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RESEARCH COMMUNICATIONS

Variations in the solar activity dependence of electron content with latitude

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Simultaneous electron content data obtained at low latitudes in the Indian zone during the solar minimum year 1975–76 have been analysed to derive the spatial variation of the effect of season and solar activity. Results indicate that the amplitude of the annual summer-to-winter variation changes with latitude and is characterized by a minimum around the crest of the equatorial *F*-region anomaly. Progressive retardation in the hour of peak occurrence with increase in solar activity has been observed at all locations except for those around the crest of the anomaly. Again, positive correlation between production rate and solar flux is minimum at the crest of the anomaly. These observations are explained on the basis of transition between the effects of interhemispheric transport of ionization and of sun's declination over the crest zone of the anomaly.

THE ATS-6 campaign in India (September 1975–August 1976) provided a unique opportunity for intercomparison of ionospheric electron content (IEC) data obtained along a chain of stations in this low latitude region. The observing stations were located over a subionospheric latitude span of 17° (11°N to 28°N) and longitude spread of 15° (69°E to 84°E). Various features of IEC variations such as morphology, short as well as long-term variability, geomagnetic storm effect, annual and semi-annual periodicities, correlation etc. have been studied using this data base[1–6]. The aim of the present study is to investigate the spatial variation of the effect of season and solar activity on low latitude IEC during the solar minimum period of 1975–76.

The IEC data used were obtained by monitoring the Faraday rotation angle of 140 MHz beacon transmission from the ATS-6 geostationary satellite during its phase-II campaign (35°E). Modulation phase measurements were used to calculate the total electron content (TEC) over Ootacumund. Comparison of the total content data obtained at Ootacamund with the Faraday content measured at Trivandrum (7.9°N, 73.3°E; subionospheric) and with the latitudinal projections of the numerical model developed earlier[7] for the same period shows that on an average IEC is about 80% of TEC at this location. In addition, data for Jan.–Jun., 1976 from Lunping, another low-latitude station, has been used for comparison. Lunping data were collected by monitoring the 136 MHz beacon transmissions from synchronous satellite INTELSAT 2F3. Consequently, the subionospheric point shifts in longitude by about 3.5° during the period of observation. Station geometry of the locations for which data have been used is given in Table 1.

The diurnal and seasonal features of electron content observed during the ATS-6 phase-II period were earlier reported for various Indian locations[1,8,9]. Singh *et al.*[1] observed that the winter anomaly i.e. winter electron content being higher than the corresponding summer values is confined to the latitude zone affected by the equatorial *F*-region anomaly whereas for locations outside this region winter IEC are appreciably lower compared to those of summer and equinox[8,10]. In Figure 1, the monthly mean IEC_{max} plotted for each of the observing stations located along 71(± 2)°E meridian is shown. The difference between summer and winter IEC_{max} is minimum around 22°N (Ahmedabad and Udaipur). Winter anomaly is evident at Ootacamund and Bombay while it is absent at Delhi and Patiala. The dashed line in the figure indicates the

Table 1. Co-ordinates of observing stations and corresponding subionospheric locations

Station	Geographic			Subionospheric		
	Lat.°N	Long. °E	Approx Dip°N	Lat.°N	Long.°E	Approx Dip°N
Ootacamund	11.4	76.7	4.4	11.0	73.5	4.0
Bombay	19.1	72.9	25.0	17.8	69.8	23.0
Ahmedabad	23.0	72.6	34.0	21.5	69.4	30.0
Udaipur	24.6	73.7	35.0	22.6	69.6	33.0
Lunping	25.0	121.2	36.0	22.7	129.5 – 133.0	35.0
Gauhati	26.2	91.8	37.0	23.8	83.6	33.5
Delhi	28.6	77.2	42.4	26.2	72.2	93.5
Patiala	30.3	76.4	46.0	28.3	72.1	47.0

