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SOLID EARTH MODELLING PROGRAMME

We carried out extensive seismic hazard work in northwest Himalaya which resulted in database on ground acceleration to better aid in design of infrastructure in this tectonically active region. Specific to Srinagar city in Kashmir, high-resolution microtremor ambient noise survey at 429 locations was conducted to map the resonance frequency, the thickness of sedimentary cover, and to identify areas prone to seismic amplification which are important for seismic hazard and risk evaluation. Probabilistic seismic hazard map for Jammu and Kashmir region was computed for 10% probability of exceedance in 50 years (return period 475 years), using a logic tree approach with weights of 0.5, 0.3 and 0.2 for the zonation, grid and fault model, respectively. We developed a modified algorithm for robust estimation of Unified Scaling Law of Earthquake parameters referred to as Scaling Coefficients Estimation (SCE) for producing seismic hazard maps of territories prone to seismic effects. Modis water vapor is validated for Indian subcontinent using 64 GPS data from 2002 to 2017 at 64 continuous sites spatially spread over the region. Modis data is unable to capture the seasonal variability of water vapor and does not perform well over coastal areas, islands and varying topography regions. Using about two decades of continuous GPS data, Indian plate motion relative to Eurasia and Somalia plate was estimated with high resolution. Continuous GNSS data of Indian observation network is analysed to study the impact of Multi-GNSS signals over Indian subcontinent. We have three high impact SCI publications and several conference and invited presentations.

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5.1 Site Effects Investigation in Srinagar city of Kashmir Basin using Microtremor and its Inversion

The Srinagar region of Kashmir Valley in North West Himalayas, covers more than 2 million inhabitants and is exposed to high seismic risk. In order to gain insight on potential site effects and subsurface structure of the region, we carried out an extensive high-resolution microtremor ambient noise survey at 429 locations. The acquired dataset was processed using the Horizontal to Vertical Spectral Ratio (HVSR) technique to map the resonance frequency, the thickness of sedimentary cover, and to identify areas prone to seismic amplification. We provide a spatial classification of the obtained HVSR curves in four types: 1) Clear peak H/V curves relating the strong impedance contrast in the subsurface; 2) Multiple peaks (or Broad) H/V curves corresponding to sloping internal stratification of sediments; 3) Two peaks H/V curves related to two different impedance contrast existing in the subsurface; 4) Flat H/V curves around and over hard rock outcroppings. The HVSR curves show the peaks in the range of 0.22 Hz to 9.96 Hz indicating heterogeneous and complex sedimentary cover in the region (Figure 5.1). Inversion of the HVSR curves gives the shear waves velocity distribution, which highlights two distinct reflective surfaces in most of the areas. In addition, we also used the estimated fundamental frequency of various types of houses / buildings located in Srinagar city to assess the possibility of resonance in case of occurrence of any earthquake. This study adds a value to the region in earthquake engineering, seismic hazard and risk evaluation purpose for Srinagar and its suburbs.

