Winter temperature and precipitation trends in the Siachen Glacier

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To examine changes in the wintertime seasonal (December, January and February) temperature and precipitation over the Siachen Glacier, one of the largest glaciers outside the polar region, an analysis of its temperature and precipitation indices is planned. In the present study, temperature and precipitation indices over a period of 23 years (1984–2006) at six stations are computed after stringent quality control checks. Various indices are analysed at these stations representing glacier accumulation, transition and ablation zone. Results show rate of increase in number of warm days at A3 (station in accumulation zone) and A1 (station in ablation zone) though slower at A3 than at A1. Further warm nights show significant decrease, cold days show increasing trends whereas cold nights show significant increase at A3. In case of ablation zone (A1), these indices show reverse trend. In case of precipitation, numbers of consecutive dry (wet) days have decreased (increased) in the A1 and reverse is observed at A2 and A3 (stations in transition and accumulation zones respectively). Based on the regional temperature and precipitation changes, it is hypothesized that the transition zone between the accumulation and ablation zones fluctuates and moves towards the accumulation zone thereby extending the ablation zone and shrinking the accumulation zone. As a result, properties of the accumulation zone slowly get converted into those of the ablation zone.

Keywords: Accumulation, climate interaction, glacier response, transition and ablation zones.

THE Karakoram Himalayan range has a number of valley glaciers with about 37% of its total area covered with glacier bodies and permanent ice beds. Siachen Glacier, with a length of about 74 km in the northwest to southeast (NW–SE) orientation is the main glacier system in this part of the Himalayas. It is bound by Karakoram range in the north and Ladakh range in the south and has numerous tributary glaciers. Precipitation in the Karakoram Himalaya occurs under the influence of extratropical cyclones called western disturbances (WDs), in Indian parlance[1].

Several studies have been made on a number of glaciers situated in the Himalayas. Kargel *et al.*[2] made digital glacier inventories of the Himalayan glaciers to record the changes in the glacier surface in contrast to the earlier map-based inventories[3]. Roy and Balling[4] and Yadav *et al.*[5] proposed that changes in glacier length, areal extent or mass balance can be used as climate indicators in the region where time series of temperature and precipitation are sparse and climate change/variability signals are not clear. Kulkarni[6] using LandSAT imageries proposed linkage between the specific mass balance and accumulation area ratio (AAR) or the equilibrium line altitude (ELA). The basis of his study is mass balance information at coarse resolutions in time and space. Berthier *et al.*[7] proposed remote sensing-based estimates of glacier elevation changes in the Himalayas. Rasmussen *et al.*[8] estimated precipitation values over the Blue Glacier, US and related those with the mass balance. They found increase in the precipitation values till 1965 followed by subsequent decrease. Shahgedanova *et al.*[9] reported recent mass balance changes in the Djankuat Glacier and looked into possible relationship with the local climate. They also looked into the interannual variabilities in the accumulation and ablation zones. Wagnon *et al.*[10] have studied mass balance and surface velocity on Chhota Shigri Glacier based on four years' study which shows that ablation period is limited to the summer months.

Though several studies on glacier melt/recession and climate change in different parts of the world have been undertaken, the Siachen Glacier is yet to be studied comprehensively. Moderate snowfall on glaciated surface, extremely low temperatures and intense wind conditions give rise to harsh weather and climatic conditions over this region. The ruggedness and inaccessibility of the region has led to limited data collection and hence limited scientific investigation. It is important to note that all the studies mentioned here are based on either mass balance or remote sensing based information. It is well known that in case of unavailability of climate data with long time series, it is imperative to use the mass balance studies to examine glacier changes[5]. However, in the present study, 23 years of temperature and precipitation records at the Siachen Glacier are available and used. These data series cover a reasonably long period and are of good quality in this part of the Himalayas.

In the present study, long-term historical wintertime seasonal (December, January and February – DJF) measurements (from 1984–85 to 2006–07) for mean maximum, minimum and daily temperatures and precipitation at 10 observatories, situated in the Siachen Glacier, of the Snow of Avalanche Study Establishment (SASE), Chandigarh, India are considered. These observations are recorded as per the World Meteorological Organization (WMO) standards. Stringent quality control checks[11] in the context of missing data, errors, repetivity, data gaps and inhomogeneity are employed in the time series used in this study. Stations with too many missing data in between are not considered. A year with more than 20% of its winter days without data is not included. Temporal

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inhomogeneity[12] and inhomogeneities due to station relocation and changes in observing procedures[13] are also looked into. It may be noted that major inhomogeneities in data series occur due to changes in instrument exposure and observation time. Therefore co-located stations observations have been amalgamated to generate a longer time series. After such rigorous data scrutiny, six observatories, situated in and along the Siachen Glacier, have been selected. The details of these stations are not given here considering the sensitivity of the area. Rather those are identified by alphabets, viz. A1, A2, A3, A4, A5 and A6 in Figure 1.