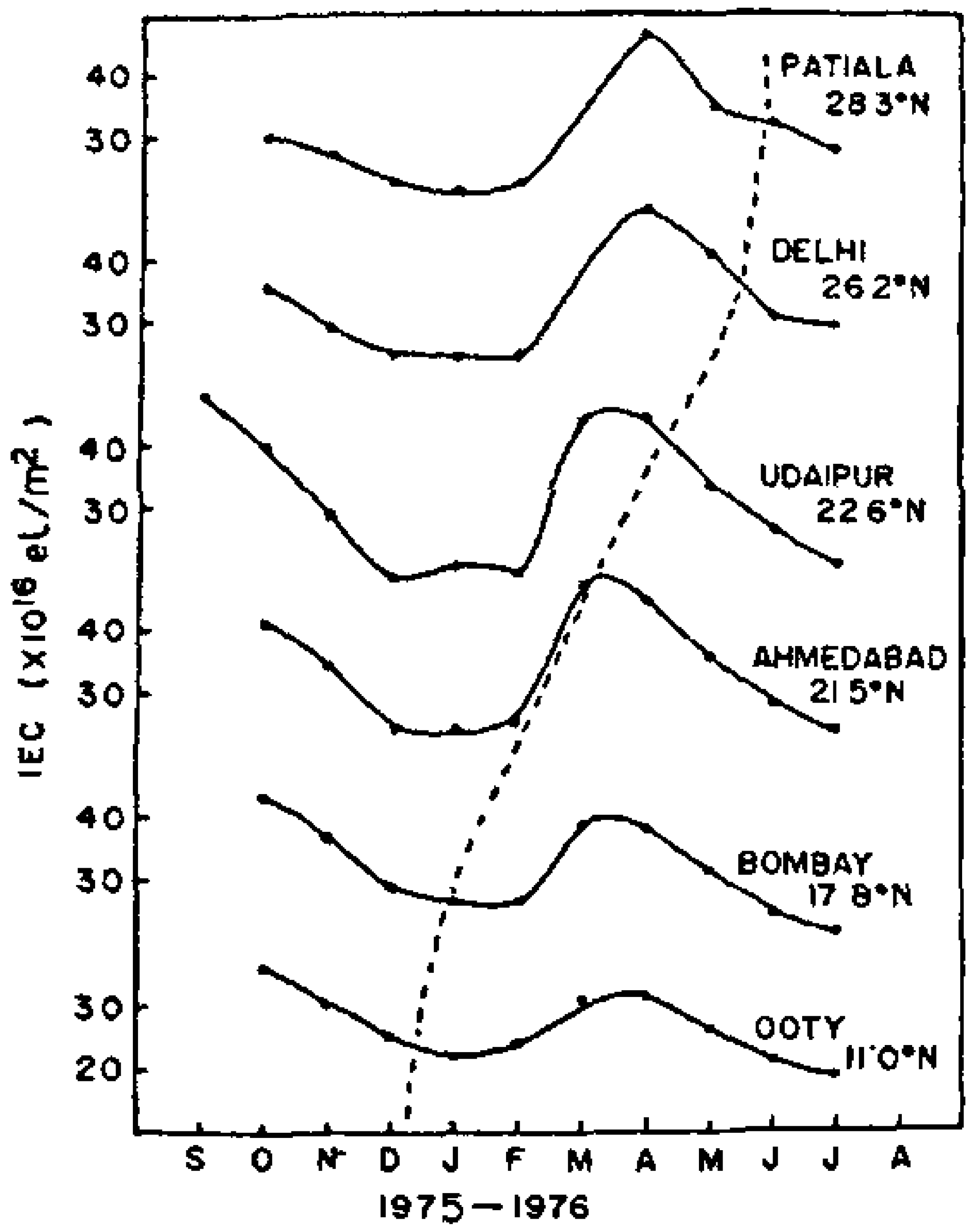

Figure 1. Monthly mean IEC_{max} plotted for observing stations located along 71 (± 2)°E longitude.

