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Solar Cycle variations of *fo*F2 from IGY to 1990

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Abstract. Noontime monthly median values of F2-layer critical frequency *fo*F2 (m) for some ionospheric stations representing low- and mid-latitudes are examined for their dependence on solar activity for the years 1957 (IGY) to 1990. This is the period for which ionospheric data in digital form is available in two CD-ROMs at the World Data Center, Boulder. It is observed that at mid-latitudes, *fo*F2 (m) shows nearly a linear relationship with R12 (the 12-month running average of the Zurich sunspot number), though this relation is nonlinear for low-latitudes. These results indicate some departures from the existing information often used in theoretical and applied areas of space research.

Key words. Ionosphere (equatorial ionosphere; mid-latitude ionosphere; modelling and forecasting)

1 Introduction

Electron concentration in the F2-region of the ionosphere is primarily due to ionization of the neutral atmosphere by the solar UV radiations. These radiations are now known to show very definitive solar cycle variations. Consequently, electron concentrations and thus, the critical frequency of the F2-region (*fo*F2) is also expected to reflect these variations. Although there were no solar UV measurements during the early years of ionospheric research, sunspots data for several decades were available and solar cycle changes in *fo*F2 were detected in the very beginning of ionospheric research (see Mitra, 1952 for early works). In fact, excellent correlations between the sunspot number and the monthly mean *fo*F2 were reported and a detailed analysis of ionosonde data for several stations by Jones and Gallet (1962, 1965) and later by Rush et al. (1983, 1984) helped in generating global maps of *fo*F2 as a function of sunspot number and other geophysical parameters. These maps have since been used by international organizations like CCIR and URSI as predictive tools for HF propagation. An important feature of these predictive models is that *fo*F2 saturates or increases very slowly at all stations for R12 (12-month running average of sunspot number) more than 150 units. This saturation, however, is not expected from theory, since there is no evidence that solar UV flux saturates at high solar activity. On the other hand, Huang (1960) in a detailed analysis of *fo*F2 data for the period 1954 to 1958 from stations in the eastern sector concluded that *fo*F2 saturation is subject to diurnal and geophysical variations. The *fo*F2-R12 plots published by him show that *fo*F2 does not always saturate at all stations for R12=150. Noontime *fo*F2-R12 plots for several stations, with geomagnetic latitudes varying from 48° S to 83° N for the period 1954–1964 published by Rao and Rao (1969) do not show much evidence of *fo*F2 saturation for R12 above 150 units for all the stations.

However, all the above studies were based on a limited data set, involving either one solar cycle or a part of it. Ionospheric data from several stations are now available in two CD-ROMs, covering the period from 1957, the International Geophysical Year (IGY), to 1990. In the present paper, we have studied the *fo*F2 (m) data obtained from these CD-ROMs for a few stations, covering low- to mid-latitudes, namely Maui (20.8° N, 203.5° E), Chungli (24.9° N, 121.2° E), Poitiers (46.6° N, 0.3° E), Slough (51.5° N, 359.4° E) and Moscow (55.5° N, 37.3° E). We have also used the data for the Indian station Kodaikanal (10.2° N, 77.5° E). Results of our analysis of 30 years of ionospheric data for the above mentioned stations indicate some departures from the existing information on the noontime R12-*fo*F2 relationship, often used in theoretical and applied areas of space research. This paper presents an improvement on the existing information.

2 Database

We have used the Ionospheric database available on the two CD-ROMS obtained from the World Data Center, Boulder and the Ionosperic data bulletins published by the National

