Epochs of phase coherence between El Niño/Southern Oscillation and Indian monsoon

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[1] We present a modern method used in nonlinear time series analysis to investigate the relation of two oscillating systems with respect to their phases, independently of their amplitudes. We study the difference of the phase dynamics between El Niño/Southern Oscillation (ENSO) and the Indian Monsoon on inter-annual time scales. We identify distinct epochs, especially two intervals of phase coherence, 1886–1908 and 1964–1980, corroborating earlier findings from a new point of view. A significance test shows that the coherence is very unlikely to be the result of stochastic fluctuations. We also detect so far unknown periods of coupling which are invisible to linear methods. These findings suggest that the decreasing correlation during the last decades might be a typical epoch of the ENSO/Monsoon system having occurred repeatedly. The high time resolution of the method enables us to present an interpretation of how volcanic radiative forcing could cause the coupling. **Citation:** Maraun, D., and J. Kurths (2005), Epochs of phase coherence between El Niño/Southern Oscillation and Indian monsoon, *Geophys. Res. Lett.*, *32*, L15709, doi:10.1029/2005GL023225.

1. Introduction

[2] El Niño/Southern Oscillation (ENSO) and the Indian Monsoon (below referred to as Monsoon) are the predominant climate phenomena in the Asian/Pacific region exhibiting oscillations on inter-annual scale with a large social and economical impact. While ENSO exhibits self-sustained oscillations of the tropical Pacific coupled ocean-atmosphere system, the Monsoon performs oscillations driven by the annual cycle of the land vs. sea surface temperature gradient. For detailed reviews of ENSO and Monsoon refer to *Philander* [1999] or *Cane* [2005] and *Webster et al.* [1998] or *Gadgil* [2003], respectively.

[3] ENSO and the Monsoon have been known to be correlated on inter-annual time scales since the pioneering work of Walker at the beginning of the last century [e.g., *Walker and Bliss*, 1932]. He found a relationship of weak (strong) Monsoons following low (high) values of the Southern Oscillation index, i.e. Monsoon failure coinciding with El Niños and strong Monsoons with La Niñas, respectively. This coupling faded during the second decade of the 19th century, only strengthening again in the 1960s. Since then, intensive studies have investigated the time dependency of the coupling between the two processes [e.g., *Webster and Yang*, 1992; *Torrence and Webster*, 1999]. Recent work finds a weakening relation since the 1980s [*Kumar et al.*, 1999; *Sarkar et al.*, 2004]. Much attention has been concentrated on understanding the coupling mechanisms such as Pacific SST and Walker circulation anomalies as well as Eurasian snow-cover [e.g., *Krishnan and Sugi*, 2003; *Robock et al.*, 2003; *Zhao and Moore*, 2004].

[4] The previous results are all based on linear correlation and wavelet analysis, respectively. In this letter, we present a method used in nonlinear time series analysis, which decomposes oscillation dynamics into time-dependent amplitude and phase, making it possible to study the relation of only the phases of ENSO and Monsoon irrespective of their amplitudes. This approach allows to corroborate earlier results with a far better time resolution and to infer so far unknown subtle relations invisible to correlation analysis.

2. Data

[5] We used the monthly mean sea surface temperature data in the eastern tropical Pacific, i.e. the NINO3 index derived from the Kaplan data [*Kaplan et al.*, 1998] as a measure for ENSO variability. The Monsoon was represented by the monthly anomalies of the All India Rainfall (AIR) index defined by [*Mooley and Parthasarathy*, 1984]. We analyze the data in the period from Jan 1st 1871 to Dec 31st 2003. We want to emphasize that for a phase analysis, it is irrelevant whether the amplitudes of the physical processes are well represented by these simple indices, provided the phases of the dynamics are sufficiently well reproduced.

[6] Since our work focuses on the inference of phase relations of inter-annual oscillations, we low-pass filtered the data in the spectral domain, i.e. high frequency variability with frequencies higher than 0.7 cycles per year is damped.

