Observation of Systematic Variations in Non-Local Seismicity Patterns from Southern California

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We have discovered systematic space-time variations in the seismicity from southern California using a new technique. 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. Using our technique it is possible to isolate emergent regions of coherent, correlated seismicity. Analysis of data taken only up to December 31, 1991 reveals that the appearance of the coherent correlated regions is often associated with the future occurrence of major earthquakes in the same areas. These major earthquakes include the 1992 Landers, the 1994 Northridge, and the 1999 Hector Mine events.

KEYWORDS: Earthquakes, Modeling, Threshold Systems, Nonequilibrium Systems, Earthquake Dynamics, Nonlinear Dynamics, Seismic Prediction.,

1. INTRODUCTION

Earthquakes strike without warning, causing great destruction and loss of life. A poignant example is the recent Izmit, Turkey, earthquake of August 17, 1999, which resulted in the deaths of over 17,000 persons. Other recent large events include the M ~ 7.6 Taiwan earthquake of September 20, 1999, whose death toll now exceeds 2000 persons, the M ~ 7.3 Landers, California, event of June 28, 1992, and the M ~ 7.1 Hector Mine, California, earthquake of October 16, 1999. Many similar examples have been documented over the course of time [*Richter,* 1958; *Scholz,* 1990].

While a long-sought goal of earthquake research has been the reliable forecasting of these great events, very little progress has been made in developing a successful, consistent methodology [*Geller et al.,* 1997; *Kanamori,* 1981]. Despite the fact that the largest of these events span distances of more than 500 km, no reliable precursors have ever been detected. It is difficult for most scientists to understand why events of this magnitude are not preceded by at least some causal process, which would presumably imply the existence of premonitory signals. In the past, the search for such signals understandably focused on local regions near the earthquake source. Many of these techniques require intensive and expensive monitoring efforts [*Geller et al.,* 1997]. Various patterns of seismic activity centered on the source region have been proposed, including phenomena such as characteristic earthquakes [*Schwartz, et al.,* 1981; *Ellison and Cole,* 1997], Mogi donuts [*Mogi,* 1969; *Mogi,* 1977], seismic gaps [*Haberman,* 1981; *House et al.,* 1981], precursory quiescence [*Knopoff and Yamashita,* 1988; *Wyss and Haberman,* 1988; *Wyss et al.,* 1996; *Kato et al.,* 1997], precursory activation [*Evison,* 1977; *Shaw et al.,* 1992; *Dodge et al.,* 1996], Time-to-Failure and Log-Periodic precursory distributions [*Bufe et al.,* 1993*; Saleur et al.,* 1996; *Gross and Rundle,* 1998], temporal clustering [*Frolich,* 1987; *Dodge et al.,* 1995; *Rundle et al.,* 1997], and earthquake triggering over large distances [*Hill et al.,* 1993; *King et al.,* 1994; *Pollitz and Sacks,* 1997]. 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.

Recent observational evidence has suggested that earthquakes can be characterized by strongly correlated dynamics [*Bufe and Varnes,* 1993; *Press and Allen,* 1995; *Knopoff et al.,* 1996; *Bowman et al.,* 1998; *Brehm and Braile,* 1998; *Gross and Rundle,* 1998; *Brehm and Braile,* 1999]. Realistic numerical simulations of earthquakes also suggest that space-time pattern structures are non-local in character, another consequence of strong correlations in the underlying dynamics [*Rundle,* 1988; *Rundle et al.,* 2000]. Variables in many of these dynamical systems can be characterized by a phase function that involves both an amplitude and a phase angle. The simulations have suggested that seismicity can be described by phase dynamics [*Mori and Kuramoto,* 1998; *Rundle et al. 2000*]. Here, the important changes in seismicity are associated primarily with rotations of the vector phase function in a high-dimensional correlation space [*Fukanaga,* 1970; *Holmes et al.,* 1996]. Changes in the amplitude of the phase function are unimportant, or not relevant. The most familiar examples of these are quantum mechanical systems, but examples also exist in the macroscopic world, including weak turbulence in fluids and reaction-diffusion systems [*Mori and Kuramoto,* 1998].

