3 Climate

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Abstract

Nepal is a relatively small, mountainous country in the Central Himalayas with a diverse climate within a short aerial distance due to its unique topography and altitudinal variation. The country is characterized mainly by six climatic zones, ranging from tropical in the southern plains to tundra/nival in the northern part with perpetual snow cover. In this chapter, a brief explanation of the climate zones; a description of the climate seasons; and overall climatic trends including temperature, rainfall, floods, drought, and frosts and cold waves of the country is provided. Further, the chapter covers the status of agro-ecozones, soil climate, and climate change and its impact. In recent decades, Nepal's climate shows trends of increasing temperature and decreasing rainfall. The country's agro-ecozones are divided into five major zones, including Tarai, River Basins, Lower Hills, High Hills, and High Mountains, ranging between 60–4800 meters (m) above mean sea level (asl). Climate is known to be one of the five soil-forming factors and has a significant influence on soil properties. For example, the properties of soils found in the High Hills and High Mountains are different than in soils found in other agro-ecozones of Nepal. Finally, we discuss the climate change impacts in Nepal and the significant risks they pose, especially on agriculture, food security, and people's livelihoods. A broad-brush description of various climatic scenarios of Nepal Himalayas is presented.

Keywords

Climate of Nepal • Climate zones • Agro-ecozones • Soil climate • Climate change

3.1 Introduction

Geographically Nepal is located in the central Himalayan region of South Asia (Khanal et al. 2020), with climatic and topographic variations that are unique in the world (Shrestha and Aryal 2011). Mountainous terrain covers most of the country, including the world's highest peak Sagarmatha (Mount Everest), reaching 8848.86 m asl (Nepal et al. 2020). The climatic variation within a short aerial distance is remarkably high due to vast altitudinal differences, meaning ranging from a tropical climate in the south to a tundra/nival/trans-Himalayan climate in the north (Karki et al. 2017; Paudel et al. 2020). The vast altitudinal variation from 60 m asl in the southern Tarai plains to 8848.86 m asl in the northern Himalayan region directly affects overall weather, climate, and their variation. Further, the climatological and topographical factors (i.e., air temperature, solar radiation regime, slope, and aspect) are directly associated with the overall variability of the country's climate (Collier and Immerzeel 2015; Karki et al. 2020; Talchabhadel et al. 2018).

The country is divided into five physiographic regions, including Tarai, Siwalik, Middle Mountain, High Mountain, and High Himalaya (LRMP 1986). This classification shows that most of the country's territory is covered by mountainous areas, which acts as a barrier. This natural barrier largely impedes humid air mass circulation, resulting in precipitation on the southern slope or sunward side of the mountain and an area of rain shadow on the leeward side of the

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trans-Himalayan region (Kansakar et al. 2004). For example, the Manang, Mustang, and Dolpa districts of western Nepal are on the Himalaya Mountains' leeward side and receive less precipitation (Karki et al. 2017). This results in the formation of arid and semi-arid environments and directly impacts agricultural activities. However, the sunward side of the mountains receives more precipitation, which is largely beneficial for farming activities and people's livelihoods (Shrestha et al. 2000). Further, it has been reported that every 1000 m increment in altitude reduces temperature by 6.5 °C, which is widely known as the standard (average) lapse rate (Chapman et al. 2002; Tabony 1985)—the primary driver of temperature variability within the country. Thus, the presence of the high mountain range largely impacts the country's overall climate. Topographical features and the distribution of meteorological/hydrological stations of Nepal are presented in Fig. 3.1.

There are six major climatic zones in Nepal: tropical, subtropical, temperate, subalpine, alpine, and tundra/nival/trans-Himalayan, ranging from the southern Tarai plain to the northern high and trans-Himalaya regions, respectively