[7] Figure 1 shows a section of the time series of the ENSO and Monsoon data, clearly emphasizing the inter-annual oscillations of ENSO and the biennial oscillation of the monsoon [*Rasmusson et al.*, 1990].

3. Phase Reconstruction

[8] When two systems exhibiting self-sustained oscillations of (at least slightly) different frequencies are brought into contact, one observes, in general, the following phenomena: For a low coupling strength, the systems evolve independently. Increasing the coupling strength, at first the frequencies start to adjust, such that the phases $\Phi_i(t)$ describing the oscillations get locked:

$$|\Phi_1(t) - \Phi_2(t)| < \epsilon \tag{1}$$

This phase coherence phenomenon is called phase synchronization [*Rosenblum et al.*, 1996]. For stronger coupling,

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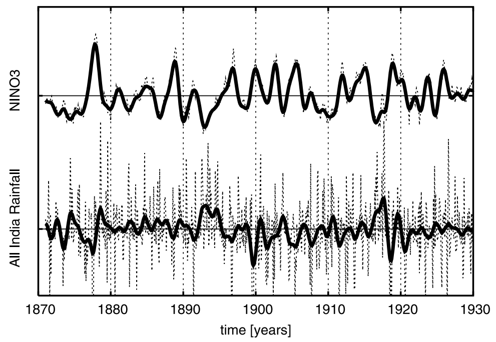

Figure 1. Section of the NINO3 (upper graph) and AIR anomalies (lower graph) time series. The dotted lines depict the raw data, the solid lines show the low-pass filtered data used for the further analysis.

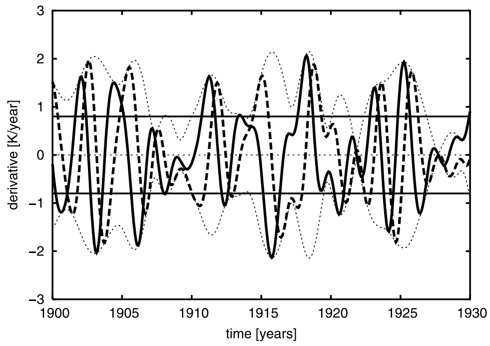

Figure 3. Smoothed derivative of the normalized and low-pass filtered NINO3 time series (solid line, section), the corresponding Hilbert transformation (dashed line). The dotted line represents the amplitude A (for details see text). For $A > 0.8$ (solid horizontal lines), we consider the phase to be well defined.

generalized synchronization might arise, i.e. the amplitudes might also adjust.

[9] When one of the systems does not perform self-sustained oscillations, as in the case of the Monsoon, phase coherence might also arise, but due to another mechanism: The Monsoon is driven by the annual cycle, which exhibits oscillations with a certain amplitude. This amplitude is modulated by external influences like ENSO. Thus (disregarding the possible influence of the Monsoon on ENSO), in this letter we are concerned with modulation rather than with synchronization in the strict sense.

[10] To investigate for coherent phase relations, one has to derive the oscillation phases of the involved systems. If one observes only a one dimensional time series $x(t)$ of one of the systems, initially one has to find a suitable two dimensional embedding. A common approach is constructing an analytical signal by use of the Hilbert transformation

$$y(t) = H(x(t)) = \frac{1}{\pi} P.V. \int_{-\infty}^{\infty} \frac{x(\tau)}{t-\tau} d\tau, \tag{2}$$

where P.V. denotes the Cauchy principal value (for details refer to *Rosenblum et al.* [1996]). The phase can then be defined as $\phi(t) = \arctan(y/x)$.

[11] This approach is meaningful only if the embedded signal rotates around a fixed center. For geophysical signals exhibiting variations on a wide range of frequencies, this requirement is rarely fulfilled. Figure 2a shows this embedding for the (low-pass filtered) NINO3 time series. Many oscillations do not cycle around a common center, such that the phase propagation will be underestimated. Suitable filtering is required to eliminate the variations of the center.

