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Climate of South Asia

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South Asia, which mainly includes India, Pakistan, Bangladesh, Sri Lanka, Nepal, and Bhutan in this article, is located between about 5° and 37°N, in tropical and equatorial latitudes, with the Indian Ocean to the south, the Great Himalayas and Karakoram to the north, the Baluchistan highlands to the west, and the meridional chains of mountains in Indochina to the east. The distinct geographical features in South Asia restrict the horizontal exchange of oceanic and continental airmasses and modify the climate to a characteristic pattern. Besides great mountains and upland systems there are also lowland depressions. Numerous bays and gulfs enhance the influence of the ocean. In winter a warm, westward-flowing current reaches eastern Sri Lanka, from where it diverges northward, affecting the southeast coast of India. During the summer a warm current in the Indian Ocean reaches the west coast of India and flows southward; from south of Sri Lanka the current moves east (Martyn, 1992).

South Asia mainly consists of four climate zones. The northern Indian edge, as well as the upland and mountainous part of Pakistan, has a dry continental, subtropical climate. The far south of India and southwest Sri Lanka are located in the zone of equatorial climates. The rest of the areas lie in the tropical zone, with hot semi-tropical climate in northwest India, cool-winter hot tropical climate in Bangladesh, and semiarid tropical climate in the center of the peninsula. The last two tropical climate zones are greatly affected by monsoon circulations (Martyn, 1992; Rao, 1981; Papadakis, 1966). In addition, mountain climate occurs in the Himalayas. Climates there vary with elevation, from permanent ice caps at high elevation to subtropical climate at lower lands.

The most important climate feature in the region is the southwest monsoon, which lasts for 4 months, from June to September. In this southwest monsoon period the precipitation is one order of magnitude more than during the rest of the year. Because temperatures in the South Asian monsoon region drop dramatically in June and July, due to the monsoon onset, March to May becomes the warmest period.

In this article the observational data for precipitation are from the rain gauges station data over land and the data are interpolated to 1° resolution (Xie and Arkin, 1997), covering 1948–2003. The surface temperature data are from the National Center for Environmental Prediction (NCEP), the Climate Analysis Center, and the Climate Anomaly Monitoring System station data achieve (CAMS, Ropelewski et al., 1985); they include data from 1948 through June 2003. The NCEP/National Center for Atmospheric Research (NCAR) Global Reanalysis data from 1948 to 2003 (Kistler et al., 1999) are used for circulation and radiation figures.

Radiation

Although the sun's altitude is high during the entire year, and the amount of daylight varies little during the year for the area south of 30°N (Martyn, 1992), the solar radiation still exhibits high seasonality and great spatial variability (Figure 1). Annual mean solar radiation amounts decrease eastward, from 290 W m^{-2} in Baluchistan to less than 240 W m^{-2} in Bangladesh. Annual mean downward long-wave radiation at the surface decreases northward, which is consistent with the temperature gradient and water vapor quantity, with the two coasts having the highest long-wave radiation (about 390–400 W m^{-2}) due to cloudiness.

January solar radiation is about 240–250 W m^{-2} in the southern peninsula and western Sri Lanka, and drops to 220 W m^{-2} in the northern peninsula and eastern Sri Lanka. Much lower solar radiation is received in the northwest subcontinent and northeast Bangladesh, with north Pakistan having the lowest (Figure 1a). The long-wave radiation shows a clear zonal pattern, with high gradients in the Himalayas associated with topography (Figure 1c). In July the solar radiation decreases southeastward from northwest South Asia. Pakistan and northwest India receive the most solar radiation, between 300 and 360 W m^{-2}. In northeast India and Bangladesh the solar radiation decreases southward from 300 to 200 W m^{-2}. The southern continent has less solar radiation, especially along the west coast of India, due to the cloudiness in these regions (Figure 1b). There are two very high downward long-wave radiation centers over the Indian Ocean, located at both sides of the Indian peninsula and associated with heavy rain in these two areas. Apart from the areas influenced by these two centers, in other parts of the peninsula and Sri Lanka it is quite uniform, between 410 and 420 W m^{-2} (Figure 1d)

