of the behaviours of the rainy seasons and the precipitations. [22] and [23] exacerbated a significant variability over the Indian Ocean. Furthermore, the climate change plays a role on the delay of the rainy seasons and the persistence of the dry spells over some parts of Madagascar [24]. These situations make the detection of the rainy seasons period difficult. Different forecasting models were developed to better fit these changes. [25] used the Auto-Regressive Integrated Moving Average (ARIMA), [14] and [15] used Fuzzy Logic for forecasting the precipitation, and even [16] and [26] modelled and forecasted the rainy seasons by the mean of Holt-Winters exponential smoothing. To face changes and to tackle the impacts due to these negative effects of climate changes, this work aims to model in order to forecast the rainy seasons and make projection closer to the reality by the mean of Fuzzy Inference System.

2. Materials and Methods

Limited by the longitudes 46°E and 48°E and the latitudes -18°S and -16°S (Figure 1), the zone of interest is observed over the central part of Madagascar: Analamanga. Climatic variables, from 1979 to 2021, such as daily precipitations from Climate Hazards Group Infrared Precipitation with Station data (CHIRPS) [27], temperatures from European Centre For Medium Range weather forecast (ECMWF) [28], Oceanic Niño Index and the Dipole Index Mode from National Oceanic and Atmospheric Administration (NOAA) denoted respectively hereinafter ONI [29], DIM, WDIM and EDIM [30] were used with Matlab.

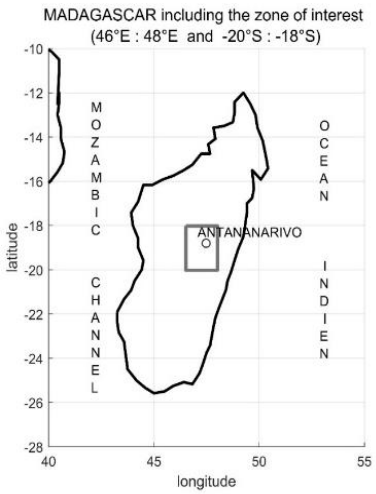

Figure 1:The zone of interest

Different definitions of the onset and the withdrawal dates of the rainy season [31, 32, 33] were used to detect wet spell throughout a year. In this paper, the onset and the cessation dates of the rainy seasons from 1981 to 2021 and the climatological wet period over all grid points were identified by applying the definitions of [34, 35, 36]. The zone of interest was divided into two regions: A and B regarding its climatological onset dates. Four serial data corresponding, each, to the spatial average: data corresponding to the onset and cessation dates over A and B denoted hereinafter OA, OB, CA and CB respectively were created. The correlation between OA, OB, CA and CB and the climatological variables such as the temperatures, the DIM and the ONI was analysed by the mean of the Pearson's correlation coefficient in order to define some predictors of the rainy seasons. 95% significant correlation coefficients were kept. Different predictors were defined regarding their own Pearson's correlation coefficients (Table 1). The value between brackets with a negative sign represents

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the number of years which precedes the actual rainy season. So, 0 represents the same year as the year of the rainy season.

Table 1: Pearson's correlation coefficients 'r' corresponding to the different predictors

Predictors	OA		OB	
	month (year)	r	month (year)	r
ONI	April (-2)	0.34	May (-2)	0.36
	May (-2)	0.36	June (-2)	0.31
DIM	February (-3)	0.31	February (-3)	0.38
WDIM			July (-3)	0.38
EDIM	January (-3)	0.38		
	February (-3)	0.38		
	March (-3)	0.38		
Temperatures	Minimal temperature (0)	-0.33	Maximal Temperature (0)	-0.34
in September	Average Temperature (0)	-0.32		
	CA		CB	
DIM	February (-3)	0.31	January (-5)	0.32
			February (-4)	0.32
			February (-3)	0.38
EDIM	May (-5)	0.38	January (-5)	0.32
	January (-3)	0.38	July (-3)	0.38
	February (-3)	0.38		
	March (-3)	0.38		
WDIM			May (-5)	0.33
			December (-5)	0.36

The model, the validation and the forecast of the onset and cessation dates were realised by the mean of Fuzzy Logic (FL). Some definitions and explanation regarding Fuzzy Logic were described by [37]. On one hand, [15, 14, 38] defined linguistic variables for forecasting the precipitations through other climatic variables. On the other hand, [39,40] applied the definition of the agronomic onset date over West Africa on the Fuzzy membership function in order to detect and forecast the onset dates of the agronomic wet spells. In this work, none clustering to create linguistic variables was done. Each observation of the variable possesses its own equation (Equation 1) related to a triangular membership function (Figure 2).

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$$\mu(x_a) = \begin{cases} 0 & if\ x_a \leq m-k\ et\ x_a \geq m+k \\ \frac{x_a-(m-k)}{m-(m-k)} & if\ m-k \leq x_a \leq m \\ \frac{(m+k)-x_a}{(m+k)-m} & if\ m \leq x_a \leq m+k \end{cases} \quad (1)$$

where 'x_a' is the observed data in year 'a'; 'm' is the value of the observation, 2k is the base of the triangle (*Figure 2*), and $\mu(x_a)$ is the membership degree corresponding to the variables.

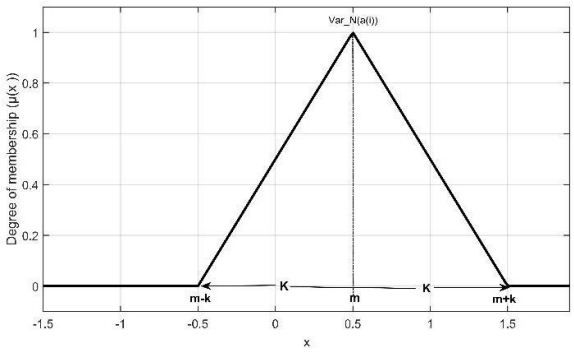

Figure 2: A representation of a triangular membership function

As can be seen in Figure 2, the maximum membership degree is reached with the value of the observed variable denoted 'm'.

33(31) equations corresponding to the 33(31) years related to the training were developed. 33 and 31 samples of triangular membership functions corresponding to some climatic variables were represented graphically in Figure 3. As a result, 33 and 31 rules were created according to the rule base if ... and ... then (Equation 2):

if (var1(a_i)) **and** (var2(a_i)) **and** (var3(a_i)) **and** … (varN(a_i)) **then** (Var_output(a_i)) (2)

a_i is the year at rank i which ranges from 1 to 33 or 31.

var1, var2,...,varN are the predictors and Var_output correspond to OA, OB, CA and CB.

