Chapter 2
Climate Variability and Change in the Sanjiangyuan Region

Glenn R. McGregor

Abstract Described as the "water tower" of Asia, the Sanjiangyuan region contains the headwaters of the Mekong, Yangtze and Yellow rivers. Climate variability and change in this region therefore has fundamental impacts on a range of climate-related ecosystem services. This chapter presents an overview of the climate controls and the characteristics of the Sanjiangyuan region as well as the nature of observed climate variability and change. The climate of the Sanjiangyuan region is the outcome of both regional and distant climate processes. The region lies in a transitional zone between semi-arid and sub-humid climate conditions, the result of geographical and seasonal contrasts in moisture receipt from distant source areas over the Indian and Pacific oceans and the South China Sea. In addition to marked temperature and precipitation seasonality, inter-annual climate variability and extremes are marked features of the region's climate. Despite the paucity of observational data, it is clear that the Sanjiangyuan region is experiencing pronounced changes in climate, the origins of which are yet to be established unequivocally. The advance of rapid economic development against a backdrop of a highly variable climate resource and an uncertain climate future raises the spectre of ecosystem service degradation and the challenge of managing climate-related ecosystem services. An improved understanding of Sanjiangyuan region climate-forcing factors at the regional to global scale, regional climate characteristics and the possible consequences of human-induced climate change will assist with meeting this challenge, as will building capacity in climate risk management.

Keywords China climate · Climate controls · Climate resources · Inter-annual variability · Climate extremes · Climate change · Climate risk management

G.R. McGregor (✉)
Department of Geography, Durham University, Lower Mountjoy,
South Road, Durham DH1 3LE, UK
e-mail: glenn.mcgregor@durham.ac.uk

2.1 Introduction

Covering an area of 360,000 km^2 and located on the Qinghai–Tibetan Plateau in the southern and eastern parts of Qinghai Province, the Sanjiangyuan region delivers significant ecosystem services. Often described as the "water tower" of Asia, the Sanjiangyuan region contains the headwaters of three major rivers: the Mekong (Lancang), Yangtze and Yellow rivers. Changes and variability in climate have a fundamental impact on the delivery of ecosystem services, ecosystem health and environmental stability and thus livelihood sustainability. The purpose of this chapter is to present an overview of the climate controls and characteristics of the Sanjiangyuan region as well as to outline the nature of observed climate variability and change.

2.1.1 Climate Controls

Controls on the climate of the Sanjiangyuan region occur at a range of scales from the continental scale of atmospheric circulation over East Asia, to the regional scale of the high and vast Qinghai–Tibet Plateau and local scales of landform and relief variations across the region.

2.1.2 Atmospheric Circulation Over East Asia

The climate of the Sanjiangyuan region is a result of the interaction between a number of components of the atmospheric circulation system of the broader East Asian region (Ding and Chan 2005; Wang and Chen 2012). These are illustrated schematically in Fig. 2.1. Chief among these are the East Asian summer and winter monsoons.

The East Asian summer monsoon flows are a product of the convergence of air from three high-pressure systems:

- the Mascarene high over the southern Indian Ocean which produces south-westerly flows over the Bay of Bengal and western parts of Southeast Asia,
- the wintertime high-pressure system over Australia and associated cross-equatorial flows from the south over Southeast Asia and
- the western Pacific subtropical high which brings moist unstable south-easterly air from the China Sea and Pacific Ocean.

All three flows converge to produce moist, unstable, generally southerly streams of air over the Sanjiangyuan region that result in elevating atmospheric moisture and precipitation levels during the summer months. For some areas of the Sanjiangyuan region, the total annual precipitation is almost wholly dependent on
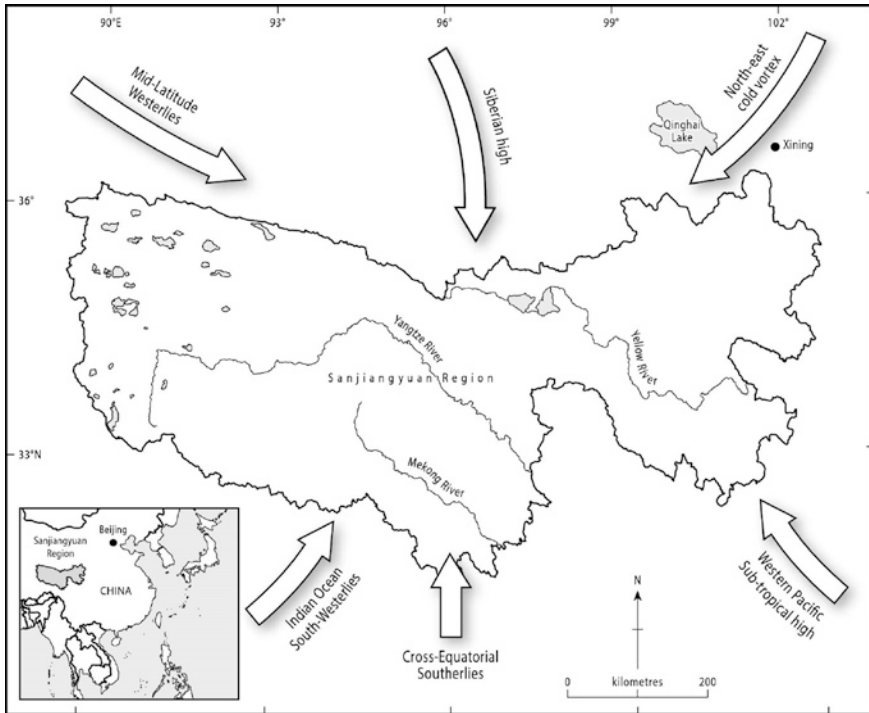
Fig. 2.1 Main air masses influencing the Sanjiangyuan region. Moist, unstable air masses of the Indian Ocean south-westerlies, cross-equatorial southerlies and the western Pacific Subtropical high merge to form the East Asian summer monsoon, which brings summer moisture and precipitation to the Qinghai–Tibet Plateau. The winter monsoon is associated with the northerly Siberian High, which brings sub-zero temperatures to the Sanjiangyuan region, suppressing precipitation. The mid-latitude westerlies and the north-east cold vortex are physically steered by the sheer bulk of the Qinghai–Tibet Plateau (*Source* Adapted from Ding and Chan 2005)

the East Asian summer monsoon. East of the Sanjiangyuan region, the flows of moist unstable air from the south converge with cold air from the middle to high latitudes, emanating from the region of a cold vortex over the north-west Pacific, to form the Meiyu front, a major feature of the East Asian monsoon.

