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Oscillatory Climate Modes in the Indian Monsoon, North Atlantic, and Tropical Pacific

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ABSTRACT

6
7 This paper explores the three-way interactions between the Indian monsoon, the North
8 Atlantic and the Tropical Pacific. Four climate records were analyzed: the monsoon rainfall
9 in two Indian regions, the Southern Oscillation Index for the Tropical Pacific, and the NAO
10 index for the North Atlantic. The individual records exhibit highly significant oscillatory
11 modes with spectral peaks at 7–8 yr and in the quasi-biennial and quasi-quadrennial bands.

12 The interactions between the three regions were investigated in the light of the synchro-
13 nization theory of chaotic oscillators. The theory was applied here by combining multichan-
14 nel singular spectrum analysis (M-SSA) with a recently introduced varimax rotation of the
15 M-SSA eigenvectors.

16 A key result is that the 7–8-yr and 2.7-yr oscillatory modes in all three regions are
17 completely synchronized, and the energy ratio analysis suggests that the NAO induces these
18 modes in the other two regions. Both these modes in the NAO appear to be connected to
19 the intrinsic variability of the Gulf Stream front. It was found therewith that the South
20 Asian monsoon is not slaved to forcing from the equatorial Pacific, although it does interact
21 strongly with it. The energy-ratio analysis pinpointed this to be the case in particular for
22 the quasi-biennial oscillatory modes.

23 Overall, these results confirm that the approach of synchronized oscillators, combined
24 with varimax-rotated M-SSA, is a powerful tool in identifying teleconnections between re-
25 gional climate modes and helping identify the mechanisms that operate in various frequency
26 bands. This approach should be applicable also to ocean modes of variability and to the
27 problems of air-sea interaction.

28 1. Introduction

29 Connections between the Southern Oscillation in the Tropical Pacific and the Indian
30 monsoon have been explored since the pioneering work of Sir Gilbert Walker and associates
31 in the early 20th century. More recently, some attention has also been given to the possible
32 effects of the North Atlantic Oscillation (NAO) on the Indian monsoon.

33 In this paper, we concentrate on potential teleconnections among all three regions: the
34 Indian monsoon, the Tropical Pacific, and the North Atlantic. Most teleconnection studies
35 so far were based on correlations between climatic time series from the regions of interest
36 (Wallace and Gutzler 1981); often the correlations found in this way were no larger in absolute
37 magnitude than 0.6, and they did not clarify in which frequency band the teleconnection
38 under investigation was most active.

39 To explore in greater depth the commonalities between the well-documented records of
40 the North Atlantic Oscillation (NAO) index, the Southern Oscillation Index (SOI) and the
41 Indian monsoon rain records — which constitute the focus of our paper — we adopt here
42 the viewpoint of synchronization between chaotic oscillators. From this point of view, each
43 regional climatic index may be considered as a chaotic oscillator that represents the regional
44 climate dynamics; teleconnections then arise as a coupling in space between such climatically
45 active regions (Duane 1997; Duane and Tribbia 2004).

46 Our synchronization analysis is based on singular spectrum analysis (SSA) and it is
47 partly described in Feliks et al. (2010). It differs from that of previous studies that relied on
48 SSA and on multichannel SSA (M-SSA), as reviewed by Ghil et al. (2002b), inasmuch as we
49 use here M-SSA to examine cross-spectral properties of the climate records from different
50 regions. Furthermore, we rely and improve upon the recently proposed varimax rotation of
51 M-SSA eigenvectors (Groth and Ghil 2011) in order to enhance the separation of oscillations
52 and the identification of synchronized oscillators.

53 Feliks et al. (2010) applied some of the present ideas and methods to study teleconnections
54 between the North Atlantic, the Eastern Mediterranean and the Ethiopian Plateau. In all

55 the climatic indices at their disposal, they found prominent oscillatory activity in the 7–8-yr
56 frequency band, as well as synchronization with the NAO index they used. An analysis
57 based on the energy ratios of the oscillatory modes they had identified raised the possibility
58 that the origin of this 7–8-yr mode may lie in the North Atlantic. These authors suggested,
59 therefore, that this mode may arise from changes in the position and the intensity of the Gulf
60 Stream front (cf. Jiang et al. 1995b; Dijkstra and Ghil 2005; Feliks et al. 2011; Brachet et al.
61 2012). They also proposed a physical mechanism of moisture flux for the teleconnections
62 between the North Atlantic, Ethiopian Plateau, and the Eastern Mediterranean.

63 The study of Feliks et al. (2010) is extended herein to the much wider areas of the South
64 Asian subcontinent and the Pacific, and it is methodologically improved and sharpened,
65 following Groth and Ghil (2011). The paper is structured as follows. In section 2, we
66 review briefly the concepts and methods of M-SSA and of the varimax rotation of M-SSA
67 eigenvectors; further methodological details are provided in the appendix. The climatic time
68 series we use are presented in section 3, where their univariate spectral properties are also
69 summarized. We study in section 4 the synchronization between the oscillations that were
70 thus identified in section 3. Concluding remarks follow in section 5.

71 **2. Methodology**

72 Univariate SSA and its multivariate extension to M-SSA rely on the classical Karhunen-
73 Loève spectral decomposition of time series. Broomhead and King (1986a,b) introduced them
74 into dynamical system analysis, as a robust version of the Mañé-Takens idea to reconstruct
75 dynamics from a time-delayed embedding of time series. The method essentially diagonalizes
76 the lag-covariance matrix into eigenvectors and eigenvalues, with the former describing a set
77 of space-time empirical orthogonal functions (ST-EOFs). Projecting the time series onto the
78 ST-EOFs yields the corresponding principal components.

79 These components provide a “skeleton” of the dynamical system’s structure, and by us-

80 ing linear combinations thereof, we are able to reconstruct trends, oscillatory modes, and
81 irregular “noise” (Vautard and Ghil 1989; Ghil and Vautard 1991; Ghil et al. 2002b). The
82 reconstructions associated with the individual ST-EOFs are referred to as reconstructed com-
83 ponents (RCs), and each RC represents a narrow-band part of the full frequency spectrum.
84 In particular, two RCs associated with nearly equal eigenvalues and dominant frequencies
85 are referred to as an oscillatory pair (Vautard and Ghil 1989; Plaut and Vautard 1994; Ghil
86 et al. 2002b). To avoid misinterpreting random fluctuations as oscillations, a statistical test
87 is performed by comparing the variance captured by such a pair of EOFs with that present
88 for the same pair in a large ensemble of red-noises surrogates (Allen and Smith 1996).

89 Recently, Groth and Ghil (2011) have demonstrated that a classical M-SSA analysis
90 suffers from a degeneracy problem, with eigenvectors not separating well between distinct
91 oscillations when the corresponding pairs of eigenvalues are similar in size. This problem is
92 a shortcoming of principal component analysis in general (Richman 1986; Jolliffe 2002), not
93 just of M-SSA in particular. In order to reduce mixture effects and to improve the physical
94 interpretation of the results, Groth and Ghil (2011) have proposed a subsequent varimax
95 rotation of the ST-EOFs. To avoid a loss of spectral properties (Plaut and Vautard 1994),
96 their proposed algorithm has been modified somewhat from the common varimax rotation
97 of Kaiser (1958), by taking into account the spatio-temporal structure of ST-EOFs; see the
98 appendix for further details.

99 **3. The climatic records and their oscillatory modes**

100 In this section, we study the spectral properties of the individual climatic records by
101 means of a single-channel SSA analysis. The climatic records are provided as monthly
102 averages and they are dominated by strong seasonal activity. Since we are interested in
103 lower-frequency activity, on interannual time scales, we first remove all frequencies higher
104 than 0.5 cycles/yr and proceed with an annual sampling rate. Such low-pass filtering avoids

105 in particular aliasing effects in the annually subsampled records.

106 We applied a Chebyshev type I filter that has a very steep roll-off at the desired cut-off
107 frequency and a nearly constant magnitude response in the passing band. When compared
108 to a 12-month (i.e., an annual mean) moving average or to a 3-month one (i.e., a seasonal
109 mean), the Chebyshev filter is much closer to an ideal low-pass filter and does practically not
110 alter the spectral properties in the desired low-frequency band (see the appendix). In the
111 filtering process of the monthly record, we pass it in both the forward and reverse direction
112 in order to ensure zero phase distortion (Oppenheim and Schaffer 2009).

113 Figure 1 shows the low-pass filtered climatic records, from which we finally derived an-
114 nually sampled time series by simply taking all July values. Single-channel SSA is applied to
115 each of these time series, and the statistical significance is assessed by means of Monte Carlo
116 SSA (MC-SSA: Allen and Smith 1996), with an ensemble size of 1000 surrogate time series.
117 To check the robustness of the peaks identified via SSA, the Mann and Lees (1996) version
118 of the multi-taper method (MTM) is applied, with three tapers; see also Ghil et al. (2002b)
119 and the documentation available at <http://www.atmos.ucla.edu/tcd/ssa>. As for SSA,
120 we assess the statistical significance of the MTM results against a red-noise null hypothesis.
121 A summary of the modes identified at a 95% level of significance — in both MC-SSA and
122 MTM, respectively — are given in Table 1, along with the percentage of variance captured
123 by the corresponding SSA mode.

124 *a. Southern Oscillation Index (SOI)*

125 The SOI is defined as a suitably normalized difference in the month-to-month fluctuations
126 in the mean sea level pressure between Tahiti and Darwin. We use the monthly index between
127 years 1876 and 2006, as compiled by the Australian Bureau of Meteorology; see [http://](http://www.bom.gov.au/climate/current/soi2.shtml)
128 www.bom.gov.au/climate/current/soi2.shtml. After a reduction of the sampling rate to
129 annual values, as explained in section 2, we applied SSA with a window width of $M = 40$ yr;
130 the results in Table 1 were found to be robust with respect to reasonable variations in M .

131 The oscillatory modes that are statistically significant can be classified into four broad-band
132 peaks, with a period of 6–7 yr, 5 yr, 3.6 yr, and 2.5 yr, respectively.

133 The 2.5-yr band contains 7% of the total variance and corresponds to the well-known
134 quasi-biennial oscillation component of ENSO (Rasmusson and Carpenter 1982; Jiang et al.
135 1995a; Paluš and Novotná 2006). The 3.6-yr peak contains 10% of the variance and is
136 probably identifiable with the low-frequency or quasi-quadrennial oscillation of ENSO (Jiang
137 et al. 1995a; Ghil and Robertson 2000).

138 *b. Indian monsoon rainfall*

139 The Indian summer monsoon rainfall occurs during the months of June–September
140 (JJAS) and its statistics are divided into several homogeneous monsoon rainfall regions by
141 the Indian Institute of Tropical Meteorology (Parthasarathy et al. 1995). Azad et al. (2010)
142 suggested a different partition into homogeneous regions, based on spectral properties, but
143 we follow here the standard one. These regions differ in the onset time of the monsoon, in
144 the total amount of rain, and in the mechanisms that influence the rainfall. In this study,
145 we analyze records from the core and the Peninsular regions that cover 138 years, from 1872
146 to 2008; see Figs. 1(b,c) for the low-pass filter version of these two records. The core region
147 represents the central and western parts of India, while the Peninsular region represents its
148 southern part. As statistically significant oscillatory modes, we can mainly identify three
149 broad-band peaks of 2.2–2.8 yr, 3.2–3.6 yr, and 7.3–7.6 yr. In the Peninsular record, we also
150 obtain a significant peak at 5 yr (cf. Table 1).

151 *c. North Atlantic Oscillation (NAO)*

152 The NAO has been extensively studied over the last two decades (Hurrell et al. 2003),
153 and its strength has been quantified using several indices. We use here the monthly index
154 over the years 1823–2008, as compiled by Jones et al. (1997); see Fig. 1 for the monthly low-

155 pass filtered record. This index is the difference between the normalized sea level pressure
156 at Gibraltar and the normalized sea level pressure over southwestern Iceland; Jones and
157 colleagues used early instrumental data back to 1823. The dataset has been modified in
158 November 2000 and the effect of this change is most evident in the summer; see [http:](http://www.cru.uea.ac.uk/~timo/projpages/nao_update.htm)
159 [//www.cru.uea.ac.uk/~timo/projpages/nao_update.htm](http://www.cru.uea.ac.uk/~timo/projpages/nao_update.htm).

160 The significant oscillatory modes have periods of 7.8 yr, 5.9 yr, 5 yr, 4.3 yr, and 2.7
161 yr, respectively. The most prominent oscillatory mode, with a period of 7.8 yr, appears in
162 the two leading RCs, RCs 1–2, in good agreement with previous findings (Robertson 2001;
163 Gámiz-Fortis et al. 2002; Paluš and Novotná 2004). A quasi-biennial component is present,
164 too, in the closely related Arctic Oscillation, constructed from hemispheric sea level pressures
165 (Trenberth and Paolino 1981; Robertson 2001).