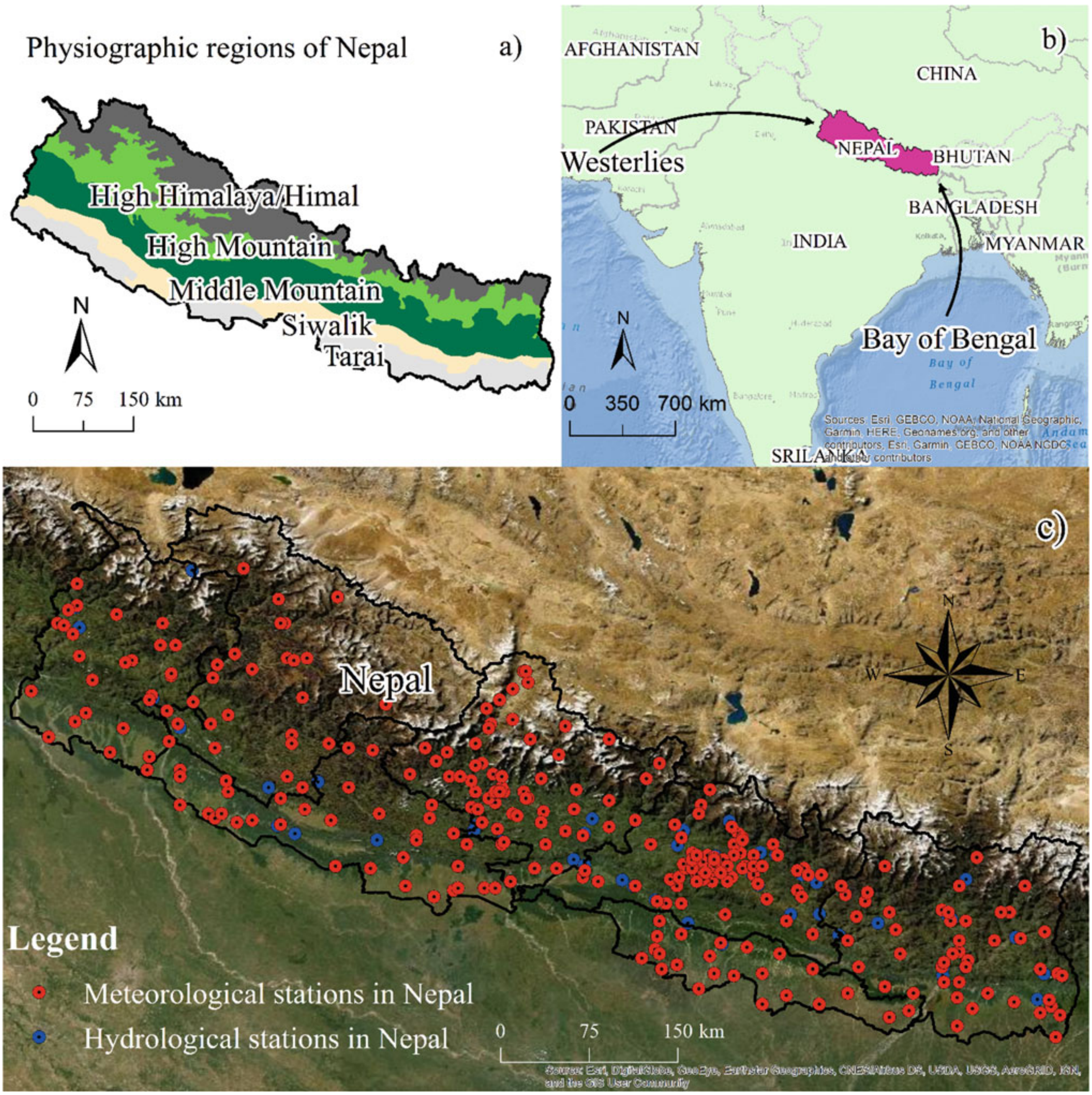

Fig. 3.1 Topography and spatial distribution of meteorological and hydrological stations across Nepal. Meteorological and hydrological station data were obtained from the Department of Hydrology and Meteorology (DHM), Government of Nepal

(Nayava 1975). The districts located in the southern Tarai plain regions experience the tropical climate, and northern districts such as Mustang and Manang in the high Himalaya regions usually experience the trans-Himalaya climate. Further, there are four main climate seasons in Nepal: pre-monsoon, monsoon, post-monsoon, and winter (Karki et al. 2017). The pre-monsoon season occurs in Nepal between March and May, and the monsoon season occurs between June to September. The post-monsoon season falls between October and November, and the winter season extends from December to February (Karki et al. 2020).

Over the last few decades, several studies have revealed a significant rising trend in temperature (Poudel et al. 2020; Shrestha et al. 1999), coupled with a declining precipitation rate (Duncan et al. 2013; Ichiyanagi et al. 2007; Shrestha et al. 2000; Talchabhadel et al. 2018). However, short-term erratic heavy rainfall occurrence has been more frequent in the last several years, creating several flood events in Nepal (Devkota 2014). During the monsoon season, these flood events devastate the rural economy and the livelihood of the farming community, especially in the southern Tarai region (Malla 2008; Pangali Sharma et al. 2019). The overall decreasing trend of annual precipitation and increasing frequency of drought events (Dahal et al. 2016) directly impact the country's agricultural systems (Wu et al. 2019). Moreover, during Nepal's winter season, especially in the Tarai regions, frosts and cold waves have been commonly noted in recent decades, causing human fatalities through exposure to cold waves and impacting the region's winter crops (Pradhan et al. 2019). These climatic characteristics, including the increasing trends of temperature, droughts, frequent seasonal floods, extended frosts, and cold waves, as well as decreasing trends of precipitation clearly show that the climate in Nepal is rapidly deviating from the long-term normal. This suggests the robust negative impact of climate change, which impacts people's livelihoods and the country's overall agricultural systems.

Based on Nepal's local landscape and dominant farming system, several suitable agro-ecozones were developed and categorized, based mainly on elevation, climatic condition, and soil/land type (Gauchan and Yokoyama 1999). These agro-ecozones help researchers formulate suitable strategies and recommend appropriate crops for farmers in their locality. Further, the soil climate is generally characterized by air, temperature, and moisture associated with soil. Warm conditions promote chemical and biological reactions that more quickly convert parent materials into the soil. As the soil is dried out, plant growth is reduced due to poor contact with soil water, which reduces the surface layer's stability (Sindelar 2015). In this context, this chapter mainly discusses the overall climate scenarios of Nepal, including climate zones, seasons, trends, agro-ecozones, soli climate, and climate change impact.

3.2 Climate Zones in Nepal

The mountainous country of Nepal contains vast topographical differences; thus, the climate also varies significantly within different regions. It is mainly categorized into six climate zones ranging from southern tropical to tundra/trans-Himalayan perpetual snow.

3.2.1 Tropical

In Nepal, the tropical climate is observed below 1000 m asl (Nayava 1975). This climate zone is located mainly in the southern part of the country (Fig. 3.2). In the tropical zones, summers are hot and winters are cold (Pradhan et al. 2013). The tropical climate zone encompasses most of the districts located in the Tarai region of the country. This zone is also known as the lower tropical zone, with an average elevation mostly below 300 m asl. The east–west highway of the country primarily runs through this lower tropical climate zone. The area above 300 m asl to 1000 m asl within this climate zone is also recognized as the upper tropical climate zone in Nepal and includes most of the Siwalik Hills. In addition, this climate zone can be observed in the lower elevation river valley areas of the hill and mountain regions. The lower tropical climate zone is a geographically plain area, and most of the soil in this zone is highly fertile. Thus, the lower part of this climate zone is more suitable for agricultural activities and the climate is more ideal for paddy, wheat, and maize crops (Rimal et al. 2018; Sharma 2001). Moreover, due to the fertile soil and tropical climate, the production of cash crops (sugarcane and jute), tropical fruits (mango, papaya, litchi, and banana), and vegetables is higher in this climate zone compared to the other climate zones in Nepal (Amatya 1976; Ghimire and Thakur 2013; Neupane et al. 2017). This climate zone is inhabited by over 50% of the country's population (CBS, 2012), and as such, many people's livelihoods are affected by the hot summer waves and cold winter waves (Pradhan et al. 2019; Pradhan et al. 2013).

