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SOME NEW INSIGHTS IN TO THE INFLUENCE OF SECULAR CHANGES IN SUNSPOT ACTIVITY ON MONSOON RAINFALL VARIABILITY AND OCCURRENCES OF MAJOR DROUGHTS IN INDIA DURING 650-2018 AD

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We have defined M cycles as modified form of Gleissberg cycles to study the quasi-periodic secular changes in sunspot activity. Using direct and proxy observations for more than 1200 years we have provided evidence for the influence of the above M cyles on the monsoon rainfall variability and occurrences of major droughts in India. The solar cycle averages of All Indian summer monsoon rainfall (AISMR) and probability of observation of below or above normal AISMR is found to show correlated variations with changes in amplitude of sunspot cycles during the years 1901-2018 AD. Major droughts in India show a preference to occur during minima and declining phases of the M cycles during the years 650-2018 AD . We could generally find low probability of occurrence of droughts in India during the medieval solar maximum epoch (1100-1250 AD) and during most of the prolonged sunspot minima periods including the Maunder minima. The evolution of mean Indian summer monsoon rainfall during 650-1900 AD is studied using proxy data from multiple sources with maxima during the 12th century and minima during 14th and 19th centuries. The association of Indian droughts with El-Nino and the possibilities of long term prediction of Indian summer monsoon rainfall variability will be also discussed

Key words: Secular changes, sunspot cycles, Indian summer monsoon rainfall, droughts in India, medieval solar maximum, Maunder minima, El Nino

1 Introduction

There are several studies in the past which has provided statistical and physical evidence (Bhalme et al,1981; Agnihotri and Dutt,2003; Kudera,2004; Bhattacharya and Narasimha,2005; van Loon and Meechl,2002; Hiremath et al,2015; Midya et al,2016) for the influence of sunspot cycles on the Indian summer monsoon rainfall variability. The observed solar-terrestrial relations is found to exhibit significant cycle to cycle variability (Hiremath,2006) .The amplitude of the eleven year sunspot cycles is known to be modulated by long period cycles(Sonnet and Finney,1990) like Gleissberg (80-90 years) cycles and Suess (around 200 years) cycles. The influence of secular solar activity variations on climate in several parts of Earth including India has been studied previously(Uberoi,1990; Agnihotri et al,2002; Youseph,2000; Youseph,2006).

In this paper we have studied the characteristics of amplitude modulation of sunspot cycles during the years 650-2018 AD and its influence on weather phenomena in India using both direct and proxy observations.The modulating long period cycles defined as M(modulating) cycles which has both similarity and differences with the well known Gleissberg solar cycles . For the current M cycle period (1901-2018 AD) we could find systematic changes in All India summer monsoon rainfall (AISMR). The probability of observation of normal monsoon rainfall is found to be high during M cycle maxima and the same is low during M cycle minima . The occurrences of major droughts in India during 650-2018 AD show a preference to occur during declining or minimum phases of the M cycles. Indian summer monsoon rainfall evolution during 650-2018 is studied using different proxy data sets. The physical basis and applications of these results will be briefly discussed.

2 Amplitude modulation of eleven year sunspot cycles: Characteristics of M cycles during the years 950-2018 AD

The amplitude of eleven year sunspot cycles are subjected to low frequency modulation. The envelope of the sunspot cycle time series or the modulating wave can be identified from direct or proxy sunspot data. We define M cycles or the modulating cycles to study the same which is a modified form of the well known Gleissberg solar cycles (Mc Cracken et al,2001).The plot of the cycle to cycle changes in amplitude (Yearly mean maximum International sunspot number for the cycle –classic or pre-revised) of sunspot cycles 14-24 (data from www.ngdc.noaa.gov/stp/solar/ssndata.html,) is shown in Fig 1. This is the current

modulating cycle (M0) spanning 118 years between 1901-2018. The two previous M cycles: M-1 is shown in Fig 2 and M-2 in Fig 3. The duration of M cycle -1 is 90 years and that of cycle -2 is 110 years. So M cycles can be considered as a kind of variable period Gleissberg solar cycles.

Smoothing of yearly sunspot data can also provide information about secular changes in solar activity or about M cycles. This smoothing is termed as secular smoothing by Gleissberg (Gleissberg,1944). The proxy of smoothed sunspot activity variations inferred from C^{14} and Be^{10} observations for the period 850-1700 AD is used to infer characteristics of M cycles prior to the year 1701 AD (USGS,2018; Usoskin,2008). The details of M cycles during 800-2018 AD with relevant remarks is given in Table 1. For the M cycle (-3) we have also considered Aurora data for the years 1500-1650 AD (Silverman,1992). The beginning or end of M cycles are either associated with prolonged or deep sunspot minima. Many M cycles are showing a double maximum structure.

3 Indian summer monsoon rainfall variability during the current M cycle (1901-2018)

Indian summer monsoon rainfall data has good spatial coverage from the year 1901 onwards and the area weighted yearly All India Summer monsoon rainfall (AISMR) data (www.imdpune.gov.in/hydrology/india/pdf) published by the Indian Meteorological Department (IMD) during 1901-2018 AD and is reliable. We have used this data to study AISMR characteristics during the current M cycle period. Two rainfall related parameters are identified for the present studies:

(i) Sunspot cycle averages of AISMR, R_f (av) for the solar cycles 14-24.

(ii) Yearly AISMR deviations ($ðR_f$) from the long period averages (LPA) of the same.

In Fig 4 we have plotted values of R_f (av) for the sunspot cycles 14-24 along with the amplitude of the sunspot cycles (R_m). We can observe correlated variations of these two parameters during the current M cycle period (1901-2018, solar cycles 14-24).

In Fig 5 (a) to 5(k) we have plotted the yearly ($ðR_f$) values separately for each sunspot cycle for the solar cycles 14-24. Here LPA is calculated for the years 1901-2018 from IMD data (884.24 mm).We can find that below LPA or negative $ðR_f$ values are more frequent during the minima of the M cycles (for eg: cycles 14 and 24). In contrast with this above LPA or positive $ðR_f$ values are more frequent during the maxima phase of this M cycle (for eg: cycle

19). The explanation of Fig 6 and 7 included in this context will be given in Section 6 (Discussion).

4 M cycles and occurrences of major droughts in India during 650-2015 AD

Periods associated with notable deficiency of monsoon rainfall for consecutive years in different parts of the country accompanied by failure of agriculture and outbreak of famines are broadly identified as major drought periods in India.This will be reflected in AISMR values for that periods. Economic historians and social scientists have compiled dates or periods of occurrences of such droughts in India back to first millennium AD. (List of Famines,2018;Balfour,1885:Paul,2012;Murton,1984,Habib,2011;Mehta,2017, Dunn,2012). In Table 2 we have given dates/periods of 29 major droughts in India which occurred between the years 650-2015 AD. Minor or local drought occurrences are excluded from this list. The inferred M cycle phases of occurrences of these droughts are also given in this Table along with the associated intensity of El-Nino reports (Quinn et al,1987; Luke,2000;Null,2019) if any during the period of droughts. The ðR_f values (observed maximum yearly deviation of Indian monsoon rainfall from normals) are inferred for droughts using direct rainfall records of India back to the year 1813 AD. IITM data (Singh and Sonatakke,1996) is used to calculate ðR_f values during the years 1813-1900 AD and for 1901-2018 AD we have used values plotted in Fig 5 from IMD data. ðR_f values for the droughts occurring between 650-1556 AD is inferred from the details of proxy Indian monsoon rainfall data published by Sinha and his collaborators (Sinha et al,2007,Sinha et al,2011). It can be found that 21 out of 29 of the Indian droughts show a preference to occur during either minima or declining phases of M cycles.

5 Indian summer monsoon rainfall characteristics during 650-1900 AD inferred from proxy data from multiple sources

Instrumental data for the Indian summer monsoon rainfall is available only from the beginning of the 19th century. So we have to rely upon proxy data for our investigations back in time from 7th century AD onwards. We have made use of different types of proxy data during different periods of study depending both on its reliability and utility. Annual proxy Indian rainfall for a given period can be considered to be proportional to the corresponding proxy Indian summer rainfall.

5.1 Speleotherm based Indian summer monsoon proxy rainfall data during the years 650-1550 AD

The published values of Indian summer monsoon proxy rainfall variations during the years 650-1550 AD by Sinha et al (2011) is found to be valuable resource for this long period. They have plotted deviations of Indian summer monsoon rainfall from recent normals (δR_f) for the above years (see Fig 2 of Sinha et al ,2011).According to these authors years with δR_f <10 % are considered as normal drought years and years with δR_f <20 % are considered as severe drought years. For our list of major droughts in India between 650-1550 AD (Table 2) we have included the δR_f values of Sinha (2011). In Table 3 we have given mean δR_f calculated from the above plot of Sinha (2011) for different sub periods with duration of 50-100 years staring from 650-700 AD and up to 1500-1550 AD. The number of major droughts in India (from Table 2) for each of this sub period is also included in this Table.Six severe drought periods are identified by Sinha in his proxy Indian summer monsoon rainfall time series between 650-1550 AD. Most of these are found in our list (Table 2) also.

Two sub-periods are of interest to us in Table 3 . During the sub-period (1100-1200 AD) within the medieval solar maximum (Jirikowic and. Damon,1984) period (1100-1250 AD) no droughts are observed and during which we have found maximum mean Indian summer monsoon rainfall (δR_f is 5%)

. Similarly during the sub-period 1300-1400 AD we could infer minimum mean Indian summer monsoon rainfall.

5.2 Pepper production in Kerala as proxy for Indian Summer monsoon rainfall during 14th to 17th centuries

Pepper is a tropical plant whose annual yield depends on climate and good rainfall. In this section we have considered pepper production information related to Kerala as a proxy for ISMR characteristics during 14th to 17th centuries of the CE. Black pepper is an important spice which is used in many food preparations and is also famous as a food preservative. It is also included in several herbal medical preparations. Black pepper grown in Kerala was

in high demand through out the world since the beginning of the Christian era . Pepper trade in Kerala was with Chinese and Arabs during the 14th and 15th centuries (Melekandathil,2007;Augustine,2014) . Portuguese imported significant part of pepper grown in Kerala during the 16th century (Om Prakash,1998). Pepper from Kerala was exported mainly to Netherlands (Dutch country) and England during 17th century (Barrendse,2015).