out on many occasions[11]. Examination of the diurnal variation on individual days for any set of data reveals that the hour at which the diurnal curve reaches its maximum varies from day to day or with season. It was observed earlier that in the Pacific zone, the time of peak occurrence of IEC is progressively delayed with increase in sunspot activity[12]. The data for each location selected as in Figure 1 have been subjected to a similar analysis and the results averaged for each month are presented in Figure 2. It might be noted from the Figure and Table 2 that the daytime maximum tends to occur late in the day with increase in solar flux at the locations outside the crest of the anomaly (Ooty, Bombay, Delhi and Patiala). The correlation coefficients are higher at these locations compared to the values obtained at the crest of the anomaly. However, the coefficients are significant only for two locations, Bombay and Delhi at the 10% confidence level.

The fact that correlation is low and insignificant at the crest of the anomaly is further illustrated in Figure 3 where data similarly analysed as in Figure 2 for three stations—Udaipur, Gauhati and Lunping are plotted. These stations are located approximately along the same latitude 23(± 1)° N and separated by a longitude crossover from anomalous electron content variations near the equator to normal seasonal variations towards higher latitudes. It was earlier observed[5] from a harmonic analysis of the same set of data for three selected locations,—Ootacamund (equatorial), Ahmedabad (crest of the *F*-region anomaly) and Delhi (outside the anomaly region) that electron content at all these locations exhibits annual and semi-annual periodicities. The annual variation is maximum in winter at Ootacamund, while at Ahmedabad and Delhi, the annual maximum occurs in summer. Further, the amplitude of this annual variation is minimum at Ahmedabad and maximum at Delhi during daytime hours when this variation is appreciable. This is reflected in Figure 1. It might be deduced from these observations that the amplitude of the annual variation is a function of latitude in the Indian low-latitude region during solar minimum. Variation of this factor on both sides of the observed minimum (~ 22°N) in terms of latitude can be described numerically by the following equations

$$\Delta IEC_{WS}(\times 10^{16}\,el.m^{-2}) = -0.42\,(\text{latitude}^\circ N) + 11.3,$$

$$\Delta IEC_{SW}(\times 10^{16}\,l.m^{-2}) = 0.92\,(\text{latitude}^\circ N) - 17.7.$$

Electron content exhibits a diurnal variation with a minimum around the pre-sunrise hours and a single maximum in the afternoon hours at about all the stations. Close to the equator, the daytime maximum is rather flat or exhibits two peaks with a noontime bite-