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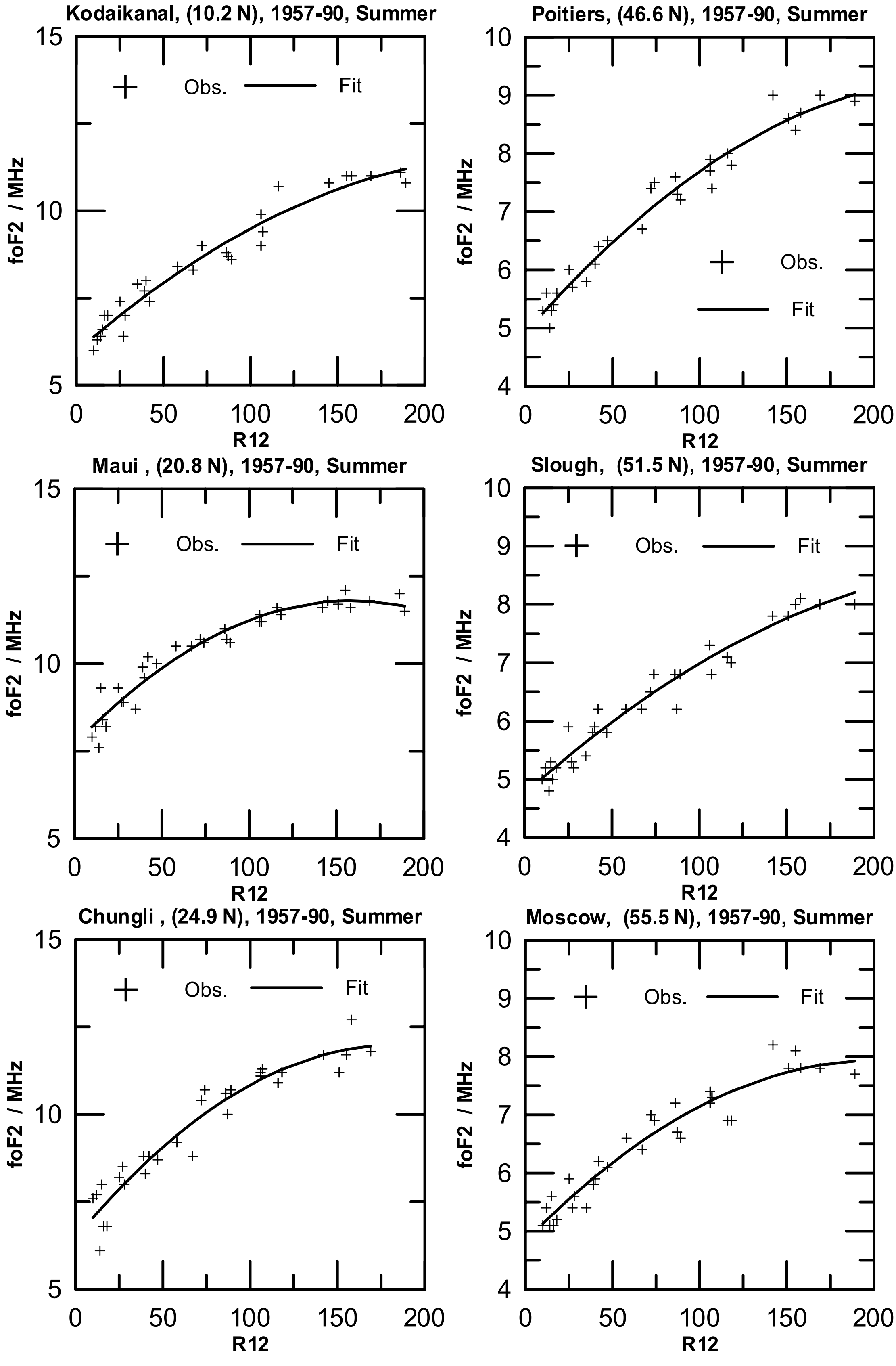

Fig. 1. Shows the plots of observed monthly median noon *fo*F2 values against R12 during summer. The regression fits are shown as solid line. The left panels show low latitude stations, while the mid-latitude stations are shown on the right panel of the figure.

