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Distinct modes of bidecadal and multidecadal variability in a climate reconstruction of the last centuries from a South Pacific coral

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Abstract The Rarotonga coral Sr/Ca time series (Linsley et al. in Science 290:1145–1148, 2000) provides a near-monthly resolved proxy record of South Pacific climate variability over the last ~300 years. Here we show that two distinct interdecadal, quasi-periodic time components with periods of ~80 and ~25 years can be identified in this time series by Singular Spectrum Analysis. Their associated spatial patterns in the global sea surface temperature (SST) field show notable differences. Whereas the multidecadal component is associated with a global SST pattern that was recently associated with solar forcing on multidecadal timescales, the bidecadal component is associated with a well known pattern of Pacific decadal to interdecadal SST variability.

1 Introduction

Massive, annually banded corals from the surface waters of the tropical and subtropical oceans provide a seasonally resolved archive of past climate variability (e.g., Tudhope et al. 2001; Cobb et al. 2003; Felis et al. 2004). Isotopic and elemental tracers, incorporated into the carbonate skeletons of these corals during growth, provide proxies of past environmental variability of the surface ocean (e.g., Felis and Pätzold 2004). A coral record from the island of Rarotonga in the subtropical South Pacific (Cook Islands) is the longest near-monthly resolved paleoclimatic reconstruction generated from a natural archive that is currently available, covering the period 1726–1997 AD (Linsley et al. 2000). This time series is based on measurements of Sr/Ca ratios in the skeleton of a single coral colony (*Porites lutea*). Coral Sr/Ca ratios provide a proxy for the temperature in the ambient seawater at the time of coral growth, and are inversely related to temperature variations (Schneider and Smith 1982; Beck et al. 1992).

Whereas the Sr/Ca signal in massive coral skeletons has been shown to provide an accurate proxy for temperature seasonality (Beck et al. 1992; Gagan et al. 1998; Felis et al. 2004), its reliability on interannual and longer timescales is still a matter of debate (de Villiers et al. 1995; Stephans et al. 2004). Up to now, only very few coral Sr/Ca based sea surface temperature (SST) reconstructions covering the past centuries are available (Linsley et al. 2000, 2004; Hendy et al. 2002). To prove the accuracy of coral Sr/Ca as a paleothermometer on interannual and longer timescales is not an easy task, as reliable long-term SST observations at most of the remote locations of coral growth are lacking. Linsley et al. (2000) report a significant correlation of annually averaged Rarotonga coral Sr/Ca with regional gridded SST of $r^2 = 0.45$, suggesting that at least some of the documented Sr/Ca variability is not directly related to SST, but to other environmental or biological processes. In theory, such processes can result in both a disturbance and an enhancement of the Sr/Ca signal in massive corals in terms of documented temperature variability.

The Rarotonga coral Sr/Ca time series was shown to be associated with a well known mode of Pacific basin-wide SST variability on decadal to interdecadal timescales (Linsley et al. 2000; Evans et al. 2001; Linsley et al. 2004), the so-called Pacific Decadal Oscillation (PDO; Mantua et al. 1997) or Interdecadal Pacific

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Oscillation (IPO; Folland et al. 2002). This mode has a spatial pattern in the Pacific SST field that is similar to that of the El Niño-Southern Oscillation (ENSO) but with higher amplitude and spatial expression at mid latitudes relative to the tropics (Zhang et al. 1997; Garreaud and Battisti 1999).

Pacific decadal to interdecadal climate variability has important socioeconomic effects in western North America through the modulation of fish stocks and droughts (Mantua et al. 1997; Cole et al. 2002). However, a better understanding of this variability, which is necessary for its prediction, is limited by the relatively short period of instrumental climate observations. Therefore, the Rarotonga coral-based SST reconstruction provides an important source of information on Pacific decadal to interdecadal climate variability during the pre-instrumental period (Linsley et al. 2000), in concert with various other proxy records from the Pacific basin and adjacent continental regions (Gedalof et al. 2002). Recent climatological and statistical analyses of the Rarotonga coral Sr/Ca time series concentrated on the interpretation of decadal to interdecadal variability in its entirety without separating distinct modes of variability within this frequency band (Linsley et al. 2000, 2004; Evans et al. 2001). Here we show that the interdecadal variability in this time series consists of two distinct, prominent components, a bidecadal and a multidecadal mode, that are quite different with respect to the associated spatial patterns in the global SST field.

