

AD-A137 136

PREDICTION OF TOTAL ELECTRON CONTENT USING THE
INTERNATIONAL REFERENCE IONOSPHERE(U) AIR FORCE
GEOPHYSICS LAB HANSCOM AFB MA L F MCNAMARA 20 SEP 83

1/1

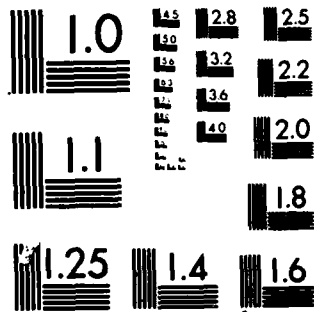
UNCLASSIFIED

AFGL-TR-83-0239

F/G 4/1

NL

END
DATE
FILMED
3 APR 84
DTIC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A



ADA 137136

Prediction of Total Electron Content Using the International Reference Ionosphere

LEO F. McNAMARA

20 September 1983

Approved for public release; distribution unlimited.

DTIC FILE COPY

SPACE PHYSICS DIVISION PROJECT 4643
AIR FORCE GEOPHYSICS LABORATORY
HANSCOM AFB, MASSACHUSETTS 01731

AIR FORCE SYSTEMS COMMAND, USAF

DTIC
ELECTR
S JAN 24 1984 D
E



84 01 23 038

This report has been reviewed by the ESD Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS).

This technical report has been reviewed and is approved for publication

FOR THE COMMANDER

H. Carlison
HERBERT C. CARLISON, Chief
Ionospheric Physics Division

Rita C. Bagalyn
RITA C. BAGALYN, Director
Space Physics Division

Qualified requestors may obtain additional copies from the Defense Technical Information Center. All others should apply to the National Technical Information Service.

If your address has changed, or if you wish to be removed from the mailing list, or if the addressee is no longer employed by your organization, please notify AFGL/DAA, Hanscom AFB, MA 01731. This will assist us in maintaining a current mailing list.

Do not return copies of this report unless contractual obligations or notices on a specific document requires that it be returned.

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFGL-TR-83-0239	2. GOVT ACCESSION NO. AD-A137 136	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) PREDICTION OF TOTAL ELECTRON CONTENT USING THE INTERNATIONAL REFERENCE IONOSPHERE	5. TYPE OF REPORT & PERIOD COVERED Scientific. Final	
	6. PERFORMING ORG. REPORT NUMBER ERP, No. 853	
7. AUTHOR(s) Leo F. McNamara *	8. CONTRACT OR GRANT NUMBER(s)	
9. PERFORMING ORGANIZATION NAME AND ADDRESS Air Force Geophysics Laboratory (PHY) Hanscom AFB Massachusetts 01731	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 62101F 46430901	
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Geophysics Laboratory (PHY) Hanscom AFB Massachusetts 01731	12. REPORT DATE 20 September 1983	
	13. NUMBER OF PAGES 43	
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report) Unclassified	
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE	
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES * NRC/AFSC Senior Research Associate on leave from the Australian Ionospheric Prediction Service, P. O. Box 702, Darlinghurst 2010, Australia		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Total electron content prediction International reference ionosphere TEC prediction by IRI		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The International Reference Ionosphere (IRI) is a model of the ionosphere, based on experimental data, that has been proposed as a standard ionospheric model. As such, it should be tested extensively to determine its range of validity. One of the ways in which the electron density profile given by the IRI, especially above the peak of the F layer, can be tested is to compare calculated and observed values of total electron content (TEC). We have therefore studied the discrepancies between calculated and observed values of TEC recorded at 15 stations covering a wide range of longitudes and latitudes, mainly in the		

DD FORM 1473 EDITION OF 1 NOV 65 IS OBSOLETE
1 JAN 73

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

20. (Contd)

→ northern hemisphere, and mainly for high levels of solar activity. We have found that the IRI produces reasonably accurate values of TEC at mid- and high-latitudes, but that it greatly underestimates the daytime values of TEC at low latitudes. We conclude therefore that the daytime electron density profile given by the IRI is reasonably accurate at mid- and high-latitudes; at least above the peak of the F2 layer. The situation at low latitudes clearly requires more work, and we have suggested two possible lines of study. The generally low discrepancies at night indicate that the nighttime electron density profiles given by the IRI correspond fairly closely to the actual profiles.