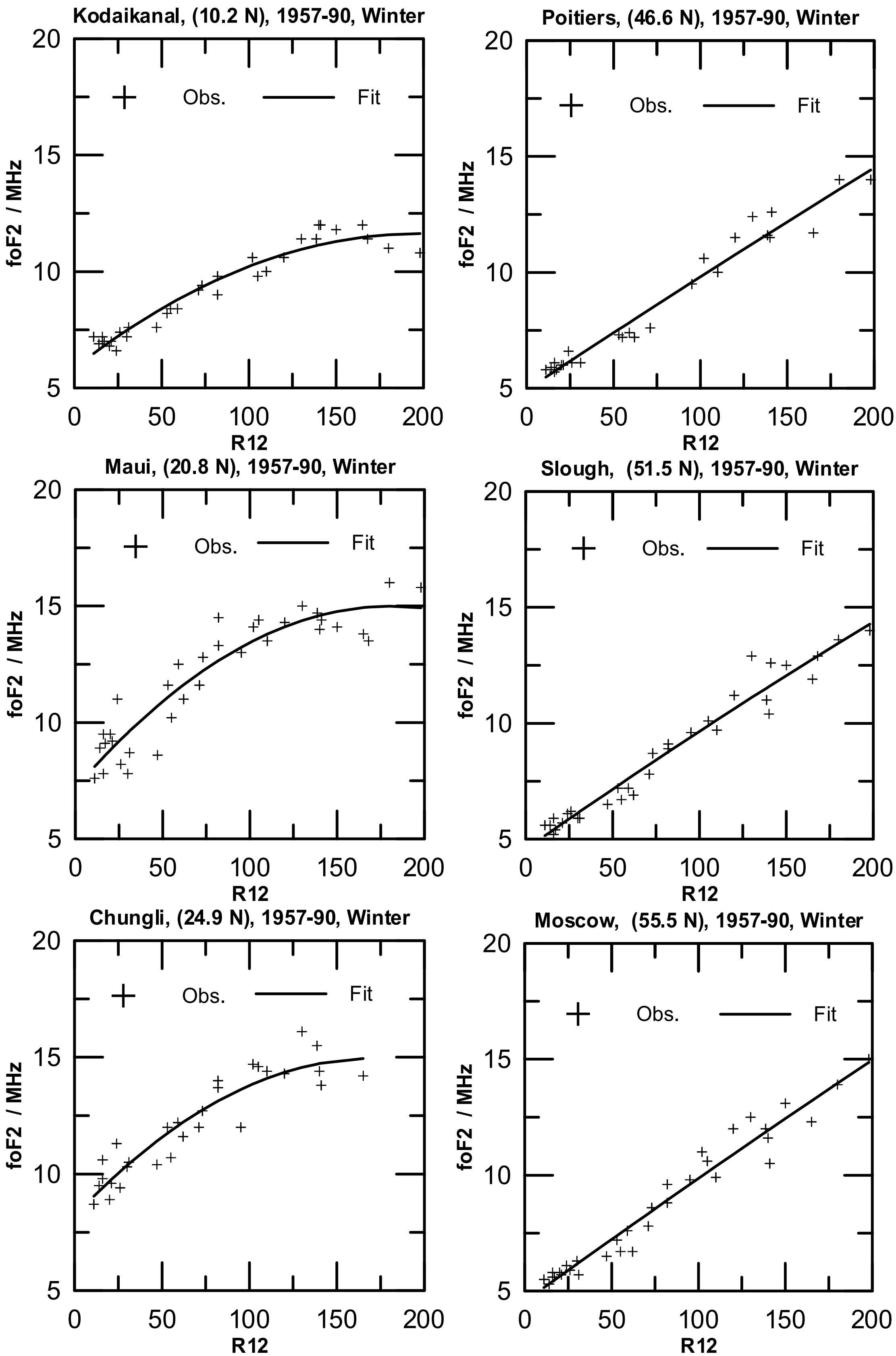

Fig. 2. Same as Fig. 1 but for winter.

