Co-production of climate change vulnerability assessment: A case study of the Indian Lesser Himalayan region, Darjeeling

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ABSTRACT
The intensity and extent of climate change impacts differ significantly with the geographical and ecological structure of the landscape. This is especially evident in mountain ecosystems where topographic, climatic and biological gradients make them extremely vulnerable to global environmental changes. Designing strategies to mitigate and adapt to global climate change on such local landscapes requires a context-specific vulnerabilities that take into account their particular characteristics. Presently, there are two main challenges in assessing climate change vulnerability in mountain ecosystems: 1) The models that are used for vulnerability assessments at global scales are being used at local scales with broad variables from few sectors that do not capture the range of characteristics of mountain ecosystems 2) indigenous knowledge about climate change are not considered in these models, which makes the implementation of mitigation/adaptation measures less successful. In this study, we highlight these issues drawing from our data collected in India’s Lesser Himalayan region (Darjeeling). We used a mixed research approach that combines a vulnerability assessment model with a participatory knowledge approach. We based climate change vulnerability around the socio-ecological system of the mountain landscape. The results from the interactive process showed that Darjeeling region is experiencing higher climate change vulnerability than the results produced by the model at the subregional level. We highlight critical variables that influence the socio-ecological system and need to be taken into account when assessing vulnerability and future adaptation scenarios. The study offers a decision support process for policymakers to plan climate mitigation/adaptation measures and future sustainability pathways.

1. Introduction
Mountains cover 24% of the world’s total land area, and about 26% of the world’s total population lives on or in the foothills of mountains (Beniston 2003). About 40% of the entire world population is directly or indirectly dependent on the diverse
ecosystem services provided by mountains (Meybeck et al. 2001). Clearly, mountain regions are among the most susceptible socio-ecological systems to the impacts of climate change (Schild and Sharma 2011). Mountain ecosystems have special characteristics (i.e. steep slopes, confined areas and considerable local relief) that make it easier to detect changes and assess climate change problems. Because of their special nature, they have become a living laboratory for many research organizations (e.g. Mountain Research Initiative, Global Mountain Biodiversity Assessment, The International Centre for Integrated Mountain Development and United Nations Framework Convention on Climate Change, etc.) studying the impacts of climate change (Beniston 2003; Kullman 2004; Schild and Sharma 2011).

Significant events of climate change in mountain regions of the world are visible through recent glacier retreat, mountain warming, extreme precipitation events and increased natural hazards, often leading to loss of life and extinction of biodiversity (Du et al. 2004; Jianchu et al. 2009; Gentle and Maraseni 2012). Mountains are rich in biodiversity, which can be divided into relatively clearly defined altitudinal zones (ecotones). Within these zones, the direct effects of climate change are evident in the form of early plant flowering, extinction and displacement of plant species, and migration of animals from lower to higher elevations (Myers et al. 2000; Byg and Salick 2009; Wester et al. 2019). As temperature increases within ecotones, species may shift to higher zones, with far-reaching effects on the ecological system (Beniston 2003; Grewer et al. 2018). Changes such as these consequently affect the various ecosystem services that mountains provide to people in these regions and the adjacent lowlands (Macchi et al. 2011; Vivirolì et al. 2020).

One of these regions is the Hindu Kush Himalayan Mountains. With the largest concentration of glaciers outside the polar regions and supplying nine major rivers in Asia, the Hindu Kush-Himalayan Mountains are one of the most critical ecoregions in the world (Kumar 2015; Vivirolì et al. 2020). The eastern region of the Hindu Kush Himalayas is particularly affected by rapidly changing climate variables. It is one of the most diverse temperate regions in the world with distinct ecoregions, biodiversity hotspots and grasslands. It is also home to about 200 different socio-economic and ethnic communities (Salick and Ross 2009; Salick et al. 2014). People in this region are largely dependent on indigenous agricultural practises and surrounding natural resources for their livelihoods. Weather changes associated with climate change have put a strain on the agriculture-based economy. Due to the unique ecological sensitivity of the region, climate change risk cannot be addressed with global or country-specific policy initiatives, but requires context-specific assessment and action.

The detection of changes in ecotones has gained acceptance in ecological research, but limited attention has been paid to impacts on socio-ecological systems, particularly in developing countries (Velma I. Grover et al. 2014; Vivirolì et al. 2020). In 1992, the United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro, Brazil, addressed the problems associated with climate change in the mountains (Debarbieux and Price 2012; Nations 1994). This was later followed by the General Assembly UN in 2002 at the Global Mountain Summit and
the World Summit on Sustainable Development (Schild and Sharma 2011). While there is growing awareness and evidence of the impacts of climate change in the mountains, there is still insufficient research and work on mitigation policies and practical measures. International and national development agendas such as poverty alleviation, urbanization and economic development inadvertently ignore the importance of protecting mountain ecosystems, particularly in developing countries such as India, Pakistan, Nepal and Bhutan (Aryal et al. 2014; Barua et al. 2014; Kumar 2015).

