Clim. Past Discuss., 6, 2055–2069, 2010
www.clim-past-discuss.net/6/2055/2010/
doi:10.5194/cpd-6-2055-2010

Climate of the Past Discussions

Technical Note: Multi-centennial scale analysis and synthesis of an ensemble mean response of ENSO to solar and volcanic forcings

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Received: 30 August 2010 – Accepted: 17 September 2010 – Published: 5 October 2010

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

The response of El Niño Southern Oscillation (ENSO) to solar and volcanic radiative forcings over the past millennium is reanalyzed and extrapolated based on historical data and numerical experiments employing the Zebiak–Cane (ZC) model of the tropical Pacific coupled ocean–atmosphere system. The results suggest a self-similarity of the centennial scale component of the reconstructed ENSO record with a shift in frequencies around 1700 AD when the frequencies almost double. This shift of regime puts forward the non-linearity of ENSO climate with a possible centennial scale forecast, suggesting an ENSO trend toward La Niña conditions for the next three decades.

1 Introduction

Climate is a complex geophysical oscillatory phenomenon with a broad spectrum of significant frequencies, with periods ranging from several decades to thousands of millions of years (Crowley and North, 1991). The complexity of the climate system arises because, as any open system, its boundaries continuously interact with the environment in different temporal and spatial scales (Pexioto and Oort, 1992). In addition, recent studies have highlighted the importance of human activities in climate changes and suggest that anthropogenic global warming (AGW) is currently active, imposing a projected change of $4 \pm 2\ ^{\circ}$C by 2100 AD that seems to exceed the values estimated for the past millennia (IPCC, 2007).

On the other hand, understanding climate at regional and local scales remains uncertain because ENSO and other signals of climate variability have not been well described and require further work, new methods and data. As Hurrell et al. (2005) suggested for the Atlantic variability, ENSO variability requires forecast in decadal and longer temporal scales, furthermore, such projections should interact with anthropogenic processes. For instance, there is no consistent indication of discernible changes in projected ENSO amplitude or frequency for the 21st century associated with the AGW (IPCC, 2007).

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To study the natural variability in the climate system, some approaches have been developed to focus in the modelling of the climate system components with specific forcing acting during a selected time period. One of these efforts was done by Mann et al. (2005) [M05, hereafter] who have investigated the response of ENSO to estimate changes in natural radiative forcing associated with volcanic and solar activities over the past 1000 yr. Their experiments were performed with the ZC model (Zebiak and Cane, 1987) that couples the tropical Pacific ocean–atmosphere system, and is computationally able to evaluate ensembles of multiple realizations of millennial forcing scenarios that intrinsically arise from tropical Pacific climate mechanisms (Mann et al., 2005).

In this paper, we attempt to advance our knowledge of the climate variability by considering simulated records of ENSO variability over the last ten centuries produced by Mann et al. (2005), reanalyzing them with a temporal decomposition of oscillations. This decomposition is achieved through wavelets and Fourier analysis, whereas to enhance low frequency contributions, the cumulative mass curve method is applied (e.g., Smith and Scott, 2005).

2 Methodology

2.1 Data

The Niño 3 index data ($N3$, hereafter) were taken from Mann et al. (2005) and IRI's database (2010) for the last millennium. Here, the N3 index is the sea surface temperature anomaly (in °C) in the central tropical Pacific (5° N–5° S, 150° W–90° W). Figure 1 displays annual mean indexes of $N3$ simulated ($N3s$) and observed values ($N3o$). The $N3s$ is the ensemble of 100 realizations of the ZC model driven by solar and volcanic forcings; whereas the $N3o$ was annually evaluated with a moving average of 13 months (centered in December), from 1857 to 2009.

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2.2 Curve mass method

To amplify the regular and larger oscillations of the ENSO signal N, a mathematical transformation, known as mass curve method (Smith and Scott, 2005), was applied:

$$\eta(t) = \int_{t_0}^{t} (N(t) - \mu) dt \tag{1}$$

where, $N(t)$ is the ENSO signal, $\eta(t)$ is the time integral of the standardized N, t is time, t_0 is initial time (1000 AD year), and µ is the long-term average of N,