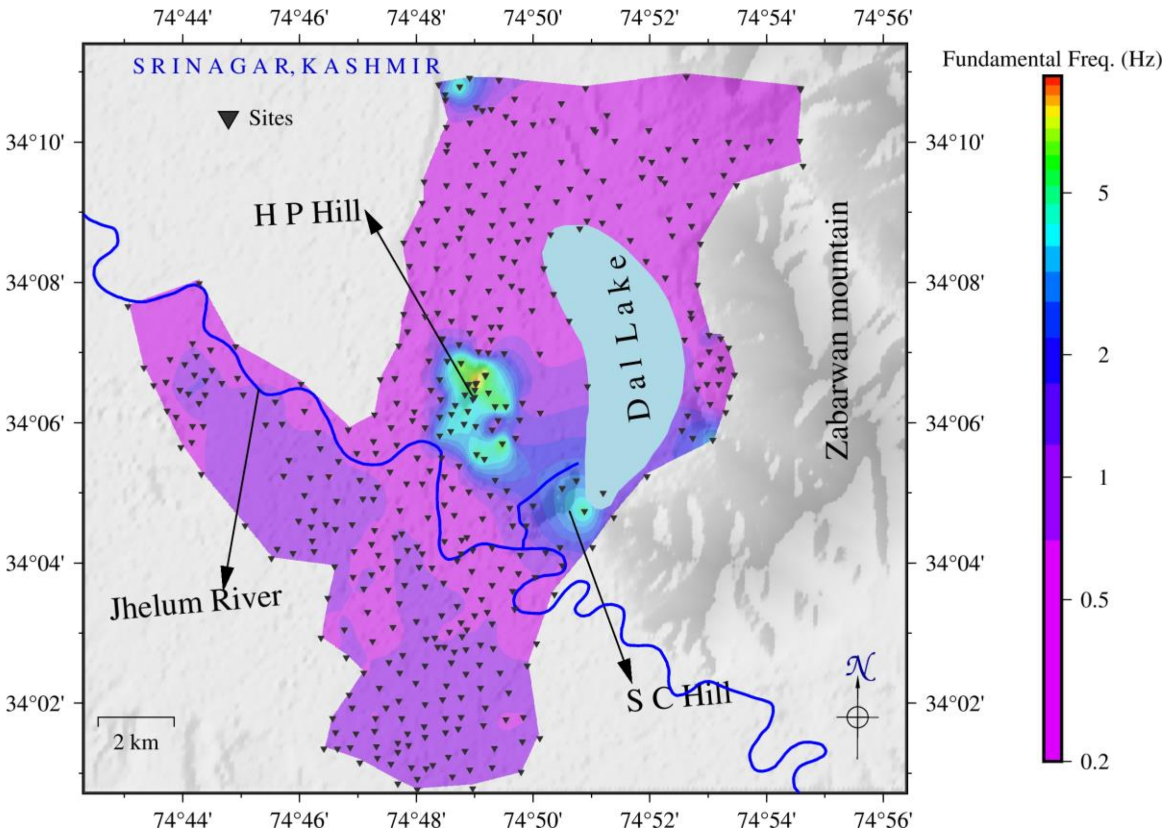

Figure 5.1 Predominant resonance frequency map for Srinagar region.

5.2 Ground motion modelling in NW Himalaya using stochastic finite-fault method

In the present study, stochastic finite-fault method based on dynamic corner frequency has been used to estimate peak ground motion at bedrock level for NW Himalayas with particular emphasis on Kashmir Himalaya. Earthquake catalogue is compiled for both pre-instrumental and instrumental era of magnitude $M_w \geq 5$ and used as seismic sources in simulating the synthetic seismograms at a regular grid of 0.2°×0.2°. Acceleration time series thus generated were further integrated to obtain velocity and displacement time series. Peak Ground values of Acceleration (PGA), Velocity (PGV) and Displacement (PGD) have been extracted from simulated time histories and mapped on a regular grid of 0.2°× 0.2° over the region. Expected PGA value for Kashmir Himalaya and Muzaffarabad is about 0.3-0.5g and for the epicentral region of 1905 Kangra event, PGA is 0.35g (Figure 5.2). The values computed here are in agreement with other studies in the region, whilst PGA expected in general is larger than official seismic zoning map of India produced by Bureau of Indian Standards. Acceleration converted intensities are compared with observed intensities and mapped to see the variations. Most of the regions have observed a higher intensity than the observed one, which might be due to use of large period catalogue (260AD- 2016) for simulation not covered by observed intensity catalogue. Major events in Kashmir Himalayas like 1555, 1885 and 2005 are simulated separately and corresponding PGA maps are plotted. Pseudo-Acceleration and Velocity response spectra (PAS, PVS) for three sites near 2005 Kashmir earthquake are compared with observed spectra that also validate our results, providing available site conditions. This study provides a first order ground motion database for better design of buildings and other infrastructure in the NW Himalayan region.