Assessing climate change impacts in the Lesser Himalayan regions of India is challenging due to limited historical data on required climate indicators and weak climate risk assessment practises at the local level. The one-size-fits-all approach of current climate models oversimplifies the climate problem and its magnitude in these regions (Schild and Sharma 2011). Researchers from various international and national organizations are collectively focusing on improving the methodology for assessing climate risks of mountain regions, but most of them base their studies on the mountain regions of developed countries such as France, Italy, Germany, Austria, Slovenia, Switzerland, Norway and Finland (Harris et al. 2009; Engler et al. 2011; Beniston et al. 2018). The lack of vital data, complex data management and unstructured policy practises in the mountainous regions of India require immediate attention to include these regions in the study of climate change vulnerability and identify possible strategies. Technological advances such as the availability of high-resolution remote sensing data along with government-collected data have enabled a better understanding of climate and ecological processes in mountainous regions, but they are limited to broader areas and sectors (Shrestha et al. 2012; Upgupta et al. 2015). Knowledge about the impacts of climate change on the socio-ecological system remains unclear, making climate change vulnerability assessment and mapping a complicated endeavour and not reflected in current climate change policies and actions at the local level.

The aim of this study is to assess the vulnerability of the Eastern Hindu Kush Himalayan Mountains to climate change based on a previously developed scientific framework and to compare the results with local communities’ perceptions and knowledge of climate variability and its impacts. We also discuss how scientifically measured impacts and local perceptions of climate change can be used to co-produce climate change risks information and improve future adaptation actions at the federal and local levels, and help them better prepare for emerging global risks.

This paper is divided into five sections. The Introduction section provides background knowledge on climate change and its impacts on the Lesser Himalayan regions of India and sets out the research objective. The Data and Method sections highlight the case study area and illustrate the methodological approach used to study climate change vulnerability. The Results section provides the results of the models and explains the findings. Finally, the discussion section discusses how scientific and local perceptions can be combined to inform and improve adaptation programmes and measures.
2. Data and method

1.1 Study area

This study is set in the Darjeeling region of the Indian State of West Bengal, with particular emphasis on seven different sites representing a mix of urban and rural areas at different altitudes (Table 1, Figure 1 and Appendix-I). Geographically, the Darjeeling region of West Bengal lies between latitudes 26° 31’ and 27° 13’ North and longitudes 87° 59’ and 88° 53’ East and has a total area of about 3149 km². The area is divided into two districts, Darjeeling and Kalimpong, and consists of 12 blocks. The area is bounded by Nepal to the west, Sikkim to the north, Bhutan to the northeast, Kishanganj district of Indian State of Bihar to the south and Jalpaiguri district in West Bengal to the southeast. The altitude of the Darjeeling region varies from 800 m to 3660 m above sea level with numerous high ridges and low-lying valleys (Chaudhary et al. 2011). Annual rainfall varies between 2000 and 2500 mm in the plains and 4000–6000 mm in the mountainous regions. The seasonal distribution of rainfall in the region varies considerably. Recently, the amount and distribution of rainfall has been erratic, which plays a crucial role in the instability of the slopes. In the Darjeeling hills, the number of days of heavy rainfall within a short period has increased, leading to an increased number of landslides at various locations (Ghosh et al. 2012). According to the 2011 census, the Darjeeling region has a population density of 585 inhabitants per km², with 60% of the total population living in urban areas. The population growth rate in the last decade (2001 to 2011) was 14.47%. Seven locations in the region were selected to conduct the primary survey of residents and semi-structured interviews, which were conducted in 2014 to 2015.

2.2 Method

2.2.1 Vulnerability assessment framework

For this study, we adopted the definition of climate change vulnerability from the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (2007), which defines climate change vulnerability as “the degree to which a system is susceptible to and unable to cope with the adverse effects of climate change, including climate

| Region | Sub-Division | Block | Total Population |
|--------|--------------|-------|------------------|
| Darjeeling | Sadar Sub Division | Darjeeling Pulbazar | 126,935 |
| Darjeeling | Sadar Sub Division | Rangli Rangliot | 70,125 |
| Darjeeling | Sadar Sub Division | Jorebunglow Sukiapokhri | 113,516 |
| Darjeeling | Mirik | Mirik | 46,374 |
| Darjeeling | Kurseong | Kurseong | 94,347 |
| Darjeeling | Siliguri | Matigara | 197,278 |
| Darjeeling | Siliguri | Naxalbari | 165,523 |
| Darjeeling | Siliguri | Phansidewa | 204,522 |
| Darjeeling | Siliguri | Kharibari | 109,251 |
| Kalimpong | Kalimpong - I | Kalimpong - I | 74746 |
| Kalimpong | Kalimpong – II | Kalimpong – II | 66830 |
| Kalimpong | Gorubathan | Gorubathan | 60,663 |

