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Seasonal modulation of seismicity in the Himalaya of Nepal

L. Bollinger,[1] F. Perrier,[2] J.-P. Avouac,[3] S. Sapkota,[4] U. Gautam,[4] and D. R. Tiwari[4]

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[1] For the period 1995–2000, the Nepal seismic network recorded 37 ± 8% fewer earthquakes in the summer than in the winter; for local magnitudes ML > 2 to ML > 4 the percentage increases from 31% to 63% respectively. We show the probability of observing this by chance is less than 1%. We find that most surface loading phenomena are either too small, or have the wrong polarity to enhance winter seismicity. We consider enhanced Coulomb failure caused by a pore-pressure increase at seismogenic depths as a possible mechanism. For this to enhance winter seismicity, however, we find that fluid diffusion following surface hydraulic loading would need to be associated with a six-month phase lag, which we consider to be possible, though unlikely. We favor instead the suppression of summer seismicity caused by stress-loading accompanying monsoon rains in the Ganges and northern India, a mechanism that is discussed in a companion article. **Citation:** Bollinger, L., F. Perrier, J.-P. Avouac, S. Sapkota, U. Gautam, and D. R. Tiwari (2007), Seasonal modulation of seismicity in the Himalaya of Nepal, *Geophys. Res. Lett.*, *34*, L08304, doi:10.1029/2006GL029192.

1. Introduction

[2] Cyclic variations of seismicity possibly provide insights into the physics of earthquake triggering. Seasonal variations have been in particular observed in various contexts and related to factors such as snow loading, precipitation and variations of the water table [e.g., *Costain et al.*, 1987; *Heki*, 2003; *Roth et al.*, 1992; *Saar and Manga*, 2003]. In this study we report seasonal variations of seismicity in the Himalaya recorded by the National Seismic Network (NSC) of Nepal [*Pandey et al.*, 1999]. We first recall the seismotectonic setting, and then discuss our observations and possible forcing mechanisms.

2. Seasonal Variations of Seismicity in Nepal

[3] Seismicity has been monitored since 1995 from 21 vertical-component, short-period stations, operated by the Department of Mines and Geology (Kathmandu, Nepal) in collaboration with the Laboratoire de Détection et de Géophysique (France). For the analysis presented here we have selected the period from 1995 to 2000, during which time the network geometry has not changed, nor has any major earthquake occurred nearby. As reported in previous studies [e.g., *Pandey et al.*, 1995], a large fraction of the seismicity is clustered along a belt following the front of the Himalaya with focal mechanisms indicating thrusting perpendicular to the range (Figure 1). As shown from the modelling of geodetic strain measured from GPS, this seismicity is associated with interseismic stress accumulation around the downdip end of the locked portion of the Main Himalayan Thrust (MHT) fault [*Cattin and Avouac*, 2000; *Bollinger et al.*, 2004]. Other clusters of seismicity occur farther north and are related to normal events along NS grabens [*Bollinger et al.*, 2004].

[4] We restrict our analysis to events located within the band of seismicity beneath the Greater Himalaya. A total of 10569 occurred within this area with local magnitudes ranging from $M_L = 0$ to 6.3. Seismic productivity in the five years investigated exhibits a strong seasonal modulation with seismicity rates in winter nearly double those in summer (Figure 2).

[5] The magnitude-frequency distribution of events recorded either in summer or in winter is shown in Figure 3a. The number of events, N, with magnitude above a given value, M_L, follows approximately the Gutenberg-Richter relationship:

$$Log_{10}N(M \geq M_L) = a - bM_L \qquad (1)$$

with a *b* value of 0.81 ± 0.04. The relationship is obeyed for magnitudes above a 'completeness magnitude', M_c, which we define here as the magnitude above which the number of events in the catalog is 95% of the number of events anticipated by equation (1). When summertime and wintertime events are considered separately, M_c shows an annual variation (Figure 3) between ~1.6 in winter and ~2.1 in summer. This variation suggests that the M_c basically reflects the detection capacity of the seismic network and is lower in the winter than in the summer due to a higher seismic noise level. However, this effect is unable to explain completely the large variation in seismicity revealed in Figure 2. Indeed, as illustrated in Figure 3b, the number of events in summer is lower than that in winter at all magnitudes above the detection threshold, up to M_L = 4.0, but with lower statistical significance (Table S1 of the auxiliary material).[1] In order to test the statistical significance of our observation, we generated 10000 random catalogs with the same number of events and the same frequency-magnitude distribution as in the real catalog. We have then varied the cut-off magnitude and computed the ratio of events occurring in the winter to