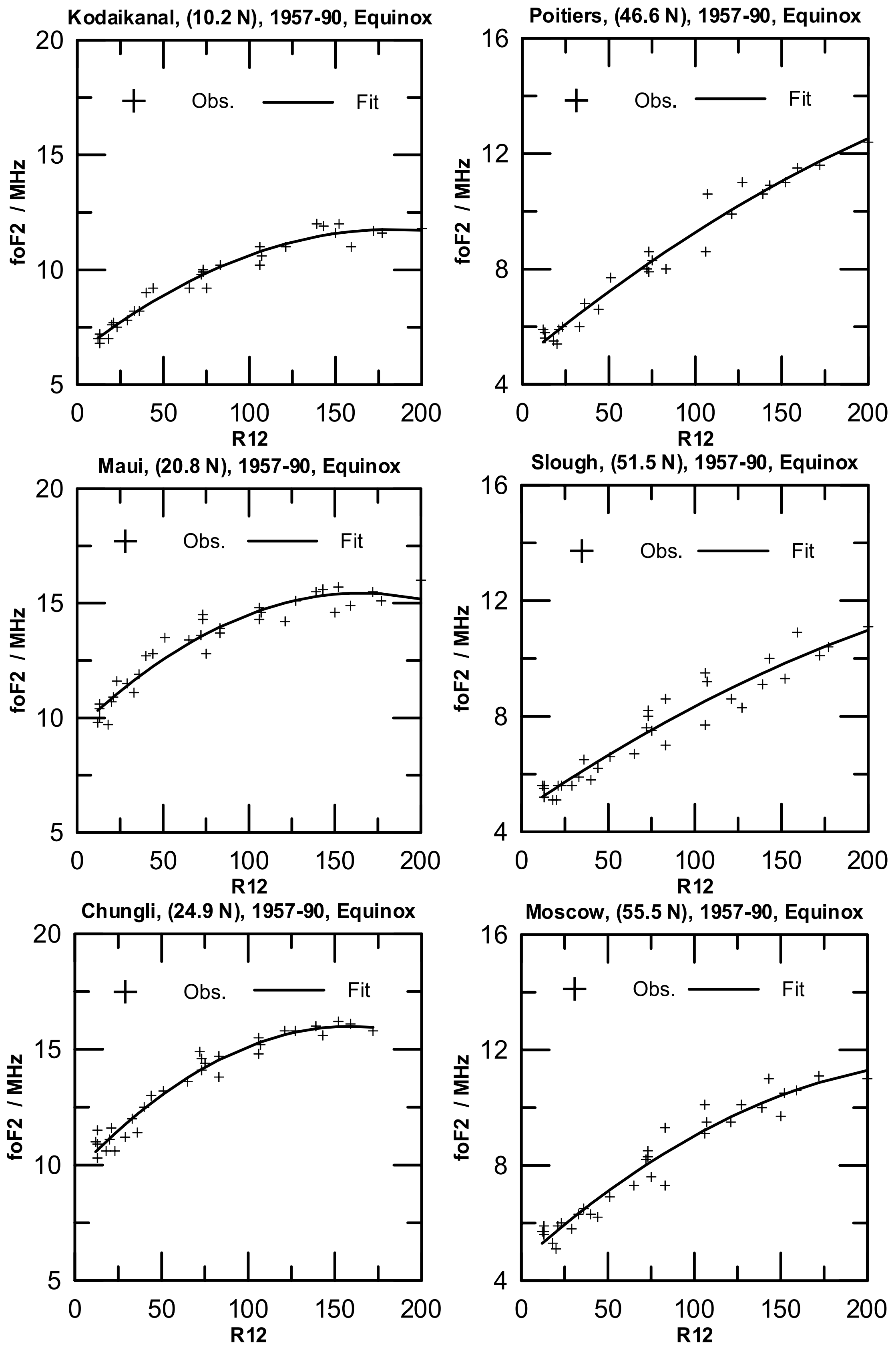

Fig. 3. Same as Fig. 1 but for equinox.