Table 1. Overview of Darjeeling region and Blocks.
Figure 1. Map of the study area with reference to the State of West Bengal and India. The Darjeeling region consists of two districts, Darjeeling and Kalimpong. Seven sites were selected for primary data collection and for understanding the people’s perception about climate change vulnerability. More details for selected sites are shared in table 1.
variability and extremes”. In this paper, vulnerability to climate change is the result of socio-ecological interactions with climate variables and is represented by three components of vulnerability: Exposure, Sensitivity and Adaptive Capacity (Füssel and Klein 2006; Kumar et al. 2016). Exposure describes the “extent to which a socio-ecological system is exposed to climatic events” (Füssel and Klein 2006). Sensitivity is the “extent to which a socio-ecological system is adversely or beneficially affected by climate stimuli” (Füssel and Klein 2006). Finally, adaptive capacity is “a set of local resources and conditions that constrain or support the ability of the socio-ecological system to successfully adapt to climate change” (Adger 2006).

Determining vulnerability to climate change requires a detailed understanding of a socio-ecological system (Berrouet et al. 2018). In this study, the concepts of socio-ecological system developed in the field of sustainability and resilience were used (Anderies et al. 2004; Filatova et al. 2013; Schlüter et al. 2013; Dullinger et al. 2020). According to Anderies et al. (2004), “the socio-ecological system is an ecological space that is closely linked to and influenced by the social system and external influencing factors”. To assess the vulnerability of a socio-ecological system to climate change, one needs to measure the rate of change of the socio-ecological system when it is exposed to a potential external or internal stress. To truly represent a socio-ecological system, one should identify the social and ecological aspects of the study area and their interaction with climate change variables.

The selection of the climate vulnerability assessment framework was crucial for this study. Currently, there are numerous vulnerability assessment frameworks, methodologies and studies in the literature, depending on the spatial context, methodology and sectoral application (Turner et al. 2003; Adger 2006; Eakin and Luers 2006; Crona et al. 2009; Hinkel 2011; Kumar et al. 2016; Sapkota et al. 2016; Ciftcioglu 2017). However, most of these vulnerability assessment studies are conducted at a coarse spatial scale (global, national and regional) and most of their applications are in the Global North (Kumar et al. 2016). There is an urgent need to highlight the vulnerability of developing countries to climate change, particularly non-coastal regions where the variance and magnitude of climate change problems are extreme and poorly understood(Mertz et al. 2009; Nath and Behera 2011; Rosenzweig et al. 2018). Previously published vulnerability assessments vary in their application, but they also do not take into account the complexity of a socio-ecological system and the representation of local communities and integration of their knowledge has been limited (Adger et al. 2013; Hiwasaki et al. 2015). Considering these drawbacks, this study uses the vulnerability assessment framework developed by Kumar et al. (2016). His vulnerability assessment framework is based on three main components of climate vulnerability: exposure, sensitivity and adaptive capacity. Within these components, the key environmental (local environment, ecosystems and available natural resources) and socio-economic (physical infrastructure, wealth, racial and cultural demographics, and institutional and governance arrangements) aspects of the local socio-ecological system and climate variables were integrated and tested in one of India’s metropolitan cities.

Adopting the vulnerability assessment framework of Kumar et al. (2016) for this study requires the development of a set of criteria for each component that reflects the socio-ecological system and potential interactions with climate variables.
Therefore, we adopted a mixed-method research approach to identify criteria that represent the social and environmental dimensions of the selected study area and incorporate them into the climate change vulnerability assessment framework to assess the patterns and magnitude of climate change vulnerability. We used a mixed-method research approach to select and define the criteria for each component of the vulnerability assessment (Figure 2).

First, a desktop literature review was conducted to identify potential criteria for each component of the vulnerability assessment framework (i.e. about 56 criteria in total: 8 criteria for exposure, 22 criteria for sensitivity and 24 criteria for adaptive capacity). Second, interviews and group discussions were conducted with experts and local
communities to complete the criteria relevant to the study area from the desktop literature review (Table 2). Finally, primary and secondary data were collected that contained appropriate information for the final criteria and to assess the thresholds for the selected criteria.

2.3 Data and analysis

2.3.1 Data collection

As explained in the previous section, a mixed-method research approach was used to establish the criteria for vulnerability assessment and a similar approach was used to collect the necessary data for the selected study area and sites studied.

The first phase of data collection involved reviewing policy documents, reports, policy briefings and development policies on climate change, environmental change, disaster management and development issues at national, regional and local levels. The second phase of data collection consisted of reviewing local development policies and collecting data from government and non-government departments for selected criteria, as underlined in Table 2 (Appendix- II). The final phase of data collection was divided into two steps. In the first step, open-ended semi-structured interviews and semi-structured group discussions were conducted with residents and various experts from government and non-government departments to verify the selected criteria. In the second step, in-depth interviews were conducted with the local people and communities of the seven selected sites from Darjeeling region to understand what local people know about environmental change and adaptation and how they perceive it. The in-depth interviews included questions on the three main components of the vulnerability assessment framework: Exposure, Sensitivity and Adaptive Capacity.

