Apparent Weekly and Daily Earthquake Periodicities in the Western United States

by Ali H. Atef, Kelly H. Liu, and Stephen S. Gao

Abstract   Analysis of apparent seismicity rate (ASR) using magnitude ≥ 1 earthquakes located in the western United States confirmed the existence of prominent spectral peaks with periods of 1 and 7 days. The number of recorded earthquakes on Sundays for the duration of 1963–2008 is about 5% higher than that on weekdays, and, more significantly, there is a 9% increase of ASR in the early morning compared with that in the middle of the days. Significant similarities in the spatial distributions of the weekly and daily variations suggest that the two types of variations have the same sources and both originate from periodic variations in cultural noise that lead to periodic variations in the detectability of the seismic networks. Comparisons with freeway traffic flow data suggest that traffic flow on the freeways is not the only significant factor in the observed periodicities. Instead, ambient noise from all the ground traffic, operating machineries, and building shaking is probably the major cause of the observed apparent periodicities. The observed temporal variations in ambient noise as reflected by the ASR can be used as objective guidelines for choosing the best time/day for noise-sensitive scientific experiments.

Introduction

Periodicity is a fundamental property of the natural world. Most periodic phenomena on Earth originated from cyclic natural movements such as self rotation of the Earth (period $T = 23.9345$ hr), rotation of the Moon around the Earth (sidereal $T = 27.3215$ days), that of the Earth/Moon system around the Sun (sidereal $T = 365.2564$ days), and that of the solar system around the center of the Milky Way ($T = 225$–250 m.y.).

In addition to those natural driving forces, recent studies have suggested that human activities might also be able to modulate natural phenomena, some of which are periodic in nature. Because many human activities have periods that coincide with natural periods (e.g., daily and annual), it is not always trivial to tell if a given periodic phenomenon has a natural or human origin. One exception is the weekly periodicity in some natural phenomena. Because of the lack of known natural causes with a 7 day periodicity, weekly variations were considered as purely anthropogenic. Recent examples include weekly periodicity of temperature (Forster and Solomon, 2003) and rainfall (Bell *et al.*, 2008). As demonstrated subsequently, human activities can also influence the sensitivity of measuring instruments and lead to periodicities that are not real.

In terms of earthquake occurrence, it has been suggested that bi-diurnal periodicity in seismicity rate could be related to tidal triggering (Rydelek *et al.*, 1988; Tolstoy *et al.*, 2002; Cochran *et al.*, 2004), and in some specific situations, annual variations in atmospheric pressure might modulate seismicity (Gao *et al.*, 2000). Annual modulations of seismicity have been suggested along the San Andreas fault (Christiansen *et al.*, 2007) and in a few other areas.

Many studies have been devoted to the daily periodicity of the apparent seismicity rate (ASR), defined here as the number of reported earthquakes per unit time in a catalog. One of the earliest formal publications on this topic was by Landsberg (1936) on the earthquake swarms in Helena, Montana, over the period of 3 October 1935–30 April 1936. The study, which used 1880 shocks that were felt and reported by an observer, found a daily periodicity with the number of shocks occurred during daytime (06:00–18:00) at about 44% versus 56% in the nighttime. The study rejected an earlier suggestion that daily variations were caused by the fact that "the observers are in the rest position at night and are more apt to perceive the shocks," although the author did not give any explanation for the observed difference and proposed to "set out to find a reason for this preference." Daily periodicity was reported in two volcanic areas (Phlegraean Fields and Vesuvius) in Italy and was attributed to day/night variations in temperature (Marzocchi *et al.*, 2001), which is contradictory to the conclusion of Rydelek *et al.* (1992), who suggested that the daily periodicity at Phlegraean Fields was an artifact caused by cultural noise. Diurnal periodicity was also observed in central Asia (Zhuravlev *et al.*, 2006) and other areas. Quarry blast events, which happen predominantly in the daytime, can cause
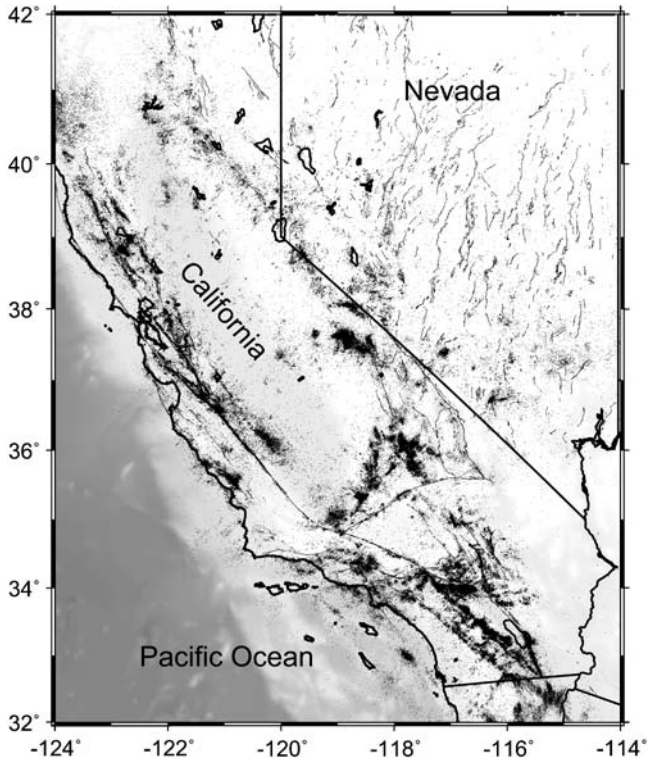
significant daily periodicity in areas with high quarry activities (Wiemer and Baer, 2000).