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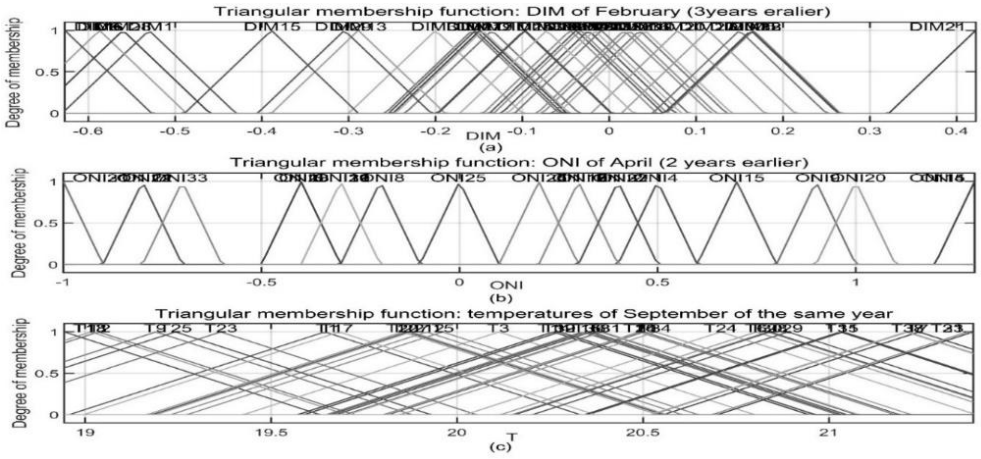

Figure 3: Examples of triangular membership functions related to: Dipole Index Mode (a) ; Oceanic Niño Index (b) and temperatures (c)

Different ranges of the parameter 'k' were used according to the input and output variables, Table 2, in order to find the best forecasting models. The maximum value of 'k' refers to the standard deviation of the serial data of the predictors. Regarding the outputs: OA, OB, CA and CB, the value of the parameter 'k' is one week.

Table 2:Different ranges of the parameter ‘k’ related to the predictors and the outputs

k	Predictors	Output
0.01 to 0.3 with a step equal to 0.05 (0.01:0.05:0.3)	ONI	OA and OB
0.01 to 0.1 with a step equal to 0.01 (0.01:0.01:0.1)	DIM	OA and OB
0.1 to 0.8 with a step equal to 0.1 (0.1:0.1:0.8)	Temperatures	OA and OB
0.01 to 0.3 with a step equal to 0.02 (0.01:0.02:0.3)	DIM	CA and CB

The best training models were chosen with the values of 'k' which correspond to the minima values of the Root Mean Squared Error (RMSE). Different values of the RMSE related to the different values of the parameter 'k' are shown in Figure 4. The solid(dashed) lines depicts the RMSE related to the validation(model) regarding different values of ‘k’.

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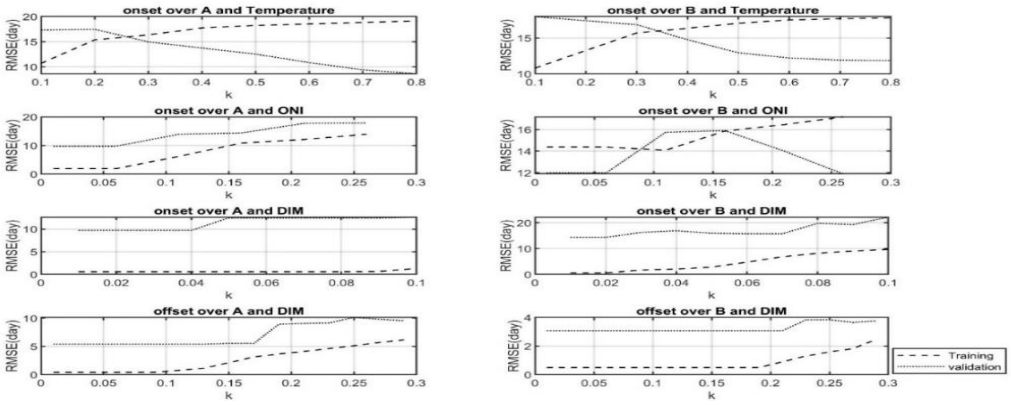

Figure 4: Different values of RMSE related to different values of 'k' corresponding to the training (---) and the validation (…) of the onset and cessation dates of the rainy seasons over A and B

80% of the serial data were kept for training and 20% were set aside for the validation and testing the model. Consequently, over 41 years (1981-2021) and over 38 years (1981-2018), 33 years and 31 years were kept for training respectively.

Different skill scores: RMSE, Mean Absolute Error (MAE), RMSE and MAEE scaled by the standard deviation denoted hereinafter rRMSE and rMAE, RMSE and MAE scaled by the average denoted hereinafter nRMSE and nMAE were used in order to verify the accuracy of the forecasting models. rRMSE and rMAE can show if the error is less than the climatological standard deviation. nRMSE and nMAE measure, in percent, the relative amount between the error and the climatological average. The less value of nRMSE and nMAE we observe, according to [41], with a certain percentage, the better the forecasted data are.

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3. Results

The fluctuation of the onset and cessation dates of the rainy seasons from 1981 to 2021 over the regions A and B are shown in Figure 5.

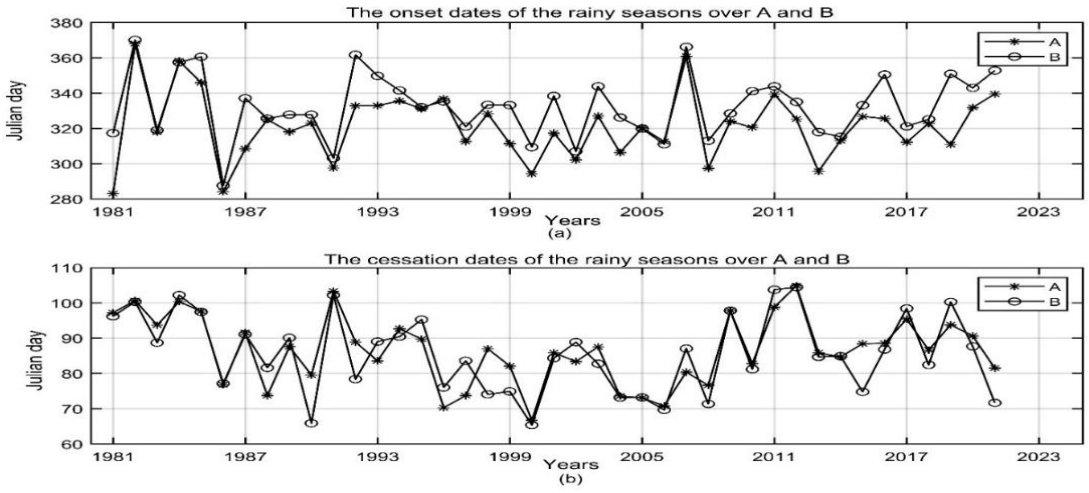

Figure 5:Evolution of the onset (a) and cessation (b) dates of the rainy seasons over both regions A and B from 1981 to 2021)

