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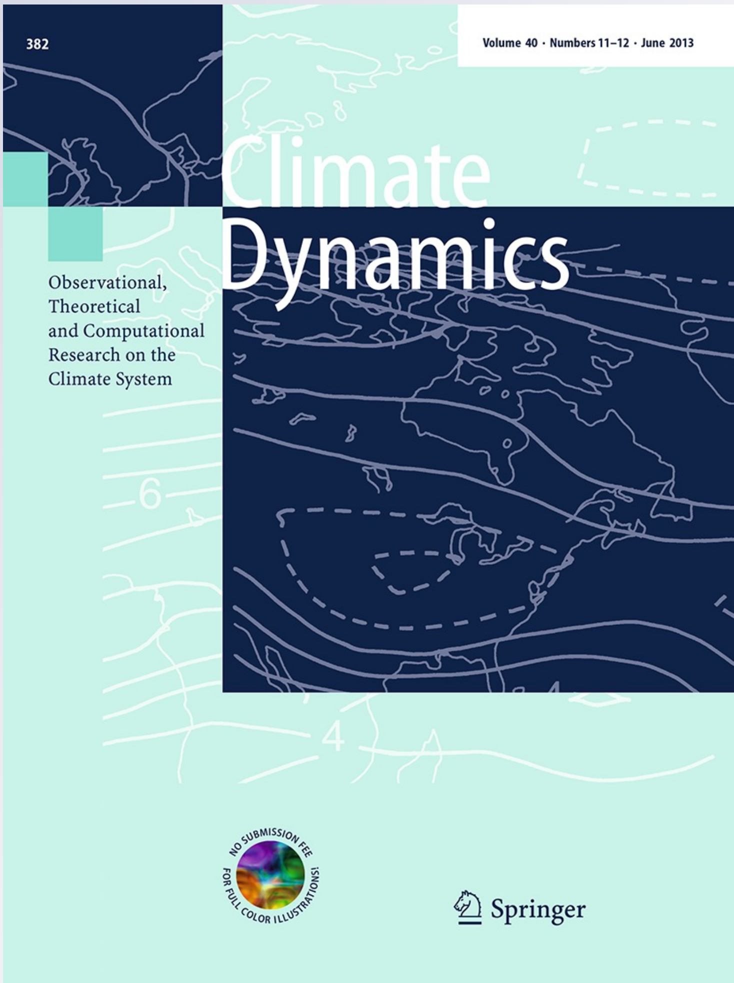
Climate Dynamics
Observational, Theoretical and Computational Research on the Climate System

ISSN 0930-7575
Volume 40
Combined 11-12

Clim Dyn (2013) 40:2589-2603
DOI 10.1007/s00382-012-1494-x



Springer

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DOI 10.1007/s00382-012-1494-x

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Received: 19 February 2012 / Accepted: 11 August 2012 / Published online: 24 August 2012

Abstract The date of onset of the southwest monsoon in western India is critical for farmers as it influences the timing of crop plantation and the duration of the summer rainy season. Identifying long-term variability in the date of monsoon onset is difficult, however, as onset dates derived from the reanalysis of instrumental rainfall data are only available for the region from 1879. This study uses documentary evidence and newly uncovered instrumental data to reconstruct annual monsoon onset dates for western India for the period 1781–1878, extending the existing record by 97 years. The mean date of monsoon onset over the Mumbai (Bombay) area during the reconstruction period was 10 June with a standard deviation of 6.9 days. This is similar to the mean and standard deviation of the date of monsoon onset derived from instrumental data for the twentieth century. The earliest identified onset date was 23 May (in 1802 and 1839) and the latest 22 June (in 1825). The longer-term perspective provided by this study suggests that the climatic regime that governs monsoon advance over western India did not change substantially from 1781 to 1955. Monsoon onset over Mumbai has occurred at a generally later date since this time. Our results indicate that this change is unprecedented during the last 230 years. Following a discussion of the results, the nature of the relationship between the date of monsoon onset and the El Niño-Southern Oscillation is discussed. This relationship is shown to have been stable since 1781.

Keywords Summer monsoon · Documentary evidence · ENSO · Western India

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1 Introduction

Despite progress in the development of alternative forms of irrigation, the majority of contemporary agricultural activity in western India (Fig. 1) is rain-fed and therefore governed by the summer (southwest) monsoon (Kumar et al. 2004; O'Brien et al. 2004). Fluctuations in the spatio-temporal distribution and quantity of monsoon rains may therefore have an adverse effect on the agricultural sector, with cascading impacts upon the wider economy. Variations in the quantity of monsoon rainfall are most important for agricultural production. However, the date of monsoon onset is also critical for farmers, since it influences the timing of crop planting and the duration of the rainy season (Raju et al. 2007).

The official date of onset for the monsoon over India is given as the date of Monsoon Onset over Kerala (MOK). This generally falls on 1st or 2nd June (standard deviation 8 days; Mooley and Shukla 1987; Rao et al. 2005). The atmospheric processes that lead to the onset of the summer monsoon are well known (cf. Pearce and Mohanty 1984; Mooley and Shukla 1987; Webster et al. 1998; Rao et al. 2005; Bhowmik et al. 2008; Tyagi et al. 2011). The monsoon onset occurs as a result of the northward advance of the Tropical Convergence Zone (TCZ; Gadgil 1988)

Fig. 1 Key locations in India mentioned in the text

from its winter position between 0° and 5°N to its mean summer latitude of 20°N. Rains advance in a northwesterly direction across the Bay of Bengal through May, with the onset of the summer monsoon over south India normally occurring in early June. Following monsoon onset, the Northern Limit of Monsoon (NLM) advances northward across the subcontinent, resulting in rainfall across India by 15th July on average (Tyagi et al. 2011).

The date of monsoon onset is regulated predominantly by the action of intraseasonal oscillations (Lim and Kim 2007). Several authors (e.g. Joseph et al. 1994; Fasullo and Webster 2003; Goswami and Xavier 2005; Lim and Kim 2007; Xavier et al. 2007) have also postulated a relationship between the El Niño Southern Oscillation (ENSO) and the date of monsoon onset, with El Niño (La Niña) conditions generally associated with a later (earlier) onset. There is some dispute as to the mechanism through which ENSO affects the date of onset, with Joseph et al. (1994) suggesting a transfer through sea surface temperature (SST) anomalies and Xavier et al. (2007) proposing an atmospheric driver. Sankar et al. (2011) highlighted the role of suppressed convection in the maritime continent region (Indonesia) in delaying monsoon onset, which may be associated with El Niño events and/or positive Indian Ocean Dipole (IOD) episodes.

Pre-onset rains may occur over peninsular western India due to the development of tropical cyclones or 'onset vortices' (Bhowmik et al. 2008). These can form within the southeastern Arabian Sea during late May at approximately 15°N and travel in a north/northwest direction (Philip et al. 1973; Krishnamurti et al. 1981; Rao et al. 2005). Occasionally a double (or 'bogus') onset may occur in late May. This is normally due to high intraseasonal oscillation activity and results in the establishment of full monsoon circulation across the subcontinent for a period lasting not longer than a week, followed by drought conditions and a delayed 'real' onset (Flatau et al. 2001; Pai and Nair 2009).