Although a significant component of the East Asian climate system, the East Asia winter monsoon has received much less attention in the literature compared to its summer counterpart from both physical process and societal impact perspectives (Chen et al. 2014a, b, c; He and Wang 2013; Li et al. 2014). The term winter monsoon describes the movement of cold air in a south and eastward direction over eastern and southern China (Fig. 2.1). Such flows make their way across the equator to form the summer monsoon over the Maritime Continent and northern Australia. The winter monsoon period is characterised by not only sub-zero temperatures in the Sanjiangyuan region but also cold air outbreaks over eastern

China (sometimes referred to as cold northerly surges), explosive cyclogenesis off the coast of East Asia and coastal weather disturbances that propagate along the coast of East China (Chan and Li 2004). The winter monsoon owes its origins to the wintertime development of the Siberian High (Fig. 2.1). This is a cold-core high-pressure system which represents a shallow but extensive layer of very cold air that develops over the continental middle latitudes in the region of Siberia–Mongolia. As such, it is extremely stable with the result that local precipitation generation processes are suppressed and flows of moist air from any direction are blocked. In the eastern parts of the Sanjiangyuan region, surges of cold air can have two origins, namely from the north-east due to anticyclonic flow on the eastern flanks of the Siberian High, and from the west as cold air slides off the plateau where air takes on the climate characteristics of the very cold-extensive high-elevation snow- and ice-covered surfaces.

2.1.3 The Qinghai–Tibet Plateau as a Barrier to Air Movements

The Qinghai–Tibet Plateau, often referred to as the "roof of the world", is a massive elevated surface that stands at more than 4000 m above sea level. The climate effects of the plateau are wide ranging. It acts as a barrier to air mass movement and physically steers the mid-latitude upper westerly winds. The Plateau is a heat sink in the winter and a heat source in the summer. It also plays a role in the formation and dynamics of the South Asian High, and winter snow extent and depth across the plateau appear to have an effect on spring and summer rainfall for a number of regions across China.

The shear physical size and elevation of the Qinghai–Tibet Plateau present a physical barrier to flows of air from the south, west and north and to a lesser extent from the east where elevations are lower. The barrier effect of the Qinghai–Tibet Plateau is demonstrated effectively by Xu et al. (2011) in a study on precipitable water with the southern Plateau noted as wetter than the central area because of the blocking effect of the plateau on the monsoon. In winter, the plateau plays an important role in steering the Asian subtropical jet stream to the south and accelerating the westerly winds on its southern flanks. During this season, because of steep south-to-north temperature gradients, wind speeds high in the jet stream tend to accelerate to the east of the plateau. The position of the upstream entrance region of the subtropical jet stream is important for wintertime precipitation over south-eastern China. This is because acceleration of air into the jet stream creates a region of strong ascending motion and thus precipitation south of the jet entrance region (Molnar et al. 2010). As a result, some of the more eastern parts of the Sanjiangyuan region (east of around 98–100°E) are affected by jet stream-related precipitation processes. Furthermore, the large amounts of condensation that occur associated with precipitation in this region generate diabatic heating and thus atmospheric instability. This, in combination with the orographic effects

of the Plateau and attendant ascending motion, creates low-level flow in the sub-tropics. As a result, moist air from the south moves in a north-westerly direction. Some of this moisture manages to penetrate into the south-eastern parts of the Sanjiangyuan region, contributing to the relatively high-wintertime precipitation totals found here in comparison with the more western parts of the Sanjiangyuan region. With the onset of the northern hemisphere spring and summer, the temperature gradient between the equator and high latitudes decreases. Consequently, the jet stream tends to weaken and move over the Qinghai–Tibet Plateau and Sanjiangyuan region during spring and further north by mid-summer, taking with it its attendant zones of ascending motion. The northward movement of the jet stream, in combination with the arrival of moist unstable flows of monsoonal air from the south, announces the arrival of the East Asian summer monsoon and increasing the levels of summer precipitation over the Sanjiangyuan region. In addition to its effects on the subtropical jet stream, it has been suggested that the Qinghai–Tibet Plateau plays an important role in acting as an obstacle to south-ward flows of cold–dry air from higher latitudes. From a geologic perspective, this may well have been important in influencing the development of the Asian mon-soon (Boos and Kuang 2010; Song et al. 2010).

As the Qinghai–Tibet Plateau can be both a heat sink and a heat source it has the potential to alter atmospheric temperature and pressure patterns. Notwithstanding some of the debates relating to the importance of Plateau heating for the generation of the summer monsoon, seasonal heating and cooling of the atmosphere over the Sanjiangyuan region have important regional climate effects. In the summer, convective heating of the atmosphere can lead to summer time convective storms and intense rainfall over valleys and high ground. In the win-ter, atmospheric cooling facilitates the development of intense inversions and very stable air, especially over valley surfaces, the consequence of which is cold-air ponding. Studies on the seasonal march of heating and cooling indicate that from late February, the more southern parts of the Qinghai–Tibet Plateau in the south of the Sanjiangyuan region begin to heat (Xu and Zhang 2008; Wonsick and Pinker 2014). By May, most of the Plateau has become a heat source for the atmos-phere with maximum atmospheric heating reached over the eastern parts of the Sanjiangyuan region in July. From late August, there is a gradual demise in heat-ing. By October, the eastern regions of the Plateau, including the Sanjiangyuan region, begin to act as a cold source which intensifies through to January (Xu and Zhang 2008). Variations in seasonal heating over the plateau and associated impacts on cyclonic activity to the north-east of the plateau appear to play a role in the sign of precipitation anomalies over east China (Wang et al. 2014a, b). Heating in spring over the Plateau is important for summer rainfall in the wider Sanjiangyuan region (Duan et al. 2013a, b).