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[1] Laboratoire de Détection et de Géophysique, CEA, Bruyères-le-Châtel, France.

[2] Equipe de Géomagnétisme, Institut de Physique du Globe de Paris, UMR7154, Paris, France.

[3] Geology and Planetary Sciences Department, California Institute of Technology, Pasadena, California, USA.

[4] Department of Mines and Geology, National Seismological Centre, Lainchaur, Kathmandu, Nepal.

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[1] Auxiliary materials are available at ftp://ftp.agu.org/apend/gl/2006gl029192.

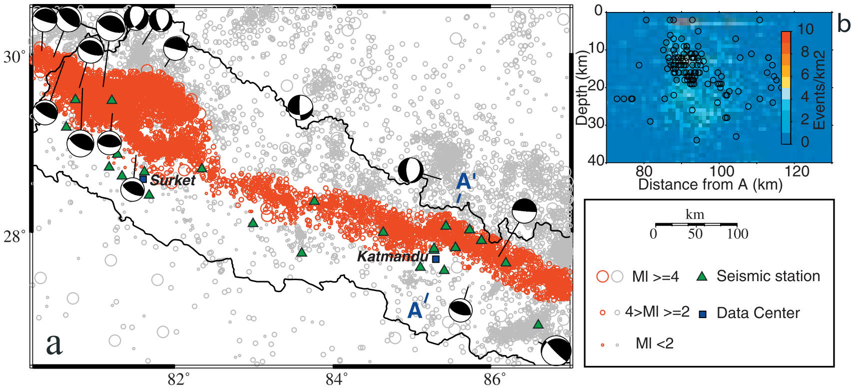

Figure 1. (a) Microseismicity recorded between 04/01/1995 and 04/11/2000 by Nepal Seismological Center, Department of Mines and Geology. In red, events within the seismicity belt at the front of the high Himalaya that were selected for the present study. Focal mechanisms from Harvard CMT catalog. (b) Density distribution of seismic events with resolvable depths through a 50 km swath centred on AA'. The depth of these events is inaccurately determined [*Pandey et al.*, 1995], most events fall within depths from 10 to 20 km (black circles), as determined from a temporary experiment [*Cattin and Avouac*, 2000].

those occurring in the summer. Figure 3b shows that the probability that the observed low ratio would be due to chance is much less than 1% up to magnitude 4. We also considered the possibility of a bias caused by temporal clustering of events. As evident in Figure 2, microseismic productivity peaked level between December 1996 and January 1997. This peak, as well as others less obvious in the catalog is attributable to aftershocks following intermediate magnitude earthquakes (ML > 4 to 5) [*Bollinger*, 2002]. To circumvent contamination from aftershocks we suppressed their effects in our catalog using the declustering method proposed by *Reasenberg* [1985]. We adjusted the spatial (5 km horizontal, 10 km vertical, and inter-event separation <80 km) and temporal ($1 \leq \tau \leq 10$ days) input parameters to exclude events those sequential occurrence occurred with P = 0.95 confidence in the catalog (Figure 3b). The ratio of summertime to wintertime events remains significantly lower than 1, in the declustered catalog, as well as lower than the 99% envelope of the 10000 synthetic random catalogs (Figure 3b).

[6] Purely instrumental effects are unlikely to produce an artificial seasonality at such high magnitudes, we conclude that the observed seasonality is genuine.