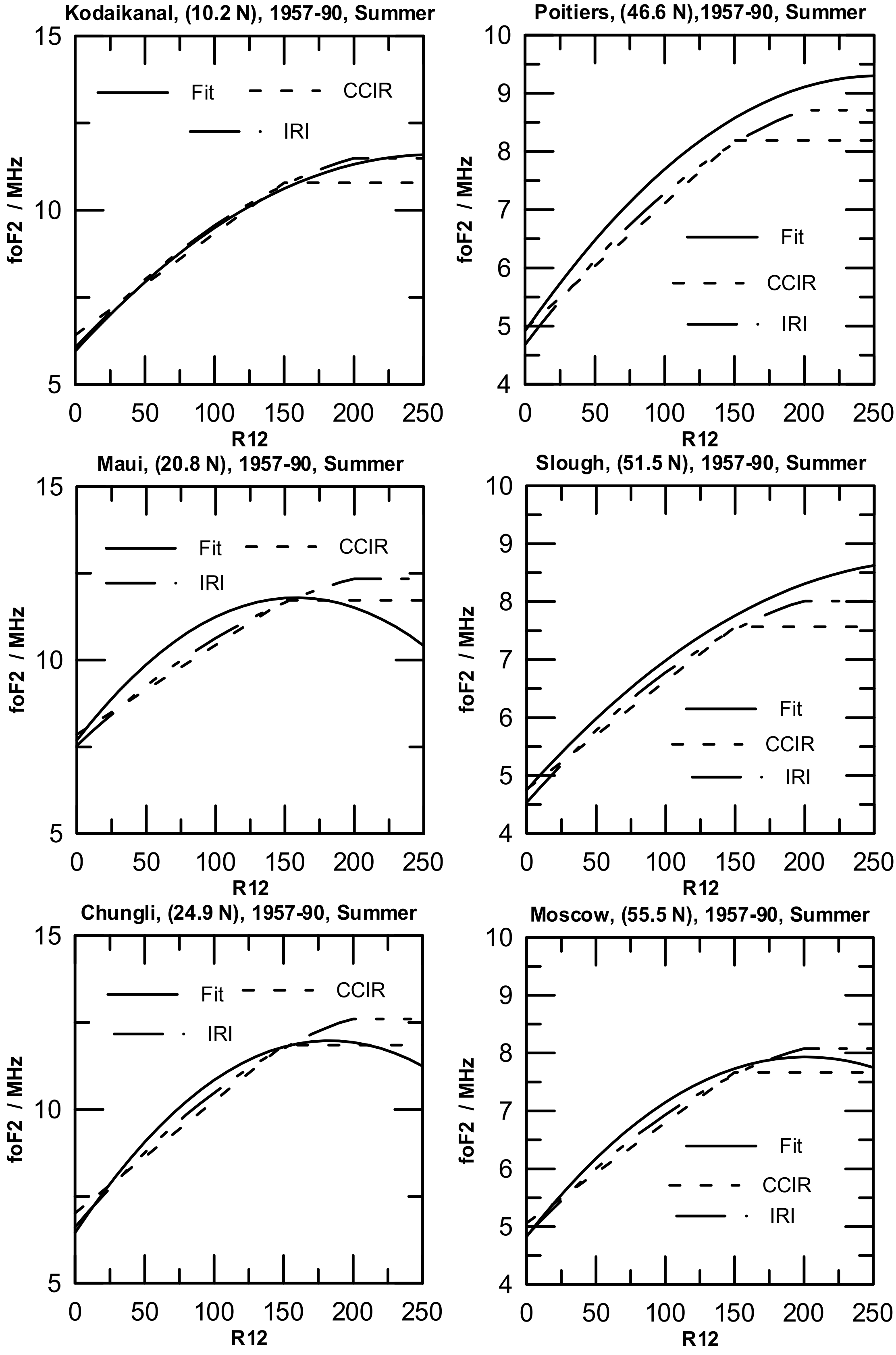

Fig. 4. Shows the variation of regressions fits with R12 along with the CCIR and IRI models for summer. Low- and mid-latitude stations are shown on left and right panels of the figure.