2 Data and methods

We analyzed the Rarotonga coral Sr/Ca based SST reconstruction from the subtropical South Pacific (21.24°S, 159.83°W, Cook Islands) published by Linsley et al. (2000). The time series has a near-monthly resolution and covers 270 full years (1727–1996 AD; Fig. 1). The term near-monthly indicates that despite the fact that the coral times series has 12 equally spaced values per year, which were derived from linear interpolation of the original Sr/Ca data of ~12–13 samples/year, the age model error of the time series is in the order of 1–2 months (Linsley et al. 2000, 2004). This is due to the facts that for the construction of the age model (1) a constant coral growth rate throughout the year was assumed, which indeed, is not the case, and (2) the annual coral Sr/Ca extremes were set to the average warmest/coolest month. However, this is the normal procedure for the age model construction of Indo-Pacific coral records (e.g., Felis and Pätzold 2004), and is assumed to represent the most objective method.

In order to identify the dominant quasi-periodic components in the coral time series Singular Spectrum Analysis (SSA) was used. The SSA method is designed to extract information from short and noisy time series by providing data-adaptive filters that help to separate the time series into statistically independent components like trends, oscillatory signals, and noise (Vautard et al. 1992; Allen and Smith 1997). Trends need not to be linear and the oscillations can be modulated in amplitude and phase (Allen and Smith 1997). End-effects are avoided by extending the initial time series, based on a fitted low-order auto-regressive process. To maximize possible signal-to-noise enhancement (Allen and Smith 1996) we use an as large as possible window but which is not longer than one third of the time series length, i.e., a 1,000-month window. Repeated SSAs with various window lengths (e.g., several hundreds months shorter or longer) show that the basic features of the identified time components remain stable and therefore are independent of the window length used. For example, the structure of the eigenvalue spectrum (Fig. 2a) and the approximate periods and amplitudes of the identified time components remain unchanged.

In most time series the main part of the variance is related to the trend. If the trend is not the focus of the analysis, it overshadows the other modes of interests. In the context of our study, removing the trend increases the signal-to-noise ratio. We subtracted the seasonal cycle and then the nonlinear trend of the coral time series. The trend was identified by SSA using a 1,000-

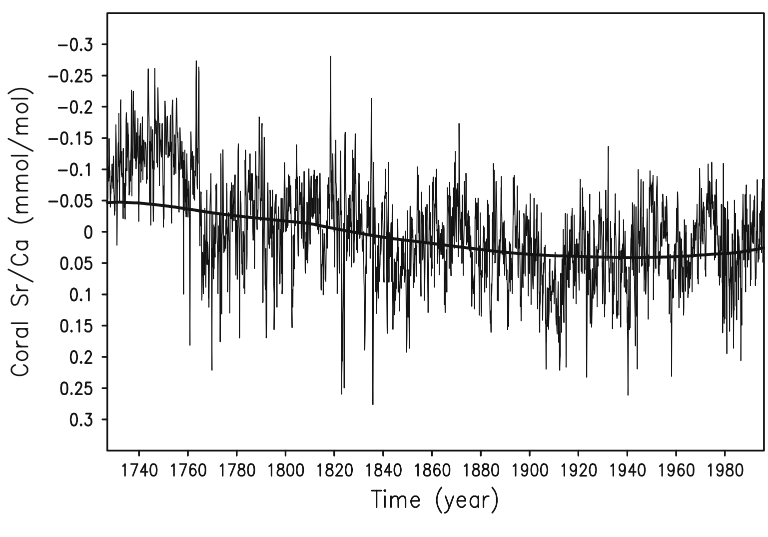

Fig. 1 The Rarotonga coral Sr/Ca time series from the subtropical South Pacific (21.24°S, 159.83°W, Cook Islands) published by Linsley et al. (2000). The near-monthly resolved, centered (mean subtracted) time series with the average seasonal cycle removed is shown (1727–1996 AD). The nonlinear trend identified by Singular Spectrum Analysis (SSA) is indicated (*bold line*). Negative coral Sr/Ca anomalies reflect higher sea surface temperature (SST); positive coral Sr/Ca anomalies reflect lower SST (Linsley et al. 2000)