There is a need to be able to forecast the timing of onset and predict its progress over the country. This is reliant on an adequate understanding of the long-term relationship between the timing of monsoon onset and global climatic modes such as ENSO (Bansod et al. 1991; Goswami and Xavier 2005; Lim and Kim 2007; Raju et al. 2007). Further to this, it is important to ascertain whether there have been any recent changes in the climatic regime governing monsoon onset in light of rising CO_2 levels. This is of particular relevance given recent work by Tyagi et al. (2011), who show that average monsoon onset over Mumbai has shifted to a later date during the last three decades of the twentieth century. If these issues are to be addressed it is essential that high quality historical information about monsoon onset and advance is available. Currently there is a lack of reliable information about the date of onset for periods prior to the late nineteenth century. The earliest published official date of monsoon onset over western India, for example, based upon the reanalysis of instrumental rainfall data (see Sect. 3.1), is for 1879 (IMD 1943). This significantly limits analyses of long-term trends, as well as constraining potential for back-trajectory analysis using climate models.

This study aims to address the research areas mentioned above by (1) extending the record of the date of monsoon onset using historical sources, and (2) exploring whether the onset date and (3) the relationship of onset date to global climate modes such as ENSO has changed over time. First, we present a reconstruction of monsoon onset dates for western India from 1781 to 1878. The reconstruction focuses upon the region around Mumbai (historically known as Bombay), and uses a combination of documentary evidence and newly uncovered instrumental meteorological data to determine the historical date of monsoon onset. Western India, and Bombay in particular, has been selected as the study area due to a wealth of available historical documentary material, owing mainly to the commercial trading operations of the British East India Company (EIC). Second, we combine our chronology of reconstructed onset dates with existing published records from 1879 to 2011 to produce an extended dataset of monsoon onset over Bombay. This extended dataset is examined to assess whether any evidence exists for a change in the climatological regime governing monsoon onset during the last 230 years. Third, we use the extended dataset to examine the stability of the ENSO-monsoon onset relationship over time. Goswami and Xavier (2005) have suggested that this relationship remained stable from 1950 to 2003; however, no studies have attempted to analyse this relationship over a 230 year time period. The paper concludes with a brief consideration of the ways in which methodologies of monsoon onset reconstruction could be improved.

2 Data sources

Two types of historical sources were used for reconstructing the date of monsoon onset over Bombay. The first were English-language narrative materials including written reports, correspondence, personal papers, diaries and newspaper articles containing anecdotal and more formal descriptions of weather conditions and longer-term climate trends. The second were instrumental meteorological observations, mostly in the form of weather summaries published in newspapers. These are referred to hereafter as 'historical' rainfall data to distinguish them from extant published instrumental data pertaining to monsoon onset, which are available from 1879 onwards (Kumar et al. 1999). Details of the main archives used are shown in Table 1 (together with the codes used in Sects. 3 and 4 when quoting from individual documents). Issues relating to the use of such sources for climate reconstruction have been discussed elsewhere (e.g. Ingram et al. 1981; Pfister 1992; Glaser 1996; Bradley 1999; Nash and Endfield 2002, 2008; Grab and Nash 2010; Nash and Grab 2010). For this study the key issues relate to the faithful transmission of the dates of recorded climatic events, and the reliability of their identification by non-expert observers. Where these issues arise they are addressed in Sect. 3.

2.1 Narrative materials

The most important source of narrative materials was the India Office Archives, housed in the British Library, St. Pancras, London, UK. These archives contain the 'India Office Records' of the EIC who formed the colonial government of the Bombay Presidency administrative region of western India during the study period. The earliest EIC records for the study area are restricted to official correspondence and documentation sent from Bombay, Surat and Bankot to the EIC Board of Directors (and later the British Government), but by 1860 documents cover the majority of present-day Gujarat and Maharashtra. The Records contain syntheses of commercial activities, revenue, military matters, judicial decisions of the Presidency government and significant events (including major droughts) that were deemed necessary to send back to London.

The India Office Archives also contain extensive collections of 'Private Papers', including correspondence, diaries (in some cases long-running) and ledger books written by colonial and military officials who were operational in western India. The climatic information within these sources is variable—they were neither created for publication, nor, with few exceptions, to record meteorological conditions—but is occasionally very detailed (Adamson 2012). Several miscellaneous documents relating to British India are also stored within the India Office Archives. Most noteworthy is a travel diary by a Dr. Anton Pantaleon Hove, entitled 'Tours for Scientific and Economical Research of Guzerat-Kattiawar and the Conkuns, in 1787–1788'.

Material within the British Library collections was supplemented by other English-language records available for the study area and period, notably those written by missionaries. Missionary activity was prohibited initially within the EIC's domains. However, rules were relaxed in the early nineteenth century, allowing the American Board of Commissioners for Foreign Missions (ABCFM), Church Missionary Society (CMS) and Scottish Missionary Societies (SMS), amongst others, to establish mission stations across western India. Collections of materials from these missionary societies are now archived at Harvard University, Boston, USA (ABCFM), the University of Birmingham, UK (CMS) and the National Library of Scotland, Edinburgh, UK (SMS). The documentation within these archives comprises reports and letters from missionaries in the field back to their respective central offices, together with private correspondence.

Further information was collected from the archives of the Government of Maharashtra, Mumbai, India. These contain the records of the Government of the Bombay Presidency and early Factory records for EIC settlements in western India during the 17th and 18th centuries. The records comprise predominantly of letters between government employees, as well as minutes of meetings, official proclamations and circulars, and petitions from the local population to the colonial government. Other miscellaneous materials were also consulted within the UK, including documents held within the National Library of Scotland, Edinburgh, and the archives of the Aberdeen Medico-Chirurgical Society (University of Aberdeen) and the Royal Society, London.

2.2 Historical instrumental meteorological observations

Back-issues of English-language newspapers from Bombay were scrutinised for reports of weather conditions during the study period, including narrative accounts of the onset

Table 1 Details and codes for archival collections consulted in the UK, USA and India

Name of collection	Archive location	Archive code
India Office Records	British Library, St Pancras, London, UK	BL followed by catalogue number
India Office private papers	British Library, St Pancras, London, UK	BL followed by catalogue number
British Library Newspaper Collection	British Library, Colindale, London, UK	BLNC followed by catalogue number
Church Missionary Society	University of Birmingham Library, UK	UBL followed by catalogue number
American Board of Commissioners for Foreign Missions	Houghton Library, Harvard, USA	HLH followed by catalogue number
Scottish Missionary Societies	National Library of Scotland, Edinburgh, UK	NLS followed by catalogue number
National Library of Scotland archives	National Library of Scotland, Edinburgh, UK	NLS followed by catalogue number
Archives of the Government of Maharashtra	Department of Archives, Government of Maharashtra, Mumbai, India	DAGM followed by catalogue number
Royal Society archives	Library of the History of Science, Royal Society, London, UK	RSA followed by catalogue number
Aberdeen Medico-Chirurgical Society	University of Aberdeen Library, UK (available online)	UAL followed by catalogue number

of the monsoon and instrumental meteorological information. The primary publications consulted were the *Bombay Courier* (1793–1844) and the *Bombay Times* (1844–1859), both housed within the British Library Newspaper Collection, Colindale, London. Issues of the *Bombay Courier* were published fortnightly in 1793, increasing to thrice weekly from 1840. The *Bombay Times* was published thrice weekly from 1844, increasing to daily in 1850. For years where data were lacking in the *Bombay Courier* and *Bombay Times*, copies of the *Bombay Gazette* and later the *Bombay Standard* were consulted. Holdings of the *Bombay Gazette* at Colindale are incomplete, so copies from 1809–1812 were consulted at the archives of the Government of Maharashtra in Mumbai.

