

Pattern Dynamics and Forecast Methods in Seismically Active Regions

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Abstract

Large, extended fault systems such as those in California demonstrate complex space-time seismicity patterns which include repetitive events, precursory activity and quiescence, and aftershock sequences. Although the characteristics of these patterns can be qualitatively described, a systematic quantitative analysis remains elusive. Our research suggests that a new pattern dynamic methodology can be used to define a unique, finite set of seismicity patterns for a given fault system. In addition, while a long-sought goal of earthquake research has been the reliable forecasting of these events, very little progress has been made in developing a successful, consistent methodology. In this report, we document the discovery of systematic space-time variations in seismicity from southern California using a new technique. Here we show examples of this analysis technique on data obtained *prior* to events in seismically active areas that show coherent regions associated with the future occurrence of major earthquakes in the same areas.

Introduction

Recent large earthquakes include the $M \sim 7.4$ event that struck Izmit, Turkey in August of 1999, the $M \sim 7.6$ Taiwan earthquake which occurred in September of 1999, and the $M \sim 7.1$ Hector Mine, California earthquake of October 1999. Many similar examples have been documented over the course of time (Richter, 1958; Scholz, 1990), yet despite the fact that the largest of these events span distances of more than 500 km, no reliable precursors have been detected with any repeatability (Kanamori, 1981; Geller, et al., 1997). It is difficult for most scientists to understand why events of this magnitude are not preceded by at least some causal process. Various patterns of seismic activity centered on the source region have been proposed, including, but not limited to, phenomena such as characteristic earthquakes (Schwartz, 1984; Ellsworth, et al., 1998), Mogi donuts (Mogi 1979), seismic gaps (Haberman, 1981), precursory quiescence (Wyss and Haberman, 1988), precursory activation (Evison, 1977; Dodge, et al., 1996), Time-to-Failure and Log-Periodic precursory distributions (Bufe and Varnes, 1993; Saleur et al., 1996), temporal clustering (Frohlich, 1987; Rundle et al., 1997), and earthquake triggering over large distances (Hill et al., 1993; King et al., 1994).

In this report, we discuss a new pattern dynamic methodology that can be used to define a unique, finite set of seismicity patterns for a given fault system. Similar in nature to the empirical orthogonal functions historically employed in the analysis of atmospheric and oceanographic phenomena (Preisendorfer, 1988), this method derives the eigenvalues and eigenstates from the diagonalization of the correlation matrix using a Karhunen-Loeve expansion (Fukunaga, 1970). This pattern dynamic technique has been successfully applied to the study of numerically modeled seismicity for fault networks similar in character and extent to those found in California

(Rundle, et al., Phys. Rev. E, 2000). We implement this same methodology in order to analyze historical seismicity in California and derive space-time eigenvalue patterns for the San Andreas fault system. The significant eigenstates for this relatively short period of time can be directly correlated with the known California faults and associated events (Tiampo et al., 2000).

In addition, while previous efforts to identify the premonitory signals to such events has naturally focused on local regions near the earthquake source, these techniques often require intensive and expensive monitoring efforts and have been largely unsuccessful (Kanamori, 1981). Since these hypothesized patterns are localized on the eventual source region, the fact that one must know or suspect where the event will occur before they can be applied is a major drawback to their implementation. We have developed a method for identifying areas of increased probability of an event, ΔP , based upon recent observational evidence that earthquake faults are characterized by strongly correlated space-time dynamics (Bufe and Varnes, 1993; Press and Allen, 1995; Bowman et al., 1998). Realistic numerical simulations of earthquakes also suggest that space-time pattern structures are non-local in character, a consequence of strong correlations in the underlying dynamics (Rundle, 1988; Rundle et al., 2000). Our procedure is based upon the idea that seismic activity corresponds geometrically to the rotation of a pattern state vector in the high-dimensional correlation space spanned by the eigenvectors of a correlation operator (Rundle et al., 2000).

Results

Observations and numerical simulations suggest that space-time patterns of seismic activity directly reflect the existence of space-time correlations in the underlying stress and strain fields³². A spatially coherent, uniformly high level of stress on a fault is a necessary precondition for the occurrence of a large earthquake. Recently, several groups have found that spatial coherence in the stress field is reflected in a similar coherence in the seismic activity (Bufe and Varnes, 1993; Bowman et al., 1998; Rundle et al., 2000).

The decomposition of nonlinear systems into their orthonormal eigenfunctions has been used successfully in the atmospheric sciences for many years (Preisendorfer, 1988; Penland and Magorian, 1993). The Karhunen-Loeve approach, the theoretical basis for EOF techniques, represents these space-time patterns as a set of eigenvectors, or normal modes, of an equal-time correlation function, their associated time series, and N total eigenfrequencies, where N is the total number of locations. The eigenvectors provide information about the spatial correlations of the patterns; the time series characterize each eigenvectors temporal pattern; the eigenfrequencies provides information about how often they occur in the data. After, a complex, linear correlation operator for the state and force is constructed in order to extrapolate future system behavior such as the El Nino southern oscillation (Penland and Magorian, 1993). Here we apply this decomposition method to historical seismicity data in southern California in order to identify basis patterns for all possible space-time seismicity configurations. These basis states are a complete, orthonormal set of eigenvectors and associated eigenvalues that are obtained from the diagonalization of the correlation operators computed for this regional historic seismicity data.