[12] *Osipov et al.* [2003] suggested the following approach: By geometrical reasoning about the curvature of phase space trajectories, they could show that a phase can also be defined by considering the time derivative of the signal:

$$\phi = \arctan \frac{\dot{y}}{\dot{x}} \tag{3}$$

Figure 2b shows that this geometrically motivated transformation eliminates most of the slow variations, such that at least all large and pronounced oscillations are centered around a common origin and a meaningful phase can be defined. To estimate the derivatives of the involved (low-pass filtered) time series, we applied a standard second order finite differences scheme with additional smoothing. The derivative $\dot{x}(t)$ and its Hilbert transform $\dot{y}(t)$ are plotted in Figure 3. The dotted line represents the envelope $A(t) = (\dot{x}(t)^2 + \dot{y}(t)^2)^{1/2}$, i.e. the amplitude of the oscillation. Finally, we calculated the phases according to equation (3) and unwrapped them by adding 2π after each oscillation. In the following we summarize all steps with the most important parameters:

[13] 1. Low-pass filter the data in the spectral domain. A smooth function (arcus tangens) damping frequencies >0.7 year^{-1} is chosen.

[14] 2. Estimate derivatives by second order difference scheme and running mean with window width $2l + 1 = 13$ months

[15] 3. Embed by Hilbert transformation with phase defined according to equation (3).

[16] 4. Unwrap the phases (add 2π after each oscillation)

[17] We tested the capability of the method by systematically applying it to synthetic data with simultaneous variability on the high frequency, inter-annual and decadal scales. Also, we compared various filtering parameters and different approaches to estimate the derivatives and found the results being robust. Additionally, we choose the envelope $A(t)$ as a measure to select regions of well

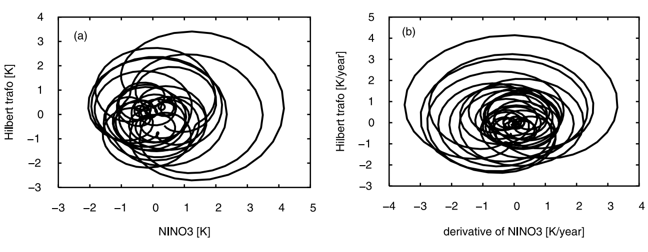

Figure 2. (a) Embedding of low-pass filtered NINO3 time series by Hilbert transformation. Many oscillations are not centered around a common center. (b) The same, but for the time derivative of the NINO3 time series. All pronounced oscillations circle around the origin.

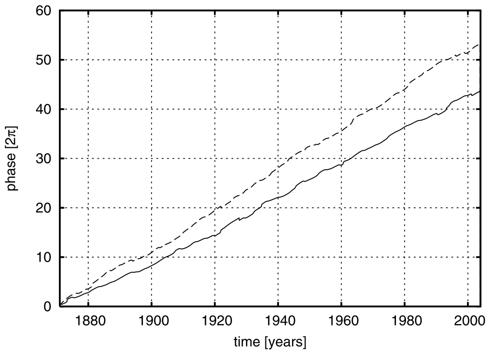

Figure 4. Phase propagation of NINO3 (solid) and Monsoon (dashed). On average, the latter one oscillates faster. However, during some periods the phases propagate similarly, suggesting to investigate for phase coherence.

defined phases: For time derivatives $\dot{x}(t)$ normalized to unit variance, $A(t) > 0.8$ appeared to be a reasonable choice to exclude spurious oscillations.

[18] The results for the unwrapped phases are presented in Figure 4. During the same time, the AIR performs more cycles than the NINO3 time series, resulting from the quite stable biennial oscillation. However, during some epochs, the phases seem to evolve similarly, suggesting that we should investigate for phase coherence.

