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RELIEF AND CLIMATE IN SOUTH ASIA: THE INFLUENCE OF THE WESTERN GHATS ON THE CURRENT CLIMATE PATTERN OF PENINSULAR INDIA

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ABSTRACT

The 1500-km-long Western Ghats mountain barrier of peninsular India interacts with the southwest monsoon in a manner which bears heavily on the exceptionally varied climate pattern of the Deccan. Karnataka Province alone concentrates five of the six major climate types of the entire Indian Union. This review explores the interactions between atmospheric structure over South Asia and relief and discusses the efficiency with which the passive margin uplift, second only to the Himalayan barrier, acts as a climatic gatekeeper to the subcontinent. Particular attention is given to rainfall patterns and regimes. These are revealed by a variety of statistical classification and mapping techniques, and the analysis is guided by the steep environmental gradient observed on the immediate backslope of the Ghats, where annual totals can drop from 6000 to 600 mm in *ca*. 80 km. This is strongly reflected in the landform, soil, vegetation and cropping patterns and raises the question of the relationship between the uplift history of the mountain barrier at geological time-scales, the history of the South Asian monsoon circulation and the stability and diversity of the climatic pattern as seen today. The tightly arranged suite of bioclimatic regions also provides a unique geographical backdrop to the agricultural diversity of South India, rarely found on such a scale in other monsoon contexts of the Tropics. © 1997 by the Royal Meteorological Society. *Int. J. Climatol*., 17: 1182–1182 (1997).

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KEY WORDS: India; Western Ghats; relief; rainfall patterns; agroclimatic diversity.

INTRODUCTION

Much of traditional climatology involves establishing the boundaries of homogeneous climatic regions, which is achieved by statistical manipulation such as averaging successive meteorological field configurations over a standard period of 30 years. The main difficulty in so doing resides in correctly establishing a connection between the layered structure of the troposphere and the modulating effects of land surface features such as sea–land boundaries, which impose horizontal gradients to air circulation, or relief, which also disturbs the vertical atmospheric structure.

Climatic gradients can be of varying intensities and dimensions. Climatology has one essential function of explaining environmental patterns, and one of its prior objectives consists in locating and isolating the thresholds that may be held responsible for empirically observed environmental clines in the landscape. The exercise then involves a discrimination between gradients and boundaries, such that these may be drawn, for instance, as lines on bioclimatic maps, although this poses many epistemological and practical problems (e.g. Lytinski, 1983).

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The Western Ghats region of southwestern India, which represents the elevated rim of the Deccan Plateau, lying in the path of the southwest monsoon, provides an interesting example taken from the tropical region to investigate the implications of orographically controlled climatic gradients and thresholds, and the following analysis presents an exploratory climatic synthesis of one of the steepest environmental gradients as yet reported in the tropics (Gunnell and Bourgeon, 1997).

FIRST-ORDER INFLUENCE OF MOUNTAIN BELTS ON THE INDIAN MONSOON: BRIEF OVERVIEW

Monsoon airflow is not a phenomenon specific to South Asia; it concerns four continents and both hemispheres (Pédelaborde, 1970; Hastenrath, 1985, Meehl, 1992). However, the Himalayan and Western Ghats mountain belts provide a unique orographic framework, which steers the atmospheric circulation in such a way as to yield a distinctive rainfall pattern.

In terms of atmospheric structure, the first-order mechanism of the Indian summer monsoon is well documented and can be summarized as follows.

(i) Towards the end of the spring season the hot and dry continental air formed in the lower troposphere in overheated northern India and Pakistan ends up being even hotter than the hot and humid monsoon air now proceeding northward from the southern Indian Ocean. This enables the arriving monsoon air mass to wedge itself under the hotter continental air, thus engendering a low-angle thermodynamic discontinuity, or intertropical front (Leroux, 1989), where cloud and precipitation develop.

(ii) Overlying this low-elevation structure, the Saharo-Arabian dynamic anticyclone merges with the Tibetan thermal anticyclone in the mid-troposphere, thereby developing a vast lid of high pressure on top of the surface low pressure system that is prevalent in South Asia during the summer months.

The air mass characteristics above Tibet are seasonal and thermally driven, and play an essential part in the process. Mean plateau elevation is *ca*. 4·5 km, and intense solar radiation is reflected back to the atmosphere due to the high albedo of the largely exposed bedrock landsurface of Tibet. This radiation being restored as heat directly to the mid-tropospheric level installs an anomalous temperature and pressure field in the high troposphere above the plateau. The resulting air mass is further supplied with latent heat of evaporation released in the mid-troposphere by massive cloud build-up above the 'monsoon trough'. This low pressure trough develops above the Ganges plains, where the Eastern branch of the Indian monsoon is deflected cyclonically by the Tibeto-Burmese foldbelt and converges towards the Ganges plain and the Himalayan mountain front (Durand-Dastès, 1961, 1979). The Tibetan air mass rotates clockwise and therefore creates a high-altitude anticyclone, which redistributes two main branches of air circulation: the southern branch sends air equatorward, which is deflected towards the east in the form of a 200 hPa airstream — the Eastern Tropical Jet, which persists from late June to early September at *ca*. 14°N (McBoyle, 1970; Durand-Dastès, 1979; Hastenrath, 1985). In contrast, the northern branch is affected by a westerly angular momentum and merges with the westerly Subtropical Jet, which skirts round the northern edge of the Tibetan landmass during the summer.

This particular relief-controlled structure of the troposphere enabled Koteswaram (1958) to interpret the Indian monsoon as the return flow in the lower troposphere of a seasonal meridian circulation pattern: the monsoon is a convergent and moist airstream that reaches the latitude of the monsoon trough and supplies sensible heat to the Tibetan high pressure cell (Figure 1). This 'steam engine' is maintained in operation so long as the heat source and sink remain in existence. When autumn polar air reoccupies the Tibetan highlands, the summer air circulation system breaks down and the monsoon 'retreats', i.e. the zonal (normal) equatorward trade-wind surface airflow is restored (this is given the rather confusing name of 'winter monsoon', a misnomer because it has not previously crossed the geographic Equator). In other words, the Hadley cell is replaced during the South Asian summer by two circulation cells. These have opposite motion and are driven by a heat source in the form of a thermal high pressure dome located over Tibet and two low pressure sinks, namely the Inter Tropical Convergence Zone (ITCZ) to the south and the Siberian summer low pressure zone to the north.