3. Comparison With Meteorological Cycle

[7] In Figure 4 we compare average rainfall with a monthly count of microearthquakes for different cut-off magnitudes, calculated for the period 1995–2000. The minimum in seismicity corresponds with maximum rainfall. The correlation is most pronounced when all events are considered. We interpret this correlation to be due to the direct or indirect effect of heavy monsoonal rainfalls on the background seismic noise during the summer monsoon. It might be envisioned that raindrop-impacts, or local run-off from atmospheric storms would generate some seismic noise directly. However, we did not detect any daily variation of the detection threshold that might be expected from this mechanism since nocturnal rainfall peaks between 11 pm and 2 am [*Ueno et al.*, 2001]. Our preferred interpretation is thus that the seismic noise results primarily from river bed-load transport. Another possibility is that seismic noise is generated by landslides activated during periods of heavy rain. However, although we find that seismic noise levels in the Himalaya are moderated by sediment transport in the mountains. The correlation between seasonal variations of seismicity and rainfall is observed at magnitudes well above the detection threshold. This argues that surface hydrology must influence subsurface seismicity directly. We discuss that possibility in the next section.

4. Discussion

[8] Earthquake triggering mechanisms are commonly discussed in terms of Coulomb failure criteria [e.g., *King et al.*, 1994]. Coulomb stress, (S), can be expressed as a function of the normal stress, σ_n, and shear stress, τ, on the fault plane as

$$S = \tau - \mu\left(\sigma_n - p_f\right), \qquad (2)$$

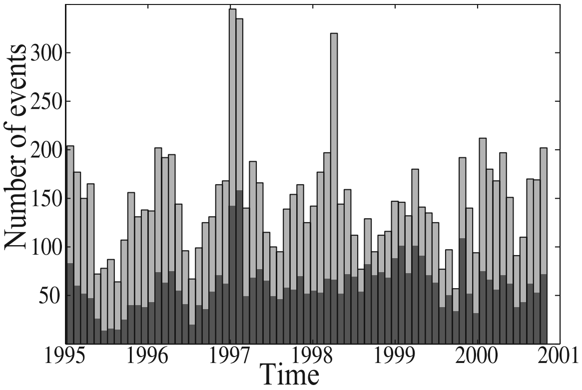

Figure 2. Variations in numbers of earthquakes each month for all magnitudes (grey) and ML > 2.5 (black) in the period 1995–2001. An annual cycle is evident with peak numbers occurring in the winter months between January and March each year.

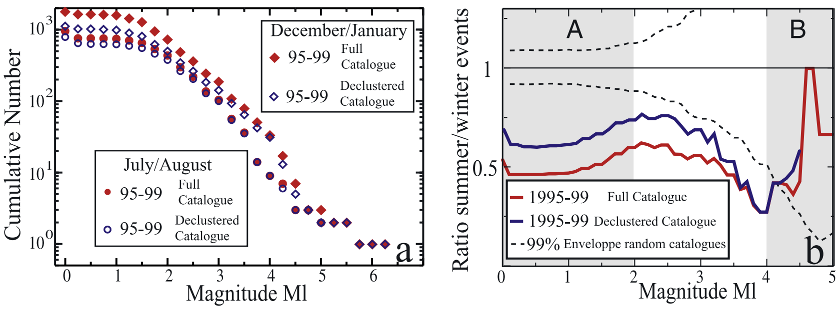

Figure 3. (a) Cumulative numbers of events vs. magnitude for winter months (diamonds) and summer months (circles). Open symbols are for an aftershock-depleted catalog generated using *Reasenberg* [1985] with P = 0.95, $1 \leq \tau \leq 10$ days, D $\leq$ 20 km, Ux = 5 km, Uz = 10 km. Summer seismicity is in each case lower than that in the winter. (b) A test for the possibility of observing the winter/summer variation by chance (diverging dashed lines symmetrical about unity), compared to the observed ratio for different magnitudes (solid curves). In grey region A, the seismic catalog is incomplete [*Pandey et al.*, 1999]. In grey region B the ratio is not statistically significant (Table S1). The dashed curves are the summer/winter ratios that contain 99% of the summer/winter ratios derived from 10^4 random catalogs with the same magnitude frequency distribution as the real total catalog.

