AD-764 711

PREDICTING THE DAY-TO-DAY VARIABILITY OF THE MID-LATITUDE IONOSPHERE FOR APPLICATION TO HF PROPAGATION PREDICTIONS

Charles M. Rush, et al

Air Force Cambridge Research Laboratories
L. G. Hanscom Field, Massachusetts

23 May 1973

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IONOSPHERE PHYSICS LABORATORY PROJECT 8666
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Unclassified

Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Air Force Cambridge Research Laboratories (LII) L. G. Hanscom Field Bedford, Massachusetts 01730	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP
3. REPORT TITLE PREDICTING THE DAY-TO-DAY VARIABILITY OF THE MID-LATITUDE IONOSPHERE FOR APPLICATION TO HF PROPAGATION PREDICTIONS	
4. DESCRIPTIVE NOTES (Type of report and inclusive dates) Scientific. Interim.	
5. AUTHOR(S) (First name, middle initial, last name) Charles M. Rush Joseph Gibbs	
6. REPORT DATE 23 May 1973	7a. TOTAL NO. OF PAGES: ~~24~~ 27 7b. NO. OF REFS: 9
8a. CONTRACT OR GRANT NO. b. PROJECT, TASK, WORK UNIT NOS. 86660103 c. DOD ELEMENT 62101F d. DOD SUBELEMENT 681000	9a. ORIGINATOR'S REPORT NUMBER(S) AFCRL-TR-73-0335 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) AFSG No. 268
10. DISTRIBUTION STATEMENT Approval for public release; distribution unlimited.	
11. SUPPLEMENTARY NOTES TECH, OTHER	12. SPONSORING MILITARY ACTIVITY Air Force Cambridge Research Laboratories (LII) L. G. Hanscom Field Bedford, Massachusetts 01730

13. ABSTRACT

Hourly values of ground-based ionosonde data have been subjected to a detailed statistical analysis in order to determine the day-to-day variability displayed by various ionospheric regions. It is found that the standard deviation about the observed F2 region monthly median critical frequency is two to three times that observed in the E and F1 regions at mid-latitudes. The day-to-day variability of foE and foF1 is such that monthly median values of those parameters can be used to represent the daily variation in the E and F1 region. This would imply that HF prediction programs which rely on median data for specification of the ionosphere yield results that can be used in day-to-day operations for those propagation modes that are controlled by the E and F1 region. As the F2 region is highly variable, a method of using timely observations of foF2 to predict the expected values of the F2 region critical frequency has been developed. The method has the advantage that errors in predicting the monthly median foF2 can be averted and the predicted values are generally closer to the actual observations than the observed monthly median.

DD FORM 1 NOV 65 1473

Unclassified

Security Classification

1a

Unclassified

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Ionospheric variability Ionospheric prediction HF propagation E and F region						

Unclassified

Security Classification

Abstract

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Predicting the Day-to-Day Variability of the Mid-Latitude Ionosphere for Application to HF Propagation Predictions

1. INTRODUCTION

Routine ground-based ionospheric soundings have over the years provided a great deal of information concerning the structure of the ionosphere and its variability in both time and space. These observations have been used to help determine the various physical mechanisms that control the ionospheric behavior and provide the basis for ascertaining how changes in the ionosphere affect propagation of electromagnetic energy over a wide band of the frequency spectrum. Perhaps the most significant and well-known aspect of the ionosphere is its apparent control over high frequency (HF) radio propagation conditions. As the ionosphere is the medium in which HF signals propagate, changes in the ionospheric structure lead naturally to changes in HF propagation characteristics.

Because of the importance of HF communication in a variety of civilian and military uses, a great deal of effort has been spent on predicting the structure of the ionosphere for the express purpose of improving HF propagation predictions. For the most part, HF prediction techniques rely upon median bases for the specification and prediction of the ionosphere and are thus only strictly valid for median conditions. There is, however, an increasing amount of effort devoted to applying

(Received for publication 22 May 1973)

median predictions in normal day-to-day applications. This would lead to meaningful results only if the median behavior of the ionosphere provided a good representation of the daily variability.

In this report, the variability of the ionosphere about its median value is investigated using data that are representative of various ionospheric regions. Although there are other factors that affect, and in certain circumstances limit, HF propagation (absorption, terrestrial and man-made noise, for example) only the variability displayed by the ionospheric electron density is studied. This has been accomplished by making use of the hourly critical frequency tabulations of the normal E (foE), F1 (foF1) and F2 (foF2) regions observed at a number of mid-latitude locations. An attempt has also been made to relate the observed daily variability of the ionosphere to the practicality of using median predictions in day-to-day operations.

It will be seen that the monthly median values of foE and foF1 provide a relatively good representation of the daily values of those particular parameters at mid-latitudes. In the F2 region, on the other hand, the daily variability of foF2 is, at certain times, quite large and the monthly median value of foF2 appears to be of little practical use in daily operations. We have, therefore, investigated methods by which this daily variability can be predicted assuming that timely observations of foF2 are available. It will be shown how much improvement in the prediction of foF2 can be obtained using immediate past values of that parameter to update a predicted value. Whether the amount of improvement that is obtained justifies the cost necessary to implement such a technique must be decided with reference to the specific application.