The importance of the Tibetan highlands as a thermodynamic node to atmospheric circulation and a major forcing factor in explaining rainfall totals of monsoon India is thus widely justified. It nevertheless seems important to distinguish between virtual precipitation, theoretically permitted by a particular tropospheric

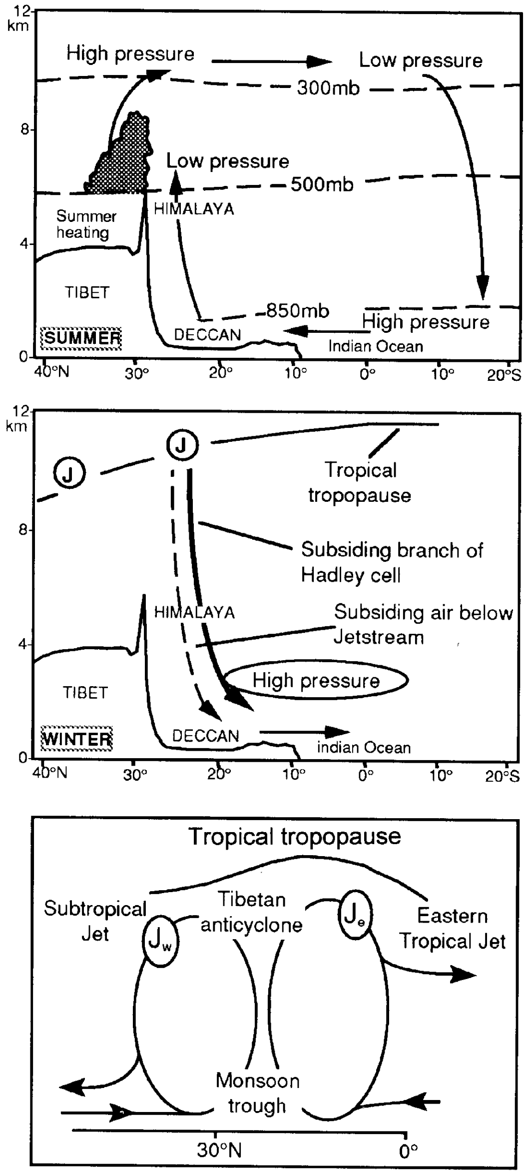

Figure 1. Airflow and pressure systems over southern Asia in relation to general atmospheric circulation in summer and winter (after Prell and Niitsuma (1989), McBoyle (1970) and Koteswaram (1958))

configuration, and actual rainfall, where an additional releasing factor such as the Himalayan mountain barrier ensures effective rainfall.

THE WESTERN GHATS: AN IMPORTANT CLIMATIC COMMUTATOR IN THE CLIMATOLOGY OF PENINSULAR INDIA

A lesser relief barrier such as the Western Ghats passive margin shoulder exerts a complex and profoundly important 'gatekeeper' effect on the climate mosaic of the entire Deccan, which is far from reflecting many popularized monsoon climate stereotypes.

North–south climatic gradient on both sides of the Western Ghats

On average, the northward-sloping ITCZ in India (Figure 1) is located close to 8–10°N in July at mid-tropospheric levels, and the south-west monsoon airflow is 5–6 km thick. It wedges out towards 20°N although, as mentioned earlier, it may shift in latitude. Within this 8–20°N latitude band, the moist monsoon air can rise and reach its dew point without any inhibition from the upper easterly flow inversion. Optimal pluvial conditions are therefore ensured by the structure of the atmosphere, and the Western Ghats provide the excess turbulence (surface roughness) required to raise the conditionally unstable moist air and trigger precipitation.

The collaboration of the mountain belt and atmospheric configuration in controlling rainfall initiation is confirmed by what is observed north of 20°N, where the Ghats interrupt, the monsoon wedge reduces to a thickness of *ca*. 1–1·5 km, and cloud formation is partly inhibited by the inversion roof provided by the low-angle

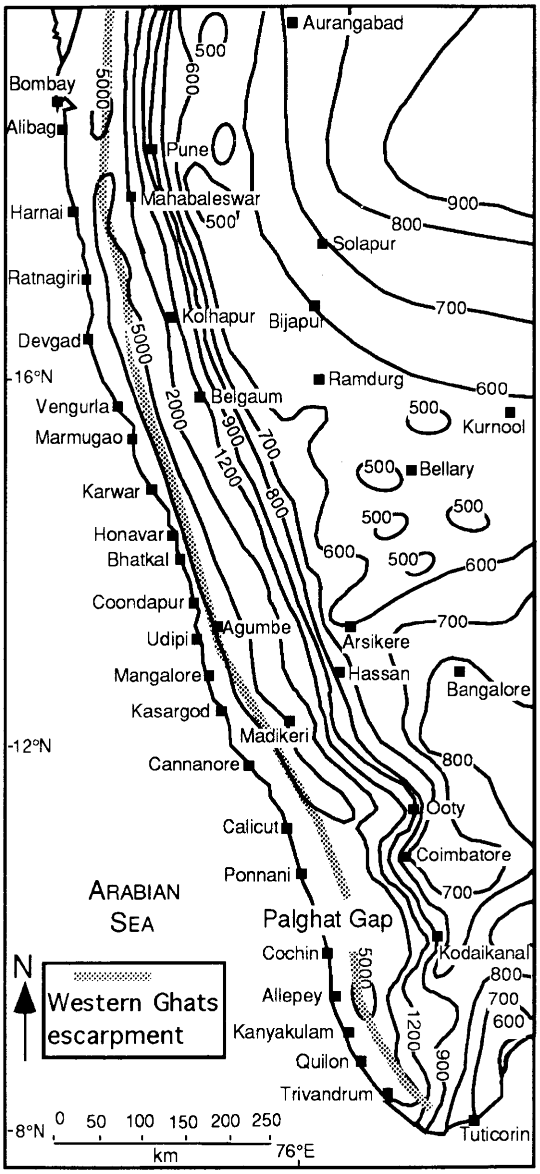

Figure 2. Mean annual rainfall (mm) over south-western India (after Dikshit, 1979). Note steep rainfall gradient along Western Ghats. Place names are used in Figures 3 and 4 and throughout the text