Figure 5 depicts the onset-dates of rainy seasons, over the region A and the region B, which fluctuate between the 280th day and 15th days of the next year. Over A(B), the minimum was registered in 1981(1986). The maximum was observed in 1982 for both regions. The cessation dates of the rainy seasons fluctuate between the 63th and 106th day of the calendar year from 1981 to 2021 over both regions. The minimum (maximum) was registered in 2000(2012) over the region A. The minimum (maximum) was detected in 2000(2011) over the region B. The climatological onset and cessation dates of the rainy seasons over all the grid points within the zone of interest were presented in Figure 6 and Figure 7 respectively in the form of a map.

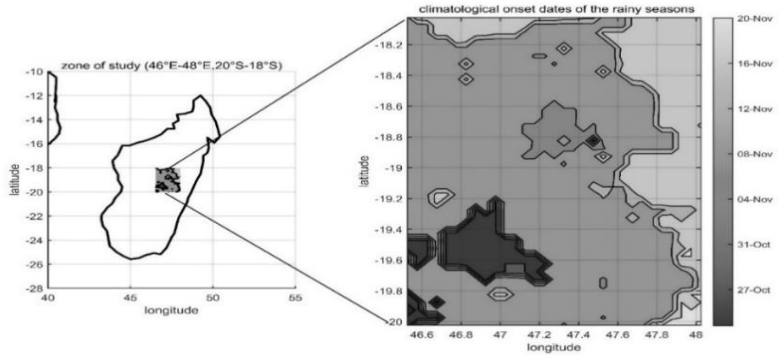

Figure 6: Spatial distribution of the climatological onset dates of the rainy seasons from 1981 to 2021 over the zone of interest

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As can be seen in Figure 6, significant part of the zone of interest possesses climatological rainy seasons which starts between 25th October and 15th November, denoted region A. The Eastern and the Northern part possess climatological rainy seasons which start between 16th and 20th November, denoted region B.

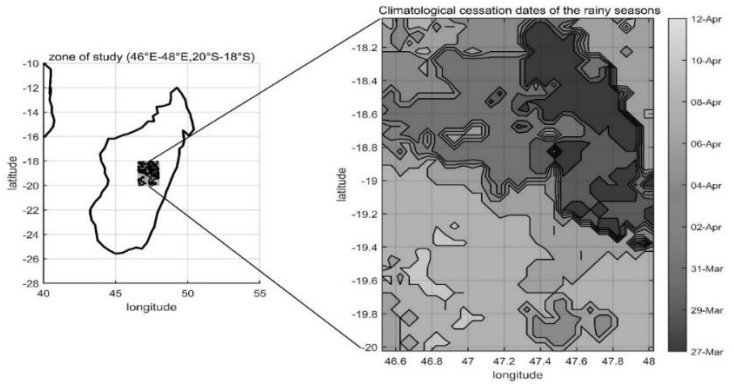

Figure 7: Spatial distribution of the climatological cessation dates of the rainy seasons from 1981 to 2021 over the zone of interest

Figure 7 shows the spatial variation of the climatological cessation dates over all the grid points. The North-Eastern, the Southern and the South-Western parts possess climatological rainy seasons which end between 8th and 12th April. The Eastern and North-Eastern part possess climatological rainy seasons which end between 27th March and 4th April. Modelling and forecasting of the onset and cessation dates of the rainy seasons over both regions are shown in Figure 8, Figure 9 and Figure 10.

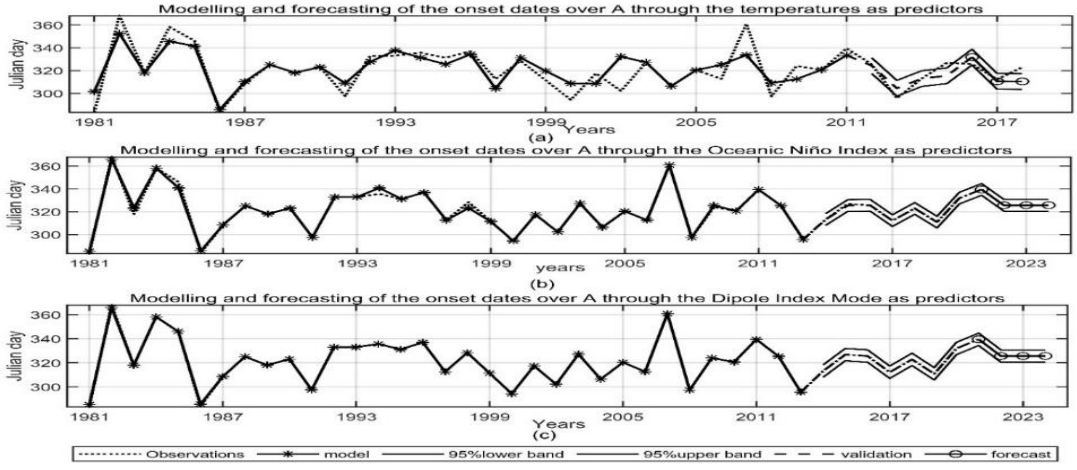

Figure 8: Modelling and forecasting of the onset dates of the rainy seasons with three predictors: the temperatures (a); the Oceanic Niño Index (b) and the Dipole Mode Index (c) over A