These results suggest that space-time patterns of seismic activity directly reflect the existence of space-time correlations in the underlying stress and strain fields. Previous research has indicated that the development of correlations in the stress field is a necessary precondition for the occurrence of large earthquakes [*Rundle et al.,* 2000]. The correlation patterns, which represent emergent space-time structures, evidently form and evolve over time intervals of years preceding the main shock. Longer time intervals and larger correlated areas are associated with larger main shocks. The probability for observing such an anomalous correlation can be computed directly from the simulated seismicity data using the square of the anomalous pattern state vector [*Rundle et al.,2000*]. These are the methods that we use in the present analysis of data from southern California.

We test the hypothesis that anomalous, non-local space-time patterns and correlations associated with recorded events can be detected in real seismicity data years prior to the main shock. The seismicity data employed in our analysis is taken from existing observations in southern California between the years 1932 and the present. Using only a subset of this data covering the period from January 1, 1980 through December 31, 1991, we compute the probability for finding an anomalous spatial correlation at all sites in southern California over several intervals preceding December 31, 1991. We then superimpose on this map the locations of main shocks larger than 5.0 that occurred between January 1, 1992 and November 1, 1999, that is, the ~ 8 years following the time interval from which we computed the probabilities. We observe a striking correspondence between regions of increased probability and the location of the recent main shocks, tending to support the results first observed in our simulations. In particular, we note that the epicenter of the recent October 16, 1999, M ~ 7.0 Hector Mine earthquake in southern California occurred at a location that is identified as one of the high probability locations. From the size of the candidate source regions, the magnitude of the possible events can be estimated as well. A likelihood ratio test of the method on both the real southern California seismicity catalog, and a second catalog in which times of events had been reassigned randomly, indicates that the method does find coherent correlated structures in the data.

2. METHOD

As mentioned above, our method is based primarily on the idea that the time evolution of seismicity can be described by phase dynamics. We therefore define a real-valued seismic phase function, $\mathrm{S}(\boldsymbol{x}_i,t_0,t)$, a unit vector whose tail is fixed at the origin, and whose head is constrained to move on the unit sphere in an N-dimensional (N large) correlation space. $\mathrm{S}(\boldsymbol{x}_i,t_0,t)$ is a non-local function, and is the mathematical embodiment of the idea that earthquake fault systems are characterized by strongly correlated dynamics. Geometrically, time evolution of $\mathrm{S}(\boldsymbol{x}_i,t_0,t)$ corresponds to rotations about the origin in a series of correlated random walk increments through small solid angles on the unit sphere. Formation of an emergent correlated pattern in seismic activity over a time interval Δt is associated with rotation of the $\hat{\mathbf{S}}$-vector in a persistent direction. When these persistent directions are examined, previously undetectable, systematic variations in seismicity become evident, as described in *Rundle et al., 2000.*

For our analysis, the phase function $\mathrm{S}(\boldsymbol{x}_i,t_0,t)$ characterizes the seismic activity in southern California between 32° and 37° latitude, and -115° to -122° longitude. It should also be noted that while our initial choice for total area was relatively arbitrary, we have varied the region size in recent analyses, by as much as a factor of two, and have found it to make little difference in the final results. In addition, the catalog was not declustered, as it is the correlations in the data set, the best known examples of which are local patterns of seismic activity or quiescence, that are identified by this method. Since it is well known that seismicity in active regions is a noisy function [*Kanamori,* 1981], we work with temporal averages of seismic activity. The geographic area is partitioned into N square regions approximately 11 km on a side, centered on a point $\boldsymbol{x}_i$. Within each box, a time series is defined using the Caltech seismic catalog obtained from the online SCEC database. For southern California, the instrumental data begins in 1932 and extends to the present. The instrumental coverage was sparse in the early years, and is substantially more complete today. In general, the seismicity catalog is considered complete for magnitudes M ≥ 3.