3.2.2 Subtropical

The subtropical climate region is found in elevation ranging between 1000 and 2000 m asl. This climate zone is located between the upper part of the tropical climate zone and the lower part of the temperate climate zone (Fig. 3.2) and mostly covers the area within the country's middle mountain physiographic region. The capital of Nepal, Kathmandu, is located within this climate zone, and it is the second most populous climate zone after the tropical climate zone (CBS 2012). In this subtropical climatic characteristic

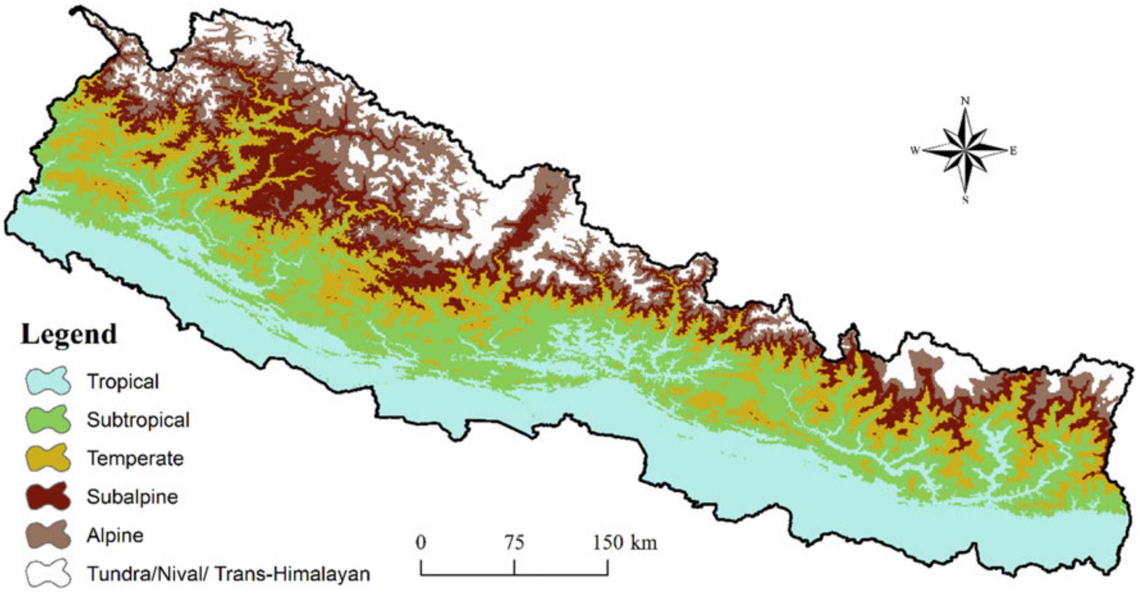

Fig. 3.2 Major climate zones of Nepal

zone, the major crops are maize, millet, rice, wheat, and potato (Pokharel 2019). Farmers in the flat and lower elevation of this climate zone have access to irrigation facilities. Farmers mainly cultivate rice and wheat in fields with very gentle slopes and produce maize, millet, potato crops, and citrus fruits and vegetables in gentle slopes (Devkota 1999; Sharma 2001).

3.2.3 Temperate

The elevation ranges between 2000 and 3000 m asl in Nepal are referred to as the temperate climate zone (Fig. 3.2). It shares boundaries with the majority of the subtropical climate zone area in the southern part of the country and the subalpine climate zone in the northern part (Devkota 1999). This climate zone is mainly situated from the upper part of the Middle Mountain physiographic region to the lower part of the High Mountain region. This zone is known for its mild climate, and the major cultivated crops within this climate zone are maize, barley, wheat, potato, rice, and buckwheat (Sharma 2001). Further, this zone is suitable for apple cultivation (Manandhar et al. 2014).

3.2.4 Subalpine

The subalpine climate zone ranges between 3000 and 4000 m asl in Nepal (Fig. 3.2). The majority of this region is situated within the High Mountain physiographic regions of the country, and some areas are extended into the High Himalayas/Himal region (Devkota 1999). The climatic condition of the subalpine climate zone consists mostly of cold weather, and as there are many areas of pastureland/grassland, inhabitants practice transhumance adaptation in different climatic seasons. During the summer season, people shift/migrate to the higher elevation from the lower elevation with their livestock for grazing, and move back to the lowland area in the winter seasons (Aryal et al. 2014; Gentle and Thwaites 2016). People in this climate zone mainly domesticate yak, sheep, and goats, and due to the cold climate, mainly cultivate buckwheat, potato, and barley (Gauchan and Yokoyama 1999; Pokharel 2019). Further, some within this climate zone in Nepal also practice fruit (apple) and vegetable farming.

3.2.5 Alpine

The elevation range from 4000 to 5000 m asl in Nepal is known as the alpine climate zone (Fig. 3.2). Due to the cold climate, few people inhabit this region. As some areas are covered seasonally by snow, farming practices are less common (Devkota 1999; Nayava 1975). However, most land in this area is used for pasture, with the potential for medicinal herbs and livestock farming (Aryal et al. 2014; Bhattarai et al. 2010; Pokharel 2019). Usually in the summer season, herdsmen from lower elevations travel with their livestock for grazing and return in the winter season (Gentle and Thwaites 2016).