Relative to daily variations, studies of weekly variations of ASR are relatively rare. A recent global-scale study using the International Seismological Center (ISC) catalog for the whole Earth over the period of 1964–2003 revealed a weekly periodicity with the peak on Sundays (Zotov, 2007). Two hypotheses regarding the nature of the periodicity were proposed, namely an artifact caused by weekly variation of cultural noise and a real physical phenomenon caused by cultural-noise-induced variations in tectonic stress (Zotov, 2007).

It is clear that although weekly, especially daily, variations in ASR have been reported for a long time, systematic studies about the characteristics and causes of such periodicities are still rare. Here we present results from a comprehensive analysis of weekly and daily periodicities in the western United States.
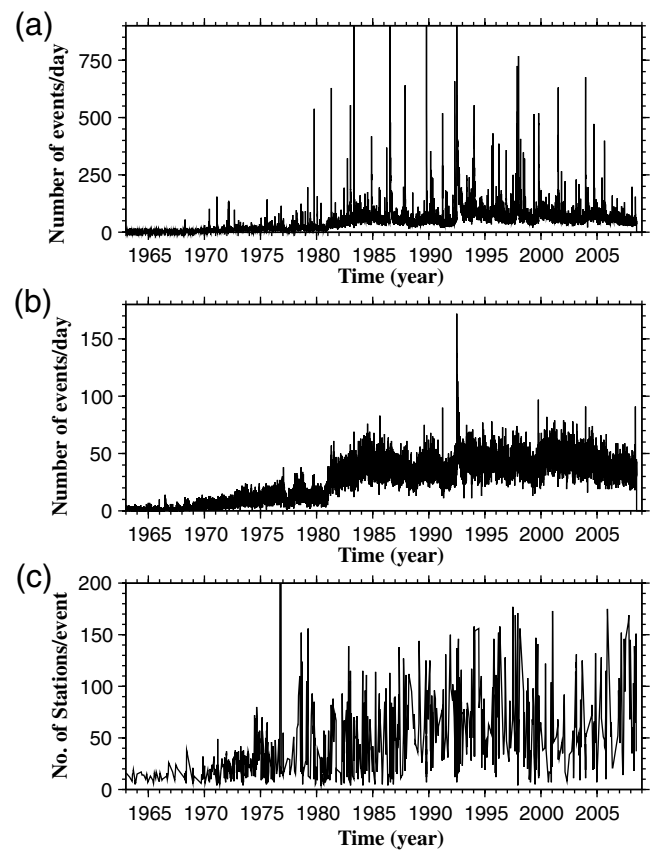
Data

The earthquake catalog used in the study contains 790,232 magnitude ≥ 1.0 earthquakes and was compiled by Advanced National Seismic Systems (ANSS, see the Data and Resources section for access information). The events occurred in the period of 1 January 1963–10 July 2008 in a $10° \times 10°$ area (Fig. 1), which includes the entire states of California and Nevada as well as the adjacent Pacific ocean. The beginning date is consistent with the establishment of the Worldwide Standardized Seismographic Network (WWSSN), which was the major seismic network in the world from the early 1960s to the mid-1970s (Huang et al., 1997).