We define the activity rate $\psi_{obs}(\boldsymbol{x}_i, t)$ as the number of earthquakes per unit time, of any size, within the box centered at $\boldsymbol{x}_i$ at time t. The geographic region that $\mathrm{S}(\boldsymbol{x}_i,t_0,t)$ represents is taken large enough so that seismic activity can be considered an incoherent superposition of phase functions. The seismicity function $\mathrm{S}(\boldsymbol{x}_i,t_0,t)$ is then defined as the time average at $\boldsymbol{x}_i$ of $\psi_{obs}(\boldsymbol{x}_i, t)$ over the period (t_0, t),

$$\mathrm{S}(\boldsymbol{x}_i,t_0,t) = \frac{1}{(t-t_0)}\int_{t_0}^{t} \psi(x,t)dt.$$

Events included in $\psi_{obs}(\boldsymbol{x}_i, t)$ or $\mathrm{S}(\boldsymbol{x}_i,t_0,t)$ are restricted to those for which the magnitude M ≥ 3, so as to ameliorate sensitivity to changes in detection thresholds through time.

Considered as a function of the N locations $\boldsymbol{x}_i$, $\mathrm{S}(\boldsymbol{x}_i,t_0,t)$ represents a vector in N-dimensional correlation space with its tail fixed at the origin. The vector space is spanned by the eigenvectors, or eigenpatterns, of an N-dimensional, Karhunen-Loeve correlation matrix $C(\boldsymbol{x}_i, \boldsymbol{x}_j)$. The elements of $C(\boldsymbol{x}_i, \boldsymbol{x}_j)$ are obtained by cross-correlating a set of N seismic activity time series associated with each box $\boldsymbol{x}_i$ [*Rundle et al., 2000].* As an aside, we note that purely random processes are characterized only by an amplitude in correlation space, not by any preferred direction. This follows from the fact that if the time series defining $C(\boldsymbol{x}_i, \boldsymbol{x}_j)$ were uncorrelated, $C(\boldsymbol{x}_i, \boldsymbol{x}_j)$ would be the identity matrix.

Figure 1 shows one example of **S**(1932,1991) superimposed on a map of southern California. It is clear that **S**(1932,1991) is an unremarkable function, and appears to show little evidence of any phenomena precursory to the M ~ 7.3 Landers, California event that occurred on June 28, 1972.

In the past [*Scholz,* 1990], investigators have generally focused on attempts to detect systematic variations in the both the amplitude and phase of $\mathrm{S}(\boldsymbol{x}_i,t_0,t)$, or alternatively the amplitude and phase variations in the corresponding rate of seismic activity $\mathrm{R}(\boldsymbol{x}_i,t)$. Following our assumption that seismicity is characterized by phase dynamics, we define $\mathrm{S}(\boldsymbol{x}_i,t_0,t)$ as the unit vector pointing in the direction of $\mathrm{S}(\boldsymbol{x}_i,t_0,t)$ using an L2 norm. As an incoherent superposition of functions must have zero mean, we remove the spatial mean of $\mathrm{S}(\boldsymbol{x}_i,t_0,t)$ and create a unit vector by dividing by the standard deviation. Therefore,

$$\hat{\mathrm{S}}(\boldsymbol{x}_i,t_0,t) = \frac{\left[\mathrm{S}(\boldsymbol{x}_i,t_0,t) - \overline{\mathrm{S}}(\boldsymbol{x}_i,t_0,t)\right]}{\sigma},$$

where $\overline{\mathrm{S}}(\boldsymbol{x}_i,t_0,t) = \frac{1}{N}\int_{allx} \mathrm{S}(\boldsymbol{x}_i,t_0,t)dx,$ the spatial mean of $\mathrm{S}(\boldsymbol{x}_i,t_0,t)$, and

$$\sigma^2 = \frac{1}{N}\int_{allx} \left[\mathrm{S}(\boldsymbol{x}_i,t_0,t) - \overline{\mathrm{S}}(\boldsymbol{x}_i,t_0,t)\right]^2 dx,$$