After modeling and extrapolating $\eta(t)$, it was then possible to forecast its values. From Eq. (1) one can write:

$$N(t) = \frac{\partial \eta(t)}{\partial t} + \mu \tag{2}$$

2.3 Decomposition method

To take into account different time-scale contributions, the transformed variable can be decomposed in two components of linear and non-linear oscillations (low and high frequency, respectively), and their calculated error as follows:

$$\eta(t) = \eta_{SS}(t) + \eta_{\mathrm{FS}}(t) + e(t), \tag{3}$$

where $\eta_{\mathrm{FS}}(t)$ is the Fourier Series (FS) component due to the multi-centennial fluctuations,$\eta_{SS}(t)$ is the non-linear component based on the self-similarity, and $e(t)$ is the error. The FS component can be written by means of:

$$\eta_{\mathrm{FS}}(t) = \sum_{j=1}^{N_{\mathrm{FS}}} \left[a_j \cdot \sin\left(j \frac{2\pi t}{P} \right) + b_j \cdot \cos\left(j \frac{2\pi t}{P} \right) \right] + e_{\mathrm{FS}}(t), \tag{4}$$

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Here, P is the FS basic period, N_{FS} represents the number of FS terms or harmonics, and j is an index component term, a and b are constants, t is time, and $e_{FS}(t)$ is the error. The self-similar component is defined as:

$$\eta_{SS}(t) = \alpha \eta_{SS}(ta) + e_{SS}(t), \tag{5}$$

with

$$t > t_1; ta = \frac{(t - t_1)}{\gamma} + t_0, \tag{6}$$

α is the amplification factor, γ is the time scale factor, and t_0 and t_1 are the initial times for the analysis and the modeled periods, respectively.

Assuming the equation of N_{FS}, the coefficients a, and b, and period P, can be jointly evaluated after a multi-linear regression that looks for a basic FS period which minimizes the RMS values of $e_{FS}(t)$. The second component of the $\eta(t)$ signal is evaluated based on the self-similarity of this component and a minimization of errors. The parameters t_0 and t_1, the time scale γ, and the amplification factor α are estimated through an iterative process that minimizes the Standard deviation of $e_{SS}(t)$.

3 Results

The annual mean smoothed indexes of simulated $N3s$ and observed $N3o$, are diplayed in Fig. 1.

To estimate climate oscillations in the simulated record of ENSO $N3s$, a wavelet analysis was applied using the online resource by Torrence and Compo (1998). Results displayed in Fig. 2 show three main and significant periodicities around 1000, 180 and 4.5 years. Two secondary oscillatory contributions are detected at periods around 360 and 83 years.

On the other hand, the calculated $\eta 3_s$ record for the last millennium (Fig. 3a) show an oscillation with maxima peaks of accumulation found during the years 1050 and 1920,

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whereas a minimum peak of accumulation is found around 1430. A FS function with NF = 1 was adjusted to $\eta 3_s$ record. This function (component 1 or c1), which explains 89.5% of the $\eta 3_s$ variance, is also depicted in Fig. 3a.

Then, the residue of $\eta 3_s$ after the FS component was eliminated (Fig. 3b) shows centennial scale oscillations with decreasing periods. Oscillations around 180 yrs-period dominates during the years 1100 and 1700, whereas oscillations around 83 yrs-period dominate since 1700 to present. This residue shows a self-similar centennial scale oscillation with decreasing periods, in which the first seven centuries, 11th–17th (years 1000–1600), are analogue to the last three centuries, 18th–20th (years 1700–1999). Then, by applying the non-linear model to the residue (see Eqs. 5 and 6, with $\alpha = 1$, $\gamma = 0.45$, $t_0 = 1000$, and $t_1 = 1700$), the component 2 arises (c2), explaining more than 71% of the variance of the same residue, during the last three centuries.

The observed and modeled $\eta 3_s$ records for the last millennium are shown in Fig. 3c. Here, the model $\eta 3_s$ is the sum of the linear FS (c1) and the non-linear self-similar (c2) components (c1 + c2), and explains the 91.5% of the $\eta 3_s$ variance for the last millennium. This sum is evaluated for the period 1700–2130 AD, however, before and after this period, the sine function is only considered.

The differentiation of the $\eta 3_s$ model superposed to the original simulated record $N3s$ and the data smoothing of 21-yr-moving-average, are shown in Fig. 4. This figure also shows the reconstruction of the $N3$ signal based only in the non-linear model component c2 (without the 910 yr model linear component or c1), with similar results that those obtained using the whole model.