The area was chosen because of its high level of earthquake activities and, most importantly, dense and sophisticated earthquake detecting networks. The universal time in the catalog was converted to local time. The aftershocks were removed using the declustering methodology of Reasenberg (1985), which resulted in a total of 443,428 earthquakes in 16,628 days. The declustering is necessary because of the contamination of the many aftershocks of the large earthquakes (Fig. 2a), which occurred randomly in time and were not expected to have a weekly or daily periodicity. The lack of significant peaks on the seismicity rate plot computed using the declustered catalog (Fig. 2b) suggests that the declustering procedure successfully removed most of the aftershocks. A few remaining peaks such as the one in the middle of 1992 are associated with remotely triggered earthquakes by the Landers or other great earthquakes (Hill et al., 1993; Gao et al., 2000).

Figure 1. Distribution of declustered earthquakes (dots) used in the study. Thin lines are active faults provided by the U.S. Geological Survey (USGS) (see the Data and Resources section for access information).
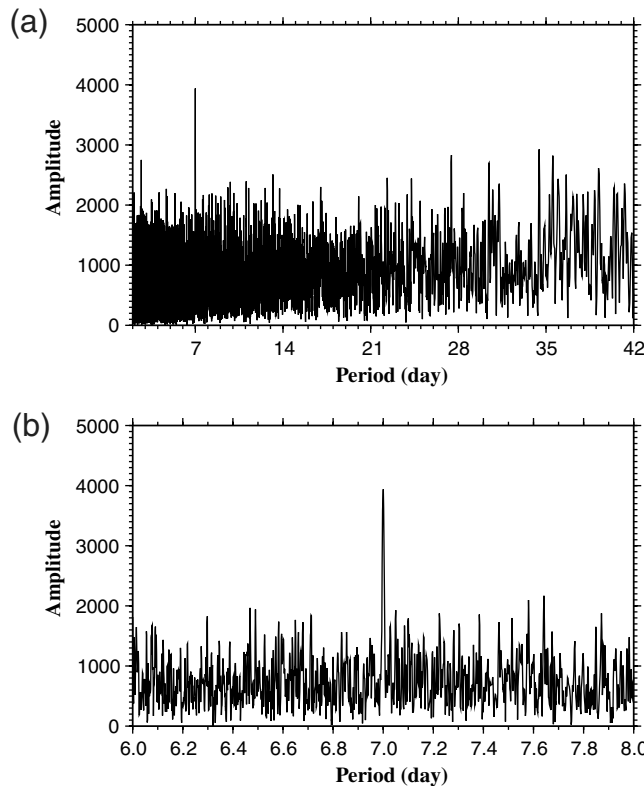

Figure 2. (a) Number of earthquakes per day computed using the original catalog. (b) Number of earthquakes per day computed using the declustered catalog. (c) Number of stations used to locate earthquakes in the magnitude range of 4.0–4.2, plotted at the time of origin of the earthquakes.

Prior to 1982, the number of recorded events was low but increased gradually with time (Fig. 2a), apparently as a consequence of the relatively low and temporally increasing number of seismic stations in the area (Fig. 2c). Since the early 1980s, the ASR has been relatively stable, although the number of seismic stations has been steadily increasing over the time period.
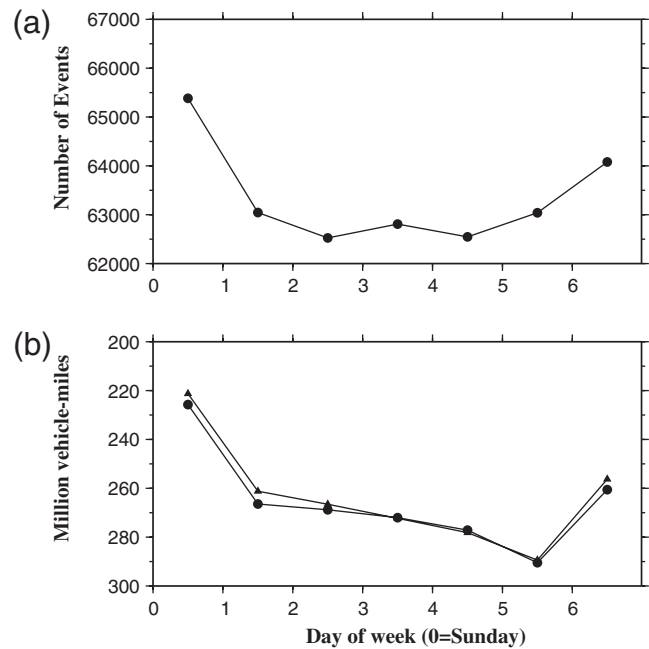
Weekly Periodicity

Figure 3 shows the amplitude spectrum of the seismicity rate (Fig. 2b). In the period range of 2 days–6 weeks, the most outstanding peak has a period of 7 days, suggesting a weekly periodicity in the seismic rate. The signal-to-noise ratio (S/N) of the peak is about 5.3, which was calculated using the ratio between the amplitude of the peak and the average amplitude over the period range of 5.8–6.8 days.