2. VARIABILITY OF THE IONOSPHERE ABOUT THE OBSERVED MEDIAN

In order to obtain a reliable estimate of the daily variability of the ionosphere about the observed monthly median, hourly values of the critical frequencies of the E, F1 and F2 regions have been obtained for a number of mid-latitude ionospheric sounding stations that were operating during the years of 1958 and 1964. These time periods were chosen to be representative of the extremes in solar activity (1958 - solar maximum; 1964 - solar minimum). Since these were years when international agreement concerning all types of geophysical observations were in effect (IGY and IQSY), the number of stations supplying observations tend to be more numerous than in other years. Data from over 150 ionosonde stations that were operating the entire year of 1958 were used to determine the variability of foF2 during solar maximum conditions, while some 40 mid-latitude stations were investigated for 1964 to determine the variability of foF2 during solar minimum conditions. Hourly data for foE and foF1 were used for all stations north of 45° geomagnetic latitude for the months of March, June, September and December in both 1958 and 1964. Only the results that apply to the mid-latitude ionosphere will be discussed here.

For each of the ionospheric parameters and stations available, the observed monthly median for each hour was determined and the individual hourly observations were then subtracted from the monthly medians. The individual deviations were also normalized to their respective hourly median values to enable study of both the absolute as well as relative variability in the various regions of the ionosphere. These deviations (both relative and absolute) were then subjected to a detailed statistical analysis and the first four statistical moments were computed for each data set (Kenney and Keeping, 1954). A standard computer program was used to determine the mean, standard deviation, skewness, and kurtosis for each set of deviations. It is the standard deviation that provides the most straightforward information concerning the variability of the hourly observations about the observed monthly median. In order to increase the significance of the results, the deviations for each station-month were grouped into three hour-time blocks centered on 0000, 0300, ... 2100 h before performing the statistical analysis. The groupings were done both in local mean time (LMT) and Greenwich mean time (GMT).

The results of the analysis indicated that the hourly deviations of foE and foF1 could reasonably be considered as a normal ensemble. The average deviation about the median rarely exceeded two percent implying that the monthly median and the monthly mean were nearly equal. The skewness, which provides an indication of the asymmetry of the data sets was also rather close to zero as it must be for a normal distribution. In the F2 region, there were occasions when the average deviation about the median was on the order of ten percent and the deviation data appeared to be quite skewed. For the most part, this was found to be associated with periods of severe magnetic disturbances. However, to a first approximation, it is felt that the F2 region deviations could also be considered as normally distributed for the majority of cases studied.

The statistical analysis indicates that the variability of the ionosphere is not only different for the different ionospheric layers but that the variability in any given layer displays local time, seasonal and solar cycle dependencies of varying degrees. Figure 1a shows the standard deviation in MHz about the monthly median of foE that is typically observed at mid-latitude locations. Shown in the figure are results obtained from data taken at Ottawa, Canada, and Slough, England, during March, June and September 1958 and 1964. The geographic and geomagnetic coordinates of these and other stations whose results are shown in the report are given in Table 1. Because the E region is under strict solar control, routine observations of foE are only available during daylight hours. For the local mean times shown (0900 to 1500 h), the standard deviation of foE about the median is never greater than 0.05 MHz, with the difference between solar maximum and solar minimum results being small. This difference is greatest during March and September and practically nil during the summer solstice. Although not shown in the figure, the standard deviation at times surrounding 0600 h and 1800 h tends to be slightly larger than for midday. However, the scarcity of reliable data at these times renders it difficult to determine how statistically significant the results are during periods surrounding sunrise and sunset.

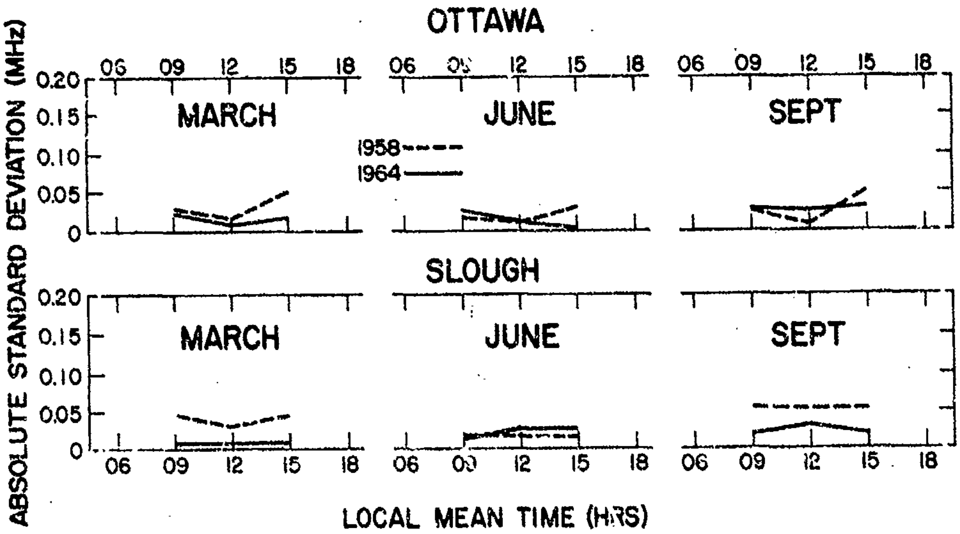

Figure 1a. Absolute Standard Deviation About the Observed Monthly Median foE at Ottawa and Slough During March, June and September, 1958 and 1964

Table 1. Stations and Coordinates Whose Results are Shown in the Present Report

Station	Geographic Lat(°)	Geographic Long(°)	Geomagnetic Latitude(°)	Dip (°)
Ottawa, Canada	45N	75W	56N	74
Slough, Great Britain	51N	00W	54N	66
Lindau, Fed Rep. Germany	51N	10E	52N	63
Moscow, USSR	56N	37E	50N	70

For the purposes of comparing these results with those for other regions, Figure 1b shows the relative standard deviation for the same data as shown in Figure 1a. It can be seen that the relative standard deviation is generally less than six percent implying that 95 percent of all observations lie within ± 12 percent of the monthly median value.