4. Phase Relation

[19] To study the occurrence of phase coherence in more detail, we calculated the difference of the phases (Figure 5). Distinct epochs become visible: The plateaus from 1886 to 1908 and from 1964 to 1980 indicate phase coherence during these intervals. In the years 1908–1921, 1935–1943 and 1981–1991, the Monsoon oscillates faster than

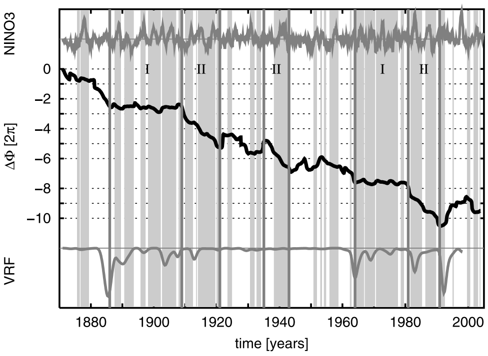

Figure 5. Phase difference of ENSO and Monsoon (black). Grey shading marks intervals of jointly well defined phases. 1886–1908 and 1964–1980 (I): plateaus indicate phase coherence. 1908–1921, 1935–1943 and 1981–1991 (II): Monsoon oscillates with twice the phase velocity of ENSO. During these intervals, both systems exhibit distinct oscillations (NINO3 time series, upper graph). 1921–1935 and 1943–1963: phases are badly defined, both processes exhibit irregular oscillations of low variance (upper graph). Lower graph shows volcanic radiative forcing index (VRF).

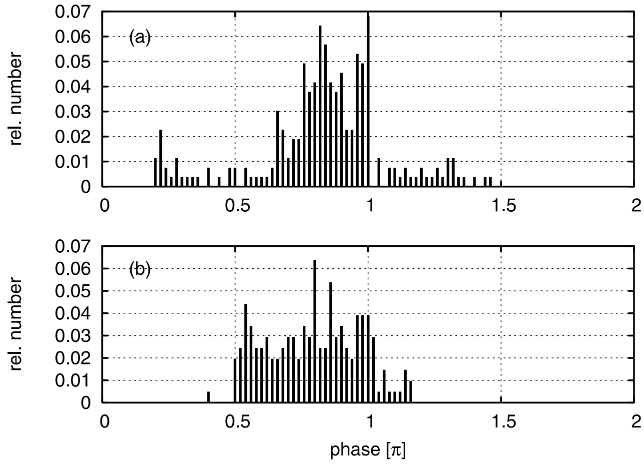

Figure 6. Histogram of phase differences for the two phase coherent intervals (a) 1886–1908, (b) 1964–1980. Both diagrams show peaks between $\pi/2$ and π, reflecting that ENSO and Monsoon are anti-correlated.

ENSO, failing when ENSO peaks on inter-annual scales as during the phase coherent intervals, but with an additional peak in between (2:1 phase coherence; plotting the difference of the Monsoon phase and two times the ENSO phase would yield plateaus). During these epochs, the phases of ENSO and Monsoon are predominantly well defined (grey shading) and both systems exhibit distinct oscillations, which are also visible in the NINO3 time series itself (Figure 5) or its wavelet spectrum [*Gu and Philander*, 1995]. During other times, especially 1921–1935 and 1943–1963, the phases are rather badly defined and both processes exhibit irregular oscillations of low variance. Figure 6 shows the histogram of phase differences of the two intervals of phase coherence. Both diagrams show distributions far away from being uniform, with peaks between $\pi/2$ and π, reflecting that ENSO and Monsoon are anti-correlated.

[20] To evaluate whether the phase coherent intervals are just coincidence, we developed a significance test taking advantage of the fact that both processes are phase locked to the annual cycle. We simulated 1,000,000 pairs of annually resolved 150 years long time series, each containing integer values from 2 to 7 representing typical inter-annual oscillations (e.g. 4 consecutive values of "4" mark one cycle of period 4 years). The probability for each period to appear was estimated from the real NINO3 and AIR time series, respectively. The probability that 6 successive oscillations appear in both time series at the same time with pairwise identical periods, i.e. the probability that one of the observed plateaus occurs incidentally, resulted as $p_1 \approx 0.014$. Thus, the probability that the two identified plateaus appear randomly within 150 years is $p_2 = p_1^2 \approx 0.0002$, i.e. the result is significant at least at the 99% level.