The total number of earthquakes that occurred during each of the 7 days in the week indicates that Sundays have the maximum number of recorded earthquakes, followed by Saturdays (Fig. 4a). *P*-tests show that the probability for Sundays and weekdays to have the same number of earthquakes is about 10^{-10} and that for Sundays and Saturdays, the probability is about 10^{-4}, suggesting that the peak on Sundays is statistically significant. Relative to Tuesdays and Thursdays, which have the least number of earthquakes, the increase is 4.6%, 2.5%, 0.8%, 0.8%, and 0.4% for Sundays, Saturdays,

Figure 4. (a) Weekly distribution of seismicity. (b) Weekly traffic flow for the periods of 12 February–18 February 2007 (line with triangles) and 10 September–16 September 2007 (line with dots) for all the freeways in California (source: Freeway Performance Measurement System—see the Data and Resources section for access information). Note that the vertical axis of (b) is reversed for easy comparison with the earthquake data shown in (a). The values are plotted at the middle of the days.

Mondays, Fridays, and Wednesdays, respectively (Fig. 4). Over the five weekdays, the apparent number of earthquakes shows an interesting symmetry. The magnitude of the Sunday maximum in the study area is similar to that found by Zotov (2007) in a global-scale study over the period of 1964–2003.

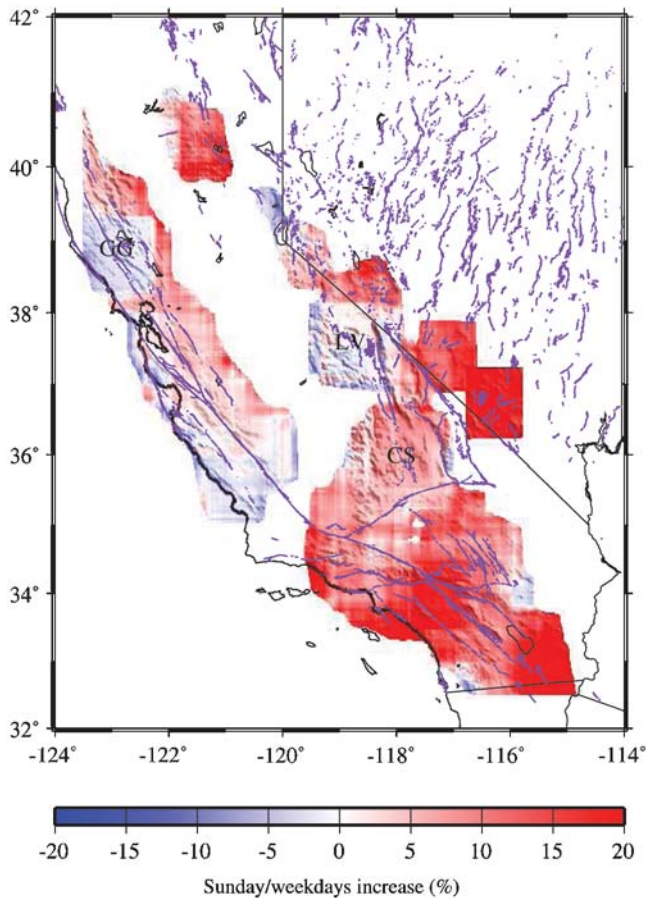To map the spatial distribution of the Sunday/weekdays difference, we calculate *W*, which is defined as

$$W = 100(3N_{\mathrm{Sun}} - N_{\mathrm{Tue}} - N_{\mathrm{Wed}} - N_{\mathrm{Thu}})/(N_{\mathrm{Tue}} + N_{\mathrm{Wed}} + N_{\mathrm{Thu}}),$$