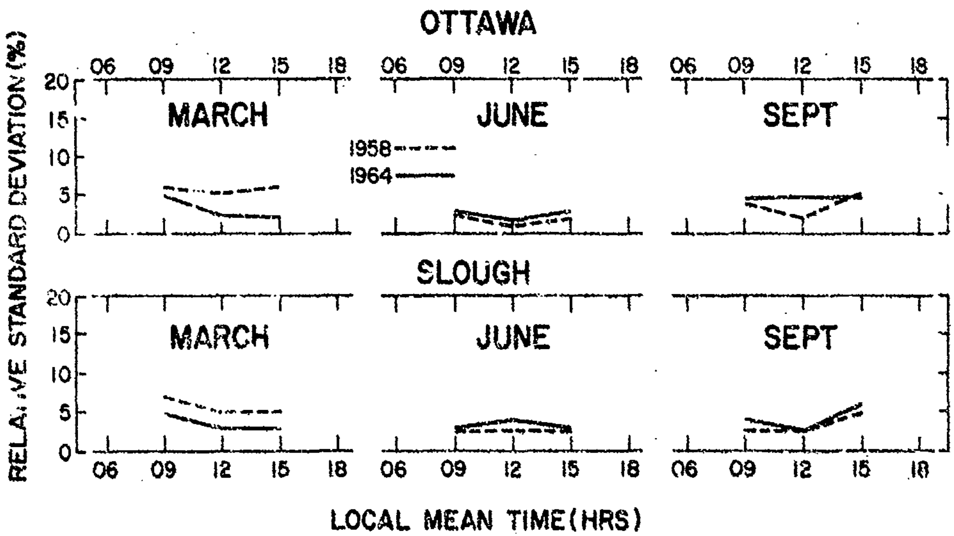

Figure 1b. Relative Standard Deviation About the Observed Monthly Median foE at Ottawa and Slough During March, June and September 1958 and 1964

Figure 2 shows the absolute (2a) and relative (2b) standard deviation about the monthly median value for foF1 for June 1958 and 1964 observed at Ottawa and Slough. As was the case with foE, foF1 is strongly solar dependent permitting the calculation of reliable statistics only when the solar zenith angle is relatively high. Comparing Figure 2a with Figure 1a, it appears that foF1 displays an absolute variability that is twice as large as foE during solar maximum but there is no significant difference during solar minimum. The relative standard deviations (Figures 2b and 1b) indicate foF1 is slightly more variable than foE, with the difference in the variabilities of the two regions being greatest during solar maximum.

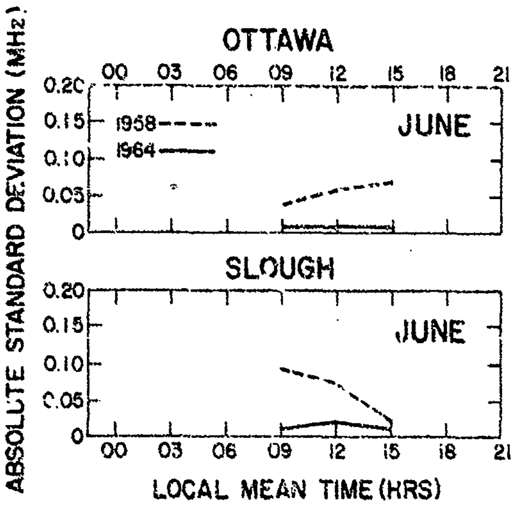

Figure 2a. Absolute Standard Deviation About the Observed Monthly Median foF1 at Ottawa and Slough During June, 1958 and 1964

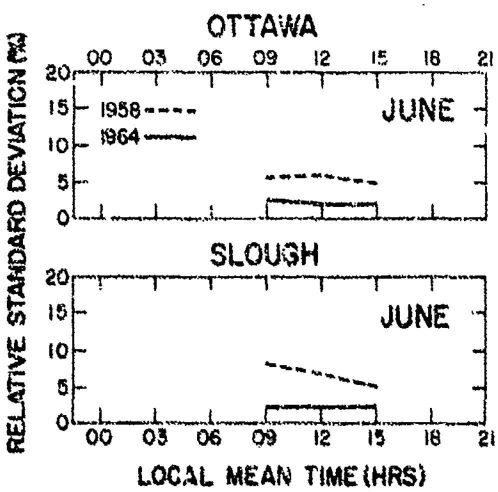

Figure 2b. Relative Standard Deviation About the Observed Monthly Median foF1 at Ottawa and Slough During June, 1958 and 1964

In Figure 3 the local time variation of the absolute standard deviation about the monthly median F2 region critical frequency is given for three locations: Slough; Lindau, Germany; and Moscow, USSR. The results are shown for the four months surrounding the solstices and equinoxes for both solar maximum and solar minimum conditions. It should be noted that the ordinate in Figure 3 is a factor of 10 larger than that in either Figure 1a or 2a. Not surprisingly, the absolute standard deviation is larger at solar maximum (1958) than at solar minimum (1964). The results show that at solar maximum, the variability of the F2 region is generally larger for all hours during equinoxes than for the time period

