Forecasts of Geomagnetic Activity by

Linear Prediction Filtering

by

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ABSTRACT

A prediction filter based on Wiener linear prediction theory has been developed for medium-term (27 days) forecasts of geomagnetic activity in Canada. Magnetic data from observatories with the Automatic Magnetic Observatory System (AMOS) in the polar cap, auroral zone and subauroral zone are used as input to the filter. The forecasts compare favourably with actual data. It is found that the optimum length of input data to the prediction filter is about 8 solar rotations and the appropriate length of the prediction filter is about one third of the length of the data. The prediction filter could be used for routine forecasting work.

INTRODUCTION:

The earth's magnetic field is not constant but fluctuates with time with periods ranging from small fractions of a second to more than 30 millions of years. While the longer period changes are of internal origin, variations with periods less than a few days are of external origin. These short term changes in the magnetic field are due to changing electrical currents in the earth's magnetosphere and ionosphere, which are the result of interaction of the solar wind with the magnetosphere and are related to features on the sun. Geomagnetic activity on the surface of the earth is directly influenced by these current systems. Therefore, for a full understanding of geomagnetic activity, it is necessary to have a knowledge of the release of solar wind plasma from the sun, the propagation and evolution of that plasma through the interplanetary medium and the interaction of the solar wind with the earth's magnetic field. Hence, ideally a "super " computer program could be developed to forecast geomagnetic activity using available solar, solar wind, interplanetary and ground geomagnetic data employing the recognized solar-terrestrial relationships. Unfortunately, none of the above segments are fully understood and the applications of magnetospheric physics to the forecasting of geomagnetic activity are as yet in a rudimentary state. At present, short term forecasts are based directly on solar phenomena and recurrence is the only technique available for longer-range forecasts. Current forecasting methods are qualitative and empirical and input data are used qualitatively. It is therefore essential to develop computer algorithms to reduce the subjectivity of particular forecasters and to allow objective comparison of the various proposed approaches. It is towards this goal that this study is aimed. Although the current study still falls far short of the complete solution to the problem, it is nevertheless a step in that direction. The present study utilizes the ground geomagnetic data for the forecasts of geomagnetic activity. A linear prediction filtering technique is employed whereby the past values are linearly combined to predict future values based on the least square criterion. To our knowledge, geomagnetic forecasts by prediction filtering techniques have not been used by other forecasting centers.

THE LINEAR PREDICTION FILTER:

Physical prediction depends fundamentally on the assumption that regularities that have occured in the past will recur in the future. The technique used here is based on the least-squares criterion and it leads to filters which are linear. The mathematical theory of such filters was originally developed by Wiener(1942). The Wiener method of smoothing and prediction was adapted by Levison(1942) to the case of finite-length discrete operators. The Wiener-Levinson algorithm was subsequently extended and implemented by Robinson who has written a number of papers and books on the subject since the late 50's. A complete, though by no means exhaustive, list of references related to linear prediction filtering including most of Robinson's work is appended to this report. Using Robinson's formalism (e.g. Robinson and Treitel,1967), a brief description of the linear prediction filtering now follows.

The basic principle is the least-squares criterion. The filter coefficients are determined such that the mean-square-error between the desired output z and the actual output y

$$I = E\left\{(z_t - y_t)^2\right\} \qquad (1)$$

is a minimum. The actual output, which is the convolution of the input x with the filter f , is

$$y_t = \sum_{s=0}^{m} f_s \, x_{t-s} \qquad (2)$$

Substituting (2) into (1) and setting the partial derivative of I with respect to each filter coefficient ($f_0, f_1 \cdots\cdots f_m$) equal to zero, the following set of simultaneous equations can be obtained:

$$\begin{array}{l}
f_0 \phi_{xx}(0) + f_1 \phi_{xx}(-1) \cdots\cdots\cdots + f_m \phi_{xx}(-m) = \phi_{zx}(0) \\
f_0 \phi_{xx}(1) + f_1 \phi_{xx}(0) \cdots\cdots\cdots + f_m \phi_{xx}(1-m) = \phi_{zx}(1) \\
\quad \vdots \qquad\qquad\quad \vdots \qquad\qquad\qquad\qquad\quad \vdots \qquad\qquad\qquad \vdots \\
f_0 \phi_{xx}(m) + f_1 \phi_{xx}(m-1) \cdots\cdots + f_m \phi_{xx}(0) = \phi_{zx}(m)
\end{array}$$

These equations are called the normal equations. The known quantities are the autocorrelation coefficients ϕ_{xx} and the cross correlation coefficients ϕ_{zx}. The solution of these equations yields the coefficients of the filter. Since the matrix of this set of equations is in the form of a Toeplitz matrix (i.e. a matrix with equal elements on any diagonal), a recursive technique developed by Levinson (1942) can be used to solve the equations. Such a recursive scheme reduces storage from m^2 to m and computer time from m^3 to m^2 for a filter of length m as compared to solution of these equations by standard methods such as the Gaussian elimination method. The reader should refer to the references in the bibliography for more detail.

The filters used in this study are time dependent in a sense that independent filters are derived at a sequence of data windows. That is, the filter coefficients are re-computed for the new set of data so that the resulting filter is data-adaptive. In this way, the most relevent recurrent features of geomagnetic activity are utilized for the forecasts.

It should be pointed out that Samson and Rostoker (1985) have recently carried out some preliminary investigations of the methods of superposed analysis and time series models in forecasting of geomagnetic activity.

THE DATA:

The data used in this study are derived from the Canadian Magnetic Observatory Network. The daily means of the hourly ranges in the X component of the earth's magnetic field recorded in stations in Ottawa, Fort Churchill and Resolute Bay are used.

These stations are equipped with the Automatic Magnetic Observatory System (AMOS). These three stations were chosen because they are located in three different zones having different magnetic characteristics. Ottawa is located in the subauroral zone ($\sim 50^\circ - 60^\circ$ N geomagnetic), Fort Churchill in the auroral zone ($\sim 60^\circ - 70^\circ$ N) and Resolute Bay in the polar cap zone ($> 70^\circ$ N).

The data are shown in Fig. 1 (Ottawa), Fig. 2 (Fort Churchill) and Fig.3 (Resolute Bay). Each figure consists of 16 panels. Each panel represents one solar rotation. The slightly more than a year's data cover a period from March 29, 1984 to June 2, 1985 corresponding to the beginning of solar Rotation 2059 and the end of Rotation 2074.

It can be seen from Figs. 1, 2 and 3 that the levels of geomagnetic activities are quite different for the three zones. The levels of activity in the subauroral zone are relatively subdued when compared to the polar cap and the auroral zone. The auroral zone has the most intense activities because it is directly under the influences of the auroral electrojets.

It is apparent from the three figures that recurrence of geomagnetic activity is prominent. The recurrence occurs approximately every 27 days which is the average period of solar rotation and can persist for up to 8 or 9 solar rotations. The dominant sources of these disturbances may be the high-speed stream of plasma emanating from coronal holes which are long-lived features co-rotating with the sun.

Besides the recurrent geomagnetic activity, sporadic activity is evident from these plots. A good example is the intense activities in Rotation 2073. There was no evidence of such activities in the previous rotation. See , for example, the plot for Rotation 2072 in the subauroral zone (Fig.1) which indicates a relatively quiet level of activity. Rotation 2074 shows that the intense activities in Rotation 2073 have died down. These sporadic activities are related to non-recurrent short-lived solar events such as solar flares and/or filament disappearances and point out the importance of short term 72 hours forecasts. While the medium term 27 days forecasts can indicate the general trend of activities, the short term forecasts can incorporate recent changes in the sun's activity to modify the medium term forecasts.

RESULTS:

The data described in the last section are used as inputs to the linear prediction filter. The outputs from the filter are the forecasted values of the daily means of the hourly ranges for the next solar rotation. The results for the subauroral zone are presented first. These are then followed by those of the auroral zone and polar cap. Qualitative comparisons are made with the actual data. The forecasts were made based on unit prediction distance using different lengths of input data and filter to establish the optimum number of solar rotations and the appropriate length of filter for the prediction.

Fig.4 shows the forecasted values for the subauroral zone as represented by Ottawa. Forecasts were made for the next solar rotation using all the data from the previous rotations with a filter of fixed length of 70 days. The use of a filter length of 70 will be justified later. The forecasted results presented here are meant for qualitative comparisons with the actual data shown earlier. There are two numbers on each panel. The first number indicates the number of rotations used to make the forecast and the second number indicates the length of the prediction filter. Except for the very active days, the forecasts generally reproduced the trends of the activities.

To see the effects of varying lengths of input data on the forecasted values, forecasts were made for Rotation 2074 using varying lengths of input and a filter of fixed length of 70 and the results are shown in fig.5. It can be seen that after 8 to 11 rotations, further increase in input data does not produce noticeable changes in the forecasted values. However, results using more rotations tend to reflect activities that occurred earlier. For example , the peak on the third day of a given solar rotation predicted using large data input is apparently due to the activities occurring at that time of the earlier rotations as shown in Fig.1. This may not be a desirable feature because the activity may have subsided and would not recur. Such a peak is absent in the actual data. Therefore, it may not be appropriate to use input data longer than 8 or 9 rotations, as will be explained later.

To see the effects of varying lengths of filter on the forecasted values, forecasts were made for Rotation 2074 using varying lengths of filter and a fixed length of data input from the previous 15 rotations and the results are shown in Fig. 6. It can be seen that features begin to appear starting at filter with length of 70. There is not much improvement by going to longer lengths of filter.

Results for the auroral zone as represented by Fort Churchill are shown in Figs. 7,8 and 9 in the same manner as before for comparison with actual data and for the study of the effects of varying lengths of data input and filter. While one cannot expect one to one correspondence between the predicted values and the actual values, the recurrent peaks evident in the actual data show up in the forecasts. The intense activities observed in Rotation 2073 which were sporadic in nature are not predictable by the filter as shown in the panel for the forecast of Rotation 2073. Again, increasing input data to more than 8 rotations and the filter length to more than 70 do not produce noticeable changes in the forecast.

