Further study of f_0F2 and $M(3000)F2$ in different solar cycles

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Abstract
Measured monthly median f_0F2 and $M(3000)F2$ for Slough over six solar cycles from 1932 onwards are examined for a selection of hours and months. Data are shown as a function of twelve-monthly smoothed sunspot number. Comparisons are made for the different solar cycles and for the rising and falling halves of each cycle. Measurements for individual cycles are compared with best-fit parabolic regression lines over all cycles to investigate possible systematic long-term effects.

Key words *ionosphere – solar-cycle dependence – long-term mapping*

1. Introduction

Since the earliest days of examination of ionospheric morphology it has been recognized that the variations of f_0F2 are complex and cannot be derived from theoretical considerations which only take account of production by photo-ionization. Many groups have investigated the long-term changes of f_0F2, seeking to establish empirical relationships in terms of indices of solar activity. Several different solar, ionospheric and mapping indices have been considered (see Bradley, 1993a for details and terminology). There have too been a number but not so many surveys of the corresponding variations of $M(3000)F2$.

Not all workers are agreed on which is the best index to use. This is perhaps not surprising because there are several separate factors which influence the choice. These include correlation, linearity, index predictability and availability. Kouris and Agathonikos (1992) and Kouris and Nissopoulos (1994) have examined the correlation of f_0F2 for six European stations over two solar cycles, finding little different results for the separate indices, but with a slightly increased correlation using the twelve-monthly smoothed sunspot number R_{12}. When measurements for the rising and falling portions of a solar cycle are separately compared some differences are found consistent with a form of hysteresis. The hysteresis was first noted in a number of $F2$-layer ionospheric characteristics by Huang Yinn-Nien (1963). The effect was shown by Rao and Rao (1969) to peak at middle latitudes and so they concluded it to be the result of geomagnetic control, a view also shared by Apostolov *et al.* (1992) and by Kane (1992b). Several investigations have addressed whether values are larger or smaller on the rising half cycle, *i.e.* whether the hysteresis is positive or negative. Results though for different locations, months and solar cycles are variable (Joachim, 1966; Ortiz de Adler *et al.*, 1993 and Smith and King, 1981). Mikhailov and Mikhailov (1992) have suggested that by using an index related to EUV solar flux (Lakshmi *et al.*, 1988) the hysteresis will be eliminated. Kane (1992a) has shown that there is some reduction of hysteresis for EUV, but not surprisingly a residual effect remains. Furthermore, Kouris (1994) has found a hysteresis between different indices. He has also (private communication) carried out correlation studies of $M(3000)F2$ with different indices, again revealing high values for R_{12}. Taking account of his latest results as well as the predictability and availability of this index, the PRIME group has adopted R_{12} for its present median f_0F2 and $M(3000)F2$ regional mapping initiative. In particular, it notes too that this index is also used in conjunction with the current internationally adopted global prediction maps of these two ionospheric characteristics (CCIR, 1993).

The CCIR numerical mapping method (CCIR, 1993) developed by combining all available measured data over the years 1954-58, supposes that f_0F2 increases linearly with R_{12} for $R_{12} < 150$ and that for higher R_{12} there is complete saturation. An alternative f_0F2 global mapping of Jones and Obitts (1970) based on the same measurement data set applies a parabolic dependence. The CCIR mapping gives that $M(3000)F2$ decreases linearly with R_{12}; no corresponding parabolic dependence maps have yet been formulated. Kouris *et al.* (1993a-c) and Mikhailov (1993) have examined the linearity of the dependence of f_0F2 and $M(3000)F2$ with different indices. Kouris in particular has addressed the statistical significance of his results. Median f_0F2 gives close agreement to a linear variation with R_{12} most times but a curvilinear (parabolic) relationship provides a better fit under some conditions, particularly in the summer daytime and winter night. For $M(3000)F2$ departures from a linear variation are reduced. Sizun (1992a,b) suggests applying a different parabolic law to the rising and falling half cycles including for $M(3000)F2$ and proposes that this be determined using ponderation (weighting) factors as necessary, based upon the numbers of daily values associated with each monthly median measurement point.