166 4. Synchronized modes

167 We have thus found so far significant oscillatory modes on interannual time scale to be
168 present in records from the North Atlantic, Tropical Pacific, and the Indian subcontinent.
169 Such a coincidence of spectral features in different regions of the world raises the possibility
170 of teleconnections between the climate variations in the regions under consideration.

171 To study this possibility in detail, we examine next the synchronization of pairs of records
172 by means of M-SSA, and look for common oscillatory modes and their role in the dynamics
173 of each region. We analyze synchronization of pairs of records by applying a two-channel
174 M-SSA to the time interval of overlap between the two records of the pair: each channel
175 corresponds to an instrumental or proxy record, nondimensionalized by dividing it by its
176 standard deviation.

177 For a given oscillatory mode of the M-SSA analysis, we evaluate the strength of coupling
178 as in Feliks et al. (2010), by the energy ratio $\varepsilon = E(\text{RC}x_1)/E(\text{RC}x_2)$, where $E(\text{RC}x_i)$ is the
179 variance in each of the two RC components, $i = 1, 2$. This ratio tends to $\varepsilon = 1$ for strong

180 coupling and tends to either $\varepsilon = 0$ or $\varepsilon = \infty$ as the coupling decreases. The dominant
181 process in such an oscillatory mode can be inferred from the energy ratio as well: When the
182 energy ratio is close to unity, the two processes are balanced in energy, and a driver cannot
183 be inferred. For weak coupling, $\varepsilon \ll 1$, x_2 dominates the mode under study, and possibly
184 drives the mechanism that activates the mode, because of its much larger energy (Feliks
185 et al. 2010).

186 *a. SOI and NAO*

187 The 130-yr interval of overlap between the SOI and the NAO index is 1876–2006. At
188 first, we carry out an M-SSA analysis with a window width of $M = 40$ and without varimax
189 rotation. The resulting estimate of power spectral density (PSD) for the ten leading ST-
190 EOFs is shown in Fig. 2.

191 We observe a grouping of the EOFs into pairs with similar PSD characteristics, referred
192 to as oscillatory pairs; see also section 2 and the appendix here. These pairs are the data-
193 adaptive equivalent of sine-and-cosine pairs in Fourier analysis and characterize amplitude-
194 modulated oscillatory modes. We see that their PSD is not always unimodal and can exhibit
195 complex, multimodal characteristics. Still, one typically assigns a dominant frequency to
196 each of these EOFs — e.g., derived from the maximum of the PSD (Vautard and Ghil 1989)
197 — in order to simplify the interpretation of the eigenvalue spectrum.

198 Allen and Smith (1997) have discussed the problem of frequency separation in the pres-
199 ence of large colored noise. They proposed an improvement in ascertaining statistical signif-
200 icance of oscillatory modes in single-channel SSA analysis by estimating a red-noise process
201 from the noisy data. In this paper, however, we do not make any explicit assumption about
202 the nature of the noise in the underlying system and show an improvement in frequency
203 separation for the case of multichannel SSA.

204 The need for such an improvement is apparent from Fig. 2: in it, one only observes a
205 clear unimodal association with a period of about 3.6 yr for the pair of EOFs 3–4. From

206 the maximum of the PSD, we see that this mode has much less energy in the NAO (heavy
207 solid) than in the SOI (light solid). This low energy of the mode in the NAO index is in
208 agreement with a single-channel SSA of the latter, in which we could not identify such a
209 mode (cf. Table 1). Hence, this oscillatory mode appears to be significantly present only in
210 the Tropical Pacific.

211 For the remaining EOFs in Fig. 2, the picture is less clear, with overlapping PSDs and
212 multi-modal, broad-band characteristics of the spectra. Furthermore, when increasing the
213 window width to a value of $M = 50$, the isolated 3.6-yr mode in Fig. 2 is also mixed in with
214 other modes (not shown).

215 A possible approach to overcome this mixing problem is a subsequent M-SSA analysis on
216 a subset of RCs. This means that we exclude EOFs 3–4 from the $M = 40$ analysis in Fig. 2
217 and reconstruct the two time series using only RCs 1–2 and 5–8, for example. Next, we apply
218 M-SSA to this reconstruction but do not constrain the new ST-EOFs to be orthogonal to
219 the previous EOFs. Such an iterative procedure should be able to better separate between
220 different frequencies in a reduced subspace, at least when the variances of two or more pairs
221 are not too close in value.

222 In general, this mixing problem is due to similar variance in different frequency bands,
223 and it is much more severe when the dimensionality of the system is larger; one needs
224 therewith a more systematic way to disentangle the degeneracy. Groth and Ghil (2011)
225 have proposed to solve this common degeneracy problem in M-SSA by applying a simple-
226 structure rotation (Richman 1986; Jolliffe 2002) of the leading ST-EOFs, while giving due
227 consideration to their spatio-temporal character.

228 In order to reduce the risk of an overrotation (O’Lenic and Livezey 1988), we multiply
229 each EOF by its corresponding singular value prior to the modified varimax rotation, as
230 described in greater detail in the appendix. This scaling prevents, in particular, the rotated
231 EOFs from being too localized in space and frequency, and the variance spectrum from being
232 too flat. At the same time, the choice of an appropriate number S of rotated EOFs becomes

233 less critical and the resulting components are more consistent over a wide range of S -values,
 234 as we will see in the following. The price to pay for this scaling is that the rotated EOFs are
 235 no longer the eigenvectors of the covariance matrix and a certain variance reduction occurs
 236 in the leading EOFs. Still, scaled varimax rotation helps reduce the problem of an artificial
 237 variance compression in the eigenvalue spectrum, i.e., of a spurious inflation of variance in
 238 the largest eigenvalues (Allen and Smith 1996; Groth and Ghil 2011).

239 The PSD estimate of the leading ST-EOFs after rotation is shown in Fig. 3. The variance
 240 localization in frequency is much sharper than prior to rotation, with a clear tendency to
 241 unimodal, narrow-band PSD features for each ST-EOF. Note that, at the same time, we
 242 have slightly increased the window width to a value of $M = 50$, in order to better separate
 243 nearby oscillations. On the other hand, M -values that are too large will tend to split a
 244 complex process into an unreasonably high number of narrow-band components.

245 To better understand the frequency separation process through modified varimax ro-
 246 tation, as well as its reliability and reproducibility with respect to parameter changes, we
 247 analyze the leading 7.8-yr mode in greater detail. Figure 4a shows the energy ratio ε between
 248 SOI and NAO of the leading 7.8-yr mode as a function of the relative number of rotated
 249 EOFs.

250 As the number S of rotated EOFs increases, the energy ratio decreases, indicating that the
 251 separation in frequency between the two time series increases. But this separation occurs
 252 in three distinct steps, rather than gradually and uniformly: (i) ε drops precipitously at
 253 $S/(DM) \simeq 0.1$, for all values of M ; it then (ii) remains nearly constant in the interval $0.1 \lesssim$
 254 $S/(DM) \lesssim 0.4$, and (iii) it finally decreases smoothly further toward zero as $S/(DM) \rightarrow 1$.
 255 The first abrupt drop can be clearly attributed to frequency separation of the leading EOFs.
 256 It is especially for large M -values, i.e. here $M = 60$ and $M = 50$, that the EOFs are
 257 susceptible to degeneracy prior to any rotation.

258 In the region (ii) of nearly constant $\varepsilon = \varepsilon(S)$, the energy ratio is pretty flat, independently
 259 of the M -value, and it thus gives a robust estimate of the energy balance. In the leading 7.8-

260 yr mode, the SOI has therewith much less energy than the NAO, especially when compared
261 with the results of a classical M-SSA analysis without rotation. This robust energy ratio
262 thus suggests that the NAO drives this oscillatory mode in the Tropical Pacific Ocean. It is
263 only for large window width ($M = 60$) that ε decreases further beyond $S/(DM) \simeq 0.4$ and
264 would thus appear to negate any link between SOI and NAO in this 7–8-yr frequency band.
265 This apparent uncoupling could, however, be due to a much too fine spectral decomposition
266 of a broader-band phenomenon.

267 To confirm our success in solving the degeneracy problem in the 7.8-yr mode, we further
268 analyze the unimodality of the corresponding RCs. We reconstruct separately the two time
269 series by means of the ST-EOF pair and perform a subsequent M-SSA analysis on the
270 resulting RCs, by using the same M -value, but without rotation. For RCs that are truly
271 unimodal, we expect to find almost the entire energy concentrated in the first two eigenvalues.
272 In the absence of rotation, however, the amount of energy is much lower, and therewith it
273 clearly points to the presence of mode mixing in the leading EOF pair (Fig. 4b). Only
274 rotating a sufficient number of components, $S/(DM) \gtrsim 0.1$, solves this degeneracy problem
275 and the RCs become unimodal. This result demonstrates quite clearly and convincingly that
276 the frequency separation process is linked indeed to a sudden jump in the energy ratio (see
277 again Fig. 4a).

278 Figure 5a shows the complete eigenvalue spectrum, with the statistical significance level.
279 We find three significant oscillatory modes with a period of approximately 7.8 yr, 5.8 yr, and
280 3.6 yr, respectively; each of these pairs of eigenvalues stands clearly out of the red-noise null
281 hypothesis of MC-SSA (Allen and Smith 1996; Ghil et al. 2002b). Note that, in contrast
282 to the previous univariate SSA analysis, we have slightly increased here the required level
283 of significance to 98%; this increase is meant to compensate for a loss of statistical power
284 of Monte Carlo SSA when the number of channels increases (cf. A. Groth and M. Ghil, in
285 preparation).

286 The corresponding RCs are shown in Figs. 5b–d. Note that, although the SSA analysis

287 has been performed on the annual records, the RCs are plotted — here and in Figs. 6–8 —
288 using a monthly sampling rate, in order to better visualize high-frequency oscillations, such
289 as the quasi-biennial oscillation. Moreover, the monthly resolution provides a more precise
290 estimation of the time lag between the two RCs of a pair. To interpolate the annually
291 sampled RCs to monthly resolution, they are first zero-padded between the samples and
292 then low-pass filtered with the same Chebyshev filter that has been employed in the annual
293 subsampling; see section 3 and the appendix. The energy ratio, on the other hand, has been
294 directly derived from the annually sampled RCs.

295 In the leading, 7.8-yr mode of Fig. 5b, we see a clear phase opposition between the SOI
296 and NAO: it is the negative phase of the NAO that is associated with an enhanced SOI index.
297 In the next, 5.8-yr mode (Fig. 5c), the two records are much closer in energy, although this
298 mode is still dominated by the NAO. The SOI lags by approximately two years behind the
299 NAO, thus pointing to NAO as the driving mechanism in this frequency band.

300 The 3.6-yr mode (Fig. 5d) is dominated by the SOI, as can be seen from the high value
301 of ε . This SOI dominance is also confirmed by single-channel SSA analyses (cf. Table 1),
302 where this mode has only been identified in the SOI and not in the NAO.

303 The teleconnection between the North Atlantic and the Tropical Pacific is of moderate
304 strength, and it is supported by mechanisms outlined in previous studies. Chiang and Vi-
305 mont (2004) have provided evidence for the extratropical atmosphere influencing the Tropical
306 Pacific through a meridional mode, analogous to that present in the Tropical Atlantic, where
307 variations in the trade winds in the northern subtropics influence tropical sea surface tem-
308 peratures (SSTs). Thompson and Lorenz (2004) have furthermore identified relationships
309 between the extratropical annular modes and the circulation in the tropical troposphere;
310 these annular modes, however, were filtered out herein by the annual subsampling (cf. the
311 appendix and Fig. 12 therein).

312 *b. Indian monsoon rainfall and NAO*

313 The years 1871–2008 are the 137-yr interval of overlap between the Indian monsoon and
314 the NAO index. From Table 1 we see that there are fewer possible candidates of common
315 oscillatory modes than in the previous case of SOI and NAO. Hence the degeneracy problem
316 is less pronounced for these two pairs of indices, namely NAO paired with either the core
317 Indian rainfall or the Peninsular rainfall.

318 First, we analyze the core region and the NAO index. In this case, although the mixing
319 effect is not totally negligible, the significant oscillatory modes in Fig. 6 exhibit practically
320 no multimodal characteristics, even in the absence of rotation (not shown). The significant
321 oscillatory modes in Fig. 6a are in good agreement with the significant modes from individual
322 single-channel SSA analyses (cf. Table 1). As for the SOI and NAO before, there is again
323 an NAO-dominated 7.8-yr mode and we are led once more to suspect that it is the North
324 Atlantic that drives this oscillation (Fig. 6b).

325 We observe further a quasi-biennial mode in EOFs 3–4, with a period of 2.7 yr. In this
326 mode, both records exhibit practically the same energy and no time delay (Fig. 6c).