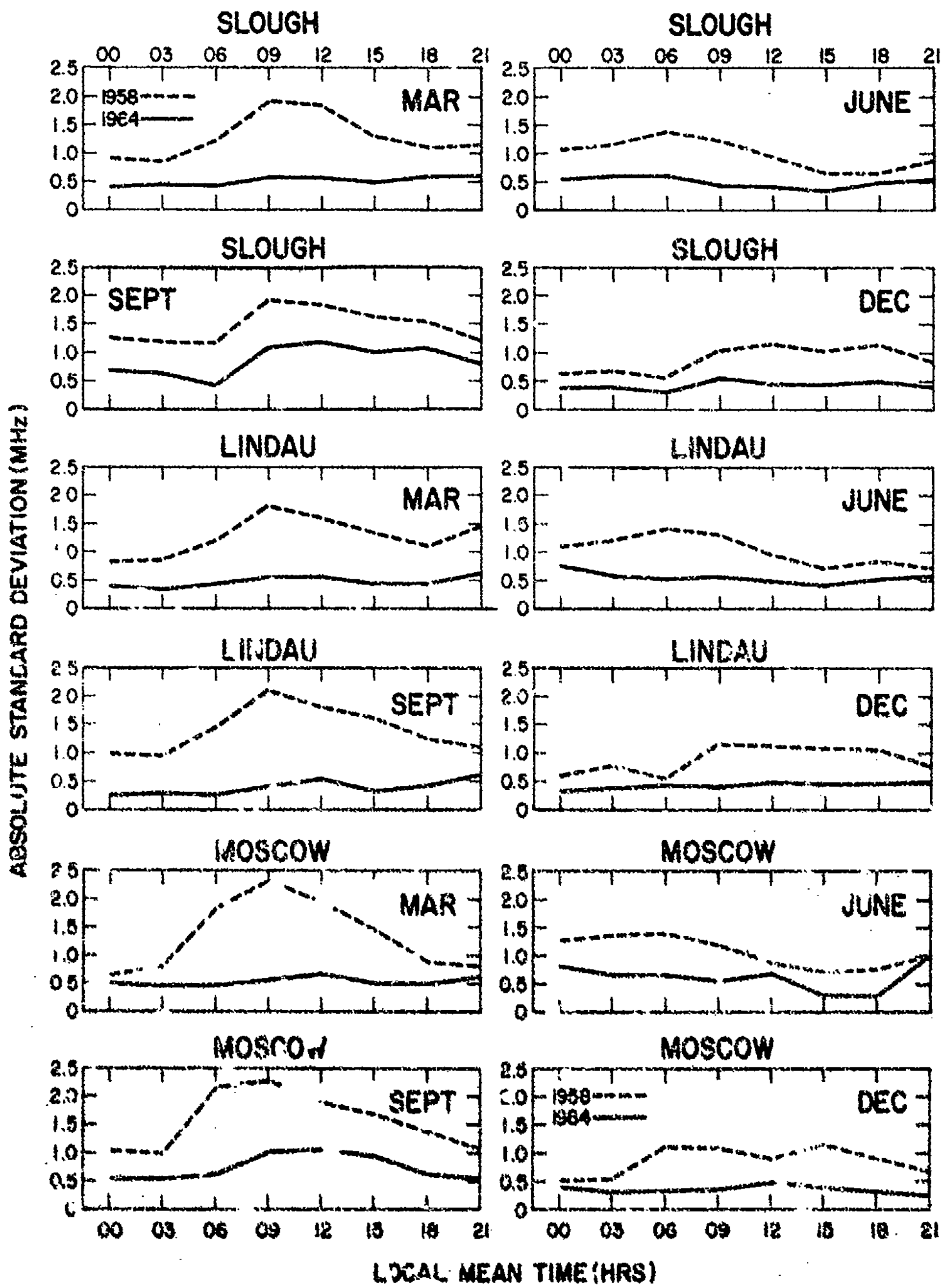

Figure 3. Local Time Variation of the Absolute Standard Deviation About the Monthly Median foF2 at Slough, Lindau and Moscow During March, June, September and December, 1958 and 1964

surrounding the solstices. During solar minimum, this doesn't appear to be the case, however. In fact, the standard deviation appears to show little seasonal or diurnal dependence during 1964, being approximately 0.50 MHz for all hours and seasons.

During solar maximum, the diurnal variation of the standard deviations at Slough, Lindau and Moscow display strikingly similar behavior at all seasons. For the equinoctial months, the largest standard deviation (~ 2.0 MHz) occurs around 0900 h LMT and generally tends to decrease at other hours. During the northern solstice, the standard deviation is higher between the hours 0000 to 0600 LMT than at other times of the day while during the southern solstice the results indicate the opposite behavior.

To compare the results of the standard deviations seen in the F2 region with those observed in the E and F1 regions, Figure 4 shows the relative standard deviation for the same times and stations illustrated in Figure 3. It is immediately obvious that the local time, seasonal and solar cycle dependencies noted in the absolute standard deviation are not as apparent in the relative standard deviation. The results in Figure 4 suggest that an average value of 15 percent provides a good measure of the standard deviation observed in the F2 region for all temporal scales. This is two to three times the variability that is observed in the E and F1 regions.

The fact that the F2 region is inherently more variable than the E or F1 region is certainly not a new finding that is unique to this study. However, the evidence presented here, which is typical of the mid-latitude ionosphere, using data taken simultaneously in time and location, does provide some indication as to how much more variable the F2 region is compared to the ionization at lower altitudes.

Not only are the E and F1 regions less variable than the F2 region, but the median value of either foE and foF1 at mid-latitudes can, for the most part, be predicted to within an accuracy on the order of five percent (Muggleton, 1972; DuCharme et al, 1971). There appears to be little doubt, therefore, that propagation predictions based upon predicted median values of foE and foF1 should be quite useful when applied to day-to-day operational requirements. In the F2 region, the problem is much more complex. The results presented here show the variability of foF2 about the <u>observed</u> monthly median value. Clearly, median <u>predictions</u> of foF2 can, at least, lead to day-to-day prediction errors on the order of 0.5 to 3.0 MHz depending on local time and phase of the solar cycle. Extreme caution should be exercised, therefore, in applying on a day-to-day basis HF propagation predictions that depend on median conditions for those radio transmissions that are obviously controlled by the F2 region.