During pre-independent India Kerala is divided in to three regions : (i) Travancore (mainly South Kerala), (ii) Cochin (Central Kerala) and (iii) Malabar (North Kerala). Pepper was cultivated in all the three regions during the medieval periods. The important pepper trade centres in Kerala in those days was Kollam (Travancore,harbour town), Cochin (harbour town since the 14th century) and Calicut (Malabar, harbour city). The annual consumption of pepper in China was very high during the medieval periods so that China has to import pepper both from Kerala and Indonesia.(Hirth and Rockhill,1911) Pepper was exported to China from Kerala through the ports of Calicut and Kollam during the 12th-14th centuries. (Liji, 2014) China used large ships for that purpose whose carrying capacity was around 1960 tons (Sen,2006). From the daily consumption of pepper in important towns in china during the 12th century (4300 kg per day on an average) it can be safely assumed that the annual Chinese pepper imports from Kerala during the medieval periods almost matched the annual pepper production in Kerala. Historic sources support uninterrupted trade of Pepper from Kerala to China during the 14th and 15th centuries so that it can be inferred that Kerala received good summer monsoon rainfall during these periods. From the narrative of Ibn Batua (African traveler and agent of Emperor Muhammad bin Tuqluq in Delhi)who visited West coast (Mangalore) and Kerala (Calicut and Kollam) during the years 1843-44 just after the mega drought period in Northern India (starting from 1835 onwards and lasting for 6-10 years) did not observe any impact of this severe drought in these places in southern India.(Lee,1829;Dunn,2012).

Reliable pepper production /export statistics related to Kerala is available during the 16th and 17th centuries from the European sources. The annual pepper production in the Malabar region in Kerala during the first half of 17th century was only one third of the total production in Kerala. The estimated annual pepper production in Kerala during specific periods during the 16th and 17th century is given in Table 4 (Berendse, 2015; Vink, 2006; Keimewicz,2017) There was a notable increase in pepper production in Kerala since 1690

due to increase in area under cultivation under the instructions from the English East India company. The qnantity of pepper imported to Portugal from India (mainly from Kerala) during different periods in the 16th century is shown in Fig 8 (Wake,2017). These statistics suggest that summer monsoon rainfall is also normal during the 16th and 17th century in Kerala

5.3 Duration of Dutch VOC ship voyage from Cape to Batavia as a proxy for ISMR during 17th and 18th centuries

It is known that wind speed in the Indian ocean during the summer (June-September) monsoon season is correlated with rainfall in India during this period (Sinha et al,2020). Mast ships from Europe to Asia/India travelled with the help of monsoon winds during the summer season while travelling via the Cape of Hood hope (Cape) in Africa through the Indian ocean. The yearly published records of average journey duration from Cape to Batavia (modern Indonesia) taken by Dutch VOC mast ships (mainly for spice trade) during the years 1852-1795 CE (Mertens,2003)can be considered as a proxy to wind speed in the Indian ocean and monoon rainfall in India during the summer season for these years. The mean journey duration of these ships for the years 1610-1794 CE for travelling from Cape to Batavia is found to be 81 days. In Fig 9 we have plotted deviation from this mean value in days (ΔD) of the observed average yearly journey duration (D) of Dutch VOC ships from Cape to Batavia for each year from 1852-1795 CE given by

$$\Delta D \text{ (days)} = (D-81) \qquad (1)$$

Ambily et al (2018) used this proxy data to infer variations of Indian summer monsoon rainfall during the Maunder minimum period (1652-1700 AD). Positive values of ΔD can be associated with slower Indian ocean wind speed and below normal Indian monsoon rainfall. The negative values of ΔD can be associated with faster Indian ocean wind speed and above normal monsoon rainfall.

Positive spikes or peaks in Figure 9 is related to droughts or acute deficiency in rainfall. During Maunder minimum period we can find one such positive spike in ΔD during the Indian drought period of 1662 AD. The positive spike in ΔD during 1791 is related to the disastrous Dojibera or Skull drought in India included in Table 2.The large positive spike in ΔD during 1748 AD is also particularly note worthy.

During 1652-1728 AD we can find that ΔD is predominantly negative suggesting normal Indian summer monsoon rainfall during this period

In contrast with this during 1729-1795 AD we can find that ΔD is predominantly positive suggesting below normal Indian summer monsoon rainfall during this period. During the second half of 18th century four major droughts are reported in India (see Table 2) supporting the inference of weakening of Indian summer monsoon rainfall inferred from ship voyage data. The VOC ship voyage information during the 18th century suggest a mean Indian summer monsoon rainfall of at least 5 % below the current normal value.

5.4 Speleotherm and oxygen isotope based estimates of Indian summer monsoon rainfall for the period 1670-2000

Yadava et al (2004) inferred Indian summer monsoon rainfall from speleotherm based observations in a cave in Western Ghats in the north Karnataka region for the years 1666-1996 AD (see Fig 7 of this paper). We have divided this data in to different sub-periods and for each sub-period we have found mean values of ISMR and the results are shown in Fig 10. . If we use the average value estimated during 1900-1996 as the normal then the average proxy rainfall for the 19th century is 11.7 % below normal ,average proxy rainfall for 18th century is found to be 5.9 % below the normal . The average rainfall during the Maunder minimum period (1666-1705) is found to be only 2,9 % below the normal .

Ramesh et al (2010) inferred annual mean rainfall in Kerala from oxygen isotope analysis of teak woods from Parambikulam in Kerala during the years 1740-1985 AD This proxy rainfall is found to be correlated with southern peninsular India annual rainfall observations (Instrumental data) during the years 1813-1985 AD. We have found period averages of this proxy annual rainfall of Kerala during 1740-1985 AD and the results are shown in

Fig 11.We can find a notable dip in annual rainfall of Kerala (Ramesh et al,2010) during 1748 AD. This is reflected in the period average for 1745-48.. The period average during the Dalton minimum period (1790-1830 AD) is found to be only 4.6 % below the mean value of annual rainfall in Kerala during the modern maximum period (1900-1985 AD) . The annual rainfall in Kerala during the 19th century (1800-19000 shows a decrease of 9 % from the period average for the 20th century.

5.5 Average Indian summer rainfall during the 16th to 19th centuries inferred from prioxy data compared to recent nornals

From the results of analysis of different proxy data discussed in Sections 5.2 to 5.4 we have inferred the deviations of the average Indian summer rainfall during the 16th to 19th centuries compared to recent normals. The recent normal or reference is assumed as the IMD area weighted Indian summer monsoon rainfall data for the years 1901-2018 (883.24 cm). Our inferences are given in Table 5.

6 Discussion

In this paper we have studied the effects of secular variations in solar activity on the monsoon rainfall variations and occurrences of droughts in India (a) Using direct and reliable observations of Indian monsoon rainfall and sunspot activity during 1901-2018 AD (b) Proxy observations of both of sunspot activity and Indian monsoon rainfall back to the year 650 AD.

We have found that sunspot cycle averages of AISMR is found to be correlated with amplitude changes in sunspot cycles during the current M cycle (0). The yearly deviations of AISMR from normals or LPA in different sunspot cycles are also organized by the. secular changes in solar activity or by the M cycles. In Fig 6 we have plotted sunspot cycle averages yearly rainfall deviation parameter $ðR_f$ (see Fig 5) defined as $(ðR_{f)})_{av}$ calculated for each sunspot cycle between cycles 14-24. From this Fig we can find that $(ðR_{f)})_{av}$ is predominantly positive (above normal) during the ascending and maxima phases of this M cycle (solar cycles 15-19) and the same is predominantly negative during the declining and minima phases of the same M cycle (sunspot cycles 14 and 20-24).

The yearly mean international sunspot numbers is plotted along with smoothed yearly rainfall deviations ðRf for the years 1954-1976 in Fig 7(a) and Fig 7(b) . We can find that ðRf is predominantly positive during the extreme active cycle 19 (1954-1964) and it becomes predominantly negative during the next sunspot cycle 20 (1964-76). See also the smoothed ðRf values plotted. The reduction in amplitude of the sunspot cycle to nearly half from 19 to 20 has probably influenced the Indian monsoon rainfall variations in a dramatic manner. Normal /above normal AISMR is observed almost during the entire duration of exceptionally active sunspot cycle 19. The solar irradiance gradient effect on Indian monsoon rainfall variability may be the reason for this result (Agnihotri et al,2011).

For majority of the Indian droughts given in Table 2 is found to occur during declining or minima phases of secular solar activity cycles (M cycles). Two severe droughts in India inferred from proxy Indian monsoon rainfall observations (Sinha et al,2011) is found to

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occur during minima phases of M cycles -6 and -7 repectively. Generally El Nino parameters (frequency/intensity) are found to show anti-correlation with sunspot activity (Asenoski et al,2014; Zhai,2017). Association of Indian droughts with El-Nino has to be understood in this perspective. During medieval maximum period there is a possibility of weakening of El-Nino phenomena in general (Naidu et al ,2020;Grove,2018) which is supported by the absence of major droughts in India during this period and occurrence of relatively strong monsoon rainfall in India,(Sinha et al, 2007;Sinha et al,2011).

Using the deviations of Indian summer monsoon rainfall from normal inferred for various sub-periods during 650-2018 AD (Table 3 and Table 5) we have estimated the mean ISMR for different periods making use of the average of Indian summer monsoon rainfall during the instrumental period (1901-2018) as the reference or normal value . The results are shown in Fig 12 . Two distinct minima and one maxima in mean ISMR is note worthy in this plot which needs explanation.

From Figure 12 we can find distinct decreases in Indian summer monsoon rainfall during the 14th and 19th centuries. This is reflected in the characteristics of major droughts occurred during these periods. During the 14th century we can infer occurrence of at least two Mega droughts lasting for a decade in India (the Tughluq period drought and the Durga Devi drought in Table 2). However these droughts has probably not affected Kerala or West coast (mainly South Karnataka region) as known from pepper production information during this century. Independent evidence suggest that these mega droughts has probably not affected southern peninsular India also.(Murton,1984). During 19th century we could find several severe droughts affecting both southern and northern India whose details are well recorded. We could infer a maxima in mean Indian summer monsoon rainfall during the medieval solar maximum period (1100-1250 AD) when we consider records during 650-2018 AD. High solar activity periods such as the recent 19th solar cycle is found to be associated with normal or above normal ISMR. Low solar activity periods such as 14th or 24th sunspot cycle is associated with below normal rainfall.

In Table 6 we have given number of occurrences of major droughts in India during prolonged sunspot minima/maxima epochs since 900 AD. The mean Indian summer monsoon rainfall for . different sub-periods (50-100 years long) is inferred in Section 5 using different proxy data sets. It is quite interesting to find that occurrence probability of

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major droughts in India is very low during both prolonged sunspot minima and maxima epochs (Table 6).. During the medieval maximum period (1100-1250 AD) no major droughts occurred in India as seen from Table 2 . Further the inferred monsoon rainfall variations during this prolonged maximum is a replica for sunspot cycle 19 where predominantly normal or above normal rainfall is obsvered. Indian summer rainfall is inferred to be normal during most of the prolonged sunspot minima periods including the Maunder minima (1650-1705 AD) and the Daltons minima (1790-1830 AD) as known from proxy Indian summer monsoon rainfall data analysis discussed in Section 5. One exception is Wolf minimum where the ISMR inferred by Sinha et al (2011) is generally deficient . Generally we can find from Figure 10 , Table 3 and Table 5 a possible inverse relation between mean Indian summer monsoon rainfall for a given sub-period (50/100 years in length) and occurrence of major droughts during that sub-period.