The South Asian High is an area of high pressure in the stratosphere that lies above the Qinghai–Tibet Plateau in summer (Xu and Zhang 2008). The South Asian High has a large spatial extent at this time of the year stretching west over the Iranian Plateau (50–70°E). The section of the South Asian High lying over the Plateau (80–100°E) is often referred to as the Tibetan High. Heating of the

Qinghai–Tibet Plateau during summer has been suggested as one of the principal factors in the establishment of the South Asian High/Tibetan High. Strong ascending motion, because of surface summer heating, results in high geopotential heights and an area of divergence in the upper troposphere above the Qinghai–Tibet Plateau. In terms of climate effects, the South Asian High is crucial for the onset of the Asian summer monsoon (Qian et al. 2005). Summer precipitation in northern China is closely associated with the longitudinal position of the South Asian High/Tibetan High in June, as opposed to the intensity of the South Asian High/Tibetan High (Huang and Qian 2003). In years with positive (negative) precipitation anomalies over northern China, the centre of South Asian High/Tibetan High moves west and north (south and east) of its climatological position.

2.1.4 Climate Effects of Local Variations in Landforms and Relief

Other elevation effects on climate include decreasing temperatures and in some cases increasing precipitation totals with altitude. While the inverse elevation temperature relationship holds for most areas across the Qinghai–Tibet Plateau and Sanjiangyuan region, precipitation dependence on altitude varies spatially. Generally, on the southern flanks of the Sanjiangyuan region, which face into the moist summer monsoon flows, there is a clear increase in precipitation with elevation due to orographic forcing (Domros and Gongbing 1988). However, in northern high-elevation parts of the Sanjiangyuan region, this association breaks down due to a combination of distance from moisture source and rain shadow effects. Further, because of the varied topography of the Sanjiangyuan region, aspect or orientation plays an important role in creating steep precipitation gradients across orographic barriers with upwind slopes wetter than their downwind equivalents (Chen and Bordoni 2014; Shi et al. 2008). At the daily timescale, local topographic effects and landscape, rather than large-scale synoptic weather systems, play an important role in determining the nature of the diurnal cycle of precipitation. For example, for hilly regions, there is a daytime precipitation peak, whereas over lakes and valleys, there are evening to nocturnal peaks (Guo et al. 2014). Similarly, there are contrasts over mountain ridges and valleys, with the former displaying morning or early afternoon precipitation peaks, while the latter tend to have late afternoon or evening peaks, as might be expected with mountain–valley local circulations (Guo et al. 2014). The diurnal variation of precipitable water over the Qinghai–Tibet Plateau is multifarious because of its topographic complexity (Xu et al. 2011).

2.2 Climate Characteristics

With the use of the terminology associated with the widely accepted Köppen–Geiger Classification (Peel et al. 2007), the climate of the Sanjiangyuan region falls broadly into the category of "arid steppe cold (BSk)". This classification is broadly in line with the climate types identified in a number of studies specifically focused on China, as discussed in Domros and Gongbing (1988) and McGregor (1993). Frustratingly, the lack of long-term observed climate data, at a suitable spatial resolution, hinders the description of possible climate sub-types within the Sanjiangyuan region. However, as more climate information becomes available, there is emerging evidence of a variety of climate sub-types across the broader Sanjiangyuan region (Geng et al. 2014; Lu et al. 2008). Given its considerable longitudinal range and the presence of significant topographic barriers, it is perhaps no surprise that available temperature and precipitation observations reveal considerable variation in climate resources across the Sanjiangyuan region. This is clearly seen when climagraphs for a number of climate stations, either within or lying just beyond the margins of the Sanjiangyuan region, are inspected (Fig. 2.2). Three broad climate sub-types are apparent: arid (Fig. 2.2a–c), semi-arid (Fig. 2.2d–f) and sub-humid (Fig. 2.2g, h).

The effects of the East Asian summer monsoon are clearly manifest in the pronounced seasonal distribution of rainfall in all three climate sub-types. For example, Yushu (Fig. 2.2g), which has a sub-humid climate, receives over 90 % of its annual total precipitation of 484 mm within the summer months. Stations further to the north and east, such as Tongde (Fig. 2.2e) and Xining (Fig. 2.2d), demonstrate similar seasonality, but decreasing precipitation amounts with annual totals of 428 and 369 mm, respectively. Greater Qaidam, Golmud and Dulan (Fig. 2.2a–c) have precipitation regimes that typify the arid regions of the wider Sanjiangyuan region with respective annual precipitation totals of 83, 38 and 181 mm, largely concentrated in the months of May to September. Stark seasonal contrasts in temperature are also evident, a result of strong summer radiation heating and advection of heat via summer monsoon flows. There is little heating in the winter due to the seasonal shift of the zone of maximum radiative heating south and outflows of cold–dry northerly continental air from the Siberian High during the winter monsoon. Overall, mean annual temperature is closely related to altitude.