327 Next, we carry out the combined M-SSA analysis of the Peninsular region and the NAO
328 index. The three significant oscillatory modes in Fig. 7 are in good agreement with the
329 significant modes from the individual, single-channel SSA analyses summarized in Table 1.
330 Since the variance of the leading 7.6-yr oscillatory mode clearly stands out above the other
331 oscillatory modes, there is no mode mixing and we can exclude EOFs 1–2 from the subsequent
332 rotation.

333 The 7.6-yr mode is shown in Fig. 7b; in it, the energy of the NAO index is but marginally
334 larger than that of the Peninsular rain. The amplitude of this joint mode decreases gradually
335 throughout the time interval of record and it vanishes entirely at the end of the interval.
336 This damping is further investigated in each time series separately by single-channel SSA
337 analysis.

338 In the Peninsular rainfall, the leading oscillatory mode is captured by RCs 1–2 and it

339 exhibits a period of 7.4 yr, whereas in the NAO index the leading oscillatory mode is still
340 given by RCs 1–2 but it has a slightly different period, of 7.7 yr. The reconstructions
341 of the 7.4-yr mode in rainfall (dashed) and of the 7.7-yr mode in the NAO index (solid),
342 respectively, are given in Fig. 8.

343 From this figure, it follows that neither mode individually is damped since 1950: in fact,
344 the rainfall amplitude is pretty constant throughout the interval, while the amplitude of the
345 NAO index increases from 1950 on. Thus, the damping of the joint mode in Fig. 7b cannot
346 really be attributed to a damping of the two indices in this frequency band. Furthermore,
347 the phase difference in Fig. 8 shifts from phase opposition until 1950 to an in-phase behavior
348 after 1985. This phase shift, rather than the amplitudes of the individual modes, results in
349 the damping of the joint mode after 1950 and its almost vanishing amplitude after 1985. To
350 examine the mechanism that might be responsible for NAO effects on the Peninsular rainfall,
351 we consider next the spatio-temporal behavior of relevant climate fields.

352 Figure 9 shows global maps of the Pearson product-moment correlation coefficient for
353 the 7.6-yr NAO component in Fig. 7b with (a) 200-hPa geopotential heights (Z200), (b)
354 mean sea level pressure (MSLP), and (c) the SST field. The correlations are calculated over
355 the time interval 1876–1940, when the covariability is strongest, with each monthly data
356 field pre-filtered to remove periods below two years in the same way as for the indices. The
357 atmospheric variables are taken from the 20th-century reanalysis of Compo et al. (2011),
358 and the SSTs from Kaplan et al. (1998).

359 The Z200 and MSLP correlation maps both show a strong NAO dipolar pattern over the
360 North Atlantic, as expected. It is notable, however, that a wave train arcs southeastward
361 from the North Atlantic at 200hPa (panel a), with an anomalous trough over central Asia.
362 This trough is centered north of the Tibetan plateau and it coincides with the positive
363 phase of the NAO. Such a trough would tend to weaken the monsoonal anticyclone at upper
364 levels, thus weakening the monsoonal circulation (Saeed et al. 2011). At the surface, MSLP
365 correlations (panel b) are generally positive over Asia and Africa, but the correlations are

366 weak. The SST anomaly correlations (panel c) exhibit an El Niño-like pattern in the Tropical
367 Pacific, together with NAO-like correlations over the North Atlantic. The former would also
368 tend to be associated with a weaker Indian monsoon. It is this physical teleconnection
369 mechanism — from the North Atlantic to Central Asia and on to the Indian subcontinent
370 — that seems to be breaking down in the second half of the 20th century.

371 After a rotation of the remaining EOFs 3–30, the 2.7-yr and 4.7-yr oscillatory modes
372 in Figs. 7(b,c) have a clear unimodal behavior, too. The energy ratio in the 4.7-yr mode
373 (panel c) suggests an impact of the Peninsular region on the NAO, while in the 2.7-yr mode
374 (panel b) it is the the NAO that has more energy. It would thus appear, in spite of the more
375 ambiguous results for the core region (Fig. 6c), that this mode, too, originates in the North
376 Atlantic.

377 The teleconnection between the North Atlantic and the Indian summer monsoon (ISM)
378 was studied recently by several authors. Syed et al. (2011) showed that there are two modes
379 in the NAO that influence the ISM: one is the summer circum-global teleconnection (CGT),
380 as suggested by Ding and Wang (2005); the other one is the summer NAO (Folland et al.
381 2009). The spatial patterns of these two modes are similar over the North Atlantic.

382 Different mechanisms have been suggested to explain the role of the CGT and NAO in
383 influencing the summer monsoon in India and Pakistan. Saeed et al. (2011) showed that the
384 positive anomaly at 200 hPa (positive CGT) over western Asia is associated with low surface
385 pressure over northern India and Pakistan. This increases the advection of moist air from the
386 Arabian Sea and the convergence of this marine air inflow over India and Pakistan. Hence
387 the updraft and rainfall increase over Southern Asia for positive CGT, and the opposite
388 occurs for negative anomalies at 200 hPa, i.e. negative CGT (cf. Fig. 9a). These authors
389 also claim that the role of the NAO over Central Asia is similar to that of CGT.

390 Ding and Wang (2005) showed that the CGT pattern is most pronounced in August,
391 when the strongest linkage between the Atlantic and Central Asia exist. The pattern in
392 September is very similar to the August one, while in July it is rather different. In the

393 present analysis, we only examined the teleconnection between the North Atlantic and India
394 through the NAO.

395 Rajeevan and Sridhar (2008) also showed that positive SST anomalies over the North
396 Atlantic shift the jet stream northward and the associated circulation changes the upper
397 troposphere’s influence on the Indian monsoon rainfall. The 7–8-yr and 2.7-yr oscillation in
398 the troposphere over the North Atlantic is probably induced by the same-period oscillation
399 found in the SST field there, as shown by Feliks et al. (2011) and by Brachet et al. (2012).

400 *c. SOI and Indian core rainfall*

401 The India core rainfall record and the SOI overlap for 130 yr (1876–2006). The eigenvalue
402 spectrum in Fig. 10a suggests common modes in the quasi-quadrennial and the quasi-biennial
403 frequency band.

404 The quasi-biennial band is separated into two nearby oscillatory modes. Both the 2.8-
405 yr oscillation in EOFs 1–2 and the 2.3-yr oscillation in EOFs 3–4 suggest an impact of
406 the Indian core rainfall on the SOI. The energy ratio in either mode is clearly below unity
407 and the Indian core rainfall may thus induce this oscillation in the Tropical Pacific Ocean.
408 Such an inference is consistent with the finding of Rajeevan and Pai (2007) that the South
409 Asian monsoon is not forced by the equatorial Pacific, but rather that the two are mutually
410 interacting systems. The 3.6-yr mode in EOFs 5–6 (Fig. 10d) is dominated by the SOI and
411 probably originates in the Tropical Pacific.

412 The interannual oscillations found in the Indian summer rainfall and in the teleconnection
413 with ENSO, as well as with the Tropical Pacific SSTs, were the subject of many studies,
414 going back to the early 20th century (Philander 1990; Sarachik and Cane 2010). Overall,
415 low monsoon rainfall is associated with El Niño years — warm Eastern Tropical Pacific
416 and negative SOI — while high monsoon rainfall is associated with La Niña years — cold
417 SSTs off the coast of Peru and positive SOI (Sikka 1980; Rasmusson and Carpenter 1983;
418 Parthasarathy et al. 1988; Kumar et al. 1999; Terray and Dominiak 2005; Rajeevan and Pai

419 2007), although there are years during which the opposite is observed.

420 Since the two quasi-biennial oscillations are quite close to each other in an otherwise
421 broad-band spectral behavior of the regional climate systems, we examine the possibility of
422 varimax rotated M-SSA to separate the two. Figure 11a shows the energy ratio between the
423 SOI and the Indian core rainfall in the leading 2.8-yr oscillatory mode, as a function of the
424 number S of rotated components and the window width M .

425 It turns out that, especially at small M , the EOFs are degenerate in the absence of
426 rotation, with multimodal characteristics of the corresponding RCs (Fig. 11b). As the win-
427 dow width M and thus the spectral resolution increases, this mode mixing vanishes and a
428 more refined solution emerges. Still, this refinement raises immediately the question of what
429 a reasonable spectral resolution might be, given the presence of high stochasticity in the
430 system's dynamics. Nonetheless, the energy ratio is rather constant over a wide plateau of
431 S -values and for different M -values (Fig. 11a). This robustness is a strong indicator for the
432 reliability of the identified energy ratio of $\varepsilon \simeq 0.5$ and, therewith, of a genuine separation of
433 the quasi-biennial band into two close but separate modes.

434 5. Concluding remarks

435 In this study we have shown that interannual oscillatory modes exist in the climatic
436 records from India, North Atlantic and the Tropical Pacific. The records we analyzed were
437 the monsoon rainfall for the Indian core region and the Peninsular region for India, the SOI
438 for the Tropical Pacific, and the NAO index for the North Atlantic.

439 Statistically significant oscillatory modes having periods of 2.2–2.7 yr, 3.2–3.6 yr, 5 yr
440 and 6–8 yr were found in climatic records from two or three regions. Such a clustering
441 of periodicities raises the possibility of teleconnection between these regions. We applied
442 systematically to the study of climatic teleconnections between the regions an approach
443 based on synchronization between chaotic oscillators. This approach was introduced in

444 Feliks et al. (2010) and has been refined here by the technical improvements introduced by
445 Groth and Ghil (2011).

446 The 7–8-yr and 2.7-yr oscillatory modes in all three regions are completely synchronized,
447 and the energy ratio analysis suggests that the NAO induces these modes in the other two
448 regions. These two oscillations in the North Atlantic are probably due to oscillations of
449 similar period in the position and strength of the Gulf Stream’s SST front. Feliks et al.
450 (2011) showed that statistically significant oscillations in the SST in the 7–10-yr band and
451 at 2.8 yr exist in two regions along the Gulf Stream track, off Cape Hatteras and in the
452 Grand Banks region.

453 The sharp SST fronts associated with the Gulf Stream spin up an atmospheric jet over
454 the North Atlantic and give rise to oscillations in the 7–10-yr band, similar in period to those
455 observed in the Gulf Stream front itself. In addition, a close correspondence is found between
456 interannual spectral peaks in the observed NAO index and the SST-induced oscillations in
457 an idealized, quasi-geostrophic atmospheric model driven by the observed SSTs (Feliks et al.
458 2011). In particular, significant oscillatory modes with periods of 8.5, 4.2, and 2.8 yr were
459 found by these authors in both the observed and model-simulated indices. These modes were
460 shown to be highly synchronized and of similar energy in both observed and model-simulated
461 time series. This result — together with many previous studies of the 7–8-yr oscillation in
462 SSTs and in sea level pressures over the entire basin (Deser and Blackmon 1993; Moron et al.
463 1998; Joyce et al. 2000; Costa and Verdière 2002) — shows that the energy flow occurs in
464 the two directions, from the ocean to the atmosphere and back, while Wang et al. (2004)
465 showed that it is the Gulf Stream region alone that affects the NAO.

466 The physical mechanism of the 7–8-yr variability in the Gulf Stream, in turn, can be
467 credibly linked to an oscillatory gyre mode of the North Atlantic’s wind-driven circulation
468 (Jiang et al. 1995b; Ghil et al. 2002a; Dijkstra and Ghil 2005; Simonnet et al. 2005; Sushama
469 et al. 2007). The results in the present paper, together with those of Feliks et al. (2010),
470 show that the 7–8-yr oscillatory mode is found around the globe, including over the Eastern

471 Mediterranean, East Africa, South Asia, and the Tropical Pacific, and that it probably arises
472 in the North Atlantic.

473 The teleconnection between the North Atlantic and the Indian summer monsoon has
474 been attributed to two separate modes: the summer CGT (Ding and Wang 2005) and the
475 summer NAO (Folland et al. 2009). Different mechanisms have been suggested to explain
476 the role of the CGT and the NAO in affecting the summer monsoon in India and Pakistan.
477 Here we have only examined the role of the NAO, and shown that a strong dipole over the
478 North Atlantic is highly correlated with a trough over Central Asia, which in turn affects
479 the upper-tropospheric circulation over South Asia.

480 The teleconnection between the North Atlantic and the Tropical Pacific exhibits a two-
481 way interaction: the 5.9-yr and 2.9-yr oscillations induced by the Southern Oscillation in
482 the North Atlantic, and the 7.3-yr oscillation induced by the NAO in the Tropical Pacific.
483 The teleconnection mechanism is plausibly based on previous studies. Chiang and Vimont
484 (2004) have shown evidence that the extratropical atmosphere can influence the Tropical
485 Pacific through a meridional mode, analogous to the one in the tropical Atlantic, in which
486 variations in the trade winds in the northern subtropics influence tropical SSTs. Thompson
487 and Lorenz (2004) have identified relationships between the extratropical annular modes and
488 circulation in the tropical troposphere.