Circulation

A characteristic feature of the South Asian climate is the atmospheric circulation associated with the monsoon evolution. The extensive Eurasian continent and the Indian and Pacific Oceans play an important role in monsoon formation. In the winter the northeast monsoon prevails and sea-level pressure decreases to the south. The Intertropical Convergence Zone (ITCZ), associated with the equatorial low-pressure belt, runs across the entire Indian Ocean along 10°S latitude. The cold air from the Siberian High, which is centered at 45°N and 105°E, approaches eastern India and the Bay of Bengal starting in October. Since the barrier of Tibet and the Himalayas blocks the advance of cold polar air, low-level northeast winds only run across the Bay of Bengal and reach northeast India. The pressure gradient is strong to the north of the Himalayas but weak over the Indian Peninsula. From October to May the southern branch of the westerly jet stream, usually flowing between 28° and 30°N, crosses the Himalayas. This westerly wind in the upper troposphere is strongest in January and gradually slackens.

Meanwhile, in western South Asia, cold air from Iran and Afghanistan reaches Pakistan and northern India. Cyclonic disturbances are more frequent over the western Himalayas and Karakoram from early November to the end of May because of strong vertical wind shear in the basic current (Hamilton, 1979). They reach the Ounjab, Rajasthan, and even Patna on the Ganges Plain. They bring clouds and precipitation in November and December, and cold weather, thunderstorms, and precipitation in the normally hot, dry period from March to May (Lockwood, 1974; Martyn, 1992).

Development of low pressure due to increased heating over land starts for South Asia in March. Heat lows are usually found in an area extending from Somalia across southern Arabia to Pakistan and northwest India between May and September, and are most intense in July. Middle tropospheric subsidence is considered to affect the heat low (Hamilton, 1979). The distribution of sea-level pressure, as well as low-level air flow over the Indian subcontinent, experiences a complete reversal from January to July (Figures 2a and 2b). Earlier northeasterlies are replaced by westerlies in April with the core of a subtropical jet stream at 200 mb near 27°N. This jet gradually weakens from an average speed of about 40 m s^{-1} in March to about 25 m s^{-1} in May (Hamilton, 1979; Keshavamurty and Rao, 1992).

In the summer the low pressures are centered over Pakistan, northwest India, and the Ganges Plains. The Indian Ocean high is strong and centered at 30°S and 60°E. At the beginning of June, as the jet stream disappears above the southern border of the Tibetan Plateau, the low over Pakistan deepens and the ITCZ moves in. The change in the direction of circulation to southwest occurs suddenly (called the burst of the monsoon) because of the very steep horizontal northward pressure gradient. The southwest monsoons, carrying enormous quantities of moisture from the Indian Ocean, reach the coast of India (Figure 2b). The monsoon circulation dominates South Asia. Because wind now blows off the sea, the summer monsoon contains far more water vapor than the winter monsoon. The depth of the summer monsoon over the Indian Peninsula decreases northwards (Martyn, 1992). Humidity, cloudiness, and precipitation all increase in the summer, but the increase of temperature is checked. When the monsoons change direction during the summer, cyclonic activity increases rapidly over very warm seas and oceans and is extremely violent over the Bay of Bengal.

Monsoon depressions form in the Bay of Bengal from June to September, move west/northwest, and reach at least the central parts of the subcontinent before weakening or disappearing. They are usually moderately vigorous, with surface winds below 20 m s^{-1} and a central pressure range from 2 to -10 mb below normal. Many depressions are probably of a baroclinic type (Koteswaram and George, 1958) and usually exist in the presence of a large zonal wind shear between the upper and lower troposphere. Monsoon depressions are an important summertime precipitation agency between 18°N and 25°N. They bring widespread rains in the southwest quadrant, with many heavy rainfall events. As a depression moves over land it usually weakens due to frictional dissipation of energy and a reduction of moisture intake. Eventually, most depressions merge into the monsoon trough over northwestern India (Hamilton, 1979).