in $1° \times 1°$ blocks (with a moving step of 0.1°) for events of magnitude 1–2. Figure 5 shows the results for blocks with $N_{\mathrm{Sun}} \geq 300$. Southern California and southwest Nevada have the largest *W* values. Areas with small positive or even negative *W* values are those with low-level human activities or places with dense local networks such as Long Valley, and Coso and the Geysers geothermal areas, where the magnitude of completeness is close to 1 for most of the study period.
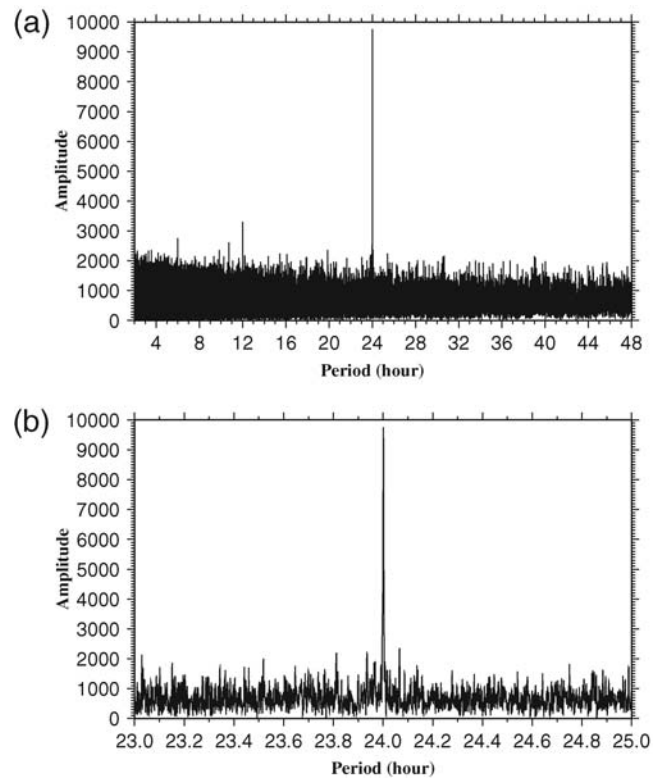
Daily Periodicity

To explore the possibility of daily periodicity, a time series of the number of events per hour was first constructed

Figure 3. (a) Amplitude spectrum of seismicity rate showing a clear peak with a period of 7 days. (b) Enlarged version of (a).

Figure 5. Spatial distribution of Sunday/weekday variations. Only those blocks with 300 or more events on Sundays are shown. Definitions: GG, Geysers geothermal area; LV, Long Valley; CS, Coso geothermal field.
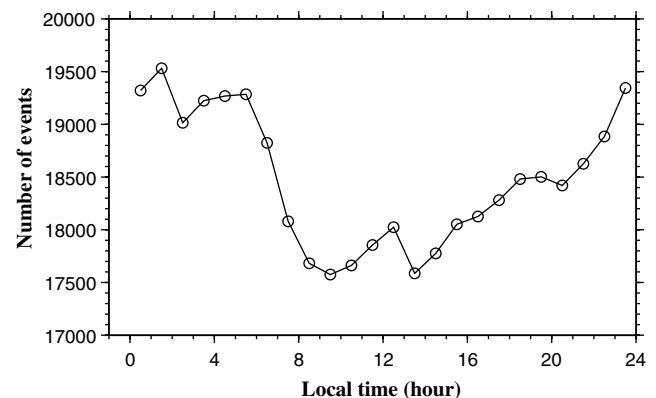

Figure 6. (a) Amplitude spectrum of seismicity rate showing a remarkable peak with a period of 24 hr. (b) Enlarged version of (a).
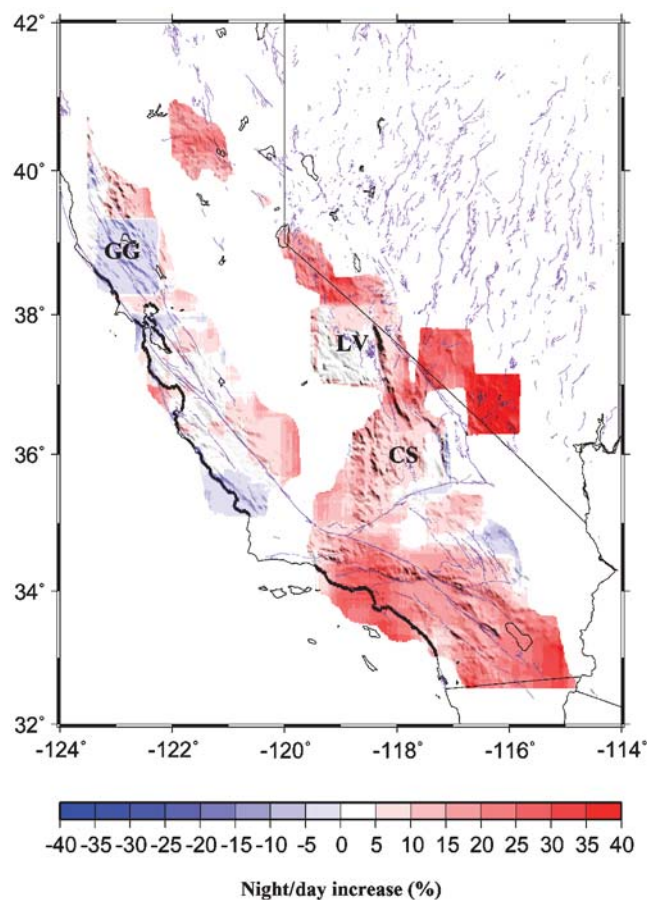
decrease in ASR is significantly greater than that of the afternoon increase.