Differences in f_0F2 between solar cycles also have been found. One problem with such studies is that very few stations have made continuous measurements over more than 20 years and so there is little evidence of whether the changes are random or systematic. The longest sequence of available data comes from Slough, England (51.5°N, 0.5°W) and this now spans 5½ solar cycles since 1932. Using Slough data available up to 1956 (cycles 17 and 18) Naismith *et al.* (1961) found a progressive decrease of f_0F2 for the same R_{12} in successive cycles. However, Barclay (1962) for cycle 19 between 1956-67 observed an increase. Apostolov *et al.* (1992), repeating the analyses of Naismith and Barclay, were able to replicate their results. They discovered though a decrease again for cycles 20 and 21 (1967-89). They concluded that there are secular variations with a periodicity of about three solar cycles. They too have favoured the adoption of different parabolic relationships for the rising and falling half cycles, but have suggested to base results on the average of the three solar cycles.

So with these differing viewpoints it is important to PRIME that the way ahead be agreed. This short note looks again at the Slough data. Particular consideration is paid to whether there are any systematic changes on the upgoing and downcoming half cycles or between cycles such as to point to the need to map separately for each of these.

2. Analysis and discussion

Figures 1 and 2 show noon monthly median f_0F2 and $M(3000)F2$ for the months of December, March, June and September plotted as a function of R_{12} with data for available years included; also given are the curvilinear best-fit lines drawn through each of these results. Figures 3 and 4 for f_0F2 in December and June respectively show the same lines in relation to the data points for each cycle separately. Figures 5 and 6 present corresponding data for $M(3000)F2$ in March and September. Analyses of f_0F2 and $M(3000)F2$ data for other months are given elsewhere (Bradley 1993b).

For f_0F2 (see fig. 1) the best-fit line is markedly parabolic in the summer and equinoxes, whereas in winter it approxi-

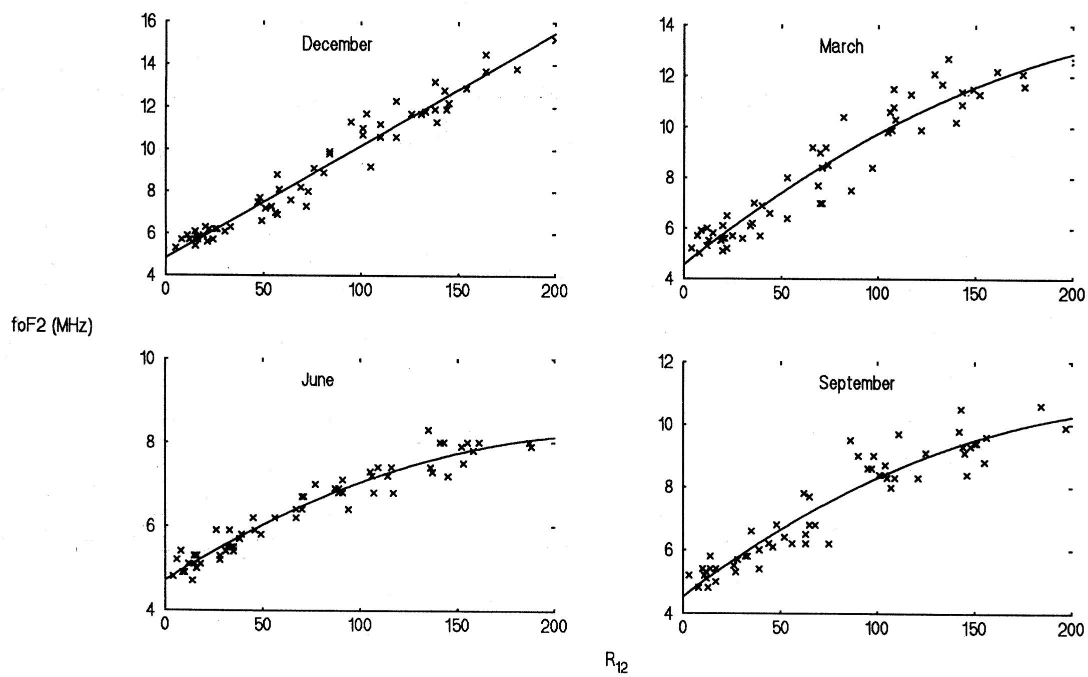

Fig. 1. Slough noon – f_0F2 1932-91.