The transition of a summer circulation to a winter circulation is of shorter duration than the reversion from winter circulation to summer circulation. The transition comes suddenly over the Himalayas as the circumpolar westerlies begin to intensify and move south. A subtropical westerly jet stream develops at the northwestern end of the Himalayas, thereafter extending southeastward. By mid-October the jet is fully established south of the Himalayas. A winter circulation develops north of 25°N by early November (Yeh et al., 1959; Hamilton, 1979).

Surface temperature

The isotherms in January generally are parallel to the latitudes except near the coasts. January mean temperatures in northern South Asia are about 10°C, which is not as cold as most parts of Asia because the Himalayas and Sulaiman block the inflow of masses of cold air from the north. On the Indian Peninsula, south of 18–20°N in the east, the temperatures exceed 20°C and can reach 24–27°C on the equator (Figure 3a). In Kashmir the mean temperature can be 1°C at Srinnagar (1666 m) and -15.7°C at Dras (Martyn, 1992), where below-zero temperatures are usual from November to April.

Land becomes progressively heated after January. The warmest period of the year precedes the monsoon from March to mid-June. In the far north the warmest month is July Figure 3b), and the warm season begins earlier southward; for instance, in southern India it begins in April. During the warm period the mean temperatures in the northern Deccan exceed 35°C (and even reach 38–42°C), and in the interior of the peninsula they reach 33°C. Because of the greater moisture brought in with the sea breezes, coasts are not hotter in the afternoon hours than the peninsular interior. The west coast of India is about 5°C cooler than the east coast.

In July the southwest monsoon is established over India and the cloudiness is heavy. Monthly mean temperatures over much of Indian Peninsula are quite uniform, around 27°C (Figure 3b). However, temperatures of over 30°C are recorded in the Great Indian Desert, and may reach 32–36°C. Temperatures in the Himalayan mountain valleys are from 24°C at elevations of 1700 m to 17°C at 3500 m (Martyn, 1992). Absolute maximums in some interior regions even exceed 40°C. The summer monsoon season is the second cooler period in the year because clouds and rain prevent the temperature from rising too much during the day. Once the monsoon ends the temperatures rise and a second annual maximum is attained. This is not as high as the pre-monsoon maximum because of the greater quantity of moisture in the air and the sun's lower altitude. Monthly mean temperatures over the entire subcontinent in October are generally within the range of 27–29°C. This is the month of the most equable distribution of temperature on the Indian Peninsula. The range of annual temperature variation is about 1–5°C for most parts of the region.

Near-surface humidity and cloudiness

In January the relative humidity on the southern peninsula is higher than 50–60%, and even 70% on the coasts. A maximum relative humidity of over 80% in Sri Lanka and Hhasi-Janitia Hills in northeast India has been recorded. The driest areas are the Indus Plain and the adjacent areas of Pakistan and western India. In the western Himalayas the humidity is high when temperatures are very low, but becomes lowest in May–July. From March to mid-June (the warm months) the relative humidity is under 30–40% on the Indus Plain, in the Punjab, Rajasthan, and at the western end of the Ganges Plain, and under 50% on the Deccan Plateau and in central Burma (Martyn, 1992). In July the areas most affected by the monsoon have relative humidity of over 80%, while the southwest coasts of India, the Khasi-Janta Hills, and some sections of the Himalayas even reach above 90%. However, there are areas in Pakistan still with relatively low humidity. On the Coromandel Coast and in eastern Sri Lanka the relative humidity reaches the lowest value in a year (Martyn, 1992). In the driest regions of Rajasthan the relative humidity does not exceed 60%, and in central India it does not reach 80%. In the eastern Himalayas, where the effects of the monsoon are strong, there are two wet periods, one in January and February and one from May through October, while two dry periods remain between these two wet periods.