Discussion

The spatial and temporal variations in the amplitudes of the periodicities suggest that the periodicities in ASR are caused by periodic variations in detectability of the seismic networks. The detectability is dependent on a number of factors, such as station density and spatial distribution, sensitivity of the instrumentation, stability of the data transferring system, data handling capability of the data center, and noise

covering the entire time period (399,065 hr). A remarkable peak with a period of 24 hr is observed on the amplitude spectrum (Fig. 6). The S/N, which is estimated using the ratio between the amplitude of the peak and the average amplitude over the period range of 22.8–23.8 hr, is 14.5, which is about three times that of the weekly periodicity, suggesting that the former is more robust than the latter. Figure 7 shows hourly distribution of the ASR. The apparent number of events in the early morning is about 9% higher than that in the middle of the day. The spatial distribution of the night/day increase (Fig. 8) for magnitude 1–2 events is similar to the Sunday/weekdays distribution (Fig. 5).

To explore possible differences in hourly variations of ASR with days of the weeks, we calculate and plot the hourly distribution of ASR for each of the seven days (Fig. 9). Several interesting features can be observed from the plots. (1) The hourly variations for the five weekdays as well as the afternoons of Saturdays are very similar, even for most of the detailed variations. (2) Sundays in the daytime and Saturday mornings have the highest ASR. (3) The ASR is the highest between 10 p.m. and 5 a.m. and the lowest between 9 a.m. and 4 p.m. for all of the 7 days. (4) The slope of the morning

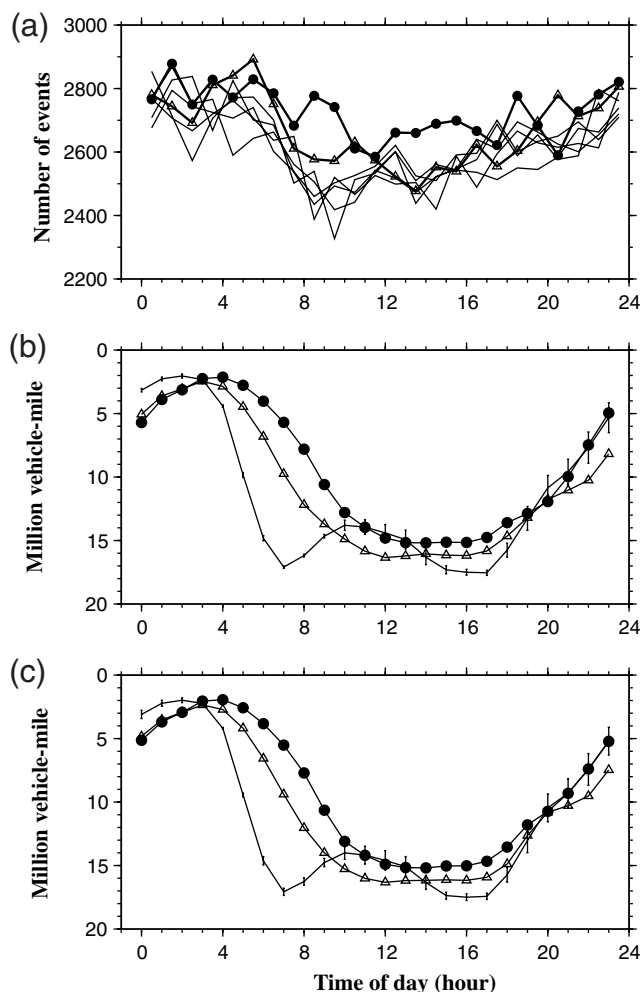**Figure 7.** Hourly distribution of apparent seismicity.