Significantly, these newspaper titles incorporate large quantities of historical instrumental rainfall data. The earliest discovered rainfall measurements date from June 1814, including data from several rain gauges in Bombay (at Byculla, the Fort, the Esplanade, Chowpatty and Colaba). No gauge presented a full run of data, the most complete data existing for Byculla (complete from 1814–1835), the Fort (complete from 1837 to 1843), and Colaba (complete from 1842, incorporating data from the Colaba Observatory from 1844). Sporadic data were available from the other gauges for the remaining years. Incomplete meteorological datasets were published for other cities around the study area, including Thane, Dapoli, Ratnagiri, Pune, Ahmednagar, Surat, Ahmedabad and Kheda. None of these data comprised of a full run of years. From 1844 to 1878 instrumental data were taken from the publication 'Report of Rainfall in the Bombay Presidency, Volume 1', which is stored in the British Library. This included data collected at the Colaba Observatory (1844–1878) and Byculla (1872–1878). Some published meteorological observations for western India that appeared within contemporary academic journals were also consulted (e.g. Banks 1790; Nicholls 1819; Skyes 1835).

3 Data collection and analysis

3.1 Defining monsoon onset

There is currently no universally accepted definition of monsoon onset and its advance over India. The Indian Meteorological Department (IMD) has two procedures for determining onset: 'operational' and 'reanalysis'. Operational onset dates are announced 'live' during the monsoon onset period and are determined using a mixture of quantitative and qualitative methodologies. Reanalysed monsoon onset dates are determined retrospectively at the end of each monsoon season from instrumental rainfall data. Reanalysed dates are generated to provide a consistent and quantitative measure of monsoon onset, and are the dates referred to in most IMD publications (e.g. Deshpande et al. 1986; Kumar et al. 1999; Tyagi et al. 2011).

Until 2006, the operational procedure for determining MOK used the approach outlined in Ananthakrishnan et al.

(1968), whereby MOK is declared on any date after 10th May where five of seven meteorological stations (Alapuzha, Colombo, Kochi, Kozhikode, Mangalore, Minicoy and Thiruvananthapuram) received rainfall of 1 mm in 24 h for two consecutive days. The susceptibility of this method to 'bogus' onsets has long been recognised (Rao 1976; Webster et al. 1998), leading to attempts to present objective definitions of monsoon onset based on remote sensing data (Fasullo and Webster 2003; Goswami and Xavier 2005; Pai and Nair 2009; Wang et al. 2009). As a result of these studies, the IMD recently adopted a new methodology to determine MOK. This is now declared if, after 10th May, 60 % of 14 stations (Allapuzha, Amini, Cannur, Kasargode, Kochin, Kollam, Kozhikode, Kottayam, Mangalore, Minicoy, Punalur, Talassery, Thiruvananthapuram and Trissur) report $\geq$2.5 mm rainfall for two consecutive days, and criteria relating to the depth of the westerlies, zonal wind speed and INSAT-derived outgoing longwave radiation are satisfied (Joseph et al. 2006; Pai and Nair 2009). The onset over other parts of India is categorised as the northward advance of the NLM. Advance is declared using a subjective method, based on a sharp rise in rainfall, but which ensures that the spatial continuity of the NLM is maintained. Position of the maximum cloud zone over the western Indian peninsular is also taken into account, and satellite water vapour images used to assess the extent of moisture incursion (IMD 2011).

The reanalysed monsoon onset dates that appear in most literature are based on pentad (5-day) instrumental rainfall data. Reanalysed onset dates across India have been published in three documents (IMD 1943, 1990; Tyagi et al. 2011). Each tabulate monsoon onset dates up to their respective year of publication using the same classification: substantial rise in rainfall for the middle day of a pentad average of rainfall (IMD 1990). Onset is declared if a marked increase in rainfall is noted, and if three or more 'rainy days' occur within the 5-day period. From 1971 to 2000, this method gives a correlation of 0.88 against the onset dates declared using the operational procedure, when comparing dates across the whole country (Tyagi et al. 2011). The average date of onset over Mumbai for 1971–2000 gives the same date for both operational and reanalysed date of onset (12th June).

The number of methods for defining monsoon onset presented a challenge for developing a methodology for reconstructing monsoon onset. The methodology adopted here is designed to be equivalent, as far as possible, to that presented in Kumar et al. (1999), Joseph et al. (2006) and Tyagi et al. (2011). Three different approaches to onset reconstruction are presented in Sect. 4. The first utilises documentary data alone, and spans the period 1781–1860. The second uses historical instrumental data alone for years where these are available (1814–1878). The third reconstruction uses a combination of historical instrumental data and documentary records, and spans 1781–1878. The methodology used in each of these reconstructions is now considered.

3.2 Monsoon onset reconstruction using documentary sources

Documents from each of the narrative sources described in Sect. 2.1 were read, with all descriptions of weather conditions during the months of May to July in each year recorded verbatim. Individual quotations were then assembled chronologically to allow a picture of conditions immediately prior to, during and following the onset of monsoon conditions to be established. Criteria were then developed to identify the date of monsoon onset over Bombay in any given year. These were based on contemporary determinants of monsoon onset over India, as described in Sect. 3.1, tailored to reflect the types of meteorological descriptions present within the documentary material consulted. The specific criteria were:

- A marked increase in rainfall, which was described by observers as being continuous. Rainfall of a short duration, described as a 'thunderstorm', 'squall' or similar terminology, was determined to be associated with an onset vortex and not genuine monsoon circulation;
- A change of wind direction to the south or southwest, with these conditions prevailing, potentially accompanied by an increase in wind strength;
- A marked drop in pressure and temperature, which is maintained.

Where information was available from other locations, this was taken into account to ensure that the spatial continuity of the NLM was maintained (i.e. that onset at Bombay occurred before onset at Gujarat and after onset at areas in the southern Konkan). Tyagi et al. (2011) demonstrated that the average onset date at Pune was 2 days before date of onset at Bombay using data from 1901 to 1980, but was the same day as onset at Bombay using data from 1971 to 2000. Onset date at Pune was therefore used to validate onset at Bombay, ensuring that advance over the two areas occurred within $\pm$2 days. Where information was available for Pune but not Bombay (as is the case for 1811–1813 and 1816), the onset date at Bombay was assigned a value of one day after onset at Pune, with error boundaries of $\pm$2 days.

For several years, the onset of the monsoon was directly declared as such by an observer. Where this was the case, and no other corroborating evidence could be found, the reliability of the observation was determined by the characteristics of the observer. This was based on their length of time in India, level of education and their interest/knowledge of meteorological phenomena (as determined by their wider writings) (cf. Glaser 1996). Where no clear declaration of onset was observed, onset was classified midway between dates exhibiting dry conditions and those exhibiting monsoon rainfall, with an error boundary assigned.

As an illustration of this methodology, two quotations from the *Bombay Courier* during 1798 allow the monsoon onset date for that year to be determined. An article from early June noted:

> Within this week past the weather has undergone a very striking change; the days insufferably hot, have been succeeded by nights of heavy rain attended with violent storms of thunder and Lightning, certain indications of the approaching Monsoon. (BLNC MC 1112, 2nd June 1798).

An article from three weeks later recorded:

> It would appear that our early rain had protracted the regular course of our Monsoon, insomuch that when we might have expected the wind in the Southwest it has been northerly and when our fields required to be deluged with rain our farmers were complaining of drought: happily however within these 2 or 3 days the weather has changed and any alarms that might have been entertained for the success of our future cultivation have subsided. (BLNC MC 1112, 23rd June 1798)

The meteorological conditions described in the second quotation suggest that the conditions in early June were associated with localised convective activity or onset vortices, and not large-scale changes in circulation patterns. The date of monsoon onset was therefore assigned as 20th June with an error bar of +1 day.