489 The teleconnection between India and the Tropical Pacific also goes both ways: the 3.7-yr
490 and 5-yr modes induced by the Southern Oscillation over India, and the 2.2-yr and 2.8-yr
491 oscillations that are equally active in both regions and strongly coupled between the two. The
492 interannual oscillation found in Indian summer rainfall and its teleconnection with ENSO
493 and Tropical Pacific SST were the subject of many studies (Sikka 1980; Rasmusson and
494 Carpenter 1983; Parthasarathy et al. 1988; Philander 1990; Kumar et al. 1999; Terray and
495 Dominiak 2005; Sarachik and Cane 2010). In agreement with some recent studies (Penland
496 1996; Rajeevan and Pai 2007), we found that the South Asian monsoon is not slaved to the
497 forcing over the equatorial Pacific, but is rather part of a strongly interactive system. Our

498 energy-ratio analysis pinpointed this to be the case in particular for the 2.2-yr and 2.8-yr
499 oscillatory modes.

500 Overall, the approach of synchronized oscillators (Feliks et al. 2010), combined with
501 varimax-rotated M-SSA (Groth and Ghil 2011), appears to be a powerful tool in identifying
502 teleconnections between regional climate modes and helping identify the mechanisms that
503 operate in various frequency bands. This approach should be applicable also to the problems
504 of air-sea interaction and to ocean modes of variability.

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Mathematical and statistical details

Multichannel SSA (M-SSA)

515 Let $\mathbf{x} = \{x_d(n) : d = 1, \dots, D, n = 1, \dots, N\}$ be a multivariate time series with D
 516 channels of length N . Each channel is embedded into an M -dimensional phase space by
 517 using lagged copies $\mathbf{X}_d(n) = [x_d(n), \dots, x_d(n + M - 1)]$, $n = 1, \dots, N - M + 1$. Note
 518 that the resulting matrix \mathbf{X}_d is constant along the skew diagonals. From this we form the
 519 full augmented trajectory matrix $\mathbf{X} = (\mathbf{X}_1, \mathbf{X}_2, \dots, \mathbf{X}_D)$, which has DM columns of length
 520 $N - M + 1$.

521 The M-SSA algorithm then computes the covariance matrix $\mathbf{C} = \mathbf{X}'\mathbf{X}/N$ of \mathbf{X} and its
 522 eigendecomposition; here $(\cdot)'$ indicates transposition. Due to finite-size effects, the sample \mathbf{C}
 523 may be biased, but effective and accurate estimation methods appear in Ghil et al. (2002b).

524 Next, one diagonalizes the appropriately estimated covariance matrix

$$\mathbf{\Lambda} = \mathbf{E}'\mathbf{C}\mathbf{E} \tag{A1}$$

525 to yield a diagonal matrix $\mathbf{\Lambda}$ that contains the real eigenvalues λ_k of \mathbf{C} , and a matrix \mathbf{E}
 526 whose columns are the associated eigenvectors \mathbf{e}_k . The \mathbf{e}_k 's form a new orthogonal basis
 527 in the embedding space of \mathbf{X} , and the corresponding λ_k 's give the variance in the direction
 528 of \mathbf{e}_k . The eigenvectors are composed of D consecutive segments \mathbf{e}_{dk} of length M , each of
 529 which is associated with a channel in \mathbf{X}_d .

530 Projecting the time series \mathbf{X} onto the eigenvectors,

$$\mathbf{A} = \mathbf{X}\mathbf{E}, \tag{A2}$$

531 yields the corresponding principal components (PCs) as columns of \mathbf{A} .

532 The pairwise uncorrelated PCs \mathbf{a}_k are linear combinations of all channels. A way to
 533 reconstruct individual channel-wise components of the system's behavior in a least-squares

534 optimal sense is given by the inverse transformation of Eq. (A2) with a subset of PCs and
 535 eigenvectors. Since we are rather interested in the reconstruction of the given channels \mathbf{x}_d
 536 instead of their embedding \mathbf{X}_d , we average along the skew diagonals of $\mathbf{a}_k \mathbf{e}'_{dk}$,

$$r_{dk}(n) = \frac{1}{M_n} \sum_{m=L_n}^{U_n} a_k(n-m+1) e_{dk}(m). \quad (\text{A3})$$

537 This yields the reconstructed components (RCs: Vautard et al. 1992; Plaut and Vautard
 538 1994). The values of the normalization factor M_n and the summation bounds L_n and U_n for
 539 the central part of the time series, $M \leq n \leq N - M + 1$, are simply $(M_n, L_n, U_n) = (M, 1, M)$;
 540 for either end they are given in Ghil et al. (2002b). In particular, the time series can be
 541 completely reconstructed by the sum of all its RCs, $x_d(n) = \sum_{k=1}^{DM} r_{dk}(n)$, as a consequence
 542 of $\sum_{k=1}^{DM} \mathbf{a}_k \mathbf{e}'_{dk} \equiv \mathbf{X}_d$.

543 *Varimax rotation of ST-EOFs*

544 The idea of a so-called simple-structure rotation is to find a posterior eigenvector rotation
 545 that simplifies the interpretation of the eigenvectors and that reduces mixture effects. There
 546 are several ways to quantify the simplicity of an eigenvector's structure (Richman 1986).
 547 Varimax rotation attempts to find an orthogonal rotation $\mathbf{E}^* = \mathbf{E} \mathbf{T}$ that maximizes the
 548 variance of the squared elements (Kaiser 1958).

549 In PCA with $M = 1$, the cost functional V_1 being maximized is given by

$$V_1 = \sum_{k=1}^S \left\{ \frac{1}{D} \sum_{d=1}^D \left(\frac{e_{dk}^{*2}}{h_d^{*2}} \right)^2 - \left(\frac{1}{D} \sum_{d=1}^D \frac{e_{dk}^{*2}}{h_d^{*2}} \right)^2 \right\}, \quad (\text{A4})$$

550 where S is the number of rotated \mathbf{e}_k^* 's, and $h_d^{*2} = \sum_{k=1}^S e_{dk}^{*2}$ is the corresponding normal-
 551 ization. Kaiser (1958) has given an explicit equation for the sequential rotation of pairs of
 552 eigenvectors that shows the algorithm's simplicity of implementation over more sophisticated
 553 optimization procedures.

554 Since the criterion V_1 maximizes the variance over all coordinates, a direct application
 555 to ST-EOFs would not only achieve the desirable effect of increasing the spatial variance

556 between the channels, but also increase the temporal variance between the data-adaptive,
 557 sine-cosine-like eigenvectors. The latter feature of standard varimax rotation can lead to an
 558 undesirable loss of correctly captured oscillatory pairs (Plaut and Vautard 1994).

559 Recently, Groth and Ghil (2011) have proposed a modification of varimax that maximizes
 560 only the variance of the spatial components. Prior to the calculation of the variance, these
 561 authors first sum over the temporal part

$$\bar{e}_{dk}^{*2} = \sum_{m=1}^M e_{dk}^{*2}(m), \quad (\text{A5})$$

562 and so the cost functional V_M being maximized becomes

$$V_M = \sum_{k=1}^S \left\{ \frac{1}{D} \sum_{d=1}^D \left(\frac{\bar{e}_{dk}^{*2}}{\bar{h}_d^{*2}} \right)^2 - \left(\frac{1}{D} \sum_{d=1}^D \frac{\bar{e}_{dk}^{*2}}{\bar{h}_d^{*2}} \right)^2 \right\}, \quad (\text{A6})$$

563 with the normalization $\bar{h}_d^{*2} = \sum_{k=1}^S \bar{e}_{dk}^{*2}$. In this way, the criterion V_M as well as V_1 attempt
 564 to bring the spatial component of the S(T)-EOFs either close to one or to zero. In the
 565 present paper, we have adopted the modified varimax rotation that takes Eq. (A5) into
 566 account. Still, this modified version retains the algorithm's simplicity of implementation,
 567 namely the sequential rotation of pairs of eigenvectors (Groth and Ghil 2011).

568 *Annual subsampling*

569 Since we wish to concentrate in the present paper on interannual time scales, we removed
 570 all subannual oscillations with a low-pass filter prior to our SSA analysis. The choice of the
 571 filter is critical in order to avoid aliasing effects in the annual subsampling of the monthly
 572 time series. An inappropriately chosen low-pass filter can not only amplitude alter the am-
 573 plitude of the oscillations, but even lead to spurious interannual oscillations in the annually
 574 subsampled time series.

575 In order to get rid of the strong seasonal cycle in climate records, typical choices include
 576 using the annual mean, as well as the seasonal winter or summer means. We compare these
 577 customary approaches to low-pass filtering with a Chebyshev low-pass filter. The favored

578 Chebyshev type I filter is very close to an ideal low-pass filter, with practically no distortions
579 of either phase or amplitude in the passband and a highly effective damping in the stopband
580 (Daniels 1974). Figure 12 shows the frequency response of this low-pass filter, together with
581 that of a 12-month as well as a 3-month moving average.

582 The Chebyshev filter comes quite close indeed to an ideal filter, with a very steep decline
583 at the desired cut-off frequency and a nearly constant magnitude in the passband. The small
584 ripples in the passband can be ignored in comparison to the strong frequency-dependent mag-
585 nitude response of the two other filters. Although the 12-month filter is more effective in
586 removing high frequencies than the 3-month filter, both filters are strongly frequency depen-
587 dent, and influence therefore any subsequent spectral analysis. In particular, when changing
588 from a monthly to an annual sampling rate, all frequencies above the Nyquist frequency of
589 0.5 cycles/yr are reflected into lower frequencies and the new time series of annually as well
590 as seasonally averaged values are susceptible, therewith, to spurious oscillations and other
591 aliasing effects.

592 To demonstrate the different approaches to annual subsampling, we consider the annual
593 mean, along with the summer and winter mean, as well as the July value after Chebyshev
594 low-pass filtering of the given monthly NAO index. In Fig. 13, we estimate the PSD of these
595 annually subsampled records (heavy solid) and compare each of them with the PSD estimate
596 of the raw NAO index on the monthly scale (light solid).

597 Since the frequency response of the Chebyshev filter has a nearly rectangular shape,
598 we observe practically no difference between the PSD estimates of the monthly and annual
599 time series in the passband (Fig. 13a). The annual mean, on the other hand, matches the
600 monthly PSD only for low frequencies and diverges with increasing frequency (Fig. 13b).
601 Both seasonal-mean values, finally, show large discrepancies over the whole spectral range,
602 with many spurious peaks in the passband (Figs. 13c, d), due to the very weak damping in
603 the stopband. The aliasing in the passband may depend, moreover, on the chosen season,
604 with possibly opposite effects in the winter and summer mean. The 7.8-yr oscillation, for

605 example, is completely damped in the summer case and strongly amplified in the winter.
606 Moreover, in the quasi-biennial band we observe even various frequency shifts.

607 The reconstructed 7.8-yr oscillatory mode is statistically significant in the Chebyshev,
608 annual-mean and winter-mean cases, but not in the summer mean. To show the effect of
609 the prefiltering on the SSA analysis, we examine in Fig. 14 the reconstruction of the 7.8-yr
610 mode in each of the annually sampled time series in which it is significant.

611 In the Chebyshev (panel a) and annual-mean (panel b) cases, the 7.8-yr mode is quite
612 similar in PSD amplitude, although a small phase shift emerges (not shown). Strong dis-
613 crepancies in both amplitude and phase arise between the winter mean (panel d) and the
614 Chebyshev case (panel a); these discrepancies can be attributed to the aliasing problem
615 found in the winter mean.

616 Given the obvious problems with using 3- or 12-month means, we have used in this
617 paper the Chebyshev type I filter for low-pass filtering. Since the results in this case also
618 appear to be independent of the month used for subsampling, the month of January was
619 used throughout, for simplicity's sake.

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TABLE 1. Oscillatory modes in the climatic records shown in Fig. 1 that are statistically significant at a 95% significance level, in both the SSA and MTM analyses. The main entries give the period in years; entries in parentheses indicate the percentage of variance captured by the corresponding mode.