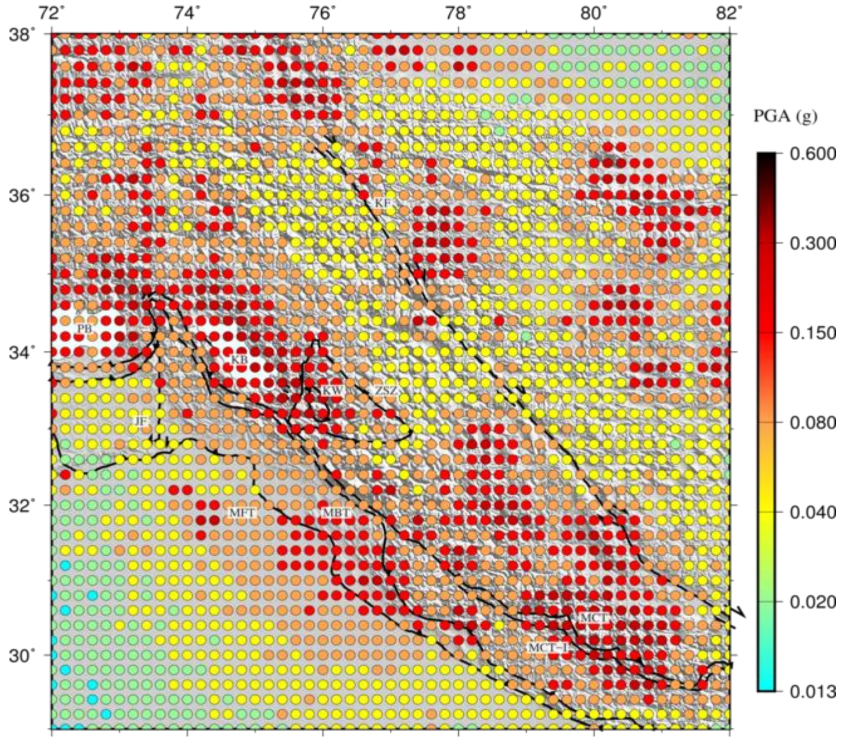

Figure 5.2 Peak Ground Acceleration map (in g) at all sites simulated using 544 earthquakes. Lines represent different fault systems in NW Himalaya. Two major basins denoted by KB and PB are Kashmir and Peshawar basins.

5.3 Unified Scaling Law for Earthquakes as Applied to Assessment of Seismic Hazard and Associate Risks

Seismic hazard assessment requires an adequate notion of the distribution of earthquakes having different magnitudes. The Gutenberg–Richter law for the recurrence of earthquakes is typically formulated as a relation linking the annual average number *N*(*M*) and magnitude *M* of earthquakes in a certain volume in space and time. The distribution of the number of seismic events by magnitudes, the Gutenberg–Richter frequency magnitude relation is of paramount importance for seismic hazard assessment of a territory. The generalization of the Gutenberg–Richter relation—the Unified Scaling Law for Earthquakes (USLE) proposed in 1988 makes it possible to take into account the pattern of epicentral distribution of seismic events when changing the spatial scale of the analysis. This is extremely important for adequate downscaling of the frequency of occurrence into a smaller area within the territory under study. It has been suggested a dual formulation of USLE where, instead of the number of earthquakes over a certain period of time, the reciprocal of their frequency of occurrence, the time between seismic events is used. In the same way, we developed a modified algorithm for robust estimation of USLE parameters referred to as Scaling Coefficients Estimation (SCE) for producing seismic hazard maps of territories prone to seismic effects. This brief review is focused on the use of the USLE approach to the assessment of seismic hazard and associated risk. These important considerations should be taken into account in the future practical assessments and mapping of seismic hazards and risks.