Unclassified

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

Accession For	
NTIS GRA&I	<input checked="" type="checkbox"/>
DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A-1	



Preface

I would like to thank R. Leitinger, J. A. Klobuchar, and D. N. Anderson for many useful discussions throughout the course of this study. The large amount of data organization would not have been possible without the cheerful support of Patricia Doherty. A large fraction of the TEC and foF2 data was supplied by the World Data Center A for Solar Terrestrial Physics, Boulder, Colorado.

Contents

1.	INTRODUCTION	9
2.	METHOD OF ANALYSIS	11
3.	"A" STATIONS	13
3.1	Hamilton/Wallops Island	13
3.2	Goose Bay/St. Johns	16
4.	"B" STATIONS	16
4.1	Narssarssuaq/Goose Bay	16
4.2	Manila/Manila	21
4.3	Lunping/Chung Li	21
4.4	Palehua/Maui	21
5.	"C" STATIONS	26
5.1	Ascension Island	26
5.2	Osan, Korea	26
5.3	Ramey	26
5.4	Athens	30
5.5	La Posta	30
5.6	Patrick	30
5.7	Shemya	30
5.8	Boulder	30
5.9	Anchorage	36
6.	DISCUSSION OF RESULTS	36
6.1	Mid-Latitude Stations	36
6.2	High-Latitude Stations	38
6.3	Low-Latitude Stations	38
6.4	Nighttime Discrepancies	39
7.	CONCLUSIONS	42
	REFERENCES	43

Illustrations

1. The IRI Electron Density Profile	10
2. Predicted and Observed Values of TEC at Hamilton for Four Months With Low Solar Activity (1976)	14
3. Predicted and Observed Values of TEC at Hamilton for Four Months With High Solar Activity ($R = 100$)	15
4. Predicted and Observed Values of TEC at Goose Bay for Four Months With Low Solar Activity (1975, 1976)	17
5. Predicted and Observed Values of TEC at Goose Bay for Four Months With High Solar Activity ($R = 100$)	18
6. Predicted and Observed Values of TEC at Narssarssuaq for Four Months With Low Solar Activity (1974)	19
7. Predicted and Observed Values of TEC at Narssarssuaq for Four Months With Medium Solar Activity (1972)	20
8. Predicted and Observed Values of TEC at Manila for Four Months With High Solar Activity (1981, 1982)	22
9. Predicted and Observed Values of foF2 at Manila for Four Months With High Solar Activity (1981, 1982)	23
10. Predicted and Observed Values of TEC at Lunping (Taiwan) for Four Months With High Solar Activity (1981, 1982, 1983)	24
11. Predicted and Observed Values of TEC at Palehua (Hawaii) for Four Months With High Solar Activity (1981)	25
12. Predicted and Observed Values of TEC at Ascension Island for Four Months With High Solar Activity (1980, 1981)	27
13. Predicted and Observed Values of TEC at Osan (Korea) for Four Months With High Solar Activity (1981)	28
14. Predicted and Observed Values of TEC at Ramey (Puerto Rico) for Four Months With High Solar Activity (1981)	29
15. Predicted and Observed Values of TEC at Athens for Four Months With High Solar Activity (1981, 1982)	31
16. Predicted and Observed Values of TEC at La Posta (California) for Four Months With High Solar Activity (1981)	32
17. Predicted and Observed Values of TEC at Patrick AFB (Florida) for Four Months With High Solar Activity (1981)	33
18. Predicted and Observed Values of TEC at Shemya (Alaska) for Four Months With High Solar Activity (1978, 1979)	34
19. Predicted and Observed Values of TEC at Boulder for Four Months With High Solar Activity (1981)	35
20. Predicted and Observed Values of TEC at Anchorage for Four Months With High Solar Activity (1980, 1981, 1982)	37
21. Calculated and Observed Values of TEC for January at a Station at 13° Dip, for $R = 137$	40
22. Electron Density Profiles at Noon in January, $R = 137$, for a Station at 13° Dip, as Given by the Anderson and IRI-BENT Programs	41