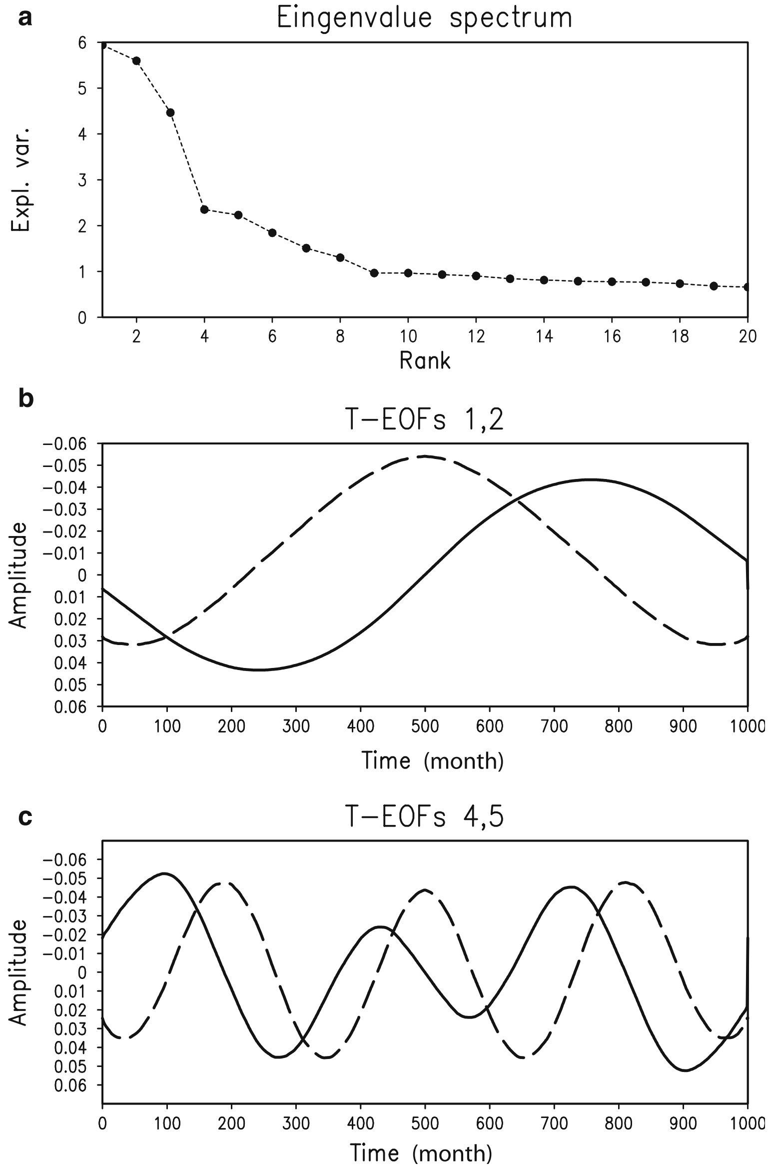

Fig. 2 Eigenvalues and time-Empirical Orthogonal Functions (EOFs) derived from SSA of the near-monthly Rarotonga coral Sr/Ca time series using a 1,000-month window. **a** Eigenvalues for the first 20 modes. **b** EOFs 1 and 2, explaining 11% of the total variance in the time series. **c** EOFs 4 and 5, explaining 5% of variance. The time-EOFs of each pair are in quadrature, indicating that each of the two pairs is associated with a quasi-periodic component

year window (Fig. 1). Therefore, by removing the trend we come closer to the stationarity assumption and increase the significance of the quasi-periodic components. A similar procedure was performed by Chao et al. (2000) to improve the statistical significance, by removing the components of no interest in an SSA. We then performed SSA on the resulting, deseasonalized and detrended coral time series (1727–1996 AD). Vautard et al. (1992) suggest that oscillatory components are optimally identified using windows of lengths longer (even several times longer) than their period. Following this suggestion we use a 1,000 months window.