It appears that 8 solar rotations of data would be an appropriate length of data for the input to the prediction filter. This also corresponds to the physical situation that long-lived features on the sun in general last no more than 8 or 9 rotations. Some features may last up to 20 rotations, but this is rather uncommon. Hence, for the forecasts in the polar cap as represented by Resolute bay, 8 rotations of data were used and the results are shown in Fig.10. The forecasts for Rotation 2074 with varying length of filter are shown in Fig.11. Again, similar conclusions from these plots can be drawn as for the auroral and subauroral zones.

To better justify the using of a filter length of 70 for the forecast, plots of normalized mean-square-error vs length of prediction filter were made and are shown in Fig.12. The normalized mean-square-error is defined as

$$Q_0 = \frac{I_0}{\Phi_{gg}(0)}$$

where I_0 is the minimum mean-square-error given by

$$I_0 = \phi_{zz}(0) - \left\{ f_0 \phi_{zx}(0) + f_1 \phi_{zx}(1) \cdots\cdots\cdots + f_m \phi_{zx}(m) \right\}$$

Q_0 is therefore a non-negative number that lies between zero and one. It is apparent that the smaller the value of Q_0, the better the prediction.

The normalized mean-square-errors were computed for the forecasts for Rotation 2074 shown previously for varying lengths of the filter. The curves level out at length of 70 and further increase in the length of the filter does not show appreciable decrease in the values of normalized mean-square-error and does not justify the longer CPU time involved. Therefore, the optimum length for the filter would be 70 days, and the optimum length for the data input would be about 8 solar rotations as previously mentioned.

DISCUSSION:

About a year's data have been test-run on the linear prediction filter. Although a more quantitative verification scheme would require a much larger suite of data, the results presented here are quite encouraging. The forecasts indicate the recurrent trends as observed in the real data. For a comparison with the manual forecast, Fig.13 shows the actual data represented by solid lines ,the forecasted values done manually by Dr. J. Hruska represented by bars and the computer forecasted values based on the linear prediction filter represented by dots. It can be seen that the forecasts by the linear prediction filter compare favourably with the manual forecasts, if not better in places. The plots on Fig.13 would be an appropriate format for the routine three zone forecasts in the future with perhaps the dots replaced by three letters A, U and Q representing active, unsettled and quiet respectively.

Some refinement and modification may be needed in the computer program of linear prediction. It is apparent from Fig.13 and the previous plots that the forecasts in the polar cap and auroral zone appear to be overestimated with respect to the real data. This is due to the fact that the earlier rotations have a general higher mean level of activity as compared to the later rotations. This feature is quite evident from the actual data from the auroral zone and polar cap in Figs. 2 and 3. Therefore the mean levels of activities in each solar rotation should be taken into consideration so that the mean level of the forecasted values can be adjusted accordingly to bring it closer to the mean levels of the more recent rotations. This in effect takes the seasonal variations into consideration. If the mean levels of the forecasted values for the polar cap and the auroral zone in Fig.13 were lowered, the computer predictions would match the real data even better.

Also, the computer program should be extended to one with multichannel inputs so that data from several stations can be used as input to the prediction filter to forecast the average values of these stations. This is necessary because of the dynamic nature of the auroral zone. The auroral zone is not fixed geographically but expands and contracts in response to the level of convection in the magnetosphere. Therefore, several stations in the auroral zone are needed to forecast the average behaviour of the auroral zone although this may not be required in the subauroral zone and the polar cap.

The sun is currently in a state of minimum solar activity as shown in Fig.14. This is the period when the 27 days recurrence effect in geomagnetic activity is most pronounced, and thus it is the time when a prediction filter which utilizes the recurrent characteristics in the time series will give best results. However, a few more years from now when the sun becomes active again and when the 27 day recurrence is weak as shown in Fig. 15 (after Sargeant,1985), the current computer program will have to be substantially modified to take into consideration the weak 27 day recurrence.

CONCLUSION:

A computer program has been developed using the linear prediction filtering technique for the forecasts of geomagnetic activity. The program has been tested using data from the AMOS observatories and the results are encouraging. The program could be implemented into routine forecasting and may help to take the bias and subjectivity out of forecasting. It is anticipated that the trends of geomagnetic activity indicated by the computer forecasts , coupled with the experience and expertise of a forecaster , will produce better predictions of geomagnetic activity in Canada.

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FIGURE CAPTIONS:

Fig.1. Daily means of hourly ranges for Ottawa in the subauroral zone from March 29, 1984 to June 2, 1985 corresponding to the start of Solar Rotation of 2059 and the end of Rotation 2074.

Fig.2. Same as Fig.1 except for Fort Churchill in the auroral zone.

Fig.3. Same as Fig.1 except for Resolute Bay in the polar cap.

Fig.4. Forecasts for the subauroral zone of the next solar rotation using all the data from previous rotations with a fixed filter length of 70.

Fig.5. Forecasts for the subauroral zone for Rotation 2074 using varying length of data input but with a fixed filter length of 70.

Fig.6. Forecasts for the subauroral zone for Rotation 2074 using varying length of filter but with a fixed length of data input of 15 rotations.

Fig.7. Same as Fig.4 except for auroral zone.

Fig.8. Same as Fig.5 except for auroral zone and for Rotation 2071.

Fig.9. Same as Fig.6 except for auroral zone.

Fig.10. Same as Fig.4 except for polar cap using data from previous 8 rotations.

Fig.11. Same as Fig.6 except for polar cap using data from previous 8 rotations.

Fig.12. Plots of normalized mean-square-error vs length of filter.

Fig.13. Comparison of the actual daily means of the hourly ranges represented by solid lines with the manually forecasted values represented by the bars and the computer forecasted valued based on the linear prediction filter represented by dots for Rotation 2069.

Fig.14. Monthly mean sunspot numbers.

Fig.15. The solar sunspot numbers and the 27 day recurrence index. A low index indicates weak 27 day recurrence (after Sargeant,1985).

ACTUAL DAILY MEAN OF HOURLY RANGE
SUBAURORAL ZONE

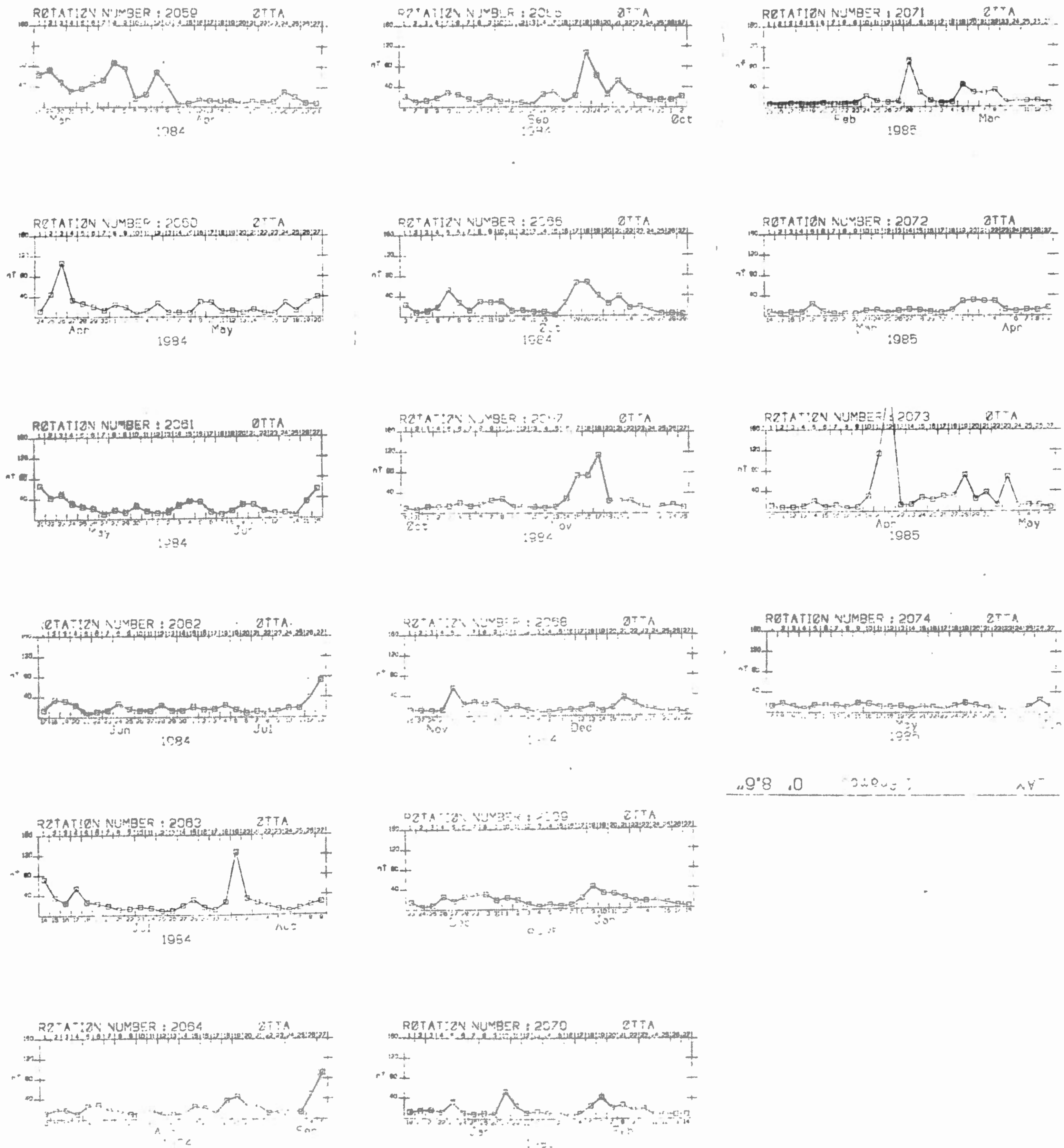
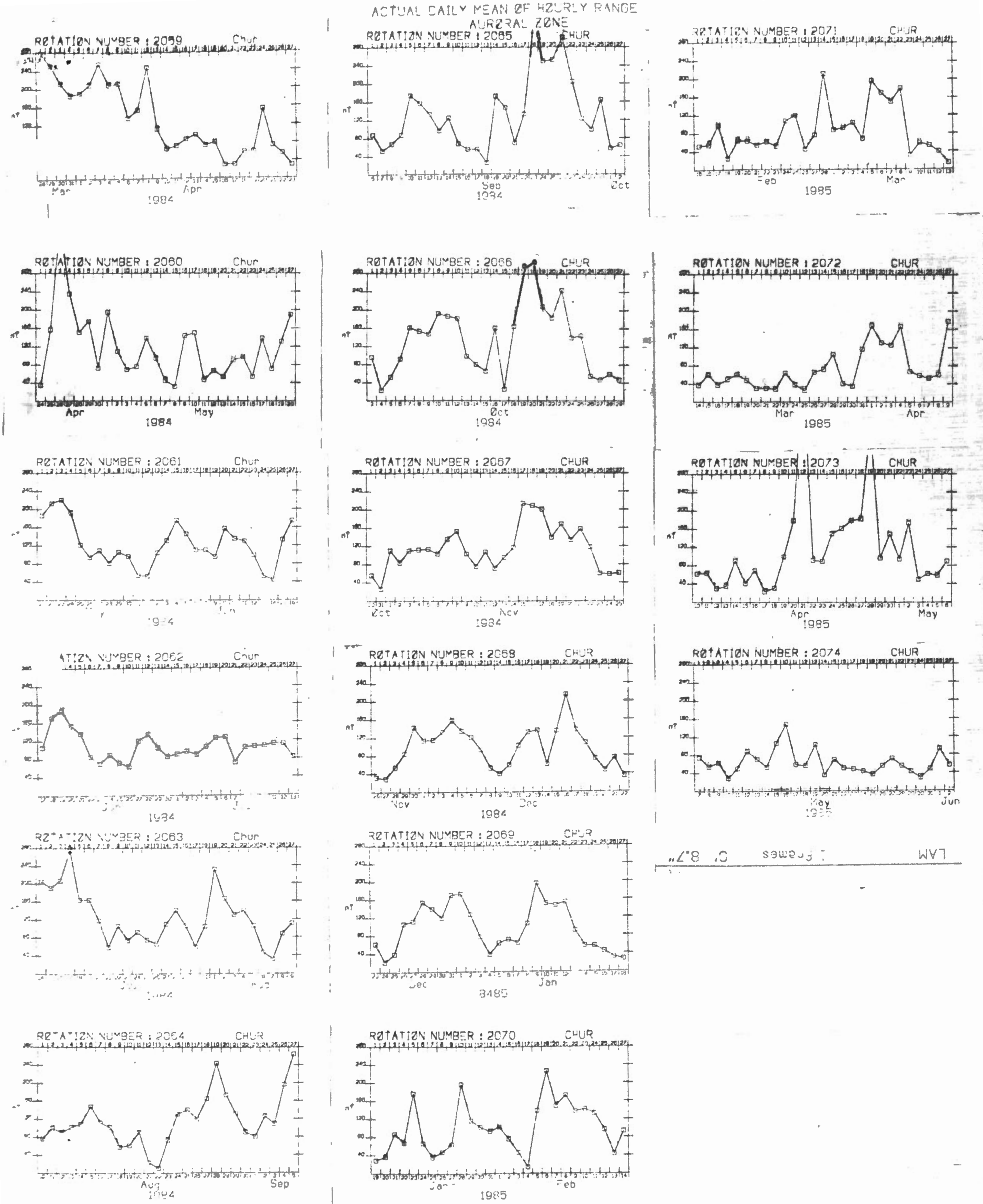