Only people older than 20 years, male or female, participated in the study. A total of 170 interviews were conducted in Hindi, Nepali and English. People provided information about their daily experiences, personal behaviour and knowledge passed down from generation to generation about past climate variables and their impact on their physical, social and economic well-being.

2.3.2 Data analysis

The pattern of vulnerability to climate change was analysed in two steps. First, we analysed the vulnerability pattern at the block level (the smallest administrative unit at the regional or national level in India), and the results were presented only at the block level. We used a Spatial Multi-Criteria tool to simulate climate change vulnerability and model the socio-ecological system within the ILWIS SMCE tool box(Uribe et al. 2014; Kumar 2015; Kumar et al. 2016). The working methodology proposed by Kumar et al. (2016) was used to build a tree of decision criteria, standardize the criteria on 0–1 scale range and finally conduct a climate change vulnerability assessment.

The pattern of vulnerability to climate change was classified into four classes: high, medium, below average and low, based on a scale of 0–1. The range of <.25 was classified as low, the range of 0.25–0.50 as below average, 0.50–0.75 as medium and vulnerability
above 0.75–1 as high. These scale ranges were based on the results of literature reviews and expert interviews. Secondly, we applied the same approach to the data collected and conducted semi-structured interviews and group discussions to analyse people’s perceptions of environmental change and adaptation and to measure vulnerability to climate change at the individual level.

Fieldwork was conducted to collect data from various sources. The data collected were in many forms (e.g. spatial, quantitative, qualitative, etc.). We used software such as QGIS and ILWIS (for spatial data), Microsoft Excel and JMP to cleanse and manage the data and conduct data analysis. Details of the data collected such as criteria, type of data and data source can be found in the Appendix-II.

3. Result

3.1 Climate change vulnerability pattern at block level

3.1.1 Exposure
Most of the blocks in Darjeeling region were found under high exposure from different climate stimuli compared to a decade ago. Nearly 60% of the total area of Darjeeling region was under high exposure range, i.e. 0.75–1.00 (Figure 3). The result of the exposure component was based on the interplays of various climate stimuli like mean temperature change, annual precipitation change, and extreme events of precipitation in Darjeeling region.

The northern, northern-western region, and central parts of Darjeeling region have experienced substantial impact of increased exposures. Increased number of days with intense precipitation (RR > 50 mm) and change in mean temperature were the key criteria that influenced the exposure component most significantly. Both criteria had a high impact on Darjeeling region, except in the Gorubathan block, where all three criteria representing exposure had below average impact (<.5 range). It was also observed from the analysis that there was an increase of .5°C to 1.5°C in the mean temperature in the entire Darjeeling region in last 15 years, especially in the block in the northern, western to the southern part of Darjeeling region.

Most of the blocks in the Darjeeling region faced an increased number of days of high-intensity precipitation (>50 mm), causing increased vulnerability to extreme events like landslides in the higher elevation and flash flooding in the plains. Blocks in the central and eastern region were severely affected by intensive precipitation in the past because of its soil type, sink zones, and fault line (Mondal et al. 2014). While there was an overall increase in annual average rainfall, the northern and central area of Darjeeling region showed a decrease in annual average rainfall.

3.1.2 Sensitivity
The sensitivity component showed that about 40% of the total area of Darjeeling region was highly sensitive (i.e. 0.75–1.00 range) to climate change variables (Figure 4). The blocks in the eastern and northern of the Darjeeling region were highly sensitive to the different climate stimuli than the southern of Darjeeling regions. Most of the block were sensitive to changes in socio-economic and physical aspects of the sensitivity
component than natural aspects. Criteria including population younger than six-year-old, accessibility to public health, and migration from the socio-economic aspect and criteria including condition of roads, housing condition, and accessibility to financial services from the physical aspect were crucial for determine the overall sensitivity of the Darjeeling region (Figure 4). Eastern blocks like Kalimpong I, Kalimpong II and Gorubathan of the Darjeeling region were the most sensitive to the criteria of social aspect. These same blocks were also found highly sensitive to criteria of physical aspects. Close to 50% of the Darjeeling region showed a medium level of sensitivity to climate stimuli and physical intervention carried by people. The overall sensitivity results showed that the high-altitude blocks of the Darjeeling region were highly sensitive to the impacts of climate change than the blocks in plains.