Figure 1 shows the first two modes for southern California, for data prior to 1998. The absolute maximum value in each plot is normalized to one, where red is positive and blue is negative, red and blue are anticorrelated. The correct interpretation is that while a red location is "on", a blue location is "off", and vice versa. The first mode is clearly the ability to detect more and more events over time, while the second mode is the Landers event.

Our simulations have suggested that these correlations in the seismicity can be described by phase dynamics, in which the important changes in seismicity are associated primarily with rotations of the vector phase function in a high-dimensional correlation space (Fukunaga, 1970; Mori and Kuramoto, 1998). Variables in many dynamical systems can be characterized by using this phase dynamical technique, represented as a phase function that involves both amplitude and phase angle. Changes in the amplitude of the phase function are unimportant, or not relevant. Examples of pure phase dynamical systems in the classical world include weak turbulence in fluids and reaction-diffusion systems. Another non-classical example is a quantum system in which the wave function is the phase function. It should therefore be possible to compute the increase in probability of observing such an anomalous correlation, ΔP , directly from the observed seismicity data. Using the fact that seismicity is an example of pure phase dynamics, it follows that ΔP can be calculated from the square of the phase function for the associated pattern state vector (Rundle et al., 2000). To emphasize the connection to phase dynamics, we call the function ΔP the Phase Dynamical Probability Change (PDPC) (Tiampo et al., 2000).

Figure 2 shows the PDPC anomalies in southern California for the time period 1978 to 1991. Note that no data after December of 1991 was used in this analysis. The triangles denote events of $M > 5$ which go off during this time period, while the open circles are events which occur after 1991. Note the frequent occurrence of large earthquakes at the locations of increased relative probability .

Conclusions

In summary, we conclude that we have observed systematic correlations in southern California seismicity. Our method employs data from existing seismic monitoring networks as well as a theoretical understanding obtained from numerical computer simulations to identify these correlations and the coherent space-time structures in seismicity. These space-time patterns in the seismic activity directly reflect the existence of correlated structure in the underlying stress and strain fields, a necessary precondition for the occurrence of large earthquakes. Depending on the nature of future seismic activity in the region, as well as ongoing modifications and extensions of the theory and technique, this procedure may prove useful in analysis of future trends in seismic activity.

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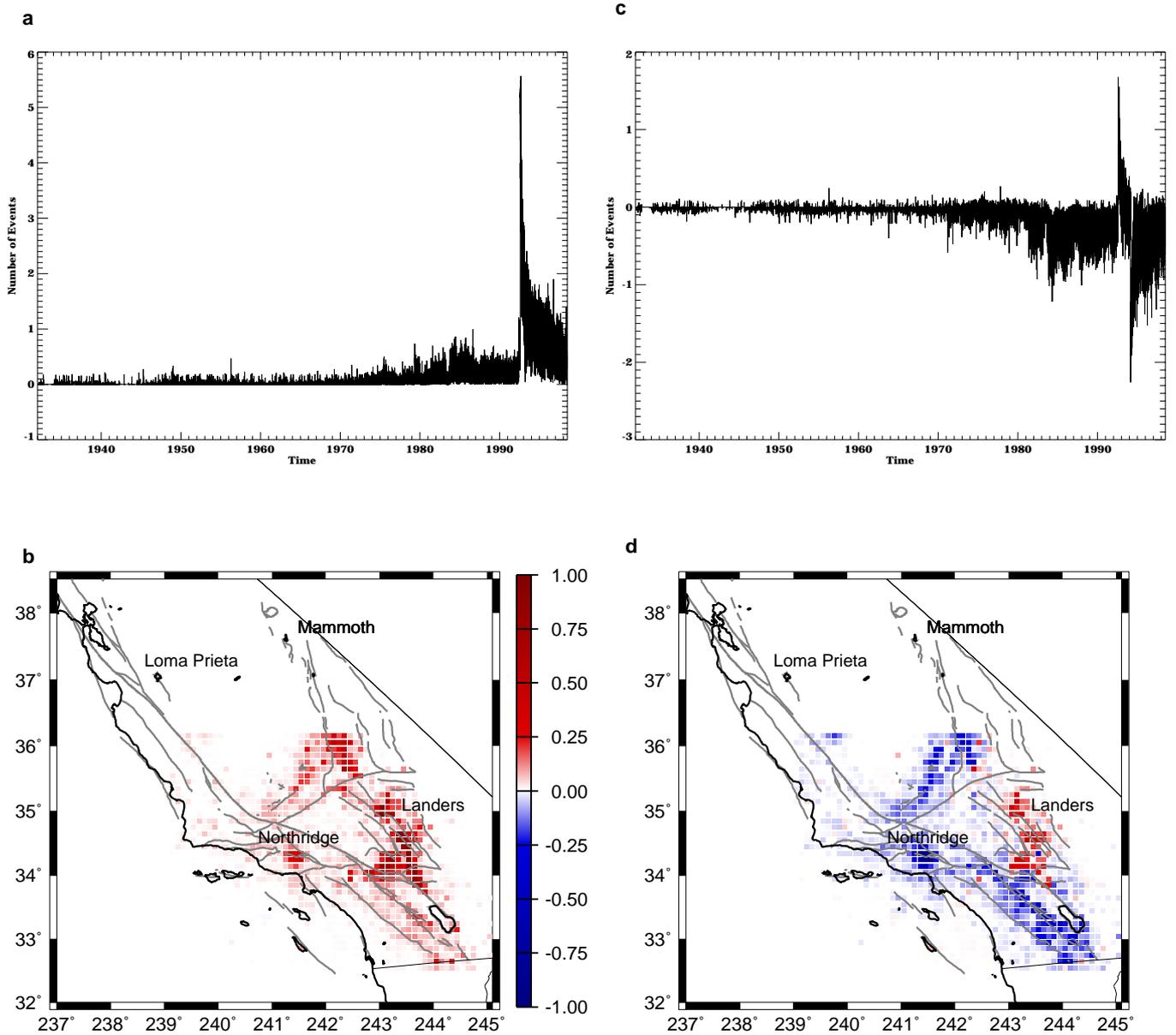