FIG. 1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Sep Øct 1984
RØTATIØN NUMBER : 2071 CHUR
Feb Mar 1985
RØTATIØN NUMBER : 2060 Chur
Apr May 1984
RØTATIØN NUMBER : 2066 CHUR
Øct 1984
RØTATIØN NUMBER : 2072 CHUR
Mar Apr 1985
RØTATIØN NUMBER : 2061 Chur
RØTATIØN NUMBER : 2067 CHUR
Øct Nov 1984
RØTATIØN NUMBER : 2073 CHUR
Apr May 1985
RØTATIØN NUMBER : 2062 Chur
1984
RØTATIØN NUMBER : 2068 CHUR
Nov Dec 1984
RØTATIØN NUMBER : 2074 CHUR
May Jun
RØTATIØN NUMBER : 2063 Chur
RØTATIØN NUMBER : 2069 CHUR
Dec Jan
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Aug Sep 1984
RØTATIØN NUMBER : 2070 CHUR
Jan Feb 1985
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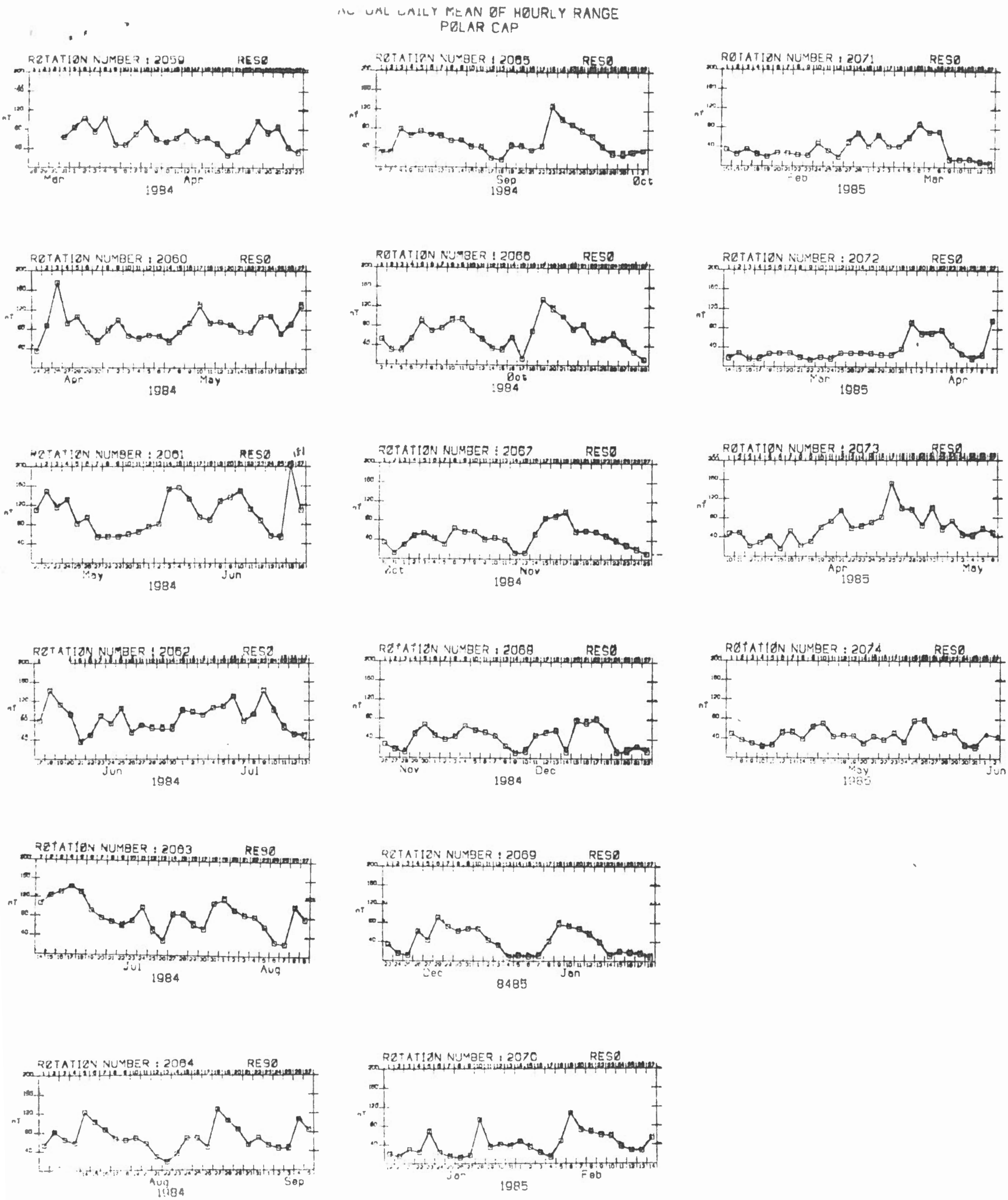
FIG. 2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Feb Mar
1985
ROTATION NUMBER : 2060 RESO
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Jan Feb
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FIG. 3

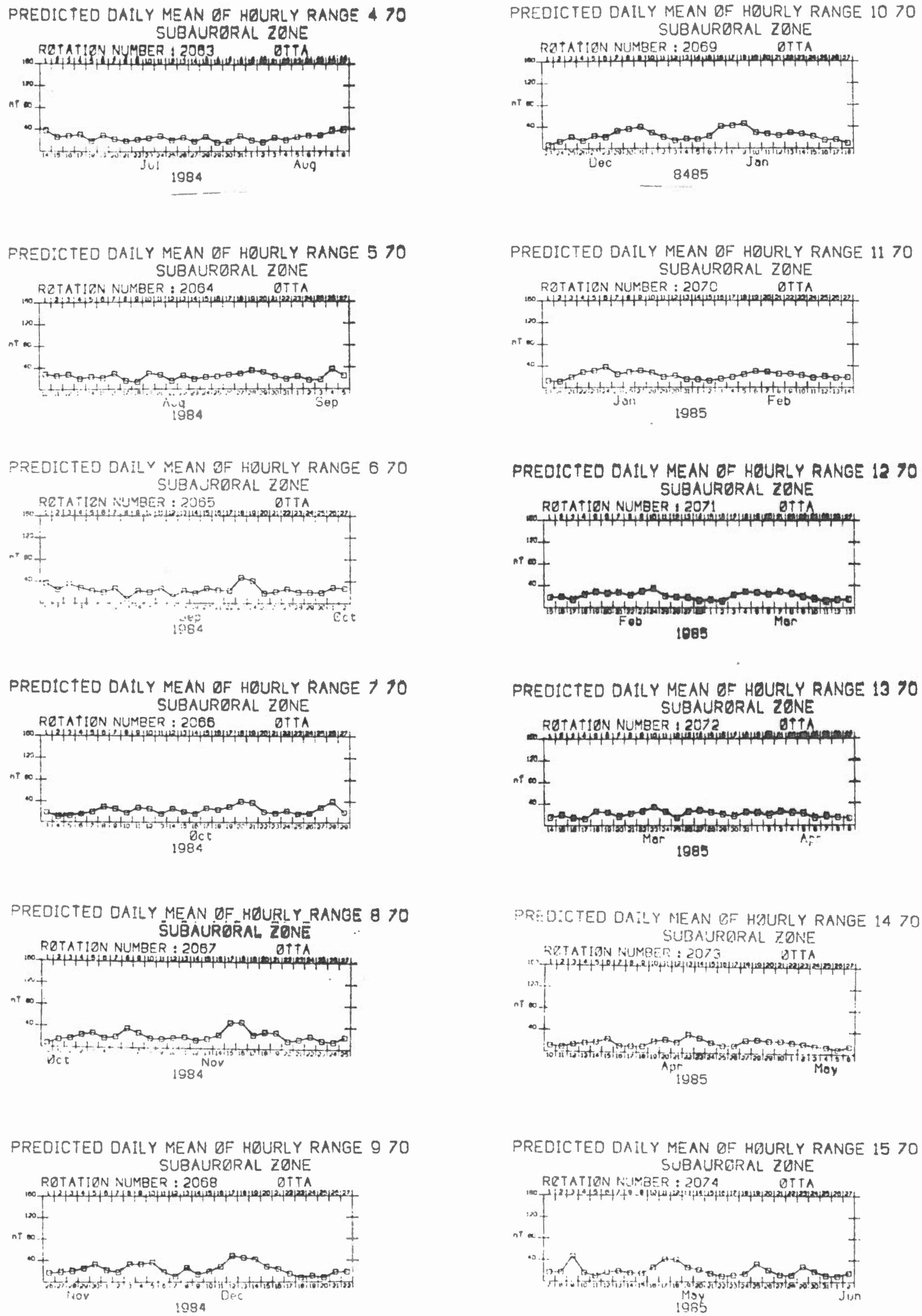
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FIG. 4