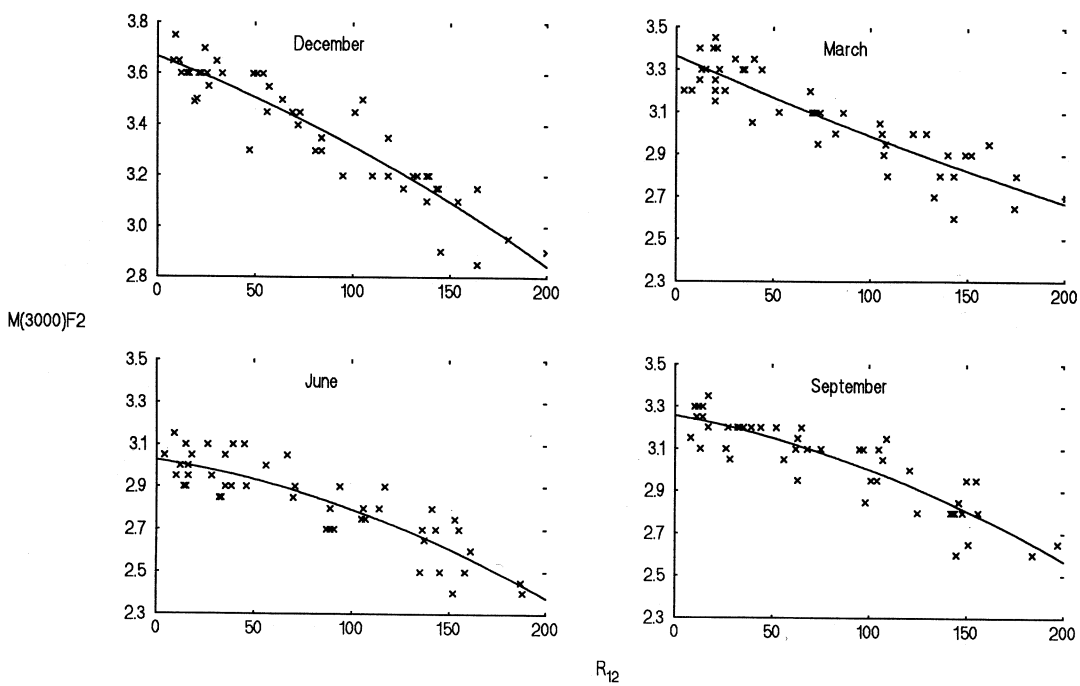

Fig. 2. Slough noon – $M(3000)F2$ 1932-91.