While climatologists have traditionally relied on station data to gain insights into climate characteristics and resources, the availability of a range of climate re-analysis products and gridded climate data sets has made it possible to gauge the nature of climate for regions where few conventional observations are available (Tong et al. 2014a, b; You et al. 2013, 2014a, b; Zhang et al. 2013). Figure 2.3a, b shows the spatial distribution of mean January and July temperatures across the Sanjiangyuan region for the period of 1971–2013 based on mapped outputs from the NCEP/NCAR re-analysis project (Kanamitsu et al. 2002; Saha et al. 2010).
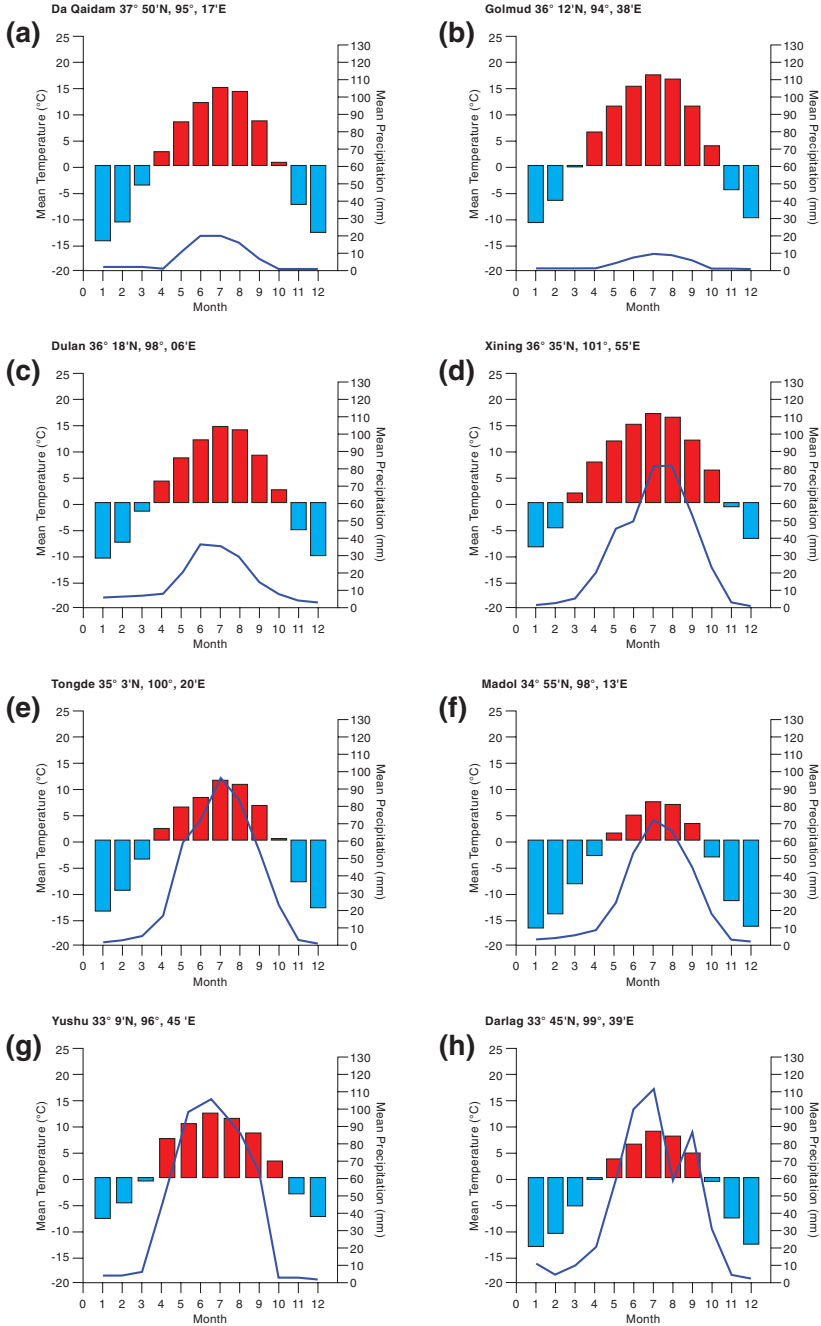
Fig. 2.2 Climagraphs for selected locations across the broader Sanjiangyuan region. *Bars* indicate temperature, while precipitation is shown as a *solid line*. Arid zones are exemplified in **a–c**, semi-arid zones in **d–f**, and sub-humid zones in **g–h** (*Data source* Domros and Gongbing 1988)
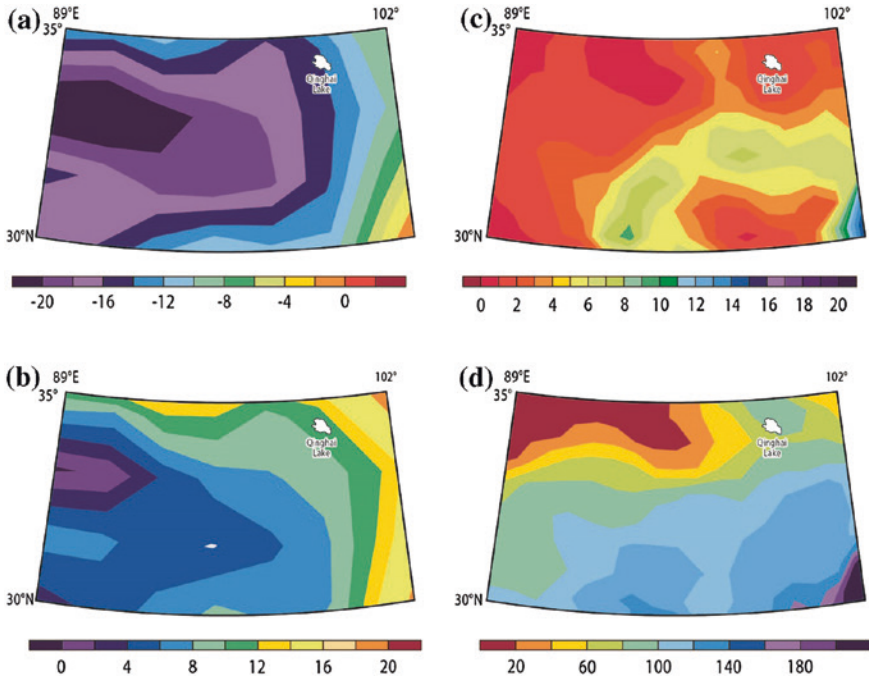
Fig. 2.3 Spatial distribution of mean temperature in °C (**a**, **b**) and precipitation in mm (**c**, **d**) for January (**a**, **c**) and July (**b**, **d**) during 1972–2012. Plots are based on twentieth-century Reanalysis V2 data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, at http://www.esrl.noaa.gov/psd/

Similarly, precipitation products from the Global Precipitation Climatology Centre (Schneider et al. 2014) have been used to construct precipitation maps for the same months and period (Fig. 2.3c, d).