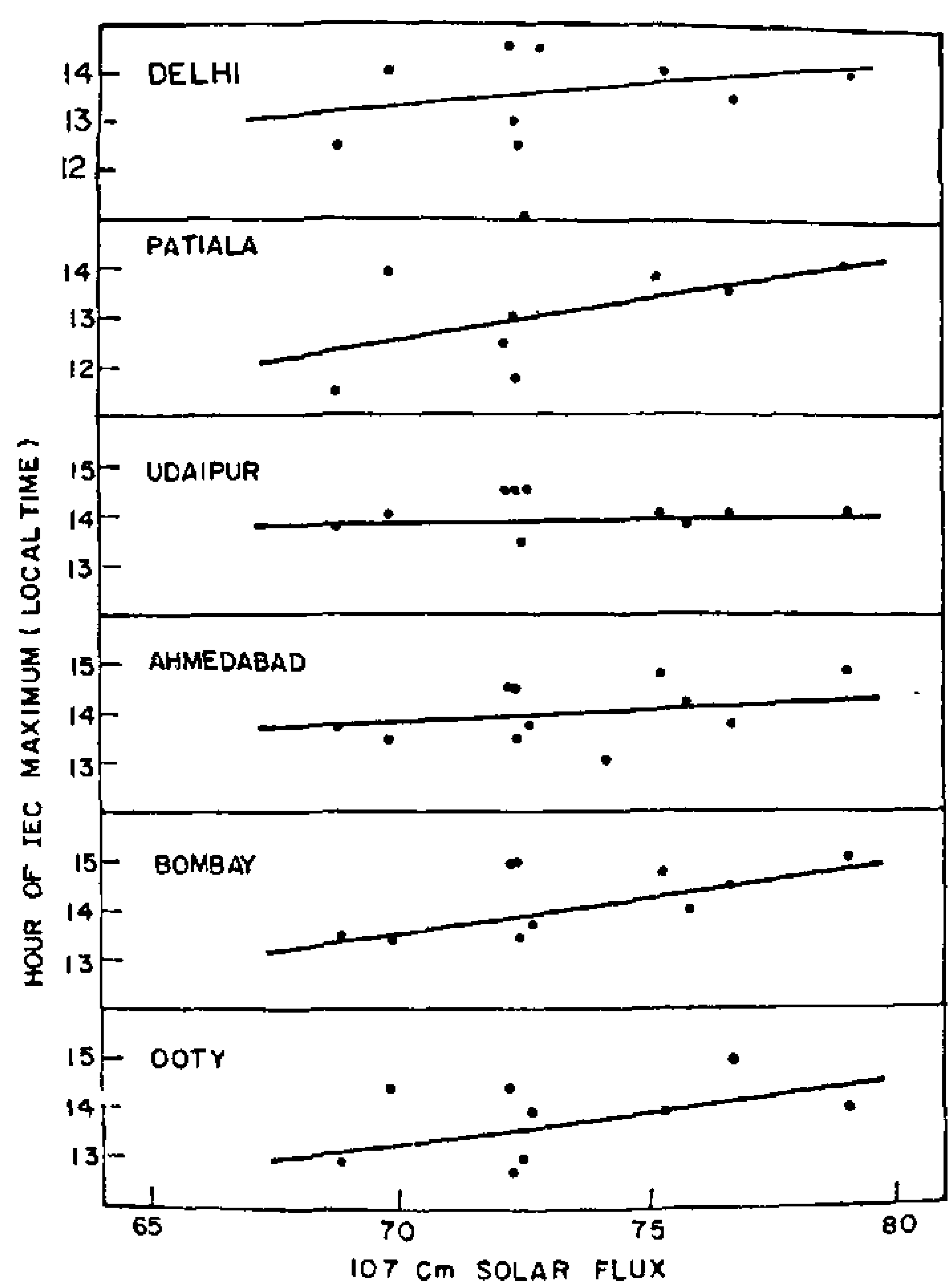

Figure 2. Hour of diurnal maximum in IEC versus 10.7 cm solar flux along the latitudinal chain of stations around 71° E meridian.

Table 2. Data from regression line and correlation analysis

	Hour of IEC_{max} vs solar flux			Morning build-up rate vs solar flux		
Station	Slope	Intercept	Correlation coefficient	Slope	Intercept	Correlation coefficient
Ootacamund	0.104	6.16	(0.423)*	0.266	−12.41	0.799
Bombay	0.133	4.35	0.576	0.148	−6.82	0.676
Ahmedabad	0.034	11.50	(0.240)*	0.158	−8.07	0.646
Udaipur	0.012	13.03	(0.099)*	0.070	−1.83	(0.450)**
Lunping	−0.096	20.88	(−0.248)	0.116	−4.79	(0.250)**
Gauhati	−0.079	19.48	(−0.370)	0.165	−8.33	(0.570)**
Delhi	0.081	7.65	0.579	0.135	−6.99	0.859
Patiala	0.146	2.38	(0.372)*	0.141	−7.29	0.788

*Insignificant correlation at 10% level of confidence.
**Insignificant values at 5% confidence level.