To derive spatial SST patterns associated with dominant variability in the coral time series composite maps were constructed based on the global SST field (Kaplan et al. 1998) for the 1856–1996 AD period and the time components obtained from SSA. In a first step all maps corresponding to time moments for which the value of the coral-based time component is higher than half of its standard deviation were selected. The standard deviation is calculated for the 1727–1996 AD period. Based on these maps, an average field was calculated. Similarly, an average field based on the maps corresponding to values in the coral-based time component that are lower than half of its standard deviation was calculated. Finally, the composite map was obtained from the difference between the first and second calculated average map. The composite map may be interpreted as the fingerprint of the coral-based time component in the global SST field. One may note that, unlike regression and correlation, composing is a nonlinear operation. However, as regression and correlation, it does not imply causality. The composite maps are compared with maps of modes obtained through Empirical Orthogonal Function (EOF) analysis (Preisendorfer 1988) of the global SST field (Kaplan et al. 1998).

The statistical significance of correlations is tested under the null hypothesis that there is no real correlation between the two variables, using the Student's t statistics (von Storch and Zwiers 1999):

$$t = r\left[\frac{N_{\mathrm{eff}} - 2}{1 - r^2}\right]^{1/2}$$

where r denotes the estimated correlation coefficient between variables and N_{eff} is the number of degrees of freedom. In order to account for the serial correlation which occurs in the time series, the effective number of degrees of freedom (N_{eff}) is estimated using the methods of Leith (1973) and Jones (1975):

$$N_{\mathrm{eff}} = N\left[\frac{1 - r_1}{1 + r_1}\right]$$

where N is the number of samples in the time series and r_1 is the lag-1 autocorrelation coefficient of the time series obtained as the product of the variables for which the significance of the correlation is estimated.

3 Results

Singular Spectrum Analysis of the Rarotonga coral Sr/Ca time series reveals two dominant quasi-periodic time components. Eigenvalues 1 and 2 as well as eigenvalues 4 and 5 have close values (Fig. 2a). Each of the two pairs is associated with a quasi-periodic component. The first component explains 11% of variance and its eigenvalues 1 and 2 are well separated from other values in the spectrum. Eigenvalues 4 and 5 are above the noise level and their associated component explains 5% of variance in the time series. The third eigenvalue is not associated with a quasi-periodic component and therefore it is not considered further. The two time-EOFs associated with each of the quasi-periodic components are in quadrature (Fig. 2b, c), confirming the significance of the time components. The reconstructed signals have periods of about 80 and 25 years, respectively (Fig. 3). The results are consistent with previous evidence for the coexistence of multidecadal and bidecadal climate variations over the Pacific Ocean (Minobe 1999; Chao et al. 2000; Gedalof et al. 2002).

3.1 Multidecadal variability

In order to derive a spatial pattern associated with the multidecadal time component in the coral time series a SST composite map is calculated. Prior to the construction of the composite map the annual SST fields for the 1856–1996 AD period were detrended and a 25-year running mean filter was applied. The resulting composite map reveals that the spatial SST pattern associated with