5.4 Probabilistic Seismic Hazard Analysis for Jammu & Kashmir, India

A probabilistic seismic hazard study is conducted for Jammu & Kashmir, India, which is situated in the NW Himalaya. This region has witnessed many big earthquakes in the past and the recent Muzaffarabad earthquake (2005, M_w 7.6), which resulted in loss of approx. 86000 lives in this region. This poses a great threat to the people lives in this region. The Kashmir valley alone accounts for 7 million population which lives under constant threat of such damaging earthquakes. Therefore, quantification of the earthquake hazard in this region is very important for future occurrence of such events in terms of possible ground shaking.

In order to estimate seismic hazard, we used three different recurrence models: a classical seismic-zonation model, a fault model and a smooth gridded seismicity model. We divided Jammu & Kashmir and the surrounding regions into about 7 large seismic source zones based on the seismotectonics, earthquake distribution and focal mechanism. For each zone, a Gutenberg-Richter (GR) magnitude-frequency distribution is used to model the seismic activity rates. The a- and b-values are calculated using instrumental data only for a period of 1960-2019 as this period exhibits homogeneous and compete data set for the analysis. A Kernel-based method is used to develop smooth gridded seismicity model for the region with 0.25^o x 0.25^o. Appropriate Ground Motion Prediction Equations (GMPE) were identified based on GEM recommendation and earlier works for the active crust and the Gangetic Plain. Results from different models were combined using logic tree with appropriate weighting scheme. The CRISIS2015 software is used to calculate seismic hazard at various ground motion periods and various return periods. The peak ground acceleration (PGA) for 10% of exceedance in 50 year observed in the Kashmir valley, densely populated region with approximately 7 million people, between 0.3 to 0.4 g (Figure 5.3). The maximum PGA observed is 0.69 g in the NW part of the study region near Hindu Kush range. The Muzaffarabad region also indicated PGA values around 0.41 g, which explains the tragic experience of the 2005 earthquake (M_W 7.6).