Temperature in both January and July demonstrates a strong west-to-east gradient of increase (Fig. 2.3a, b), reflecting elevation control with western high-elevation areas possessing lower temperatures than the eastern parts of the Sanjiangyuan region. Such strong longitudinal temperature differences across the broader Sanjiangyuan region may influence the magnitude of summer rainfall over some parts of China (Zhu et al. 2010). Climatologically, the entire Sanjiangyuan region experiences sub-zero temperatures in the core winter month of January, while in July, temperatures in the east of the Sanjiangyuan region can range between 12 and 16 °C on average (Fig. 2.3a, b). During winter, cold and dry continental air, mass-related stable atmospheric conditions, in combination with the high relative relief, produce severe inversions. This can lead to very poor air quality in valley settings where there is significant urban development (e.g. Xining). As evident from the climagraphs, a comparison of the January and July temperature maps indicates significant seasonal contrasts in temperature across the Sanjiangyuan region, with seasonal ranges in the order of 20–30 °C.

A noteworthy feature of the precipitation climatology of the Sanjiangyuan region, as hinted at by the climagraphs, is the almost region-wide extremely low winter precipitation totals. This is clearly demonstrated by the mapping for the core winter month of January (Fig. 2.3c). Low totals are the result of the out-flow of cold–dry polar continental air from the region of the Siberian High to the north. Any precipitation that falls is usually in the form of snow due to the low temperatures and the result of the penetration of weather disturbances from the east emanating from the area of the north-east cold vortex over the North Pacific (Fig. 2.2). These disturbances are steered by the topography. Hence, most winter precipitation is restricted to the lower elevation areas, as can be seen for the cres-cent-shaped area of relatively high precipitation in the south-eastern sector of the Sanjiangyuan region (Fig. 2.3c). In stark contrast to January, precipitation totals for July are significant (Fig. 2.3d). The spatial distribution of precipitation in this month reflects elevation, topographic barriers and distance from moisture source effects. The general south-east-to-north-west decrease in precipitation reflects the distance of areas within the Sanjiangyuan region from the Indian Ocean/Bay of Bengal, equatorial and western Pacific moisture sources (Fig. 2.1). Not only is there a general south-to-north precipitation gradient but also a noticeable west-to-east precipitation decrease is evident. This is due to the high elevation of the south-western parts of the Sanjiangyuan region which prevents moisture reaching elevated plateau surfaces as the majority of moisture in the summer monsoonal flows is carried below 3500 m. Further, the Qinghai–Tibet Plateau steers moist monsoonal flows originating from the Bay of Bengal region in an eastward direc-tion. The Qaidam Basin, which lies to the north of the wider Sanjiangyuan region, is an area of persistent winter to summer low precipitation totals. Indeed, this is one of the driest areas in China. The Qaidam Basin has a typical continental inter-montane desert climate, resulting from rain shadow effects. Flows of moist air are generally prevented from entering the basin due to topographic blocking by the Kunlun Mountains to the south. However, disturbances associated with the East Asian Summer Monsoon do provide limited moisture to the area during the sum-mer months of May to September. Total annual precipitation at Greater Qaidam is only 83 mm (Fig. 2.2a). Annual precipitation for inner parts of the Qaidam Basin can be as low as 25 mm. Due to the high elevation of the basin, summer precip-itation is often in the form of snow. However, the number of annual snow days remains low at around 12–13, compared to 37–38 snow days a year in the sub-humid locations in the south of the Sanjiangyuan region such as Yushu (Domros and Gongbing 1988).

2.3 Climatic Variability

Climatic variability in the Sanjiangyuan region can manifest itself in a num-ber of ways such as anomalously warm/cold and/or dry/wet summers or win-ters and climate extremes (Wang et al. 2012a, b). Such anomalies are often due
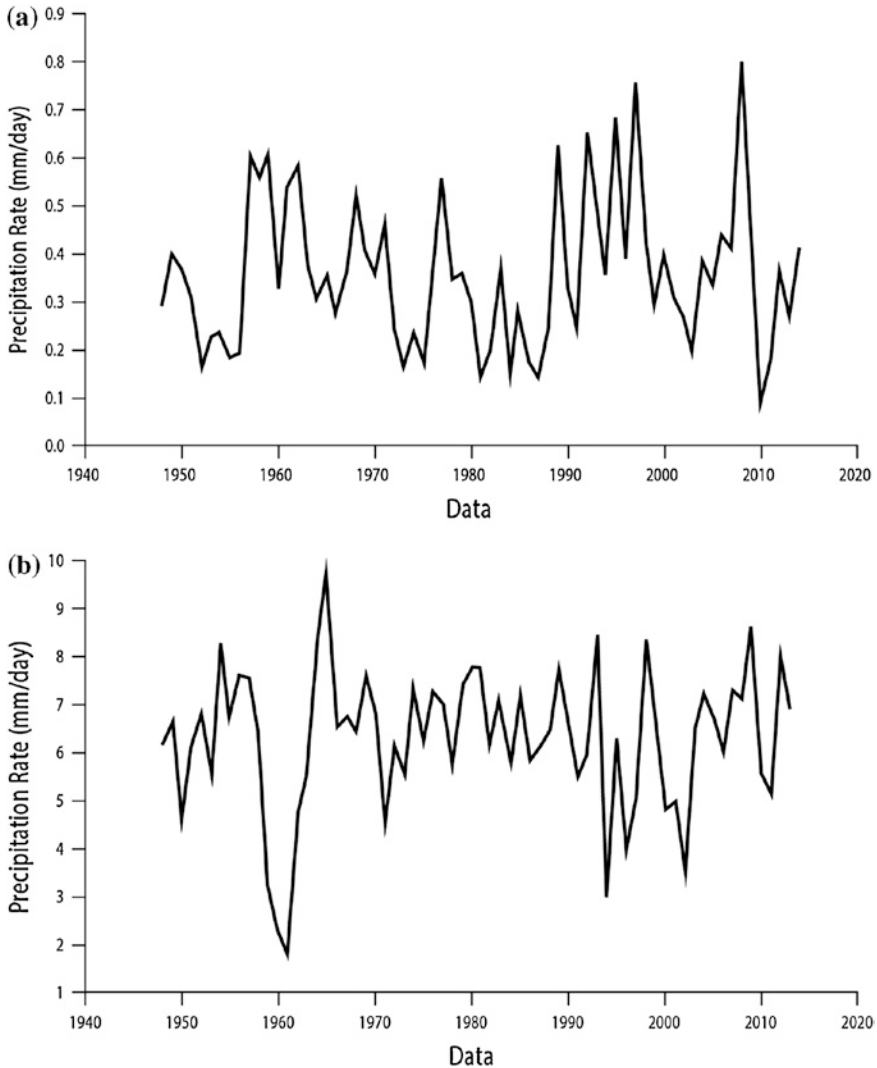
Fig. 2.4 Mean January (**a**) and July (**b**) precipitation in the Sanjiangyuan region expressed as mm per day. The mean total precipitation for January and July can be established by multiplying the mm day^{-1} numbers on the vertical axis by the number of days for January and July. Plots are based on twentieth-century Reanalysis V2 data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, at http://www.esrl.noaa.gov/psd/