Determining the date of monsoon onset for some years was more difficult. In 1824, for example, low rainfall apparently fell during the latter half of June. The then Governor of Bombay, Mountstuart Elphinstone, wrote in his diary for 13th June 1824 that:

> At 11½ o'clock the Monsoon has just set in after the pleasantest hot season I have ever spent. The thermometer which was 92° has fallen to 82° and I am sitting in my coat. It is a moderate shower with wind but not deluge & no storm. (BL MSS Eur F88/426, 13th June 1824).

However, on the same day another observer, Lucretia West, wrote, "It has rained very hard to day, but I fear not the Monsoon" (BL MSS Eur D888/1, 13th June 1824). West and Elphinstone's interpretation of conditions continued to vary throughout the month, with Elphinstone writing on 18th June "There has been no heavy rain yet but the rains are quite set in" (BL MSS Eur F88/426, 18th June 1824) and West concluding on 22nd June that "We have Shower's but no regular Monsoon" (BL MSS Eur D888/1 22nd June 1824). The *Bombay Courier* summarised rainfall conditions over Bombay during June 1824 thus:

> Although Bombay has been visited by a few inconsiderable showers, during the last ten days, we are concerned to state that as yet there is little appearance of the regular monsoon. We have strong South west breezes it is true, which serve to allay the excessive heat of the season, but a supply of rain, the great requisite, is still wanting. (BLNC MC 1112 3rd July 1824).

Interpretation of the date of monsoon onset in this case is dependent on a relative assessment of the reliability of observers. Mountstuart Elphinstone had lived in India for 28 years before 1824, and had resided in Bombay from 1819. He had a strong interest in meteorology and wrote about science in his diaries (Adamson 2012). West had arrived in Bombay in 1823 and had only experienced one monsoon before 1824 (ibid.). It is inferred, therefore, that Elphinstone's observations are of greater reliability than West's. As such, 13th June was assigned as the date of monsoon onset over Bombay for 1824. Although the *Bombay Courier* mentions "little appearance of a regular monsoon", the description of winds from the southwest suggests that the monsoon had set, albeit with a reduced intensity.

3.3 Monsoon onset reconstruction using historical instrumental meteorological data

Historical instrumental rainfall data for 1814 and 1817–1878 identified within the sources described in Sect. 2.2 were digitised and combined with other previously published data. The date of monsoon onset at Bombay was determined using the methodology outlined by the IMD (IMD 1990; Tyagi et al. 2011), whereby monsoon advance over a location is declared by analysing significant increases in precipitation observable in pentad rainfall. Under this method, monsoon rainfall is declared to have started on the middle day of a 5-day period where significant increases in rainfall occur and where at least three 'rainy days' are apparent.

Only days exhibiting rainfall at $\geq$2.5 mm were deemed to be 'rainy' for this analysis. This was selected to be concurrent with the existing IMD methodology for determining MOK (cf. Joseph et al. 2006; Pai and Nair 2009), described in Sect. 3.1. In order to avoid false classifications due to bogus onsets, or the action of onset vortices, onsets were discounted if a pentad exhibiting 3 days of significant rain was then followed by at least 4 days of no rain or rain at <2.5 mm.

3.4 Monsoon onset reconstruction using combined documentary and historical instrumental data

For the final reconstruction of the date of monsoon onset over Bombay between 1781 and 1878, a combined methodology using historical pentad rainfall data and documentary information was adopted. This allowed for both prevailing meteorological conditions described by observers and within historical instrumental rainfall data to be taken into account. For the years 1781–1813, documentary data alone were used, as these were the only data available. For years after 1814, historical pentad rainfall data were used as the first point of reference as these provide the best comparison with re-analysed monsoon onset dates for 1901–2011 published by the IMD (Tyagi et al. 2011; Tyagi, personal correspondence).

A slight departure was necessary from the IMD methodology to ensure continuity between years where historical instrumental data were available and years where they were not. It is possible under the IMD method for the date of monsoon onset to be declared on a day exhibiting no rainfall, which is highly unlikely when using the documentary reconstruction approach. Where this occurred, the date of monsoon onset determined under the pentad methodology was moved backwards or forwards by one day, according to which best agreed with the documentary reconstruction. For the final years of the reconstruction period where historical rainfall data were available only, an error bar of ± 1 day was assigned if the middle date of the pentad exhibited rainfall below the 2.5 mm threshold. An error bar of -1 day was assigned if both the second and third days of the pentad exhibited rainfall below the threshold, with the onset date given as the fourth day. There were no instances where the third and fourth days of the pentad exhibited rainfall below the threshold.

Where reconstruction dates using documentary data alone differed from historical pentad rainfall by one day only, dates from pentad rainfall were assigned. Where the dates differed by more than one day, the onset dates were chosen that were deemed to be most reliable, following these criteria:

- If the documentary information was regarded to be unreliable, or if the descriptions of the date of onset were ambiguous, the date from the historical pentad rainfall was selected.
- If the historical pentad rainfall data were ambiguous due to a lack of a marked spike in rainfall, or if disagreements were evident between rain gauges in Bombay, onset date was selected from the documentary data. This was particularly relevant if documentary data contained information on pressure changes or wind direction, which were published regularly in the *Bombay Times* during the latter years of the reconstruction period.
- Where information from other areas was available, a date was selected which allowed the spatial extent of the NLM to be maintained (see Sect. 2).

Where disagreements existed between the documentary and historical instrumental data that could not be overcome using these criteria, a mid-point date was assigned with error bars indicating the range of possible dates.

4 Results

The reconstructed dates of monsoon onset over Bombay using documentary-only, historical instrumental-only and combined documentary and historical instrumental data sources are summarised in Table 2 and plotted (with error bars) in Fig. 2. In comparison with previous studies (e.g. IMD 1943, 1990; Deshpande et al. 1986; Chowdhury et al. 1990; Kumar et al. 1999; Tyagi et al. 2011), these results extend our knowledge of the date of monsoon onset for western India by 97 years.

The mean date of monsoon onset for the period reconstructed using documentary sources only (1781–1860) was 9th June (160.4 Julian days), with a standard deviation of 7.1 days. This is similar to the mean and standard deviation of the date of monsoon onset over Bombay derived for the twentieth century (cf. IMD 1943, 1990; Deshpande et al. 1986; Chowdhury et al. 1990). The mean date of monsoon onset for the period 1814–1878 determined from historical instrumental data only was 10th June (161.0 Julian days) with a standard deviation of 7.2 days.

A comparison of the reconstructed onset dates during the period of overlap of documentary and historical instrumental data (1814–1860) permits the documentary-based reconstruction to be validated (Fig. 3). The mean date of onset during this period, reconstructed using only documentary sources, was 10th June (161.2 Julian days) with a standard deviation of 7.1 days. The comparable mean date of onset using historical instrumental data only was also 10th June (161.0 Julian days) with a standard deviation of 7.2 days. A Fisher F-test and Student's t test found a 94 % probability that the variances within the two reconstruction methods are equal and a 96 % probability that the means are equal. The correlation coefficient between the results from the two approaches is 0.88, significant at >99.99 %. The strong agreement between the two approaches validates the use of documentary data alone for the early years of the reconstruction period.