We can predict the possible change in sunspot cycle averaged monsoon rainfall in India for the following situations :

(A) If the amplitude of the current sunspot cycle (predicted or observed) is found to show distinct increase from the previous sunspot cycle in the ascending or maxima phases of M cycles then the cycle averaged monsoon rainfall of India Rf (av) will probably increase from the previous cycle . The probability of observation of major droughts will be relativcely less in this situation in India.

(B) If the amplitude of the current sunspot cycle (predicted or observed) is found to show distinct decrease from the previous sunspot cycle in the descending or minima phases of M cycles then the cycle averaged monsoon rainfall of India Rf (av) will probably decrease from the previous cycle . The probability of observation of major droughts will be relativcely high in this situation in India.

We can observe situation (A) during sunspot cycles 15-19 . No major droughts was also not observed in India during these cycle periods (see Table 2). During sunspot cycle 20 and 24 we have situation (B). In sunspot cycle 20 there are two severe droughts (1965 and 1972) and in cycle 24 we have one severe drought (2009) observed in India where summer monsoon rainfall decrease from the LPA was 20% or more.The results of this study will be thus helpful to develop a long term prediction model for Indian monsoon taking in account also the secular variations in solar activity including the “special effects” of prolonged maxima/minima on monsoon rainfall discussed in this paper. If the forth coming sunspot

cycle 25 amplitude is higher than cycle 24 (Svalgaard,2019; Bhoumik and Nandy,2018) then it resembles situation (A). In this case the probability of observation of normal monsoon rainfall in India in next cycle will be slightly enhanced compared to the current cycle 24. According a recent review by Petrovay (2020) the difference between amplitudes of sunspot cycles 24 and 25 is likely to be within 20 %,

7.Conclusions

1 We have defined a new secular solar cycle series called M cycles which can be considered as variable period Gleissberg cycles. Using direct and indirect sunspot activity observations we have studied the characteristics of M cycles between the years 800-2018 A

2 The solar cycle averages of All Indian summer monsoon rainfall (AISMR) and probability of observation of below or above normal AISMR is found to show correlated variations with changes in amplitude of sunspot cycles or organized with respect to the phases of M cycles during the years 1901-2018 AD.This result may have a predictive value.

3 From a study of both direct and proxy Indian monsoon rainfall data in addition to reliable famine reports we could find that major droughts in India show a preference to occur during minima and declining phases of the M cycles during the years 650-2015 AD.

4 The absence of Indian droughts during the medieval prolonged maxima period (1100-1250 AD) is particularly note worthy. Major drought occurrences during prolonged sunspot minima is also surprisingly observed to very less.

5 Using multiple proxy data we have studied the evolution of mean Indian summer monsoon rainfall during different sub-periods within 650-2018. It suggests an inverse relation between mean ISMR and occurrences of major droughts in India.

6. If the amplitude of cycle 25 is enhanced (by about 20% as predicted by some recent studies) with respect to cycle 24 then the monsoon rainfall on an average will be also slightly enhanced compared to the current cycle..

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Table 1. Secular M cycle characteristics for M(0) to M (-7) covering the years 800-2018 AD

M cycle number	Period of M cycle (AD)	Dates of maxima (AD)	Remarks
M(0)	1901-2018	1957 (SS 19)	secondary maximum during SS 21 and 22 is observed
M(-1)	1810-1901	1837 (SS 8) 1870 (SS 11)	both maximum has almost equal amplitude
M (-2)	1701-1810	1727 (SS -2) 1770 (SS 3)	
M (-3)	1550-1650	1580 1600-1610	Auroral observations support double maxima
M(-4)	1350-1450	1370-80	
M(-5)	1080-1280	1200-1220	overlaps with Medieval solar maximum period
M(-6)	900-1040	940	
M(-7)	800-900	840	

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Table: 2 . Dates of occurrence of major droughts in India along with its identification with name/place of occurrence during the years 650-2015 AD. The M cycle phases are given for each drought.The associated El Niino occurrence with relative intneisty (W-weak,M-moderate,S-strong and VS-very strong) also given.The inferred monsoon rainfall deviation from the mean (ðRf %) is also given for droughts for which proxy/direct data available.

Date or period of drought (AD)	Name/Place of drought	ðRf (%)	M cycle Phase	El Nino strength if present
650	All India Famine	< -10	Dec/Min	
1022	-do-		Dec	
1033	-do-	<-10	Dec	
1052-54	Tanjore ,Tamil Nadu	<-10	Min	
1290-92	Rajasthan , Haryana	< -20	Min	
1335-45	Tugluq regime - Mega Drought (North India)	<-10	Min	
1396-1408	Durga Devi -Mega Drought (Maharashtra)	<-20	Dec	
1556	Gujarat and Deccan		Asc	
1595-98	-do-		Min	M
1630-32	Deccan Famine		Dec	
1661	All India Famine		Min	S
1702-04	Deccan Famine		Min	S
1769-70	Bengal Famine		Asc	
1783-84	Chalisa Famine		Dec	S
1791-92	Doji bara or Skull Famine		Min	VS
1837- 38	Agra Famine	-18	Max	M
1860-61	Upper Doab Famine	-14	Min	M
1864-67	Orissa Famine	-14	Min	
1869	Rajaputana Famine	-14	Max	

Table 2 (contd)

Date or period of drought (AD)	Name/Place of drought	ðRf (%)	M cycle Phase	El Nino strength if present
1873-74	Bihar Famine	-11	Max	M
1876-78	Great Indian Famine	-29	Max	VS
1899-1900	Indian Famine	-26	Dec	S
1905-06	Bombay Famine	-18	Min	W/M
1965-67	Bihar drought	-20	Dec	S
1972	Maharashtra Famine	-24	Dec	S
1979	West Bengal Famine	-18	Max	W
2002	All India drought	-13	Dec	M
2009	-do-	-21	Dec	M
2015	-do-	-14	Dec	VS

Table 3 Inference of deviations of mean Indian summer monsoon rainfall from the recent normals during different sub-periods of 650-1550 AD using proxy data from Sinha et al (2011)

Period (CE)	Indian Summer Monsoon Rainfall Deviation (%)	Remarks	Number of major droughts In India
650-700	-5		1
700-800	0		0
800-900	-5		0
900-1000	0	Medieval Warm Period	0
1000-1100	0	Medieval Warm Period	3
1100-1200	5	Medieval Warm Period	0
1200-1300	-5		1
1300-1400	-15	other proxy data suggest -10 %	2 Mega droughts
1400-1500	-5		1
1500-1550	0		0

Table 4 Pepper production in Kerala 16th and 17th centuries

Period (CE)	Average annual Pepper production (pounds)	Average annual Pepper production (metric tons)
1513-15	4 million	1846
1583	4.4 million	1996
1635	4.25 million	1928
1680	4.5 million	2041
1663	3.9 million	1769
1690	5.5 million	2495
1700	6.5 million	2948

Table 5 : Mean Indian summer monsoon rainfall deviation from the recent normal during 16th to 19th centuries inferred using different Proxy data as mentioned.

Period (CE)	Indian Summer Monsoon Rainfall Deviation (%)	Remarks (sources of inference of ISMR)	Number of major droughts In India
1500-1600	-5	Pepper production ,Kerala	2
1600-1700	0	-do- , VOC voyage data and Yadava et al (2004)	2
1700-1800	-5	Yadava et al (2004)	4
1800-1900	0	Ramesh et al (2010) and Yadava et al (2004)	7
1900-2018	0	Reference Normals (IMD data)	4

Table 6. Details of occurrences of major droughts in India during different prolonged sunspot minima/maxima periods from 1040-1830 AD.Signature of the droughts in proxy Indian monsoon rainfall data series is also given if available.

Name of prolonged Solar minima/maxima	Period (AD)	Number of major Indian droughts and dates (AD)	Remarks aboutdroughts Indian monsoon rainfall from different published.proxy data series
1 Oort's minimum	1040-1080	1 (1052-54)	Also seen in Sinha et al (2011)
2 Medieval maximum	1100-1250	0	From Sinha et al (2011) we can find that proxy Indian monsoon rainfall shows normal/excess conditions almost through out this period.
3. Wolf minimum	1280-1350	2 (1335-45, 1290-92)	weak monsoon rainfall more frequent as seen from Sinha et al (2011) during this period
4.Sporer minimum	1450-1550	0	There are reports of occurrence of a minor drought during 1460-65 AD (Deccan or Pant drought) reported by Mehta (2017) This is not seen in Sinha et al (2011) proxy data.of Indian summer monsoon rainfall.
5 Maunder minimum	1645-1700	1 (1661-62)	Seen in proxy monsoon data by Ambily et al (2018)
6 Daltons minimum	1790-1830	1 (1791)	Seen in proxy monsoon data by Yadava et al (2004)

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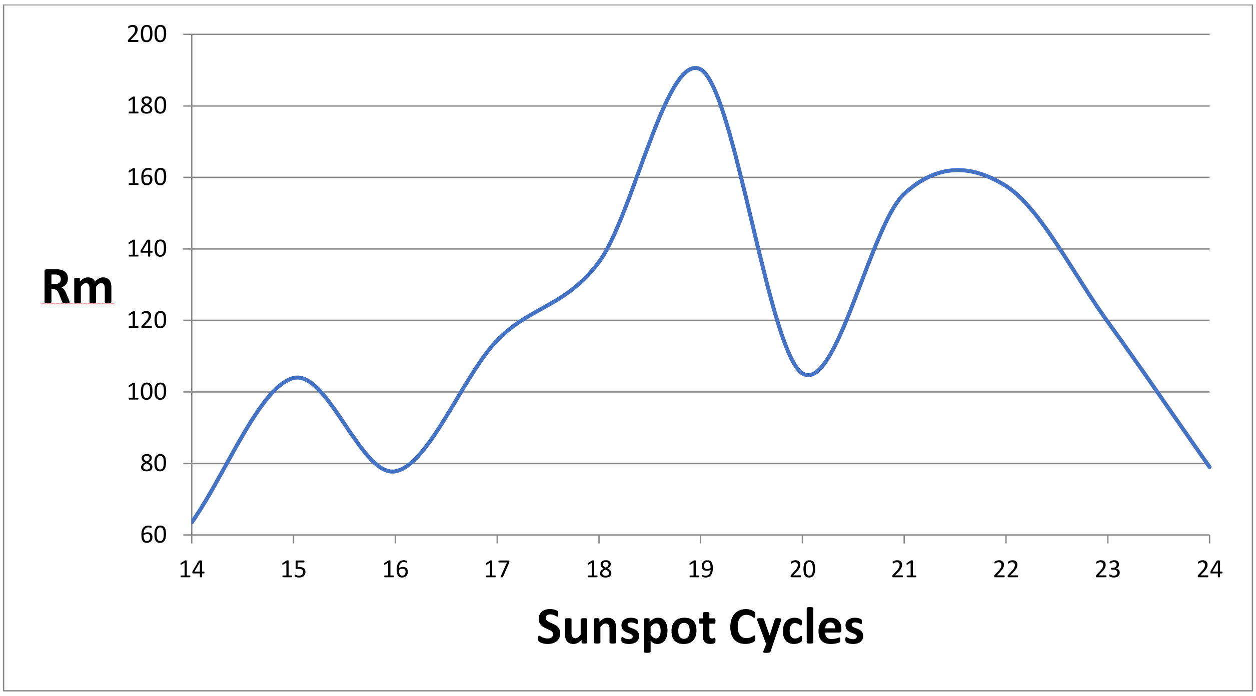


Fig 1 Variations of the amplitude of sunspot cycles (maximum classic yearly sunspot number for the cycles) for M cycle (0) covering sunspot cycles 14-24 (1901-2018 AD).