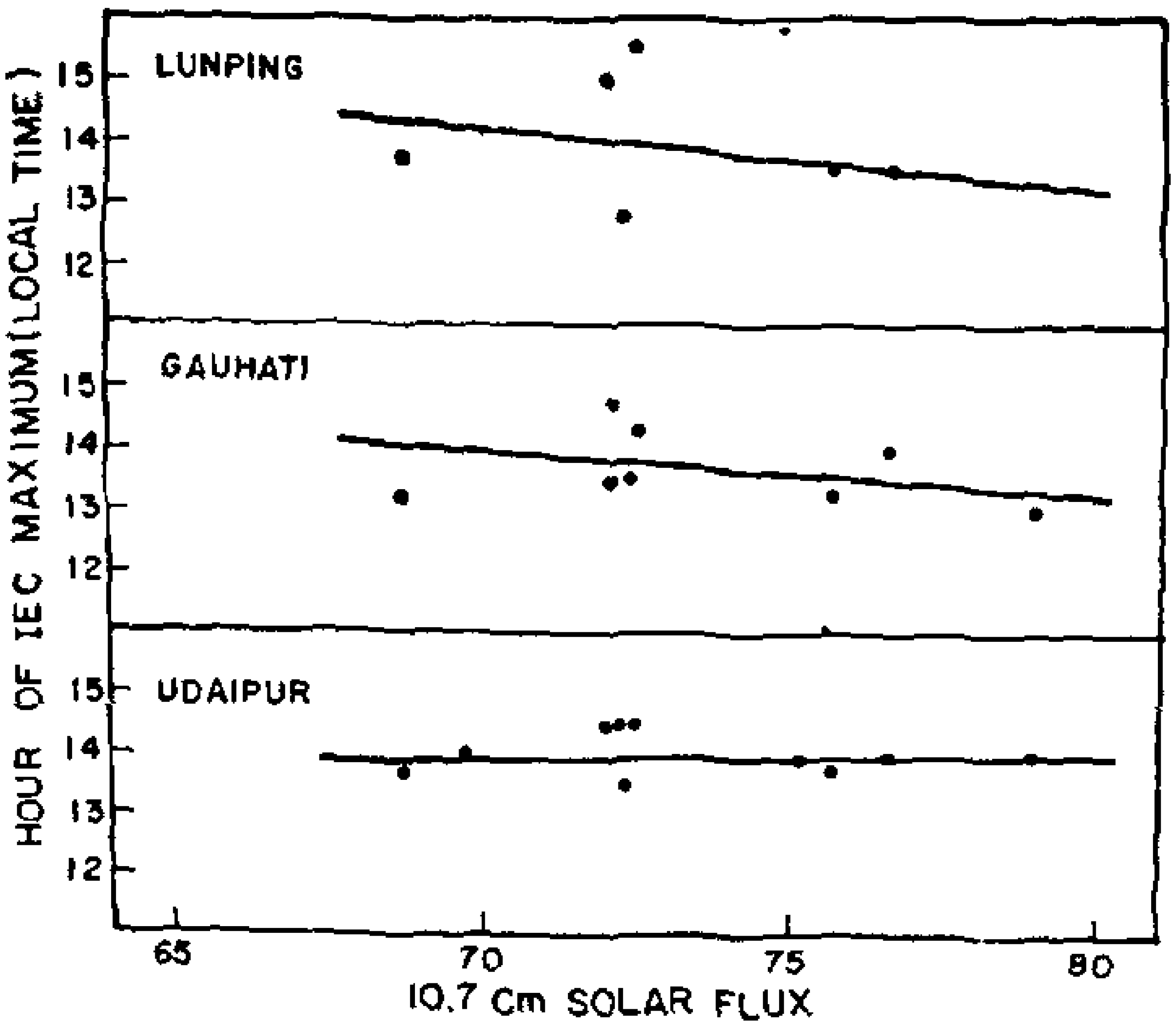

Figure 3. As in Figure 2 for the three stations located around the same latitude (23°N) but with large longitudinal separation.

