Chapter 7
Discussion and conclusion

“We should not be defeated by problems. We should defeat them”
— A.P.J. Abdul Kalam

This thesis gives the results of investigations of three main problems in the physics of the earthquakes which have mainly been less attended for the Kutch region so far. There are three main themes addressed in this thesis and discussion part is already presented at the end of respective chapters and here discussion part is summarized in brief to lead to major conclusions of the present study.

The first theme is what happens under the earth when earthquake occurs i.e. the characterization of source parameters for aftershock sequence of Jan 26, 2001 Bhuj earthquake. However, there is a large ambiguity in calculating independent source parameters, the purpose of this study is to estimate source parameters most accurately, which possibly can increase the precision of overall characterization of source parameters and empirical relations developed therein. In Chapter 4, source parameters of moderate earthquakes from the next hour of the occurrence of Jan 26, 2001 Bhuj earthquake to end of 2012 are characterized. The values for source parameters like seismic moment, rupture parameters and radiated seismic energy are found close approximation to the global values of other intraplate earthquakes. The stress drop values are scattered and considerably higher. Stress drop estimation and its relation with other source parameters have been shown to be highly complex and difficult to incorporate. Even so fault wise distribution of stress drop over Kutch region presented here is very useful to readers to have an idea about stress release mechanism over the region. For the Kutch region, first time empirical relations between source parameters are presented in this thesis. These empirical relations help to estimate various source parameters for future potential earthquake and hazard associated with it. First time, second order source parameters like apparent stress, radiated seismic energy, scaled energy and Zuniga parameter are derived and discussed for Kutch region in this thesis, which are earlier not determined for not only Kutch region but for
other part of Indian region as well. The source parameters help to understand dynamic processes of earthquake and physics lying behind earthquake.

The second theme of the thesis is the study of interrelation between an earthquake event and meteorological parameters. Amongst the great debate and criticism, it is now renowned that occurrence of earthquake event has put forward its sign on weather and climate change. Many scientists have tried to prove such a claim using remote sensing data, derived data and other indirect methods for different parts of the world. A comprehensive review of the available literature concerning the earthquake and weather interrelation shows that there is a requirement for more detailed study in this regard. In this thesis, first time in the world, interrelation between these two parameters are studied using a large dataset actually recorded by manually operated ground-based meteorological observatories. The attempt is made here to come to the concrete conclusion by supportive results followed by rigorous and extensive analysis. At the conclusion it can be claimed that meteorological parameters like maximum air temperature and atmospheric pressure clearly exhibit anomalous behavior during the occurrence of an earthquake and increase in rainfall activity leads changing pattern of rainfall and climate in turn over the study region. Results lead to the following main conclusions-

The temperature changes during an occurrence of an earthquake are awfully noticeable. As a representative element of weather, maximum air temperature is considered in this study. Maximum air temperature rises over the respective observatory in absence of special weather phenomenon like heat wave, hot day, dust storm etc. during winter even and during the occurrence of earthquake event. The maximum temperature falls over the respective observatory in absence of special weather phenomenon like cold wave, cold day, dense cloudiness, rainfall, thunderstorm, fog, haze etc. during summer even and during the occurrence of earthquake event. The maximum temperature rises or remains steady over the respective observatory in presence of special weather phenomena like cold wave, cold day, rainfall, fog, haze, thunderstorm etc., instead it should fall during these weather phenomena and the maximum temperature falls or remains steady over the respective observatory in presence of special weather phenomena like heat wave, hot day, dust storm etc., instead it should rise during these weather phenomena. Highest departure
in maximum temperatures within 24-hours or 48-hours from the occurrence of the earthquake event has been observed within ±3-days of the occurrence of the earthquake event. On seasonal scale, maximum +ve anomaly is observed during post-monsoon season for all three observatories, i.e. at the onset of winter season while general pattern of temperature during this season is to fall. Similarly, normal pattern of summer is to rise in temperature while maximum -ve anomaly is observed during summer season.

**Another meteorological parameter under study is atmospheric pressure.** As atmospheric pressure changes are very peculiar in its type, present study is restricted to preliminary level, i.e. to check the hypothesis whether atmospheric pressure changes during the occurrence of an earthquake. In this study, noticeable changes of light to moderate level in atmospheric pressure are found during an occurrence of earthquake events. The degree of the changes in the normalized pressure are likely to be associated with the prevailing meteorological parameters in the earthquake regions, location of earthquakes, proximity of the epicenter and also season in which the earthquake occurred. There may to be governed by numerous parameters prevailing in the earthquake epicenters and surrounding regions. Processes of stress accumulation, release of stress prior to the earthquake and energy exchange between earth’s crust and atmosphere after an earthquake in the epicentral region is likely to be responsible for the atmospheric pressure changes during seismic activity. The exchange of water vapor in the atmosphere during occurrence of an earthquake is also one important factor responsible for atmospheric pressure changes. The nature of such changes and the hidden physical processes is yet to be explored. Even though pressure changes with respect to earthquake event found during the preliminary study are quite visible, it is very difficult to establish one-to-one relation between these two parameters. The theory presented here attempts to explain the pressure changes as a natural consequence of the seismic activity in absence of other controlling parameters on atmospheric pressure. At the conclusion, it is suggested that we should develop a method that will help to establish direct relation between these two parameters. It can be achieved by designing a specific chamber where very sensitive microbarometers and microseismometers both together installed in all four directions in a seismogenic region where other meteorological and geological parameters are silent and only these two
parameters can be observed for their mutual effect. By this, we will be able to remove the noise signal in both the parameters or to fix a minimum average noise level and obtain clear signals and later, we can apply this method to moderate and large earthquakes. It is an invitation for further investigation to meet up earthquake challenges.