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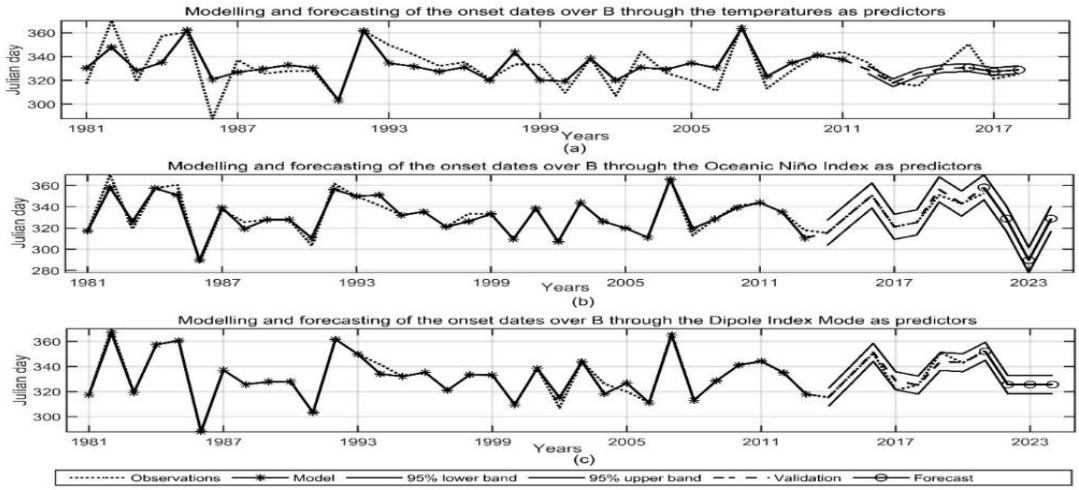

Figure 9: Modelling and forecasting of the onset dates of the rainy seasons with three predictors: the temperatures (a); the Oceanic Niño Index (b) and the Dipole Mode Index (c) over B.

Figure 8 and Figure 9 show that, with temperatures as predictors(a), the curves of the predicted variables do not overlap very well the curve of the actual data. However, with ONI (b) and DIM (c) as predictors, the curves of the predicted variables overlap the curves of the observed variables. Regarding the cessation dates, Figure 10 the forecasted dates overlap the observed dates.

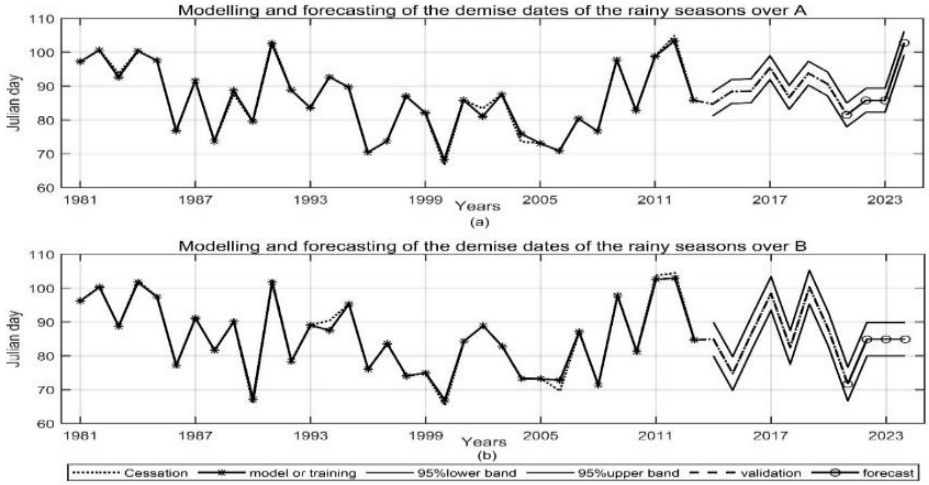

Figure 10: Modelling and forecasting of the cessation dates of the rainy seasons with the predictors: the Dipole Mode Index over A (a) and B (b)

Different skill scores values of the forecasting models of the onset and cessation dates related to the different predictors are given in Table 3.

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Table 3: Different values of RMSE, rRMSE, nRMSE, MAE, rMAE and nMAE as forecast accuracy measure (skill score)

Onset over A				*Onset over B*		
predictors	RMSE	rRMSE	nRMSE(%)	RMSE	rRMSE	nRMSE(%)
T	13.78	0.73	4.29	8.14	0.45	2.45
ONI	1.73	0.09	0.54	4.18	0.23	1.26
DIM	0.52	0.03	0.16	0.57	0.03	0.17
	Cessation over A			cessation over B		
DIM	0.76	0.08	0.87	0.80	0.07	0.94
	Onset over A			Onset over B		
	MAE	rMAE	nMAE	MAE	rMAE	nMAE
T	13.74	0.73	7.30	2.20	0.40	4.27
ONI	0.72	0.04	2.33	0.70	0.13	0.22
DIM	0.14	0.01	0.12	0.04	0.01	0.05
	Cessation over A			cessation over B		
DIM	0.33	0.03	0.31	0.36	0.03	0.39

The forecasting model of OA(OB) linked to the temperatures, *Table 3*, possesses a value of RMSE being 13.78 days (8.14 days) and a value of MAE being 13.74 days (2.20 days). The minima values of RMSE and MAE correspond to the forecasting models linked to DIM over both regions. Furthermore, the values of rRMSE and rMAE are less than 1. The calendar of the rainy seasons is set in Table 4.

Table 4: Forecast of the onset dates and the demise dates of the rainy seasons over the region A and the region B, with each, their error in days

	region A	*region B*
Predictors	Onset dates	
Temperatures	06/11/2017(±7)	23/11/2017(±3)
	06/11/2018(±7)	25/11/2018(±3)
ONI	22/11/2022(±5)	25/11/2022(±12)
	22/11/2023(±5)	17/10/2023(±12)
	23/11/2024(±5)	26/11/2024(±12)
DIM	22/11/2022(±5)	22/11/2022(±7)

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	22/11/2023(±5)	22/11/2023(±7)
	23/11/2024(±5)	23/11/2024(±7)
	Demise dates	
DIM	27/03/2022(±4)	26/03/2022(±5)
	27/03/2023(±4)	26/03/2023(±5)
	14/04/2024(±4)	27/03/2024(±5)

With ONI and DIM as predictors, the rainy seasons over A(B) is supposed to start on 22nd (25th) November in 2022 and 2023 (17th October 2023) and on 23rd (26th) November 2024. and supposed to end on 27th(26th) March in 2022 and 2023 and on 14th April (27th March) 2024.

4. Discussion

From Figure 5, earlier onset over A(B) was observed on 9th(5th) October 1981 and in 1982, the rainy season started later than normal start: on 5th(7th) January over A(B). Earlier demise dates of rainy seasons were registered on 5th(6th) March 2000 over A(B). Late demise date was observed on 14th April 2012 over A. The Eastern and North part of the zone of interest, region B, Figure 6, possesses a late climatological rainy season than the region A. A Southwest-Northeast gradient is observed, Figure 6, regarding the onset dates of the climatological rainy seasons. The climatological cessation dates over all grid points within the zone of interest, Figure 7, barely vary with a discrepancy of two days.