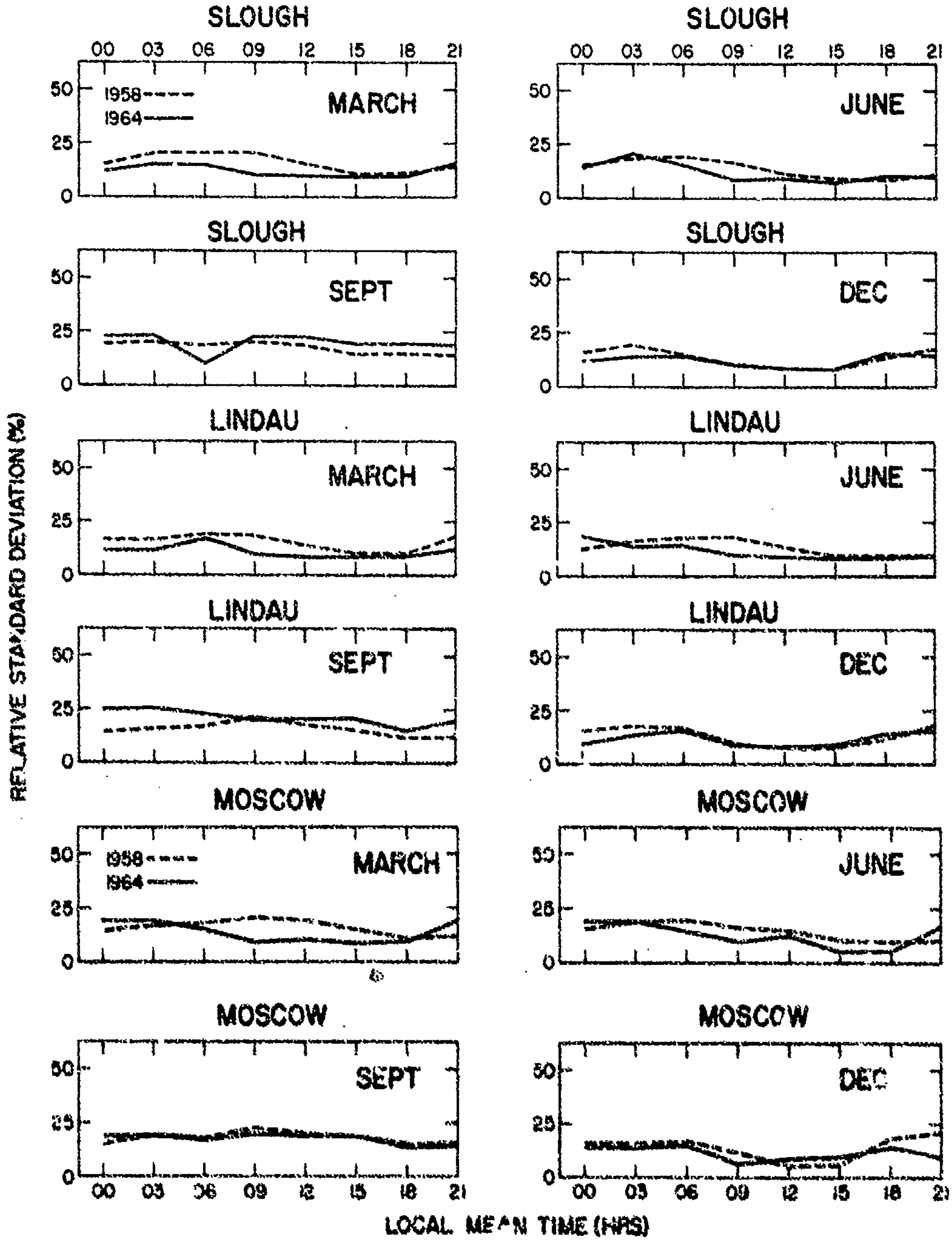

Figure 4. Local Time Variation of the Relative Standard Deviation About the Monthly Median foF2 at Slough, Lindau and Moscow During March, June, September and December, 1958 and 1964

3. SHORT-TERM PREDICTION OF foF2

Because the F2 region displays considerable variability, there have been many attempts to develop a short-term prediction capability for foF2 on a time scale shorter than a monthly median (Bennett and Friedland, 1970). Most of these studies have been concerned with relating changes in foF2 to corresponding changes in selected geophysical variables such as the 10.7 cm solar flux and the geomagnetic activity index, Kp. The disadvantage of this type of approach when applied to timely predictions is that the independent geophysical variables upon which changes in foF2 depend, must themselves be predicted. Thus, any errors in the predicted values of the geophysical variables will be reflected in the corresponding predicted values of foF2. A notable exception, however, is the work of Gautier and Zacharisen (1965) and Zacharisen (1965) who have attempted to develop a short-term prediction scheme based upon statistical properties of the foF2 distribution. Using auto-correlation and cross-correlation coefficients determined from deviations of foF2 from the monthly mean value, they have shown how much improvement can be obtained using timely observation of foF2. In actual practice, however, the monthly mean value of foF2 is not known in advance and it must therefore be predicted.

In this study we attempted to find a short-term prediction scheme for foF2 based upon immediate past observations of foF2. It was assumed that data were available at particular locations at least 24 h in advance of the time a prediction is to be made. The problem then is to find a sufficiently general prediction scheme that leads to prediction errors that are smaller than those obtained using median predictions over a large temporal and geographical scale.