4 Discussions

The comparison of indexes of simulated ($N3s$) and observed values ($N3o$) during the period 1856–2010 shows a good match with similar multidecadal and longer trends (Fig. 2). In addition, ZC model simulates changes similar to those obtained from corals data by Cobb et al. (2003), when volcanism and solar forcing are accounted for Mann et al. (2005). Hence, these two comparisons support the ability of the ZC model to simulate ENSO with solar and volcanic forcing over the past millennium with a resolution greater than multidecadal.

This study has detected millennium scale and centennial scale oscillations in ENSO, which have been previously identified in simulated and proxy based reconstructions of ENSO. One of these previous simulations, developed by Emile-Geay et al., 2008, using the ZC climate model, simulates the response of the ENSO system to solar and orbital forcing over the Holocene. They found that when both forcings act together, the oscillations with periods around 850–900 contribute with a confidence above 95%.

One of these previous reconstructions, which is based on a high-resolution marine sediment record off the coast of Peru spanning the last 20 000 years, has provided a lithic proxy for El Niño flood events (Rein et al., 2005). The wavelet analysis of the lithic record shows the existence of a broad spectrum of oscillations from 2–4 yrs to 7–8 thousand yrs. Specifically, the global wavelet spectrum showed peaks with periods around 70–90, 150–220, and 850–950 years, which characterize oscillations during last 1900, 2000 and 4000 yrs, respectively.

To explain these periods, several direct or indirect forcings have been proposed in the literature. The climate oscillation of 900–1000 years is thought to be linked to an orbital (eccentricity-linked) period which modulates incoming solar radiation (Loutre et al., 1992). A period of around 178.8 years is interpreted as a fundamental cycle in the sun's motion discovered by Jose (1965) and studied by Fairbridge, Sanders and Shirley (Fairbridge and Sanders, 1987; Fairbridge and Shirley, 1987). Schove (1955) reported a 78-year variation between long and short sunspot cycles as well as a possible 200-year period. More recently, the Glaissberg cycle of solar activity, of around 80–83 years, has been suggested to be possibly related with Sun's rotation rate and impulses of the torque in the Sun's irregular motion (Landscheidt, 1999).

The detected components with centennial scale oscillations (residue and c2) show a strong self-similarity, in which the frequency of the ENSO signal almost double and keep the amplitudes nearly constant. The existence of non-linear (self-similar)

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oscillations suggests that the external forcings, solar and volcanic, could be non-linear with a self-similarity behavior, and that the *ZC* model has only linearly transformed its input. This hypothesis could be supported taking into account the linear correlation between solar forcing and the corresponding reconstructed ensemble of the *ZC* model (Mann et al., 2005).

The experimental centennial scale analogue forecast, supported by the non-linear oscillations, shows a trend toward La Niña for the next decades (with and without the linear component, c1) (see Fig. 4). On the other hand, the possible explanation of this self-similar trend as a random occurrence could be discarded, because a Monte Carlo simulation based on a Gaussian distribution of the first 700 years (supposing 16 degrees of freedom) shows that a correlation above 0.8 for the last 300 years occurs only one time in 4.5 million trials. It means that, accepting these parameters and assumptions, we have to wait around three billion years to reproduce the self-similarity randomly. On the other hand, the consequent forecast trend toward La Niña conditions is very important from a paleoclimatic perspective, because simulations from different models indicate that a change in the mean state of tropical Pacific SSTs to more La Niña-like conditions, could explain drought conditions in North America occurred during the mid-Holocene (Seagar et al., 2007).

5 Conclusions

An analysis of the climate variability for the last millennium has been presented in this study based on the reconstruction of ENSO, made through a physical model forced by natural radiative influence of solar and volcanic activity that has been validated using proxy reconstructions and direct observations of sea surface temperature.

Through this analysis, we have detected contributions of different long-term oscillations in the ENSO climate simulated records. Firstly, a millennium scale oscillation, which is recorded both in other ENSO simulations and also in proxy reconstructions, has made possible to identify centennial scale non-linear oscillations in the ENSO's climate.

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The detected non-linear oscillations in ENSO will be useful to propose internal and/or external forcing mechanisms in future modeling efforts of inter-annual, inter-decadal and longer timescales.

Through the analyses of non-linear oscillations, we have explained the observed records of N3 temperatures for the past 100 years based on the reconstructed variability previously occurred, 1480–1700 AD, forecasting a trend toward La Niña for the following decades. This forecasted information is of supreme interest, assuming the possibility of future floods in the western areas of North and South America.