to inter-annual variations in the atmospheric circulation patterns that influence an area. Considerable inter-annual climatic variability is apparent from time series plots of January and July precipitation rate expressed as millimetres per day for the eastern part of the Sanjiangyuan region (Fig. 2.4a, b). Notwithstanding

the large differences in precipitation rate between the core winter and summer months, high inter-annual precipitation variability is evident. In terms of ecosystem services, summer precipitation is of particular interest (Mou et al. 2013; Shen et al. 2011), with clear evidence for both anomalously dry and wet summers. Of particular note are the low precipitation rates in the early 1960s which equate with a period of widespread famine in China associated with monsoon-related crop failures. Anomalously dry summers also occurred in 1992, 2002 and 2010–11.

From a climate risk management perspective, knowing the likelihood of upcoming climate anomalies a season ahead can help significantly with advanced planning in climate sensitive sectors of the economy and society, especially those exposed to extreme events such as droughts or floods. Accordingly, there has been an increasing interest in seasonal climate prediction (Lee et al. 2013), including some analyses for the Qinghai–Tibet Plateau (Hartmann et al. 2008). The scientific basis of such predictions depends on developing an understanding of the way in which a number of large-scale modes of atmospheric and oceanic circulation variability may influence climate on a range of timescales (Sun and Zhan 2012). Much effort has been invested in exploring how potential drivers of climate variability, such as the El Niño–Southern Oscillation (ENSO), may influence climate over the Qinghai–Tibet Plateau (e.g. Fan et al. 2012; Ha et al. 2012). Relationships between local/regional climate and variations in the components of the global atmospheric or oceanic circulation system over great distances are often referred to as teleconnections. Several examples are outlined below.

2.3.1 Variations in Temperature Associated with Changes in Atmospheric Pressure Patterns

In an analysis of temperature variability, both positive and negative temperature anomalies were found to be associated with departures of pressure patterns from the long-term mean (Yin et al. 2000). Different pressure–height anomaly patterns were found for the cold (October–March) and warm (April–September) seasons. Key regions where variations in atmospheric pressure patterns appear to influence temperature variability over the Qinghai–Tibet Plateau include Eurasia and the western Pacific. ENSO events were also found to be significantly correlated with temperature anomalies (Yin et al. 2000).

2.3.2 Variations in Precipitation Associated with Changes in Atmospheric Pressure Patterns

Variations in moisture flux from the Bay of Bengal, the South China Sea and North China are critical for determining winter and spring precipitation anomalies

(Wu et al. 2013a, b). It is noted that teleconnections play a role in drought and flood occurrence, such that sea surface temperature anomalies in the equatorial Pacific give rise to periods of drought or flood over extensive parts of southern China by influencing variations in atmospheric moisture transport and thus precipitation anomalies. Although focused on the Mei-Yu front, the work of Kosaka et al. (2011) highlights atmospheric processes and teleconnections over East Asia that may well be pertinent to the Sanjiangyuan region. Kosaka et al. (2011) found that precipitation anomalies over the Mei-Yu region are associated with anomalies of mid-tropospheric horizontal temperature advection. Anomalous warm (cool) advection causes increased (decreased) Mei-Yu precipitation via prompting adiabatic ascent (descent). The anomalous precipitation either bolsters or suppresses vertical motion, through positive feedback. In addition to these local processes, a number of teleconnection patterns appear important, including the Pacific–Japan teleconnection pattern, ENSO and the so-called Silk Road pattern which is the pattern of atmospheric disturbance along the summertime Asian jet. The importance of the Southern Oscillation, the atmospheric component of ENSO, for determining the nature of extreme monthly precipitation over the Qinghai–Tibet Plateau and the seasonal dependence of the relationship has been highlighted by Wan et al. (2013).

Not only do teleconnections to the east over the wider Pacific Basin play a role in precipitation variability, but those upwind to the west also appear important (Liu and Yin 2001). For example, in investigating the relationship between the summer North Atlantic Oscillation and East Asian summer rainfall, Sun and Wang (2012) found that changes in the summer North Atlantic Oscillation pattern can have fundamental impacts on atmospheric flow divergence, vertical motion, water vapour transport, total cloud cover and thus rainfall anomalies over central and northern Asia. Focusing on extreme dryness and wetness on the Qinghai–Tibet Plateau, Bothe et al. (2010) found that extreme cases of drought and wetness can be associated with circulation anomalies in the North Atlantic/European sector and associated downwind atmospheric disturbances across the Eurasian continent. In the case of drought, an intense high-pressure anomaly over Scandinavia, associated with a marked negative surface temperature anomaly, alters North Atlantic storm tracks so that cyclonic systems follow a more south-west-to-north-east route than usual. This generates disturbances over Eurasia which, on reaching south-eastern Asia, suppress moisture supply from the Bay of Bengal and hence enhance dryness over the Qinghai–Tibet Plateau. In contrast, Qinghai–Tibet Plateau wetness is associated with Atlantic storm tracks that take a more west-to-east trajectory across Central Europe. These ultimately interact with atmospheric moisture flows from the Bay of Bengal to guarantee generous moisture supply to the Qinghai–Tibet Plateau (Bothe et al. 2010). Similarly, but at a shorter timescale, eastward propagating areas of anomalous convection associated with the 30–60 day Madden Julian Oscillation influence precipitation at the intra-seasonal timescale (Jia et al. 2011). The main influence of the Madden Julian Oscillation is to modulate moisture transport from the Bay of Bengal, the South China Sea and the western Pacific subtropical high, thus impacting upon summer rainfall totals and monsoon active and break phases.