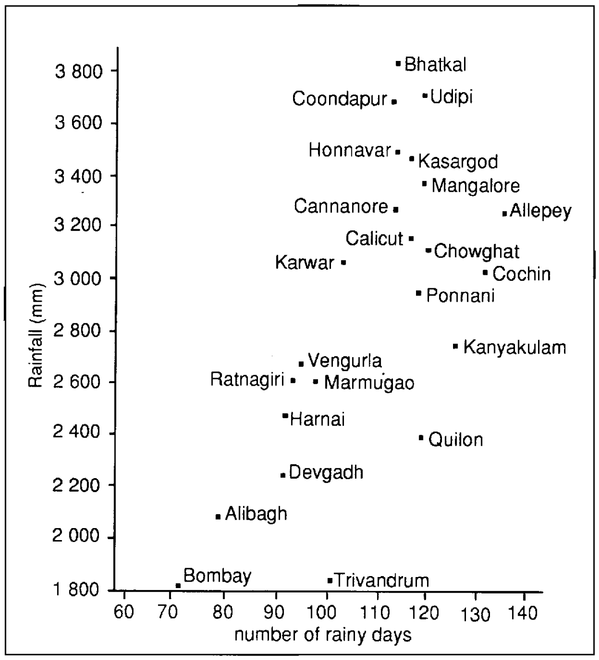

Figure 3. Spread of rainfall totals in the Konkan–Malabar coastal region, seaward of the Western Ghats escarpment (after Dikshit, 1979)

intertropical front. This explains to a large extent the low summer precipitation in the semi-arid Indian north-west. The Western Ghats, however, are solely responsible for the continuity of a semi-arid belt along the entire rain-shadow region of the Deccan, from the Satpura Ranges (22°N) to Cape Comorin (Figure 2), as described below. An account must first be made of the north–south variations that are encountered within both this semi-arid belt in the Ghats rain-shadow and the windward seaboard region.

Windward of the Ghats: a typical monsoon climate pattern, with a few variations. A map of the progression across India of the monsoon 'front', defined as a pentad during which a sudden increase in daily precipitation

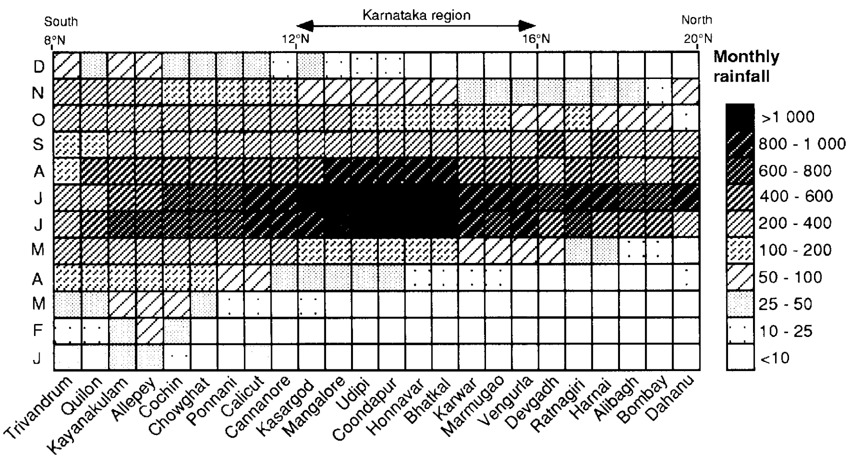

Figure 4. Distribution of annual rainfall according to latitude in the Konkan–Malabar region, seaward of the Western Ghats escarpment (after Dikshit, 1979)

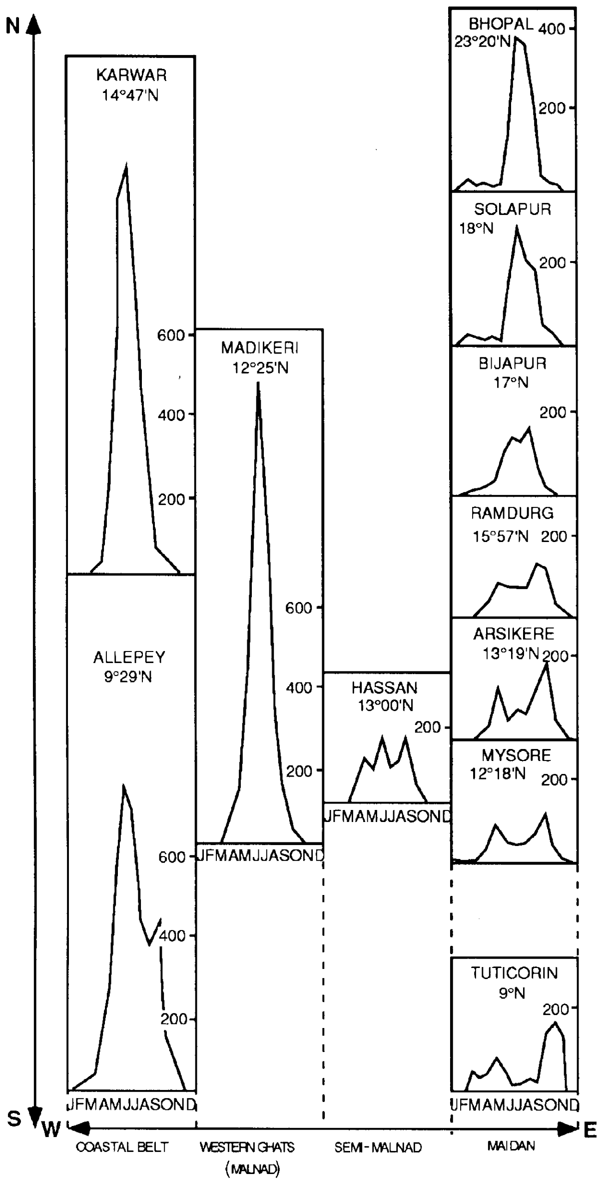

Figure 5. Diversity of rainfall regimes according to latitude and longitude in relation to the Western Ghats escarpment (data from Pascal, 1982)