The cloudiness and its annual variation are varied; they depend on atmospheric circulation and topography. With the arrival of the summer monsoon, which carries a huge amount of moisture from the Indian Ocean, South Asia becomes one of the most overcast parts of Asia, normally over 80%. It even reaches 90% in western India in the upper reaches of the Godavari and the windward slopes of the Khasi-Jaintia Hills. The southern and northern parts of the region have greatest cloud cover from June to August, and from July to August, respectively. During the rest of the year the cloudiness is much less. In the west the cloudiness is 10–22% during the November–April period. In the east on the Bay of Bengal the lower cloudiness is about 22–45% during January–March. In January it is scanty (under 30% or even lower) in most parts of South Asia; but in the far north of India, where a westerly circulation is frequent, cloudiness is greatest (Martyn, 1992).

Precipitation

Precipitation attracts much more attention than any other aspect of Indian subcontinent meteorology. Precipitation in South Asia exhibits strong spatial variability. Pakistan and northwest India, where there is very little water vapor in the air and little precipitation due to limited evaporation and to dry air currents, have the most arid areas in South Asia. Annual precipitation is less than 250 mm in the driest parts of these areas (Figure 4a). Despite considerable low-level convergence into the low-pressure areas, there are very little clouds and precipitation because of extremely low humidity and/or because of stable inversion (Hamilton, 1979). From the east coast of India the precipitation decreases inland south of 17°N. The interior of the peninsulas, especially the lee side of the Western Ghats, has low precipitation, less than 1000 mm per year. Low precipitation is also found in the upper basin of the Bhima River (around 18°N) and its tributaries. In northern India there is a low precipitation strip from about 28°N and 75°E to 25°N and 87°E; but topographic effects and monsoons produce significant precipitation along the Himalayas.

In monsoon areas the precipitation exceeds 1000 mm per year. Maximums of precipitation coincide with higher elevations in the Ghats and the eastern Himalayas. In the Khasi-Jaintia Hills the precipitation can reach as much as 11 000 mm per year. On the Malabar Coast and at the southern end of the Western Ghats in India the value reaches more than 3000 mm per year. In Sri Lanka the annual precipitation is also affected by monsoons and is higher than 1300 mm per year; in the southwest it exceeds 2200 mm per year. The pattern of rainy days is similar to that of annual precipitation. The highest number of rainy days (200 per year) is recorded in southwest Sri Lanka. The rainy days number about 170 per year in the eastern Himalayas and about 150 on the Malabar Coast. The interior regions of India have rain on 5–80 days per year, while in the Great India Desert it falls on less than 5 days (Martyn, 1992; Rao, 1981).

The precipitation in South Asia is linked to seasonal changes in the atmospheric circulation. Rains develop over southern India and the southern Bay of Bengal in May–June (Webster et al., 1998). The abrupt northward jump appears with the onset of the South Asian summer monsoon. Based on analysis of various data sets it was found that the South Asian monsoon onset was associated with the reversal of the meridional gradient of upper tropospheric temperature south of the Tibetan Plateau (Flohn, 1957; Li and Yanai, 1996).

The monsoons bring most of the region's precipitation (Figure 4c). On the Indian Peninsula north of 13°N the rainy season begins in mid-June and lasts until September; in Bangladesh it lasts until October. The monsoon usually advances from two locations – one from the Bay of Bengal to central and southern India in June and reaching northwest India by early July, and the other one over the Arabian Sea 1 month later. This progression of monsoons is associated with large-scale ascent through the troposphere with strong lower tropospheric convergence and upper tropospheric divergence. The periods of maximum thunderstorm frequency precede and follow the summer rains (Hamilton, 1979). In most parts of South Asia the spatial distribution of annual precipitation is similar to that in this period. The southwest monsoon rain provides water for agriculture in the world's very populous regions.

Orographic influence is dominant as onshore winds blow to the Western Ghats and the Khasi-Jaintia Hills. The main impact of the southwest monsoon is in a 250-km long stretch of the Himalayas between 87 and 90°E. Not only do the Himalayas receive heavy rains, but also the plains adjoining the foothills receive more rain than the plains further south. Even in north Pakistan the precipitation also ensues from monsoons from June to September. A trough (the monsoon trough) extends east-southeastward from Indo-Pakistan heat low to the northern part of the Bay of Bengal near 25°N in June and July and shifts a little further north in July–August, by which time it dominates weather over the Indian subcontinent. It retreats southward and disappears in September as a near-equatorial trough near 10°N. The position of this trough is an index of the activity of the monsoon over the subcontinent. If the trough is in a normal position it will be a normal monsoon year. When the trough shifts to the foothills of the Himalayas this indicates a break situation (Rao, 1981; Hamilton, 1979).