In case of temperature, daily, monthly and seasonal (DJF) mean time series of maximum, minimum and dry bulb temperatures are prepared in the mentioned observatories. Further, five temperature values (dry bulb at 0300 UTC and 1200 UTC of previous day, dry bulb at 0300 UTC of current day, maximum and minimum temperature) are averaged for generating the final time series. Due to landuse[14] and topography[15], temperature records at different observatories show highly variable patterns during winter. Therefore, to remove these biases five temperature records are considered to generate normalized time series. Further, anomalies are calculated by subtracting the respective mean values and then dividing those by the respective standard deviations[16]. Precipitation during winter (DJF) over the Siachen Glacier is received in the mixed form of snow, sleet and liquid water, etc. Thus a large uncertainity is implicit in obtaining equivalent liquid water content based on the density

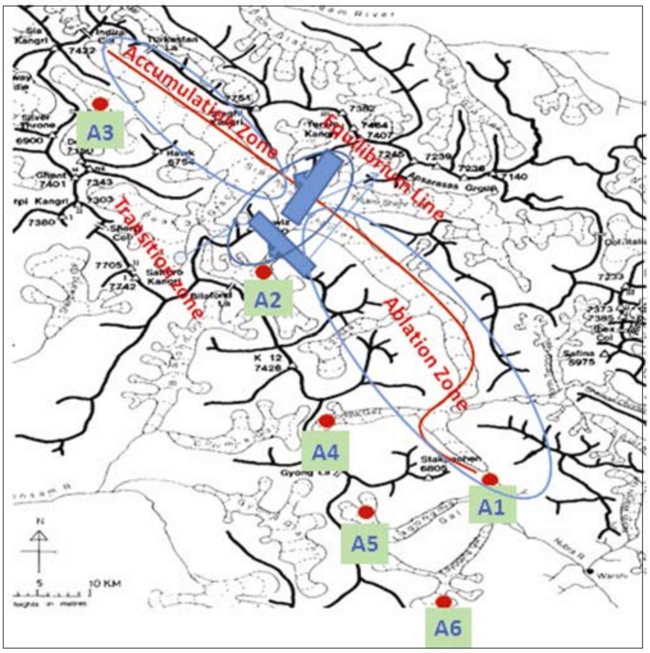

Figure 1. Distribution of stations and various defined zones along the Siachen Glacier.

factor[17]. Also, geographical positioning, elevation, sun aspect, etc. of stations strongly affect processes such as snowdrift and snow sheltering, and thus the observed snow depth. And hence these issues need careful examination. Therefore, apart from employing quality control checks, as mentioned earlier, snow records (in cm) are converted into water equivalent (in mm) by multiplying them with corresponding densities. And then time series are normalized and anomalies are computed as in the case of temperature.

Out of a suite of 33 indices, four temperature indices (Table 1) are selected and computed from homogenized daily maximum, minimum and dry bulb temperatures using European Commission funded project based Statistical Dynamical Downscaling of Extremes (STARDEX), diagnostics extremes indices software (available at http://www.cru.uea.ac.uk/projects/stardex/). These indices include warm events (warm days, warm nights) and cold events (cold days, cold nights). These indices based on percentiles represent the number of days either above 90th or below 10th percentile level. In case of precipitation, four precipitation indices are selected (Table 1). They illustrate precipitation type, frequency, intensity and extremes. The maximum number of consecutive dry (wet) days is used to characterize the length of dry (wet) spells. The very wet days and the heavy precipitation days describe some extreme features of precipitation. For very wet days, the 95th percentile reference value is obtained from all non-zero total precipitation events. This method is adopted here since there is a considerable difference in precipitation amounts among these stations. The monthly, and consequently seasonal, values are not considered when the data for more than three consecutive days or more than five random days are missing in a given month. These eight indices are selected from the set for detailed analysis for a number of reasons. First, it is decided that a concerted effort to analyse these indices would be of more value than trying to cover a large number, particularly since the indices themselves are to a large degree inter-correlated. There is also statistical reason for choosing these indices. These indices could be considered indicators of climate change over the Siachen Glacier.