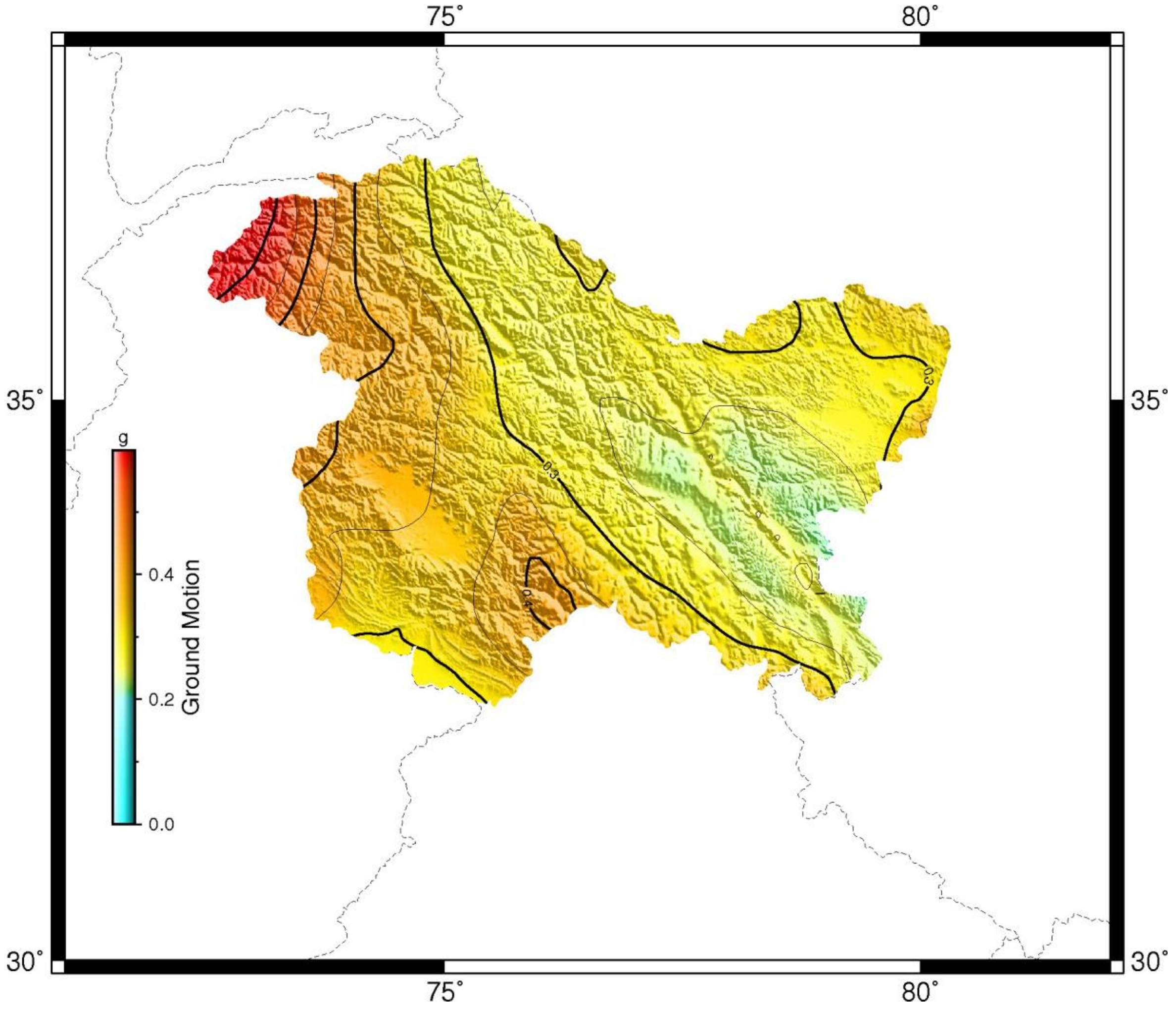

Figure 5.3 Hazard maps computed for 10% probability of exceedance in 50 years (return period 475 years), using a logic tree approach with weights of 0.5, 0.3 and 0.2 for the zonation, grid and fault model, respectively; displayed for Peak Ground Acceleration (PGA).

5.5 Multi-GNSS studies in Indian subcontinent

Satellite navigation is undergoing substantial changes with the development of multiple GNSS (Global Navigation Satellite System) constellations. At present, GPS and Glonass systems are fully functional and can be used for geodetic studies. For the first time in Indian subcontinent, daily precise positions are estimated for continuous mode GNSS stations using standalone GPS, Glonass and combined GPS-Glonass data. Results are being analysed to the study impact of multi-GNSS signals on precise position and velocity estimates with millimeter accuracy. Also correlation studies of multi-GNSS raw data are carried out to find the effect of multipath, SNR (Signal to Noise Ratio) on the position estimates. Figure 5.4 shows the multipath effect on L_1 signal (MP1) and L_2 signal (MP2) from 2015 to 2019. Results show that Baramulla station with clear view has very low MP1, MP2 values compared to Gulmarg because of tree canopies near the station.