SOI	Indian rainfall		NAO index
	core	Peninsular	
6–7 (8%)	7.6 (8%)	7.3 (9%)	7.8 (12%)
			5.9 (8%)
5 (7%)		5 (7%)	5 (7%)
3.6 (10%)	3.2–3.6 (5%)	3.5 (8%)	4.2
2.5 (7%)	2.7 (6%)	2.8 (6%)	2.7 (6%)
	2.2–2.4 (23%)		

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- 1 The climate records used in this study, shown at a monthly sampling rate and after filtering out all frequencies above 0.5 cycles/yr. (a) Southern Oscillation index (SOI); (b,c) Indian rainfall, over the core and Peninsular regions; and (d) North Atlantic Oscillation (NAO) index. 37
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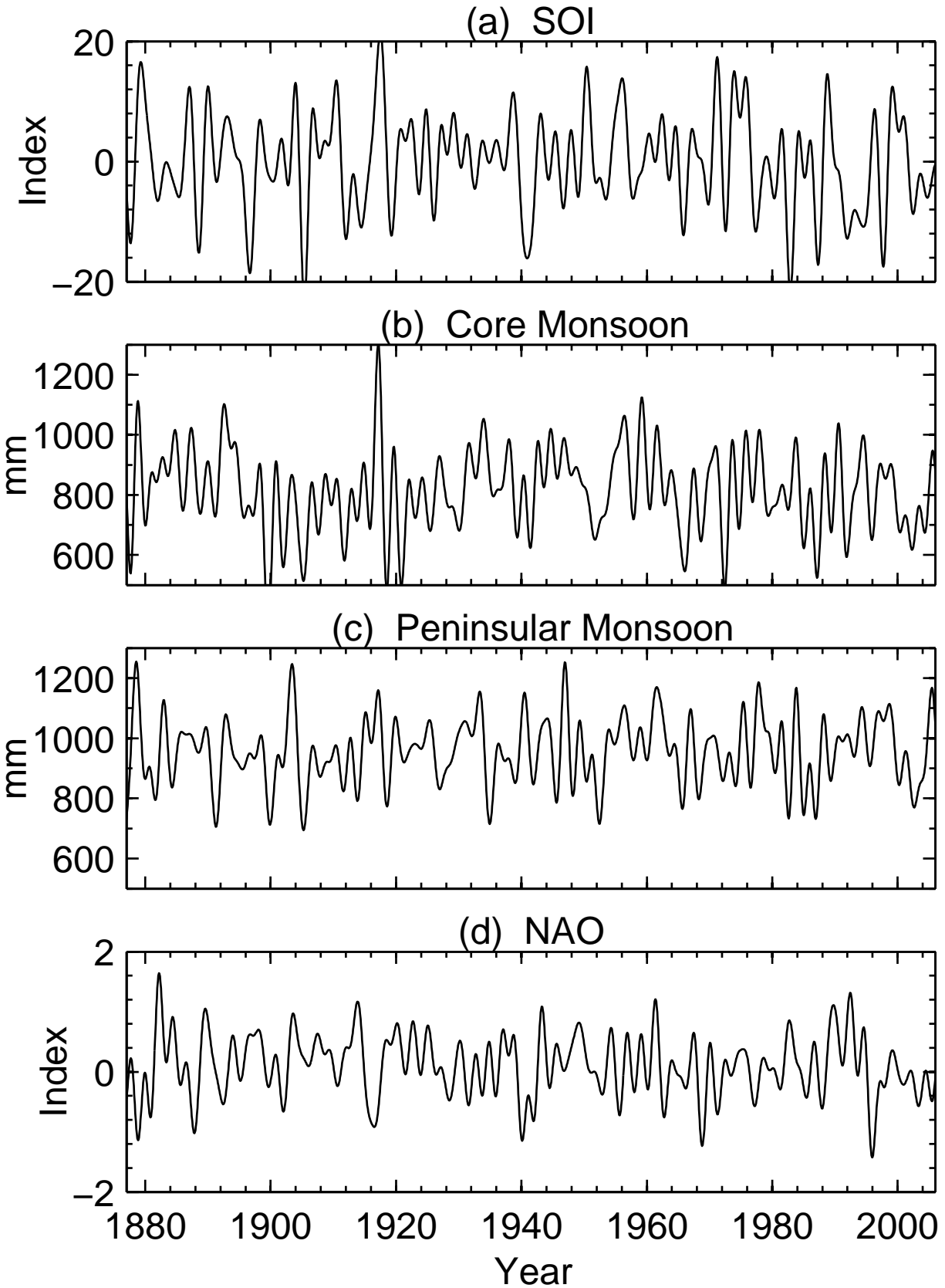


FIG. 1. The climate records used in this study, shown at a monthly sampling rate and after filtering out all frequencies above 0.5 cycles/yr.³⁸ (a) Southern Oscillation index (SOI); (b,c) Indian rainfall, over the core and Peninsular regions; and (d) North Atlantic Oscillation (NAO) index.

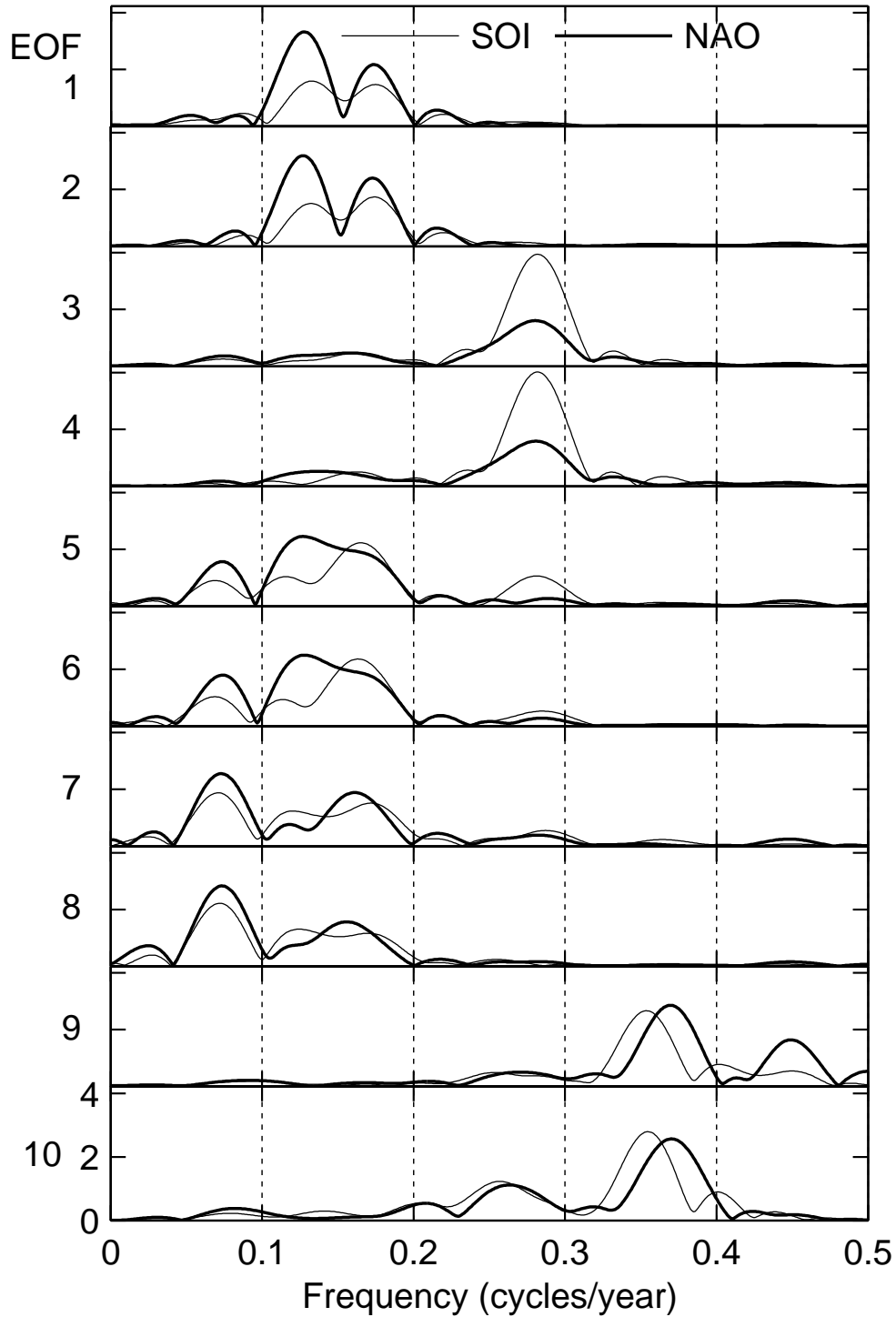


FIG. 2. Estimates of power spectral density (PSD) for the ten leading ST-EOFs from an M-SSA analysis of SOI (light solid) and NAO (heavy solid). Window width is $M = 40$. The ST-EOFs have been tapered by a Tukey window, with parameter $\alpha = 0.5$, in order to reduce leakage effects in the Fourier transform, cf. Oppenheim and Schaffer (2009).