Further, all trends pertaining to the given indices have been calculated using a three group resistant line method[18] with statistical significance determined using the Kendall tau test[19]. When a trend is indicated as 'significant', it has at least 95% significance using this test. The three-group resistant line method is more resistant to outliers than least-squares linear regression, a property derived from the fact that one of the most resistant measures of a sample is the median. The method divides the series (by time) into thirds and determines the trend of the line through the median of the first and last thirds.

Though six stations are found suitable for this study, primary discussion is based on the results from three stations (A1, A2 and A3), which are situated along the

Table 1. Definition of temperature and precipitation indices used in the study. T_{max} and T_{min} are daily maximum and minimum temperatures respectively

Temperature and precipitation indices	Definition	Units
Warm days	Percentage days with T_{max} > 90th percentile	day
Warm nights	Percentage days with T_{min} > 90th percentile	day
Cold days	Percentage with T_{max} < 10th percentile	day
Cold nights	Percentage with T_{min} < 10th percentile	day
Mean climatological precipitation	Seasonal (DJF) total precipitation/number of days with P > trace	mm day^{-1}
Heavy precipitation days	Number of days precipitation ≥ 10 mm	day
Maximum number of consecutive dry days of p	Maximum number of consecutive dry days (trace days are excluded)	day
Maximum number of consecutive wet days of p	Maximum number of consecutive wet days	day

p denotes total precipitation. Data length of 1988–2006, except at A2: 1994–2006, is used for computing these indices.

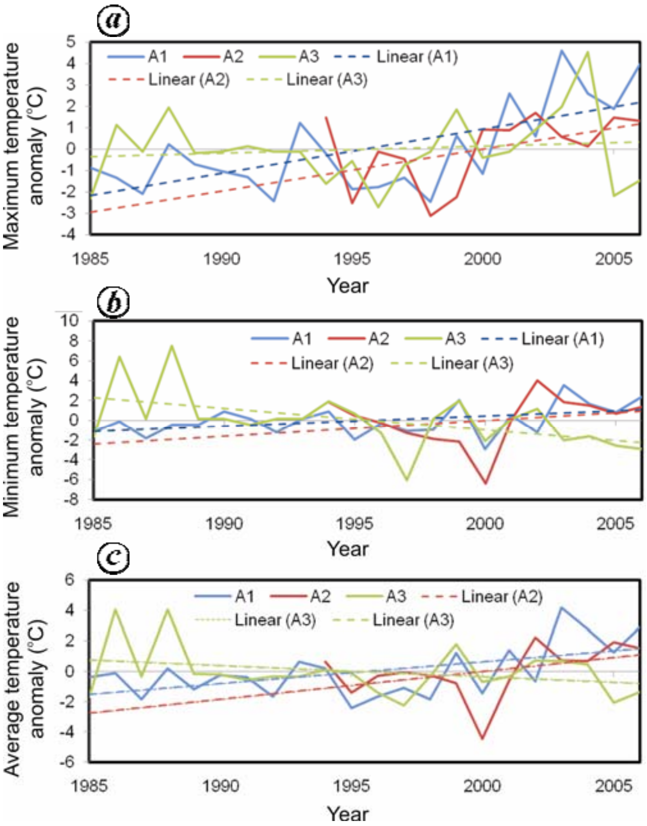

Figure 2. Time series of (***a***) maximum, (***b***) minimum and (***c***) average temperature anomalies at stations situated in ablation (A1), transition (A2) and accumulation (A3) zones.

Siachen Glacier. For the sake of quick reference again, stations A3, A4, A5 and A6 are situated in the accumulation zone, A2 is in the transition zone and A1 in the ablation zone (at the snout of the Siachen Glacier) as shown in Figure 1. Also, the same period of 1988–2006 is considered for comparing various indices.