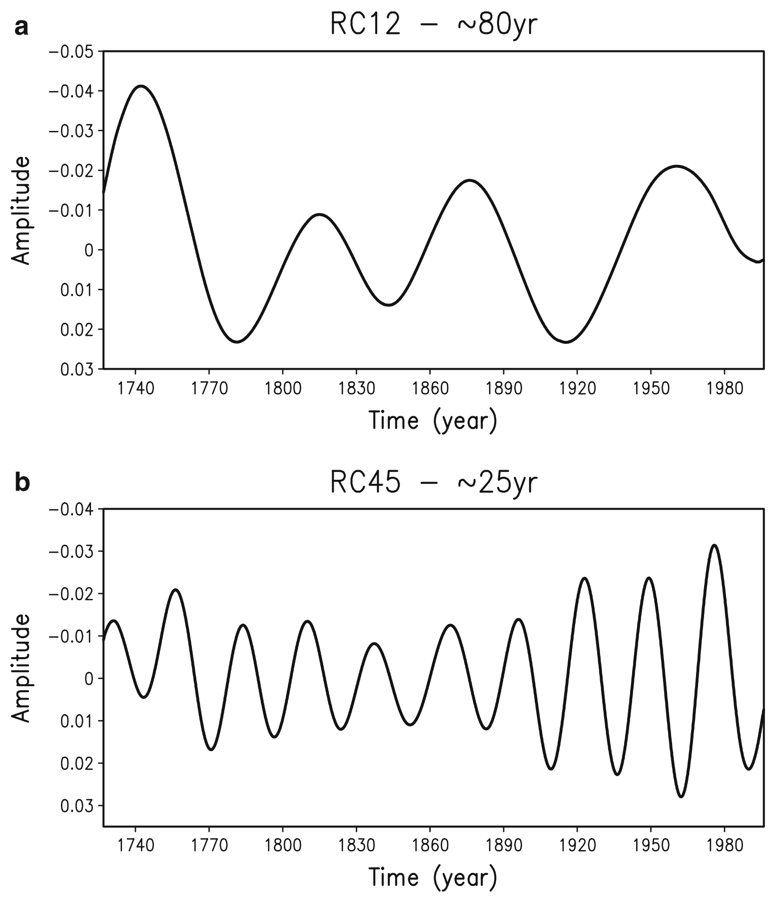

Fig. 3 The two dominant quasi-periodic components in the Rarotonga coral Sr/Ca time series as identified by SSA. **a** The first reconstructed component has a period of ~80 years and is based on EOFs 1 and 2. **b** The second reconstructed component has a period of ~25 years and is based on EOFs 4 and 5. See also Fig. 2