To find the optimum prediction technique, various predictors were used and deviations between predictor and observation were computed on an hourly basis for each predictor. The standard deviation for each data set was then computed and used to provide an indication of the prediction error. The predictors used were running means, running medians and weighted means for each hour. The value computed from the past data was used to predict the value of foF2 for the same hour in 3-, 5-, 7-, 9- and 15-day intervals. A prediction was made for every hour of every day and the deviations at each hour were grouped into the normal monthly intervals.

Comparing both the standard deviations between predictor and observation as well as the number of times a particular predictor came closest to the observation showed that the weighted mean predictor was the best possible prediction technique of those that were investigated. A simple weighting scheme was used in computing the weighted mean predictors and was of the form

$$\text{Weighted Mean Prediction} = \frac{(m\,D_{-1} + (m-1)\,D_{-2} + \ldots\,D_{-m})}{\sum_{i=1}^{m} i}$$

where m is the number of days used in computing the weighted mean and D_{-1} is the value of foF2 the day preceding the prediction day; D_{-2} is the value of foF2 two days preceding the prediction day and D_{-m} is the value of foF2 m days preceding the prediction day. If a value for a particular day were missing, no prediction was made for that day.

Figure 5 shows the diurnal behavior of the standard deviation in MHz that results using a 3-, 5- and 7-day weighted mean prediction for the months indicated using data observed at Slough, Lindau and Moscow during 1958. Also shown for comparison is the standard deviation about the observed monthly median value of foF2. Other than for a few hours centered near midday in March, the standard deviation either closely agrees with or is less than the standard deviation about the observed monthly median. Obviously, if predicted monthly median values were used, then standard deviation about the predicted median would be larger than those computed about the observed median. For all practical purposes, results shown in Figure 5, along with those from other stations, indicate that using past foF2 data as a predictor, the standard deviation can be reduced to or closely match that computed from the observed median. The inherent advantage in using past observations to predict future values of foF2 lies in the fact that the parameter itself is used in the prediction and there are no dependencies on independent geophysical variables which could be a possible source of error.

Judging from Figure 5, there appears to be little difference in the standard deviations using a 3-, 5-, or 7-day weighted mean, and in principle, any of the three should yield comparable results. In practice, however, it would be desirable to keep to a minimum the amount of data needed to make an accurate prediction and it would appear that the predictor requiring the smallest data base would be the optimum to implement. We chose to use the 5-day weighted mean as the predictor.

Despite the fact that observations of foF2 can be used to predict future values of foF2 with an accuracy comparable to that of observed median, the standard deviations, at least during solar maximum, are quite large at certain times. The question arises as to how useful are observations gathered on a time scale less than 24 h in reducing the prediction error. To test this out, it was assumed that data are available one to six hours in advance of the time a prediction is to be made. These data were used to 'update' the 5-day weighted mean prediction.

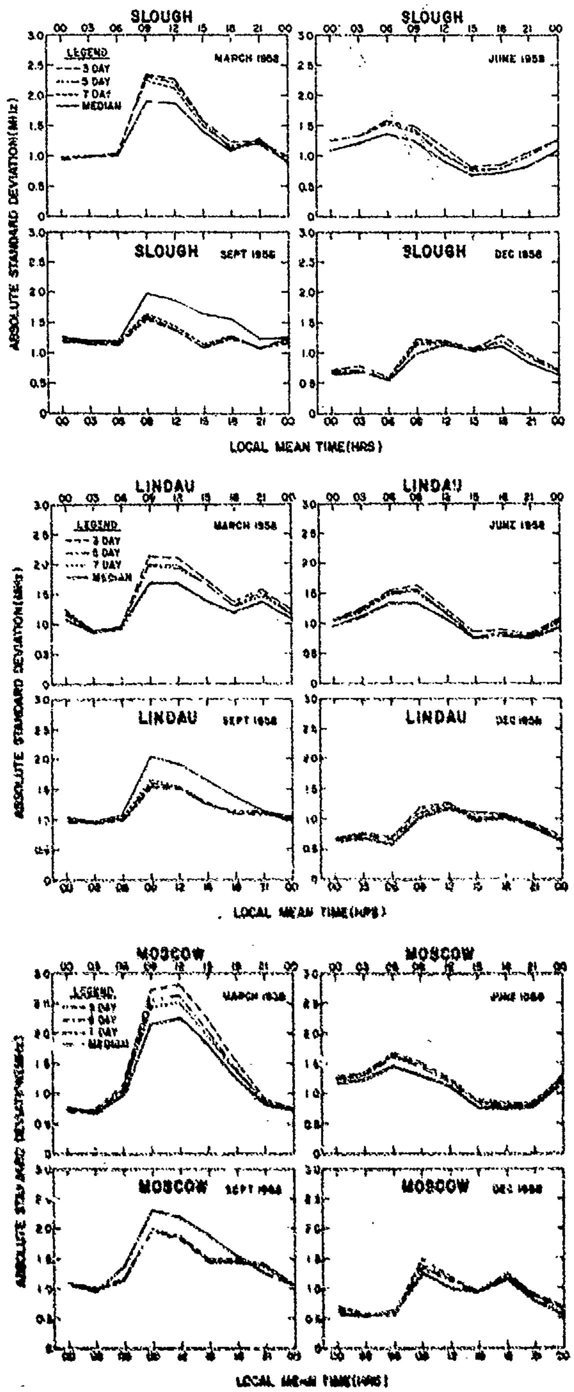

Figure 5. Diurnal Behavior of the Standard Deviation of the Errors Associated With a 3-, 5- and 7-day Weighted-mean Prediction at Slough, Lindau and Moscow During 1958

The updating scheme employed was a straightforward percentage change. If data were one hour old and if the difference between the observation and the 5-day weighted mean prediction was ten percent at that hour then the 5-day weighted mean for the next hour was adjusted by ten percent. Similar schemes were applied to data that were 2-, 3-, . . . 6-h old.