3.1.3 Adaptive capacity
About 52% of the total area of Darjeeling region has below average adaptive capacity (.25-.50 range). The adaptive capacity of various blocks of Darjeeling region was measured based on three key aspects: basic facilities, economy, and social (Figure 5). The overall adaptive capacity of Darjeeling region varied from 0.3 to 0.55. The southern and eastern blocks had a below average adaptive capacity compared to others in the region. Block with medium adaptive capacity has well-established economic activities like tea production (e.g. Darjeeling Sadar, Kurseong and some area of Kalimpong-I and II blocks), cash crop production (e.g. Kalimpong-I and II blocks), social infrastructure (e.g. Kurseong and Siliguri blocks), and social integration like awareness, participation, and higher education levels (e.g. Darjeeling Sadar, Kurseong, and Matigara block). Most blocks in the Darjeeling region need urgent attention for necessary public facilities and economic activities to adapting to climate change impacts and make necessary behavioural change. It was also observed during the field work and from the analysis that the rural area of the Darjeeling region has very low accessibility by road and public transport and has limited access to the public facilities like public health, educational facilities, and market areas. Darjeeling region was having limited agricultural and tea production because of changes in mean temperature and rainfall pattern. This had a negative impact on the overall livelihood opportunities in the rural region and resulted in the seasonal migration to nearby towns and cities for better livelihood options.

3.1.4 Overall climate change vulnerability pattern
Figure 6 shows the pattern and extent of climate change vulnerability in Darjeeling region. The northern and eastern blocks of the Darjeeling region were found to have high climate change vulnerability (0.75–1.00 range). This pattern and extent of climate change vulnerability were influenced by two components, severity of exposure and high susceptibility of various criteria within sensitivity. The overall adaptive capacity of Darjeeling region was observed below average to low. Climate change vulnerability assessment shows that about 52% of the total areas of Darjeeling region need urgent attention in terms of adaptation response to climate change. Blocks at high altitudes, like Kalimpong I and Kalimpong II, Darjeeling Pulbazar, and Rangli Rangliot, were the most vulnerable. These blocks have been experiencing severe
Table 2. Vulnerability assessment criteria.

| Component         | Aspect                  | Criteria                                              | Reference                                      |
|-------------------|-------------------------|-------------------------------------------------------|------------------------------------------------|
| Exposure          | Climate variable        | Mean temperature increase                             | (Kumar et al. 2016; Zander et al. 2015)         |
|                   |                         | Rain range (>900 mm/year)                             | (Mirhosseini et al. 2013)                     |
|                   |                         | Number of days/years with heavy rain (RR >30 mm)      | (Mirhosseini et al. 2013)                     |
| Sensitivity       | Environmental           | Rate of land use change                               | (Liu and Shi 2017)                            |
|                   |                         | Area under forest or wildlife protected area          | (Mundoli et al. 2015)                         |
|                   |                         | Soil type and slope                                   | (Mundoli et al. 2015)                         |
|                   |                         | Water source and quality                              | (Hoque et al. 2016)                           |
| Physical          | Road condition          | Percentage of liveable houses                         | (Kumar et al. 2016)                           |
|                   |                         | Accessibility to essential services (e.g. public health centre and educational facilities) | (Tapsuwan et al. 2018)                        |
|                   |                         | Landslide zone and frequency of landslide             | (Bai et al. 2018)                             |
| Socio-economic    | Percentage of people younger than six years             | (Watts et al. 2019)                                  |
| Adaptive Capacity | Basic facilities        | Accessibility to clean drinking water connection      | (Bain et al. 2020)                            |
|                   |                         | Accessibility to efficient cooking fuel               | (Aberilla et al. 2020)                        |
|                   |                         | Accessibility to public transport                     | (Kumar et al. 2016)                           |
| Economic          | Percentage of households who own their homes            | (Kumar et al. 2016)                                  |
|                   | Percentage of households owning any kind of asset      | (Kumar et al. 2016)                                  |
|                   | Local government or communities-based organization      | (Berman et al. 2012)                                |
|                   | Awareness and knowledge of different policies and scheme run by local government | (Deng et al. 2017)                                |
| Social            | Percentage of people who are literate                    | (Wu and Lee 2015)                                  |
|                   | Social welfare programmes                                   | (Hills et al. 2018)                                |
|                   | Accessibility of media                                     | (Barkemeyer et al. 2018)                            |

Consequences of climate change (e.g. landslides, flash flooding, number of days with increased temperature, and change in the mean temperature) compared to the previous decade.

3.2 People perception of climate change vulnerability at site level

3.2.1 Exposure

Most people who were interviewed have experienced high exposure from various climate variables (Figure 7_i). About 70% respondents from all the selected sites reported they had experienced an increase in numbers of high-intensity rain days, hot days, and overall changes in average temperature and in their lifetimes. Meteorological data from Regional India Meteorological Department from these sites also confirmed that there have been changes in the trend of climate variables. Respondents and their immediate local communities observed changes in the seasonal shift, erratic climate events, drought in summers, decrease in annual precipitation, and increased numbers of days with intense rainfall.