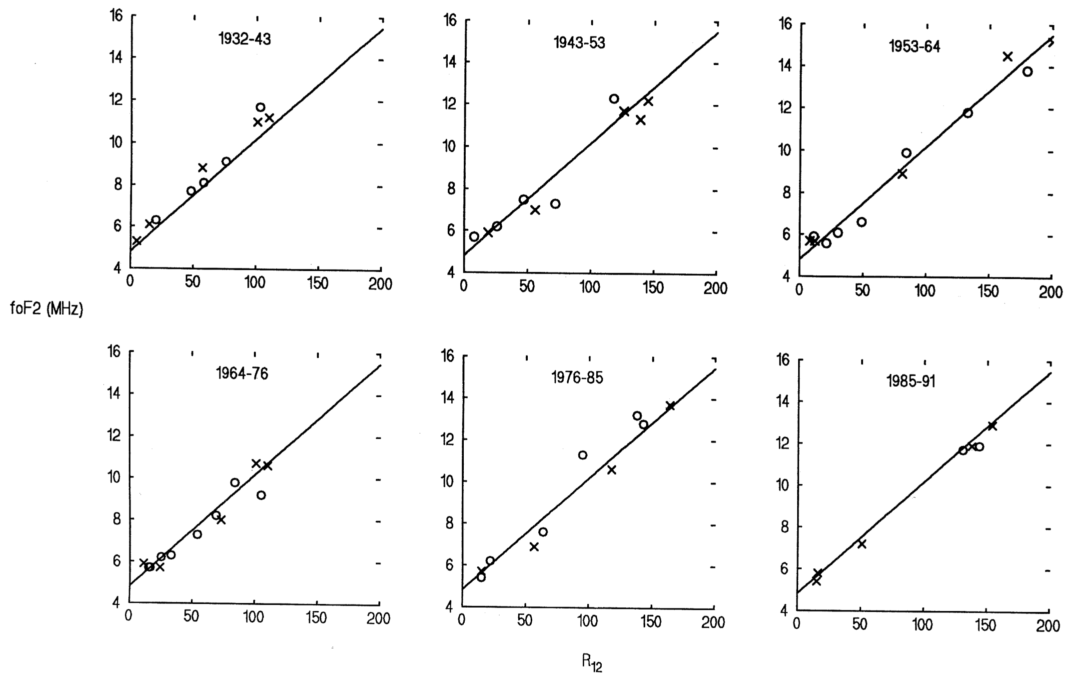

Fig. 3. Slough noon $-f_0F2$ in December: $\times$ = upgoing; o = downgoing.

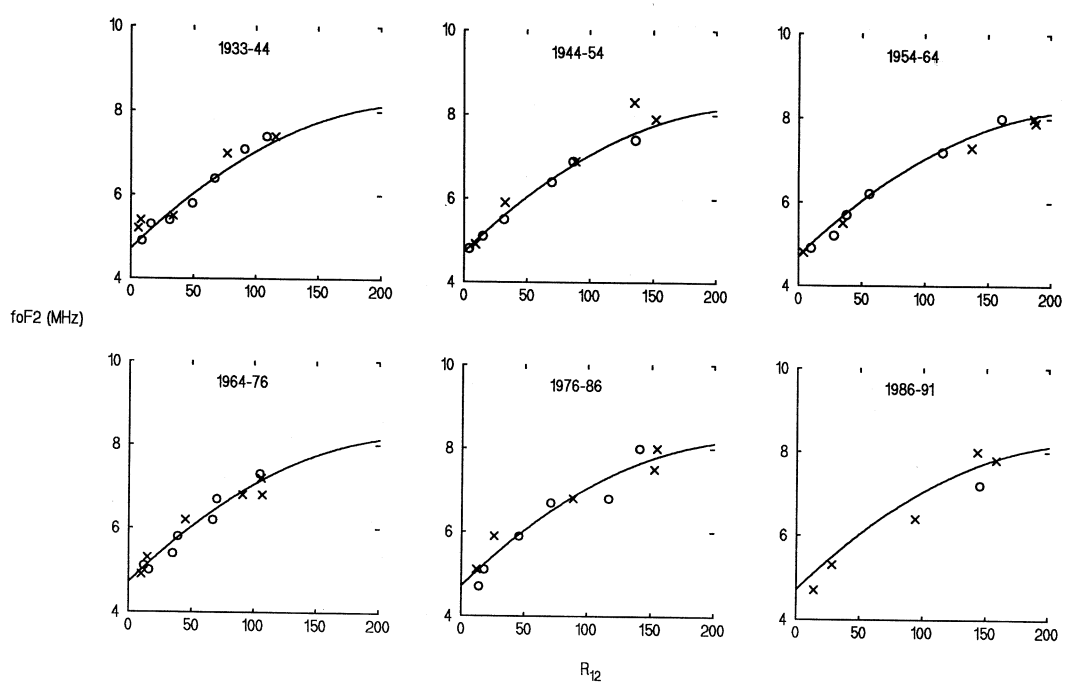

Fig. 4. Slough noon $-f_0F2$ in June: $\times$ = upgoing; o = downgoing.