Figure 8. Spatial distribution of night/day variations. Only those blocks with 700 or more events during 0.0–5.0 a.m. are shown.

level in the vicinity of the recording sites (Schorlemmer and Woessner, 2008). Among these factors, daily and weekly variations in ground vibrations associated with cultural noise are the most likely causes of the observed ASR.

The cultural-noise origin of the observed ASR periodicities is evident from the high-level similarities between the spatial distribution of Sunday/weekday variations (Fig. 5) and that of the night/day variations (Fig. 8). The best-fitting relation between the two spatial variations is

$$W = (0.75 \pm 0.64) + (0.60 \pm 0.04)D,$$

where W is the Sunday/weekday distribution and D is the night/day distribution. The cross-correlation coefficient between the two data sets is 0.75. Therefore, the two spatial distributions are positively correlated with a slope that is significantly different from zero (Fig. 10). Because it is generally accepted that phenomena with a 7 day periodicity are almost certain to be caused by human activities, the high positive correlation between the daily and weekly ASR suggests that the night/day periodicity is most likely also caused by human activities, rather than natural causes such as daily

Figure 9. (a) Hourly distribution of apparent seismicity during each of the 7 days in a week. Thin lines are for the five weekdays, the line with dots is for Sundays, and the line with triangles is for Saturdays. (b) Hourly distribution of freeway traffic flow for 10 September–14 September 2007 (Monday–Friday, the line with error bars), 15 September 2007 (Saturday, the line with triangles), and 16 September 2007 (Sunday, the line with dots). (c) Same as (b) but for the period 12 February–18 February 2007.

variations in ground temperature, atmospheric pressure, tides, or geomagnetic field.

Most large earthquakes were located by seismic stations distributed on the whole Earth. Because the majority of the earthquakes used in the study are small and because the study area is mostly bounded by areas with relatively few seismic stations, earthquakes used in the study were mostly located by stations within the study area. During time periods when the cultural-noise level in the study area is high, the detectability of the seismic networks is low, and consequently, some of the small earthquakes could not be detected. Such periodicities in cultural noise have been observed from analysis of seismograms recorded by the NORSAR small-aperture array in Norway (Ringdal and Bungum, 1977). In areas covered by a dense seismic array such as the geothermal areas, the vast majority of all the earthquakes with
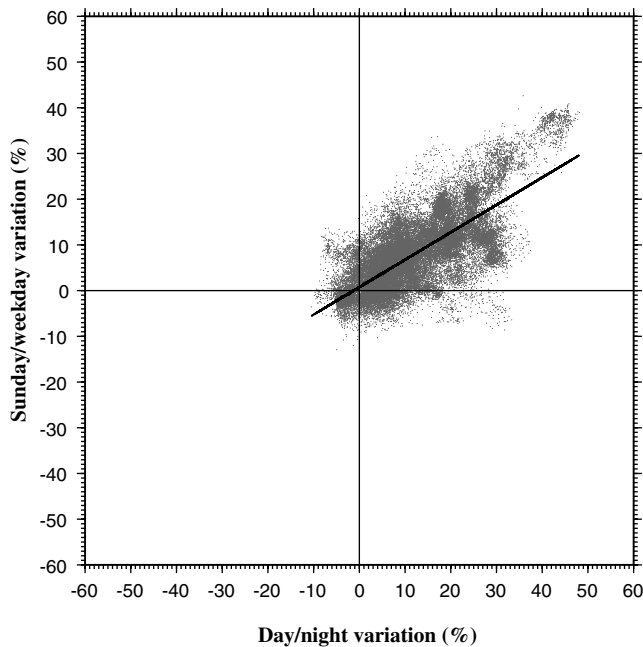
Figure 10. A scatter plot showing the relationship between Sunday/weekday and night/day spatial distributions (Figs. 5 and 8).

magnitude ≥ 1.0 were recorded, resulting in low variations in the ASR between times with low (nighttimes and weekends) and high (daytimes and weekdays) cultural-noise levels (Figs. 5 and 8).