yields consecutive daily rainfall totals of more than 10 mm per day (Anathakrishnan and Soman, 1988; Bansod *et al*., 1991), reveals that the monsoon retreats southward about five times more slowly (10 to 11 weeks) than it advances northward (about 2 weeks). The result is that Kerala benefits from longer wet seasons than northern India (Figure 3). In this way, for similar rainfall totals, stations located north of *ca*. 10°N along the Arabian Sea margin show typical, unimodal monsoon rainfall regimes because monsoon retreat does not provoke a second October peak. To the south of that limit, in Kerala, the regime becomes bimodal (Figure 4). The Western Ghats do not interfere directly with this latitudinal gradient in regimes, and the observed lengthening of the dry season from 3 months in the far south to 6 months near Bombay is important although not particularly original, because a similar latitudinal pattern is also encountered for instance in coastal western Africa.

In the rain-shadow of the Ghats: the monsoon loses its grip over the Deccan. By contrast, the importance of the Western Ghats as a climatic barrier is made apparent when it is observed that a 1100-km-long semi-arid belt, approximately bounded by the 650 mm isohyet, is strictly parallel to the strike of the Ghats escarpment, whereas the south-west monsoon is virtually perpendicular to it. Precipitation diagrams (Figure 5) reveal an inverse pattern to the unimodal monsoon distribution previously described for stations at the same latitude: the coastal summer rainfall mode, with 75 to 150 mm of rainfall between June and September, becomes a summer low with a total of 20 to 30 rainy days over the same period. Protected from direct monsoon influence by the elevated plateau rim, a subtropical bimodal rainfall pattern prevails and the Ghats remove a large part of India from the realm of monsoon climatology. It follows that the rainfall regime of the Deccan interior reflects the pattern of convective precipitation related to the seasonal migration of the heat equator. Convective instability, when the sun is at its most vertical, is facilitated by the fact that vegetation is a degraded form of dry deciduous forest with *Albizia* on crystalline rocks and thorny scrub (*Acacia*) on the Deccan trap and Precambrian basement alike. Vast openfield landscapes on black or red soils and numerous bare rock surface (inselbergs, etc.) also contribute.

In the semi-arid rain-shadow of the Ghats, the rainfall pattern evolves in two opposite directions from a nodal point situated near Mysore (12°N):

(i) At Mysore, rainfall comes as nearly two equal peaks in May and October, with a 'little dry season' in between, which is, however, not totally devoid of summer showers (Figures 5 and 6(a)).

(ii) Progressing north from Mysore, the October peak becomes more prominent than the one in May, as for instance in the case of Arsikere (13°N). Closer still to the Tropic of Cancer, as in Ramdurg (16°N), the October maximum shifts to September and the May secondary peak fades away. Further north (Bijapur, 17°N, Solapur, 18°N), the summer remission fills out and the initial spring and autumn modes virtually merge into a unimodal monsoon regime, with rainfall totals, however, much lower than on the west coast at a similar latitude.

The two rainfall maxima of May and October exert a strong control on human activity, where the short spring showers, called 'mango showers', are conducive to the blossoming of (culturally important) mango trees and further towards the Ghats themselves, of coffee trees (essential to the economy of Karnataka State). The more abundant October showers, called 'Diwali rains', are essential to the rabi crop of sorghum (jowar) in the black soil regions.

(iii) Progressing south from Mysore, i.e. towards the Equator, the twin rainfall peaks shift towards the equinoxes, which is in agreement with the apparent movement of the sun at those lower latitudes. However, the 'little dry season' lengthens significantly due to the higher elevation of the Southern Ghats and the more effective rain-shadow effect than further north. The dry season everywhere reaches 6 to 8 months (Blasco and Legris, 1973), which it did only locally north of Mysore, for instance in the lee of the Bababudan hills of Karnataka (föhn effect), and the climate becomes truly bixeric: the 'little dry season' at Coimbatore, Madurai or Trichinopoly expresses a neat cut-off from summer monsoon influence. This is confirmed *a contrario* by the fact that Salem, a city in interior Tamil Nadu which receives a little more summer rain, is in line with the Palghat Gap — a major breach in the Western Ghats where monsoon influence can penetrate. At the south-eastern tip of India, the dry season locally reaches 10 months, with a rainfall maximum centred between October and December, which is the exact negative of the true summer monsoon climate found along the Arabian Sea coast. Over in the Coromandel and the Bay of Bengal regions, annual precipitation diagrams can be bi- or trimodal, with a secondary maximum in April reflecting convective rainfall, but the Western Ghats influence is no longer the main control on average rainfall, which owes its pattern to the regional pressure field.

Structure of the atmosphere and relief: on the difficulty of correctly apportioning climatological factors

There are admittedly two minor aspects in which the mountain barrier exerts a poor control on climatic parameters. First, the influence of the Western Ghats on temperature distribution in southern India during the summer is negligible. The monsoon imposes a general cooling trend over the entire Deccan and, regardless of rainfall, the autumn temperature peak is always lower than the spring one due to the slow retreat of the monsoon and therefore the greater cloud cover.