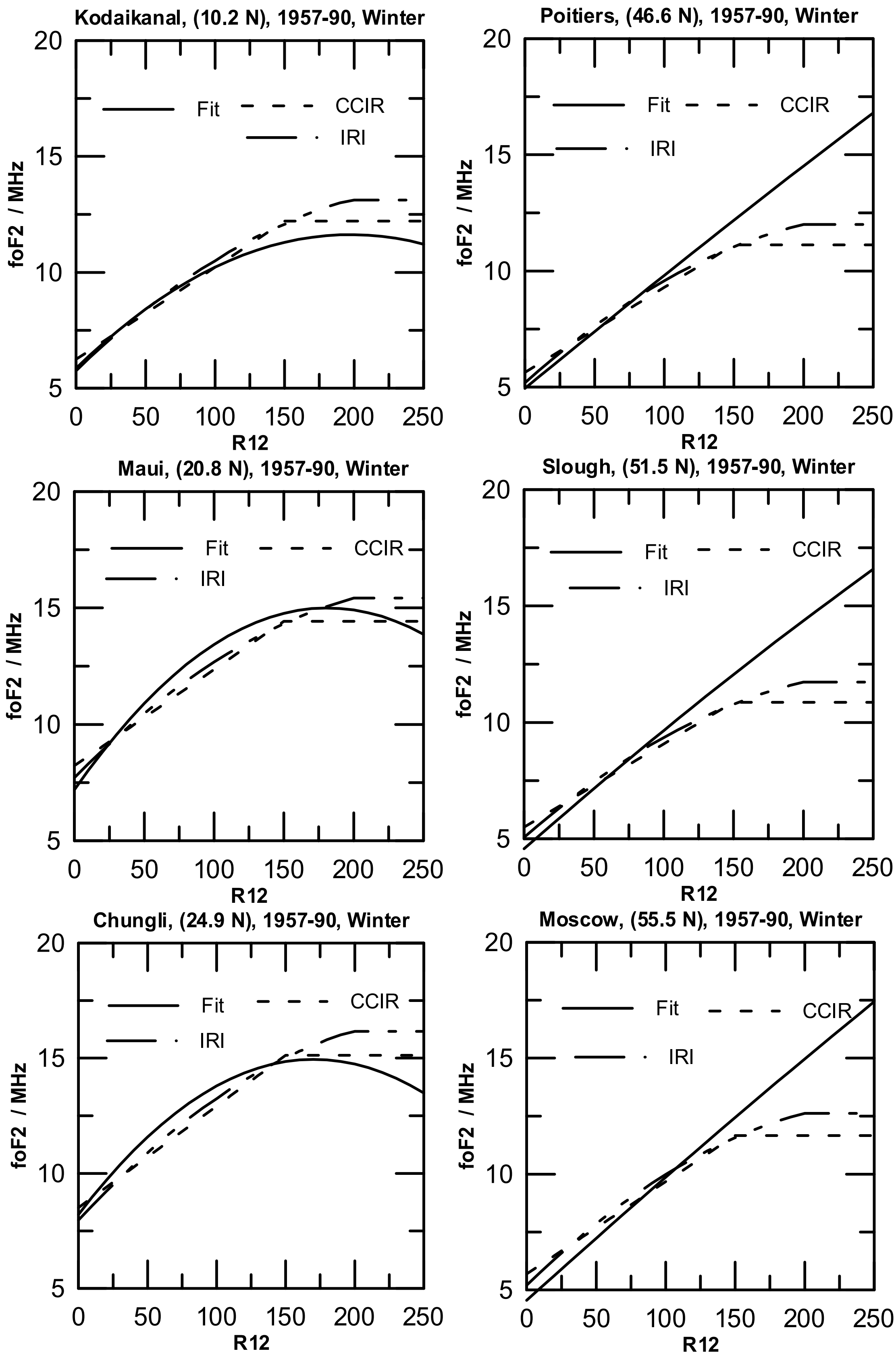

Fig. 5. Same as Fig. 4 but for winter.