Temporal variations in precipitation are associated with shifts of position in large-scale upper tropospheric circulation, the low-level monsoon trough, and the development of synoptic disturbances. The precipitation maximum occurs in May–August (some areas extend to September). Rain is very heavy, especially at the start of the monsoon season and during tropical cyclones. Along the Coromandel Coast the rains begin in July, sometimes even in August. There is rain on more than 20 days in a month. In some areas, rainy days reach 25–28. However, it is very dry on the southeast tip of the peninsula. In the northwestern parts of the subcontinent the precipitation also decreases progressively westward.

A seasonal reversal of winds at lower levels, the displacement of the monsoon airmass by the continental airmass, and development of anticyclonic flow indicate withdrawal of the monsoon. From mid-September, as the surface temperature falls, the atmospheric pressure over the Indus and Ganges Plain rises rapidly and becomes higher than that over the Bay of Bengal. In October the ITCZ lies at 10°N and only affects southern India. Southern India and southwest Sri Lanka have two rainy seasons due to the movement of the ITCZ. The first one is from May to July, and the second one is from October to November. In addition, tropical cyclones have prolonged heavy rainfall on the Coromandel Coast in fall. The turn of the monsoons is the time when tropical cyclones develop over the Bay of Bengal. In the Bay of Bengal, based on 70-year records, 15% of cyclones arise in April and May, and 38% arise in October and November (Rao, 1981). Fall cyclones are much stronger than the pre-monsoon ones. Some are listed as severe cyclonic storms with winds of 48 knots or more. The most violent cyclones over the Bay of Bengal cross the central Deccan along the Krishnai river valley. Others turn to blow up the eastern coast toward Bangladesh. Considerable flood damage has occurred in the Ganges delta. Apart from this, the cyclones are accompanied by high winds, tidal waves, and heavy rain. There can be disastrous flooding.

The winter precipitation over South Asia is only a small fraction of the annual amount, except in Kashmir and its surroundings (Figure 4b). During winter in Kashmir, Karakoram, cyclonic precipitation is dominant. On the east coast of Sri Lanka the rainfall is still more than 30 mm per month, decreasing to 15 mm per month along the west coast.

Impact of the Himalayas/Tibetan Plateau on the South Asian climate

The northern edge of South Asia is bounded by the Himalayas, which run along the southern periphery of the Tibetan Plateau; it extends over the latitude–longitude domain of 70–105°E, 25–45°N, with a mean elevation of more than 4000 m above sea level. Strong contrast exists between the eastern and western parts of the Plateau in both land surface features and meteorological characteristics.

The sharp edge of the Himalayas and the vast and high Plateau force the large-scale airflow to go around rather than over it. This effect is clearly seen in the flow features well above the Plateau. The mid-tropospheric westerly jet stream is situated to the south of the Plateau before the onset of the summer monsoon, but it suddenly jumps to the north side with the monsoon onset. Earlier, the thermal influences of the Tibetan Plateau were inferred from the presence of a huge upper tropospheric anticyclone above the Plateau in summer (Flohn, 1957) and from the pronounced diurnal variations in the surface meteorological elements along the periphery of the Plateau (Yeh and Gao, 1979).

During winter the Tibetan Plateau is a cold source; it acts as a heat source from March until October. The elevated heat source above the Plateau acts to warm the mid-upper tropospheric air, and the temperature over the Plateau in summer exceeds that over the Indian Ocean (Yanai et al., 1992). This meridional gradient of temperature, appearing in May–June, is crucial for the onset of the South Asian monsoon. Concurrent with the reversal of the temperature gradient, the rain belt associated with the ITCZ over the Indian Ocean suddenly moves onto the Indian subcontinent and reaches the foot of the Himalayas

With the cooling of the Plateau surface the westerly jet stream retreats to the south side of the Plateau in late October; this is just after the end of the southwest monsoon in India and almost concurrent with the commencement of the northeast winter monsoon over southeast India (Matsumoto, 1992).