Table 2 Date of monsoon onset over Bombay, reconstructed using (a) documentary information only, (b) historical instrumental rainfall data only, and (c) combined documentary and instrumental data

Years	Documentary evidence only	Instrumental rainfall data only	Combined data	Years	Documentary evidence only	Instrumental rainfall data only	Combined data
1781	18 June		18 June	1830	17 June	16 June	16 June
1782	29 May		29 May	1831		9 June	9 June
1783	4 June		4 June	1832	12 June	22 June	22 June
1784	6 June		6 June	1833	17 June	16 June	17 June
1785				1834	13 June		13 June
1786	12 June		12 June	1835		7 June	11 June
1787	11 June		11 June	1836	19 June		19 June
1788	12 June		12 June	1837	14 June	21 June	21 June
1789	3 June		3 June	1838		13 June	11 June
1790				1839	23 May		23 May
1791				1840	12 June	6 June	12 June
1792				1841	7 June	7 June	7 June
1793				1842		7 June	9 June
1794				1843	21 June	19 June	21 June
1795	7 June		7 June	1844	20 June	18 June	19 June
1796	7 June		7 June	1845	4 June	5 June	5 June
1797				1846	9 June	1 June	9 June
1798	20 June		20 June	1847	30 May	27 May	30 May
1799				1848	26 May	26 May	26 May
1800	9 June		9 June	1849	4 June	2 June	4 June
1801	17 June		17 June	1850	12 June	11 June	12 June
1802	23 May		23 May	1851	9 June	7 June	7 June
1803	7 June		7 June	1852	18 June	13 June	16 June
1804	13 June		13 June	1853	12 June	11 June	12 June
1805				1854	6 June	6 June	6 June
1806				1855	14 June	12 June	12 June
1807	9 June		9 June	1856	1 June	31 May	1 June
1808				1857	7 June	6 June	17 June
1809				1858		19 June	19 June
1810	6 June		6 June	1859	3 June	5 June	5 June
1811	4 June		4 June	1860	10 June	10 June	10 June
1812	9 June		9 June	1861		1 June	1 June
1813	28 May		28 May	1862		10 June	10 June
1814	16 June	16 June	16 June	1863		5 June	5 June
1815				1864		20 June	20 June
1816				1865		7 June	7 June
1817	4 June		4 June	1866		13 June	13 June
1818	12 June	10 June	11 June	1867		15 June	15 June
1819	6 June	2 June	5 June	1868		7 June	7 June
1820	13 June	12 June	13 June	1869		18 June	18 June
1821	20 June	18 June	19 June	1870		14 June	14 June
1822	28 May	27 May	27 May	1871		7 June	7 June
1823	17 June	16 June	17 June	1872		17 June	17 June
1824	13 June	12 June	13 June	1873		9 June	9 June
1825	9 June	21 June	22 June	1874		7 June	7 June
1826	1 June	30 May	1 June	1875		15 June	15 June
1827	12 June	10 June	10 June	1876		14 June	14 June
1828	15 June	14 June	15 June	1877		18 June	18 June
1829	15 June	15 June	15 June	1878		20 June	20 June

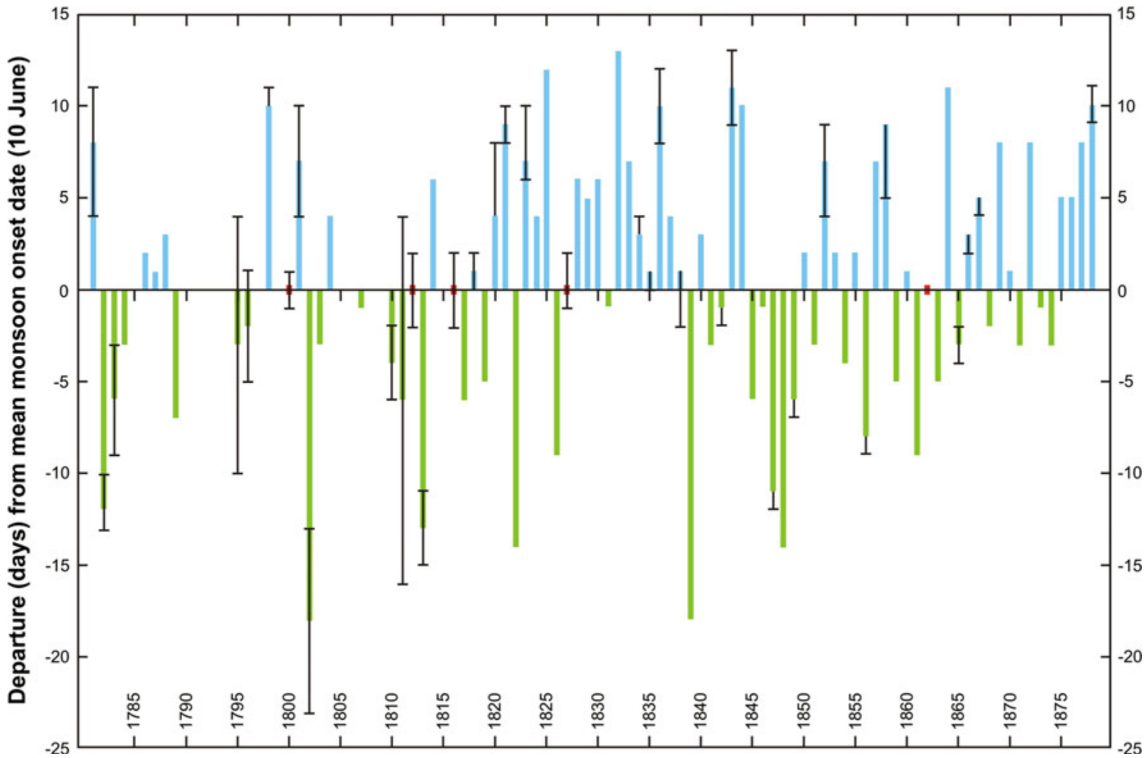

Fig. 2 Reconstructed date of monsoon onset over Bombay for 1781–1878. Positive values indicate a later date of monsoon onset. For a discussion of *error bars* please see Sects. 3.2 and 3.4

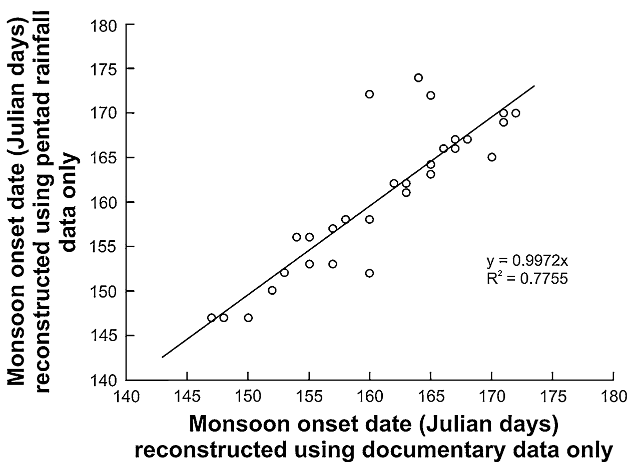

Fig. 3 Correlation between monsoon onset dates reconstructed using documentary data and pentad historical instrumental rainfall data for the period of overlap of documentary and instrumental data (1814–1860)

Between 1814 and 1860, the monsoon onset date identified from historical pentad rainfall data was within ±2 days of the onset using documentary data. However, there was greater discrepancy in 5 years (1825, 1832, 1837, 1846 and 1852), ranging from 5 days to 14 days difference between the two data sources (Table 3). The greatest discrepancy occurred in 1825, where monsoon onset was dated to 9th June using documentary data and to 22nd June using historical pentad rainfall. The reason for this discrepancy was extremely heavy rainfall on 9th June, which was declared as the monsoon onset within the diaries of Mountstuart Elphinstone and Lucretia West, and by the *Bombay Courier*. However, historical instrumental rainfall data show that this rainfall lasted for one day only and was followed by 8 days exhibiting no rainfall, suggesting an intense onset vortex on 9th June and a late onset; 22nd June was therefore selected as the date of monsoon onset.