Tables

1. Geographic Locations of the Observing Stations, Sub-ionospheric Points and Ionosonde Stations for the 15 Cases Considered

12

Prediction of Total Electron Content Using the International Reference Ionosphere

1. INTRODUCTION

The International Reference Ionosphere (IRI) is an empirical model of the ionosphere based on experimental observations. It is the outcome of work by the URSI Working Group G4, which is identical to the COSPAR task group on the International Reference Ionosphere. The goals and status of the IRI have been discussed by Rawer et al.¹ The aim of the IRI is to establish a compendium of height profiles through the ionosphere for the four main parameters, namely plasma density, temperature of ions and electrons, and ion composition. These parameters are generated from a descriptive model containing reliable data that can be used to obtain average profiles.

The IRI working group is well aware that the present model is inadequate in some areas and has encouraged tests of the model's validity. We describe here a test of the model's ability to reproduce observations of total electron content (TEC) over a wide range of conditions. If the tests are successful, they will confirm the validity of the electron density profile $N(h)$, especially in the region above the peak of the F2 layer which contains approximately 2/3 of the TEC.

(Received for publication 15 September 1983)

1. Rawer, K. (1978) Goals and status of the International Reference Ionosphere, Res. Geophys. Space Phys. 16:77.

Rawer² has described the construction of the IRI $N(h)$ profile, which is illustrated in Figure 1. The key value is the peak electron density NMF2, which is derived using the CCIR model.³ The bottomside profiles are mainly based upon ionograms reduced to true height profiles. The peak height HMF2 is obtained from the parameter M3000F2 using an empirical relationship due to Bilitza.⁴ The topside profile shape is deduced from a summary of topside ionosonde measurements (mainly ALOCETTE) as given by Bent and Llewellyn.⁵ However, because of limitations in the presentation of these data, the IRI uses a modified form of the original data.²

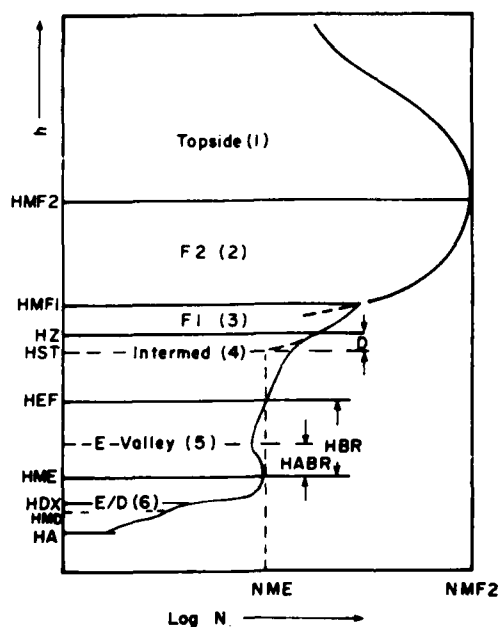


Figure 1. The IRI Electron Density Profile

2. Rawer, K. (1981) Introduction to IRI 1979, In "International Reference Ionosphere - IRI 79", J. V. Lincoln and R. O. Conkright (Eds.) Report UAG-82, World Data Center A for Solar Terrestrial Physics, Boulder, Colorado.
3. CCIR (1974) Atlas of Ionospheric Characteristics, CCIR Report 340-2, International Union for Telecommunications, Geneva.
4. Bilitza, D. (1977) Modell zur Darstellung der Höhe des F2 - Maximums mit Hilfe des M-3000 - Wertes des CCIR, Kleinheubacher Ber. 20:4.
5. Bent, R. B., and Llewellyn, S. K. (1970) Description of the 1965-71 Ionospheric Model Used in the Definitive Systems (DODS), DBA-Systems, Melbourne, FL.

A test of the IRI, as far as its ability to calculate TEC is concerned, has been published by McNamara and Wilkinson.⁶ These authors found that at 31° S, the IRI yielded discrepancies in TEC sometimes exceeding 30%, but usually less than 20%. We present here a much more extensive analysis based on data from 15 stations, covering a range of magnetic dip angles 14 to 77°.