3.2.6 Tundra/Nival/Trans-Himalayan

The tundra/nival/trans-Himalayan climate exists in the area located above 5000 m asl in Nepal (Fig. 3.2). Due to the extreme cold climate, the area above 5000 m is not habitable. The nival is also called the tundra in Nepal Himalaya (Nayava 1975), where the land is mostly covered by snow all year round, resulting in minimal vegetation. Within this climate zone, trans-Himalayan climates are observed on the leeward side of the Himalaya mountain range. As discussed earlier, this climate zone receives less precipitation; thus, it is also called the rain shadow area (Shrestha et al. 2000). Moreover, due to the low air temperature and decreased humidity, these areas are less suitable for agriculture (Chapagain 2016), resulting in low human population density. The Manang, Mustang, and Dolpa districts are located within this climate zone, representing regions that receive less precipitation and contain arid and semi-arid landscapes.

Additionally, a revised Global level Köppen–Geiger classification study (Kottek et al. 2006) shows there are mainly eight climate types in Nepal: polar frost climate (EF), polar tundra climate (ET), temperate climate with dry winter and warm summer (Cwb), temperate climate with dry winter and hot summer (Cwa), cold climate with dry winter and warm summer (Dwb), cold climate with dry winter and cold summer (Dwc), arid steppe cold climate (BSk), and tropical savanna (Aw) (Karki et al. 2016).

3.3 Climate Seasons in Nepal

There are mainly four climate seasons in Nepal (Talchabhadel et al. 2018). Pre-monsoon occurs between March and May, followed by monsoon season from June to September, post-monsoon season from October to November, and winter between December and February (Karki et al. 2017).

A wet and warm climate is observed mainly between June and September. During this period, a low-pressure zone is created, which attracts moist air from the Indian Ocean (Shrestha et al. 2000). Further, the period between October and May is marked by a dry season with cold temperatures. These months create high air pressure that produces dry air and moves to other regions (Karki et al. 2017). April and May are noted as the hottest months, and for some part of the country, primarily the southern Tarai tropical region, the temperature peaks around 38 to 40 °C (Karki et al. 2020). The months of June and July are known for their high rainfall intensity and thunderstorms that drive most rain-fed cultivation; however, this also creates landslides in the Hill and Mountain regions, along with flooding. These detrimental events cause severe property damage and losses in the Tarai region of the country and negatively impact people's lives (Karki et al. 2017; Pangali Sharma et al. 2019; Shrestha et al. 2000). The details of each climate season in Nepal are described herein.

3.3.1 Pre-Monsoon (March–May)

The pre-monsoon climate season in Nepal occurs from March to May. The pre-monsoon climatic season is mainly active for three months, with moisture-laden air and winds typically originating from the Bay of Bengal and creating short-term light rainfall in some areas (Nayava 1975; Shrestha et al. 2000). This depends on local weather conditions and the effect of cumulonimbus clouds (Talchabhadel et al. 2018). During this season, thunderstorm and hailstorm events are seen comparatively more often due to the impact of cumulonimbus clouds (Aryal 2018). Usually, the days are sunny, with rising temperatures and scattered thundershowers, especially during the afternoons and evenings. Outside of this season, April–May are the hottest months. The temperature of these months ranges up to 40 °C in the Tarai regions (Karki et al. 2020). Further, around 12.5% of rainfall occurs during Nepal's pre-monsoon season (Karki et al. 2017).

3.3.2 Monsoon (June–September)

The term monsoon is also known as the rainy season (between June and September) in Nepal (Brewin et al. 2000). The monsoon season refers to heavy periodic winds/breezes blowing predominantly from the Bay of Bengal (Nayava 1975), which carry heavy showers and humidity throughout most parts of Nepal. Similarly, some rainfall in the country is due to western Arabian sea winds (Shrestha et al. 2000). The monsoon season begins in the middle of June, peaks in July/August, and ends in September of each year (Karki et al. 2017; Nayava 1975). This season records the highest rainfall in Nepal; however, different regions vary in rainfall intensity (Barros and Lang 2003). Moreover, Nepal's distinct landscape features and associated environmental factors influence this season (Nayava 1974).

3.3.3 Post-Monsoon (October–November)

The post-monsoon season in Nepal lasts between October and November. Out of the four seasons, the post-monsoon season is the shortest. Noticeable characteristics of this season include windy days and the likelihood of cyclones forming in some parts of the country (Shrestha et al. 1999). In this season, a decreasing order temperature is observed due to changing seasonal weather and sometimes several days of continuous rainfall (Shrestha et al. 2000). The prevailing climatic conditions across Nepal during this season are between hot and cold; thus, this season is also known as a mild climatic season. The ending month of this season (November) is quite dry, mainly due to the dry and windy atmosphere (Merz et al. 2006).

3.3.4 Winter (December-February)

Winter is the coldest season in Nepal and occurs between December and February. The winter season happens after the post-monsoon season and before the pre-monsoon season each year. During this season, the majority of the High Mountain and trans-Himalayan regions are covered by snow with freezing temperatures (Nayava 1975). Further, the country's Middle Mountain regions and Hill regions also feel much colder compared to other seasons. Similarly, the southern part of the country (Tarai region) is highly affected by cold waves, and many people in the region lose their lives due to extreme cold events (Pradhan et al. 2019). The cold waves and frost in this region also impact farmers' agricultural activities and livelihoods (Malla 2008). The days become shorter, and the nights are longer than other seasons.

3.4 Climatic Trend in Nepal

3.4.1 Temperature

Historically, the temperature trend in Nepal showed a sharp increasing order by 0.06 °C yr^{-1} between 1977 and 1994 (Shrestha et al. 1999). The increasing trend was also reported until 2000 (Shrestha and Aryal 2011). A recent study from Nepal Himalaya based on data from 115 temperature stations from the Government of Nepal's Department of Hydrology and Meteorology (DHM) noted the temperature trend was rising noticeably by 0.05 °C yr^{-1} between 2000 and 2015 (Paudel et al. 2020) (Fig. 3.3). Thus, the overall long-term temperature trend in Nepal was observed to be rising significantly. The rising trend varies across different physiographic regions of the country. Many studies have reported that the noticeable increasing trend of temperature has impacted the overall livelihood of people and agricultural activities in Nepal (Gentle and Maraseni 2012; Malla 2008; Manandhar et al. 2011).