The time series of normalized seasonal (DJF) temperature and anomalies are calculated as

$$\frac{1}{\mathrm{SD}}\left(\frac{x_i-\bar{x}}{\bar{x}}\right) \quad \text{and} \quad \left(\frac{x_i-\bar{x}}{\mathrm{SD}}\right)$$

respectively. Here SD is standard deviation, x_i the actual time series and $\bar{x}$ is the mean of that time series. Figure 2 *a–c* presents winter time seasonal (DJF) mean temperature anomalies corresponding to maximum, minimum and daily mean temperatures. Figure 2 *a* depicts increasing trends in the seasonal maximum temperature across the Siachen Glacier. Increasing trends at A1 and A2 are of somewhat similar order but increasing trend at A3 is slower. And as the figure shows, by 1995 warming rates at A1 and A2 have taken over the warming rate of A3. In case of seasonal minimum temperature in Figure 2 *b*, contrasting trends are seen. Significant increasing (decreasing) trends at A1 and A2 (A3) are observed. Further, analysis of average temperature shows significant decrease of ~ 1°C in the daily mean temperatures at A3 (in accumulation zone), rise of ~ 2°C at A1 (in ablation zone) and increase of 0.5°C at A2 (in transition zone). On combining these results together, it can be stated that at ablation zone, warming is prevalent whereas at accumulation zone, cooling is prevalent.

To investigate local warming trends, temperature indices pertaining to warm events are analysed and presented in Figure 3 *a* and *b* with corresponding trends and *p*-values in Table 2. Significant increasing trends in the percentage number of warm days are observed in all the three zones with different rates of increase. In the accumulation zone, the rate of increase of number of warm days is smaller than that in the ablation zone (Figure 3 *a*). When the maximum temperature T_{max} is above its 90th percentile in a season, i.e. warm days, stations located in the ablation (A1) and transition (A2) zones show higher increase in such number of days whereas A3 in the accumulation zone shows comparatively slower increase. It illustrates that increase in maximum temperature in accumulation zone is slower than in the ablation zone (Figure 2). In case of percentage number of warm nights, fluctuating patterns emerge. Figure 3 *b* illustrates variability in the percentage number of warm nights in winter corresponding to the highest minimum temperature in all the three zones. It is found that when the minimum temperature T_{min} is above its 90th percentile, increase, though not significant, in percentage number of warm nights at A1 (in the ablation zone) and significant decrease at A3 (in the accumulation zone) are seen. Significant increasing trend is also observed in percentage number of warm nights at A2 (in the transition zone).

The characteristics corresponding to cold events (cold days and cold nights) based on temperature indices are presented in Figure 3 *c* and *d* with corresponding trends and *p*-values in Table 2. In the accumulation zone, the number of cold days show increasing trends whereas in the ablation zone (A1) and transition zone (A2), the reverse is observed. Analysis pertaining to the number of cold days in the winter season is presented in Figure 3 *c*. At A1 cold days, below 10th percentile of T_{max}, have reduced which at A3 increased. Similar analysis pertaining to cold nights, below 10th percentile of T_{min}, is carried out and is presented in Figure 3 *d*. Analysis shows contrasting trends between the ablation and the accumulation zones. It shows significant increase in the percentage number of cold nights in the accumulation zone and decrease in the percentage number of cold nights in the ablation and transition zones in winter season.

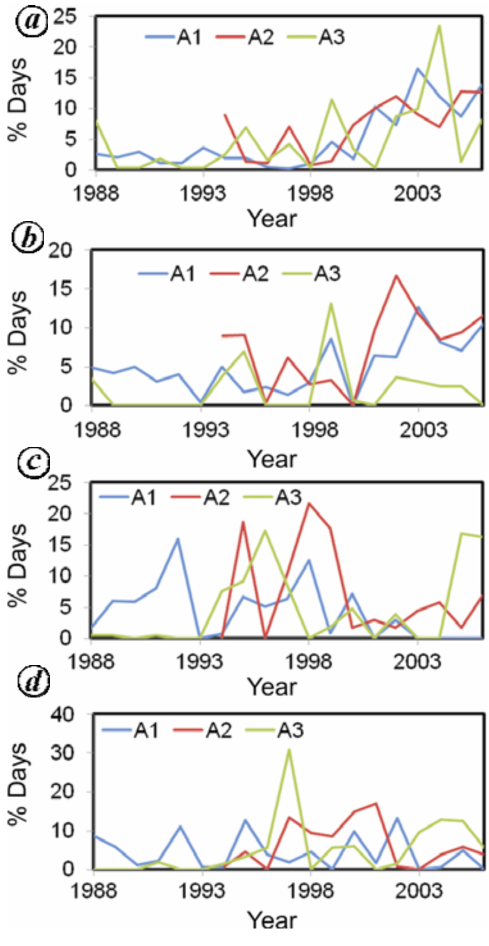

Figure 3. Time series of percentage of number of (***a***) warm days, (***b***) warm nights, (***c***) cold days and (***d***) cold nights at stations situated in ablation (A1), transition (A2) and accumulation (A3) zones.