Precipitation exerts a primary control upon discharge variability in rivers (see Huang et al. 2016, Chap. 4) and the functionality of wetlands (see Li et al. 2016, Chap. 9; Gao 2016, Chap. 10). Accordingly, because of the importance of summer stream flow for providing water resources for economic development dependent on irrigation and power generation, there has been a focus on how variations in large-scale atmospheric and oceanic circulation patterns might influence water resource availability in the wider Sanjiangyuan region. For example, variations in stream flow in the upper Yangtze Basin are associated with sea surface temperatures in the eastern Indian Ocean "Indian dipole" and western Pacific Ocean "ENSO" regions via their influence on precipitation patterns and spring snowmelt (Xu et al. 2007). Positive (negative) ENSO and Indian Ocean dipole episodes are important for severe dryness (wetness) over the Qinghai–Tibet Plateau (Bothe et al. 2010), while the interplay between the Indian Ocean Dipole and El Nino Modoki events can influence the strength of the East Asian monsoon (Feng and Chen 2014).

2.3.3 Decadal-Scale Variations in Teleconnection Patterns

Beyond the intra-seasonal and inter-annual timescales, there is emerging evidence of possible decadal-scale variations in teleconnection patterns which may well impact the climate and thus shape ecosystem and landscape processes over the broader Sanjiangyuan region. For example, the meridional teleconnection over the western North Pacific and East Asia changed around the 1970s (Lin et al. 2010). This period has also been highlighted as significant for an alteration of the position and intensity of the summer North Atlantic Oscillation with consequent effects on precipitation in those areas influenced by weather patterns from the west (Sun and Wang 2012). The non-stationary relationship between the summer North Atlantic Oscillation and rainfall and snowfall over China points to decadal-scale sea surface temperature anomalies in the North Pacific and North Atlantic as important for moderating summer North Atlantic Oscillation precipitation relationships (Chu et al. 2008; Gu et al. 2009). However, the impact of inter-decadal variations in ocean–atmosphere process on summer precipitation in China cannot be ignored, as manifest by Pacific Decadal Oscillation (Ding et al. 2009; Duan et al. 2013a, b; Mao et al. 2011). Decadal-scale changes in aridity and drought occurrence are attributed to Pacific Decadal Oscillation phases, together with possible influences from the Atlantic Meridional Oscillation (Fang et al. 2010; Li and Bates 2007; Qian and Zhou 2014).

2.3.4 Wider Effects of Climate Variability on the Qinghai–Tibet Plateau

Through inter-annual variations in the amount of winter snow, the Qinghai–Tibet Plateau can have a fundamental effect on the intensity of the summer monsoon,

and thus, precipitation totals over some parts of eastern China (Liu and Wang 2011; Wu et al. 2012; Xu et al. 2013). When there are positive winter snow depth anomalies over the eastern parts of the Qinghai–Tibet Plateau/southern parts of the Sanjiangyuan region (between 90°E and 102°E, centred on 30°N), precipitation is greater than normal in eastern China south of the Yangtze River and across north-east China north of around 45°. The aforementioned areas of above normal precipitation are matched with an intervening area of below normal spring precipitation which equates with the north-eastern parts of the Sanjiangyuan region. In terms of effects of Qinghai–Tibet Plateau winter snow cover on summer precipitation, there are some subtle differences to that of spring precipitation such that positive snow anomalies in the northern parts of the Sanjiangyuan region between 90°E and 103°E centred along 35°N are associated with negative precipitation anomalies in the Yellow River Basin, northern China and southern China. At the same time, positive precipitation anomalies are experienced in the Yangtze River Basin.

2.4 Climate Trends and Climate Change

The spectre of human-induced climate change has provided impetus to the search for evidence of trends in a range of climate variables as well as stimulating climate change modelling studies and impact assessments.

2.4.1 Climate Trends on the Qinghai–Tibet Plateau

Observational studies of climate trends reveal a range of alterations in temperature and precipitation characteristics and climate-related phenomena. The climate of the Qinghai–Tibet Plateau experienced moisturising and warming over the period of 1961–2007 in five climate zones covering alpine grassland meadow and desert areas (Li et al. 2010). Warm and wet events have increased, while cold and dry events have decreased. The most significant changes are in winter and autumn, with north-ern Qinghai exhibiting the greatest and most significant decrease in the frequency of extremely low-temperature events. Unlike temperature, the trend in wetness is spatially heterogeneous and seasonally dependent, with increases in precipitation days and amount evident for all climate zones in winter and spring, while summer and autumn display a weak but statistically insignificant decrease in these precipitation metrics. Of all the climate zones considered, south-eastern Tibet was found to demonstrate the largest decrease in the frequency of severely dry events (Li et al. 2010). Similar directions of change in climate variables have also been found in the Sanjiangyuan region where minimum, maximum and mean air temperature as well as precipitation all showed significant increases from 1960 to 2009 (Liang et al. 2013).

In the Qaidam Basin immediately to the north of the Three Rivers Region, climate warmed significantly at an average rate of 0.53 °C per decade over the period

of 1961–2010 (Wang et al. 2014a, b). Seasonally, the greatest warming (0.43–1.01 °C per decade) was found for winter. Annual precipitation has increased at a rate of 7.38 mm per decade with summer demonstrating the greatest increases of around 4 mm per decade.