3.4.2 Precipitation

Long-term-climatic-data-based historical studies about climate change in Nepal reported that Nepal's precipitation trend was decreasing (DHM 2017; Shrestha et al. 2000). A recent

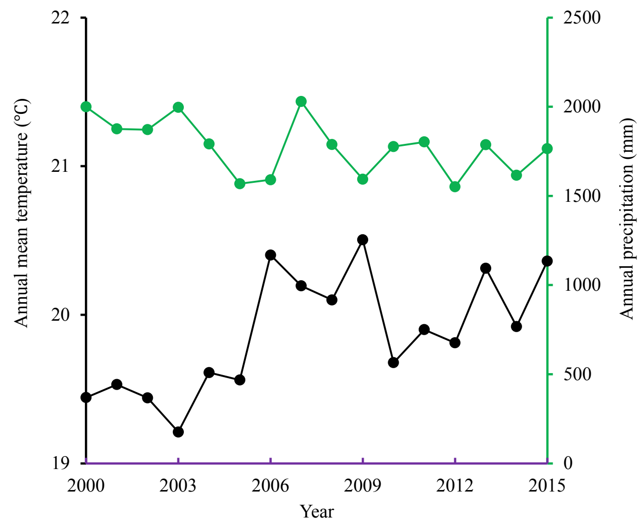

Fig. 3.3 Observed climatic trends (temperature and precipitation) in Nepal between 2000 and 2015. The trend calculations were based on observed daily weather records between 2000 and 2015 (115 stations for temperature and 272 stations for precipitation). *Data source* DHM, Nepal, and modified after Paudel et al. (2020)

study based on DHM Nepal data from 272 rainfall stations revealed that annual total precipitation declined by -16.09 mm yr^{-1} (Paudel et al. 2020) (Fig. 3.3). The long-term precipitation trend by different climatic seasons in Nepal shows that around 80% of precipitation occurs during monsoon season, while the remaining 20% occurs during the other three climatic seasons; with 12.5% during pre-monsoon, 4% during post-monsoon, and 3.5% during the winter season (Karki et al. 2017). Further, the decreasing trend of precipitation directly impacted the overall agricultural activities in Nepal (Malla 2008). The spatial pattern between 1980 and 2000 shows that the surrounding area of Pokhara has higher precipitation records; however, this was less in the upper Mustang and Dolpa regions of the country (Fig. 3.4).

3.4.3 Floods

Flooding events in Nepal are normally seen more frequently during the monsoon season compared to the other seasons because the monsoon season is known as the rainy season, and there has been highest rainfall across the country within this season (Nayava 1974). The studies show that overall flood events mainly impacted the Tarai regions (Pangali Sharma et al. 2019) because the landscape of this region consists of flat plains, allowing the floods to easily spread to more areas compared to the country's Hill and Mountain regions. A recent synthesized study about flood disasters in Nepal reported that there are fourteen districts in the Tarai regions highly affected by floods (Pangali Sharma et al.

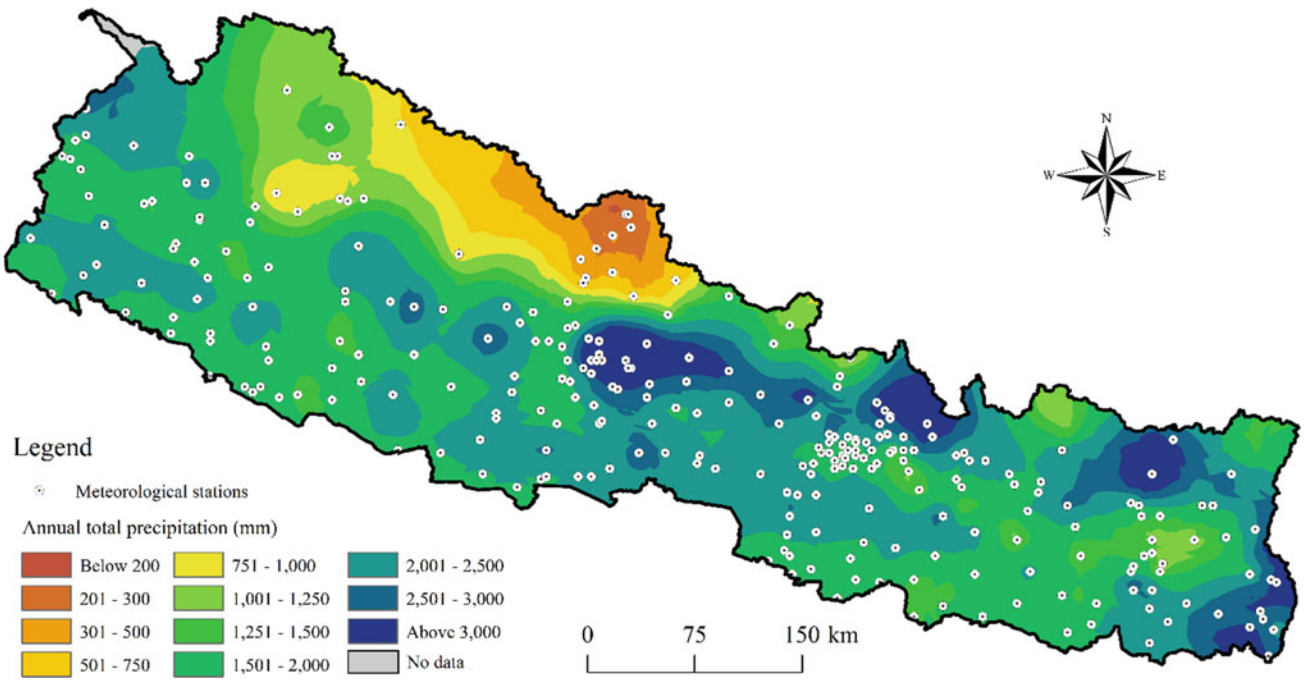

Fig. 3.4 Annual total precipitation distribution of Nepal between 1980 and 2000. The dotted symbols show the distribution of meteorological stations within the country. *Data source* Humanitarian Data Exchange (https://data.humdata.org/)