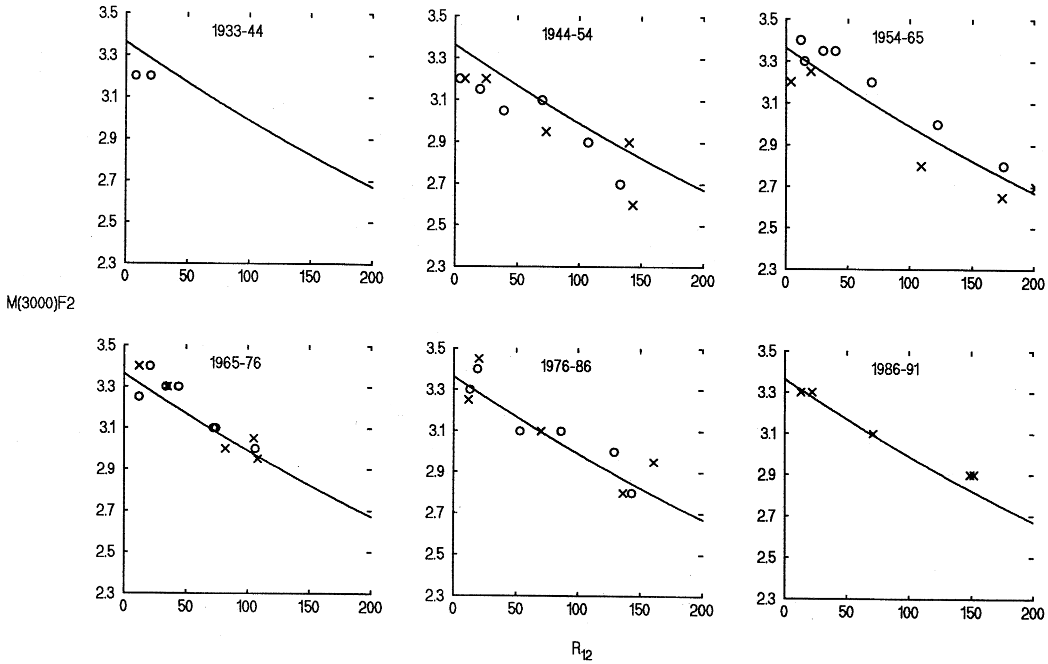

Fig. 5. Slough noon – $M(3000)F2$ in March: $\times$ = upgoing; o = downgoing.

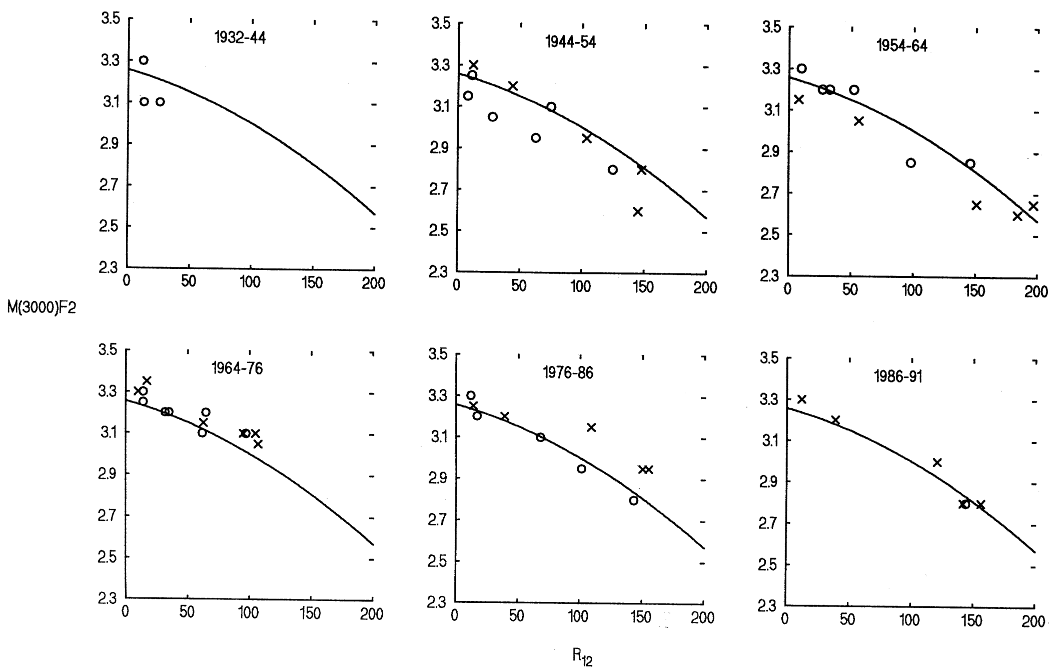

Fig. 6. Slough noon – $M(3000)F2$ in September: $\times$ = upgoing; o = downgoing.