It should be noted that in 1986 the *ZC* model did open new perspectives in the interseasonal and interannual forecast. Now, the same model applied to reconstruct the ENSO natural history during the last millennium has opened new perspectives to decadal and centennial scale forecast of the ENSO natural variability, providing elements for a non-linear modeling and a possible centennial forecast.

The dynamics of El Niño thus appear to have played, and will play, an important role in the response of the global climate to changes in radiative forcing. Our results emphasize the importance of long-term solar and volcanic forcings in the climate system. Further multidisciplinary research effort in relation to these mechanisms, forcings and impacts associated with multidecadal and longer oscillations detected in the ENSO phenomena is still needed.

Supplementary material related to this article is available online at: http://www.clim-past-discuss.net/6/2055/2010/cpd-6-2055-2010-supplement. cp-2010-71-supplement-version1.zip.

Acknowledgements. The author thanks James Shirley, Guillermo Auad, Elsa Arellano-Torres, and Christopher Landsea, for their constructive comments and suggestions. This work has been supported by a NSF grant (GEO-0452325) through the IAI project CRN-II-2050 and the Institute UC MEXUS and CONACYT through an international collaborative project IMTA-SIO/UCSD of the 2008 Climate Change Program.

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References

Crowley, T. J. and North, G. R.: Paleoclimatology, Oxford Monographs on Geology and Geophysics, 18, Oxford, UK, 349 pp., 1991.

Emile-Geay, J., Cane, M., Seager, R., Kaplan, A., and Almasi, P.: El Niño as a mediator of the solar influence on climate, Paleoceanography, 22 (3), A3210, doi:10.1029/2006PA001304, 2007.

Fairbridge, R. W. and Sanders, J. E.: The Sun's orbit AD 750–2050. Basis for new perspectives on planetary dynamics and Earth-Moon linkage, in: Climate, history and predictability, Rampino, edited by: Rampino, M. R., Sanders, J. E., Newman, W. S., and Königsson, L. K., Van Nostrand-Reinhold, New York, USA, 446–471, 1987.

Fairbridge, R. W. and Shirley, J. H.: Prolonged minima and the 179-yr cycle of the solar inertial motion, Sol. Phys., 110, 191–220, 1987.

Hurrell, J. W., Visbeck, M., Busalacchi, A., Clarke, R. A., Delworth, T. L., Dickson, R. R., Johns, W. E., Koltermann, K. P., Kushnir, Y., Marshall, D., Mauritzen, C., McCartney, M. S., Piola, A., Reason, C., Reverdin, G., Schott, F., Sutton, R., Wainer, I., and Wright, D.: Atlantic climate variability and predictability: A CLIVAR perspective, J. Climate, 19(20), 5100–5121, 2006.

IPCC: Climate Change 2007: in: The Physical Science Basis, edited by: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M. and Miller, H. L., Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, USA, 996 pp, 2007.

IRI (2010): International Research Institute for Climate and Society, IRI/LDEO Climate Data Library, http://iridl.ldeo.columbia.edu/SOURCES/.Indices/.nino/.EXTENDED/.NINO3/, access: 10 January 2010.

Jose, P. D.: Sun's Motion and Sunspots, Astron. J., 10(1), 193–200, 1965.

Landscheidt, T.: Extrema in sunspot cycle linked to Sun's motion, Sol. Phys., 189, 413–424, 1999.

Loutre, M. F., Berger, A., Bretagnon, P., and Blanc, P.-L.: Astronomical frequencies for climate research at the decadal to century time scale, Clim. Dynam., 7, 181–194, 1992.

Mann, M. E., Cane, M. A., Zebiak, S. E., and Clement, A.: Volcanic and Solar Forcing of The Tropical Pacific Over the Past 1000 Years, J. Climate, 18, 447–456, 2005.