Y. Xue and M. Yanai

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Cross-references

Asia, Climates of Siberia, Central and East Asia
Asia, Climate of Southwest
Monsoon and Monsoon Climate
Tropical and Equatorial Climates

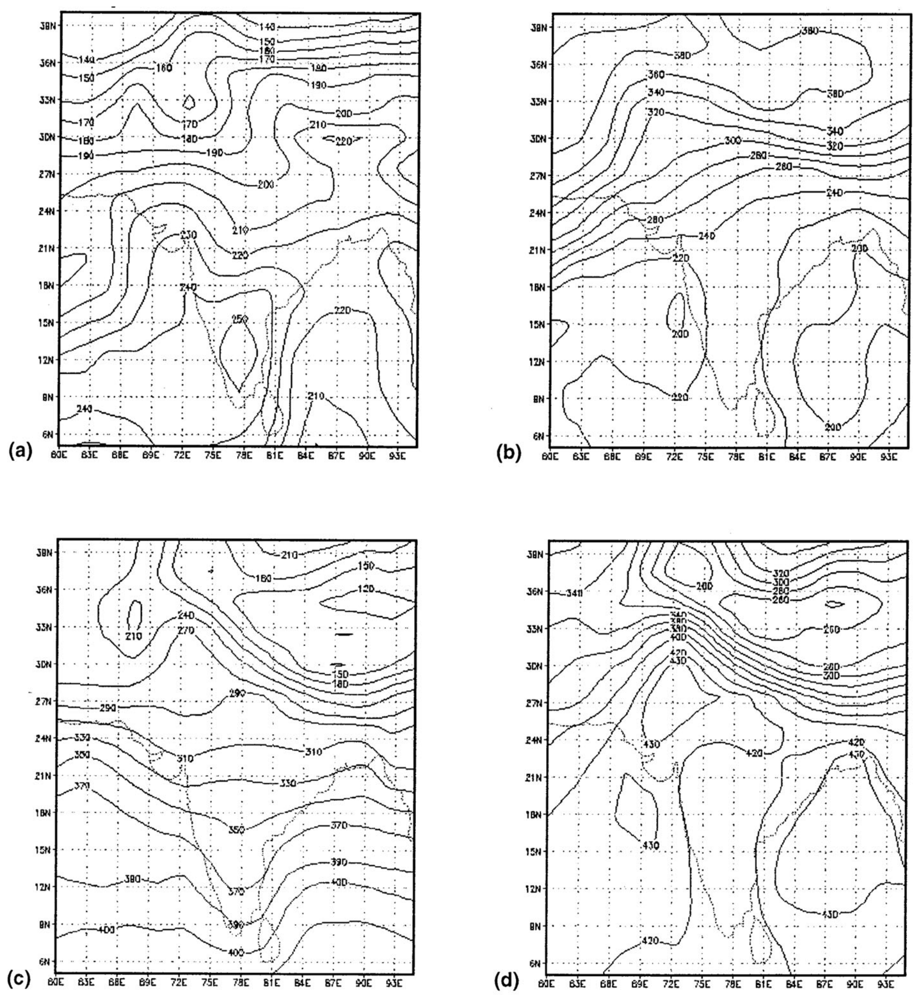

Figure 1 Monthly mean radiation flux at the surface ($W\,m^{-2}$): (**a**) January mean downward short-wave radiation; (**b**) July mean downward short-wave radiation; (**c**) January mean downward long-wave radiation; (**d**) July mean downward long-wave radiation.