2019). The studies show that rainfall in Nepal has been decreasing during the past few decades (Paudel et al. 2020; Shrestha et al. 2000) but the flood disaster and event results show an increasing number of events and amount of property loss, as well as an increasing number of casualties (Pangali Sharma et al. 2019). This occurs due to erratic short-term heavy rainfall, which has occurred more frequently in Nepal in recent years (Devkota et al. 2017; Manandhar et al. 2011). During the three-day period from 22 to 25 September 2020, there was short-term heavy rainfall in Nepal, and some areas of south-central Nepal received more than 300 mm of rainfall (http://www.dhm.gov.np/). The tip of western Nepal also experiences very high rainfall and has been the site of several flood and landslides events. These kinds of short-term heavy rainfall, flood, and landslide events have largely impacted people's livelihoods, and many have lost their lives and property.

Further, because the Tarai region of Nepal is known as the floodplain area, the soils of this area are more fertile than those in the Hill and Mountain regions (Bajracharya and Sherchan 2009). Due to the erratic short-term heavy monsoon rainfall, the flood events occur more frequently during the monsoon season, and as a result the Siwalik, Middle Hill and High Mountain regions of Nepal experience high rates of soil erosion (Chalise et al. 2019). The eroded soil is washed away by floods and can be deposited in the Tarai region due to plain topography and lower velocity of the river, increasing the fertility of the topsoil in the Tarai regions compared to the other regions of the country.

3.4.4 Drought

Drought is one of the most complex, harmful, and least understood extreme climatic events. It is dependent on several variables, including precipitation, temperature, land surface parameters, altitude, and wind, among others. Furthermore, our understanding of drought varies depending upon different factors such as intensity, location, and sector (Khatiwada and Pandey 2019). It is well known that the major factor influencing drought evolution in Nepal is the lack of precipitation linked with summer monsoon (south-easterly) and wintertime (westerly) circulations. The amount of annual precipitation generally decreases from east to west (Shrestha 2000), and winter monthly precipitation amounts in western Nepal are on the order of 50 mm or less. This is brought about mainly by synoptic weather disturbances that are dynamically different from the monsoon season (Barlow et al. 2005).

Drought has a devastating impact on rural livelihoods that depend mainly on rain-fed subsistence agriculture. A small reduction in precipitation can have a serious impact on activities such as crop production and may disturb social harmony by creating water-use conflicts (Ghimire et al.

2010). Since the 1990s, droughts have resulted in food deficits, especially since 40 out of 75 districts experienced a food deficit in 2008/2009, leading to serious nutritional crises (MoAC et al. 2009). It is crucial to examine and understand the climate drivers that lie behind the development of drought in Nepal.

3.4.5 Frosts and Cold Waves

Besides drought, frosts and cold waves are another major seasonal disaster in Nepal. Frosts dominate in the high altitudes of Nepal whereas cold waves dominate in low altitudes. The country was ranked as one of the world's most vulnerable countries for a natural disaster by the World Bank in 2011 (MoHA and DPNet-Nepal 2015). Nepal is expected to experience an increase in temperature, more frequent heatwaves, and shorter frost durations in the future.

A dry winter and cool summer (temperature below 22 °C) dominate in the 10% of Nepal occupied by the mountainous region. The elevation between 4000 and 6000 m asl (about 19% of Nepal's area) experiences the polar type of climate, while frost and snow cover the remaining area (9%) above 6000 m asl creating permanent frost and cold desert conditions (Poudel et al. 2020; Sharma 2016).

During the winter, the low-lying districts become colder than the High Mountain region, which experiences lower temperatures for at least half the year. Cold waves that bring unexpected freezes and frosts can kill plants during the early and most vulnerable stages of growth, resulting in crop failure that directly impacts agricultural productivity (Malla 2008; Panday 2012). Such cold waves create vulnerabilities for people's livelihoods and cause many to lose their lives, especially in the southern low land (Tarai) region (Pradhan et al. 2019).

3.5 Agro-Ecozones and Soil Climate

The agro-ecozones of Nepal promote systematic farming and agricultural development. Agro-ecozones are conceptualized by grouping neighboring areas that share similar topography, altitude, climatic conditions, and soil types (Carson 1992; Gauchan and Yokoyama 1999). The concept adopted from Carson (1992), and from Gauchan and Yokoyama (1999) shows five agro-ecozones in Nepal (Table 3.1 and Fig. 3.5). Out of these five, the Tarai agro-ecozone is situated in the southern part of the country, and most of its landscape is flat with fertile soil. This agro-ecozone is conceptualized below 600 m asl and covers some areas of the Siwalik region of the country. The Tarai agro-ecozones are normally subcategorized as lower wetland, mid-wetland, upland/dry land, forest mixed land, and flood-prone land (Gauchan and Yokoyama 1999). The overall climate of this zone is tropical. Paddy, wheat, potato, legume/oilseed, maize, vegetable crops are cultivated in the irrigated lowland area; similarly, maize and mustard are the main crops cultivated in the upland area within the Tarai agro-ecozone (Rimal et al. 2018).

The river basin's agro-ecozones in Nepal are mainly situated between 600 and 1200 m asl with subtropical and with valley floor land types. Most of this zone is located within the Siwalik region and partly within the Middle Mountain region (Fig. 3.5). This zone's primary agricultural potential is subtropical fruits and food grains. The details of the Lower Hills (1200 to 2200 m asl), High Hills (2200 to 3500 m asl), and High Mountain (3500 to 4800 m asl) agro-ecozones are summarized in Table 3.1 and presented in Fig. 3.5. Further, due to its extreme climatic conditions and topography, the landscape of the High Himalayas/Himal region, which is situated above 4800 m asl, is conceptualized as having no agricultural potential (Gauchan and Yokoyama 1999).