These important significant/non-significant contrasting responses of glaciers may be attributed to climate change and the environmental stress in the region due to increased defence population. Also, glacier response to climate change and environmental stress is not homogeneous across the Siachen Glacier. Due to these contrasting temperature regimes, the glacier mass balance may behave differently in the accumulation and ablation zones. Further, the equilibrium line (EL) which primarily divides the accumulation and the ablation zones (Figure 1), lies in the transition zone. Thus, it may be hypothesized that the transition zone moves towards accumulation zone and thereby the accumulation zone shrinks and ablation zone spreads. EL approaches A2 where the mean temperature rises as in the ablation zone. This analysis may be extended to suggest that in the past A1 might have gone through similar process which has eventually moved EL from the ablation to the accumulation zone. Also, since A4, A5 and A6 also show similar patterns as of A3, in future these stations in accumulation zone may undergo the same process. Due to such transition processes, the tributary glaciers may break off from the main glacier. It clearly illustrates that the accumulation zone of the Siachen Glacier shows cooling tendency whereas the ablation and the transition zones show warming.

Precipitation-forming processes are complex to understand over the Siachen Glacier at regional scale. Precipitation at different stations is not homogeneous which indicates variability due to various thermodynamical and orographical processes[20]. Though there are variable trends in the precipitation across the Siachen Glacier, careful scrutiny of dry and wet phases shows some interesting results. It is important to note that orography plays a dominant role in precipitation-forming processes than the large scale circulation[15] over this region of the Himalayas. Therefore, it is imperative that the amount of precipitation received at a station will depend primarily on the orographic situation of that station. Therefore, it is difficult to quantity the exact precipitation amount variation. Nonetheless, an attempt is made to provide an analysis on the precipitation pattern over the Siachen Glacier.

Precipitation patterns at these stations in the Siachen Glacier are also analysed. Trend and *p* values for precipitation indices for the chosen stations in the Siachen Glacier are presented in Table 2. Significant variations are observed in the number of total precipitation (snow + rain) events. Analysis shows varying results. Mean climatological precipitation shows increasing trend at A1 and decreasing trend at A2 and A3 with positive trend in number of heavy precipitation days at A1 and negative at A2 and A3. To analyse it further, indices pertaining to consecutive dry and wet days are studied. A wet day is defined as having water equivalent of at least 1 mm. This relatively high threshold is used since during winter (DJF) over the Siachen Glacier, most of the precipitation is received in the form of snow. Also, this relatively high

Table 2. Trends and *P* values for temperature and precipitation indices

Temperature and precipitation indices	A1 34°11′49″N, 77°12′28″E, 3570 m Trend	A1 *P* (trend)	A2 34°59′32″N, 76°57′14″E, 5215 m Trend	A2 *P* (trend)	A3 35°34′55″N, 76°47′32″E, 5995 m Trend	A3 *P* (trend)
Warm days	0.0122	0.0384*	0.0182	0.0001*	0.0045	0.0317*
Warm nights	0.0084	0.6394	0.0253	0.0006*	– 0.01	0.0176*
Cold days	0.0065	0.5214	0.0069	0.002*	– 0.0045	0.0309*
Cold nights	0.0109	0.0017*	0.0084	0.0041*	– 0.0028	0.1812
Mean climatological precipitation	0.0297	0.1578	– 0.0731	0.0009*	– 0.0183	0.2968
Heavy precipitation days	0.3893	0.2727	– 0.3626	0.0005*	– 0.0383	0.3061
Maximum number of consecutive dry days	– 0.0102	0.8364	0.7461	0.0006*	0.2641	0.5073
Maximum number of consecutive wet days	1.2246	0.465	– 5.3202	0.0007*	– 0.0351	0.0345*

*Values are significant at $P < 0.05$.

threshold was used as previous studies have found that lower thresholds can be sensitive to problems such as underreporting of small snowfall amounts and changes in the units of measurements[21,22]. A dry day is defined as having less than 1 mm water equivalent of snowfall. Therefore, wet day index is calculated by first determining the 90th percentile threshold of all events greater than 1 mm for DJF, then for each winter counting the number of events above this threshold and then presented in the percentage. Dry day index is calculated by simply determining the maximum number of consecutive days with water equivalent less than 1 mm. These indices show that there is decreasing (increasing) trend in maximum number of consecutive dry days at A1 (A2 and A3) (Table 2). In case of maximum number of consecutive wet days increasing (decreasing) trend at A1 (A2 and A3) is observed. There are variations in trends and their significance. This overall distribution can be attributed to the physical reasoning of precipitation-forming processes which are closely associated with warming pattern and hence more evaporation than the condensation processes in the atmosphere. As such, precipitation-forming process over the Siachen Glacier is complex.