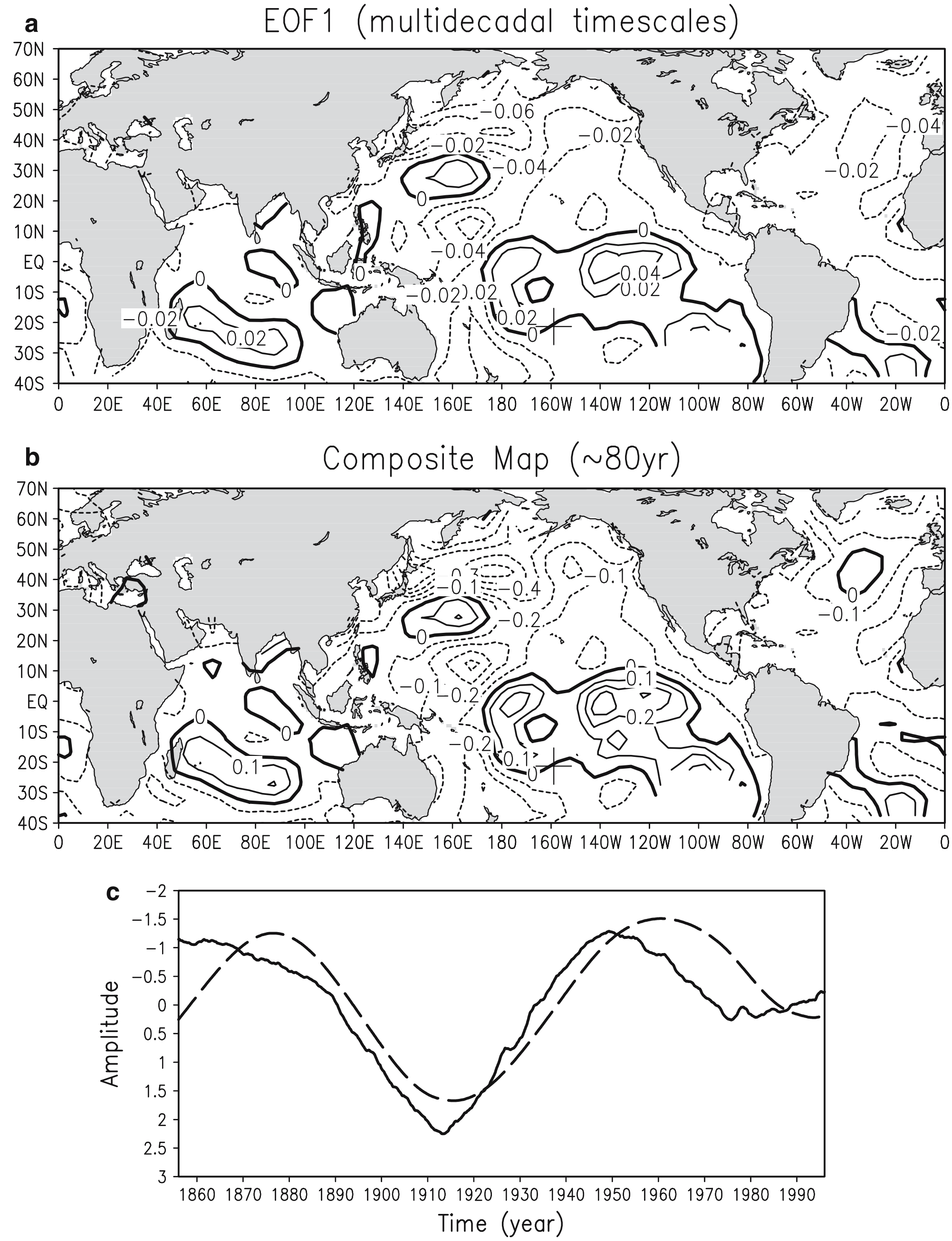

Fig. 4 **a** The first eigenvector obtained from an EOF analysis of the global sea surface temperature (SST) field (Kaplan et al. 1998) for the period 1856–1996 AD. Prior to EOF analysis the annual SST fields were detrended and a 25-year running mean filter was applied. Note that the sign of the pattern is changed to emphasize its similarity with the composite map in **b**. **b** Composite map based on the ~80-year component derived from the Rarotonga coral Sr/Ca time series by SSA and the global SST field (Kaplan et al. 1998) for the period 1856–1996. Prior to construction of the composite map annual SST fields were detrended and a 25-year running mean filter was applied. The location of Rarotonga is marked by a cross. Units are °C. **c** The principal component (PC) associated with the first EOF of the filtered (>25-year band) global SST field (*solid line*) and the ~80-year time component reconstructed from the Rarotonga coral time series by SSA (*dashed line*). As for the associated pattern, the sign of the PC is changed to emphasize its similarity with the coral-based component

the ~80-year component in the coral time series contains a center of positive anomalies in the central North Atlantic, high loadings in the western North Pacific and positive anomalies in the eastern tropical Pacific (180°W–100°W; Fig. 4b). This spatial pattern shows strong similarities to the first eigenvector obtained from an EOF analysis of the global SST field (Fig. 4a). Prior to EOF analysis the annual SST fields were detrended and a 25-year running mean filter was applied. This first EOF explains 38% of the variance in the >25-year band. The principal component (PC) associated with the first EOF of the filtered (>25-year band) global SST field shows obvious similarities to the ~80-year time component reconstructed from the Rarotonga coral time series by SSA (Fig. 4c), albeit there are discrepancies towards both ends of the series. This is likely due to differences in the methods (SSA and EOF), related to the narrower filtering produced by SSA in comparison to the EOF method. However, the overall similarities in the time components as well as in the associated spatial SST patterns between the multidecadal modes identified in both the coral time series and in the global SST field suggest that the Rarotonga coral-based SST reconstruction is an important proxy for the dominant multidecadal variability in the global SST field.

We note that the percentage of variance explained by the second EOF (30%) of the filtered (>25-year band) global SST field (Kaplan et al. 1998) is com-