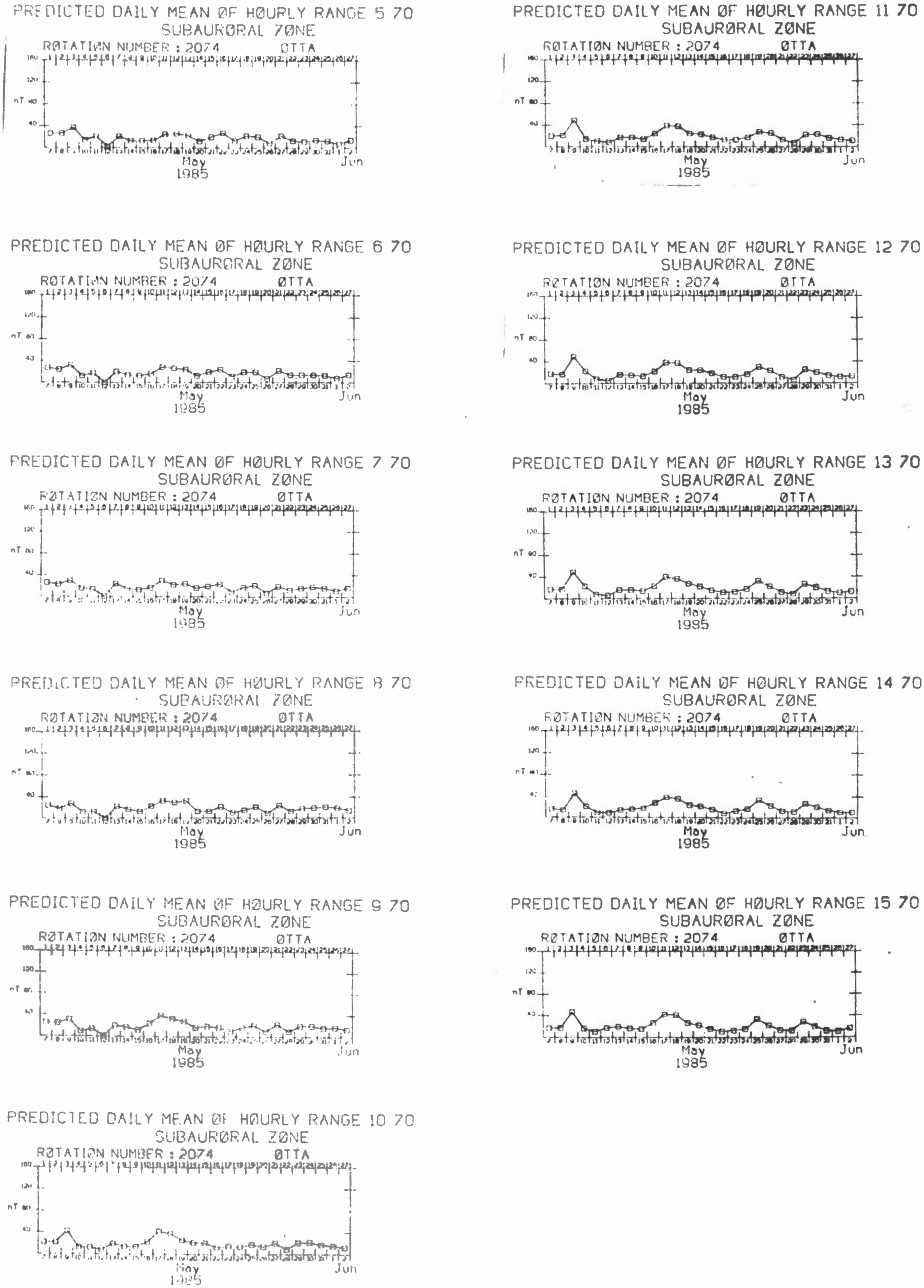
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FIG. 5

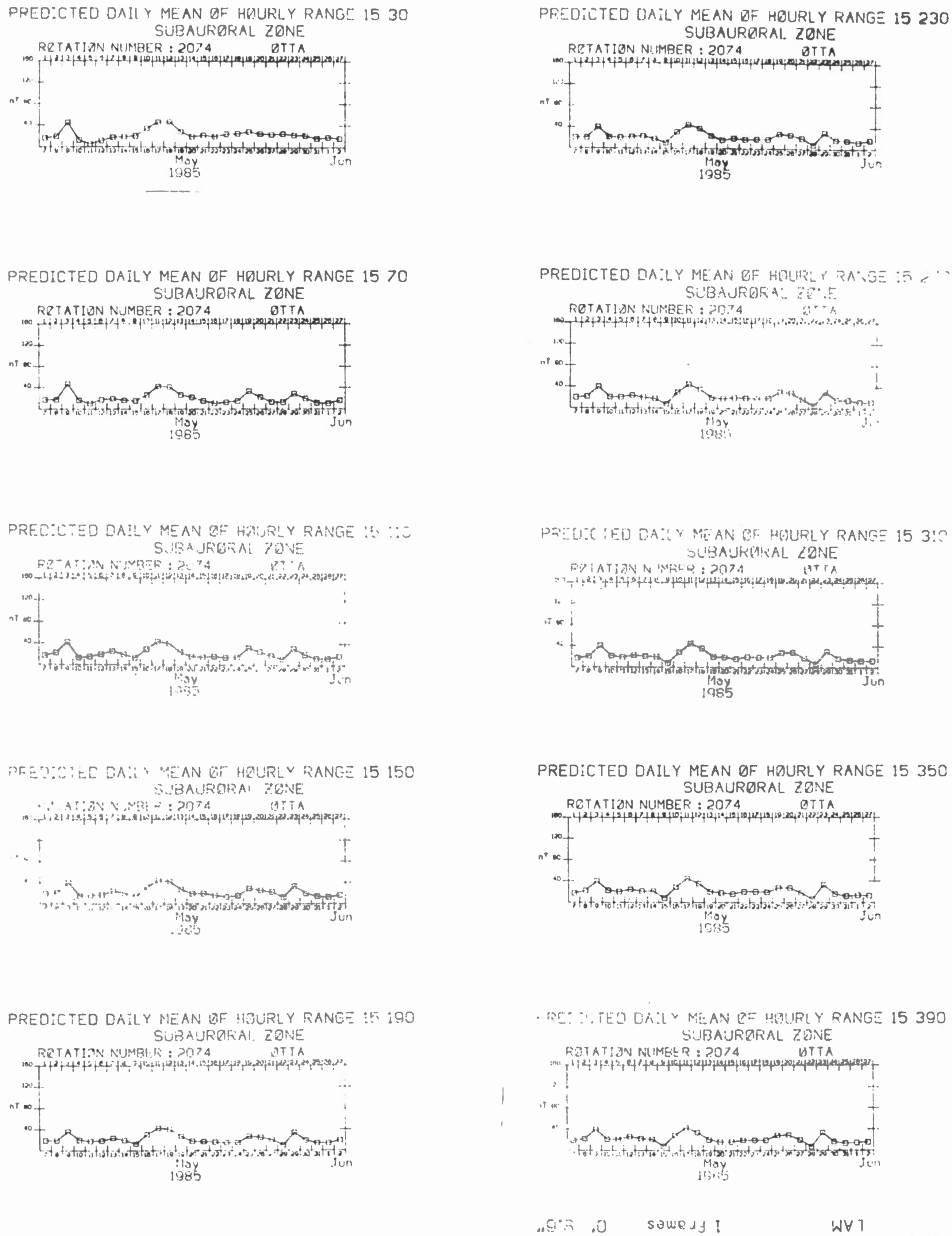
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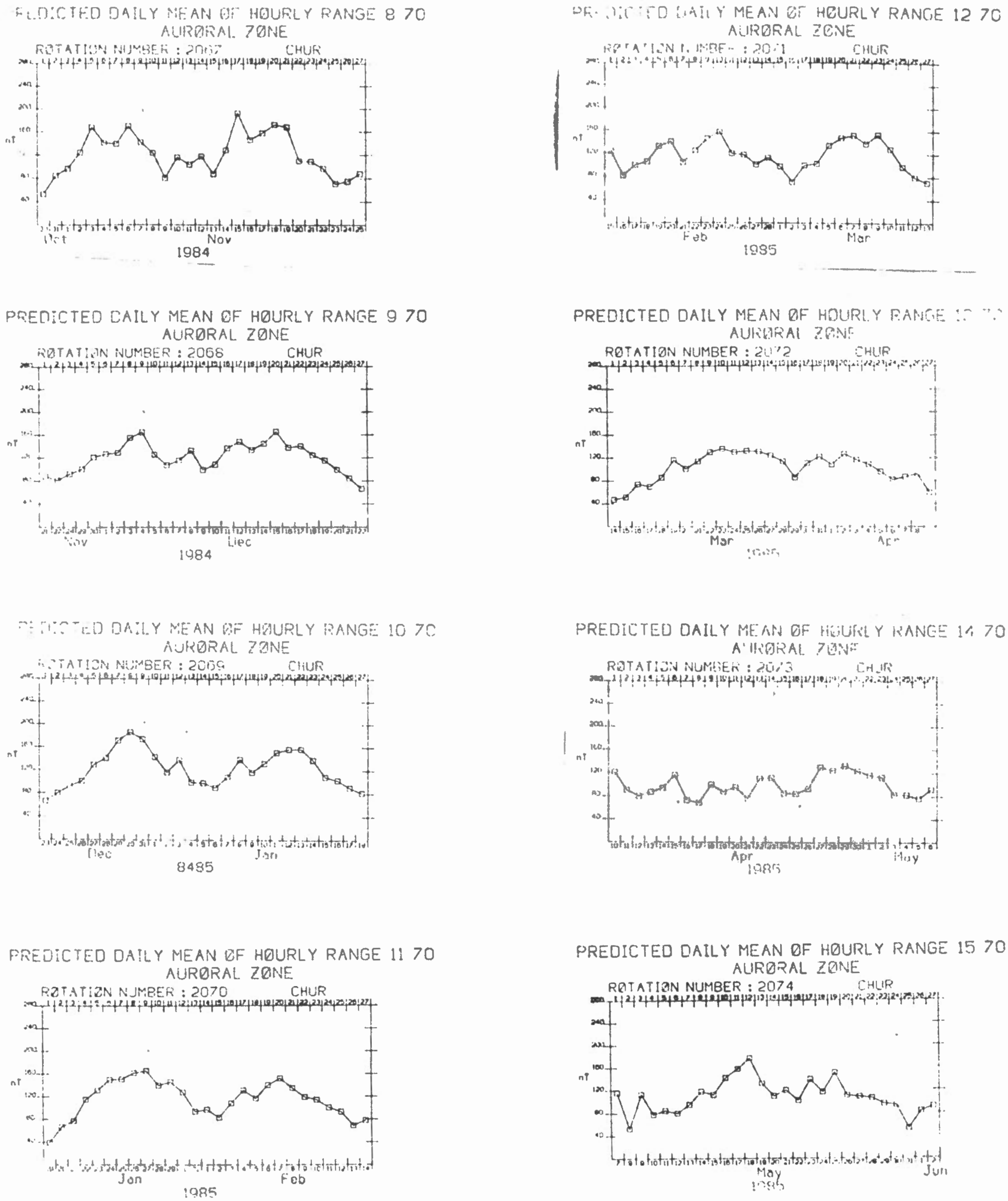
FIG. 6