where μ is a friction coefficient and p_f an effective fluid pressure. Accordingly, a Coulomb stress increase should result in enhanced seismicity. Variations of S can be induced by changes of any of the parameters τ, σ_n, μ and p_f. We shall assume that the earthquakes are dominantly thrust events on gently dipping fault planes as suggested from the available focal mechanisms (Figure 1). As pointed out in a number of past studies, a periodic loading, with period T, superimposed over a secular loading rate, $\dot{S}_0$, will have substantial effect on seismicity only if the amplitude of periodic stress variation, S_m, is of the order of magnitude of the secular increase over a cycle $\dot{S}_0 \cdot T$ [e.g., *Vidale et al.*, 1998; *Lockner and Beeler*, 1999; *Heki*, 2003]. If the amplitude of the seasonal term is smaller than the limit for stress rate reversal, $\frac{1}{2\pi}\dot{S}_0 \cdot T$ seismicity is expected to correlate with the stress rate, while in the case of stress reversal the seismicity will tend to correlate more with the peak coulomb stress. Given the rapid secular rate of stress increase and the fact that no obvious stress shadow is observed, we believe that we are always in the regime where the seismicity rate should correlate with the stressing rate. The annual stress increase due to interseismic loading is estimated to ~6 kPa within 5 km of the centroid of microseismic activity beneath the Greater Himalaya [*Bollinger et al.*, 2004], providing an estimate of the order of magnitude of the stress variations needed to explain the observed fluctuations of seismicity.

[9] Seasonal stress variation in the Himalaya could result from erosional unloading, atmospheric pressure fluctuations, snow load, hydrological load and temperature variations. Erosion in the Himalaya dominantly results from landsliding and mass transport during the monsoon. It reaches a maximum, estimated to 5–8 mm/yr on average, near the front of the high range where slopes are steepest [*Lavé and Avouac*, 2001]. Erosion results in a decrease of the vertical stress, of probably less than 100 Pa/yr on average, hence an increase of S for shallow thrust events. The effect is small in comparison to interseismic loading and it should enhance seismicity during the summer rather than in the winter, the opposite of what we observe.

[10] Variations of snow load and of atmospheric pressure lead to seasonal stress variations of the order of a few kPa, of the same order of magnitude as the interseismic loading. Both effects are a maximum in the winter [e.g., *Putkonen*, 2004], and both would again inhibit winter seismicity. Again, the opposite of what we observe.

[11] Thermoelastic strain up to 10^{-4} might be generated due to the large yearly surface temperature variations, an effect thought to contribute to geodetic seasonal variations [e.g., *Prawirodirdjo et al.*, 2006]. Assuming a thermal diffusivity of 8.64×10^{-2} m^2d^{-1} and a soil thickness varying between 0 and 2 m, we estimate that the phase delay between the temperature and the peak strain computed from *Ben-Zion and Leary* [1986] would vary between 0 and

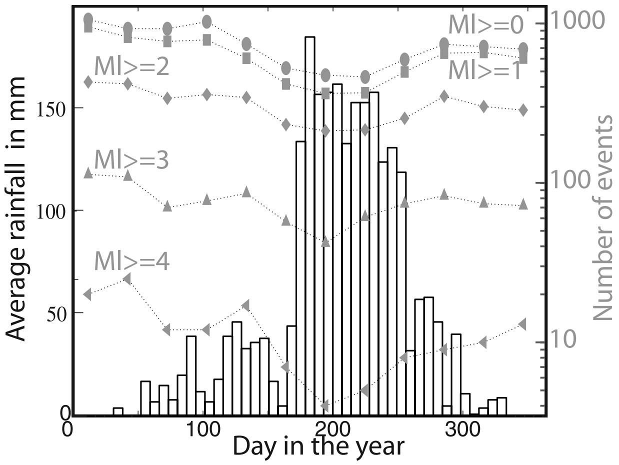

Figure 4. Eight day averages for rainfall for 1998 (vertical bars, rainfall data from http://hydro.iis.u-tokyo.ac.jp/GAME-T/GAIN-T/routine/nepal/) compared to monthly averages for numbers of earthquakes in different magnitude ranges (symbols) averaged over the period range 1995 to 2000. Maximum precipitation corresponds to minimum earthquake activity in all magnitude bands with no discernable lag or lead.