2. METHOD OF ANALYSIS

The IRI profiles are essentially monthly median profiles and are referenced to monthly median values of foF2 and M(3000)F2. These parameters are calculated using the CCIR coefficients for a given month and linear interpolation in the smoothed sunspot number R .[†] Consequently the most appropriate comparison of calculated values of TEC is with observed values which have been linearly related to R . However, this necessitates a long sequence of data covering a solar cycle and only a few such data sets are available.

Since it is the IRI N(h) profile which is of most interest to us here, we would like to test it under conditions for which it is the major source of error. The other main potential source of error is in the calculation of foF2, so it is advantageous to use observed values of foF2 at the sub-ionospheric point wherever possible. Again, the values of foF2 should be linearly related to R .

We have, therefore, adopted a three-pronged approach in which we first of all aim for the ideal test and then successively lift the restrictions. We consider three types of stations/data:

- (1) "A" Stations are those for which a set of TEC data and a set of observed foF2 data are available for a solar cycle,
- (2) "B" stations are those for which corresponding TEC and observed foF2 data are available on a monthly basis,
- (3) "C" stations are those for which the CCIR method must be used to calculate foF2.

Table 1 lists all the stations considered, arranged in increasing order of dip angle. For each station we have considered where possible, data for March, June, September, and December at low and high levels of solar activity. When particular years must be used, we have used 1976 ($R \sim 13$) and 1981 ($R \sim 140$) if the corresponding data were available. The exact values of R are not important.

6. McNamara, L. F., and Wilkinson, P. J. (1983) Prediction of total electron content using the International Reference Ionosphere, *J. Atmos. Terr. Phys.* 45:169.

[†] For convenience in this report, we shall use the symbol R instead of the usual R_{12} .

Table 1. Geographic Locations of the Observing Stations, Sub-ionospheric Points and Ionosonde Stations for the 15 Cases Considered

Station				S. I. Point			Ionosonde		
Class	Name	Lat.	Long.	Dist.	Lat.	Long.	Name	Lat.	Long.
B.	Manila	14.6	121.1	14.5	13.6	121.2	Manila	14.6	121.1
C.	Ascension Island	-8.0	345.6	30.4	-7.4	345.6			
B.	Lunping	25.2	122.2	35.2	23.0	121.8	Chung Li	25.9	121.2
B.	Palehua	20.7	203.7	38.7	19.8	202.6	Maui	20.3	203.5
C.	Osan	37.1	127.0	51.0	34.0	127.4			
C.	Ramey	18.5	292.8	51.3	17.1	292.6			
C.	Athens	38.0	23.6	54.5	34.1	18.4			
C.	La Posta	32.5	242.9	58.0	30.0	245.0			
C.	Patrick	28.2	279.4	60.0	26.3	280.4			
C.	Shemya	52.5	174.1	63.0	46.8	181.7			
C.	Boulder	40.0	254.7	68.3	36.3	259.6			
A.	Hamilton	42.6	289.2	72.9	38.7	289.3	Wallops I.	37.9	284.5
C.	Anchorage	61.2	210.2	73.7	52.0	224.0			
A.	Goose Bay	53.5	299.5	76.9	47.5	297.8	St. Johns	47.6	307.3
B.	Narsarsuaq	61.2	314.6	77.5	53.1	307.8	Goose Bay	53.3	299.5

The IRI has been made available as a FORTRAN computer program by World Data Center A for Solar Terrestrial Physics.⁷ We have modified the WDC-A version to permit the optional use of the Chiu⁸ model of foF2 and HMF2 and of the original Bent topside profile above HMF2.⁹ Listings of the Chiu model are given by Lincoln and Conkright.⁷ The modifications to include the original Bent topside profile were taken from the program SLANTEC¹⁰ with some extra coding required because of different systems of units.

It would be expected that, in general, the IRI would yield values of TEC somewhat less than the observed values, since the IRI sets the electron density to zero above 1000 km. The TEC observations were obtained using the Faraday rotation technique, which yields the TEC out to about 2000 km.¹¹ Tests using the Bent ionospheric model indicate that the altitude range 1000 to 2000 km contributes $\leq 5\%$ of the TEC up to 2000 km. This discrepancy would not be noticeable in the present context.