difference of 14° between Udaipur and Gauhati and 60° between Udaipur and Lunping. At Udaipur the correlation between the phase of daytime maximum and 10.7 cm solar flux is insignificant, whereas negative correlation has been observed at the other two locations. Thus, irrespective of longitudinal position in the Indian and Pacific low-latitude region, solar activity has either negligible or negative correlation with the time of occurrence of diurnal maximum in IEC at the crest of the anomaly. In contrast, at locations outside the peak of the anomaly, solar activity appears to have a positive influence on the time of the day at which electron content should reach its diurnal maximum.

Sun's activity has a direct influence on the rate at which ionization builds up in the *F*-region of the ionosphere and is reflected in electron content in the form of a steep slope during the early morning hours. Dabas *et al.*[13] investigated the solar activity dependence of integrated production rate at Delhi and found a linear positive dependence of this factor on solar activity. Similar result is expected at all the locations in the low-latitude region. However, in the light of observations of the solar activity influence on hour of daytime maximum, a latitudinal variation might be evident in this parameter also. In Figure 4, the morning build-up rate ($\Delta IEC/\Delta T$) averaged for each month is

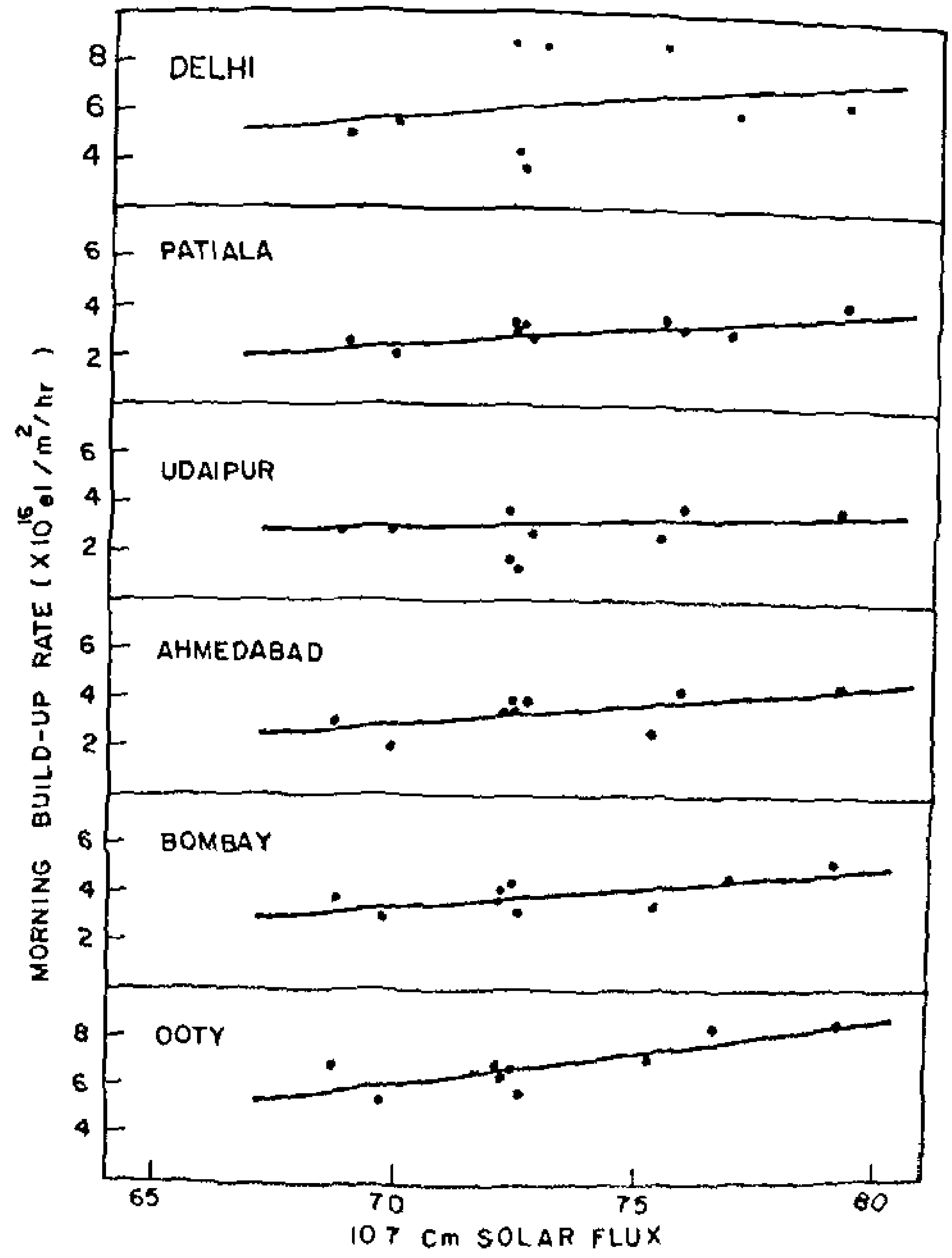

Figure 4. Morning build-up rate ($\Delta IEC/\Delta T$) of ionization averaged for each month plotted against 10.7 cm solar flux for the stations along 71°E.

plotted against the monthly mean 10.7 cm solar flux for the stations which form the north–south axis as in case of Figure 2. It may be observed that the build-up rate of ionization in the *F*-region shows a positive correlation with solar flux at all the locations. The correlation coefficients obtained between production rate and solar flux (Table 2) were found to be significant at the 5% level at Ootacamund, Bombay, Ahmedabad, Delhi and Patiala.

In Figure 5, IEC data similarly analysed for the longitudinal chain of three stations lying along the anomaly crest are shown. The build-up rate at Gauhati and Lunping also exhibits increase with solar activity, but the rate of increase is slower compared to that at stations nearer or farther from the equator. The corresponding correlation coefficients are low and insignificant at the 5% level of confidence.