36 days depending on the local conditions. It appears therefore unlikely that thermoelastic stresses generated at the surface will interact constructively at large wavelengths, a necessary condition for them to be of any influence at seismogenic depths.

[12] The monsoon regime induces strong seasonal fluctuations of the hydrology. Well monitoring in alluvial deposits at the front of the High Himalayan range shows seasonal variations of up to 10 meters in the water table, equivalent to 10^5 Pa [*Dongol et al.*, 2005]. This, in turn, would generate an increase of the vertical stress, hence inhibiting shallow thrust events in the summer months. We doubt that this mechanism be the dominant factor given that the aquifers sampled by these wells are restricted to the major Himalayan valleys and are therefore rather localized, limiting their effects at seismogenic depth. However, aquifer loads in the Ganges basin, water level in the rivers as well as soil moisture and induced plant mass contribute to very large gravity variations monitored by GRACE experiment [e.g., *Tapley et al.*, 2004; *Ramillien et al.*, 2005], corresponding to seasonal water equivalent loads of several decimeters. The analysis of geodetic strain determined from continuous GPS time series has revealed seasonal strain variations consistent with the effect of annual variations of this surface loads (P. Bettinelli et al., Extreme sensitivity of Himalayan seismicity to small geodetic strain variations induced by seasonal variations of water storage in the Ganges basin, submitted to *Nature*, 2007, hereinafter referred to as Bettinelli et al., submitted manuscript, 2007). This mechanism therefore appears to be the most probable cause of the seasonal variations of seismicity reported in this study.

[13] Finally, we consider the possible contribution of seasonal changes in pore fluid pressure p_f and or the coefficient of friction μ in (1) [e.g., *Cocco and Rice*, 2002]. Changes in these physical properties might arise in the presence of fluids at midcrustal depths. There is indeed ample evidence for the presence of fluids at these depths in the Himalaya. First, meteoric fluid signatures are observed in geothermal springs [*Kotarba*, 1985]. Second, a midcrustal high conductivity has been inferred from magnetotelluric sounding [*Lemonnier et al.*, 1999]. A conductive zone with an inferred well-connected fluid phase coincides with the maximum in observed micro-seismicity. Third, abundant fluids are considered essential to generate the observed retrograde metamorphism in rocks believed to have once been at these seismogenic depths [e.g., *Sachan et al.*, 2001].

[14] Following an increase in surface hydraulic pressure, fluid diffusion downward will produce an increase in subsurface pore pressure resulting in an increase in Coulomb failure conditions. In addition to decreasing μ, subsurface pore-pressure changes will also enhance hydrofracture conditions in suitable oriented cracks. Both phenomena are able to enhance microseismicity, yet we note that if this effect is significant it is almost precisely anti-correlated with the phase of maximum precipitation. In the following, we analyse in more detail the anticipated phase delay attending fluid diffusion processes.

[15] Let us consider that meteorological forcing on the surface produces diffusion of pore pressure at depth. Our observations suggest that if this effect is important that pressures are modulated at seismogenic depths after a delay of 5 to 7 months (Figure 4). In a one-dimensional diffusion process, the phase delay φ at a depth x, expressed in fraction of the period T, is given by

$$2\pi\varphi = \frac{x}{\lambda} \tag{3}$$

where λ is the attenuation length related to the diffusivity α by

$$\lambda = \sqrt{\frac{\alpha T}{\pi}}. \tag{4}$$

From an estimate of φ for an assumed depth x, an estimate of α can be obtained from (4) and (3)

$$\alpha = \frac{x^2}{T}\frac{1}{\pi}(2\varphi)^2. \tag{5}$$

[16] In our case, x should be in the range of seismogenic depth in the Himalaya, *i.e.* 10 to 15 km. Taking φ varying from 0.4 to 0.6, we obtain a diffusivity range from $6.5.10^3$ to $3.3.10^4$ cm^2 s^{-1}.