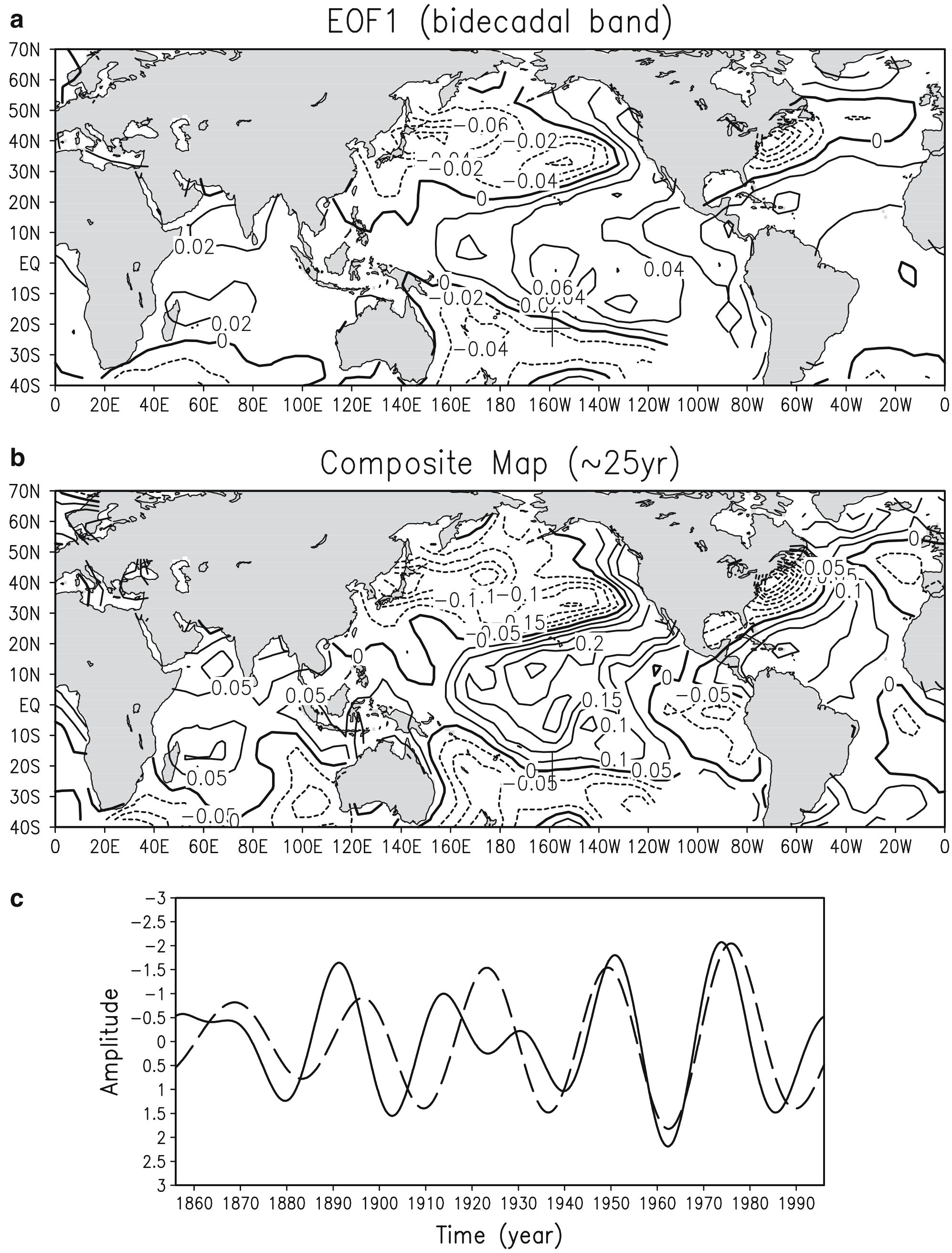

Fig. 5 **a** The first eigenvector obtained from an EOF analysis of the global SST field (Kaplan et al. 1998) for the period 1856–1996 AD. Prior to EOF analysis the annual SST fields were detrended and filtered in the 18- to 32-year band. **b** Composite map based on the 25-year component derived from the Rarotonga coral Sr/Ca time series by SSA and the global SST field (Kaplan et al. 1998) for the period 1856–1996. Prior to the construction of the composite map annual SST fields were detrended and filtered in the 18- to 32-year band. The location of Rarotonga is marked by a cross. Units are °C. **c** The PC associated with the first EOF of the filtered (18- to 32-year band) global SST field (*solid line*) and the ~25-year time component reconstructed from the Rarotonga coral time series by SSA (*dashed line*)

parable to that explained by the first EOF (38%). The difference between the variances explained by the first and second EOF appears to be smaller than their sampling errors (North et al. 1982). Therefore, without a priori knowledge about the two modes, they appear as not well separated from a statistical point of view. However, observational and modeling studies suggest that a multidecadal mode originates in North Atlantic region (Delworth et al. 1993; Mann and Park 1994; Delworth and Mann 2000). Based on this information, we performed a similar EOF analysis on the North Atlantic SST field (80°W to 0°, 0° to 70°N). The analysis reveals two dominant modes explaining 72% and 13% of variance. The spatial structures of the North Atlantic EOFs (not shown) are very similar to the Atlantic signatures of the global EOFs. The dominant mode for the North Atlantic region corresponds to the second global EOF while the second North Atlantic EOF is associated with the first global EOF. Given that the two North Atlantic modes explain significantly different percent of variance (72% and 13%), we conclude that the first and the second EOF of the filtered (>25-year band) global SST field are well separated according to North et al. (1982) when additional information about the modes is considered. This is consistent with the space and time distinction between the two multidecadal modes emphasized by Lohmann et al. (2004).