Figure 1: First two KLE modes for southern California seismicity, 1932-1998. a) Principal component (PC) time series for first KLE mode; b) first KLE mode, normalized to maximum; c) PC time series for second KLE mode; and d) second KLE mode, also normalized to the maximum.

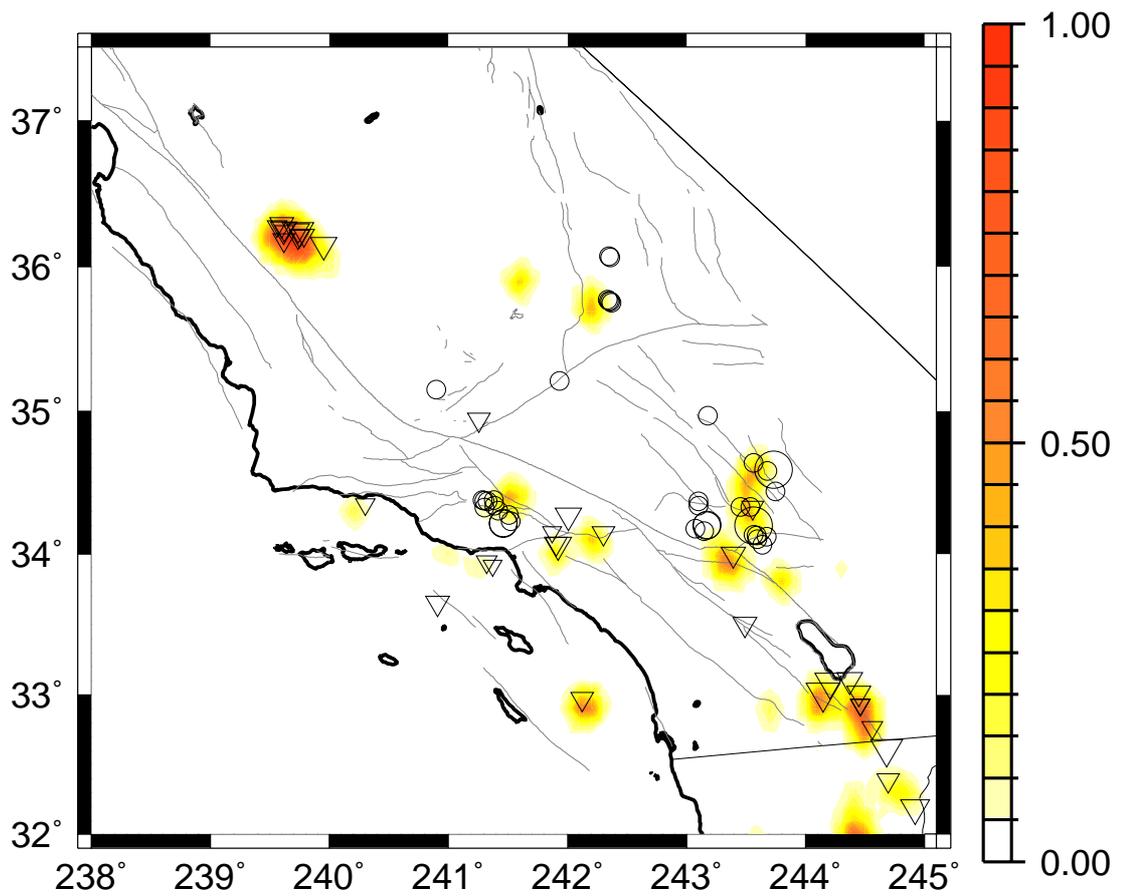


Figure 2: PDPC anomalies for the period 1978 through 1991, computed from data prior to 1992. Triangles denote events which occur between 1978 and 1991; circles denote earthquakes that occur between 1992 and 2000. Normalized to the maximum.