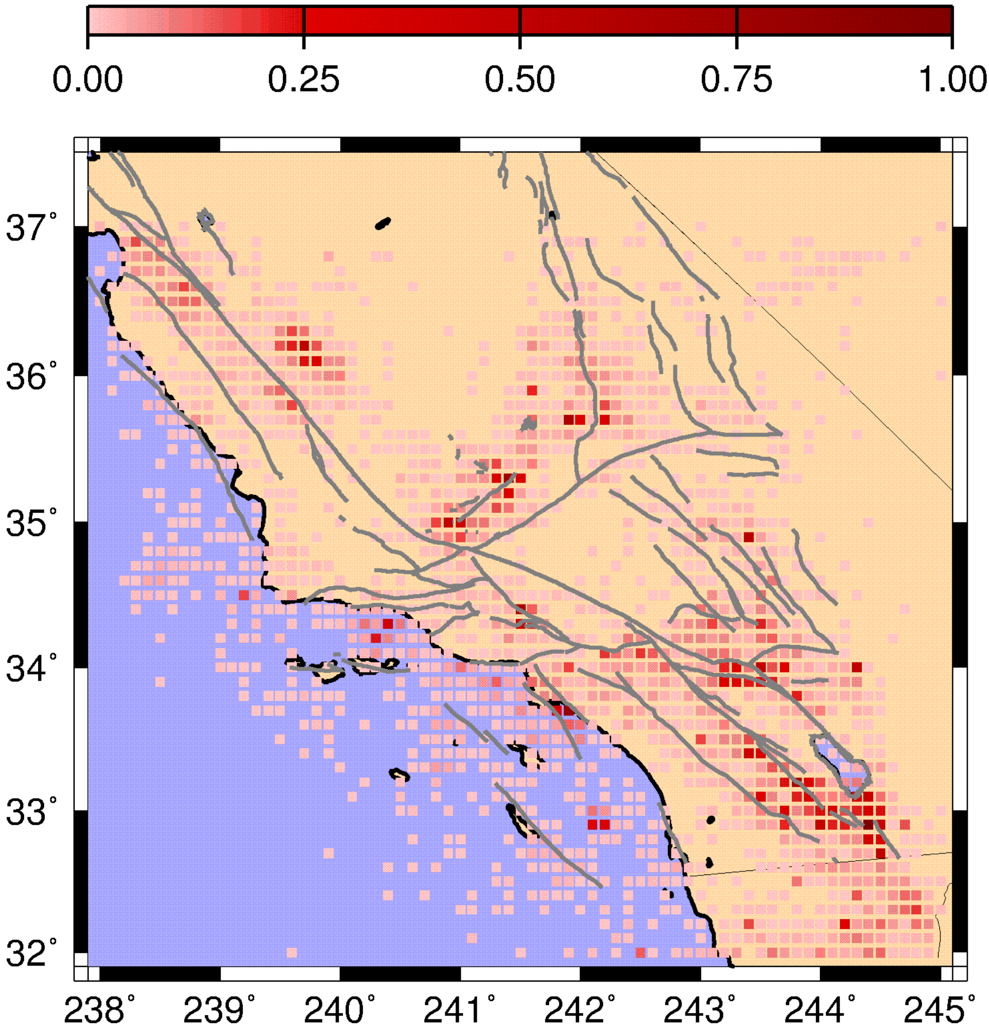

Figure 1. Normalized seismicity function S(1932,1991), M > 3.0, for southern California.

the variance of $\mathrm{S}(\boldsymbol{x}_i, t_0, t)$.

Under the phase dynamics assumption, the important changes in seismicity $\Delta\mathrm{S}(\boldsymbol{x}_i,t_1,t_2) = \mathrm{S}(\boldsymbol{x}_i,t_0,t_2) - \mathrm{S}(\boldsymbol{x}_i,t_0,t_1)$ over the time interval (t_1, t_2) correspond to rotations in correlation space about the origin.