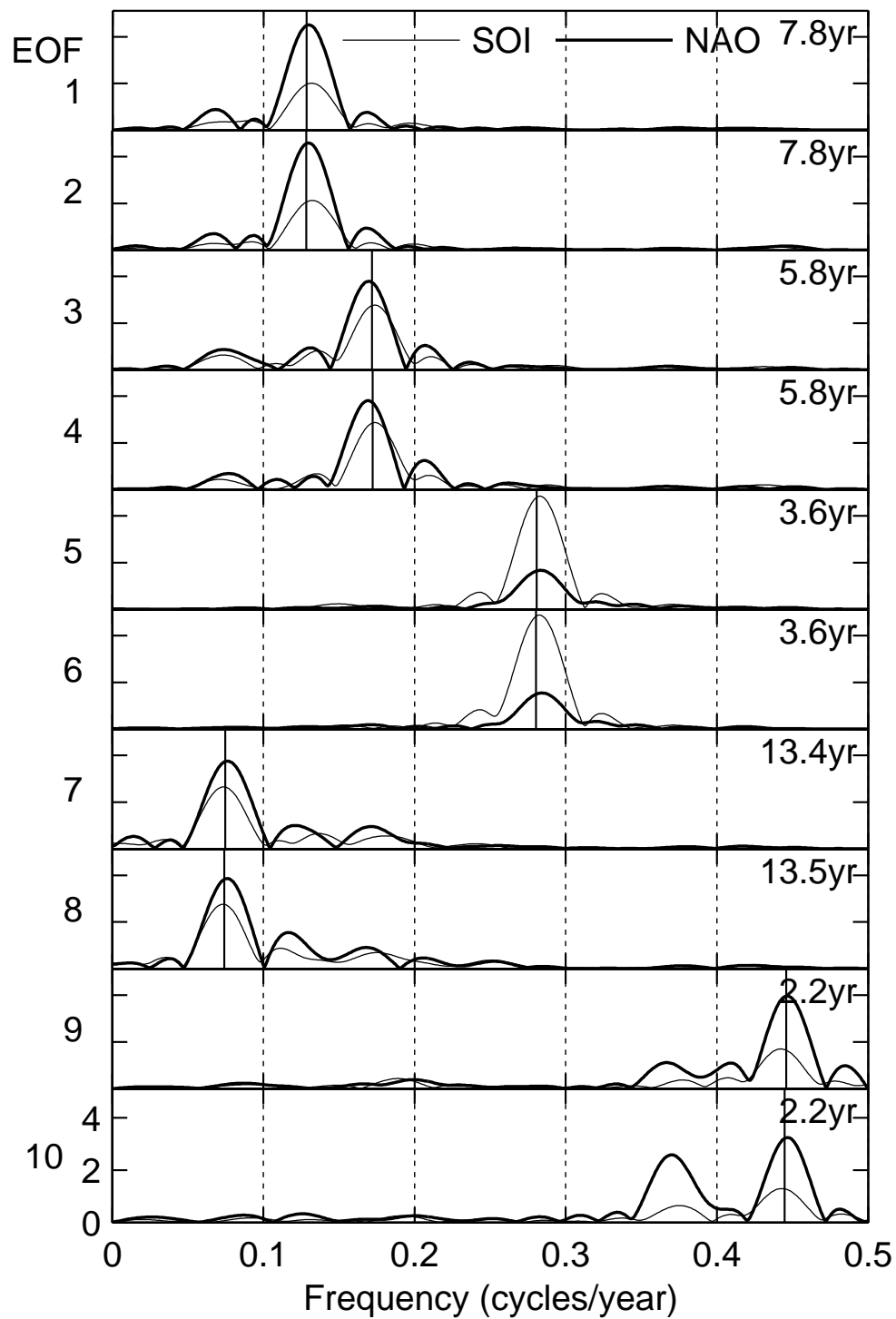


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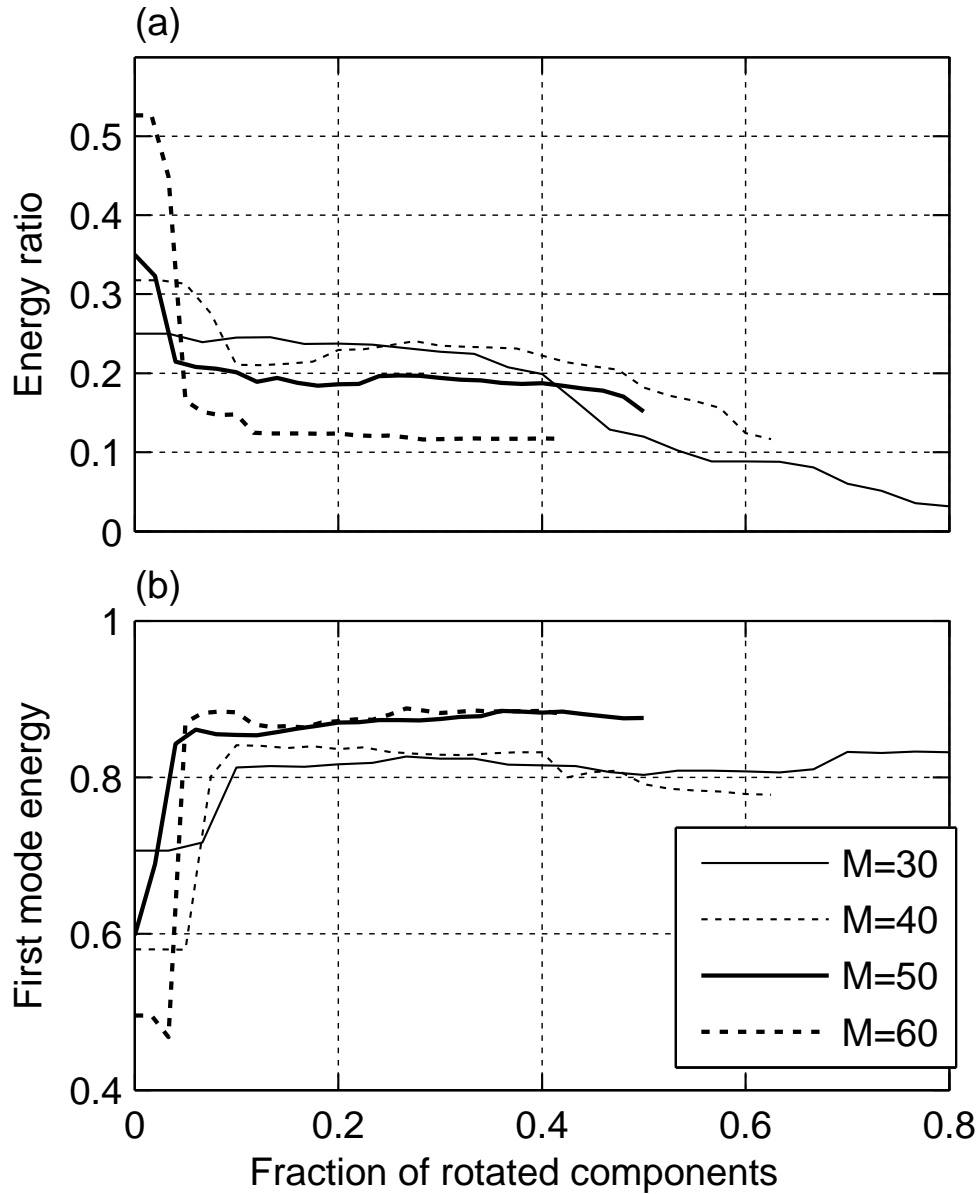


FIG. 4. M-SSA analysis of the SOI and NAO indices, as a function of the relative number $S/(DM)$ of rotated EOFs and for different values of the window length M ; here $D = 2$ is fixed. (a) Energy ratio ε of the leading 7.8-yr oscillatory mode; and (b) the unimodality index of the corresponding RCs.

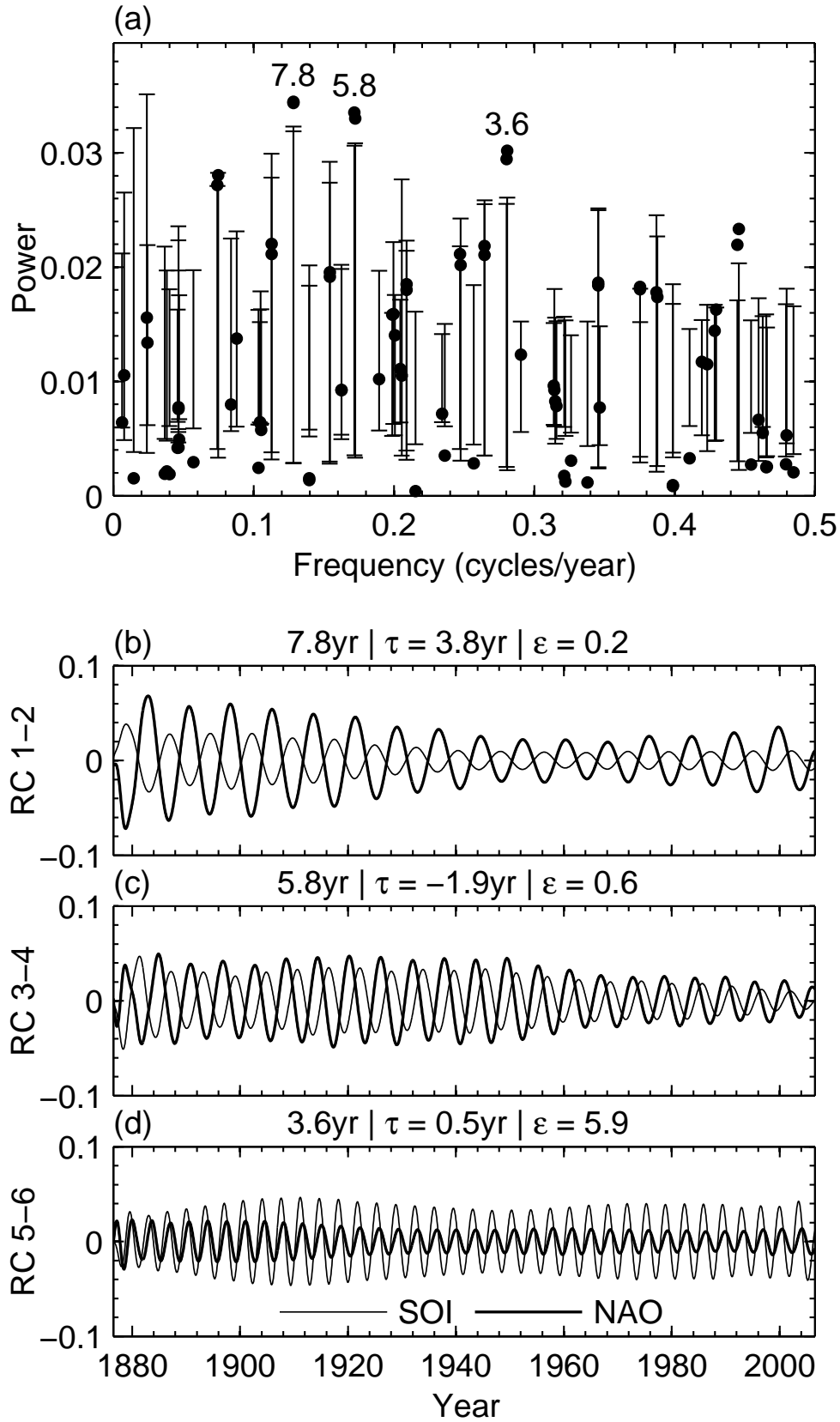


FIG. 5. MC-SSA analysis of the SOI and NAO indices. (a) Eigenvalue spectrum, with the statistical significance level. The error bars represent the 1% and 99% quantile from an ensemble of 1000 surrogate data, while the numbers indicate the period length (in years) for the significant oscillatory modes. (b–d) RC pairs corresponding to the significant oscillatory modes; NAO – heavy solid, SOI – light solid. Window width $M = 50$ and number of rotated components $S = 30$.

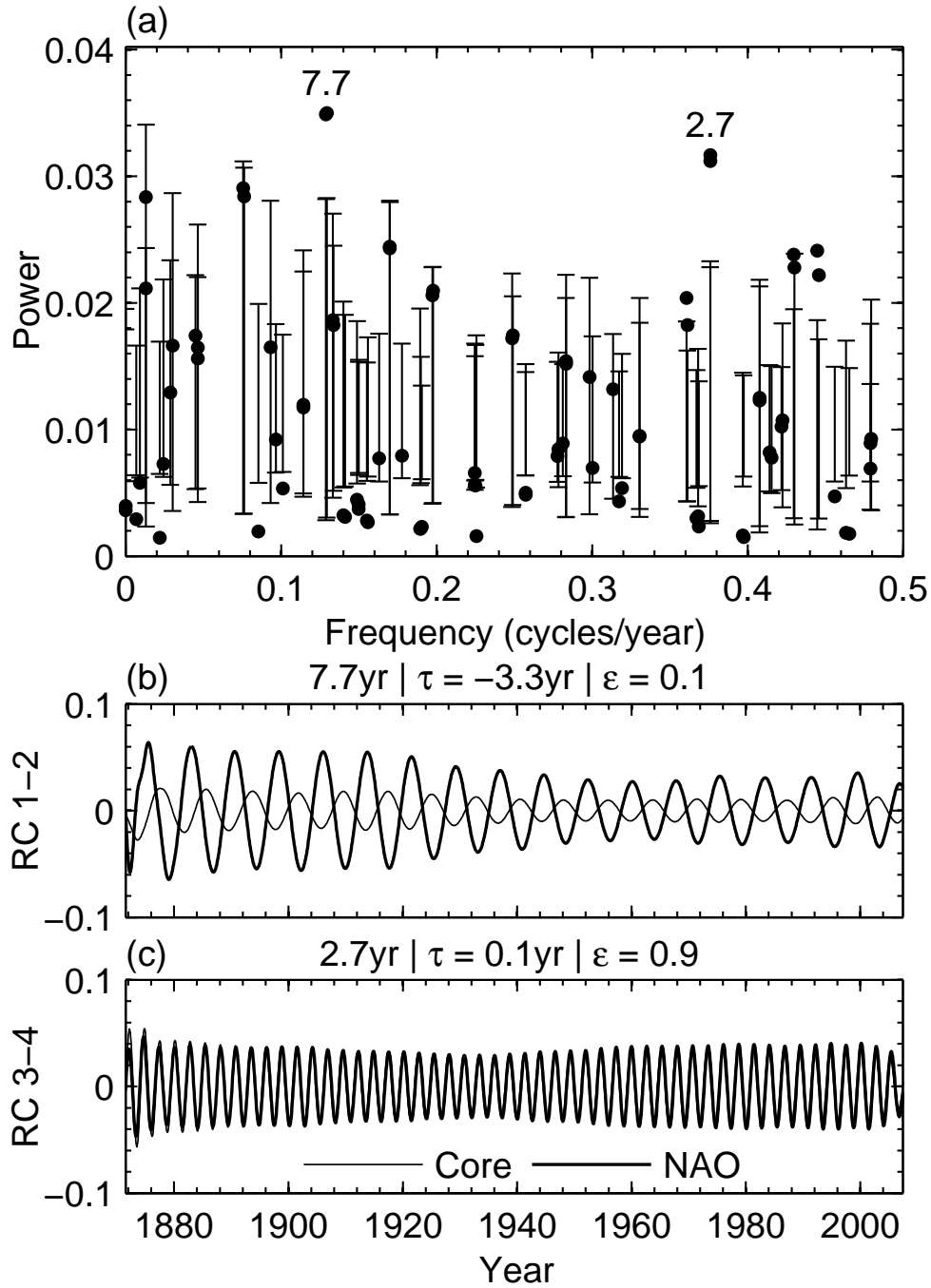


FIG. 6. MC-SSA analysis of the Indian core rainfall and NAO. (a) Eigenvalue spectrum, together with the level of significance. The numbers indicate the period (in years) for the significant oscillatory modes. (b, c) RC pairs corresponding to the two significant oscillatory modes; NAO – heavy solid, core rainfall – light solid. Window width and number of rotated components as in Fig. 5.