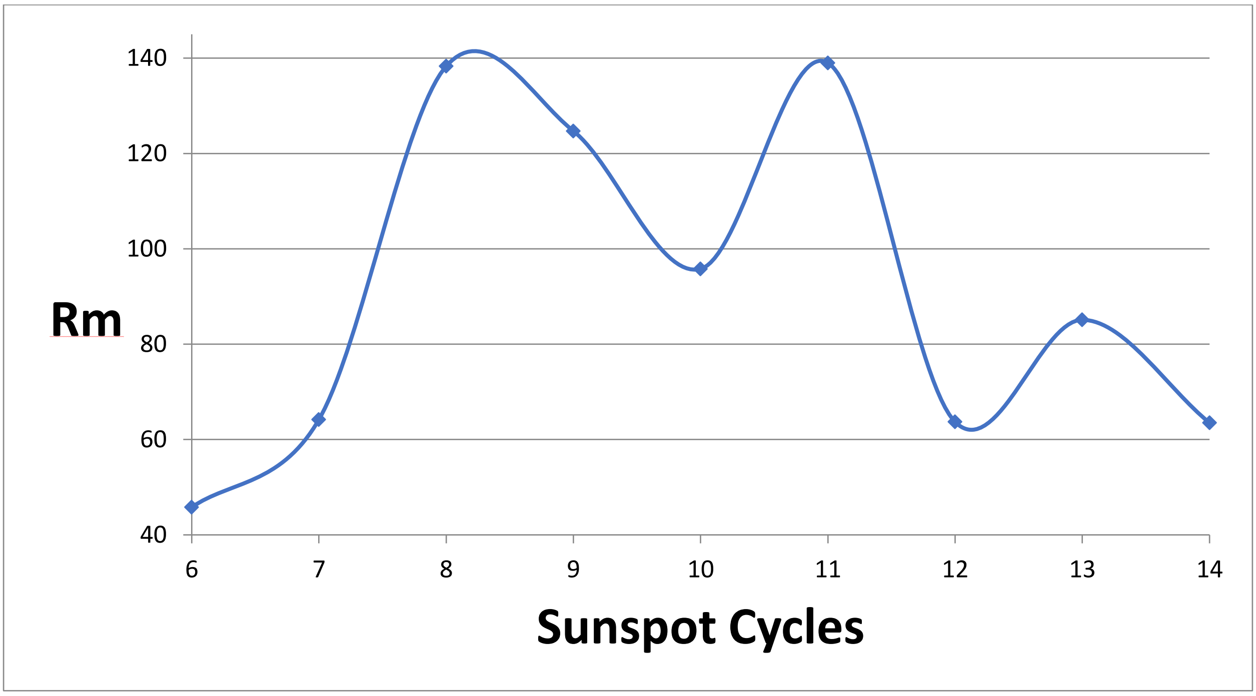


Fig 2 Variations of the amplitude of sunspot cycles (maximum classic yearly sunspot number for the cycles) for M cycle (-1) covering sunspot cycles 6-14 (1810- 1910 AD).

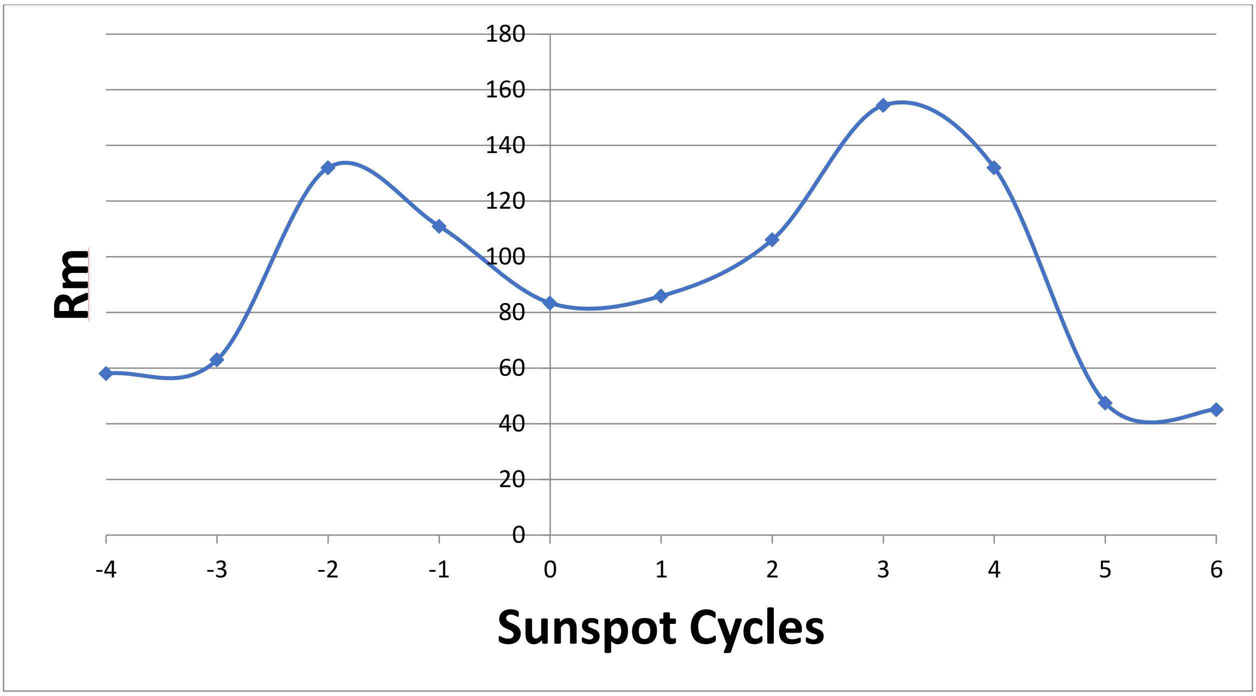


Fig 3 Variations of the amplitude of sunspot cycles (maximum classic yearly sunspot number for the cycles) for M cycle (-2) covering sunspot cycles -4 to 4 (1701- 1810 AD).

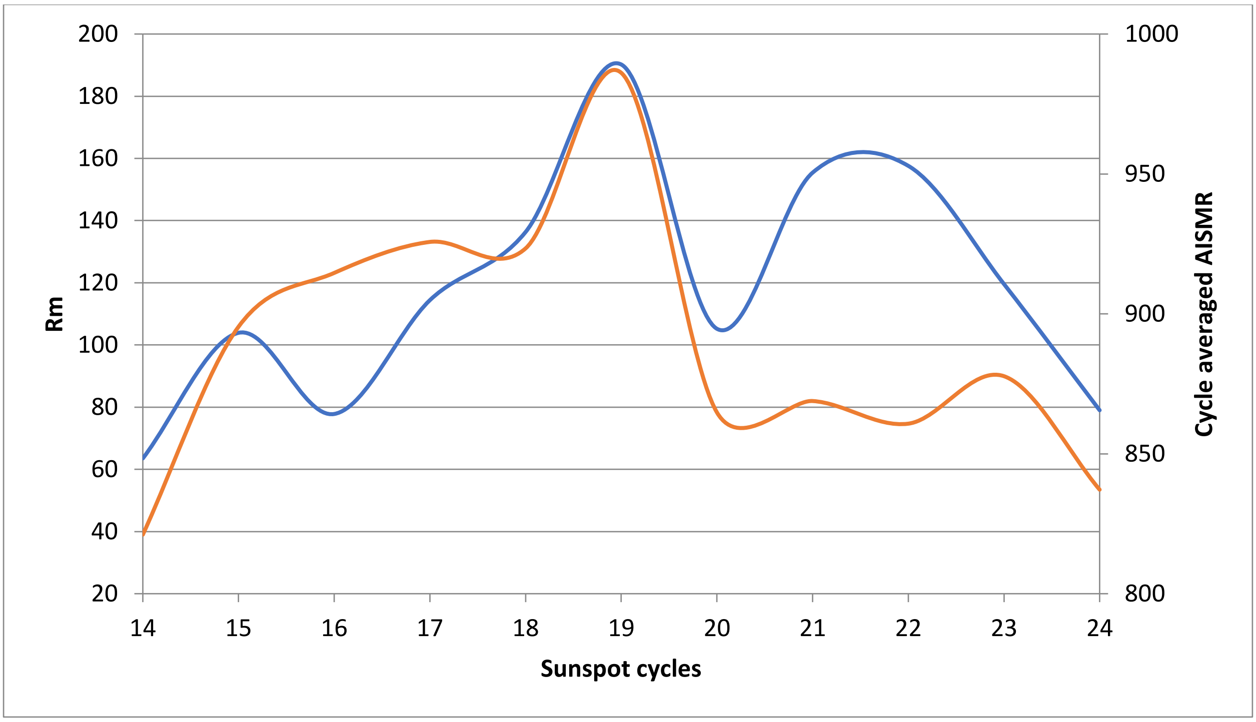


Fig 4. Amplitude of the sunspot cycles (Rm) and cycle averaged All India Summer Monsoon Rainfall (AISMR)-R_f (av) for the sunspot cycles 14-24 during the secular M cycle (0) .