Peixoto, J. P. and Oort, A. H.: Physics of Climate, American Institute of Physics, New York,

520 pp., 1992.
Schove, D. J.: The Sunspot Cycle, 649 B.C. To A.D. 2000, J. Geophys. Res., 60, 127–145, 1955.
Smith, P. G. and Scott, J. S.: Dictionary of water and waste management, Elsevier Butterworth-heinemann, Oxford, UK, 486 pp., 2005.
Seager, R., Graham, N., Herweijer, C., Gordon, A. L., Kushnir, Y., and Cook, E.: Blueprints for Medieval hydroclimate, Quaternary Sci. Rev., 26, 2322–2336, 2007.
Rein, B., Lückge, A., Reinhardt, L., Sirocko, F., Wolf, A., and Dullo, W.-C.: El Niño variability off Peru during the last 20 000 years, Paleoceanography, 20, PA4003, doi:10.1029/2004PA001099, 2005.
Torrence, C. and Compo G. P.: A Practical Guide to Wavelet Analysis, B. Am. Meteorol. Soc., 79, 61–78, 1998.
Zebiak, S. E. and Cane M. A.: A model El NinoSouthern Oscillation, Mon. Weather. Rev., 115, 2262–2278, 1987.

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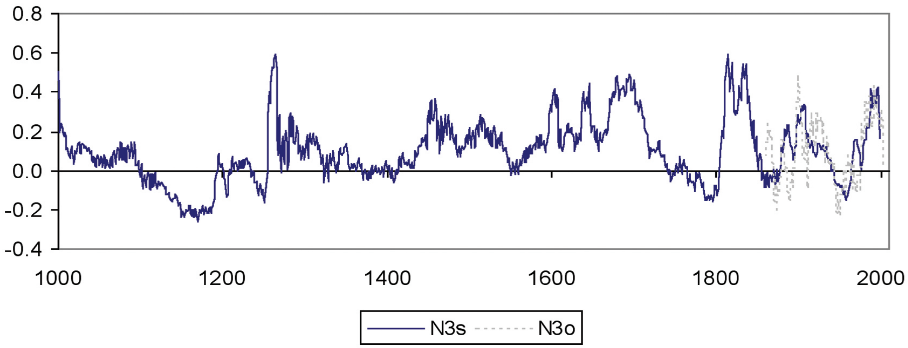

Fig. 1. *N*3 smoothed signals in °C. Simulated (*N*3*s*) information, obtained from M05, for the last 1000 years and observed (*N*3*o*) for last 150 years information, obtained from databases of M05 and IRI (2010), respectively. Both signals are smoothed 21-yr-moving-average.

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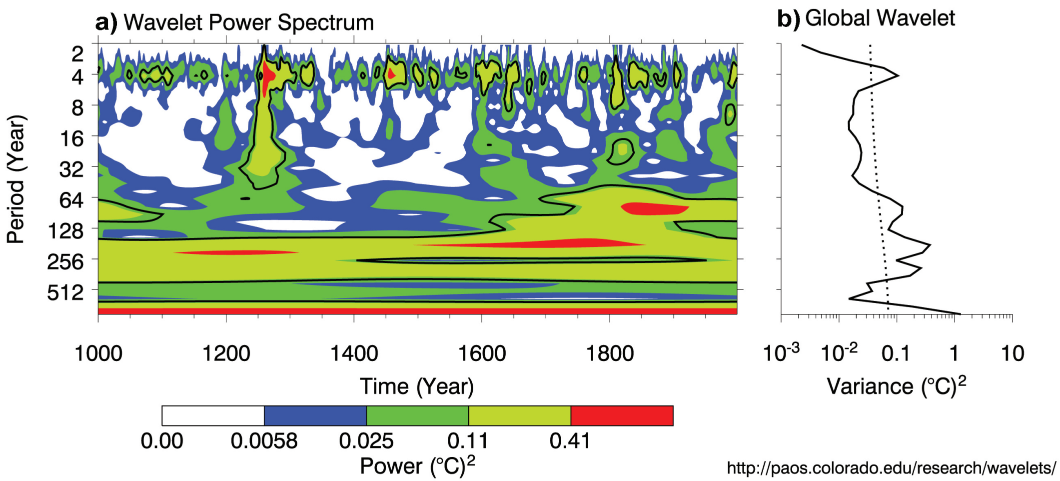

Fig. 2. **(a)** Wavelet power spectrum of *N*3. The contour levels are chosen so that 75%, 50%, 25%, and 5% of the wavelet power is above each level, respectively. Black contour is the 10% significance level, using a red-noise (autoregressive lag1) background spectrum. **(b)** Global wavelet power spectrum (black line). The dashed line is the significance for the global wavelet spectrum, assuming the same significance level and background spectrum as in (a) (Torrence and Compo, 1998).