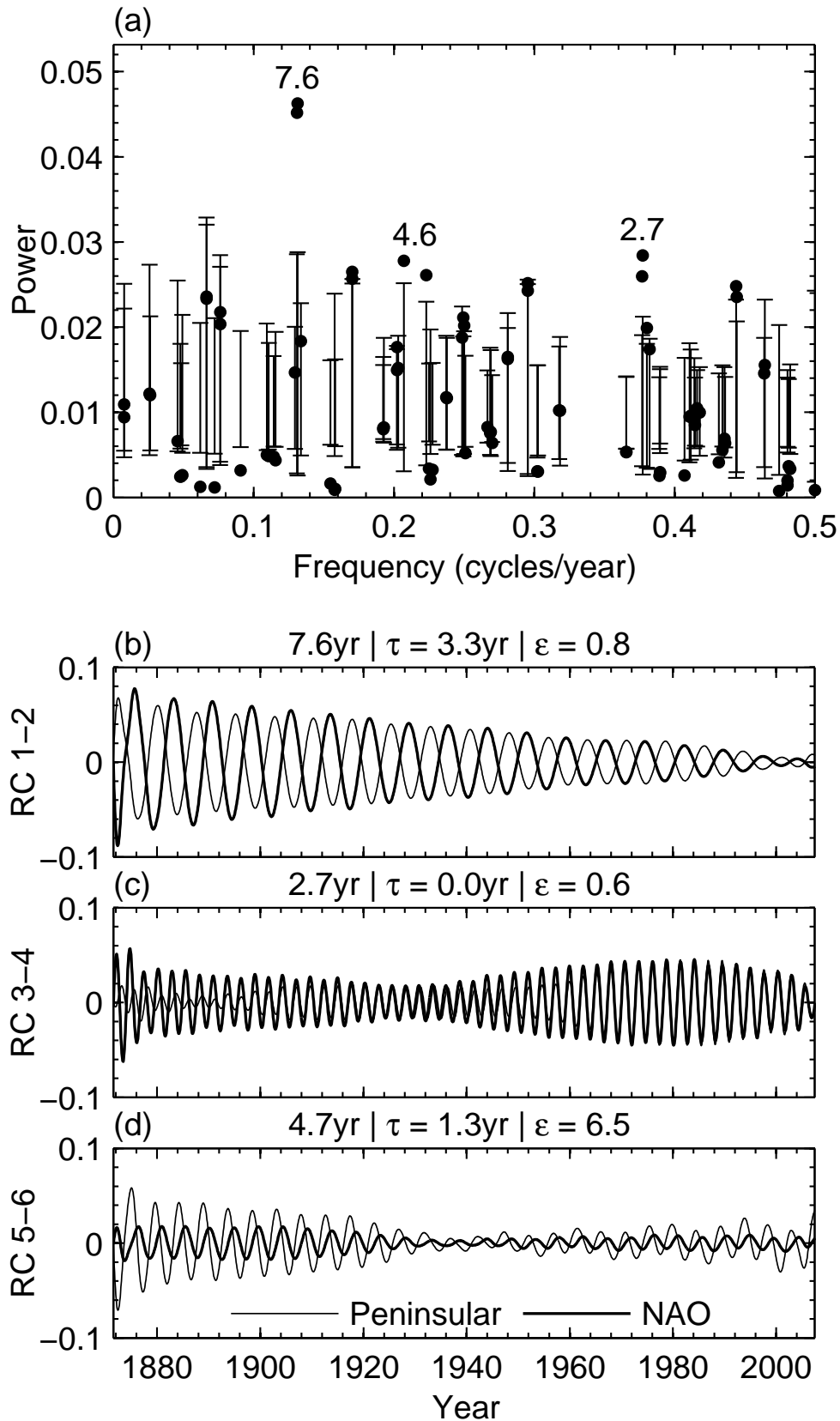


FIG. 7. MC-SSA analysis of the Indian Peninsular rainfall and NAO. (a) Same as in Fig. 6; (b–d) RC pairs corresponding to the three significant oscillatory modes; NAO – heavy solid, Peninsular rainfall – light solid. Window width $M = 50$ and rotated components $S = 3\text{--}30$.

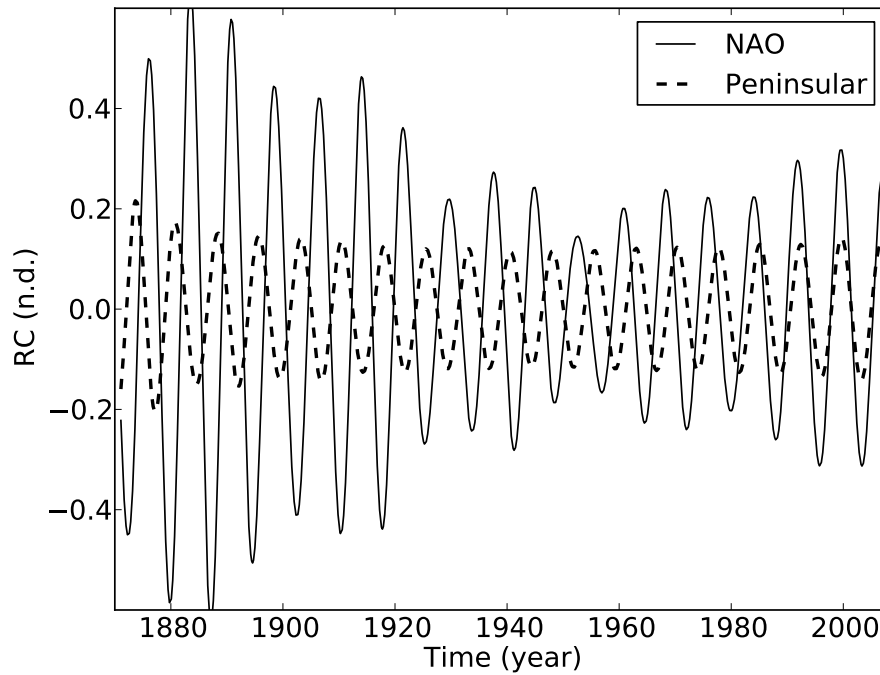


FIG. 8. The single-channel SSA reconstructions of the 7.7-yr oscillatory mode of the NAO index (solid line) and of the 7.4-yr mode of the Peninsular rainfall (dashed line) from their respective low-pass filtered monthly records. The window width for both analyses is $M = 480$ months = 40 yr.

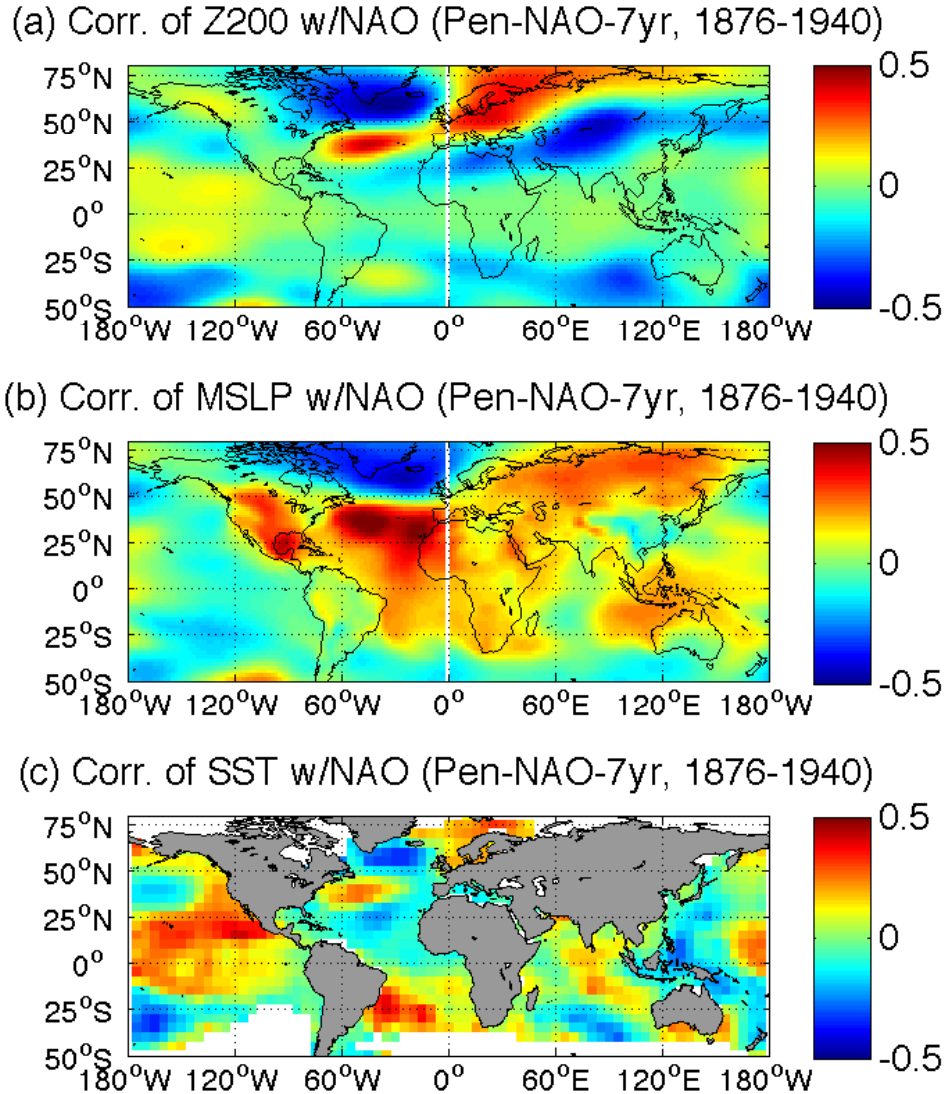


FIG. 9. Maps of the Pearson correlation coefficient between the NAO component of the joint 7.6-yr oscillatory mode in Fig. 7b. (a) 200hPa geopotential heights (Z200); (b) mean sea level pressures (MSLP); and (c) sea surface temperatures (SST). See text for details. Correlation values exceeding 0.25 are statistically significant at the 95% level with a two-tailed Student t-test and 60 degrees of freedom.

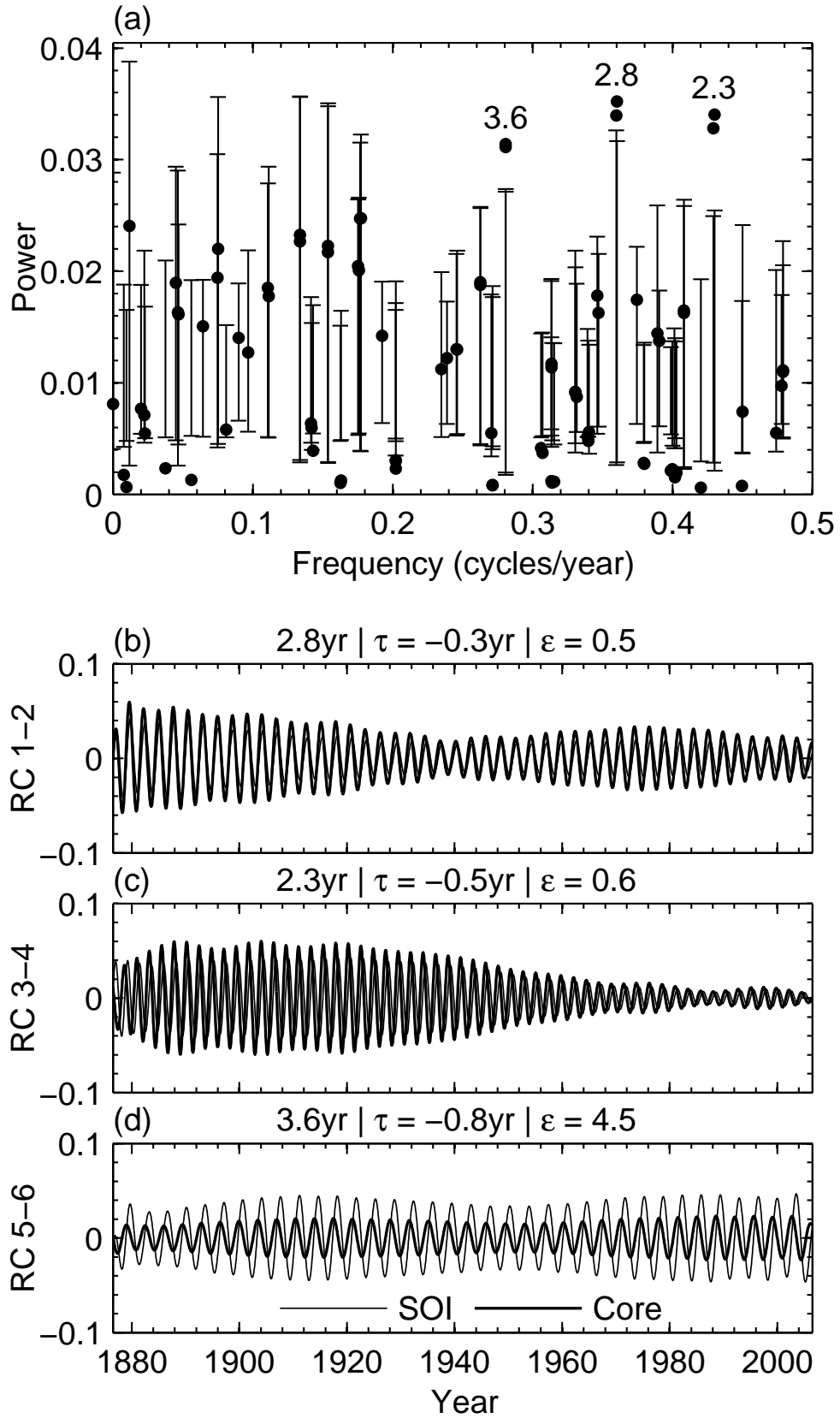


FIG. 10. MC-SSA analysis of the SOI and the Indian core rainfall. Same panels and parameter values as in Fig. 5.