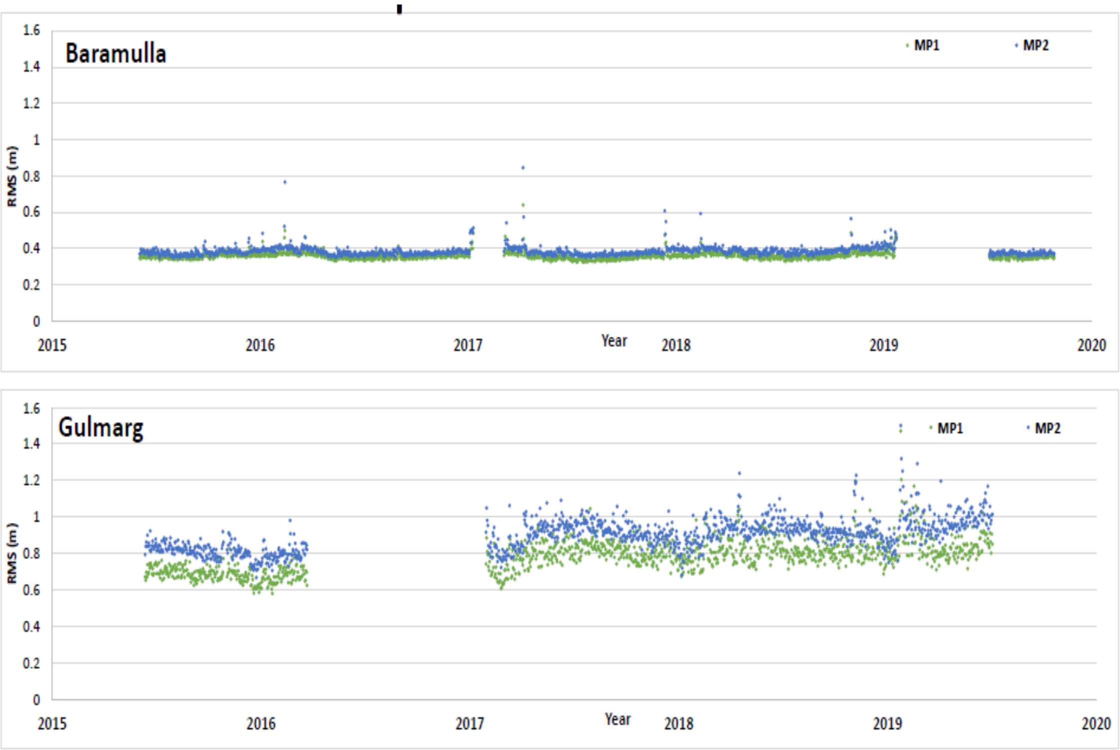

Figure 5.4 Multipath effect on GNSS signals in Baramulla and Gulmarg stations

5.6 Present day high-resolution GPS estimates of India-Eurasia and India-Somalia plate motions

High resolution velocities of continuous global positioning system sites (cGPS) and rotation sequences from the India–Somalia Antarctic–Nubia–North America–Eurasia Plate circuit are used to reconstruct the Indian plate motion relative to Eurasia and Somalia (Figure 5.5). Our new rotations indicate that India–Somalia plate motion slowed down by 25–30 per cent from 19.7 to 12.5–11.1 Ma, but remained steady since at least 9.8 Ma and possibly 12.5 Ma. Our new India–Eurasia rotations predict a relatively simple plate motion history, consisting of NNE-directed interplate convergence since 19 Ma, a ≈50 per cent convergence rate decrease from 19.7 to 12.5–11.1 Ma, and steady or nearly steady plate motion since 12.5–11.1 Ma. Instantaneous convergence rates estimated with our new India–Eurasia GPS angular velocity are 16 per cent slower than our reconstructed plate kinematic convergence rates for times since 2.6 Ma, implying either a rapid, recent slowdown in the convergence rate or larger than expected errors in our geodetic and/or plate kinematic estimates.