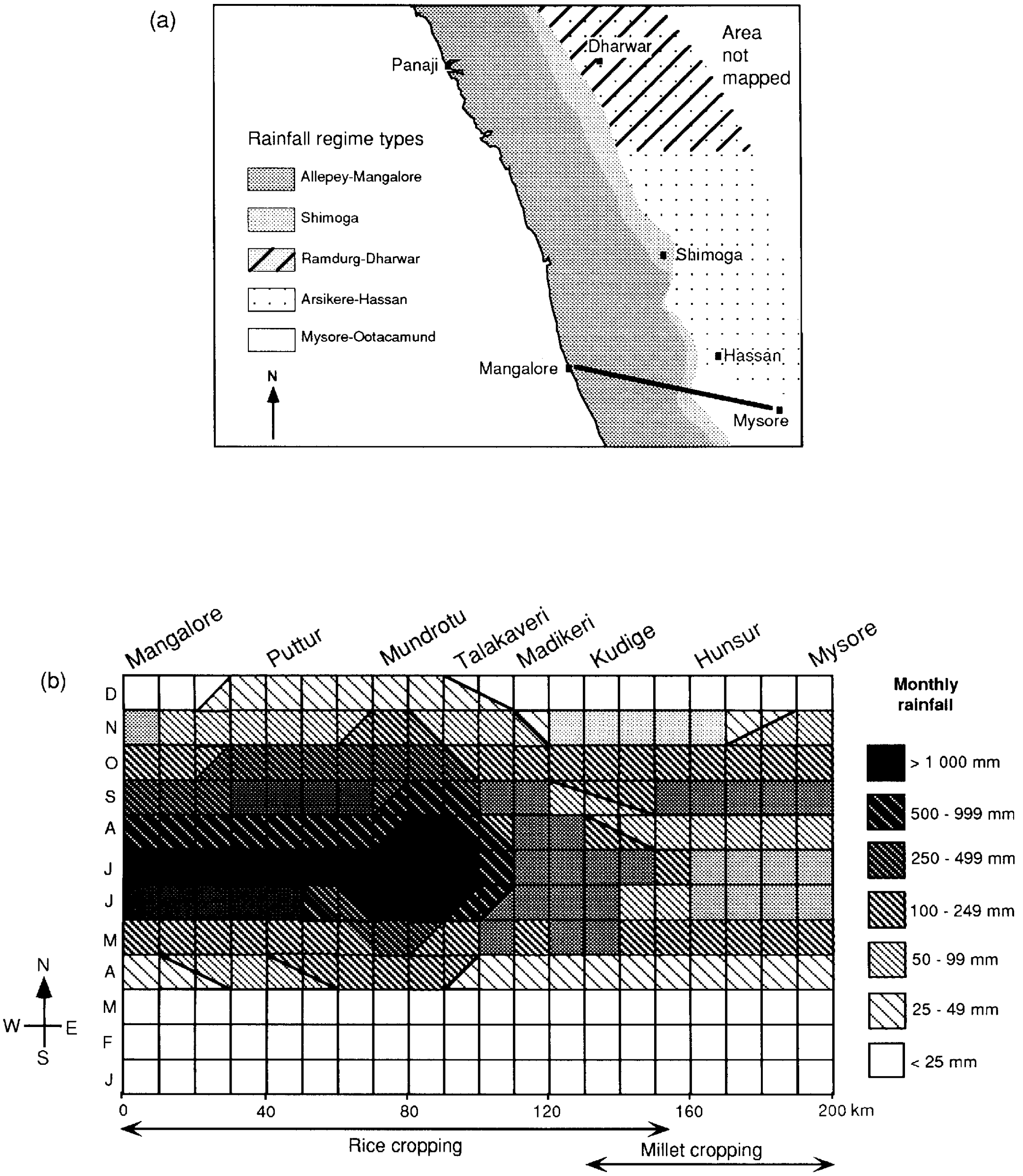

Figure 6.(a) Rainfall regime types (after Pascal, 1982) with climatic traverse between Mangalore and Mysore. (b) Gradual disappearance of summer monsoon rains in the rain-shadow of the Ghats and impact on cropping patterns (after Petit, 1987)

Second, although precipitation tails off in the interior Deccan, it is not the case for relative humidity, which, in stations such as Shimoga, Hassan or Mysore, increases suddenly with the onset of the summer monsoon. The September rainfall peak therefore finds some of its supply in this moist, though unsaturated air.

Clearly, the Western Ghats do not constitute an absolutely hermetic climatic barrier, and rather intervene as an environmental filter, but the influence of the Ghats escarpment on rainfall, as presented above, is nevertheless indisputable. A finer discrimination on the relationship between rainfall and relief can be highlighted by further evidence. Ramanchandran and Banerjee (1983) studied, for the summer monsoon period of seven consecutive years (1970–1976), the correlation between rainfall along the west coast and the backslope of the Ghats week by week. The results highlight a clear north–south gradient in the trends:

(i) a strong positive correlation ($r = +0{\cdot}67$) was found between precipitation trends on the windward and the leeward side of the escarpment in Maharashtra—when rainfall is above (below) normal in the Konkan coast region, it is also above (below) normal in interior Majarashtra;
(ii) a similar positive correlation exists in Karnataka, to the south, but it becomes much weaker ($r = +0{\cdot}30$);
(iii) in the far south, an inverse correlation ($r = -0{\cdot}25$) is reported between rainfall in Kerala and in Tamil Nadu, on either side of the Southern Ghats.