Figure 6 shows the diurnal variation of the standard deviation resulting from updating the 5-day weighted mean with data that are 1-, 2-, 3-, 4- and 6-h old using the same stations illustrated in Figure 5. It can be seen that the amount of improvement in the prediction (smaller standard deviation) generally decreases with increasing time lag used in the updating process. There are times (0600 h LMT in March and 0900 h LMT in December) when the only improvement afforded is obtained using data 1-h old while at other times, particularly during the midday period at equinox and most all hours during the summer solstice, data up to 4-h old, yield significant improvements in the prediction of foF2. During the winter solstice, it appears that data over 2-h old applied in the manner as described above, are of little use in reducing the prediction error.

The effect of short-term data in reducing the prediction error in foF2 clearly has a diurnal dependence. Data observed shortly before or at local sunrise are of little use in updating the 5-day weighted mean except within 1 or 2 h after sunrise. On the other hand, foF2 observed around 0900 h LMT can be used to reduce the prediction error for a time period 3 to 6 h in advance. At periods surrounding local sunset, a behavior comparable to that at sunrise is seen in the effectiveness of short-term observations of foF2 to reduce the prediction error. Generally, it can be said that when the ionosphere undergoes significant changes such as accompany the sunrise and sunset transitions, observations of foF2 before such transitions are of little value when applied to the updating scheme used here.

Figure 7 shows the comparison between the standard deviations obtained using the median foF2, the 5-day weighted mean foF2 and the 5-day weighted mean updated using the previous hour's observation for the 1964 data at Slough, Lindau and Moscow. Generally, the 5-day weighted mean yields a better approximation to the observed daily hourly values than does the observed monthly median. It can be seen that in many instances updating the 5-day weighted mean with data only 1-h old does not lead to a significant reduction in the standard deviations. In fact, in some instances (midday in December), such updating causes an increase in the standard deviation. The difference in the effect of short-term updating in foF2 that is observed between solar maximum and minimum is probably associated with the fact that the ionosphere during solar minimum is not subjected to as many of the large-scale perturbations that occur during solar maximum conditions.

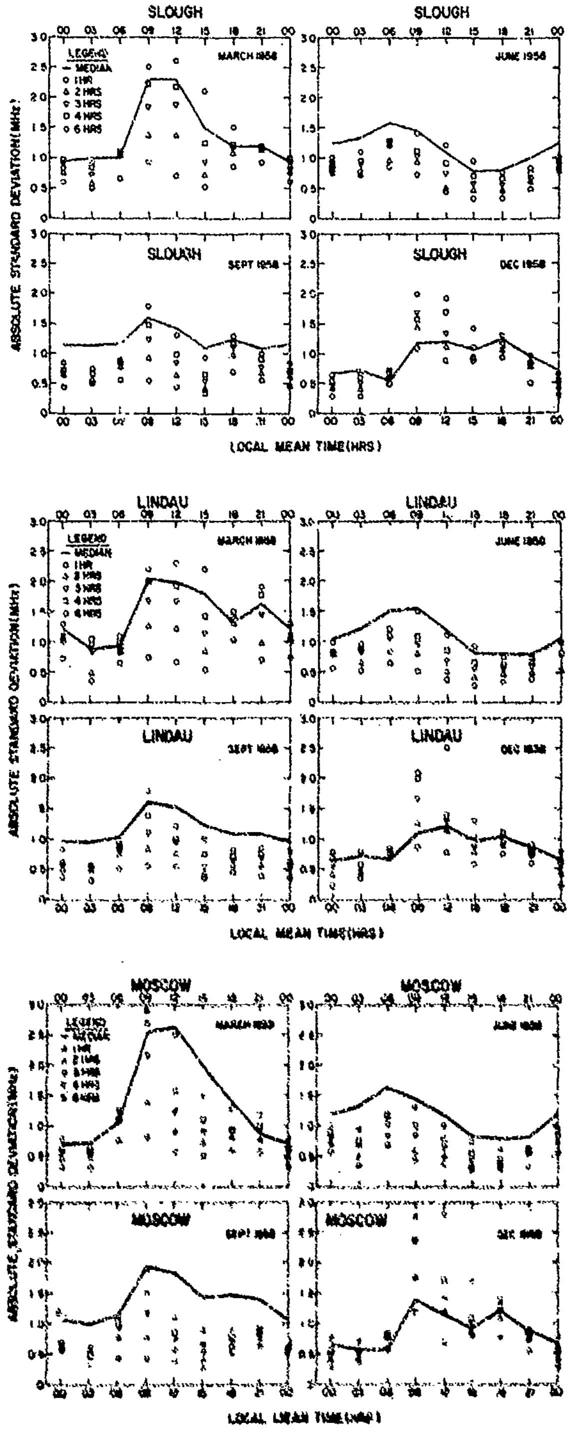

Figure 6. Diurnal Variation of the Standard Deviation of the Errors Resulting From Updating the 5-day Weighted-mean Prediction With Data 1-, 2-, 3- ... 6-h Old During 1958