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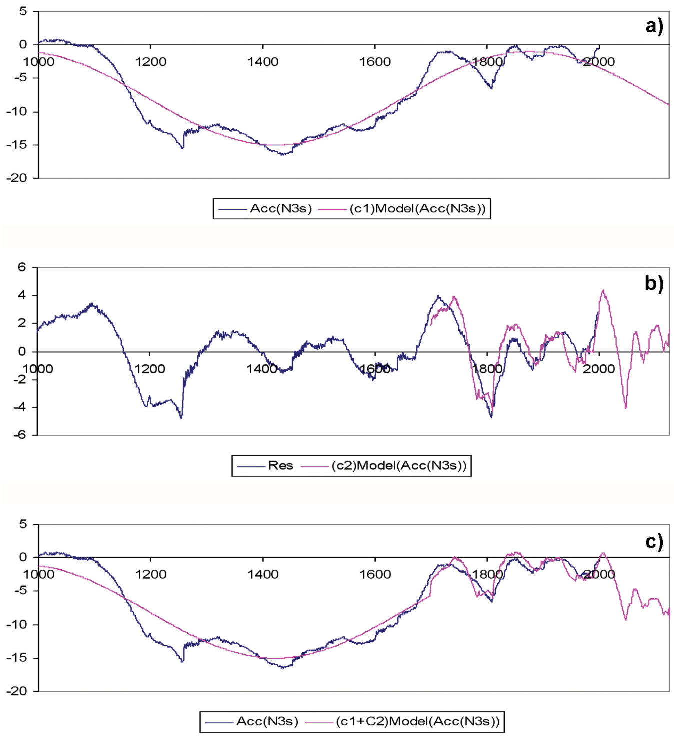

Fig. 3. **(a)** Accumulated *N*3*s* ($\eta 3_s$) information and its simple model (c1, see Eqs. 3 and 4), obtained from database M05 and a FS model with NF = 1, a period of 908 years, respectively. **(b)** Residue of Accumulated *N*3*s* ($\eta 3_s$) information after eliminating the millennium component (c1, 908 yr oscillation). A simple non-linear model (c2, Eqs. 3, 5 and 6), with $\alpha = 1$, $\gamma = 0.45$ (see Eqs. 2–4), $t_0 = 1000$, and $t_1 = 1700$, is also displayed. **(c)** Accumulated *N*3*s* ($\eta 3_s$) information and its simple complete model [c1 + c2, see (a) and (b)].

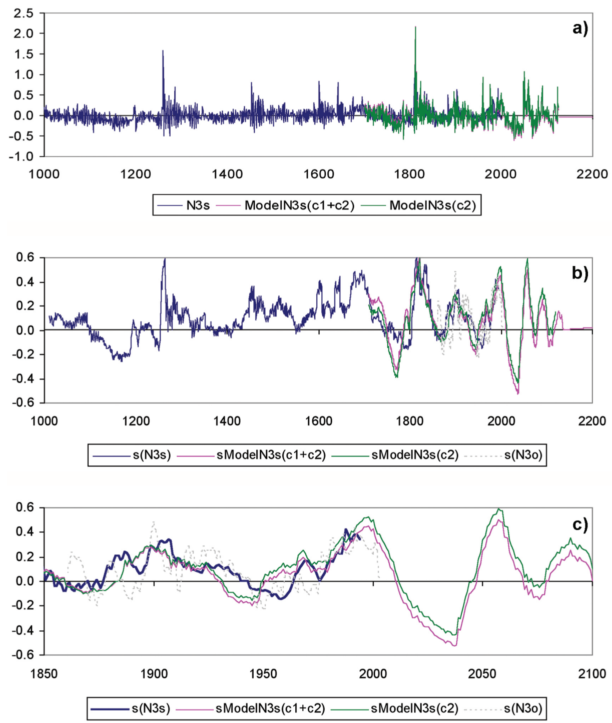

Fig. 4. Comparison of three *N*3 annual average records. Simulated, 1000–1999 AD, with CZ model (M05) (nEnsemble), and obtained from differentiation of the accumulated signal obtained from the two components model, FS and SS (c1 + c2 = Linear + Non Linear Models) (Fig. 3c), 1700–2140 AD, and obtained from only the SS (c2, Non-linear) component, 1700–2140 AD. **(a)** Values, **(b)** smoothed (21yr-moving-average) values; and **(c)** a zoom of smoothed values over 1900–2100 AD. Observed smoothed 21-yr-moving-averages (N3o) for last 150 years information are also depicted.