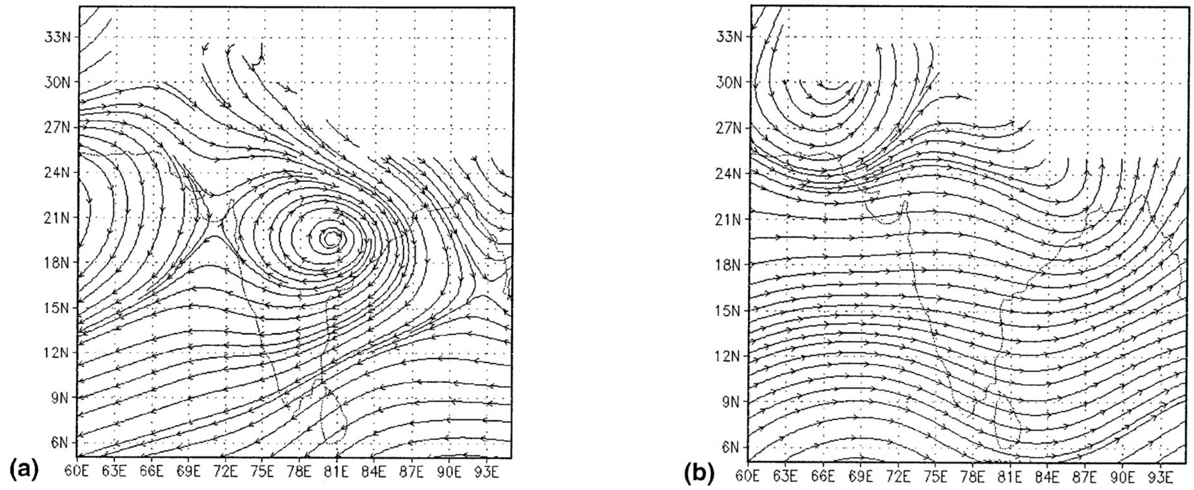

Figure 2 Monthly mean streamline at 850 mb: (**a**) January; (**b**) July.

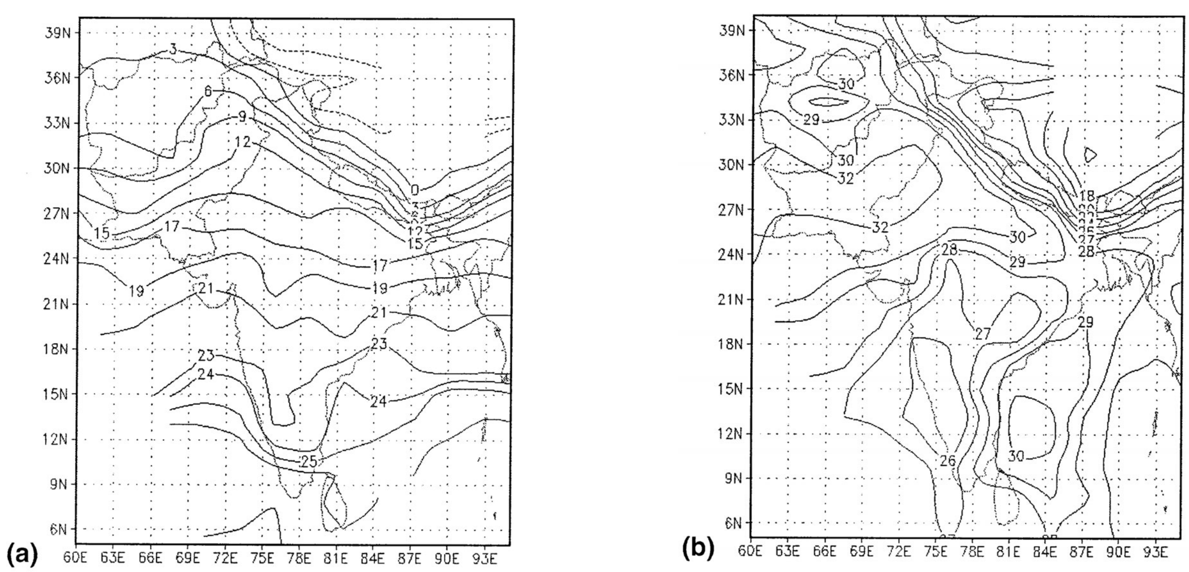

Figure 3 Monthly mean surface temperature: (**a**) January; (**b**) July.