Climate has a direct influence on soils. Warm conditions promote the chemical and biological reactions that parent materials into the soil. Similarly, the development of the soil profile and the soil's physical and chemical composition are greatly affected by weather and have a role in crop performance. Furthermore, differences in soil fertility are an essential driver of species turnover in productive environments (Paoli et al. 2006). Soil develops its ability to support the current ecosystems under changing climate—this will lead to changes in the communities of plants growing in different parts of the country.

Not only does climate influence soil, but also soil can influence climate; for example, soils that are wetter or denser hold heat and stabilize their surroundings during temperature changes more than looser, drier soils. In Nepal, local rice varieties are valued, especially in remote mountain areas adapted to diverse ecosystems, including cold stress, water scarcity, flood conditions, and poor soils (Sthapit et al. 2008). Many studies have used estimated realized climate niches to predict potential biogeographical changes in species distribution. This may be due to low temperatures in the temperate zone being directly linked to vital eco-physiological processes. In contrast, warm temperatures, especially in the Tarai region, are more indirectly related to moisture limitations, resistance to pathogens, and species competition (Vetaas 2002).

3.6 Climate Change and Its Impact

Nepal has observed a decreasing trend of precipitation and an increasing trend in temperature (Fig. 3.3) in recent decades (DHM 2017; Paudel et al. 2020), along with a rising trend of drought and flood events (Dahal et al. 2016; Pangali

Table 3.1 Agro-ecozones and farming promises in Nepal

Agro-ecozone	Elevation range, m	Climatic condition	Landform	Farming promise
Tarai	60 to 600	Tropical climate	Wetland, upper and mixed wetland, dry land fans, foot slope fans, and valley floor	Paddy, wheat, potato, legumes/oilseeds, maize, vegetables, and tropical fruits
River basins	600 to 1200	Sub-tropical climate	Valley floor	Foodgrains and subtropical fruits
Lower hills	1200 to 2200	Warm temperate climate	Hill side terraces and slopes	Citrus, temperate fruits, off-season vegetables
High hills	2200 to 3500	Cool temperate climate	Steep slopes and terraces	Temperate fruits and vegetables, seed potato
High mountain	3500 to 4800	Alpine climate	Steep/flat area	Livestock production

Sources Carson (1992) andGauchan and Yokoyama (1999)

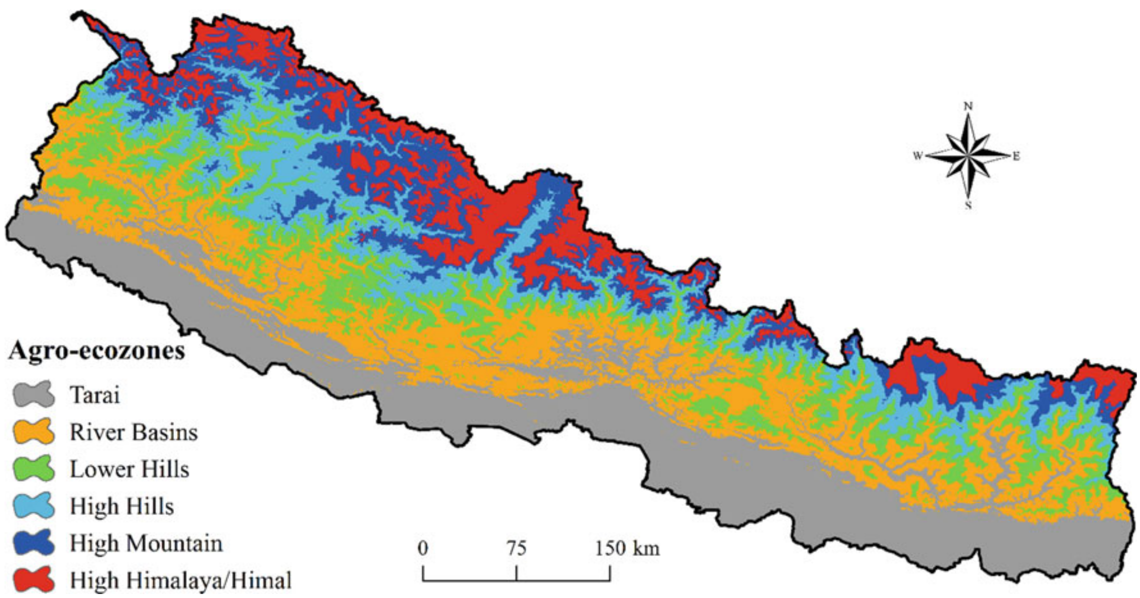

Fig. 3.5 Delineated agro-ecozones of Nepal, adopted from Carson (1992) and Gauchan and Yokoyama (1999)

Sharma et al. 2019). These indicate ongoing climate changes within the region.

Climate change has impacted several sectors in Nepal; however, the impact is most noticeably reflected in the agricultural system (Malla 2008). This impact is more significant on the vulnerable, marginalized communities residing at different ecological zones of the country, such as the communities in the lowland area (Tarai region) that have been the victims of frequent flash-flood events. Likewise, extended cold waves have also largely impacted the Tarai region (Pradhan et al. 2019). However, the Glacial Lake Outburst Flood (GLOF), avalanches, and landslides have more significantly impacted the Mountain and Hill regions of the country. Due to different scales of landslides in different years, especially during the monsoon season, a large number of people have lost their property and their lives (Sudmeier-Rieux et al. 2012). These are all associated with climate change impact driven primarily by anthropogenic activities. To mitigate these climate change impacts in Nepal, suitable adaptation strategies need to be developed based on local geography and conditions. Further, there is an urgent need to develop drought-resilient crops and improved irrigation systems to minimize the impacts of climate change on agriculture and people's livelihood (Paudel et al. 2020).