AURØRAL ZØNE
CHUR
Nov
1984
Feb
Mar
1985
PREDICTED DAILY MEAN ØF HØURLY RANGE 9 70
AURØRAL ZØNE
RØTATIØN NUMBER : 2066
CHUR
nT
Nov
1984
PREDICTED DAILY MEAN ØF HØURLY RANGE
RØTATIØN NUMBER : 2072
CHUR
nT
Mar
AURØRAL ZØNE
CHUR
Dec
Jan
8485
PREDICTED DAILY MEAN ØF HØURLY RANGE 14 70
CHUR
Apr
May
PREDICTED DAILY MEAN ØF HØURLY RANGE 11 70
AURØRAL ZØNE
RØTATIØN NUMBER : 2070
CHUR
nT
Jan
Feb
1985
PREDICTED DAILY MEAN ØF HØURLY RANGE 15 70
AURØRAL ZØNE
RØTATIØN NUMBER : 2074
CHUR
nT
May
Jun

FIG. 7

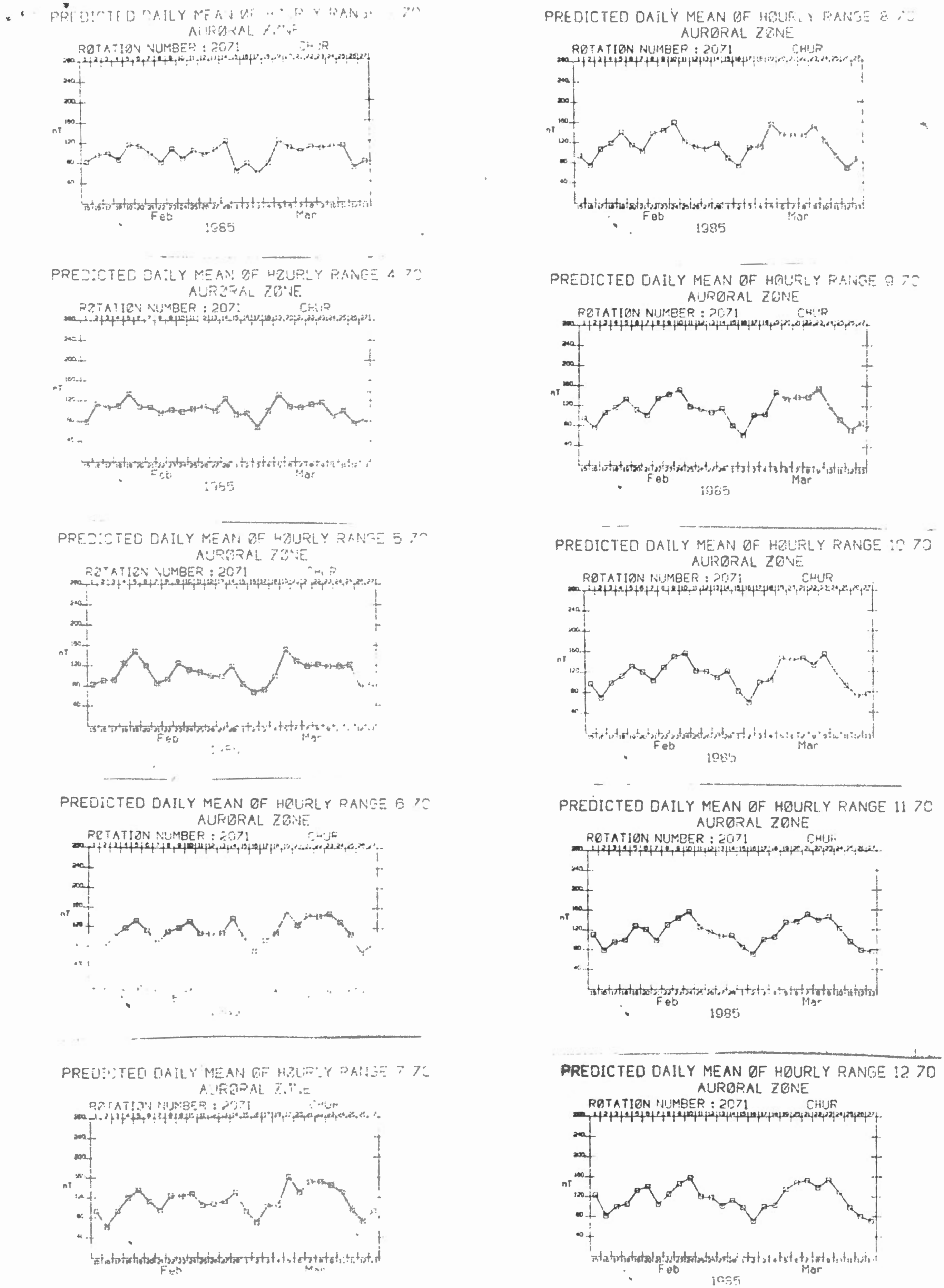
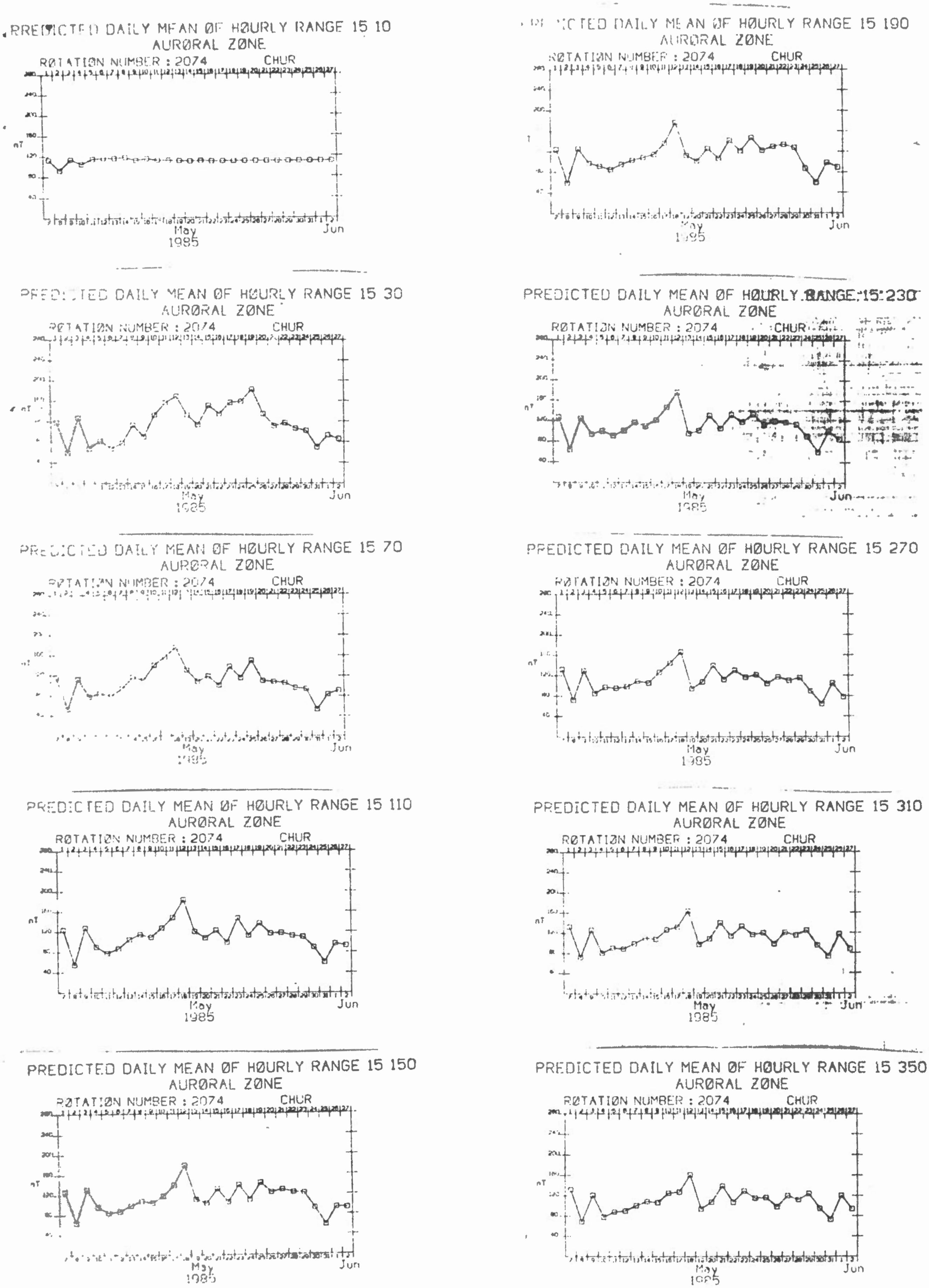