For the Pacific basin, multidecadal modes of variability were detected in both instrumental and proxy records of climate (Minobe 1997; Chao et al. 2000; Gedalof et al. 2002). It is interesting that the SST pattern reported by us in association with the multidecadal mode identified in both the Rarotonga coral Sr/Ca time series and the global SST field is almost identical to a pattern that was recently presented in association with solar forcing on multidecadal timescales (Lohmann et al. 2004). This points to a possible solar origin of the multidecadal mode, which requires further investigations.

3.2 Bidecadal variability

Similarly, in order to derive a spatial pattern associated with the ~25-year component identified in the coral time series through SSA, a composite map is calculated. Prior to the construction of the composite map as well as prior to EOF analysis the annual SST fields were detrended and filtered in the 18- to 32-year band. In order to suppress secondary maximum that might occur for a pure rectangular filter, the filtering window is buffered at both ends by cosine tails. The spatial SST patterns revealed by the composite map related to the ~25-year component in the coral time series and by the first eigenvector obtained from EOF analysis of the filtered (18- to 32-year band) global SST field show strong similarities (Fig. 5a, b). This first eigenvector explains 40% of variance in the bidecadal band. The two spatial SST patterns resemble the signature of ENSO-like variability in the Pacific basin (Zhang et al. 1997; Garreaud and Battisti 1999). The corresponding time components are in phase after the 1930s but the PC associated with the first EOF of the filtered (18- to 32-year band) global SST field leads the ~25-year time component reconstructed from the coral time series by several years prior to the 1930s (Fig. 5c).

For the Pacific basin, quasi-bidecadal modes of SST variability that share common features with the mode identified in both the Rarotonga coral Sr/Ca time series and the global SST field were described in several studies (Latif and Barnett 1994; White and Cayan 1998; Minobe et al. 2002). Furthermore, our results are consistent with earlier evidence for this mode in the Rarotonga coral time series (Linsley et al. 2000; Evans et al. 2001; Linsley et al. 2004). The spatial pattern of this so-called PDO or IPO (Mantua et al. 1997; Folland et al. 2002) in the Pacific SST field is similar to the signature of ENSO but with higher amplitude and spatial expression at mid latitudes relative to the tropics (Zhang et al. 1997; Garreaud and Battisti 1999).

Our results are consistent with the spatial SST pattern reported by Evans et al. (2001) in connection with interdecadal variability in the Rarotonga coral Sr/Ca time series (their Fig. 1a). In our analysis of this time series we detected two distinct modes of interdecadal variability, a bidecadal and a multidecadal mode. Therefore, one should expect that the superposition of the SST fingerprints associated with these two modes reveals a spatial pattern similar to that reported by Evans et al. (2001). Indeed, the SST pattern in the Pacific basin obtained as a sum (point by point) of the composite maps associated with the multidecadal (Fig. 4b) and the bidecadal coral-based mode (Fig. 5b) is very similar to that reported by Evans et al. (2001; not shown).

4 Summary

Singular Spectrum Analysis of the Rarotonga coral Sr/Ca based SST reconstruction from the subtropical South Pacific published by Linsley et al. (2000) reveals two distinct interdecadal, quasi-periodic components with periods of ~80 and ~25 years. Their associated spatial patterns in the global SST field show notable differences. Whereas the bidecadal component is associated with a well known pattern of Pacific decadal to interdecadal SST variability that was also detected by Evans et al. (2001) in this time series, the multidecadal component is associated with a global SST pattern that may be related to solar forcing on multidecadal timescales. The results emphasize that climate reconstruction based on proxy records and the understanding of climate modes are simultaneous tasks.

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