Climate is one of five factors with a strong influence on soil formation, primarily through the interplay of temperature, moisture, and various patterns of weathering and leaching. Lately, anthropogenic causes have established themselves as above natural variability in the climate system, quickening the rate of climate change over the past century (Crowley 2000). Given accelerated population growth, specifically in urban areas, excessive and indiscriminate use of natural resources has imposed undue pressure on the environment. The assessment report AR5 of the Intergovernmental Panel on Climate Change (IPCC) stated that long-term simulations for the twenty-first century show more frequent adverse weather conditions attributed to climate change (IPCC, 2013). Compared to the late twentieth century, the projected changes for the twenty-first century show a high probability of a decrease in the frequency and magnitude of cold days and nights, along with an increase in the frequency and magnitude of unusually warm days, heat waves, and precipitation (Seneviratne et al. 2012). However, the magnitude and extent of climate change's impact on soils are poorly understood, as soils themselves can be a source or sink of C, at times switching from C sink to C source with antagonistic effects on climate change (Bliss and Maursetter 2010). Predicting the impact of climate change on soil processes is also difficult because global and regional climate models are based on assumptions that yield uncertainties for different climate trajectories.

Another serious impediment in applications of General Circulation Models (GCMs), specifically in the Himalayan region, is the mismatch between the spatial resolution of the GCMs and the region's complex terrain, illustrating the need for high-resolution regional climate models that more realistically represent the region's topography (Panday et al. 2015). Traditionally, Nepal has been a predominantly subsistence-oriented agrarian economy. To a large extent, its wide variety of climatic zones, ranging from tropical to alpine/tundra is due to its large and steep altitudinal gradient, resulting in a high degree of agro-ecological diversity. Orographic forcing is the dominant factor affecting precipitation in the region (Lang and Barros 2004). Various studies using GCMS and regional climate models (RCMs) further indicate that the temperature in Nepal will increase by 2.5 to 5 °C by 2100 (Immerzeel et al. 2012; Nepal 2016).

In addition, more frequent and high-intensity rainfall events are likely to be more common in the future, leading to an increase in rainfall erosivity levels (Mondal et al. 2015). In the Himalayan region, the effects of climate change are very likely to cause a dramatic increase in the number of warm nights, a reduced number of frost-free days, an increase in the number of consecutive dry days, and frequent extreme precipitation (Panday et al. 2015). In addition, climate change is likely to alter the region's hydrological cycle. The cascading effects of altered hydrological phenomena include glacial retreat, inconsistent snow cover change, the bursting of glacial lakes, and flash floods (Kang et al. 2010). The local downstream impact from such climate-change-induced phenomena on people's livelihoods is profound yet largely unknown, mostly due to the lack of pertinent ground truth measurements in this region (Eriksson et al. 2009).

Soil erosion is a natural process of soil transport mainly due to various erosive forces (wind, water, ice, gravity, etc.). Natural soil erosion occurs everywhere—albeit at a slow rate in cases where there is little to no human intervention. Lately, anthropogenic pressure such as improper and unsustainable land use and deforestation have triggered an accelerated rate of soil erosion. This is especially critical to Nepal, as the terrain is characterized by a diversity of fertile but fragile physiographic landscapes. Past research in Nepal has shown different magnitudes of annual soil loss due to erosion in the landscape. Disturbance of soils and the removal of vegetation from landscapes with steep slopes combined with frequent and high-intensity rainfall will only further increase the severity of landslides and soil erosion.

The effects of climate change on soil can be immediate or extended over time, ranging from less than a year to hundreds of years. Change in climate can cause changes in soil parameters on a varying timescale. Soil parameters such as soil temperature, moisture, bulk density, permeability, porosity, and nitrate content fluctuate more quickly (< 1 yr) compared to pH, hydraulic conductivity, cation exchange capacity (CEC), organic matter content (10 to 100 yr) and mineral composition, texture, and particle-size distribution (> 100 yr) (Varallyay 1990). However, the key impact of climate change on soils will be primarily driven by changes to soil-moisture regimes (Bullock 2005). Warmer temperatures and less rainfall will result in less soil moisture, which in turn could have large unwanted implications for the natural and agricultural ecosystem, disrupting the normal carbon cycle (Bullock 2005).

Additionally, an increase in soil temperature will expedite the rate of various soil processes (e.g., nitrification, mineralization, and weathering) given the soil-moisture levels are ample. There is a lack of unanimity among the scientific community regarding the fate of soil organic matter (SOM). One study conducted in the mid-Himalayan region to predict short-, medium-, and long-term trends of soil organic carbon (SOC) dynamics using the CENTURY model (used for simulating carbon and nutrient dynamics for various ecosystems (e.g., grassland, shrubland, pasture, forest) (Parton et al. 1993) found that SOC for A2 and B2 scenarios could drop by up to 19.2% by 2099 (Gupta and Kumar 2017).

3.7 Conclusion

The climatic variation in Nepal within its various agro-ecozones is mostly due to vast topographic variation within a short aerial distance. The altitudinal gradient from the southern Tarai plain to the northern high Himalaya contributes to the six major climatic belts in Nepal, forming a tropical climate in the south to a tundra/nival/ trans-Himalayan climate in the north. Nepal has four major climatic seasons: pre-monsoon, monsoon, post-monsoon, and winter. The monsoon season is marked by heavy rainfall, preceded by the high-temperature pre-monsoon season. The increasing trend of temperature, the decreasing trend of precipitation, and the increasing episodes of drought can be observed in the climate archives of the country. The changing climate has primarily impacted the agricultural system and people's livelihood. The magnitude of impact, however, varies by region. Further, the country has five major agro-ecozones with varying premises of farming and these zones are more suitable for formulating farming strategies and policy for the country's overall agricultural development. Moreover, the development of the soil profile and its physical and chemical composition are greatly affected by climate and play a critical role in crop performance.

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