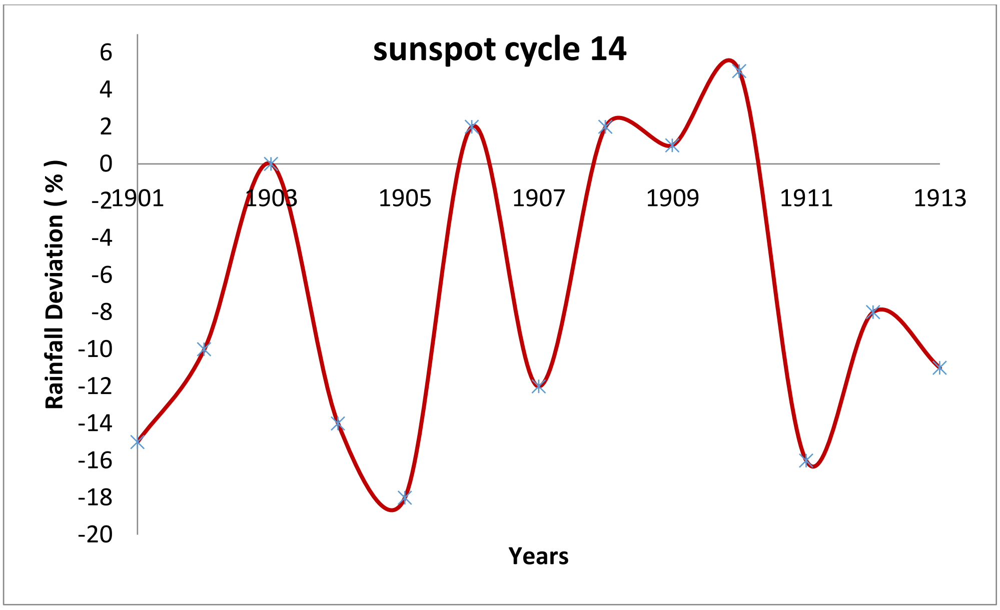


Fig 5 (a)

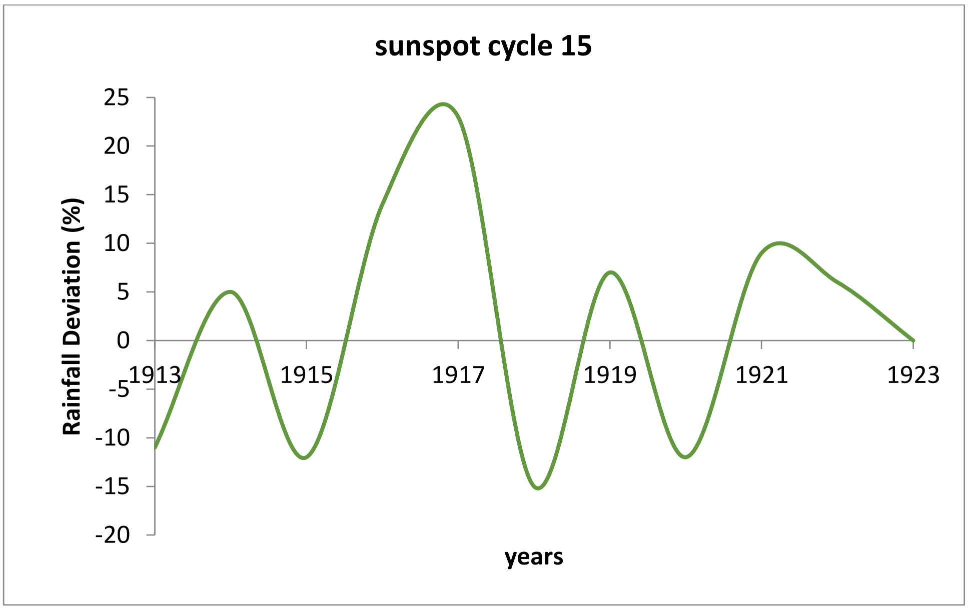
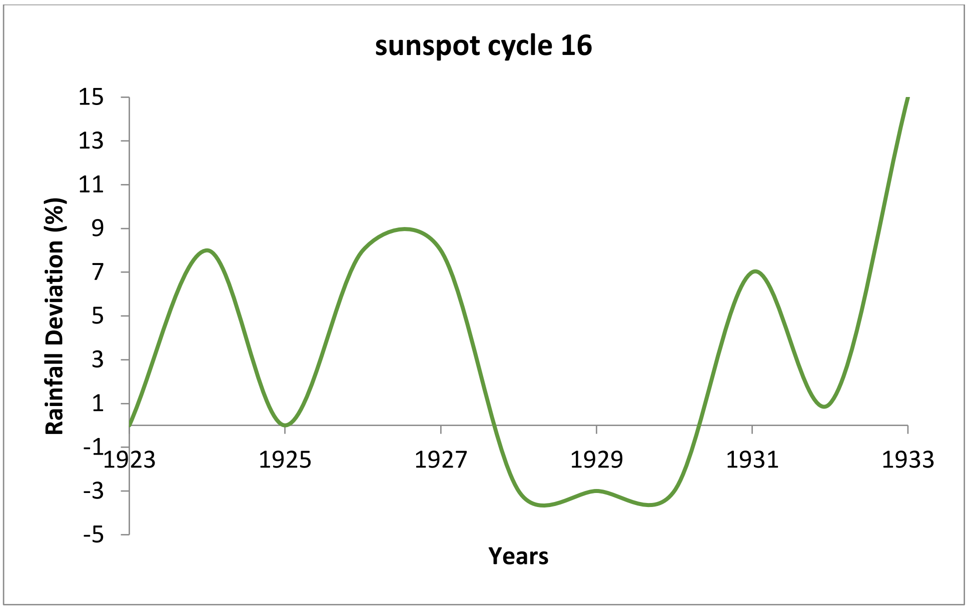


Fig 5 (b)

Fig 5 (a) to 5 (k) : Variations of the yearly deviation of All India Summer monsoon rainfall ($\eth R_f$) from normals for each sunspot cycle from 14-24 covering years 1901-2018 AD.



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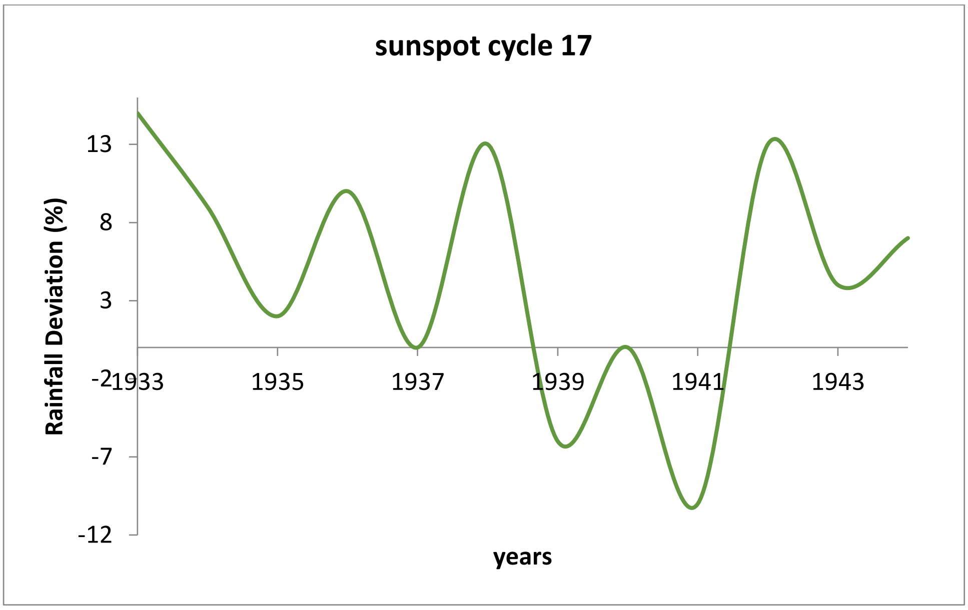
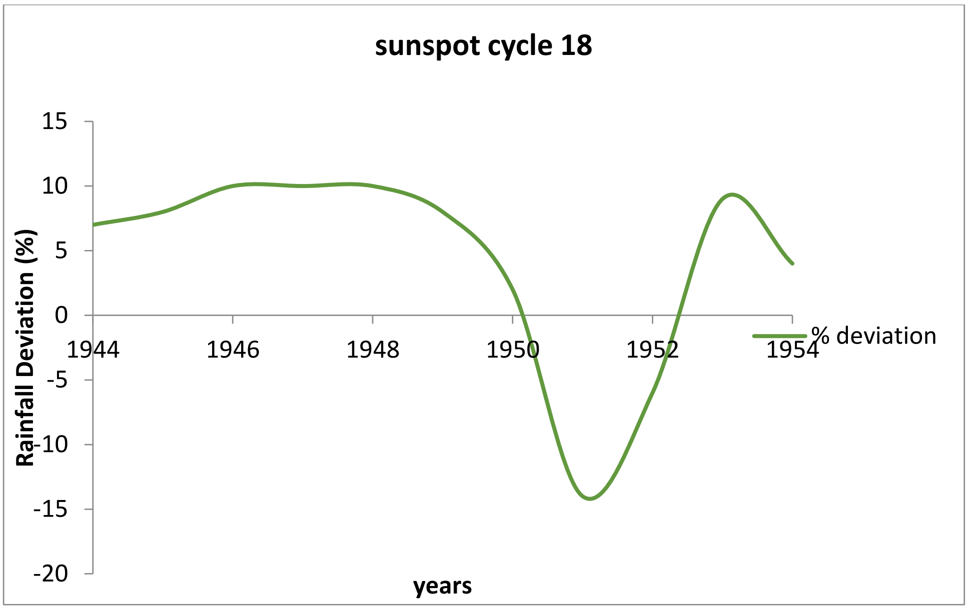


Fig 5 (d)

Fig 5 Contd.....



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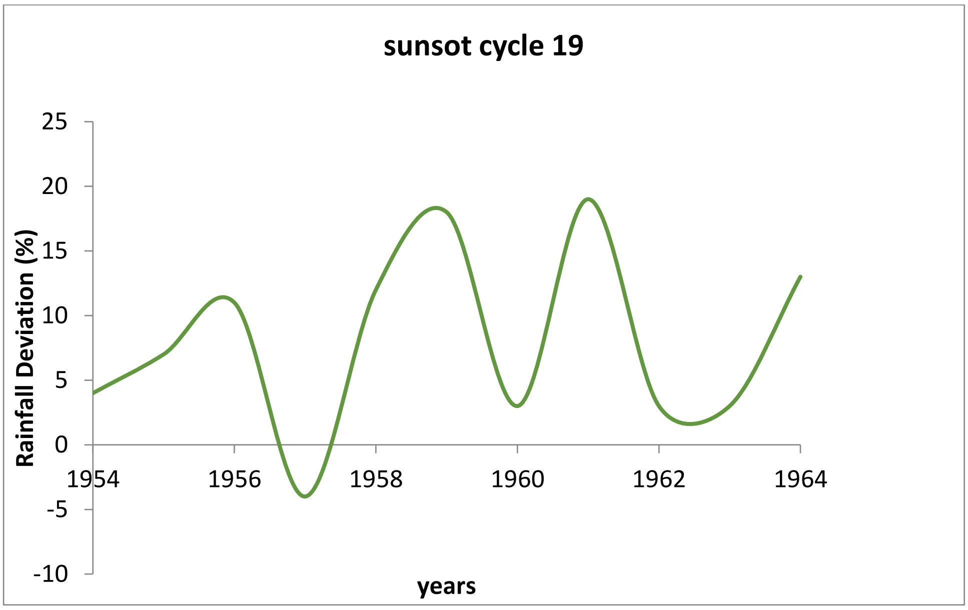

Fig 5 (f)

Fig 5 Contd…..