The present study examines the wintertime trends in temperature and precipitation over the Siachen Glacier during 1984–2006. It shows that rate of increase of number of warm days is slower in the accumulation zone than in the ablation zone. In case of warm nights, significant decrease (increase) occurs in the accumulation (ablation) zone. Cold days have significantly increased in the accumulation zone and reverse is observed at the ablation and transition zones. It is found that there is significant increase (decrease) in the number of cold nights in the accumulation (ablation) zone. In case of precipitation, mean climatological precipitation is observed increasing in the ablation zone and reverse is seen in the transition and accumulation zones. Similar patterns are found in case of heavy precipitation event. Further, numbers of consecutive dry (wet) days have decreased (increased) in the ablation and reverse is seen in the transition and accumulation zones.

These results indicate different trends in the temperature indices in the accumulation and ablation zones. It is found that the temperature of the whole glacier does not respond homogeneously to climate change and local environmental stress. Therefore, it is hypothesized that EL in the transition zone between the accumulation and ablation zones might be moving from the ablation zone towards the accumulation zone. In other words, accumulation zone shrinks and ablation zone spreads.

The study of the impact of global warming on the glaciers is very complex. It is not entirely correct to arrive at any inference based on the visual observations of the snout of glacier only. Energy balance of glaciers needs to be looked into more critically. In short, glacier dynamics needs to be examined in a holistic way in order to study the impact of global warming along with the local environmental stresses on the Siachen Glacier. It can be very well stated that the Siachen Glacier in itself responds differently to the impact of climate change/global warming on temperature and precipitation.

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ACKNOWLEDGEMENTS. We acknowledge the cooperation and guidance of Mr A. Ganju, Director, Snow and Avalanche Study Establishment, Chandigarh, India for this study.

Received 18 August 2009; revised accepted 12 May 2010

Fossil fruits from Early Eocene Vastan Lignite, Gujarat, India: taphonomic and phytogeographic implications

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A small collection of fossil fruits of dicotyledonous plants, having close affinity with modern taxa, *Ziziphus xylopyros* Willd. (Rhamnaceae), *Combretum decandrum* Roxb. and *Terminalia chebula* Retz. (Combretaceae) and *Lagerstroemia flos-reginae* and *Lagerstroemia parviflora* (Lythraceae) is reported from the subsurface beds of the Cambay Shale Formation exposed in an open-cast lignite mine at Vastan village near Surat, western India. Well preserved fossilized fruits have limited transport to burial histories from their plant producers and therefore have great potential to provide excellent data about the character of forests such as the one that may have contributed to the formation of the extensive Lower Eocene lignite deposits of western India. The fossilized fruits from Vastan are referred here to four new form species, viz. *Ziziphus eocenicus*, *Combretum vastanensis*, *Terminalia cambaya* and *Lagerstroemia sahnii*. The habitat and present day distribution of extant comparable taxa suggest the prevalence of tropical deciduous forest with moisture-loving plants in the Vastan mine area during the Early Eocene period. Such deciduous forests presently occur in south Coimbatore, Palghat and moister parts of Mysore region of southern India.

Keywords: Cambay Shale Formation, Early Eocene, fossil fruits, Gujarat, Vastan Lignite Mine.

In the last five years, the Vastan Open Cast Lignite Mine, near Surat, western India, has attracted several national and international teams of researchers for its very rich and diverse Early Eocene floral and faunal remains that occur in the subsurface beds of the hydrocarbon-rich Cambay Shale Formation. A highly diverse herbivorous land mammal fauna, besides insects preserved in amber, and birds has already been documented from the lower part of the Cambay Shale Formation exposed in the mine section (e.g. Rana *et al.*[1], Rose *et al.*[2] and references therein) and new fossils are still being unearthed. The fossils of lower vertebrate (fish, snakes, lizards and frogs) and invertebrate animals (mainly molluscs, foraminifers and ostracods) are also abundant[3,4]. The multiple lignite

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