**As far as to concern about the study of rainfall activity over the region**, a significant change in rainfall parameters after the 2001 Bhuj earthquake ($M_w$ 7.7) in the Kutch region is observed. This study indicates that all the rainfall parameters like annual total rainfall, number of rainy days and heavy rainfall days have significantly increased, which implies that rainfall activity is increased and rainfall pattern over Kutch region is being changed. It can be concluded from the preliminary study that there is an impact of seismic energy release vice-a-verse change on temperature and in turn on the weather dynamics which all together results in change in rainfall pattern.

**The third theme of the thesis deals with seismic hazard analysis.** As it is well known that to assess seismic hazard in any region, earthquake catalogues and data bases is the first essential input to define source zones and to describe them. During reviewing existing literature, a homogeneous and complete catalogue was not found for Kutch and Gujarat as a whole region. Therefore, firstly, this important task of preparing a homogenous and complete catalogue for the study region is achieved. The data from historical time to present time is categorized in to three time scale i.e., historical time to 1900; pre-instrumental age data to the early instrumental age data i.e. 1900-1963 and since 1964 to the present time-modern instrumental age data. After compilation of a reliable, homogenous and complete catalogue for the Gujarat region, seismic hazard assessment is carried out on the basis of both the approaches as an individual study, i.e. Deterministic seismic hazard analysis (DSHA) and Probabilistic seismic hazard analysis (PSHA). The DSHA is based on near density and point density functions of cluster analysis theory. Results leads to conclude that Gujarat region exhibits some specio-temporal earthquake clusters and out of total five such clusters three clusters are significant. Using the empirical relations presented by Wells and Coppersmith, potential earthquake in each cluster is estimated. The Kutch cluster has potential to generate large earthquakes of $M_w$ ~ 8.0 while two another clusters
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namely Junagarh and Surendranagar in the Saurashtra region may generate earthquakes of $M_w \sim 5.6$ and $M_w \sim 4.4$ respectively and later properties of Kutch cluster in terms of three basic laws are presented and 2001 Bhuj aftershock sequence practically follows the three basic laws i.e. Gutenberg-Richter relationship, Omori’s decay law and finally Bath’s law of maximum aftershock.

Similarly, PSHA is based on Bayesian extreme value model. On the basis of information on seismic source, geological and tectonics trends and possible similar focal mechanisms, three seismogenic zones are defined in the Gujarat region. Thenafter, using the basic seismicity parameters, historical and updated estimates of seismicity have been obtained for all three zones. On the basis of results of PSHA, the Gujarat region as a whole divided in three zones namely, Kutch zone, Saurashtra zone and Gujarat mainland zone. The different seismicity parameters like slip rate, seismic moments of the events and conventional G-R parameter are calculated. Incorporating different computational exercises with Baye’s theorem, seismic hazard assessment is achieved in terms of probability for 2, 5 and 10 years of short time recurrence period and 20, 50 and 100 years of long-time recurrence period and for 0.1, 0.25 and 1.0 coefficient of variance. In the present study, the probability of the occurrence of the maximum magnitude is estimated that is expected in a time interval $t$, on the basis of a complete earthquake catalog for historical time to the present. The major concerns that have emerged from this study are that the seismic hazard level from Kutch to Saurashtra and Gujarat mainland varies spatially. The Kutch region exhibits higher probability of occurrence of moderate to strong magnitude and Saurashtra and Gujarat mainland shows higher probability for moderate magnitude earthquake. The variation in probability for Saurashtra zone and Gujarat mainland zone is higher compared to Kutch zone but probability of occurrence of earthquake is less in both these zones compared to Kutch zone for the same coefficient of variances. These results have potentially useful implications in the probabilistic seismic hazard assessment (PSHA) for the entire Gujarat state. The zone wise comparative seismic hazard categorization could be useful for design purpose to identify the priority regions for earthquake resistant designs. The results of both the approaches of DSHA and PSHA are complementary to each other. The seismic potentiality presented in this thesis can be
interpreted for both short-term as well as for long-term seismic hazard, especially, for region like Kutch which witnessed several moderate to large earthquakes in past and recent past and aftershock activity is still going on in the region after the Jan 26, 2001 Bhuj ($M_w$ 7.7) earthquake. Consequently, this region is more vulnerable for moderate to large earthquakes in near future.