In other words, the pattern reflects an unequal influence of the passive margin uplift as a climatic commutator according to latitude. When normal aerological conditions prevail and guarantee a normal or particularly heavy monsoon, the Ghats play their predictable role as a physical barrier that triggers heavy rainfall on the windward side. When the monsoon breaks down due to unfavourable aerological conditions, it appears that a third-order, very shallow (1·5 km) low pressure trough develops in Tamil Nadu and southern Karnataka. This trough is orientated parallel to the strike of the Southern Ghats and exacerbates precipitation in interior Tamil Nadu, which is normally dry during this period. Under these circumstances, the Ghats are, as it were, denied the possibility of exercising their habitual role as rainfall provider to Kerala. Although the orientation and depth of the trough suggests a close relationship with the presence of the Ghats, which reach a maximum elevations of *ca*. 2600 m, it is difficult in that particular region to assert that the mountains are actually instrumental in causing the occasional apparition of the trough. If this were the case (although the exact process remains to be investigated), it could explain why the Ghats of Maharashtra and Karnataka, which represent the shoulder uplift of an elevated plateau never reaching more than *ca*. 1900 m, are less efficient at decoupling the rainfall trends of the coastal region and the interior than the Southern Ghats, which are a true mountain range with two steep, back-to-back fronts. Furthermore, the elevation factor may also play a major part and could confirm the speculations of Trenberth and Chen (1988), who consider that a continental-scale topographic mass starts to exert an important climatic effect above a threshold mean elevation of *ca*. 1500 m, after which any further increase in altitude should not have any major determining consequences: the Ghats north of *ca*. 14°N are thus just too low to secure a fully out-of-phase rainfall pattern on either side of the escarpment.

It must be stressed that the correlations presented above concern the *variation* in rainfall, and do not challenge what has been said about the contrasts in rainfall values, and therefore the importance of the passive margin mountain as a climatic gatekeeper.

THE SHARP EAST-WEST CLIMATIC GRADIENT ON THE IMMEDIATE BACKSLOPE OF THE WESTERN GHATS

Aspects relating to rainfall

In Karnataka State, the decrease in rainfall is extremely sharp, exceptional for a non-collisional foldbelt, as well as a non-volcanic (i.e. Mount Cameroon) and non-insular environment. Totals decrease from 5000 to 1000 mm in a mere 30 to 50 km from west to east, and in the region of Sakleshpur, the horizontal gradient steepens to 100 mm km^{-1} over a stretch of 10 km. The region can be subdivided conveniently into two main bioclimatic regions: the *maidan*, or open country in the east, approximately bounded by the 900 mm isohyet, and the humid and hilly *malnad* in the west. The number of rainy days rapidly falls from 125–150 $year^{-1}$ to just 25–50 $year^{-1}$ (Petit, 1987; Figure 6(b)). Bhagamandala, at the source of the river Cauvery in the Ghats, receives 80 per cent of its yearly rainfall in the summer months, whereas Mysore, 80 km to the east, receives 53 per cent in May and 43 per cent in September–October: the implications for the agricultural calendar are obviously far reaching, and impose for instance a major dividing line between rice and millet cropping regions.

The shoulder uplift in the west of the Karnataka plateau exerts a climatic filtering effect which is reflected in a large number of statistical parameters. Everywhere in the *maidan*, for instance, the probability for a given rain-gauge station of receiving 1000 mm from June to August is nil, whereas it reaches 100 per cent in the coastal region, on the windward side of the Ghats. Interannual variability of rainfall is also much greater in the Deccan interior than seaward of the Ghats: below the 500 mm isohyet in the central Deccan, the coefficient of variability of rainfall during the monsoon season always exceeds 30 per cent, whereas at the same latitude (10–15°N), variability in the coastal region ranges between 15 and 20 per cent (data calculated over 60 years: 1901–1960;