During high sunspot years, the winter anomaly in IEC is not confined to the region within the equatorial *F*-region anomaly and is observed at as far as Delhi[14]. Movement of ionization from the summer to winter hemisphere is believed to be one of the reasons for the *F*-region winter anomaly. It may be conjectured that during low solar activity, this interhemispheric transport of ionization is limited to the latitude belt within the anomaly crest but when sunspot activity is higher, it extends much beyond. Outside the anomaly region, the level of ionization in summer and winter seems to be controlled by the position of the sun with respect to the observing station in solar minimum. The location farthest from the equator has the lowest IEC_{max} in winter. This explains the observed increase in the amplitude of the annual variation with increase in latitude northward of the anomaly crest. Similarly the other two factors investigated in the present analysis indicate that the crest region of the equatorial anomaly exhibits characteristics different from those observed either at lower or higher latitudes in the Indian zone. Transition between the effects of interhemispheric transport of ionization and of sun's declination on IEC occurs around the crest of the anomaly. The magnetic field lines corresponding to *F*-region heights at the low latitude stations (Ootacamund and Bombay) cross the equator at heights of ~ 300 km and ~ 600 km respectively, whereas ionization which produces the equatorial anomaly under the effect of $E \times B$ fields rises upto altitudes of ~ 900 km above the equator before its descent along magnetic field lines to effectively produce the equatorial anomaly at higher latitudes.

In the context of the present observations, it appears that during solar minimum, interhemispheric transport of ionization takes place along field lines confined only to lower heights. The effect of sun's declination being effective at latitudes higher than the crest of the anomaly, equilibrium condition is reached between these two processes at the crest of the anomaly and this might explain the observed difference in behaviour of IEC at the crest region from that at locations towards the equator or to the north.