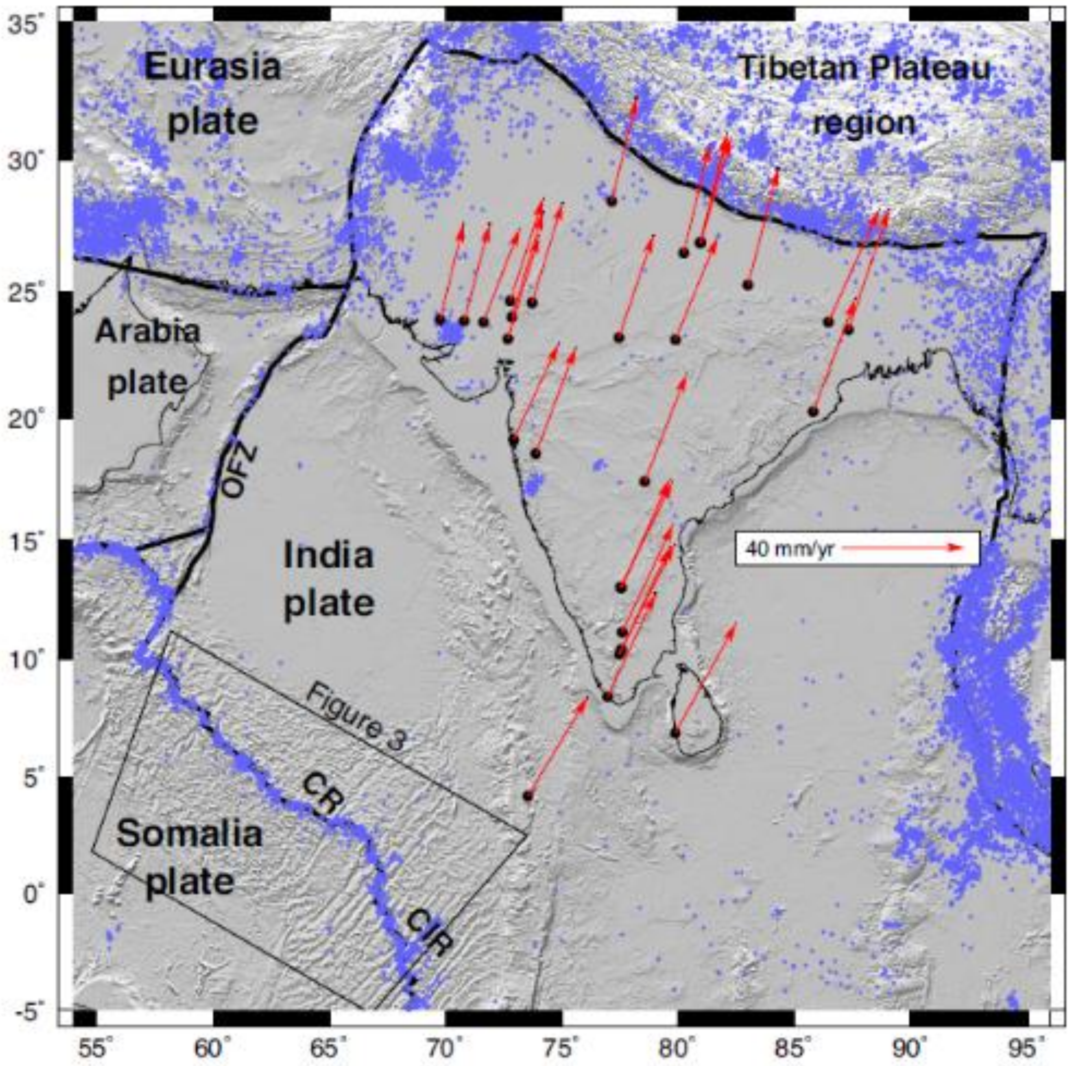

Figure 5.5 Indian Plate GPS velocities (red arrows) relative to Eurasia along with seismic events (blue dots) from 1964 to 2016.

5.7 GPS and MODIS water vapor in Indian subcontinent

MODIS (Moderate Resolution Imaging Spectro-radio-meter) Terra level 3 water vapor data is validated using 64 cGPS (continuous Global Positioning System) stations spatially spread over the Indian subcontinent between geodetic latitude 5° to 35° N and geodetic longitude of 70° to 96°E. MODIS water vapor has high bias and RMSE (Root Mean Square Error) for coastal regions, islands and varying topography region such as the Himalayas. Further, MODIS data is unable to capture the seasonal variation in water vapor during monsoon months. Empirical relations for spatial and seasonal variability of GPS water vapor (Figure 5.6) for the Indian subcontinent are proposed.