All forecasting models have small values of RMSE and MAE (Table 3). Furthermore, with a value of nRMSE ≤15% [41], all the models are defined ‘good’. The forecasting models of the rainy seasons related to the DIM as predictors are the best models. That would be related to the geographical situation of the Indian Ocean Dipole. The forecast of onset date of the rainy season in 2023 is quite earlier than the others, 17th October (Table 4), this forecast is related to the ONI in May and June of the year 2021(Table 1). A late forecast of the demise date, 14th April 2024(Table 4) over A is linked to the January DIM of 2021, the May EDIM [30] in 2019, the January, February and March EDIM [30] of the year 2021 (Table 1). As can be seen in Table 4**,** the best forecasting models possess an error varying between 4 days and one week.

The training models of the onset dates related to the temperatures (Figure 4) over both regions lose its accuracies when the value of ‘k’ increases. However, the more the value of ‘k’ increases, the better the quality of the validation of the model. This means, the smaller(larger) the base of the triangular membership function is, the better the training models (validations of the model) are. This might be another issue for improving the rainy seasons forecasting model related to the temperatures.

5. Conclusion

To tackle the negative impacts of climate changes, this work aims to model and forecast the rainy seasons of Analamanga accurately by the mean of Fuzzy Logic.

The detection of the onset and cessation dates of the rainy seasons leaded to the subdivision of the zone of interest into two regions. Denoted region A, it possesses climatological rainy periods which start between 25th October and 15th November. Denoted region B, it possesses climatological rainy seasons which start from 16th November.

The use of the Pearson's coefficient correlations leaded to the determination of some predictors, such as the ONI, the DIM, the EDIM, the WDIM [30] and the temperatures, of the onset and cessation dates of the rainy seasons over both regions A and B.

The Fuzzy Inference System with its triangular membership function was used to model and forecast the rainy seasons. Values of RMSE and MAE being less than 14 days were observed. Moreover, values of nRMSE and nMAE were less than 10%. This leads us to conclude that the models are 'good' [41]. Values of rRMSE and rMAE less than 1 lead us to conclude that the forecasting model of the rainy seasons over Analamanga by the mean of the FL with the triangular membership functions are excellent. Actually, the output of the models possesses errors less than the standard deviation of the serial data of the observed onset and cessation dates. After comparing the forecasting models related to the different predictors, the best one is the forecasting models of the rainy seasons related to the DIM over both regions. Nevertheless, the choice of the base, related to the parameter 'k', of the triangular membership functions plays an important role in the choice of the best model throughout the training and the validation. An analyse in depth of the choice of the parameter 'k' should be a focus in future proposal for improving the forecasting model of the rainy seasons. Moreover, other climatic variables with a high values of Pearson's coefficient correlation might be used as predictors of the rainy seasons. An investigation of the same method on Sub-seasonal to Seasonal(S2S) data can be of interest to future researches.

6. Aknowledgements

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8. Tables

Table 1: Pearson's correlation coefficients 'r' corresponding to the different predictors

Predictors	OA		OB	
	month (year)	r	month (year)	r
ONI	April (-2)	0.34	May (-2)	0.36
	May (-2)	0.36	June (-2)	0.31
DIM	February (-3)	0.31	February (-3)	0.38
WDIM			July (-3)	0.38
EDIM	January (-3)	0.38		
	February (-3)	0.38		
	March (-3)	0.38		
Temperatures	Minimal temperature (0)	-0.33	Maximal Temperature (0)	-0.34
in September	Average Temperature (0)	-0.32		
	CA		CB	
DIM	February (-3)	0.31	January (-5)	0.32
			February (-4)	0.32
			February (-3)	0.38
EDIM	May (-5)	0.38	January (-5)	0.32
	January (-3)	0.38	July (-3)	0.38
	February (-3)	0.38		
	March (-3)	0.38		
WDIM			May (-5)	0.33
			December (-5)	0.36

Table 2: Different ranges of the parameter 'k' related to the predictors and the outputs

k	Predictors	Output
0.01 to 0.3 with a step equal to 0.05 (0.01:0.05:0.3)	ONI	OA et OB
0.01 to 0.1 with a step equal to 0.01 (0.01:0.01:0.1)	DIM	OA et OB
0.1 to 0.8 with a step equal to 0.1 (0.1:0.1:0.8)	Temperatures	OA et OB
0.01 to 0.3 with a step equal to 0.02 (0.01:0.02:0.3)	DIM	CA et CB

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Table 3: Different values of RMSE, rRMSE, nRMSE, MAE, rMAE and nMAE as forecast accuracy measure (skill score)

Onset over A				*Onset over B*		
predictors	RMSE	rRMSE	nRMSE(%)	RMSE	rRMSE	nRMSE(%)
T	13.78	0.73	4.29	8.14	0.45	2.45
ONI	1.73	0.09	0.54	4.18	0.23	1.26
DIM	0.52	0.03	0.16	0.57	0.03	0.17
	Cessation over A			cessation over B		
DIM	0.76	0.08	0.87	0.80	0.07	0.94
	Onset over A			Onset over B		
	MAE	rMAE	nMAE	MAE	rMAE	nMAE
T	13.74	0.73	7.30	2.20	0.40	4.27
ONI	0.72	0.04	2.33	0.70	0.13	0.22
DIM	0.14	0.01	0.12	0.04	0.01	0.05
	Cessation over A			cessation over B		
DIM	0.33	0.03	0.31	0.36	0.03	0.39

Table 4: Forecast of the onset dates and the demise dates of the rainy seasons over the region A and the region B, with each, their error in days

	region A	*region B*
Predictors	Onset dates	
Temperatures	11/06/2017(±7)	11/23/2017(±3)
	11/06/2018(±7)	11/25/2018(±3)
ONI	11/22/2022(±5)	11/25/2022(±12)
	11/22/2023(±5)	10/17/2023(±12)
	11/23/2024(±5)	11/26/2024(±12)
DIM	22/11/2022(±5)	11/22/2022(±7)
	11/22/2023(±5)	11/22/2023(±7)
	11/23/2024(±5)	11/23/2024(±7)
	Demise dates	
DIM	03/27/2022(±4)	03/26/2022(±5)
	03/27/2023(±4)	03/26/2023(±5)
	04/14/2024(±4)	03/27/2024(±5)