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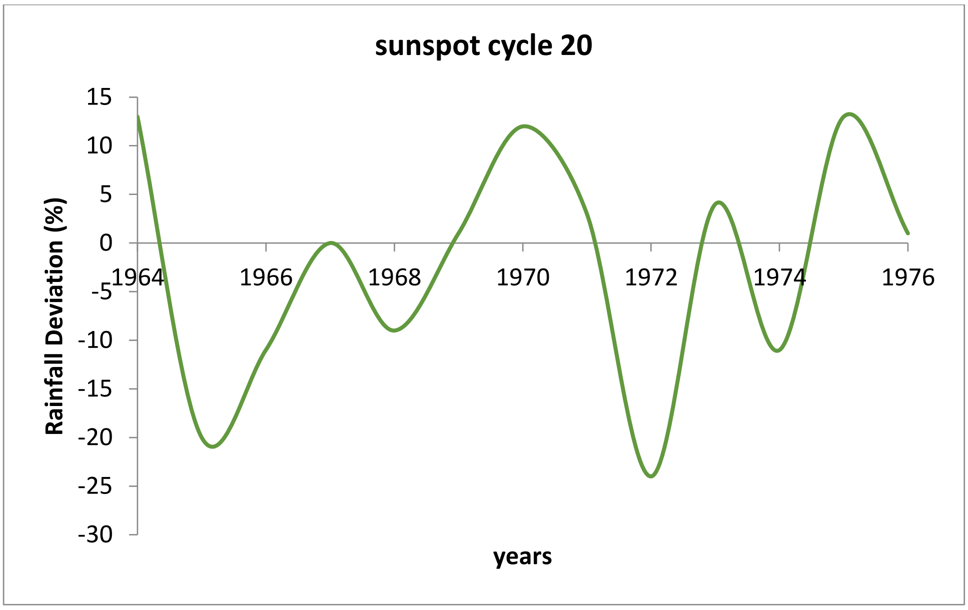

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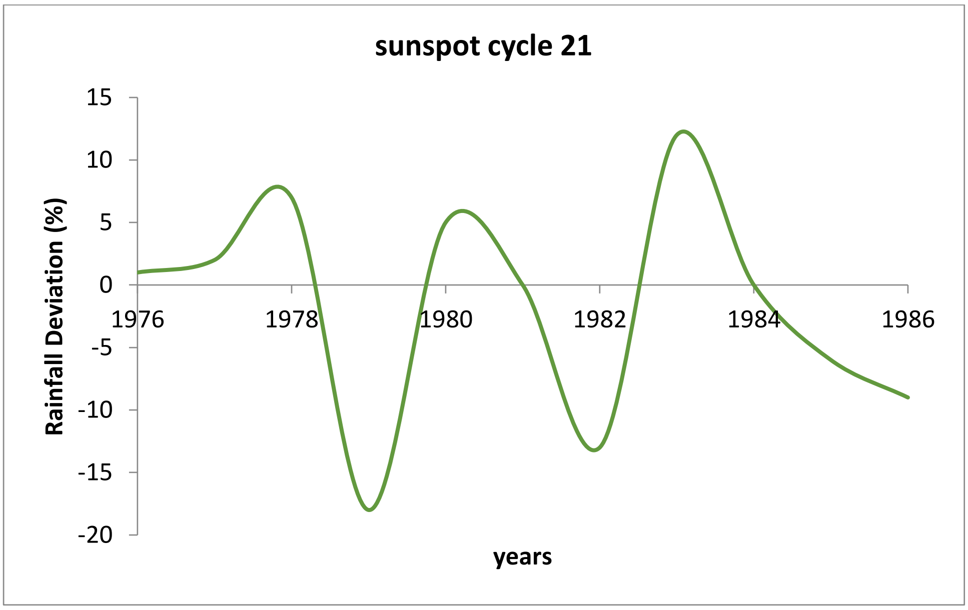

Fig 5 (h)

Fig 5 Contd…..

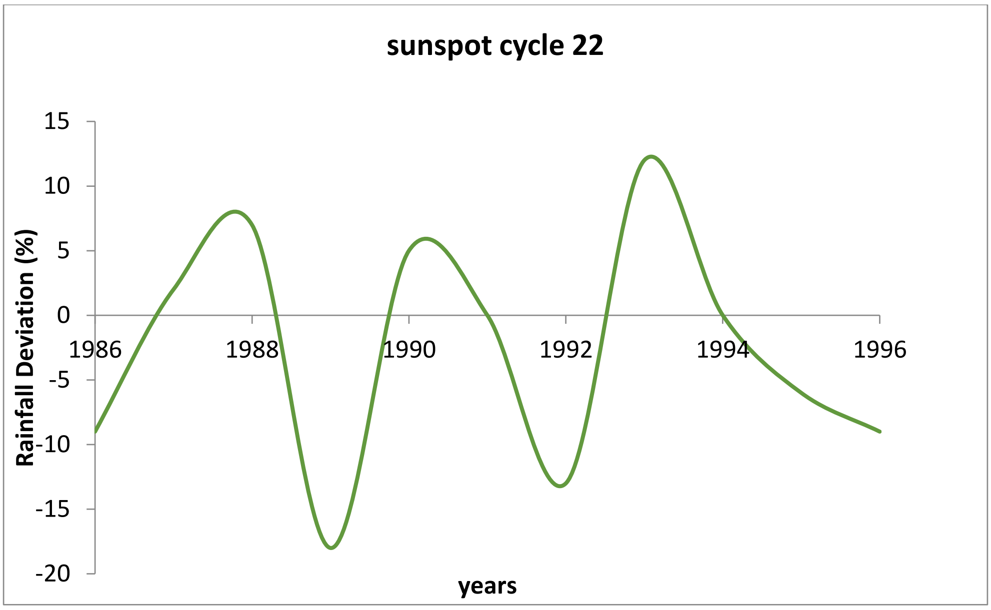
sunspot cycle 22
Rainfall Deviation (%)
15
10
5
0
-5
-10
-15
-20
1986
1988
1990
1992
1994
1996
years

Fig 5 (i)

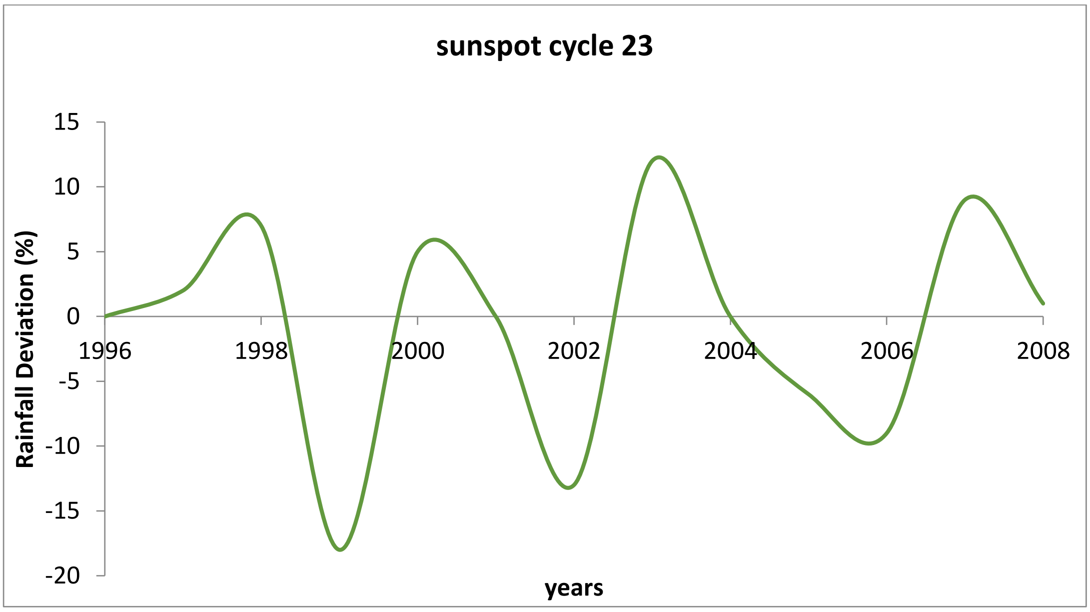
sunspot cycle 23
Rainfall Deviation (%)
15
10
5
0
-5
-10
-15
-20
1996
1998
2000
2002
2004
2006
2008
years

Fig 5 (j)

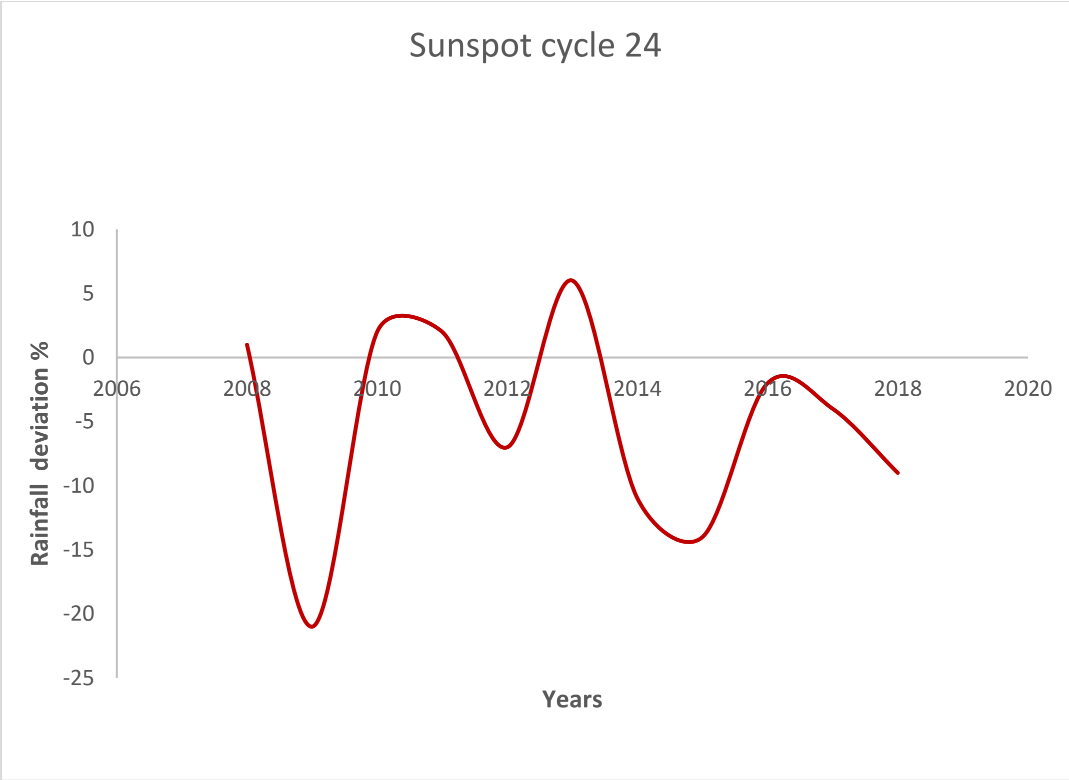
Sunspot cycle 24
10
5
0
-5
-10
-15
-20
-25
Rainfall deviation %
2006
2008
2010
2012
2014
2016
2018
2020
Years