(Due to the large number of references cited above, they will not be listed here. See References, page 43.)

3. "A" STATIONS

These are the stations for which a long sequence of TEC data covering a solar cycle is available, in conjunction with a sequence of foF2 data at the sub-ionospheric point, also covering a solar cycle. There are in fact only two such stations, Hamilton and Goose Bay.

For each of these stations, we have correlated the observed monthly mean values of TEC at each hour with the smoothed sunspot number R. The least squares fit regression lines have then been used to determine the values of TEC corresponding to R = 0 and R = 100. A similar technique was applied to foF2 at the sub-ionospheric point.

It was found that the values of TEC for R = 0 were unreliable at night when the values were very low. Consequently, we have been forced to use actual observations for low solar activity in lieu of R = 0 results.

3.1 Hamilton/Wallops Island

The Hamilton TEC that was used covered the period 1967 to 1980. The sub-ionospheric point lies very close to Wallops Island (see Table 1) for which foF2 covering the period 1975 to 1981 were used. The correlation coefficients of TEC and foF2 with R were usually ~ 0.95.

Figures 2 and 3 illustrate the observed and calculated diurnal variations of TEC for Hamilton at solar minimum (1976, R = 13) and maximum (R = 100 exactly), for March, June, September and December.[†]

It can be seen that there are no major discrepancies between the observed values of TEC and those calculated using the IRI. [Note that for 1976, Hamilton must be considered a "B" station.] In general, the discrepancies for R = 100 are least when the R = 100 values of foF2 at Wallops Island are used. They are greatest in December, R = 100, between about 08-12 LT. The figures also include the results for a profile in which the IRI topside profile is replaced by the Bent profile.⁹

[†] In all diagrams, the TEC is plotted as a function of local time in units of

10^{15} el m⁻², and the following code is used for the data points:

- x Observed monthly mean value (OBS)
- Value given by the original IRI (IRI)
- o Value given by the IRI bottomside and Bent topside models. This may be the value obtained using the CCIR value of foF2 (IRI-BENT) or using the observed value of foF2 at the sub-ionospheric point (IRI-BENT-OBS)
- + Value given by the IRI using the observed value of foF2 (IRI-OBS)

Where necessary, the data points for the predicted values have been slightly offset from the corresponding hour.