In addition to mean, maximum and minimum temperature trends, intra-annual temperature variability for the eastern and south-eastern areas of the Qinghai–Tibet Plateau has shown a significant decreasing trend over the period of 1960–2008 (Song et al. 2014a, b). In contrast, a significant increase in inter-annual temperature variability is observed. Interestingly, increases in inter-annual temperature appear to be associated with changes in the frequency of cold/warm nights and warm days, whereas intra-annual variability is associated with an upward (downward) trend in cold (warm) extremes. Significant increases in precipitation in the upper Yangtze region for June, July and August are related to changes in intense precipitation such that more precipitation falls in intense events as opposed to moderate and weak events (Jiang et al. 2008).

Apart from temperature and precipitation, potential evaporation and sunshine hours in the Sanjiangyuan region have increased, while relative humidity and wind speed decreased (Liang et al. 2013). Such changes have profound implications for the effectiveness of aeolian processes and associated desertification processes (see Li and Wang 2016, Chap. 8). Mean annual ground surface temperatures over the period of 1980–2007 increased at greater rates than mean annual air temperature (Wu et al. 2013a, b), while the lower altitudinal limit of permafrost has risen by 25 m in the north and between 50 and 80 m in the south of the Qinghai–Tibet Plateau over the last 20–30 years (Cheng and Wu 2007). Such trends have broader implications for degraded permafrost across the Qinghai–Tibet Plateau (Jin et al. 2008; Yang et al. 2010). Chen et al. (2014a, b) also note the importance of soil freeze–thaw processes for the climate of the Qinghai–Tibet Plateau. As lake levels are generally responsive to changes in climate, some attention has been given to the analysis of limited lake records for the Sanjiangyuan region (Bianduo et al. 2009; see Li et al. 2016, Chap. 9). To the north of the Sanjiangyuan, there has been an overall decrease in the level of Qinghai Lake, despite some short-term but unsustained peaks (Zhang et al. 2011a, b). Analyses of lake level in terms of variations in precipitation, evaporation and run-off reveal that decreasing lake levels (−0.7 m per decade) are associated with rising temperatures at a rate of 0.3 °C per decade. The period of high lake levels between 2004 and 2009 may be due to accelerated glacier and snow cover melt in preceding years (Zhang et al. 2011a, b). In addition, glacier retreat will have grave implications for hydrological processes across the Qinghai–Tibet Plateau (Yao et al. 2007).

2.4.2 Hypotheses to Explain Observed Climate Trends

A variety of explanations have been put forward for the observed changes in temperature and precipitation over the Qinghai–Tibet Plateau (Guo and Wang 2012;

Zhu et al. 2011). Wang et al. (2014a, b) contend that pollution emissions from industrial processes and urbanisation are the main factors contributing to climate warming over the Qaidam Basin, along with a weakening of zonal wind speed (You et al. 2014a, b). Guo and Wang (2012) suggest that the significant warming in northern parts of the Qinghai–Tibet Plateau may be related to pronounced stratospheric ozone depletion, via its influence on radiative and dynamical heating. In terms of variations and trends in East Asian monsoon precipitation, Xu et al. (2013) and Wen et al. (2010) consider that observed changes in summer precipitation can be explained by changes in the apparent heat source over the Qinghai–Tibet Plateau.

A widely invoked explanation for observed trends in climate and climate-related ecosystem services is human-induced climate change at the global scale. While for the Qinghai–Tibet Plateau, no specific climate change attribution experiments have been conducted, Wen et al. (2013) demonstrate that there are greenhouse gas-related anthropogenic effects in daily extreme temperature for China at large. At the regional level, some modelling studies have raised the possibility of the role of changing land use and land surface climatology in observed temperature changes via altering land–atmosphere energy exchanges (Chen et al. 2014b; Chen and Wu 2007; Li and Xue 2010; Lian and Shu 2009). There are a burgeoning number of climate change simulations for China as a whole, but uncertainty exists around the regional specificity and nature of change, especially relating to precipitation projections (e.g. Chen and Sun 2013; Kusonoki and Arakawa 2012; Seo et al. 2014; Shi et al. 2011; Song et al. 2014a, b; Sun et al. 2010; Wei and Bao 2012; Xin et al. 2013a, b; Xu et al. 2009).

Relatively speaking the number of studies addressing the impact of climate change on the Qinghai–Tibet Plateau and more specifically the Sanjiangyuan region is meagre in comparison with elsewhere in China (Wang et al. 2013). Notwithstanding this, there is a growing literature on climate impacts, especially relating to vegetation and grassland health (Chen et al. 2013; Fan et al. 2010; Piao et al. 2012; Qin et al. 2014; Wang et al. 2011; Xu et al. 2008; Zhang et al. 2010) and water resources (Tong et al. 2014a, b; Zhang et al. 2011a, b, 2012). These studies point to potential detrimental changes to a range of ecosystem services, a major concern given the significance of such services for sustainable development and poverty alleviation (Beardsley 2014; Gosling 2013; Howe et al. 2013; Munang et al. 2013; Rodriguez-Labajos 2013; Zhang et al. 2014; Zhao et al. 2013).

2.5 Concluding Remarks

The climate of the Sanjiangyuan region is the outcome of both regional and distant climate processes with marked seasonality in temperature and precipitation. The region lies in a transitional zone between semi-arid and sub-humid climate conditions, the result of geographical contrasts in moisture receipt from distant source areas over the Indian and Pacific Oceans and the South China Sea. In addition to

marked seasonality, inter-annual climate variability and extremes are marked features of the region's climate. This poses challenges for managing human activities that are climate sensitive. Despite the paucity of observational data, it is clear that the Sanjiangyuan region is experiencing pronounced changes in climate, the origins of which are yet to be established unequivocally. The advance of rapid economic development and associated landscape transformation, against a backdrop of a highly variable climate resource and an uncertain climate future, raises the spectre of ecosystem service degradation in the wider Sanjiangyuan region. While regional development is inevitable, the risk posed by a variable climate resource can be reduced through an improved understanding of Sanjiangyuan region climate-forcing factors at the regional to global scale and assessing the possible consequences of human-induced climate change. To achieve this, not only are improvements in climate monitoring, analysis and modelling required, but it is also imperative to build capacity in terms of trained climate risk managers who understand the complexity of environmental risk and the extent to which climate variability and change might alter that risk.

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