Thus the important observable is this difference $\Delta\mathrm{S}(\boldsymbol{x}_i,t_1,t_2)$. Recall that $\mathrm{S}(x_i, t_0, t)$ is a spatially local function. However, due to the normalization above, which involves information from the entire active region of N boxes, $\mathrm{S}(\boldsymbol{x}_i,t_0,t)$ is a spatially non-local function.

We now compute the increase in probability $\Delta\mathrm{P}(\boldsymbol{x}_i, t_1, t_2)$ associated with formation of a spatial correlation at location $\boldsymbol{x}_i$ over the time interval $\Delta t = (t_2 - t_1)$. Because a correlation function can be interpreted as a probability, the eigenvectors of the correlation operator $C(\boldsymbol{x}_i, \boldsymbol{x}_j)$ are effectively the square root of a probability. Any vector such as $\mathrm{S}(\boldsymbol{x}_i,t_0,t)$ can be written as a linear expansion of such a complete set of eigenvectors which span the correlation vector space. Thus, the increase in probability $\Delta\mathrm{P}(\boldsymbol{x}_i, t_1, t_2)$ is related to the square of $\Delta\mathrm{S}(\boldsymbol{x}_i,t_1,t_2)$. In addition, as the principle of conservation of probability implies that the integral over all space of $\Delta\mathrm{P}(\boldsymbol{x}_i, t_1, t_2)$ is equal to zero, we find that $\Delta\mathrm{P}(x_i,t_1,t_2) = |\Delta\mathrm{S}(\boldsymbol{x}_i,t_1,t_2)|^2 - \mu_\mathrm{P}$, where μ_P is the spatial mean of $|\Delta\mathrm{S}(\boldsymbol{x}_i,t_1,t_2)|^2$.

3. RESULTS AND DISCUSSION

Figure 2 shows plots of all ΔP > 0, using only existing seismicity data acquired prior to January 1, 1992, six months before the June 28, 1992 occurrence of the M ~ 7.3,Landers, CA, earthquake. Recall that the increase in ΔP above the background level as measured by μ_P should be interpreted as a tendency to form a spatially correlated region of seismic activity, and that such regions evidently must be present for larger earthquakes to occur. An increase in ΔP appears to represent an increased chance of an earthquake occurring near that location. The color coding on Figure 3 is scaled to the largest value of ΔP on any of Figures 2 a, b, c or d. The largest 30 percent of points is represented by red, approximately 20 percent by yellow, and approximately 50 percent are between white and green. At the moment, we have not yet found a method to convert these relative numbers into absolute values of probability change, however, we expect that this may be possible with further study. The inverted blue triangles represent events that occurred during the time period covered by the plot, to indicate colored boxes that need not be analyzed further.

Blue circles represent more recent events of magnitude M > 5.0 that occurred after January 1, 1992. It should be emphasized again that no data for these more recent events was used in constructing the colored boxes in Figure 2. In particular, we include circles representing the 1992 Landers sequence and the recent M ~ 7.1 Hector Mine events. These earthquakes are evidently associated with a long-lived arcuate structure of colored boxes cutting across the local fault geometry that began forming prior to 1980. This structure continues down to the southeast of the Landers mainshock, east of the 1992 Joshua Tree earthquake, and the lack of subsequent activity to date may indicate this site as a potential rupture zone in the near future.

Visual examination of Figure 2 indicates that recent large events (blue circles) that occurred after January 1, 1992 are clearly associated with detectable locations of positive ΔP that formed prior to January 1, 1992. However there is clearly some variability, particularly for smaller events, depending on the choice of time interval (t_1, t_2). Larger events tend to be associated with larger colored regions that form earlier and persist longer after the event. Since earthquake fault dynamics are now believed to be associated with critical phenomena [*Rundle and Klein,* 1995; *Klein et al.,* 1997; *Gell-Mann et al.,* 2000; *Rundle et al.,* 2000], we hypothesize that there may be a scaling relation between the area A of the correlated region and the time interval t prior to the main shock at which the correlation begins to form such that $t \propto A^\eta$, where η is a critical exponent near 1. Since the linear size of our boxes is approximately 11 km, one should not expect events significantly smaller than M ~ 6, whose characteristic linear source dimension is 10