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9. Figures

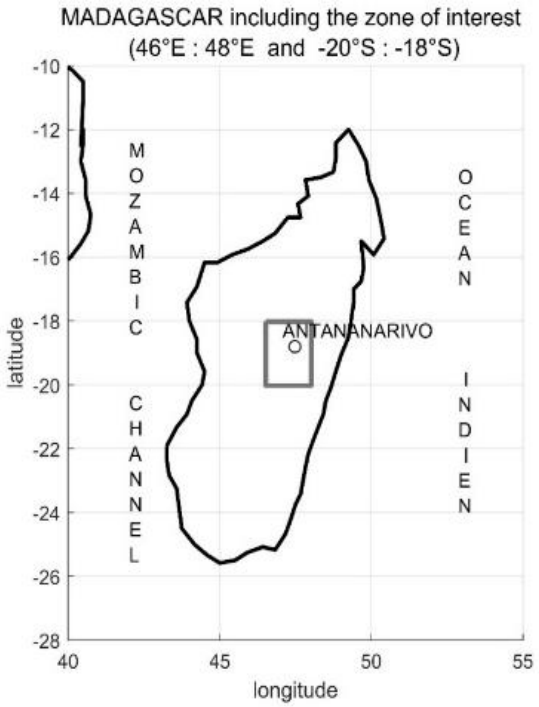

Figure 1: The zone of interest

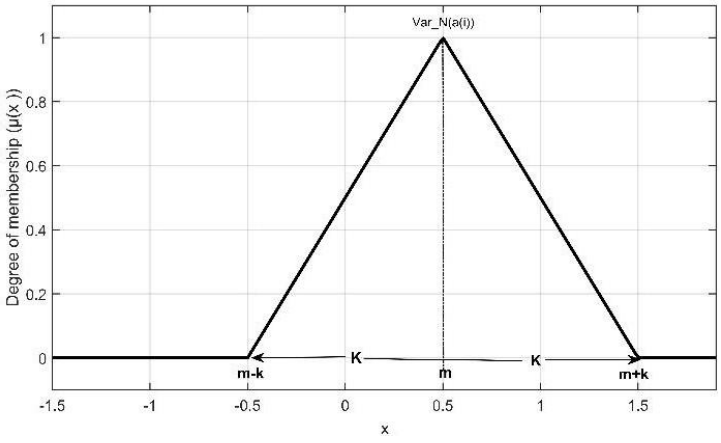

Figure 2: A representation of a triangular membership function

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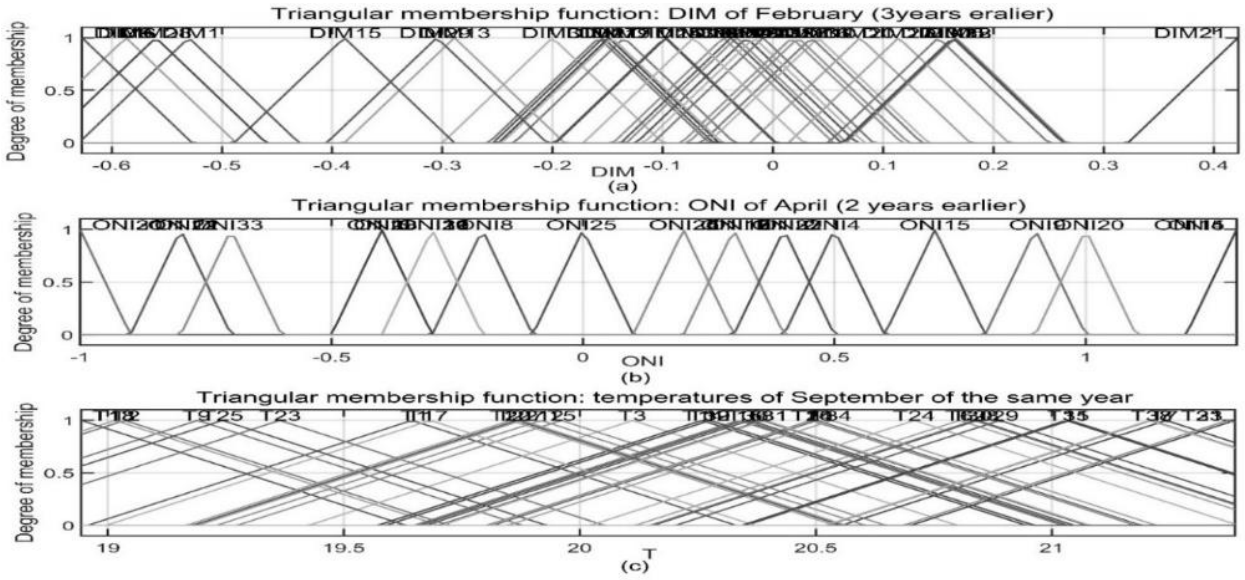

Figure 3: Examples of triangular membership functions related to: Dipole Index Mode (a) ; Oceanic Niño Index (b) and temperatures (c)

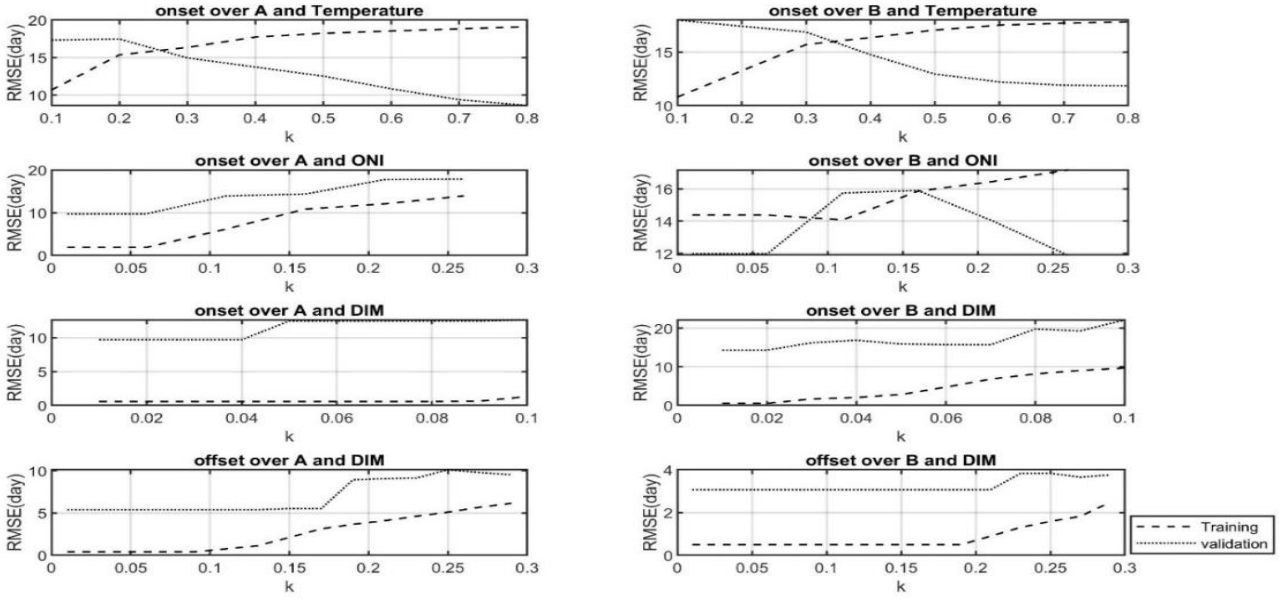

Figure 4: Different values of RMSE related to different values of 'k' corresponding to the training (---) and the validation (…) of the onset and cessation dates of the rainy seasons over A and B