mates to a linear relationship consistent with the findings of Kouris *et al.* (1993a-c). Comparing the numbers of data points either side of the best-fit lines there are found to be no clear trends of changes between cycles. For example, in December values in cycle 17 are predominantly high whereas in cycle 18 they are low; agreement is good for the other cycles. In June cycles 17 and 18 have high values but cycle 22 exhibits low values. A more rapid increase in annual mean f_0F2 for the cycles with smaller maxima of R_{12} has been reported by Smith and King (1981); the effect is reduced because of storm effects but is still present in the monthly medians. Patterns for other months differ. Some differences from other workers may arise because here comparisons are made for each cycle separately with the mean over all cycles rather than just with the previous cycle. The hysteresis is evident with a tendency for enhanced ionization just after the cycle peak in more cycles than not, with variable results for the different months and no evidence of a rotation switch between successive cycles. This is not surprising since monthly median f_0F2 is influenced by the effects of geomagnetic storms on the daily values; these may lead to value increases or decreases depending on the season and storm magnitude. Since the numbers of storms can vary irregularly for the rising and falling half cycles, so the hysteresis may be positive or negative, confirming the desirability for predictions in adopting a mean relationship through both data sets. The position can be quite different from one month to another.

There is closer agreement to a linear variation for $M(3000)F2$ than with f_0F2 (see fig. 2) March being imperceptibly different from linear, having regard for the data scatter. Changes between cycles too appear irregular with the exception of cycle 18 where values are some 5% lower than the mean, corresponding to greater $F2$-layer heights in all four months considered. The physical cause of this effect is not readily evident. There are two possible sources of long-term change: there could be differences in incident ionization or in the Earth's magnetic field. Secular field changes are known to arise over much longer timescales than a solar cycle. At low latitudes the region where the difference between the geographic and geomagnetic equators is most longitude sensitive is known to be steadily drifting westwards across the Atlantic Ocean. Likewise at northern high latitudes the position of the magnetic pole which controls the auroral zone moves irregularly. For middle latitudes the magnetic declination which determines thermospheric plasma drift is believed to have a periodicity of around 500 years. All these changes may be very long term, but over the orders of several tens of years they can be significant. For example, between 1820 and 1970 the declination at London, England changed from 24°W to 7°W. Bremer (1992a,b), from a statistical examination of 30 years of vertical-incidence ionosonde measurements at Juliusruh (54.6°N, 13.4°E), has concluded that there has been a 2% perceptible reduction in $F2$-layer peak heights. There was no detectable change in f_0F2. Bremer suggests this layer height change could be the first experimental confirmation of an atmospheric response to a cooling of the stratosphere, mesosphere and thermosphere due to an increasing content of «greenhouse» gases in the atmosphere. Of note here though must be that the change reported by Bremer is in the opposite sense to that found above for Slough. Clearly at different locations magnetic and ionization production effects will have differing relative importances and further studies using data sets collected in different geographic regions are needed to seek to differentiate between these separate possible causes.

3. Conclusions

There is some evidence of changes in f_0F2 and in $M(3000)F2$ between cycles but these are irregular and small in relation to the scatter and non-repeatable hysteresis features which cannot meaningfully be embodied in a PRIME long-term mapping initiative for telecommunication prediction purposes. For f_0F2 it is concluded that use should be made of a single parabolic relationship for a given month to define the solar-cycle variations by combining all available measurement data without regard for which cycle they relate to, or whether for the rising or falling half cycles. Since the solar-cycle law will clearly be different for different locations it is proposed that mapping should take place at three separate reference solar epochs corresponding to low, medium and high solar activity. These «anchor» points would then be used to specify the parabola and so to give values at a chosen location for any intermediate epoch of interest. In the case of $M(3000)F2$ the departures from linear are less severe and it remains to be determined whether the additional complexity of mapping at three anchor points is justifiable or if a linear variation involving two anchor points will suffice.

Acknowledgements

The research activity reported in this paper has been performed as part of the National Radio Propagation Programme at RAL and has been funded by the Radiocommunications Agency of the U.K. Department of Trade and Industry. Thanks are extended to the referees for their valuable comments on the first abbreviated version. Acknowledgement is made to M. I. Dick for graphical presentations.

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