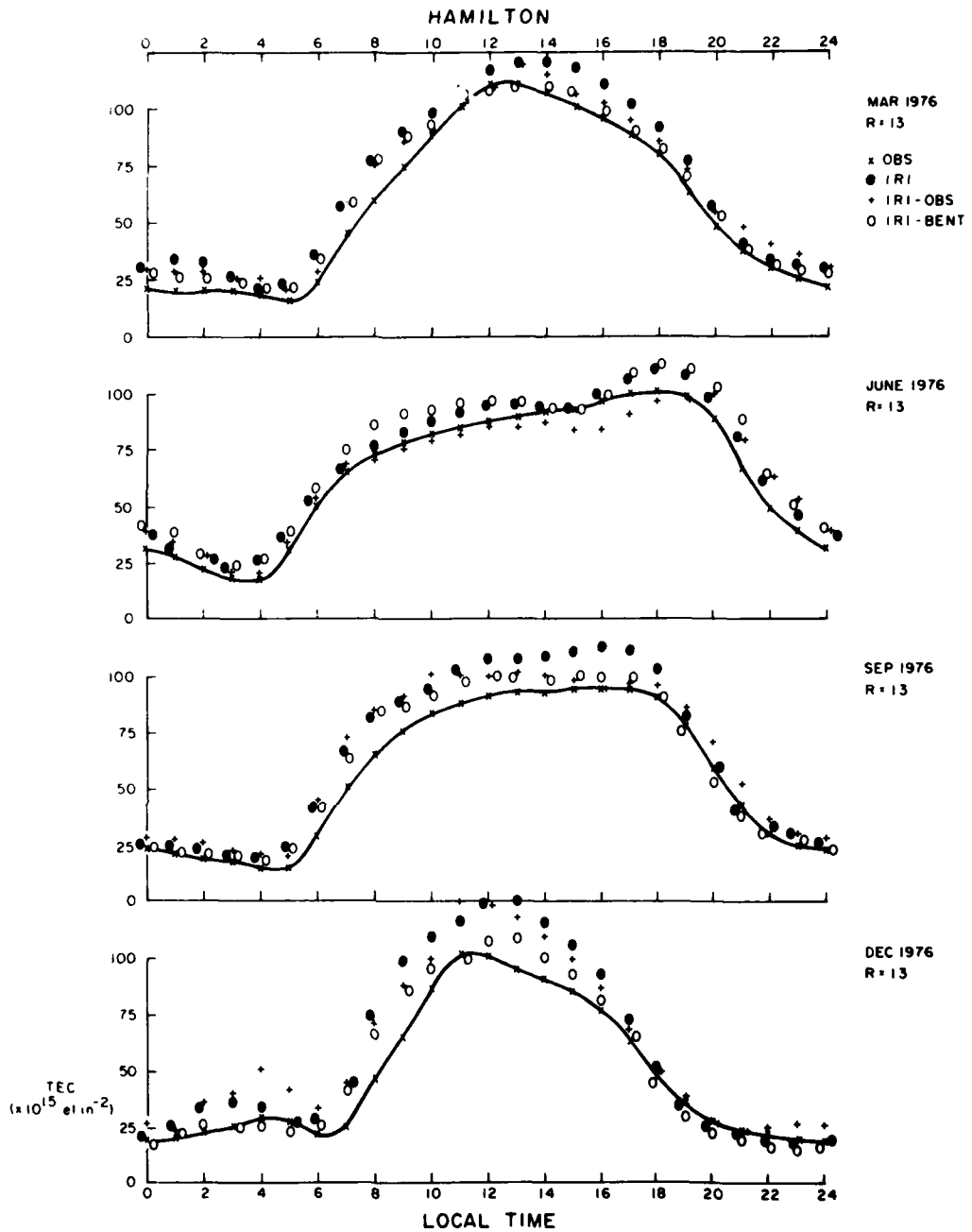


Figure 2. Predicted and Observed Values of TEC at Hamilton for Four Months With Low Solar Activity (1976). The TEC is in units of 10^{15} el m $^{-2}$. The key to the plotted points is given as a footnote in Section 3.1