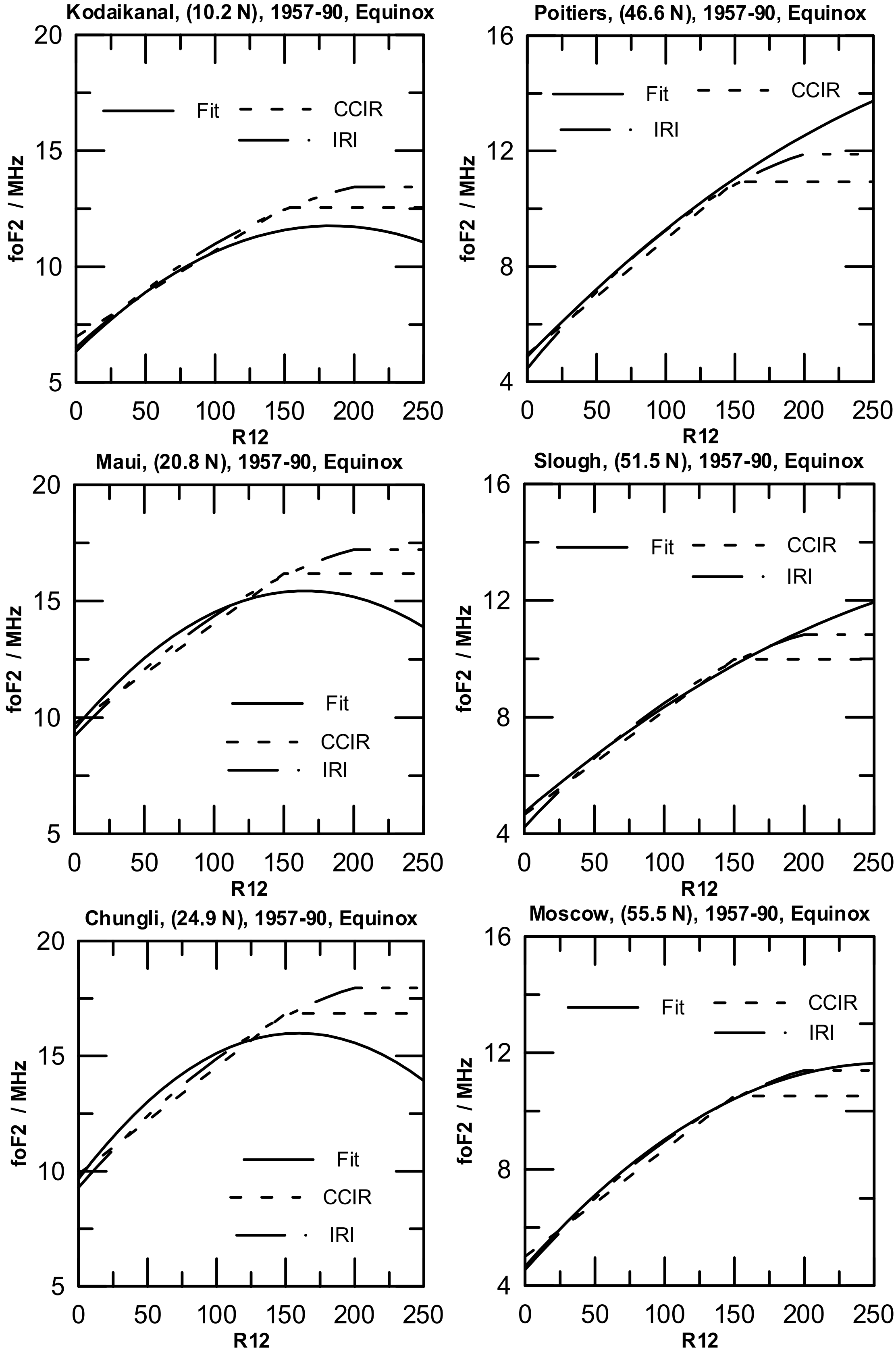

Fig. 6. Same as Fig. 4 but for equinox.

Physical Laboratory (NPL), New Delhi, India. These bulletins contain ionospheric data for Indian stations. In the present paper, we have selected six stations covering locations from low- to mid-latitudes for the period 1957–1990. The quality of data for these locations is known to be excellent, since these data have undergone some stringent tests to bring these to a "highest possible level of correctness before being archived and made available to users" (NGDC, 1994), and the data for most of the stations exist on a continuous basis for more than 30 years. The noontime monthly median *fo*F2 (m) values have been examined with respect to their dependence on conventional solar index R12 (12-month running average of sunspot number). We have selected the months of June, April and January as representatives of summer, equinox and winter seasons respectively.