The site level results showed that the interviewees from Signalila Forest-I, Kalimpong and Rangli Rangliot sites perceived high exposure to climate variables compared to the other sites (Figure 7_ii). These sites were located mostly in medium to high altitudes, with most of the area under forest and agricultural land use. Our analysis also showed that most of the
people from these sites were involved in agricultural activities. They considerable change in climate variables like temperature and rainfall have severely impacted the agriculture production and local ecosystem services. However, one-third of the total interviewed people were living in and around urban areas like Darjeeling town, Siliguri, and Kurseong. Whereas, these respondents experienced milder impacts of direct climatic changes.
compared with people living in rural sites. However, they have highlighted signs of second-order impacts of climate change, like a change in seasons, which impacted local tourism, availability of water in summer, and observed landslide events during high intense rain.

3.1.2 Sensitivity

About 65% of the total respondents were highly sensitive to climate exposure. 100% of people interviewed at Signalila Forest-I, Kalimpong II, and Rangli Rangliot sites were found highly sensitivity (Figure 8). These were also the sites that fall under high exposure range to climate variables. Respondents from Siliguri site were having least sensitive to climate exposure among all the surveyed sites. One reason was a high urbanized area in low altitude foothill of Darjeeling region, which mitigated many of the measured aspects of climate vulnerability. The high-sensitive sites, according to the perception of the respondents, were those that lacked access to health and public facilities, lacked access to clean water, showed significant land-use changes, high unemployment rate, and had an inadequate physical infrastructure. Sites in and around urban areas (e.g. Darjeeling and Kurseong) had medium sensitivity because of better accessibility to physical, social, public infrastructure, and suitable employment opportunities.

3.1.3 Adaptive capacity

The adaptive capacity of the respondents was measured using three main areas: economy, public services and facilities, and social aspects. According to the interview and group discussion analysis, respondents from Signalila Forest-I, Kalimpong II, and Rangli Rangliot site were found to have the lowest adaptive capacity, and they were representing about 33% of total interviewees (Figure 9). About 95% of the total sampled interview showed low to medium adaptive capacity. The main reason identified for having the low adaptive capacity in these regions was lack of necessary public infrastructure and services. A few interviewees highlighted that “the local government is not effective and does not efficiently allocate needed resources in the region”. It was also observed during the field work and institutional analysis that the political instability in the region has resulted in government institutions in the rural areas no longer receiving financial or administrative help from the district and state level. Respondents for foothills sites like Siliguri, Darjeeling were found to have better adaptive capacity compared to other regions due to better physical development and good livelihood opportunities.

3.1.4 Overall vulnerability pattern

The result of the overall vulnerability showed that about 72% of the total interviewees were in the high climate change vulnerability range (Figure 10). Exposure was the key component of high climate change vulnerability among interviewees. People living in the higher altitudes sites like Signalila Forest-I, Kalimpong II, and Rangli Rangliot were exposed to several climate variables, like increased number of hot days, mean temperature change, and increased number of intense rainy days. Communities in the foothills of Darjeeling hills noted an increase in the dry season,
fluctuation of pre-monsoon and after-monsoon rains, and an increase in mean temperature. Highly vulnerable sites face greater sensitivity to climatic changes resulting in loss of agriculture production and ecosystem services. These climate

Figure 4. (B) Spatial distribution of the sensitivity component of climate change vulnerability in Darjeeling region, India. The overall scores are based on the scores of various aspects of sensitivity component which include b1) physical aspect, b2) socio-economic aspect and b3) environmental aspect. Figures b1, b2 and b3 follow the same colour and scoring schema as subfigure (B). The different colours indicate overall scores of the sensitivity component of climate change vulnerability and various aspects of sensitivity component. These scores are on a scale of 0–1 and are divided into four classes, namely: 0–0.25 (low), 0.25–0.50 (below average), 0.50–0.75 (medium), and 0.75–1 (high).
changes also cause negative repercussions on the development of the communities. The people also showed low levels of adaptive capacity because of low levels of climate awareness, lack of employment opportunities, and lack of participation at any stage of policy preparation or even in the local government.

**Figure 5. (C) Spatial distribution of the adaptive capacity component of climate change vulnerability in Darjeeling region, India.** The overall scores are based on the scores of various aspects of adaptive capacity component which include c1) basic facilities aspect, c2) economic aspect and c3) social aspect. Figures c1, c2 and c3 follow the same colour and scoring schema as subfigure (C). The different colours indicate overall scores of the adaptive capacity component of climate change vulnerability and various aspects of adaptive capacity component. These scores are on a scale of 0–1 and are divided into four classes, namely: 0–0.25 (low), 0.25–0.50 (below average), 0.50–0.75 (medium), and 0.75–1 (high).
4. Discussion

This study documented the climate change vulnerability pattern of the Darjeeling region in the Eastern Hindu-Kush Himalayan range and compared the results how local communities from study area perceived climate change vulnerability, how it varies among peoples and locations, how their knowledge about climate change represented in climate change assessment for developing adaptation strategies.