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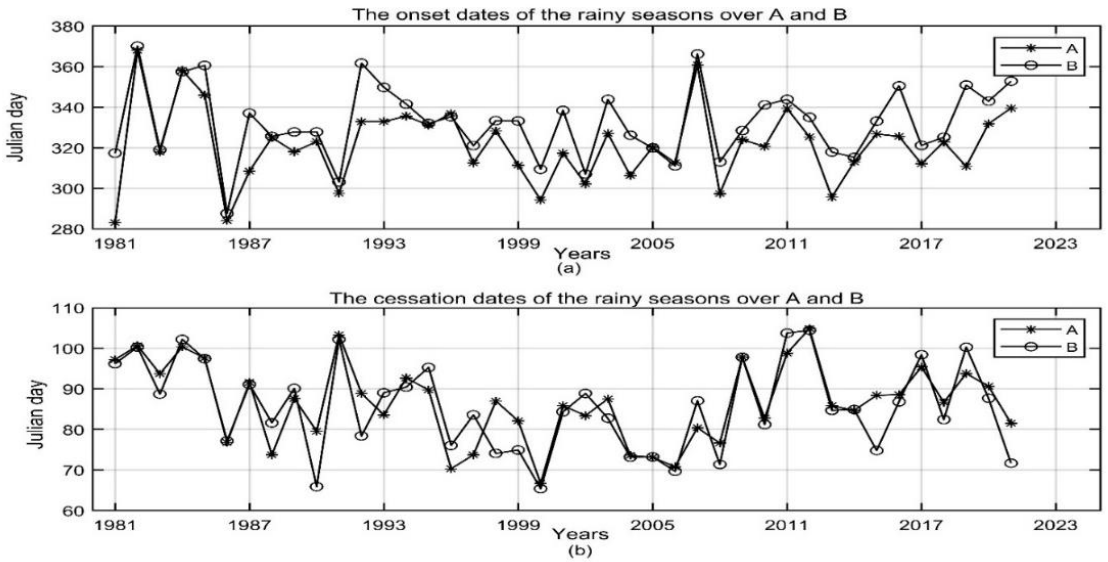

Figure 5: Evolution of the onset (a) and cessation (b) dates of the rainy seasons over both regions A and B from 1981 to 2021)

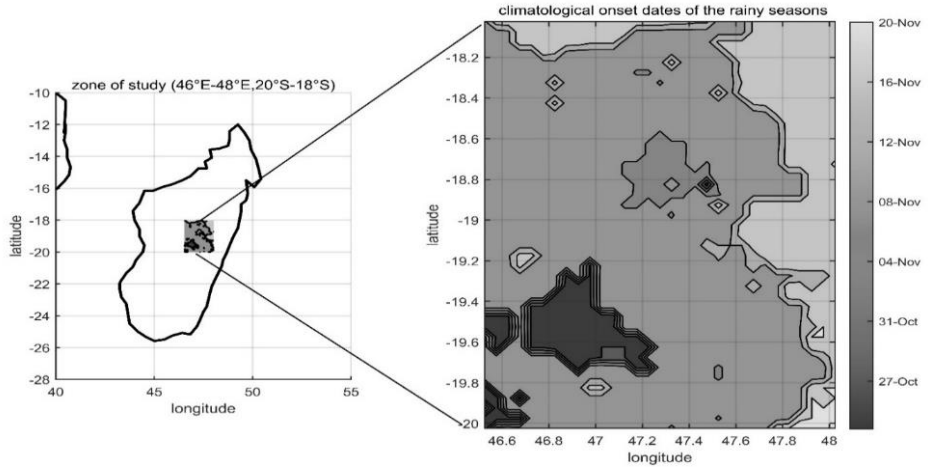

Figure 6: Spatial distribution of the climatological onset dates of the rainy seasons from 1981 to 2021 over the zone of interest

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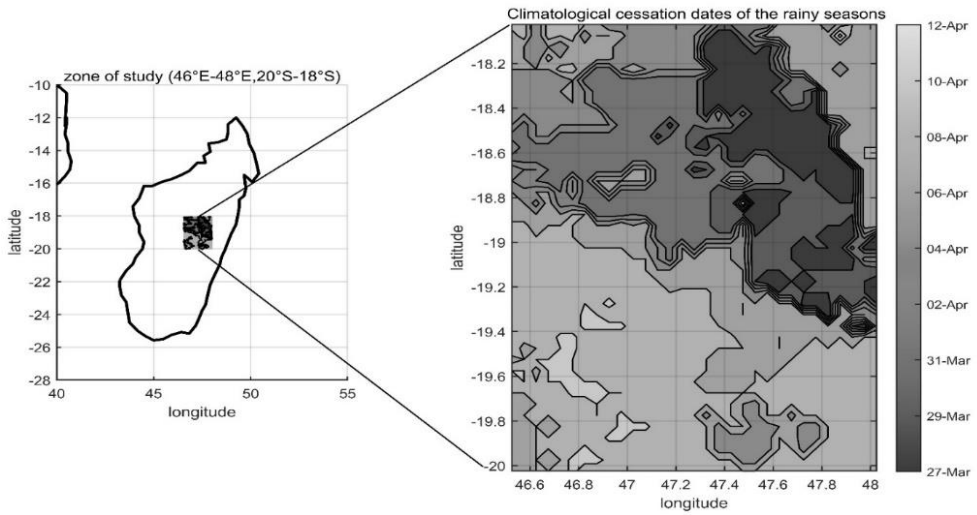

Figure 7: Spatial distribution of the climatological cessation dates of the rainy seasons from 1981 to 2021 over the zone of interest