Discrepancies between the two methodologies for 1846 and 1852 arose as the monsoon commenced without a marked spike in rainfall. During 1846, rainfall of below 10 mm (but heavy enough to classify as monsoon onset using the pentad methodology) was registered at Colaba from 1st–3rd June. This was followed by 5 days of no rain or rain <5 mm. Rainfall recommenced on 9th June, which was in agreement with a report from the *Bombay Times* (BL SM 73 10th June 1846). The date of onset for this year was therefore assigned as 9th June. Similarly, 6 days of moderate rainfall occurred from 12th to 17th June 1852, which registered as onset under the pentad methodology. However, monsoon onset was not identified from documentary data until 18th June when a marked spike in rainfall was observed. As no obvious break period was evident for this year it was not possible to classify a

Table 3 Date of monsoon onset reconstructed using documentary and historical instrumental data for years exhibiting large differences between the two methodologies, with onset date selected and justification for selection

Years	Descriptions of onset from documentary material	Observations from instrumental data	Selection of date of monsoon onset, and justification
1825	Monsoon onset first declared within documentary data on 3rd June, and then again on 9th June due to very heavy rainfall. Dry conditions then reported until 24th June	Rain on 1st June and 8th June, both measuring $\sim$ 0.7 inches. 16 inches reported on 9th June. Then no rain until 19th, 22nd, 23rd, and continuous from 25th June. Pentad method suggests 21st June as date of onset	22nd June Based on pentad rainfall methodology. Earlier rainfall is considered to have been a heavy cyclonic disturbance. 22nd selected as no rainfall on 21st
1832	One reporter states the monsoon set in on 12th June. Next available report is for 18th June at Ahmednagar, which states that the monsoon set in "8 or 10 days later than usual"	Significant rainfall ($\geq$2 inches) on 13th, 17th, 21st, 22nd June, and continuous from 24th June. Rainfall at Thane only reported from 23rd June. Pentad rainfall suggests 22nd June as date of onset	22nd June Based on pentad rainfall, and agreement with rainfall at Thane
1837	Reports from the *Bombay Courier* mention heavy rainfall at Bombay and Pune on 14th and 15th June, described as a 'severe storm', or 'hurricane'. No further reports of conditions are available, as later weather reports focus on damage caused by the storm	Heavy rainfall recorded on 14th and 15th June, followed by 5 days of negligible or no rainfall. Heavy rain recommenced on 21st June. Pune, Dapoli and Thane exhibit similar trends. Pentad rainfall gives 21st June at the Fort and 14th June at Byculla as date of onset	21st June Occurrence of 5 days of dry weather after the rain of 14th/15th suggests that this was the result of an intense onset vortex
1846	First report of monsoon rains on 2nd June. However, newspaper reports state that the fall was partial. On 10th the *Bombay Times* reported that the monsoon had set in at last "after much coquetting and delay"	Mild (<15 mm) but significant rainfall at Colaba on 1st, 2nd and 3rd June, then little rain until 9th June. Heavy rainfall daily after 9th June. Pentad rainfall gives 1st June as date of onset	9th June Based on newspaper reports, which state that the falls of rain recorded on 1st–3rd June were localised showers and not full monsoon
1852	Showers of rain reported around 11th June. Next report is on 17th June, which states that only showers had been experienced up to that date, and that the rain had been from the S to SSE ("a most unusual quarter"). Heavy rain reported from 18th June, with reports that the monsoon set in over Pune on 17th	Significant but mild (<1 inch) rain on 12th, 13th, 15th and 16th June, with heavy and continuous rain from 18th June. Pentad rainfall gives 13th June as date of onset	13–18th June Due to ambiguity, a mid-point onset date of 16th June has been selected, with error bars. Rainfall data not considered sufficient alone, due to reports of wind direction, and date of advance over Pune

temporary advance, therefore an onset date of 16th June was assigned with error bars of −3 days and +2 days.

Figure 2 displays variations in the reconstructed monsoon onset date over Bombay for 1781–1878 as derived from combined documentary and historical instrumental data. The mean date of onset was 10th June (161.2 Julian days), with a standard deviation of 6.9 days. This is again equivalent to the mean and standard deviations of monsoon advance over Bombay presented in other papers (IMD 1943, 1990; Deshpande et al. 1986; Chowdhury et al. 1990), which supports the viability of the method. During the 97 years of the study period, monsoon onset dates occurred before 10th June on 40 occasions and after 10th June on 41 occasions. The date of onset fell on 10th June on 3 occasions (1827, 1860 and 1862). No data exist for the remaining 14 years. The earliest recorded date was 23rd May, which occurred in both 1802 and 1839, whilst the latest date of monsoon onset was 22nd June, recorded in 1825.

It is difficult to infer trends in monsoon onset date prior to 1800 owing to data gaps. However, a period of generally early monsoon onset is evident in the data during the 1780s and a period of later than average onset around the turn of the century. After 1800, four distinct periods of monsoon onset date are apparent: a period of early onset from 1782 to 1820, a period of late onset from 1821 to 1838, a period of early onset from 1839 to 1863, followed by a further period of late onset from 1864 to 1878. This represents a quasi-20 year periodicity in the date of monsoon onset between 1780 and 1878, although a power spectrum analysis reveals no statistically significant trends.

5 Discussion

5.1 Long-term trends in monsoon onset date

A comparison of the results of this study with published monsoon onset dates for post-1878 suggests that the climatic regime that governs monsoon advance over western India has not changed substantially. Figure 4 depicts the

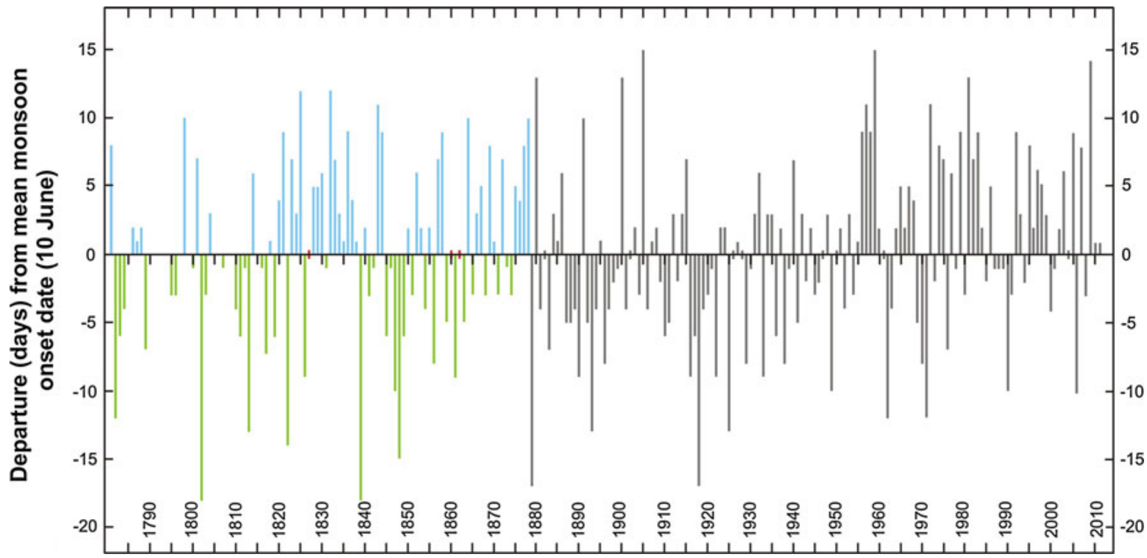

Fig. 4 Date of monsoon onset from 1781 to 2011. Data are from this study, Deshpande et al. (1986), Kumar et al. (1999) and Tyagi (personal communication). Onset dates for 1879–2011 are from IMD weather reports, declared during the operational phase of the monsoon. Data is expressed as a departure (in number of days) from the average onset date of 10th June between 1781 and 2011. Positive values indicate a later date of monsoon onset