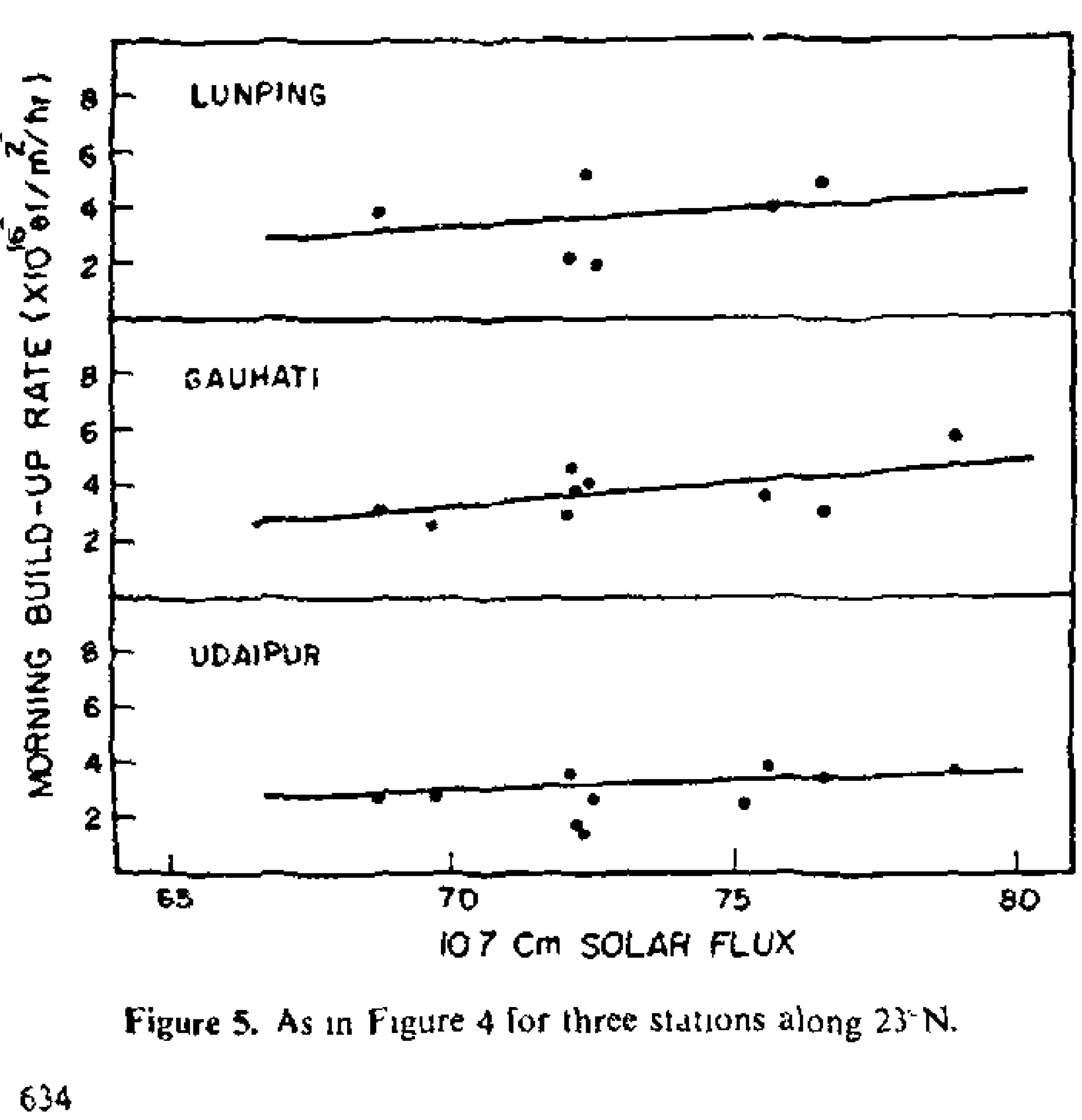

Figure 5. As in Figure 4 for three stations along 23°N.

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