The Himalayan region is one of the most complex socio-ecological systems in the world. It is the youngest mountain range in the world and home to crucial biodiversity hotspots, eco-zones, and many tribal communities (Chaudhary et al. 2011). Our semi-structured interview in seven sites from various locations of Darjeeling region showed that the local communities have already started observing detectable changes in the patterns of climate variables and its impact on the local socio-ecological system. It was further confirmed by the exposure component results based on climate change vulnerability assessment carried at the block level. However, people’s perception of climate change differs in terms of time and spatial location. Considerable differences in climatic vulnerability among people and as well as at villages level were found based on which village people belong, what kind of resource they have, and the physical location (i.e. urban or rural and plain or hilly). Contrary to that the climate vulnerability observation at the block level was broad, and most current climate policies and actions in the region were based on these observations. For example, significant climate change impacts have been observed from hilly block of Darjeeling region, but those results were still broad and

Figure 6. Spatial distribution of climate change vulnerability of Darjeeling region, India. The overall scores are based on the scores of exposures, sensitivity and adaptive capacity (as described in the method section and illustrated in Figure 3(A), 4(B), and 5(C). The different colours indicate overall scores of climate change vulnerability. These scores are on a scale of 0–1 and are divided into four classes, namely: 0–0.25 (low), 0.25–0.50 (below average), 0.50–0.75 (medium), and 0.75–1 (high).
did not represent and disclose the vulnerability experience of local communities. Although majority of interviewed people from all seven sites were observing high climate vulnerability; whereas, it was not the case with climate vulnerability assessment carried using scientific climate vulnerability framework. The results of the assessment framework showed high vulnerability among hilly block only. These are also those blocks that have high sensitivity to physical, social, and ecological change. This variation in results could be explained because of limited involvement of various stakeholder specially local communities, from remote areas of the study area during the application of climate vulnerability assessment framework.

Local communities, especially elderly of the communities, have developed multi-faceted, complex and relational socio-ecological understandings of the ecosystems in which their communities are situated. However, compared with scientific vulnerability assessment, such knowledge is rarely utilized or integrated for understanding core drivers of vulnerability. Scientific climate change vulnerability assessments that capture environmental change are important and receive well-earned attention, but such initiatives typically focus on highly specific parameters without informing communities how to enhance their adaptative capacity, or describing which driver, sector, or area needs attention now of in future for developing climate policies and development strategies. This limitation has short- or long-term repercussion in terms of policy decision made at the local level, specially block and village level. When we involve a

Figure 7. People’s perception of the exposure component of climate change vulnerability at selected survey sites in Darjeeling region, India. (i) the people’s perception of the exposure component of climate change vulnerability from 170 interviews is presented as a histogram showing the percentage of respondent count and the different scale ranges (0–1) on the y-axis against the overall conducted survey on the x-axis. (ii) the people’s perception of the exposure component of climate change vulnerability is presented as a histogram showing the different sites of data collection on the x-axis and the percentage of respondent count and the different scale ranges (0–1) on the y-axis. The different colours indicate score range of 0–1 and are divided into four classes, namely: 0–0.25 (low), 0.25–0.50 (below average), 0.50–0.75 (medium), and 0.75–1 (high).
wide range of stakeholder from local communities and their knowledge with scientific method, we can devise socially acceptable adaptation policies which is not the case at present, specially marginalized area like Darjeeling region in India.

Present practices of scientific assessment of climate change risks and policy decisions in India have limited involvement of local communities or even their local political representatives (Banerjee 2015; Kumar et al. 2016; Dubash et al. 2018; Prasad and Sud 2019). Scientists or even policymakers are often sceptical about the observations made by non-scientists (Byg and Salick 2009). While current study showed that the result of scientific carried climate change vulnerability compare to observations of local communities are broad. The observations of local communities support scientific results and provide precise nature of local observations of climate change vulnerability. Presently, available development and climate policies in the Darjeeling region has a limited impacts and most of these policies are broad climate initiatives or directives of State and Central government.

With changing socio-demographic structure, urbanization and land use change in Darjeeling regions have soared the demand for the basic resource. It has resulted in over-exploitation of natural resources such as forests, water, and land for agriculture, resulting in hydrological imbalance, soil erosion, and socio-ecological disparity. Extensive areas of land and forest have been cleared for commercial agriculture rather than traditional subsistence farming. Crops are harvested just after the monsoons, affecting soil
Figure 9. People’s perception of the adaptive capacity component of climate change vulnerability at selected survey sites in Darjeeling region, India. (i) the people’s perception of the adaptive capacity component of climate change vulnerability from 170 interviews is presented as a histogram showing the percentage of respondent count and the different scale ranges (0–1) on the y-axis against the overall conducted survey on the x-axis. (ii) the people’s perception of the adaptive capacity component of climate change vulnerability is presented as a histogram showing the different sites of data collection on the x-axis and the percentage of respondent count and the different scale ranges (0–1) on the y-axis. The different colours indicate score range of 0–1 and are divided into four classes, namely: 0–0.25 (low), 0.25–0.50 (below average), 0.50–0.75 (medium), and 0.75–1 (high).

cohesiveness. Massive bursts of rainfall during the off-monsoon seasons, make these areas prone to erosions and landslides, whereas foothill (e.g. Matigara, Naxalbari, Phansidewa, and Kharibari) are less prone to climate vulnerability but second-order events like floods and urban heat Island could be observed every season. All these observations show the current state of adaptative capacity of Darjeeling region, block, as well at the site level.