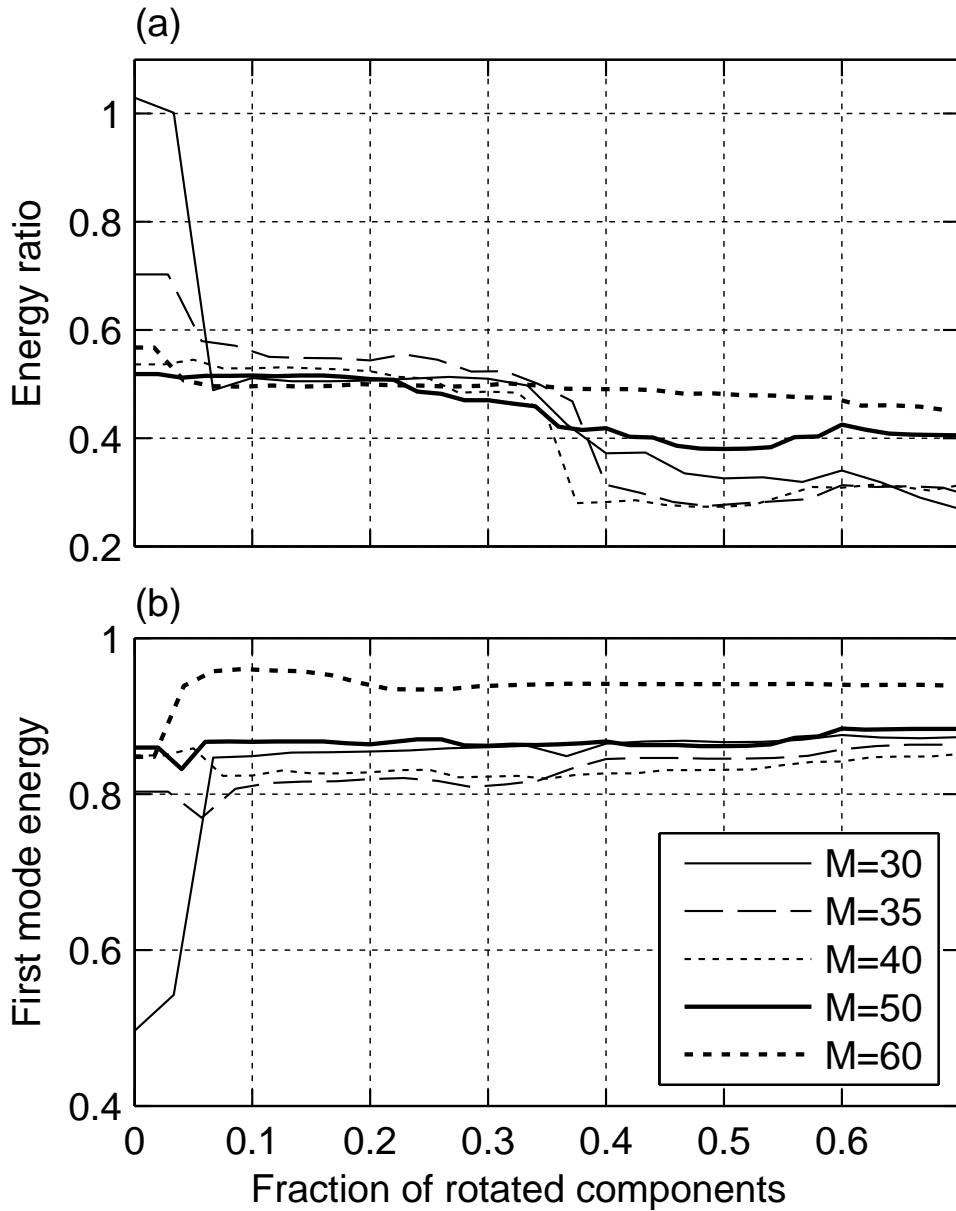


FIG. 11. MC-SSA analysis of the SOI and the Indian core rainfall, as a function of the relative number $S/(DM)$ of rotated EOFs and for different values of the window length M ; here $D = 2$ is fixed. (a) Energy ratio ε of the leading 2.8-yr oscillatory mode; and (b) the unimodality index of the corresponding RCs.

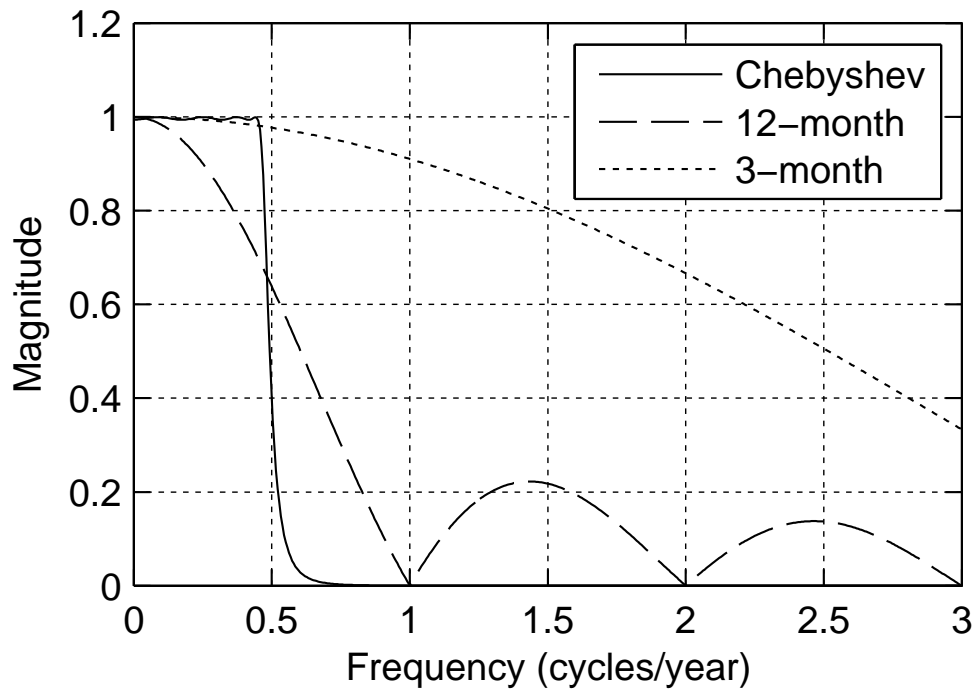


FIG. 12. Frequency response function of three different low-pass filters: Chebyshev (solid), 12-month moving average (dashed), and 3-month moving average (dotted). The Chebyshev type I filter of order eight has been set to have its cut-off frequency at 0.45 cycles/year (Daniels 1974).

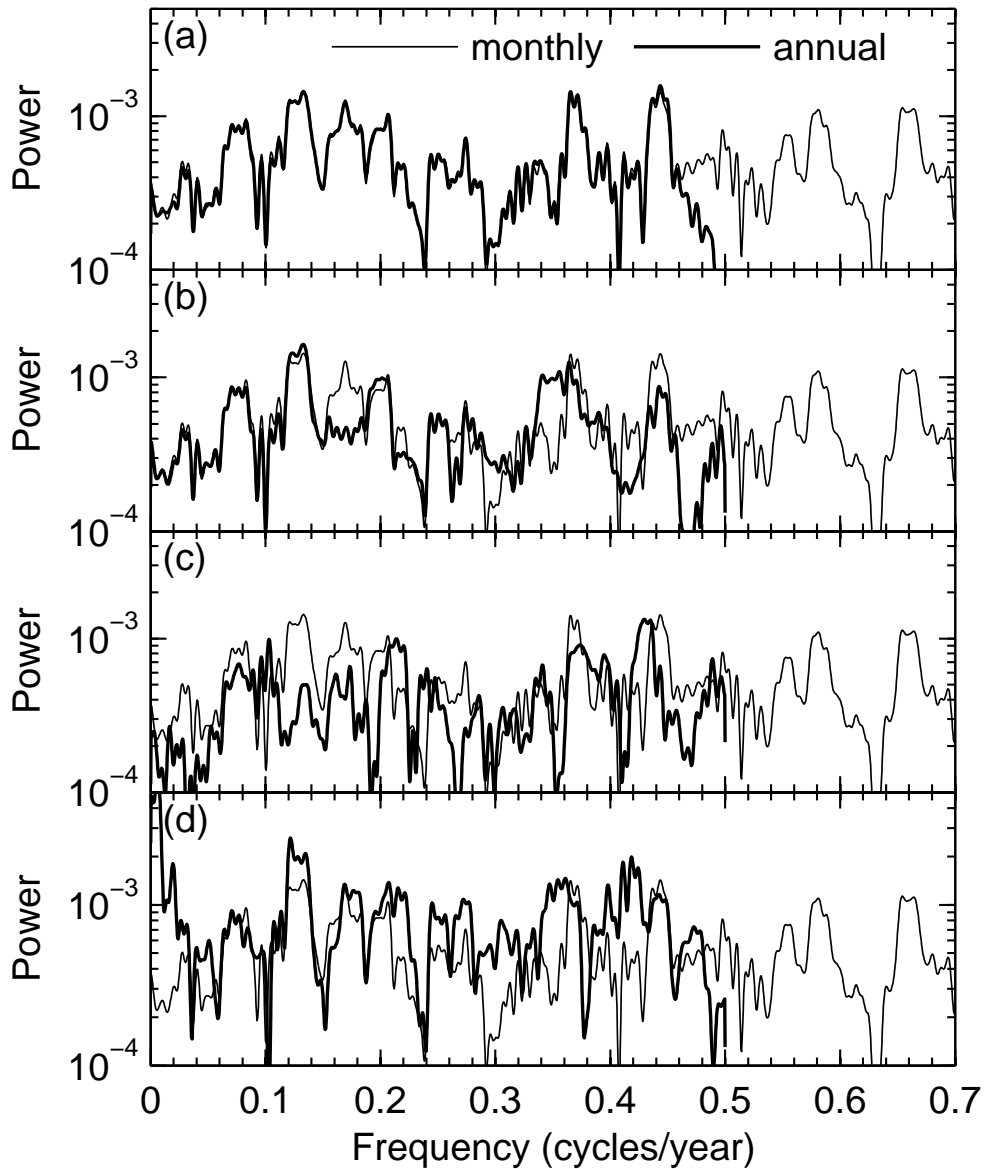


FIG. 13. PSD estimate of the monthly as well as the annually subsampled NAO index. (a) July value after Chebyshev type I low-pass filtering; (b) annual mean; (c) summer mean (JJA); and (d) winter mean (JFM). All PSD estimates used MTM with three tapers; the correct PSD estimate from monthly values in all four panels is light solid, the filtered and subsampled estimate is heavy solid. For ease of comparison, the PSD estimate of the monthly NAO index has been scaled by $(1/12)$ and the PSD estimates of the seasonal mean values by $(1/2)$.

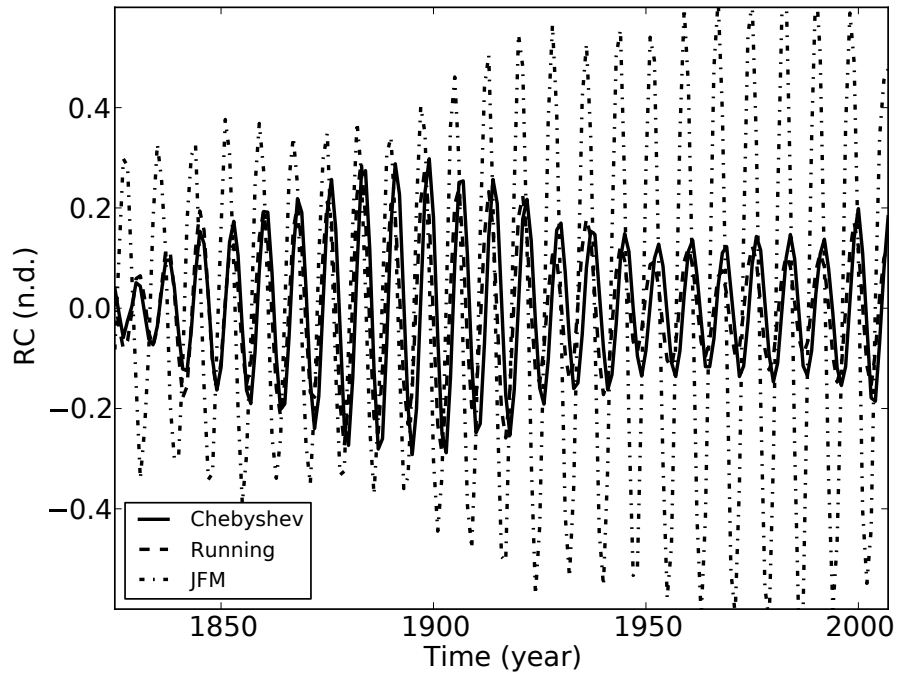


FIG. 14. The RC of the 7.8-yr oscillatory mode of the NAO index: winter-mean (JFM, dotted), January sampling of the time series pre-filtered by a Chebyshev type-I filter (Chebyshev, solid), and January sampling of the time series pre-filtered by a 12-month running mean (Running, dashed).