In the modern society moving vehicles are undoubtedly an important source of ground vibration. To investigate the effect of vehicle flow on the observed ASR, we obtained representative daily (Fig. 4b) and hourly (Fig. 9b,c) traffic flow data from a database managed by University of California, Berkeley, for all the freeways in California. As expected, the weekends have the lowest traffic flow. This is consistent with the ASR observations. However, from Monday to Friday there is a progressive increase in traffic flow and this is not observed in the ASR (Fig. 4). Instead, the ASRs during all five weekdays are similar in spite of the large differences in traffic flow between Mondays and Fridays. Based on those observations we conclude that moving vehicles (at least those on the freeways) might not be the sole significant contributor to the observed temporal variation in the ASR.

This conclusion is further evidenced by the lack of close correspondence between the ASR and hourly traffic flow (Fig. 9). For instance, while the morning rush hour peaks at 7–8 a.m., the lowest ASR occurs between 8 and 9 a.m. This phase delay can also be observed between the traffic low around 11 a.m. and the ASR high peak at 1 p.m. The significant difference in the slope between the morning decrease and afternoon increase in the ASR is not observed in the traffic data (Fig. 9). The small peak-to-peak variations during Sundays observed in the ASR data are also inconsistent with the large (almost similar to that of weekdays) peak-to-peak variations in the traffic data on Sundays.

Our favorite hypothesis for the cause of the observed temporal variations of ASR is that they are caused by a combination of traffic flow (freeway and nonfreeway), working machineries such as those in factories and mines in the area, and shaking buildings. Based on this hypothesis, the high ASR in the night and early morning corresponds to low levels in traffic flow, machinery operation, and building shaking. The rapid decrease in ASR from 6 to 8 a.m. during weekdays is mostly caused by traffic on the freeways and local streets during the morning rush hours. From 8 to 12 a.m. on weekdays, the combination of high-traffic flow and operating machineries as well as building shaking triggered by the occupants results in the lowest ASR in the day. Around noon on weekdays, some machines are turned off and a portion of drivers stop for lunch, leading to a local high in ASR. Over the afternoons and evenings in weekdays, machines are gradually turned off and the level of building shaking gradually reduces, which cause a gradual increase in ASR.

The ASR observations indicate that the combined cultural-noise level on Saturdays (especially in the afternoon) is comparable to that over weekdays. This probably suggests that a significant percentage of machineries is working on Saturdays (plus an excessive number of outdoor activities and mowing lawn tractors, etc.). The ASR variation on Sundays is probably dominated by traffic flow. The morning hours are especially quiet except for a brief high around 8 a.m.

Unlike the well-documented freeway traffic flow data, at the present time there is a lack of quantitative measurements of the number and types of operating machineries and other factors mentioned previously. Consequently, the explanation remains as a hypothesis that requires testing in the future.

Weekly and daily periodicities presented in the study can be used as general guidelines for choosing the best day/time for conducting scientific experiments that favor low ambient ground noise. Examples of such experiments including active-source seismic experiments and some particle physical experiments. The difference in the reliability of the results could be significant when the experiments are conducted on a regular base. Obviously, the quietest time is between 10 p.m. and 4 a.m. each day, including the weekends. If daylight is needed for the experiments, Sunday midmorning is the best, while Sunday afternoon and Saturday morning are also among the quietest time periods.

Conclusions

Several conclusions can be drawn from the study:

1. There is an apparent weekly periodicity and a daily periodicity in earthquake occurrence in the ANSS earthquake catalog for the western United States.
2. During times when the cultural-noise level is low such as in the nighttime and on weekends, more earthquakes were detected by the seismic networks.
3. Our favorite model is that the cyclic nature of the cultural-noise level leads to the observed periodicities

in the ASR. Therefore, both the weekly and daily periodicities are artifacts and were caused by variations in the detectability of the seismic networks in the study area.

4. More studies are needed to pinpoint the actual sources of the cultural noise and the mechanisms of noise generation.

5. This study underlines the importance of minimizing cultural noise when establishing seismic stations.

Data and Resources

The ANSS seismic catalog used in the study was searched using www.ncedc.org/cnss/catalog-search.html (last accessed July 2008). The traffic flow data were obtained from the Freeway Performance Measurement System at pems.eecs.berkeley.edu (last accessed July 2008, user account applications are subject to approval). Active fault data were obtained from the U.S. Geological Survey (USGS) at http://earthquake.usgs.gov/regional/qfaults/google.php (last accessed July 2008). Figures in the article were produced by the Generic Mapping Tools (GMT) (Wessel and Smith, 1998).

Acknowledgments

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