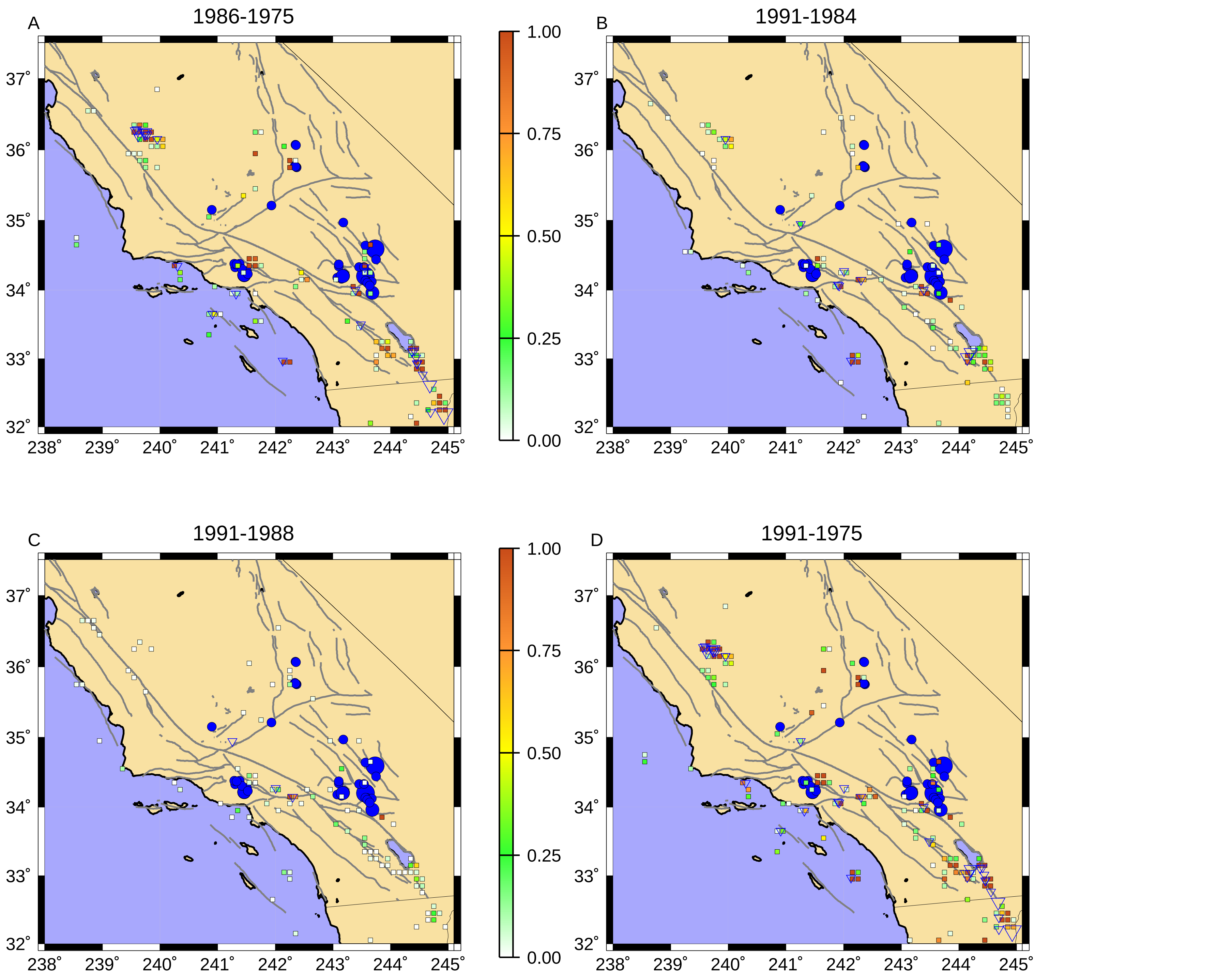

Figure 2. Maps of delta P for the time intervals a) 1986-1975, b) 1991-1984, c) 1991-1988 and d) 1991-1975. In constructing these maps, no data is used from time periods after December 31, 1991. Inverted triangles represent events that occurred during the indicated time periods, with three sizes corresponding to magnitudes M of: 5 < M < 6, 6 < M < 7, 7 < M. Filled circles represent events that occur after January 1, 1992, with circle sizes corresponding to the same magnitude ranges as for the inverted triangles.