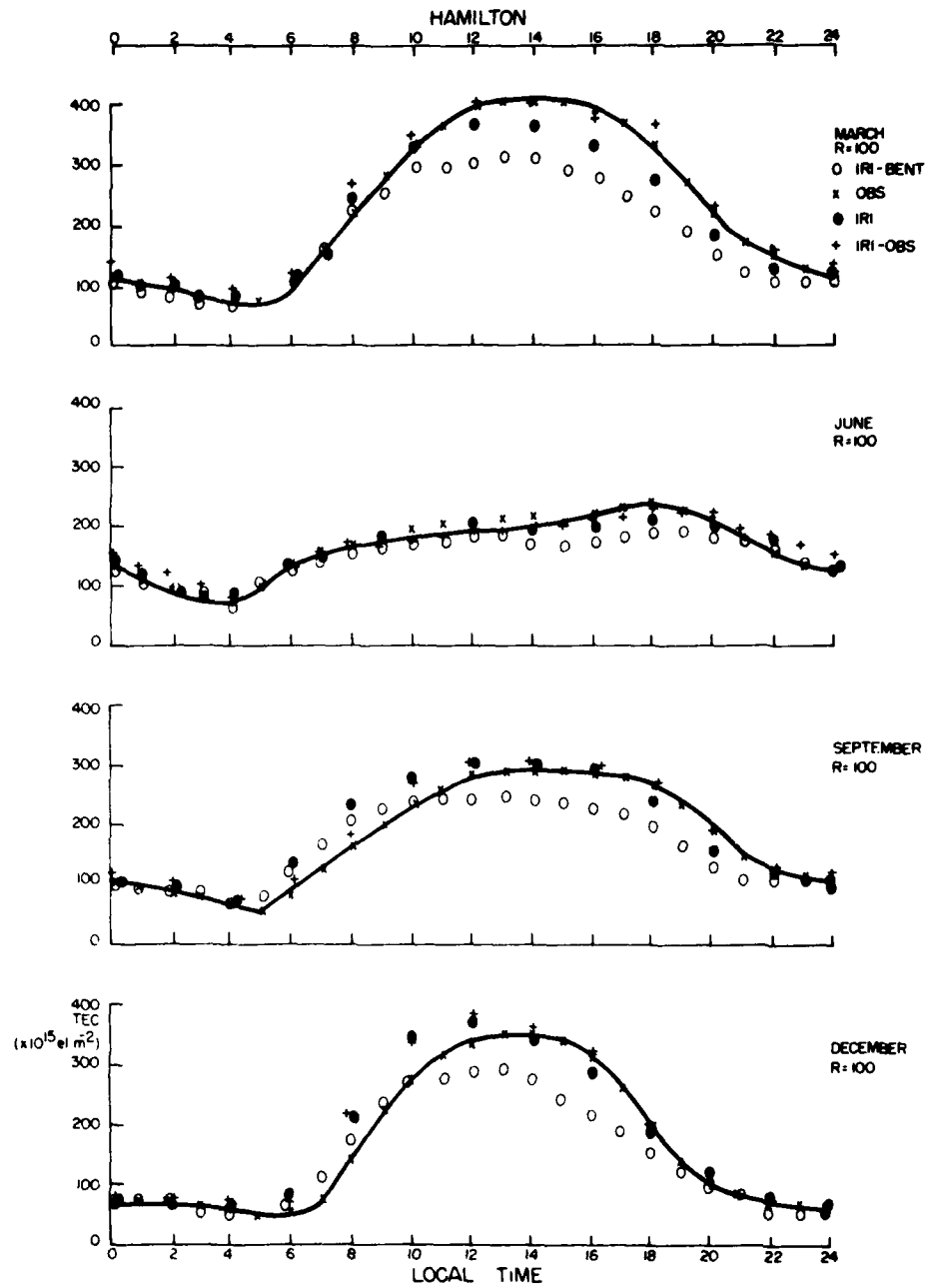


Figure 3. Predicted and Observed Values of TEC at Hamilton for Four Months With High Solar Activity (R = 100)

3.2 Goose Bay/St. Johns

The Goose Bay TEC data covered the period 1973 to 1980, while the St. Johns' foF2 data covered the period 1970 to 1978. Figures 4 and 5 show the calculated and observed diurnal variations of TEC for Goose Bay for solar minimum ($R \sim 13$) and solar maximum ($R = 100$) respectively. The greatest discrepancies occur for December, $R = 100$, between about 08 and 12 LT (as with Hamilton). The accuracy of the CCIR predictions of foF2 for St. Johns is such that the use of "observed" $R = 100$ values of foF2 does not lead to a significant reduction in the discrepancies (Figure 5).

For the low solar activity data, Goose Bay may be considered to be a "B" station and comparisons made using the monthly median values of foF2 observed at St. Johns. Figure 4 shows that when this is done, the discrepancies between the observed and predicted values tend to increase. This is possibly because St. Johns is not quite at the sub-ionospheric point for Goose Bay, but it is also possible that the better results given using the predicted values of foF2 are the result of fortuitous cancellation of errors in foF2 and in the N(h) profile.

4. "B" STATIONS

"B" stations are those for which corresponding values of TEC and foF2 at the sub-ionospheric point are available, but the data do not cover a solar cycle. There are four such stations, Manila, Lunning (Taiwan), Palehua, and Narssarssuaq, which have sub-ionospheric points near the ionospheric stations at Manila, Chung Li, and Goose Bay (see Table 1). We consider Narssarssuaq first because it causes the least trouble.

4.1 Narssarssuaq/Goose Bay

Narssarssuaq data are available for only 1972-1974, so we consider data for "low" activity (1974, $R \sim 30$, Figure 6) and "medium" activity (1972, $R = \sim 60$, Figure 7). Figure 6 and 7 show that the values of TEC given by the IRI are quite accurate in March, April, June and September, especially when the observed Goose Bay foF2 values are introduced. There is a tendency for the diurnal variations of the TEC based on the observed values of foF2 to be somewhat irregular, corresponding to irregular variations in foF2 due to the low sample sizes and the complexities of the Goose Bay ionograms. A discrepancy between the observed and calculated values of TEC remains for December in both 1972 and 1974, between 08 and 14 LT, even when the observed foF2 values are used. This indicates an error in the N(h) profile given by the IRI.