PREDICTED DAILY MEAN ØF HØURLY RANGE 6 70
PREDICTED DAILY MEAN ØF HØURLY RANGE 9 70
PREDICTED DAILY MEAN ØF HØURLY RANGE 11 70
PREDICTED DAILY MEAN ØF HØURLY RANGE 12 70
AURØRAL ZØNE
RØTATIØN NUMBER : 2071
CHUR
nT
Feb
Mar
1985

FIG. 8



PREDICTED DAILY MEAN ØF HØURLY RANGE 15 10
AURØRAL ZØNE
RØTATIØN NUMBER : 2074
CHUR
May
1985
Jun
PREDICTED DAILY MEAN ØF HØURLY RANGE 15 190
AURØRAL ZØNE
RØTATIØN NUMBER : 2074
CHUR
Jun
PREDICTED DAILY MEAN ØF HØURLY RANGE 15 30
AURØRAL ZØNE
RØTATIØN NUMBER : 2074
CHUR
May
Jun
PREDICTED DAILY MEAN ØF HØURLY RANGE 15 230
AURØRAL ZØNE
RØTATIØN NUMBER : 2074
CHUR
May
Jun
PREDICTED DAILY MEAN ØF HØURLY RANGE 15 70
AURØRAL ZØNE
RØTATIØN NUMBER : 2074
CHUR
May
Jun
PREDICTED DAILY MEAN ØF HØURLY RANGE 15 270
AURØRAL ZØNE
RØTATIØN NUMBER : 2074
CHUR
May
1985
Jun
PREDICTED DAILY MEAN ØF HØURLY RANGE 15 110
AURØRAL ZØNE
RØTATIØN NUMBER : 2074
CHUR
May
1985
Jun
PREDICTED DAILY MEAN ØF HØURLY RANGE 15 310
AURØRAL ZØNE
RØTATIØN NUMBER : 2074
CHUR
May
1985
Jun
PREDICTED DAILY MEAN ØF HØURLY RANGE 15 150
AURØRAL ZØNE
RØTATIØN NUMBER : 2074
CHUR
May
1985
Jun
PREDICTED DAILY MEAN ØF HØURLY RANGE 15 350
AURØRAL ZØNE
RØTATIØN NUMBER : 2074
CHUR
May
Jun

FIG. 9

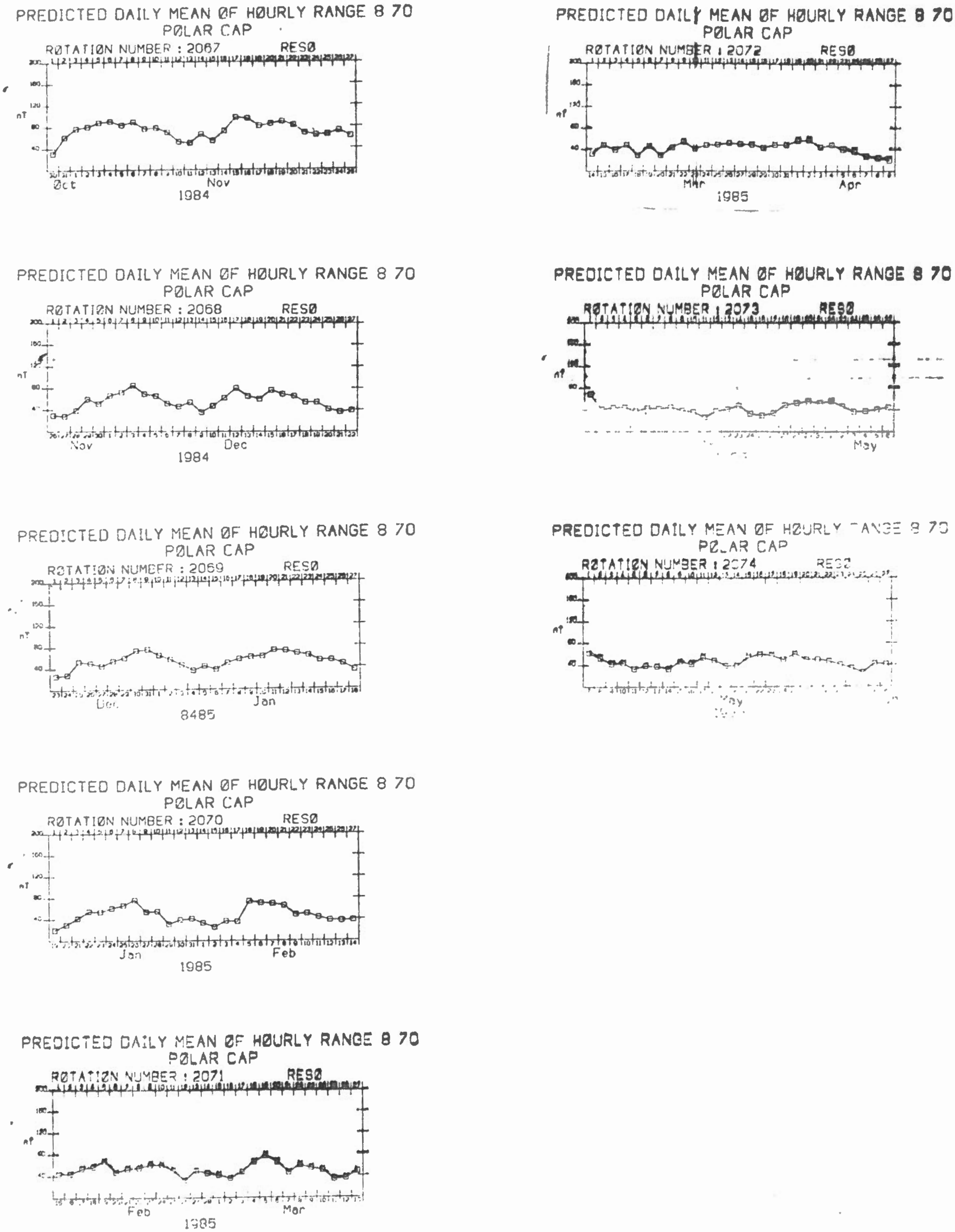

PREDICTED DAILY MEAN ØF HØURLY RANGE 8 70
PØLAR CAP
RØTATIØN NUMBER : 2067
RESØ
nT
Øct
Nov
1984
PREDICTED DAILY MEAN ØF HØURLY RANGE 8 70
PØLAR CAP
RØTATIØN NUMBER : 2068
RESØ
nT
Nov
Dec
1984
PREDICTED DAILY MEAN ØF HØURLY RANGE 8 70
PØLAR CAP
RØTATIØN NUMBER : 2069
RESØ
nT
Dec
Jan
8485
PREDICTED DAILY MEAN ØF HØURLY RANGE 8 70
PØLAR CAP
RØTATIØN NUMBER : 2070
RESØ
nT
Jan
Feb
1985
PREDICTED DAILY MEAN ØF HØURLY RANGE 8 70
PØLAR CAP
RØTATIØN NUMBER : 2071
RESØ
nT
Feb
Mar
1985
PREDICTED DAILY MEAN ØF HØURLY RANGE 8 70
PØLAR CAP
RØTATIØN NUMBER : 2072
RESØ
nT
Mar
Apr
1985
PREDICTED DAILY MEAN ØF HØURLY RANGE 8 70
PØLAR CAP
RØTATIØN NUMBER : 2073
RESØ
nT
May
PREDICTED DAILY MEAN ØF HØURLY
PØLAR CAP
RØTATIØN NUMBER : 2074
nT
May