km, to be well resolved by our procedure. Yet even the smaller circles associated with M ~ 5 - 6 events seem to occur in proximity to colored boxes, albeit those that appear only a short time interval before the main shock.

To test the hypothesis that the formation of correlated regions identified by this method are indeed coherent space-time structures that are related to future large events, we carried out a likelihood ratio test [*Bevington and Robinson,* 1992; *Gross and Rundle,* 1998] on our model using a comparison to a random seismicity catalog. The random catalog was constructed from the instrumental catalog by using the same number of events at the same locations, but assigning occurrence times drawn from a uniform probability distribution over the years 1932-1991, resulting in a Poisson distribution of interevent times. Randomizing the catalog in this way should destroy whatever coherent space-time structure exists, effectively declustering the catalog. We applied our method to this random catalog and obtained the colored boxes shown in Figure 3, which corresponds to the same time period as Figure 2d, 1991-1975. One can see that there are many more colored boxes in Figure 3 than in 2d, and that the boxes are more broadly distributed in space.

To apply the likelihood ratio test to both Figures 2d and 3, we assumed a probability density function for each box, colored or not, with a Gaussian distribution, whose peak value is $\Delta\mathrm{P}(\boldsymbol{x}_i, t_1, t_2) + \mu_{\mathrm{P}}$, since probabilities in a likelihood test must all be positive, and whose width is that of the colored boxes, approximately 11 km. We then calculated the log likelihoods for the blue circles in both Figures 2d and 3, and found values of -14.5439 for Figure 2d and —17.4239 for Figure 3. These values correspond to a likelihood ratio of $e^{2.88}$ ~ 17.8142, indicating that the colored boxes obtained from the actual instrumental catalog are more likely to be associated with the locations of the blue circles than the colored boxes obtained from the random catalog. The physical reason for this large ratio is that the likelihood test invokes a penalty for colored boxes that are not sufficiently near to blue circles (‘‘false positives’’), and there are many more such boxes in Figure 3 than in Figure 2d. From this test, we conclude that there are coherent space-time correlation structures in the instrumental catalog that our method identifies. This supports the theory that earthquake fault systems contain space-time correlations which are effectively destroyed by declustering the catalog.

In analyzing the meaning of Figure 2 we emphasize that while our method may identify higher risk areas, there is no certainty at this time that every box will be located near the site of a future large earthquake. There are a number of examples in Figure 2 where a box appears during one time period, then disappears over a longer time period without the occurrence of a major earthquake (false negatives). One example of this is the colored boxes which appear near 34.7° latitude, 238.6° longitude, during the period 1975 to 1986, but disappear during the periods 1986 to 1991 and 1988 to 1991. Further attempts at optimization of the method must focus on better spatial location of events and the identification of a minimum number of both false positives and false negatives.