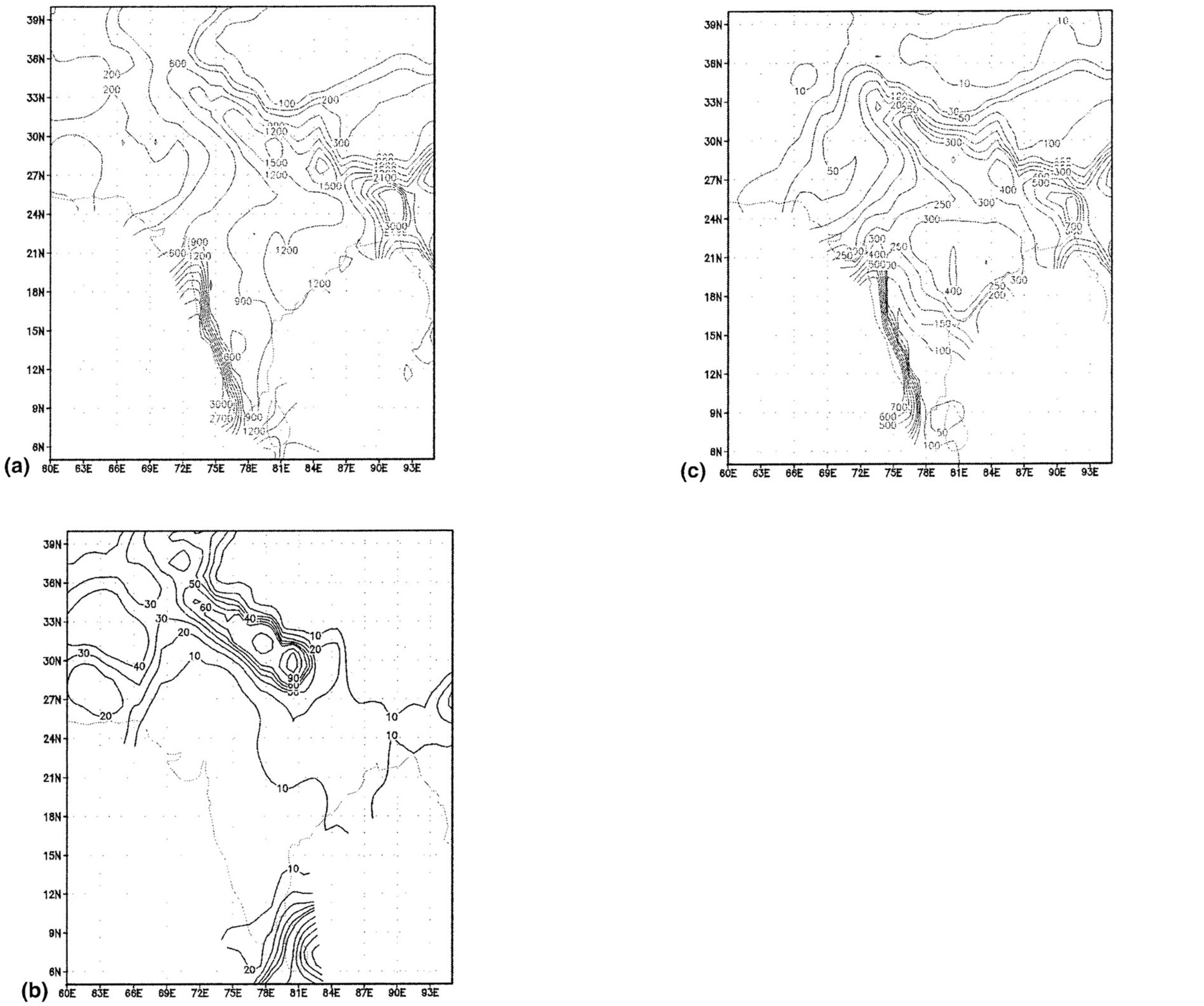

Figure 4 Precipitation: (**a**) Annual mean (mm $year^{-1}$); (**b**) January mean (mm $month^{-1}$); (**c**) July mean (mm $month^{-1}$).