FIG. 10

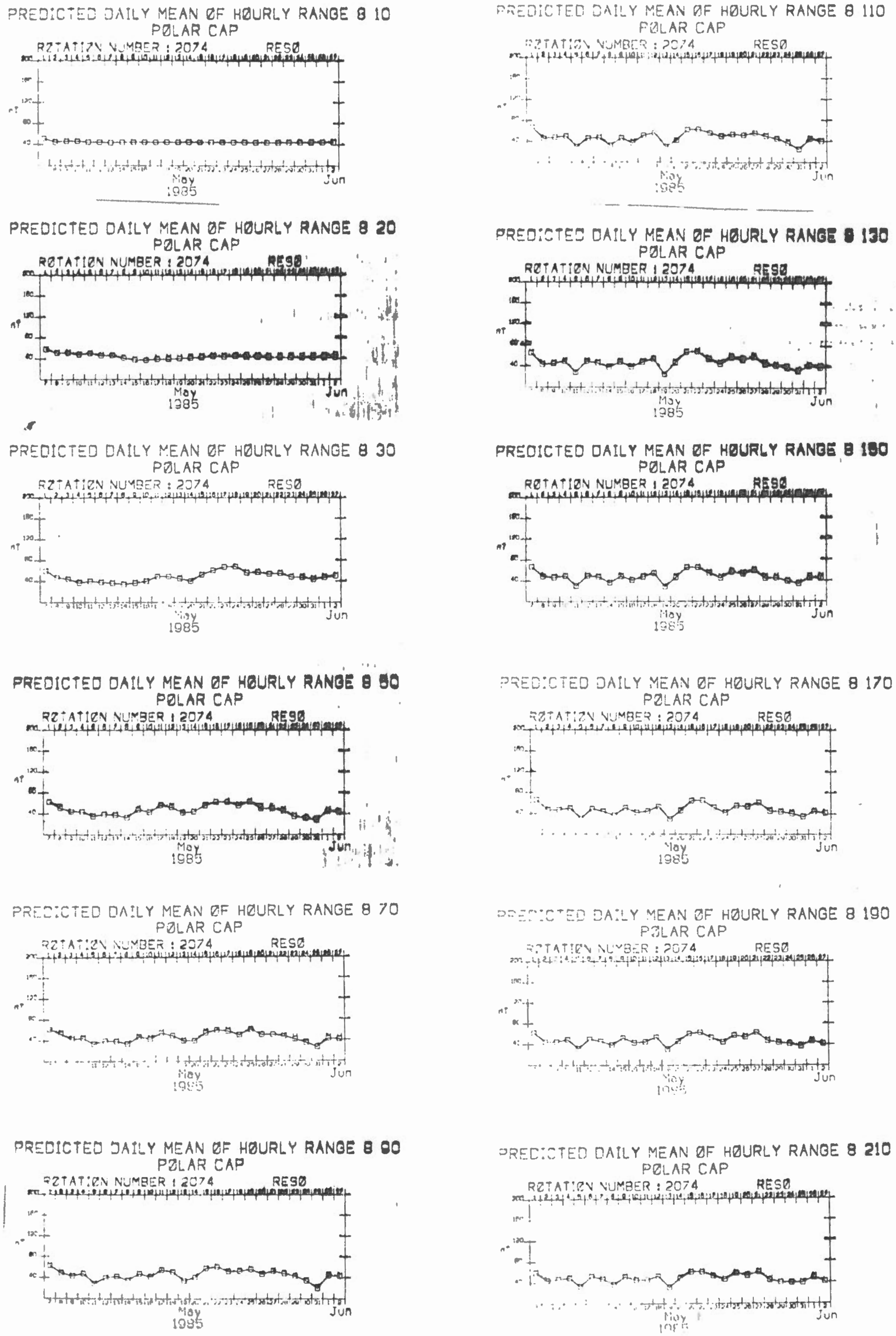

PREDICTED DAILY MEAN ØF HØURLY RANGE 8 10
PØLAR CAP
RØTATIØN NUMBER : 2074 RESØ
May 1985 Jun
PREDICTED DAILY MEAN ØF HØURLY RANGE 8 110
PØLAR CAP
RØTATIØN NUMBER : 2074 RESØ
May 1985 Jun
PREDICTED DAILY MEAN ØF HØURLY RANGE 8 20
PØLAR CAP
RØTATIØN NUMBER : 2074 RESØ
nT
May 1985 Jun
PREDICTED DAILY MEAN ØF HØURLY RANGE 8 130
PØLAR CAP
RØTATIØN NUMBER : 2074 RESØ
nT
May 1985 Jun
PREDICTED DAILY MEAN ØF HØURLY RANGE 8 30
PØLAR CAP
RØTATIØN NUMBER : 2074 RESØ
nT
May 1985 Jun
PREDICTED DAILY MEAN ØF HØURLY RANGE 8 150
PØLAR CAP
RØTATIØN NUMBER : 2074 RESØ
nT
May 1985 Jun
PREDICTED DAILY MEAN ØF HØURLY RANGE 8 50
PØLAR CAP
RØTATIØN NUMBER : 2074 RESØ
nT
May 1985 Jun
PREDICTED DAILY MEAN ØF HØURLY RANGE 8 170
PØLAR CAP
RØTATIØN NUMBER : 2074 RESØ
May 1985 Jun
PREDICTED DAILY MEAN ØF HØURLY RANGE 8 70
PØLAR CAP
RØTATIØN NUMBER : 2074 RESØ
nT
May 1985 Jun
PREDICTED DAILY MEAN ØF HØURLY RANGE 8 190
PØLAR CAP
RØTATIØN NUMBER : 2074 RESØ
nT
May Jun
PREDICTED DAILY MEAN ØF HØURLY RANGE 8 90
PØLAR CAP
RØTATIØN NUMBER : 2074 RESØ
May 1985 Jun
PREDICTED DAILY MEAN ØF HØURLY RANGE 8 210
PØLAR CAP
RØTATIØN NUMBER : 2074 RESØ
May Jun

FIG. 11

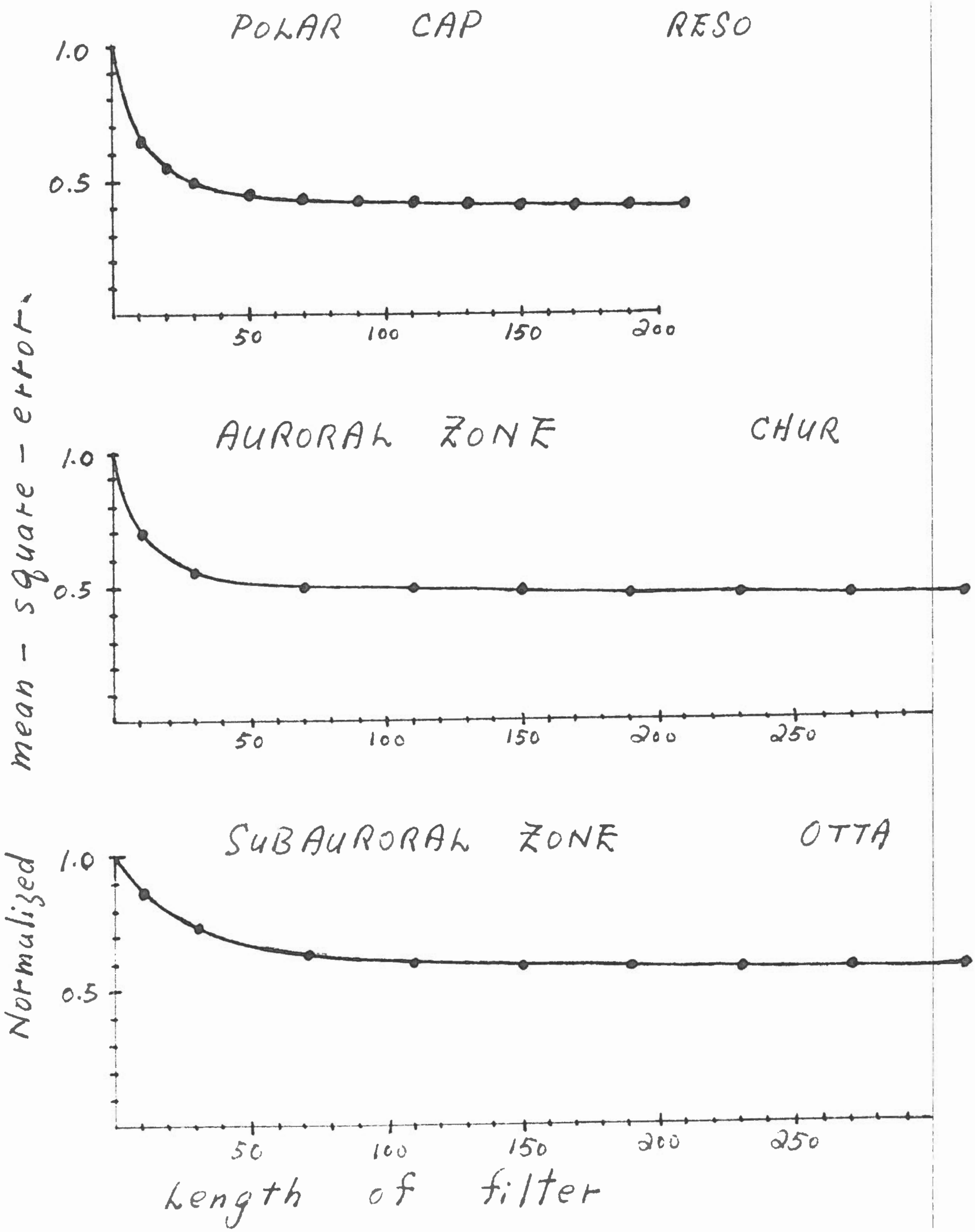

POLAR CAP
RESO
AURORAL ZONE
CHUR
SUBAURORAL ZONE
OTTA
Normalized mean - square - error
1.0
0.5
50
100
150
200
250
Length of filter