Table 4 Number and percentage of years where the date of monsoon onset was classified as early (i.e. before 3rd June), normal (3rd to 17th June) and late (after 17th June) for the reconstruction period (1781–1878) and for the period 1900–1984 (as presented in Deshpande et al. 1986)

Years	Early	Normal	Late
1781–1878	10 (12 %)	62 (73 %)	13 (15 %)
1901–1984	12 (14 %)	63 (75 %)	9 (11 %)

dates of monsoon onset for the periods 1781–1878 (this study) and 1879–1996 (Deshpande et al. 1986; Kumar et al. 1999), together with more recent data for 1997–2011 (Tyagi, personal correspondence). The mean date of monsoon onset/advance over Bombay for this extended period remains as 10th June (161.3 Julian days), with a standard deviation of 6.7 days. A Lepage (1971) test comparing 30 years prior to and following 1878 indicated no change in scale or location parameters (T = 1.34, critical value in $\chi^2 = 9.2$, $p = 0.51$), indicating robustness in the reconstruction methodology.

Deshpande et al. (1986) defined onset dates over Bombay as 'early' if prior to 3rd June (i.e. <1 standard deviation from the mean of 10th June), 'normal' if between 3rd June and 17th June, and 'late' if after 17th June (i.e. >1 standard deviation from the mean). Given the equivalent mean and standard deviation between the reconstructed dates of monsoon onset for 1781–1878 presented here and those for 1900–1984 (compiled by Deshpande et al. 1986; see Sect. 4), it is appropriate to rank the results of this study in the same manner. The number and percentage of years from this study falling within each category, together with the percentages from 1900 to 1984, are shown in Table 4. As can be seen from the table, the distributions are essentially identical ($p = 0.94$ from a Pearson's Chi-square test).

The earliest date of monsoon onset identified within this study (23rd May in 1802 and 1839) is one day earlier than the earliest monsoon advance over Bombay recorded between 1901 and 1986 (24th May 1918; Deshpande et al. 1986). However, given the ambiguities in determining the date of monsoon onset for 1802 from documentary evidence noted in Sect. 4, onset in this year may have been as many as 6 days earlier than the 1901–1986 record. Monsoon onset over Bombay occurred later than 22nd June on only three occasions between 1901 and 1986: in 1905 (25th June), 1959 (25th June) and 1981 (23rd June) (ibid.).

Viewing the dataset presented in Fig. 4 as whole, periods of generally earlier and later monsoon onset date are apparent. Earlier onsets are suggested from approximately 1782–1820, 1839–1863 and 1879–1929. Later periods are evident from approximately 1821–1838, 1864–1878 and 1955–2011. A period of fluctuating onset is apparent between 1930 and 1955. Tyagi et al. (2011) recently identified that the mean date of monsoon onset over Mumbai from 1971 to 2000 (for both operational-phase and re-analysed onset) has shifted later by 2 days relative to the 1900–1971 average, from 10th to 12th June. Our study allows this shift to be viewed within a longer-term perspective. Figure 5 presents 31-year running averages of monsoon onset date from 1810 (i.e. 1781–1810) to 2011 (i.e. 1982–2011). This shows that average monsoon onset

Fig. 5 31-year averages of monsoon onset date over western India from 1810 (1781–1810) to 2011 (1982–2011). Data for 1781–1878 and 1997–2011 are from this study; data for 1879–1996 are from Deshpande et al. (1986) and Kumar et al. (1999); data for 1997–2011 are from Tyagi (personal communication)

date has fluctuated from 8th June (158.6 Julian days) during the early 18th and late 19th centuries, to later than 13th June between 1955 and 1984. Our results therefore demonstrate that the shift in the second half of the twentieth century has been unprecedented during the last 230 years, both in duration and the intensity of delay.

5.2 Relationship between ENSO and monsoon onset date

As mentioned in Sect. 1, the date of monsoon onset is regulated by intraseasonal oscillations, the IOD and ENSO. The analysis of the relative contribution of these three phenomena to monsoon onset variability over longer timescales is constrained by a lack of reliable historical reconstructions of the IOD and intraseasonal oscillation activity. However, a number of annually resolved, proxy-derived reconstructions of historical ENSO activity are available (e.g. Quinn and Neal 1992; Ortlieb 2000; Garcia-Herrera et al. 2008; Gergis and Fowler 2009). Of these, the most comprehensive is that published by Gergis and Fowler (2009). This reconstruction is now used to explore the stability of the relationship between ENSO and monsoon onset over Mumbai during the past 230 years.

Table 5 presents monsoon onset dates classified as early, normal or late for El Niño, La Niña and other years (as defined by Gergis and Fowler 2009) within (a) the reconstruction period (1781–1878), (b) the instrumental period (1879–2011) and (c) the period 1781–2011. It should be noted here that it was necessary to amend the Gergis and Fowler (2009) record slightly to avoid circularity. This is because the Gergis and Fowler (2009) chronology is based partly on a documentary reconstruction of ENSO by Whetton and Rutherfurd (1994) which includes a drought chronology for India as a proxy of El Niño conditions. Years which exhibit droughts in India in the Whetton and Rutherfurd (1994) reconstruction have therefore been amended within the reconstruction used here, by removing the record from the chronology and adjusting the magnitude classification according to the methodology presented by Gergis and Fowler (2009).

Table 5 Monsoon onset dates for Bombay classified as "early", "normal" or "late" within El Niño, La Niña and other years (as defined by Gergis and Fowler 2009) for (a) the reconstruction period (1781–1878), (b) the instrumental period (1879–2002) and (c) all available onset dates up to the latest date of Gergis and Fowler (2009) (i.e. 1781–2002)

	Early	Normal	Late	Total
(a) Reconstruction period (1781–1878)				
El Niño years	1	20	6	27
La Niña years	4	29	2	35
Other years	4	14	5	23
Total	9	63	13	85
(b) Instrumental period (1879–2002)				
El Niño years	4	44	8	54
La Niña years	9	28	5	40
Other years	3	21	2	24
Total	16	93	15	124
(c) All available onset dates for Bombay (1781–2002)				
El Niño years	5	64	14	81
La Niña years	13	57	7	75
Other years	7	35	7	47
Total	25	156	28	209

Data from this study, plus Deshpande et al. (1986), Kumar et al. (1999) and Tyagi (personal correspondence)

El Niño years during all three timeframes appear to be associated with a slightly delayed monsoon onset, and La Niña years with an early onset. It is interesting to note, however, that nine years during the reconstruction period that exhibited non-normal onset were associated with