Fig 5 (k)

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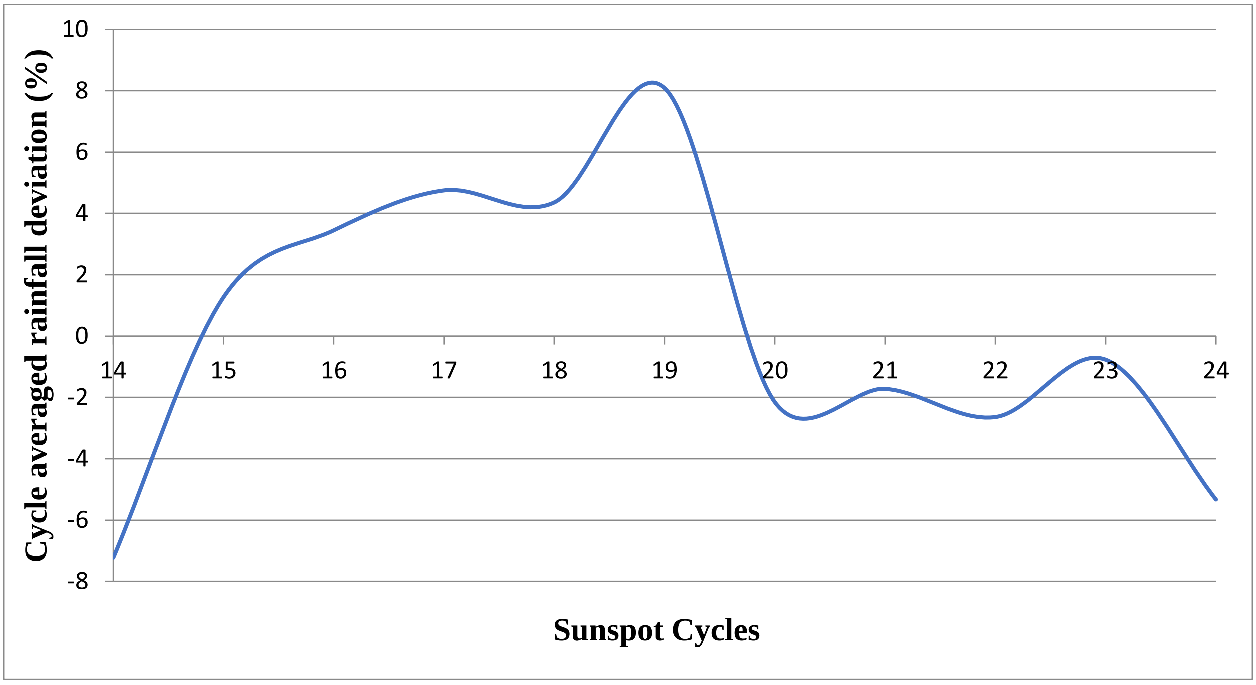

Fig. 6 Sunspot cycle averaged Indian monsoon yearly rainfall deviations- $(\eth R_{f})_{av}$ for the sunspot cycles 14-24

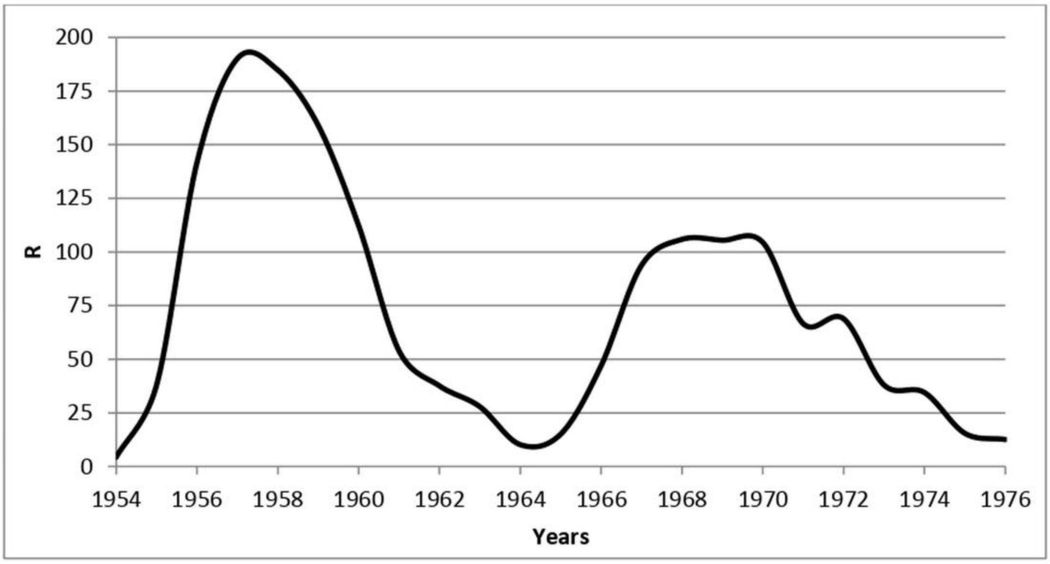

Fig 7 (a): Yearly mean sunspot number (R) for the years 1954-1976 (Solar cycles 19 and 20)

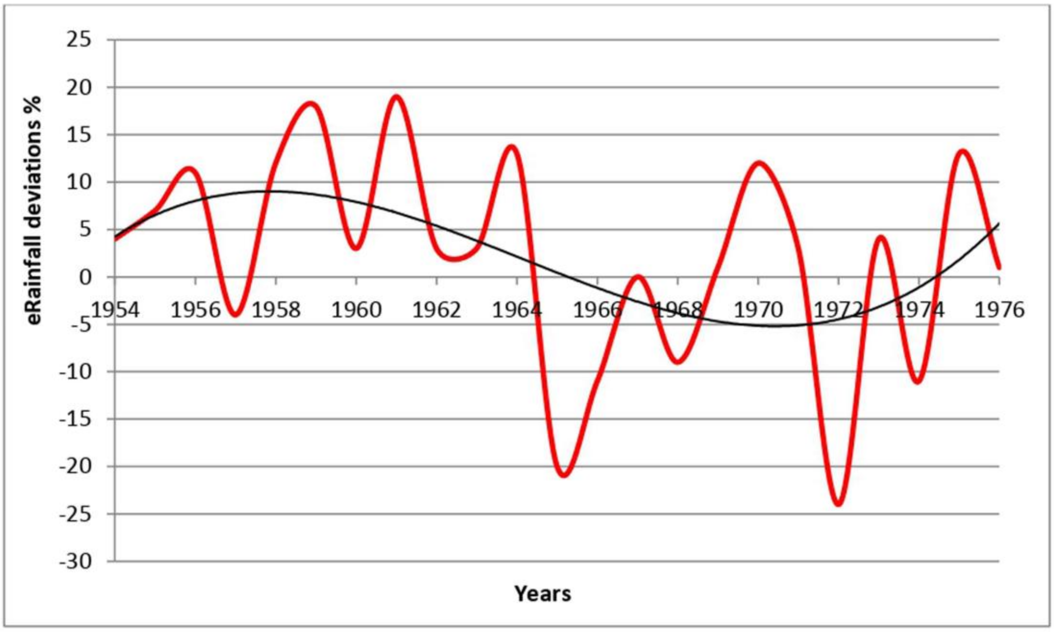

Fig 7 (b): Yearly All India monsoon rainfall deviations from the normals for the sunspot Cycles 19 and 20 (years 1954-1976). The smoothed curve clearly shows the transition from positive to negative values of the rainfall deviations as amplitude of cycle 20 drops nearly half of cycle 19

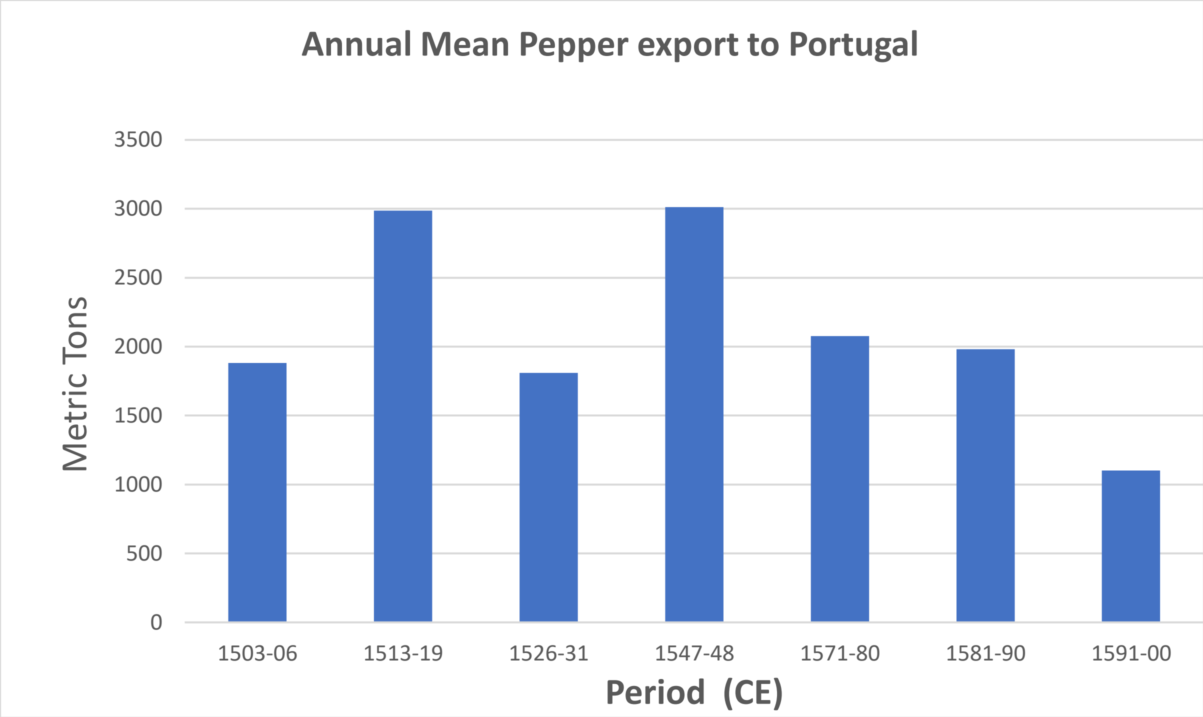

Fig 8 Portuguese pepper imports from India during the 16th century (after Wake,2017)