[21] Theoretically, our approach allows to investigate for the direction of coupling [*Rosenblum and Pikovsky*, 2001], i.e. whether the modulating influence of ENSO on Monsoon is dominating or if a possible reverse influence has to be taken into account. However, we tested the robustness of our coupling directionality index with several toy models resembling the ENSO/Monsoon system and came to the

conclusion that the dynamical noise is too high and the time series too short to obtain any reliable results.

5. Discussion

[22] We presented a method used in nonlinear time series analysis to study the relationship of two oscillating systems with respect to their phases but independently of their amplitudes. We could identify distinct epochs, especially two intervals of phase coherence from 1886 to 1908 and from 1964 to 1980. Interestingly, these epochs show high variability and distinct oscillations of ENSO as well as Monsoon, in contrast to the intervals 1921–1935 and 1943–1963, where both processes show low variability and no coherence. These results corroborate earlier findings of *Torrence and Webster* [1999]: Our intervals of phase coherence coincide with regions of high wavelet coherence.

[23] In contrast to previous sliding correlation and wavelet analyses, which intrinsically have to average (here roughly two decades), we estimate an almost instantaneous phase of only the dominant oscillation and hence are able to estimate the onset of phase coherence with an accuracy of around one ENSO cycle.

[24] *Gershunov et al.* [2001] discussed whether the changes in correlation strength between ENSO and Monsoon could be spurious due to stochastic fluctuations. *Maraun and Kurths* [2004] studied the difficulties of testing for significant wavelet coherence. Here we show that the correlation changes occur due to changing phase relations and confirm that the intervals of phase coherence are highly significant.

[25] *Kumar et al.* [1999] found that 21 year sliding correlations between ENSO and Monsoon were high from 1856 to the early 1980's, but decreased to insignificant values afterwards. They suggest that global warming may cause the decoupling. Since our approach decomposes signals into phase and amplitude, we gain a more detailed insight: In 1981, the monsoon decoupled from the ENSO cycle and coupled with double phase velocity until 1990, i.e. the Monsoon still fails after strong El Niños but peaks additionally shortly after. Similar behavior occurred in the periods 1908–1921 and 1935–1943, indicating that it is a typical event either due to unknown external forcing or intrinsic to the ENSO/Monsoon system. Thus, our results indicate that global warming might be not the only cause of reduced correlations between the two processes. This 2:1 coherence is invisible to correlation analysis: The additional Monsoon peaking neutralizes the Monsoon failure coherent with ENSO and thus causes the observed decrease in correlation. For similar reasons these epochs are also invisible for wavelet analysis.

[26] The high time resolution allows us to precisely determine the onset of phase coherent intervals and thus to suggest a mechanism that might cause the coupling. The lower graph in Figure 5 displays the volcanic radiative forcing index of *Sato et al.* [1993]. Interestingly both intervals of phase coherence coincide with periods of strong volcanic radiative forcing and start with two major eruptions, of Krakatau (1883, Sunda strait) and Mount Agung (1963, Bali), both located in southern Indonesia and exhibiting large climatic forcing [*Robock*, 2000]. We now introduce an idea, which might help to understand the recent findings of *Adams et al.* [2003]: Volcanic forcing might not cause single ENSO events, but rather either increase the coupling between ENSO and Monsoon, causing more regular oscillations of the total system, or cause more regular oscillations of one of the systems (probably ENSO), increasing the coupling between them. The climatic impact of volcanoes is based on radiative forcing mainly by sulphate aerosols. Blocking of short-wave radiation causes summer cooling (and winter warming) and overall global cooling lasting for 1–3 years. Multiple eruptions have caused cooling even on decadal scales, e.g. in the period from 1883 to 1912 and from 1963 on [e.g., *Bertrand et al.*, 1999]. This cooling effect could reduce the land/sea temperature gradient and thus make the Monsoon more sensitive to ENSO influence [see, e.g., *Kumar et al.*, 1999]. For a detailed review of possible mechanisms, refer to *Robock* [2000]. This idea needs further evaluation by means of detailed time series analysis and model simulations.

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