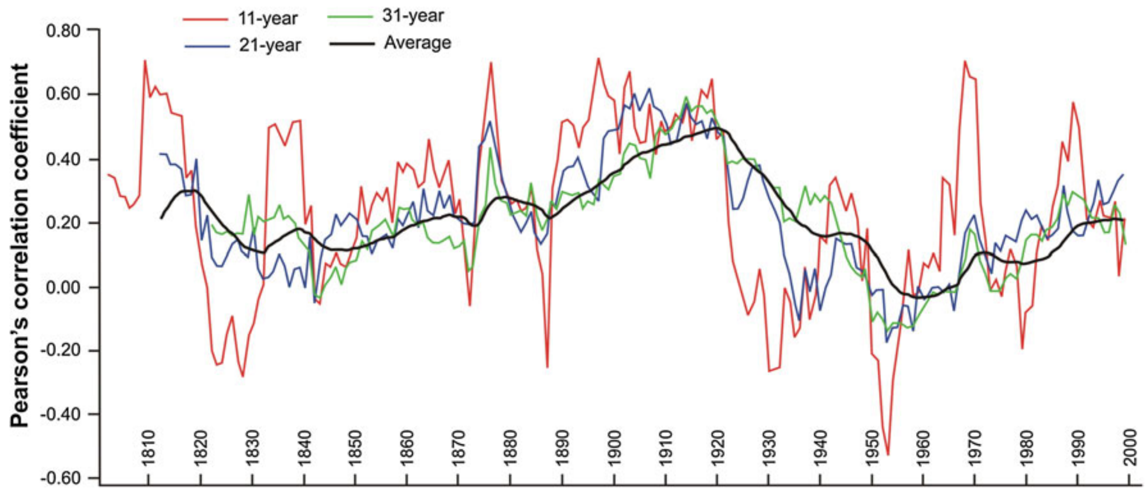

Fig. 6 Sliding correlations between the date of reconstructed monsoon onset over Bombay and the modified ENSO chronology of Gergis and Fowler (2009). The solid black line is the smoothed average of the 11-, 21- and 31-year correlations

neither El Niño nor La Niña years. This phenomenon is not noted within the instrumental period and it is suggested that this represents a statistical anomaly rather than any change within the climatic regime over time.

Correlations were determined between the reconstructed onset date and the amended ENSO record of Gergis and Fowler (2009) using a Pearson's correlation coefficient. The correlation for the reconstruction period was found to be 0.18, significant at 90 %, compared with 0.21 (significant at 95 %) for the instrumental period. The correlation for the entire series up to the latest date in Gergis and Fowler (2009) (1781–2002) is 0.19, significant at 99 %. To investigate the apparent difference in correlation between the reconstructed and instrumental period further, 11-, 21- and 31-year running correlations were generated between the Gergis and Fowler (2009) ENSO record and the extended 230 year monsoon onset record (Fig. 6). The 11-year running correlation indicates that there were decades during both the reconstruction and instrumental period (e.g. 1820s, 1930s, 1950s) when the correlation between ENSO and monsoon onset switched from positive to negative. However, overall, the correlations exhibit pseudo-random fluctuations. These fluctuations were found to be not significant at the 95 % level, using the methodology presented by Gershunov et al. (2001). This indicates stochastic variability in the correlation, as would be expected within any correlated data. Using these results, it is not possible to state that any change in the long-term correlation between ENSO and the date of monsoon onset over Mumbai has occurred, at least for the duration of this study. This implies long-term stability in the ENSO-monsoon onset relationship.

Our results agree with, and extend, those of Goswami and Xavier (2005), who identified stability in the relationship between ENSO and the length of the monsoon season (and hence onset date) using instrumental data for 1950–2003. However, the correlations generated by Goswami and Xavier (2005) were much higher than those in this study. This is not surprising, given that we base our reconstruction (see Sect. 3) on classical methodologies that associate onset with a sharp increase in rainfall (Kumar et al. 1999; Joseph et al. 2006; Tyagi et al. 2011). Monsoon onset dates generated using these methods generally exhibit lower correlations with ENSO (cf. Fasullo and Webster 2003; Xavier et al. 2007).

It would benefit future analyses of the ENSO-monsoon onset relationship if historical estimates of onset could be determined using objective (i.e. non-classical) methodologies. The simplest way to undertake this would be to calibrate documentary-based onset reconstructions with onsets determined using modern methodologies. However, onset dates using objective methodologies have only been generated from 1951, and have been calculated for MOK only. Robust documentary reconstructions calibrated directly against these data would therefore need to be generated up to $\sim$ 1970 to provide an adequate crossover period for verification (Pfister 1992). This would seem unnecessary given the existence of onset dates from the late nineteenth century determined using classical methodologies. Fasullo and Webster (2003) have published the correlation between the date of monsoon onset derived using their objective methodology and that derived using the classical IMD methodology ($R = 0.74$). It would be helpful if the exact relationship between the two methods were known. This could result in a re-analysis of onset dates prior to 1951, which may then be used as calibration for documentary reconstructions stretching further back in time.

6 Conclusions

This investigation has utilised narrative material and instrumental data contained within historical documents archived in the UK, USA and India to reconstruct annual monsoon onset dates over western India for the period 1781–1878. The results of this study extend the record of monsoon onset date for the region by 97 years. The mean date of monsoon onset over the Bombay area during the reconstruction period was 10th June (161.2 Julian days), with a standard deviation of 6.9 days. This is similar to the mean and standard deviation of the date of monsoon onset derived from instrumental data for the twentieth century (e.g. IMD 1943, 1990; Deshpande et al. 1986; Chowdhury et al. 1990). The earliest identified onset date was 23rd May (in both 1802 and 1839) and the latest 22nd June (in 1825), giving a range of 30 days.

Combining our reconstruction of monsoon onset over Mumbai with previously published and newly available data for 1879–2011 indicates that the climatic regime governing monsoon advance over western India did not change substantially from 1781 to approximately 1955. After this date, a period of generally later monsoon onset is evident. Tyagi et al. (2011) have demonstrated previously a 2-day delay in average monsoon onset date from 1971 to 2000, relative to the 1900–1971 average. The longer-term perspective provided by our study shows that this recent shift probably began some 15 years earlier, and is unprecedented during the last 230 years in both duration and intensity of delay. We make no attempt to attribute cause to this apparent shift.

El Niño years during the period 1781–2002 appear to be associated with a slightly delayed monsoon onset and La Niña years with an early onset, supporting previous studies (e.g. Joseph et al. 1994; Fasullo and Webster 2003; Goswami and Xavier 2005; Lim and Kim 2007; Xavier et al. 2007). A long-term analysis of the stability of ENSO-monsoon onset relationship using both reconstructed and previously published onset dates indicates that the relationship has remained stable over time. This supports and extends the findings of Goswami and Xavier (2005). Our study highlights some of the methodological challenges present in reconstructing monsoon onset, particularly given the changing approaches used to define monsoon onset during the past 100 years.

Overall, this study has underlined the value of using historical documentary materials for the reconstruction of past climate phenomena, particularly where these phenomena impact upon everyday lives. It is hoped that the results may add to research regarding the relative contributions of ENSO, IOD and intraseasonal oscillations to monsoon onset date over time. Furthermore, our extended chronology offers a new historical dataset for utilisation within back-trajectory analysis.

Acknowledgments The archive-based research for this paper was undertaken whilst GCDA was in receipt of a doctoral research scholarship provided by the University of Brighton. Grants to GCDA to support visits to the Houghton Library, Harvard, USA and the Archives of the Government of Maharashtra, Mumbai, India were provided by the Dudley Stamp Memorial Fund (administered by the Royal Geographical Society), the Royal Historical Society and the Indian National Trust for Arts and Cultural Heritage (INTACH) UK Trust. Both authors are extremely grateful to Dr Ajit Tyagi of the IMD for providing dates of monsoon onset over Mumbai for 1997–2011.

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