[17] This range of values of diffusivity is plausible. For comparison, diffusivity estimated from reservoir induced seismicity is generally of the order of 10^4 cm^2 s^{-1} [*Talwani and Acree*, 1985]. Hydrologically induced seismicity yields comparable values [e.g., *Roeloffs*, 1988; *Saar and Manga*, 2003; *Gao et al.*, 2000]. The observed phase delay between the meteorological forcing and the seismicity is thus compatible with diffusion of pore pressure.

[18] Note that in this model the amplitude of the diffuse pore pressure would be larger at shallower depth. At the depth of the MHT, about 10–15 km, the effect should be dampening by a factor of 5 at least. We estimate amplitudes of pore pressure changes at this depth of 10 km to about 10 kPa, a value that is consistent with estimates elsewhere [*Saar and Manga*, 2003]. Because the area around the downdip end of the locked portion of the MHT is near critical failure [e.g., *Bollinger et al.*, 2004], such low amplitude variations may be sufficient to generate hydroseismicity.

[19] However, the half-year delay between rainfall at the surface and increased pore pressure at seismogenic depth would be a surprising coincidence. In addition, given the wide range of hypocenter depths (5 to 15 km), the phase delay between forcing at the surface and earthquake triggering should vary a lot. The locations of microearthquakes are insufficiently well resolved to test this possibility, and there have been insufficient larger events with better depth resolution to subject this to a rigorous test. However, no noticeable depth dependence with time has been observed in the data. Consequently, the diffusion of pore pressure, although possible, does not appear to us probable. We favor the direct mass loading induced by the summer monsoon as the dominant mechanism driving the seasonal variations of seismicity reported in this study.

5. Conclusion

[20] In this paper, we report evidence for seasonal modulation of midcrustal seismicity in Nepal, correlated with the meteorological forcing. We show that this effect is in

part due to a poorer detection level in summer probably due to enhanced seismic noise induced by bedload transport along the Himalayan rivers or landsliding. We suggest that an important corollary to our study is that the seismic noise level in the Himalaya has utility as a measure of mass-wasting and sediment transport in the mountains.

[21] Following the removal of aftershock clusters, a 5 years annual stack of seasonal microseismicity rates demonstrates conclusively that earthquakes along the shallow Main Himalayan Thrust are more numerous in winter than in summer, independent of magnitude range. We exclude winter snow loading, atmospheric pressure changes and erosion as possible causes of enhanced winter seismicity, but we find that an antiphase correlation between summer hydraulic loading and winter seismicity can be contrived by invoking suitable coefficients of fluid diffusion. We consider this improbable because fluid diffusion would have relatively modest effects at seismogenic depths, and variable phase delays to intermediate depths, resulting in time/depth dependent seismic triggering that we do not observe. Our favored explanation is that the observed suppression of Himalayan seismicity in the summer months is caused by reduced Coulomb failure conditions resulting from hydraulic loading in the Ganges plain and northern India during the summer monsoon, as argued by Bettinelli et al. (submitted manuscript, 2007).

[22] Whereas some of these plausible forcing mechanisms generate unique time structures, their respective contribution to the seasonality emphasized here cannot be resolved further, because of a loss of phase resolution introduced by stacking yearly averages to reduce the annual variance. It is possible that the availability of future continuous GPS displacement data, and future extreme monsoon events, may provide further insight into the cause of the observed annual variations in seismicity.

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J.-P. Avouac, Geology and Planetary Sciences Department, California Institute of Technology, Pasadena, CA 91125, USA.

L. Bollinger, Laboratoire de Détection et de Géophysique, CEA, BP12, Bruyères-le-Châtel F-91680, France. (laurent.bollinger@cea.fr)

U. Gautam, S. Sapkota, and D. R. Tiwari, Department of Mines and Geology, National Seismological Centre, Lainchaur, Kathmandu, Nepal.

F. Perrier, Laboratoire de Géomagnétisme, Institut de Physique du Globe, 4 place Jussieu, Paris F-75005, France.