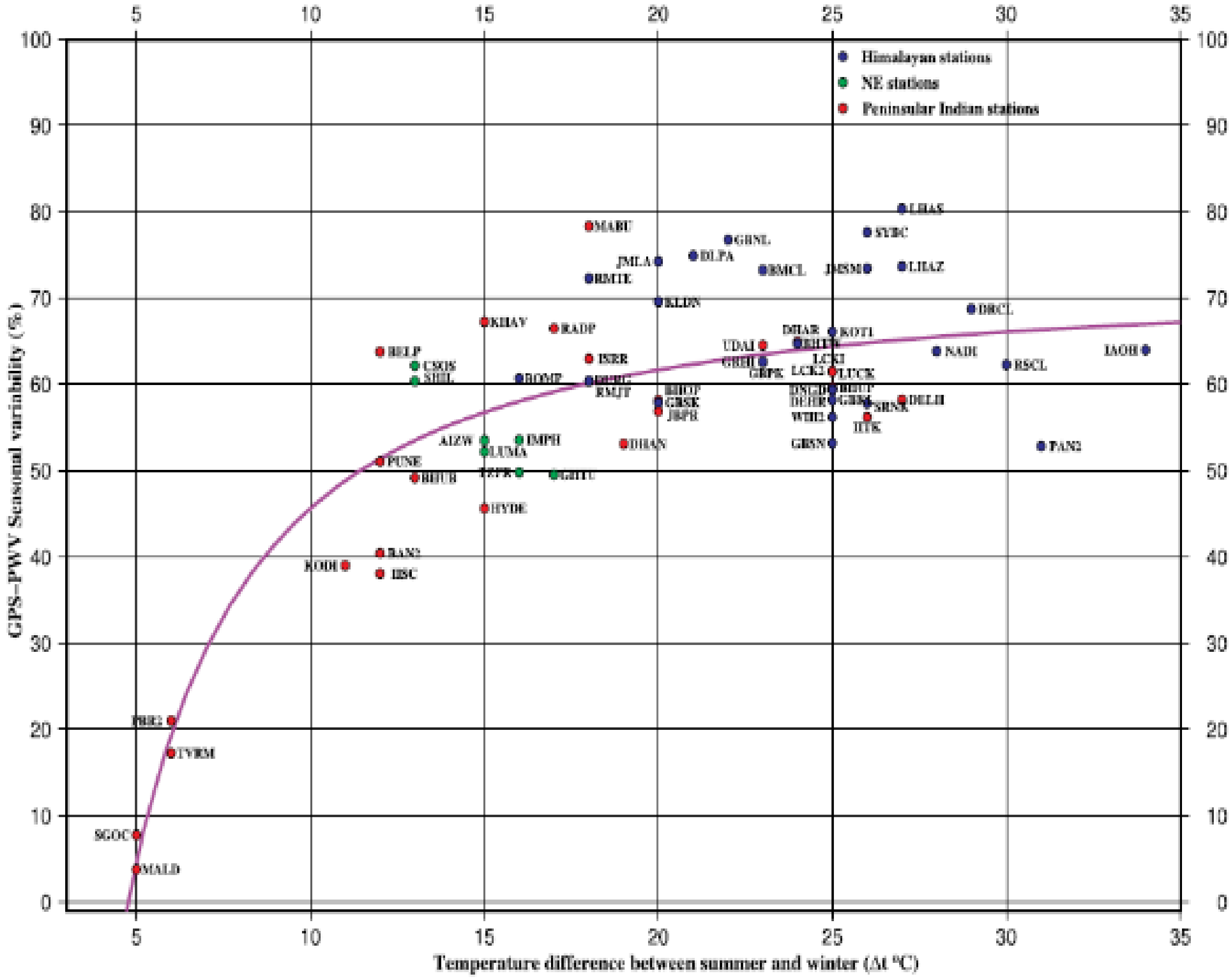

Figure 5.6 Empirical relation for seasonal variability of water vapor (2002-2017)