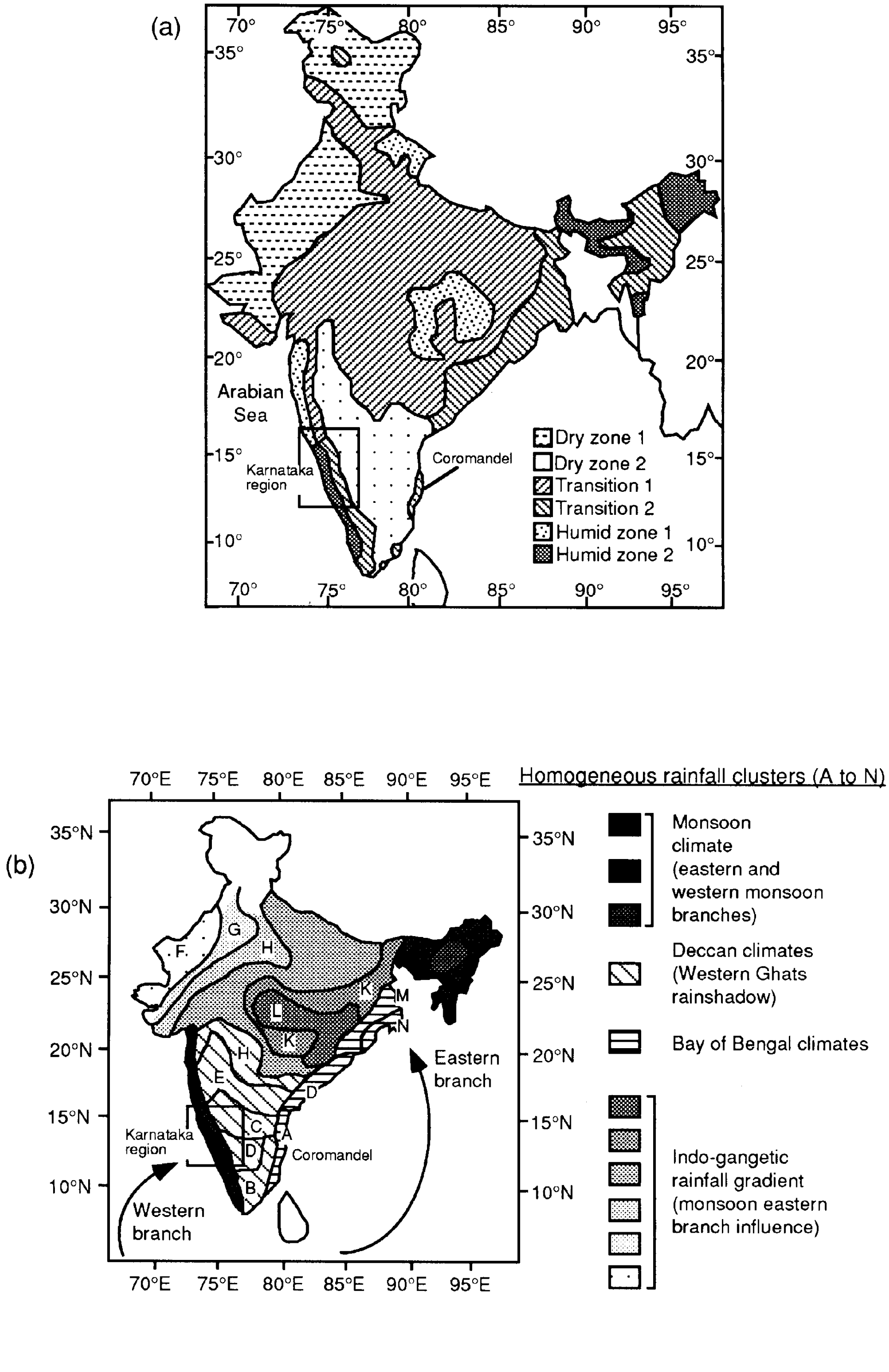

Figure 7.(a) Climatic classification of India according to Singh (1986) from a rainy season index defined as the number of consecutive days where $P > 50$ mm. (b) Climatic classification of India by cluster analysis of rainfall regions (after Gadgil and Joshi, 1983)

Katiyar, 1990). Similarly, reporting the return period for extreme rainfall deficits within a radius of 150 km for 306 Indian rain-gauge stations, Gregory (1987) showed that 50 per cent rainfall deficits will occur once every 50 years around Goa or Mangalore, whereas they occur every 5 to 10 years in the *maidan*. Finally, the frequency of extreme intensity monsoon precipitation events also reflects the relative separation of two climatic worlds by the Western Ghats: only stations located in the Konkan seaboard and the Mahabaleshwar Ghats are known to register, once a year or more, intensities exceeding 250 mm 24 hr^{-1} (1901–1960; Katiyar, 1990). The rest of the west coast records a slightly lower frequency for such events, with only 10 to 40 occurrences over the 60 years of data. The *maidan*, in contrast, recorded only 10 occurrences over the same period. Maximum probable precipitation maps (PMP; Dhar *et al*., 1981) for peninsular India reveal a significant anchoring effect in the Western Ghats region, where extreme rainfall is predicted to be the highest alongside cyclone-prone coastal strips of the Bay of Bengal. Expected PMP values are *ca*. 850 mm, and 750 mm for Agumbe, and it is significant to note that recorded values actually agree quite well with expected ones: 840 mm in one day on 24 July 1924 at Bhagamandala (the 'Cherrapunji' of South India). It must, however, be remembered that monsoon rainfall intensity is not always as high as that of storms in the semi-arid Deccan belt during April and May: cloud bursts can deliver 80 mm hr^{-1} in *maidan* regions, which receive only six times that amount annually. All these examples nevertheless confirm the much greater irregularity of the semi-arid climate in the rain-shadow of the Ghats, with regard to averages as well as to extreme events.

In summary, the coastal climate under direct monsoon influence suffers less extreme deficits and less frequent departures from the normal than in the semi-arid Deccan interior. The Western Ghats therefore sharply separate a coastal region with a unimodal, more regular and balanced rainfall pattern from a continental region with a multimodal, more excessive and irregular rainfall pattern.

Seasonal aspects

As shown previously with rainfall regimes, the length of the dry season varies on the backslope of the Ghats, both with latitude and with longitude, which calls for further examination of the impact of the Western Ghats escarpment on climate patterns. Pascal (1982) used the traditional and easily obtained Gaussen index, where a dry month occurs when $P < 2T$ (P being mean annual rainfall and T mean annual temperature). Bourgeon (1989) defined a dry month as one where the vegetation demand for water (calculated as potential evapotranspiration, or PET) is 75 per cent short of being fulfilled (50 per cent in the first occurring dry month). This latter method is limited by the small number of stations where data are sufficiently reliable to calculate Penman PET, but whichever method is used, overlapping trends emerge.

At 13° of latitude, the transition is very abrupt, and one passes from four to eight dry months in 60 km from west to east. To the north of 14°30′N, the dry season lengthens both seaward and on the backslope of the Ghats escarpment and the gradient slackens: a minimum of 60 km is necessary to proceed from five dry months in the west to seven in the east. The critical threshold in terms of landscape differentiation appears to be the transition between four and five dry months, in that it separates a humid region of evergreen forest and 'udic' soil control section characteristics (terminology after the US Soil Taxonomy) from one of 'ustic' soil control sections and deciduous vegetation, where, for instance, irrigation is required. In fact, Bourgeon (1989) found from various humidity measurements at 30 cm depth at the end of the dry season (April) that vegetation probably provides the surest index of soil moisture properties. Vegetation patterns may thus offer a more reasonable empirical indication of climatic thresholds in the landscape than more arbitrary calculations, which is, for instance, illustrated in the profound differences in PET maps of India according to whether they are based on Thornthwaite or on Penman calculations (Krishna Kumar *et al*., 1987). The Linacre formula, which is sometimes used for *ad hoc* purposes by forestry and soil scientists (e.g. Peterschmitt, 1993), may provide the best trade-off between analytical precision and calculation expenditure in tropical environments.

Singh (1986) approached the Indian climatic classification problem by using a comprehensive rainy season index defined as a sequence of consecutive months where $P > 50$ mm. Even though the resulting categories are unsurprisingly heavily weighted by the summer monsoon months, the author reaches an all-India climate typology which falls into six categories. Interestingly, Singh's classification exhibits no less than five of the six all-India categories in Karnataka State alone (Figure 7(a)), which has to be attributed to the direct effect of the Western Ghats in that region and fully agrees with the foregoing analysis.