The key finding of the study was the low adaptative capacity of the Darjeeling region. However, block lying in the foothills have better adaptative capacity compared to rural and hilly area partly because of better connectivity with other neighbouring region, better economic opportunities and planned physical development. When low adaptative capacity coupled with an absence of effective policies for physical, social and economic development of the area, adaptation to climate change vulnerability becomes harder. So far, physical growth in the region, especially in mountainous block has been very erratic, with high-density housing on acute slopes, high-rise buildings, and slums in urban areas. Such conditions create condition for high sensitivity of socio-ecological system to various climate events. As this region lies in the seismic zone IV, the physical infrastructure is in great danger to earthquakes and climate-related events such as cyclones, landslides, cloudbursts, and glacial lake outburst flooding (Chhetri and Tamang 2013). These concerns were also reported during the interview from seven sites. However, there were large variations in climate concerns among people because of their location and local socio-economic factor.
Considering the sensitivity aspect of the region and economic and social activities in this region (i.e. mostly agriculture and ecosystem-based services), which amplifies concern about climate change vulnerability, policy maker at various spatial scale fails to connect various component of climate change vulnerability and their impacts at local level. That was also the case in Darjeeling region. For example, large parts of this region have an economic base in the production of tea, spices, and vegetables. High-quality tea and spices account for an outstanding value in the national and international market, and in the last decade, production has been severely hampered because of changing climate variable (Patra et al. 2013). This climate change concerns need immediate action within local development policies at either sectoral or spatial level.

Surveyed people and communities revealed that the communities in the rural areas have already showing sign of adapting to changing climate. They have already initiated local adaptation practices like protecting their immediate physical and ecological environments, which are important for their livelihood and day-to-day survival. Whereas people from urban areas are concerned with climate change impacts on their business and physical infrastructure. Communities confirmed that agricultural production directly linked to weather patterns, but most people failed to associate it with the effects of global environmental challenges. People also described how changes in the local climate were having impacts on health. People have become more vulnerable to heatwaves,
mosquitoes, flies and pests that have increased in the high altitudes of Darjeeling region. The number of cases of malaria are increasing in the mountainous regions, which used to be predominant only in the plains (Sharma et al. 2009).

Results of this study showed that the climate change vulnerability assessment is continuously developing and improving on providing more knowledge. However, current climate change vulnerability assessment studies have limited knowledge represent of local climate condition and communities, specially marginalized regions of the world. Specially, when climate change vulnerability is not a purely environmental phenomenon, but it very much associated with the social, economic, and ecological dimension of system that is still missing in current vulnerability assessment and climate policy practices. To understand these associations, local communities, stakeholder, and their knowledge is crucial in influencing the vulnerability of particular people and communities (Adger et al. 2013; Gentle et al. 2014). Specially, people and communities from mountain and rural settings, they are by nature marginalized and underrepresented in global studies. They experience inflated consequences of internal and external global risks like climate migration, environmental degradation, market failure, agriculture production, and political instability. These communities also lack awareness of climate issues and have limited resource to adapt and weak representation in the government to make meaningful policy decision. Currently, decision-making power at the local government institution in Darjeeling region is weak or missing altogether. Communities are coping with climate concerns within their personal capacity or with the help of local self-help groups, which have a limited impact. Development of effective current and foresee adaptation response and its implementation by local institutions needs a revival.

In India, the National Mission for Sustaining Himalayan Ecosystem (NMSHEs) is responsible for research and development of climate change impacts and is one mission of India’s National Action Plan on Climate Change. The Darjeeling region also comes under the purview of this mission, which conducts extensive research, developing suitable management and policy guidelines, and working with different stakeholders to implement these guidelines. The study highlighted that integrating the knowledge of local communities and their participation into the scientific climate change vulnerability will not only track/monitor/capture aspects of pattern, but the extent of the vulnerability as well. Local knowledge should be utilized to identify future risks and critical areas of concern and devise adaptation policies, such as expanding current developmental policies to include climate change concerns, building institutional capacity of governing bodies, and spreading awareness. However, most studies on climate change in the Himalayas focus on snow, vegetation, treeline, soil and fauna and are conducted on very broad scales, ignoring the cultural and social dimension of the mountain communities. There is serious urgency for interdisciplinary studies such as this to that integrate world risk knowledge and perception by communities, the results of which can be accessed by the local institutions and government bodies for climate change mitigation and future adaptation responses.
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