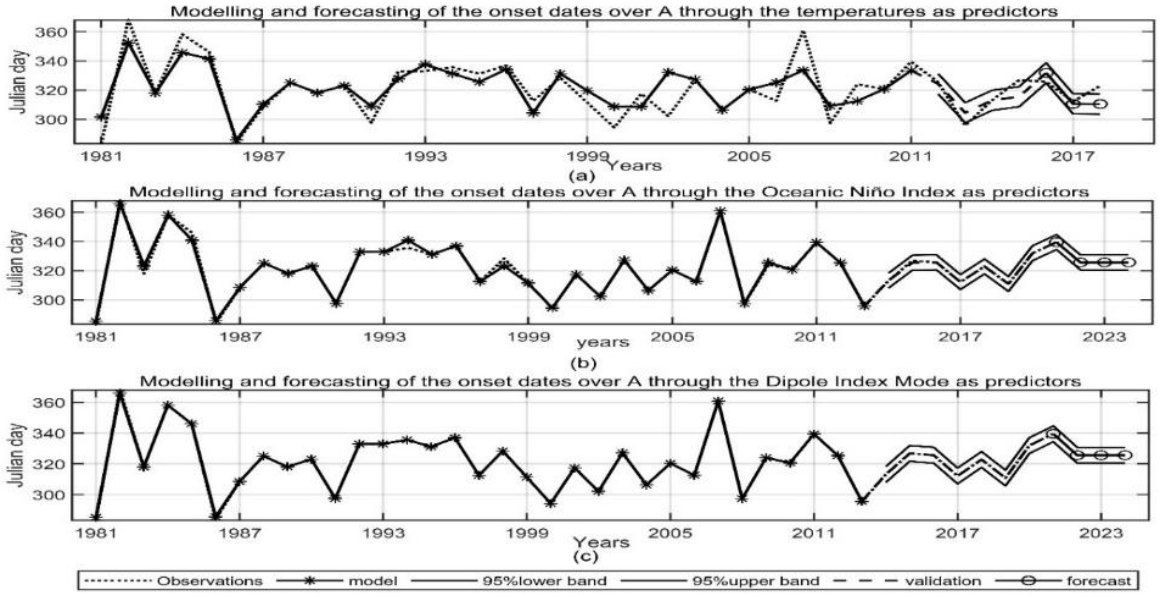

Figure 8: Modelling and forecasting of the onset dates of the rainy seasons with three predictors: the temperatures (a); the Oceanic Niño Index (b) and the Dipole Mode Index (c) over A

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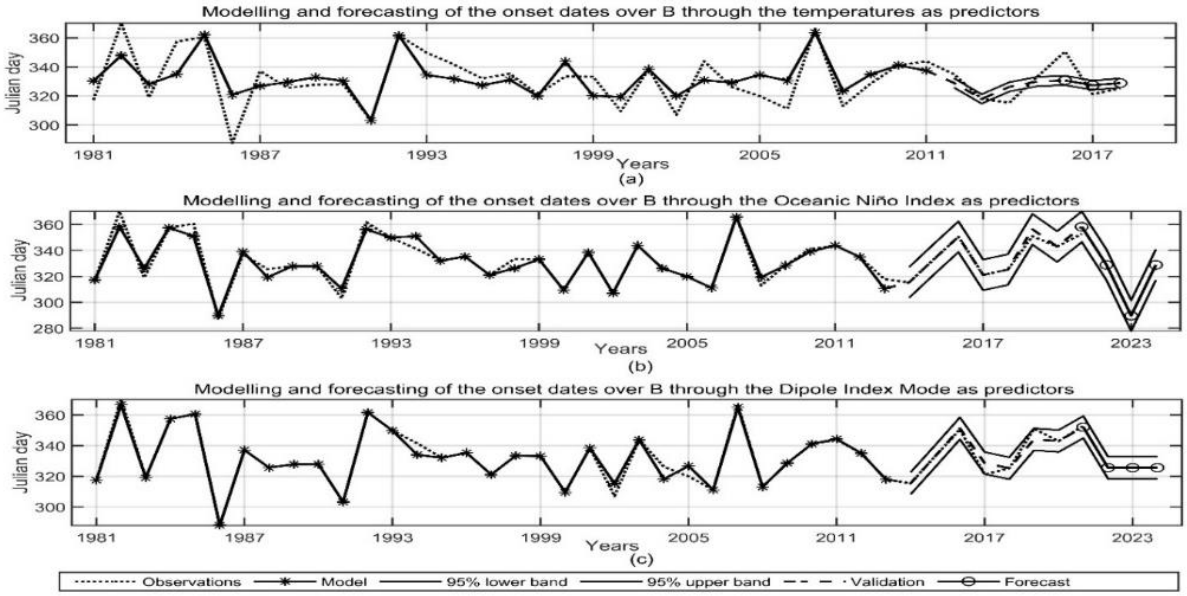

Figure 9: Modelling and forecasting of the onset dates of the rainy seasons with three predictors: the temperatures (a); the Oceanic Niño Index (b) and the Dipole Mode Index (c) over B.

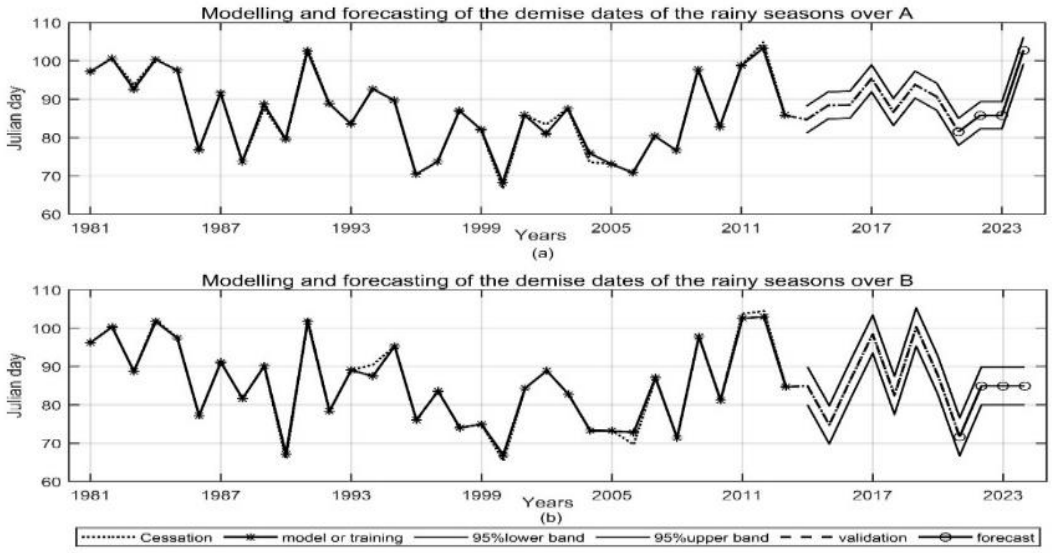

Figure 10: Modelling and forecasting of the cessation dates of the rainy seasons with the predictors: the Dipole Mode Index over A (a) and B (b)