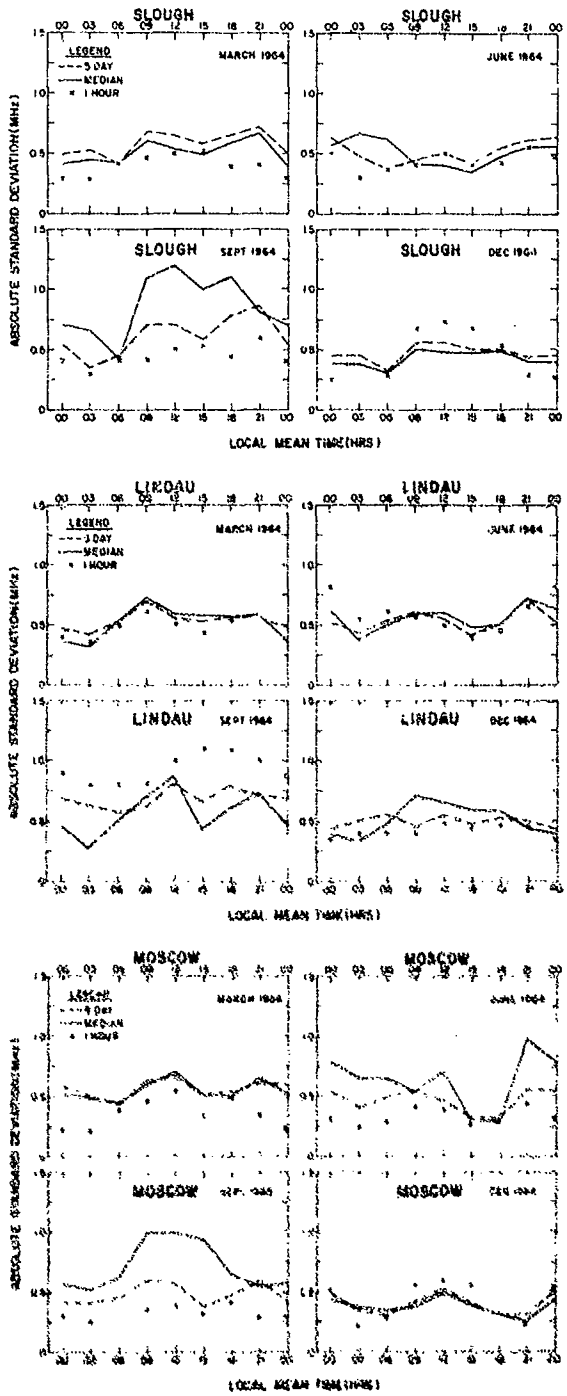

Figure 7. Diurnal Behavior of the Standard Deviation of the Errors Associated With the 5-day Weighted-Mean Prediction and the Standard Deviation Resulting From Updating the 5-day Weighted-mean With Data 1-h Old

These perturbations, due to geophysical phenomena, such as solar flares and geomagnetic storms, can lead to rapid changes in the ionosphere within a period of hours. Thus, data obtained over five days would be inherently more variable during solar maximum than during solar minimum. This would imply that data taken in hourly increments should have a larger effect on reducing the overall ionospheric variability during solar maximum conditions than during solar minimum conditions.

It is quite conceivable also, that the degree of improvements afforded by short-term updating is a strong function of the updating scheme itself. We have given equal weight in the updating procedure to all data. It is probably more reasonable to weigh the effect of the observation used in the short-term update according to the lag between the time the observation is made and the time it is applied to correct the 5-day weighted mean prediction. Thus, smaller weights would be used as the lag increases. However, the amount of improvement in the prediction by using decreasing weighting factors becomes correspondingly small, thus diminishing the usefulness of short-term updating.

4. DISCUSSION

The results described in the previous sections clearly show that the F2 region is far more variable than either the E or F1 regions. The relative variability of foF2 about the observed median is two to three times that of foE and foF1. The standard deviations of foE and foF1 about the observed monthly medians are such that the monthly median value of those parameters at a particular hour provides a reasonable estimate of the daily hourly value at mid-latitudes. This would imply that HF prediction techniques such as described by Barghausen et al, (1969) and Headrick et al, (1971), which rely on monthly median ionospheric predictions, can be employed with some confidence in day-to-day operations for those propagation paths that are controlled by the normal E and F1 regions. For the F2 region, no such statement can be made. The standard deviation of foF2 typically varies from 0.5 to 0.7 MHz during solar minimum conditions to 0.7 to 2.5 MHz during solar maximum. Uncertainties of this order in foF2 when applied to oblique transmissions via the F2 region lead to uncertainties in the computed maximum usable frequency on the order of 1 to 2 MHz during solar minimum and 2 to 5 MHz during solar maximum, assuming the monthly median value of foF2 can be accurately predicted.

To avoid errors associated with the inability to predict the monthly median value of foF2 exactly, a prediction scheme based on observations of foF2 observed over a 5-day period has been shown to yield results that are comparable to or better than the observed monthly median. In addition, it has been seen that during certain times, particularly daylight hours at solar maximum, observations of foF2 obtained in hourly, bi-hourly or tri-hourly intervals can be used to produce significant improvement in the prediction of foF2. Whether such a scheme is cost-effective, however, is open to serious question. It appears that using the statistical type of approach adopted here, an uncertainty on the order of 0.5 MHz will be found at all times. A further limitation is that the predictions depend on observations at particular locations. These predictions must then be extended or extrapolated to regions where data are not available, such as over the oceans. This limitation can, however, be minimized somewhat by employing a synoptic mapping technique such as described in a previous report (Rush, 1972).

There appears to be little doubt that further work is required in order to specify, model and predict the ionospheric structure if such efforts are to be applied to the prediction of day-to-day HF propagation characteristics. The most important area is in the prediction of foF2 itself. As means have been devised that yield predicted values of foF2 with a standard deviation of 0.5 to 0.7 MHz using simple statistical techniques, any future approaches, be they mathematical or physical, must yield yet smaller standard deviations if they are to be of any further operational use.

Acknowledgments

The authors are grateful to Drs. T. Elkins and K. Toman for meaningful discussions during the course of this work and for their comments concerning the original manuscript.

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