3 Analysis and results

In order to determine the relationships between the *fo*F2 (m) and R12, a regression analysis was carried out for each station, and it was observed that the relationship is nearly linear at mid-latitudes. For low-latitudes, a second degree fit gives a better correlation. This is demonstrated in Fig. 1 to 3, where the variation of *fo*F2 (m) with R12 is shown for summer, winter and equinox respectively. These figures contain both the observed data and regression fits. It can be observed from Fig. 1–3 (right panels) that at mid-latitudes, *fo*F2 (m) varies more or less linearly with R12, right up to the highest level of solar activity recorded so far. However, during summer, the variation of *fo*F2 (m) with R12 is nonlinear. At low-latitudes (left panels), however, *fo*F2 (m) shows more or less a quadratic variations with R12 up to around 150 during all the seasons. After R12 of 150 it is observed that during winter and equinox, *fo*F2 (m) either shows saturation or a decrease. However, in summer, the increase of *fo*F2 (m) with R12 is faster at lower levels of solar activity and very slow at higher levels.

Since the linear relationship seen by us between *fo*F2 (m) and R12 was observed only at mid-latitudes, we examined *fo*F2 (m) data for a few more mid-latitude stations (Washington (38.7° N, 252.1° E), Boulder (40.0° N, 254.7° E), Rostov (47.2° N, 39.7° E)). Here too similar behaviour was observed.

4 Comparison with empirical models

International Reference Ionosphere (IRI) is the most widely used empirical model for upper atmospheric studies and is being updated and improved off and on following the annual IRI Workshops. This model used the CCIR coefficients up to its 1990 version (Bilitza, 1990). This version, as expected, shows *fo*F2 (m) saturation for R12 above 150 units. In the 1995 version, the solar index R12 was replaced by the ionospheric index IG12 (Bilitza, 1997) and it shows *fo*F2 (m) saturation for R12 above 200. The latest IRI model (Bilitza, 2001) again uses the ionospheric index IG12 in place of solar index R12. Figures 4–6 show the comparisons of regression curves with the CCIR and IRI models at all the six stations for summer, winter and equinox respectively. It can be observed from these figures that during all the seasons, for low-latitudes (left panels), the agreement between the observed fit and the models is fairly good at low solar activity, with somewhat lower values for models. During high solar activity, it can be noticed that in the observed fit, there is a tendency of either saturation or fall in *fo*F2 (m) after R12 of 150, in agreement with CCIR, whereas IRI shows saturation beyond R12 of 200. Further, it can be seen that during equinox, the observed fit shows lower values of *fo*F2 (m) at high solar activity as compared to model values. For mid-latitudes, as seen in Figs. 4–6 (right panels), the agreement between the IRI and the observed fit is found to be fairly good for summer and winter months, during the low solar activity periods. This agreement becomes excellent during equinox, right up to R12 of 200. However, CCIR shows saturation for R12 above 150 units. During high solar activity, as shown in the right panels of Figs. 4–6, *fo*F2 (m) values of the fit are higher than those obtained from the IRI, especially during winter and summer months. It is to be noted that both the CCIR and IRI show the saturation effect in *fo*F2 (CCIR beyond R12 of 150 and IRI beyond R12 of 200). It seem to us that the saturation effect may not occur at all at mid-latitudes, even beyond R12 > 200. This can be inferred from the figures if the observed values are extrapolated for R12 beyond 200. However, some stations like Slough and Moscow might be the exceptions during summer.

5 Conclusion

Detailed analyses of a long series of solar and ionospheric observations indicate that *fo*F2 (m) at mid-latitudes increases linearly with R12 right up to the highest level of solar activity so far. However, at low-latitudes, the observed *fo*F2 (m) values show a tendency to saturate, and in some cases even fall beyond a certain level of solar activity during all the seasons. Comparative studies with the CCIR and IRI show, in general, a fairy good agreement with the observed *fo*F2 during low solar activity period. However, major discrepancies exist during high solar activity period, at both the low- and mid-latitudes, especially for equinox and winter months respectively. The observations do not provide much evidence of *fo*F2 saturation at mid-latitudes.

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