FIG. 12

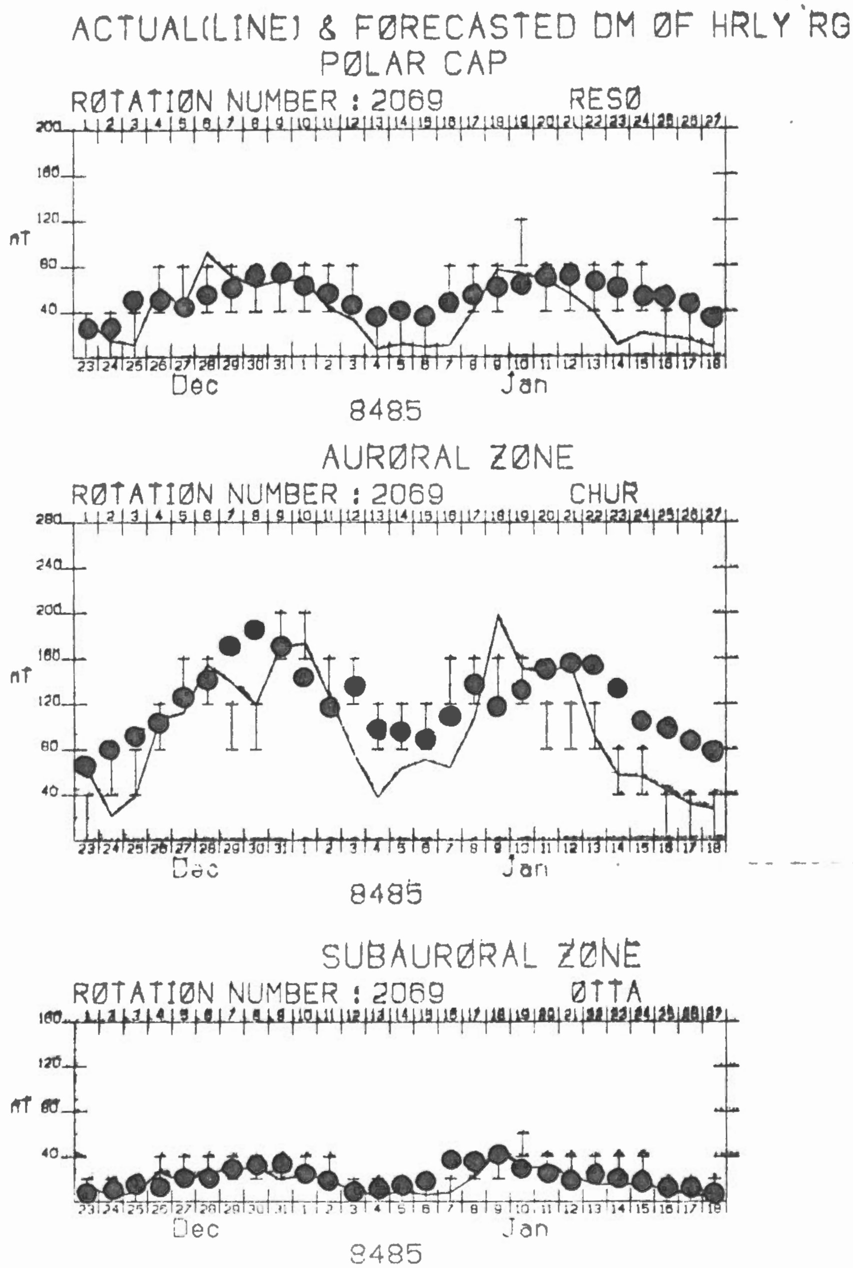

ACTUAL(LINE) & FØRECASTED DM ØF HRLY RG
PØLAR CAP
RØTATIØN NUMBER : 2069
RESØ
nT
Dec
Jan
8485
AURØRAL ZØNE
RØTATIØN NUMBER : 2069
CHUR
nT
Dec
Jan
8485
SUBAURØRAL ZØNE
RØTATIØN NUMBER : 2069
ØTTA
nT
Dec
Jan
8485

FIG. 13

MONTHLY MEAN SUNSPOT NUMBERS
January 1944 – October 1983

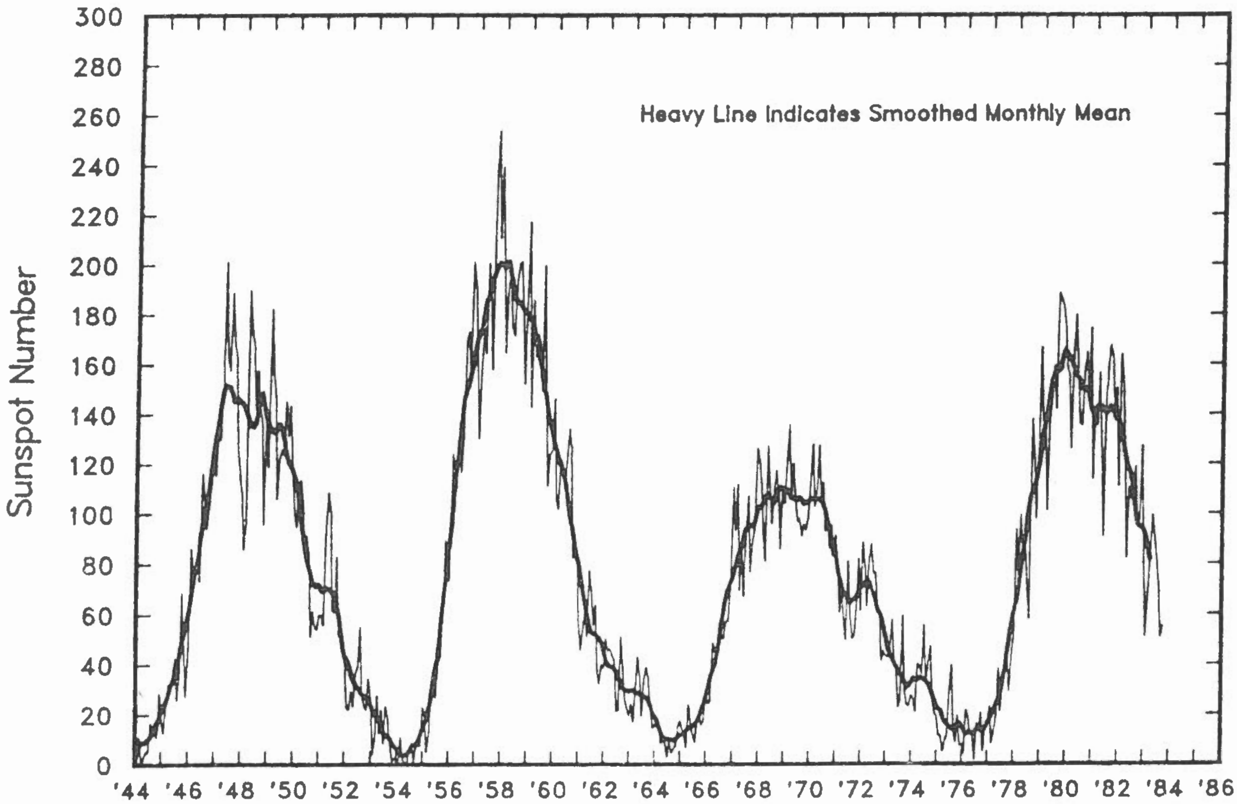


FIG. 14

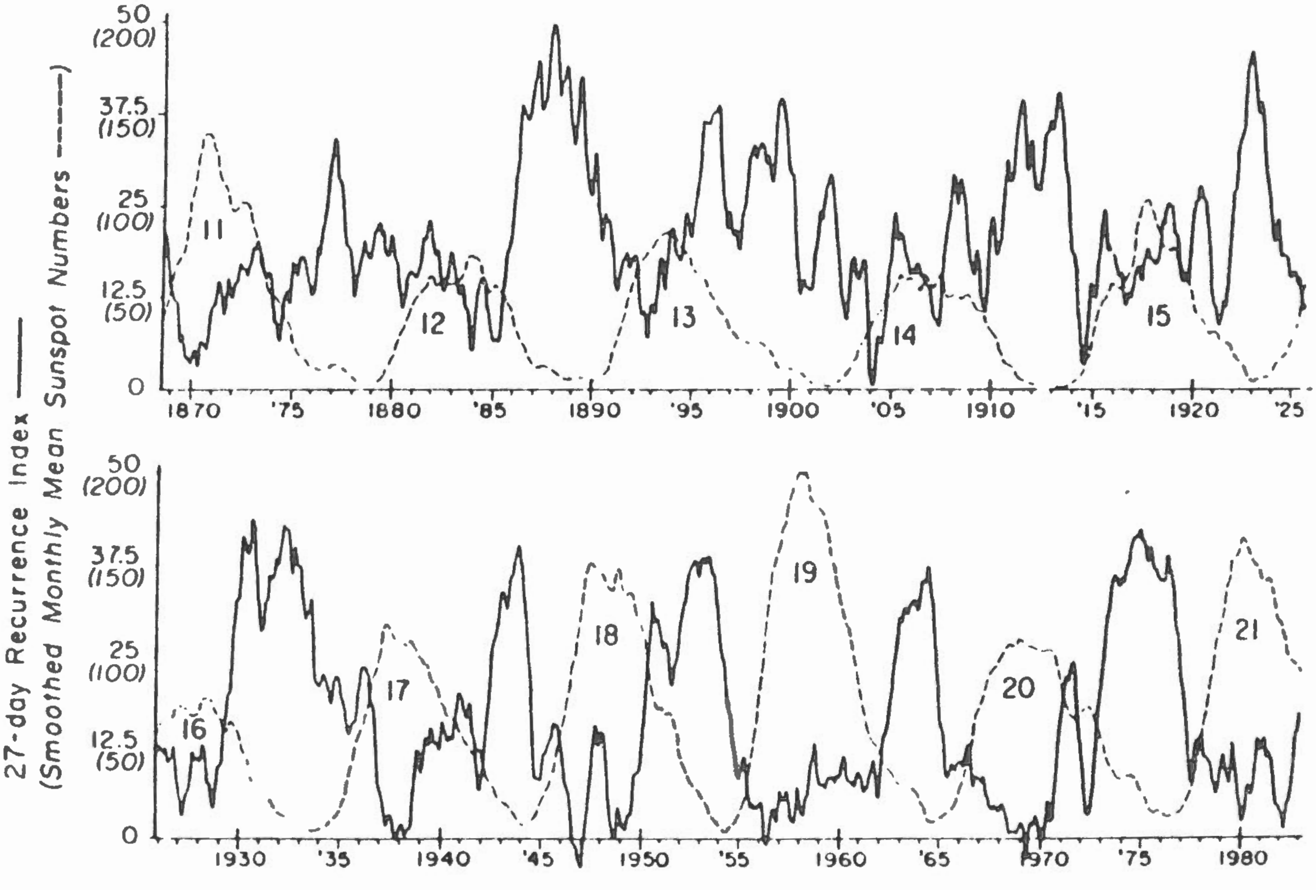

27-day Recurrence Index ——
(Smoothed Monthly Mean Sunspot Numbers - - - -)
50 (200)
37.5 (150)
25 (100)
12.5 (50)
0
1870 '75 1880 '85 1890 '95 1900 '05 1910 '15 1920 '25
11 12 13 14 15
1930 '35 1940 '45 1950 '55 1960 '65 1970 '75 1980
16 17 18 19 20 21

FIG. 15