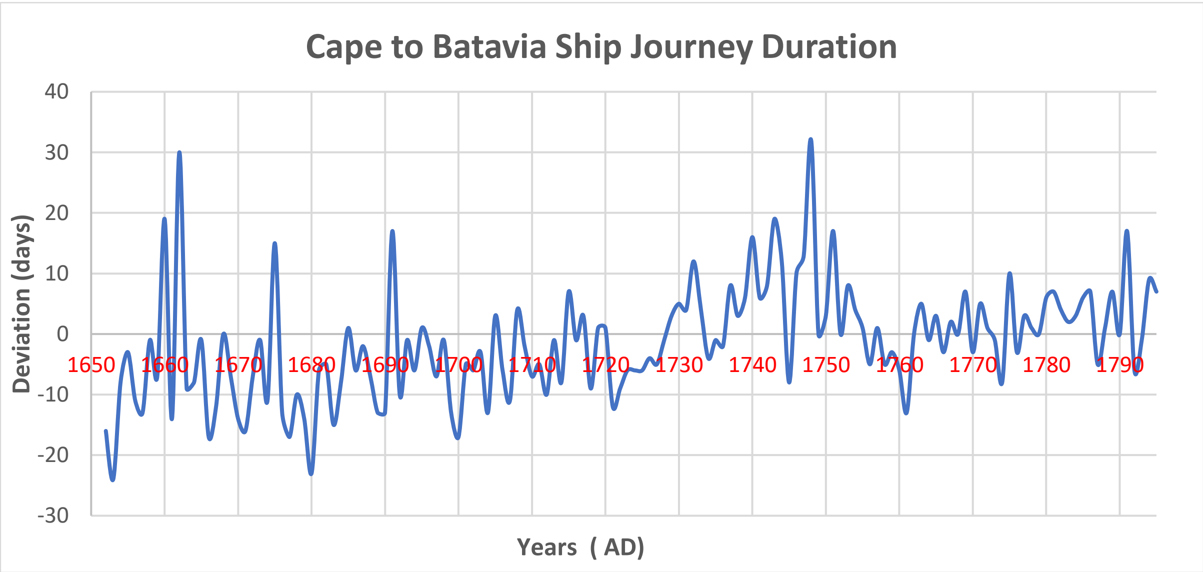

Fig 9 Deviations of the Cape to Batavia annual mean VOC ship voyage duration from the long term averages during the years 1652-1795 (estimated from Mertens,2003)

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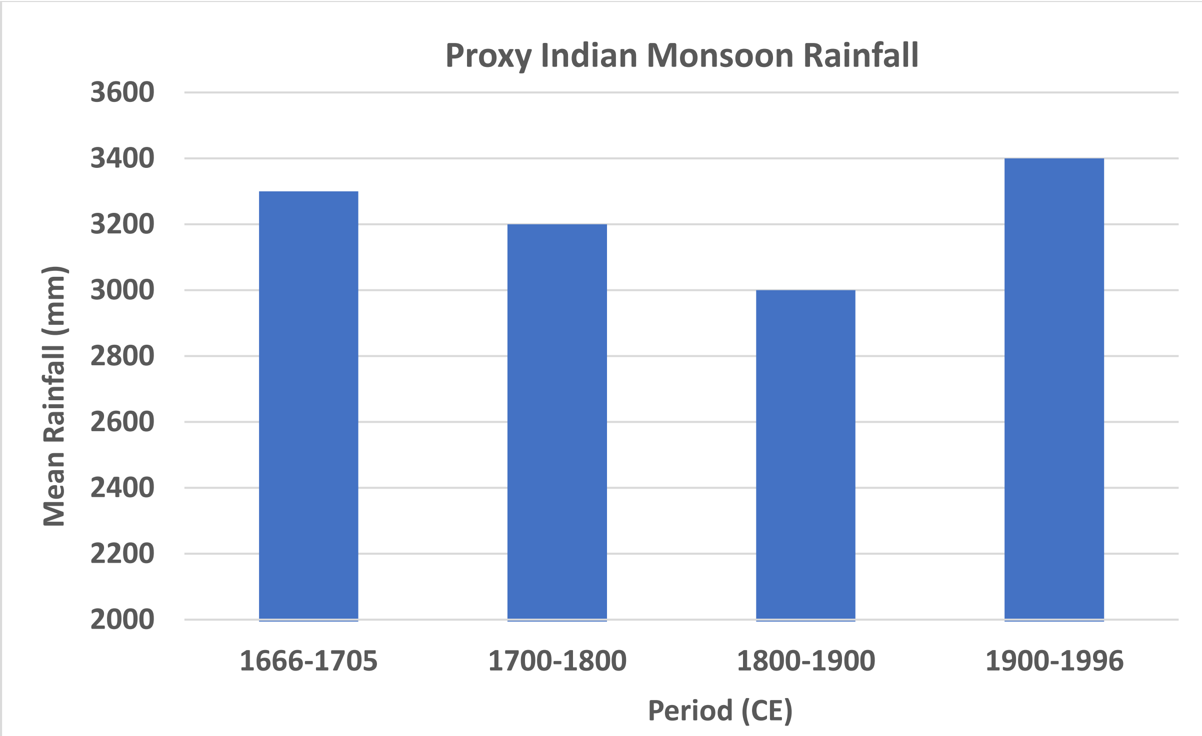

Fig 10 Period averages of Speleotherm based proxy Indian monsoon rainfall (calculated from Yadava et al, 2004)

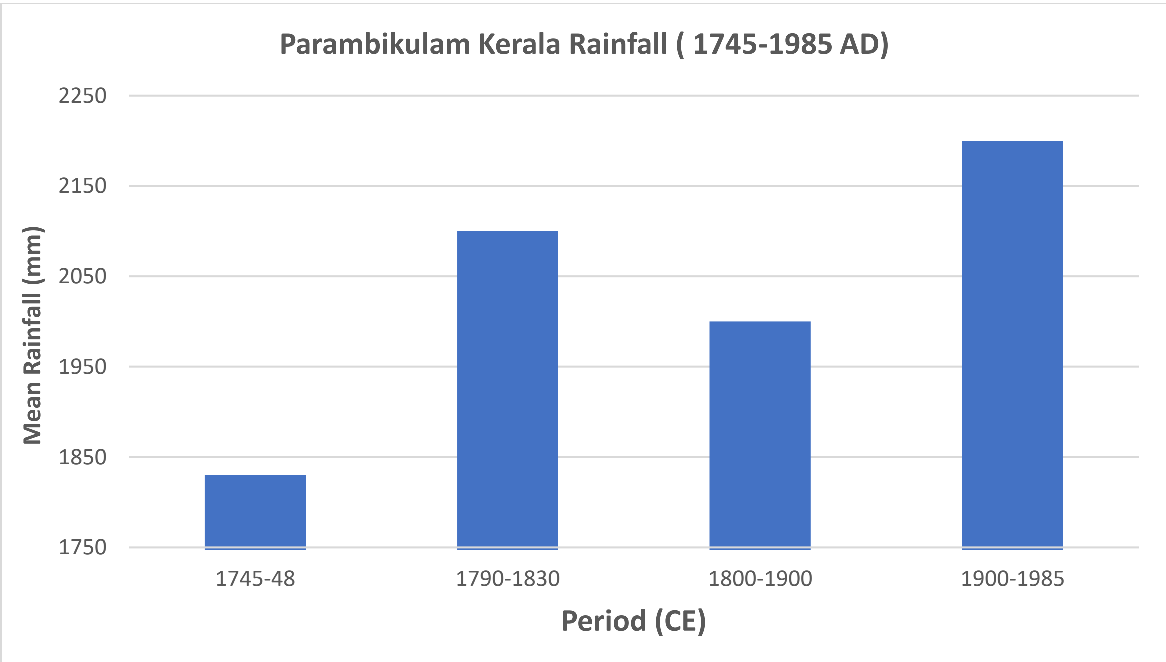

Fig 11 Period averages of Parambikulam (Kerala) annual monsoon rainfall inferred from oxygen isotope measurements (calculated from Ramesh et al,2010).

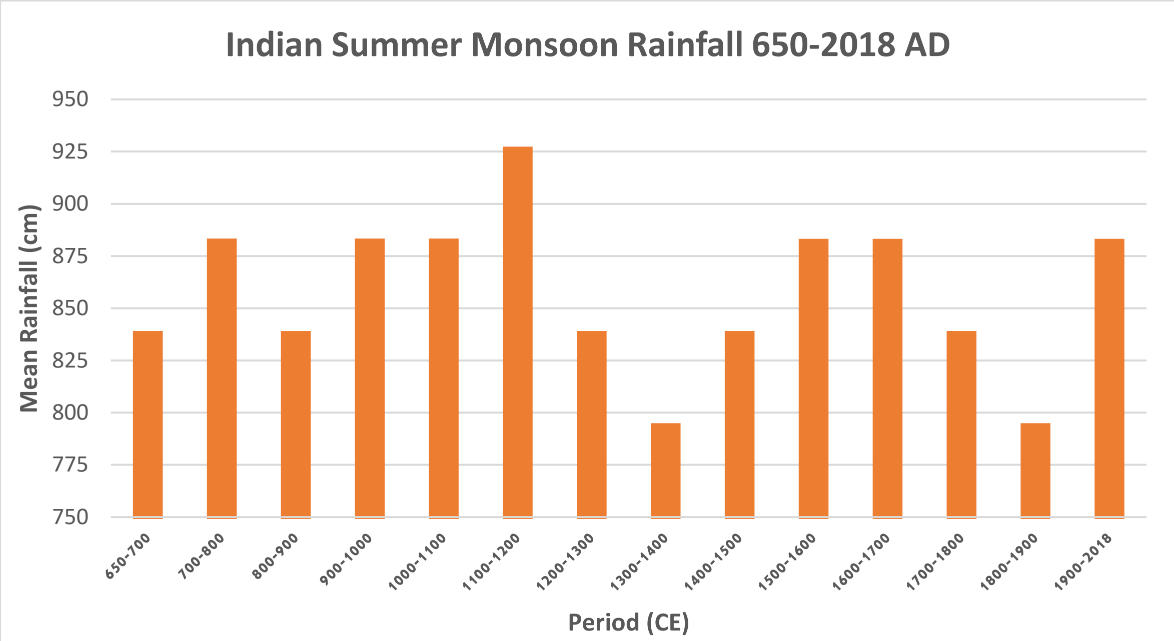

Fig 12 Period averages of Indian summer monsoon rainfall calculated using different proxy data from 7th century to 19th century AD with reference to recent normals (1901-2018).