In addition, it appears that, as coherent space-time structures form in the underlying physics which drive the earthquake system, our method attempts to fit the nearest known locations of previous seismicity. One example of this is the four red boxes in the location of the 1971 San Fernando earthquake, as shown in Figure 2d. We hypothesize that these locations are simply the nearest locations available to the method for applying the increased probability associated with the adjacent 1994 Northridge event. In examining the time periods shown, we note that the method described above effectively subtracts out the effects of any San Fernando aftershocks remaining in the catalog in 1975. To test the assumption that the changes in probability are not exclusively associated with the location of aftershock sequences, we plotted the change in $\mathrm{S}(\boldsymbol{x}_i, t_0, t)$, $\Delta\mathrm{S}(\boldsymbol{x}_i, t_1, t_2)$. The results show that the four squares adjacent to the 1994 Northridge event denote an area of *decreased* $\mathrm{S}(\boldsymbol{x}_i, t_0, t)$, i.e. precursory quiescence, not aftershocks due to the 1971 San Fernando earthquake. Events which go off during this time period, such as the 1983 Coalinga earthquake and the 1979 Imperial Valley event, display seismic activation, while the Landers sequence is a complicated mix of positive and negative $\Delta\mathrm{S}(\boldsymbol{x}_i, t_1, t_2)$. These findings support our conclusions from both the numerical simulations and theoretical analysis that this technique does not simply identify areas associated with past events and their aftershock sequences.

1991-1975

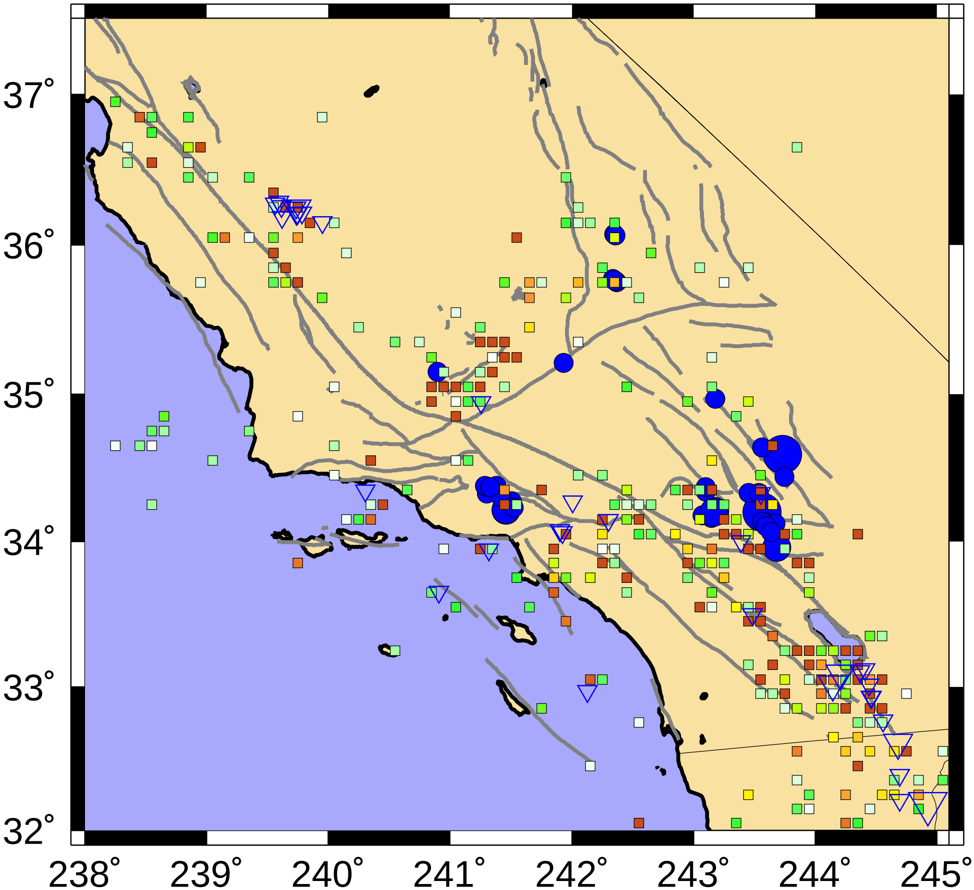

Figure 3. Map of delta P > 0 for the time interval 1991-1975, for the random catalog generated by applying a uniform random distribution of times between 1932 and 1991 to the same locations as the actual catalog.

4. CONCLUSIONS

In summary, we conclude that we have observed systematic variations in seismicity prior to recent southern California earthquakes. Our method employs data from existing seismic monitoring networks as well as a theoretical understanding obtained from numerical computer simulations to identify 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 future 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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