Finally, the role of the Western Ghats in the climatic configuration of peninsular India is also broadly confirmed by the statistical cluster analysis approach of Gadgil and Joshi (1983). These authors show first of all that the summer monsoon explains 84 per cent of precipitation variance in the Konkan – Malabar region, which strongly confirms the monsoon 'identity' of the Indian west coast. The climatic clusters also reveal the north–south climatic gradient in the semi-arid Deccan (Figures 4 and 7(b)), which breaks down north of the Narmada rift where the Western Ghats disappear. In the Indo-Gange plains, a south-east to north-west climatic gradient takes over, under the direct influence of the north-eastern, Bay of Bengal branch of monsoon airflow.

In summary, all the climatic classification methods reviewed tend to converge towards the idea of a clear monsoon/non-monsoon dichotomy on either side of the Western Ghats ridge, which, by the same token, confirms the usefulness of confronting a 'naturalistic' approach (e.g. vegetation and soil suites, Gunnell and Bourgeon, in press) to a statistical approach. Each can serve as a control on the other, especially as statistical methods, such as cluster analysis, can generate uncorroborated aberrations when successive sorting iterations are carried out indiscriminately and are not guided by a specific research objective (see discussion in Anyadike, 1987): this approach, used by Gadgil *et al*. (1988) in a climatic classification of Karnataka State, yielded, for instance, no fewer than 16 'homogeneous' subregions when Pascal (1982) succeeds in explaining the entire vegetation distribution of the region using only five seasonal regime categories. Thematic mapping from field work and satellite imagery still provides the best guarantee against statistical artefact.

DISCUSSION

The Western Ghats clearly play a key part in the unusual climatic diversity of the Indian subcontinent. As an orographic commutator of monsoon advection, the elevated plateau rim fulfills two major functions.

(i) First, on the windward side of the escarpment, the Western Ghats confirm the status of the Indian west coast as the chief standard-bearer of the typical unimodal South Asian monsoon climate. A monsoon climate also prevails in north-eastern India, but there it is somewhat altered by the additional importance of 'nor'westers' and cyclones, which, over the last 70 years, were in the latter case six times more frequent in the Bay of Bengal than in the eastern Arabian Sea (Rao, 1981).

Furthermore, it would seem that although the mountain barrier polarizes precipitation along the crest of the Ghats and on the immediate scarp foot, an important secondary band of convective cloud formations and precipitation also exists offshore, with for instance 100–200 mm day^{-1} observed between 23 and 25 June 1979 (Ogura and Yoshizaki, 1988). It is supposed that the monsoon air, when ascending over the Ghats escarpment, liberates a dose of latent heat that sets a thermally driven, third-order circulation cell into motion. Its descending branch offshore compensates the forced ascension along the Ghats and, if above normal sea-surface temperatures (SSTs) in the eastern Arabian Sea prevail (a recorded, although not regular phenomenon) and wind shear turbulence affects the incoming monsoon airflow (a predominant situation), the additional heat and vapour can form the observed clouds. Because the clouds develop to considerable heights, the roof of the formation tends to be driven offshore by the base of the Eastern Tropical jet inversion, which could explain the band of precipitation occurring several dozen kilometres away from the continent margin itself. In other words, the Western Ghats do not only trigger rainfall *in situ* but would also appear to play a role in driving a subsidiary, precipitation-forming circulation pattern which amounts to a sophisticated version of a sea-breeze.

(ii) Second, as a climatic filter, the Western Ghats deny the entire Deccan of a monsoon climate in spite of the Indian subcontinent belonging to the first-order realm of monsoon circulation. Although true monsoon climates affect only certain fringes of the Indian landmass, a crucible of tropical climates, as if nested in the monsoon circulation pattern, occupies the core of peninsular India. Virtually all the climatic types expected to be found in the intertropical zone are assembled in the rain-shadow of the Western Ghats, including some that are particularly rare by any standard: Blasco and Legris (1973) quote for instance the Coromandel coast (Tamil Nadu) where rainfall graphs have possible equivalents only in coastal southern Vietnam or, at a similar latitude in the opposite hemisphere, in the region of Bahia (Brazil). This, therefore, contrasts with the Konkan–Malabar monsoon climate, which is in many ways unoriginal: the precipitation diagram of Bombay bears a striking resemblance with that of Banjul (Gambia); Bhatkal, in coastal Karnataka, has a pattern very similar to those of Konakry or Freetown; Sunticoppa (on the immediate backslope of the Ghats) resembles Odienné (Ivory Coast), and Trivandrum, with its 'little dry season' in August, could almost be substituted for Abidjan (including interannual variability).

The implications suggested by the study on the role of the Western Ghats in steering monsoon airflow and imposing a particular pattern to the climates of the Deccan are varied and wide-ranging. Among these, the historical problem of determining when the passive margin shoulder became sufficiently uplifted to act both as an effective barrier to monsoon influence and a precipitation-enhancing relief feature would deserve particular attention (Gunnell and Fleitout, 1997) — especially as the palaeobotanical and geomorphological record reveals that the entire peninsular India was hot and humid from the Mesozoic to the mid- to Late Cenozoic (e.g. Meher-Homji, 1989; Pascal, 1991; Fawcett *et al*., 1994). The currently observed climatic diversity is therefore recent at geological time-scales. Also, in terms of applied climatology, the consequences of the observed climatic diversity across restricted areas such as Karnataka raise the whole question of agroclimatic potential and land capability in tropical regions. Clearly, according to the time during which the current climate mosaic has prevailed, the soil development pattern will have been affected, and the chances of fertile soils developing in at least some of the subregions will be greater than in other tropical regions or climatic belts with fairly uniform soil and/or vegetation covers. The sustainability of agriculture, deriving either from self-sufficiency, or from complementary interactions between adjacent agroclimatic regions with closely knit economic relations, is an important issue in the developing world (Gunnell, 1997). Any comparison between the monsoon regions of the world, for instance India and western Africa, should avoid overlooking these broader climatic aspects, which involve soil types and palaeoclimatological impacts on relict features in the landscape, size and closeness of contrasting rainfall subregions as well as interannual variability, which can all bear on land capability evaluation and suitably conceived rural development programmes.

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