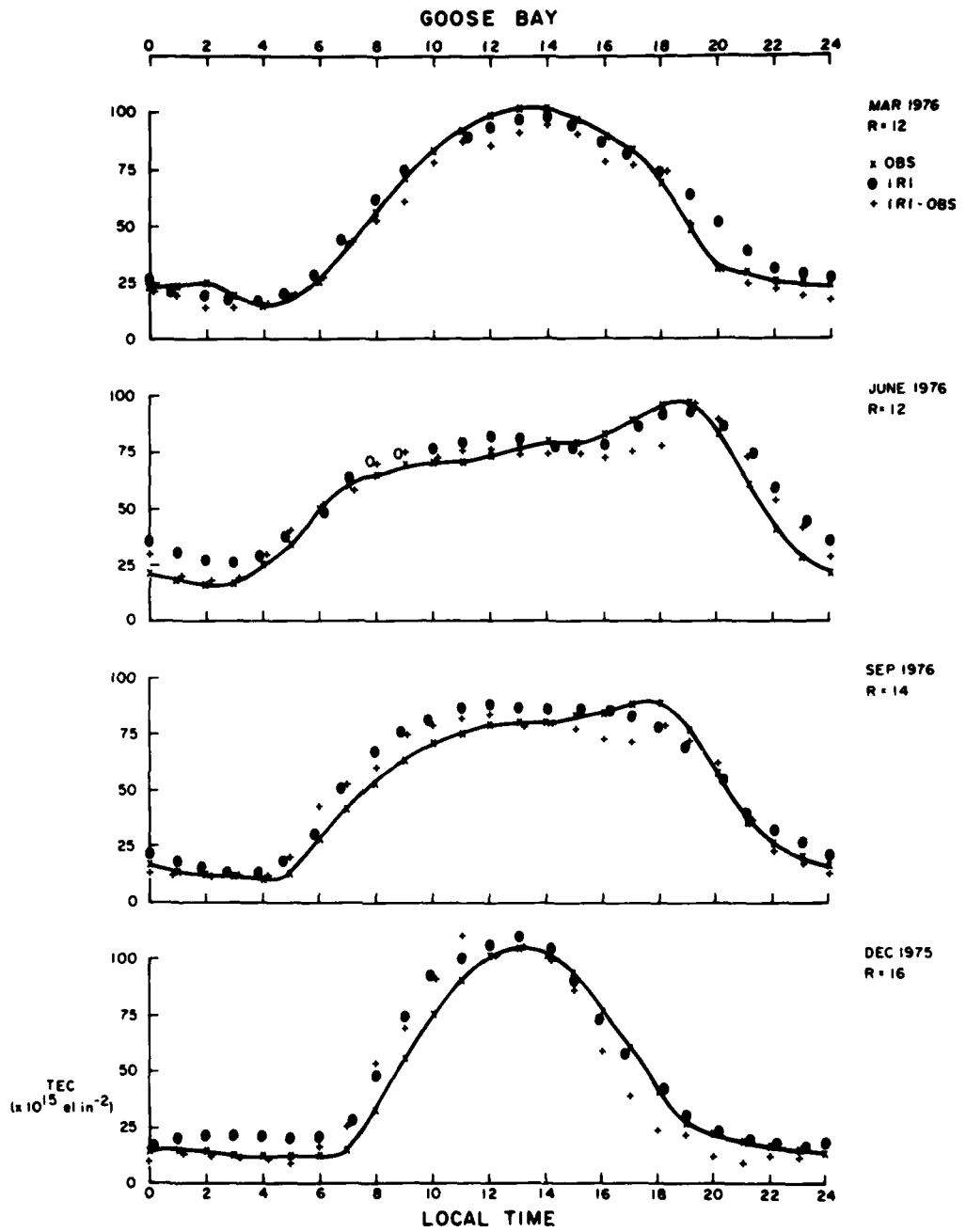


Figure 4. Predicted and Observed Values of TEC at Goose Bay for Four Months With Low Solar Activity (1975, 1976)

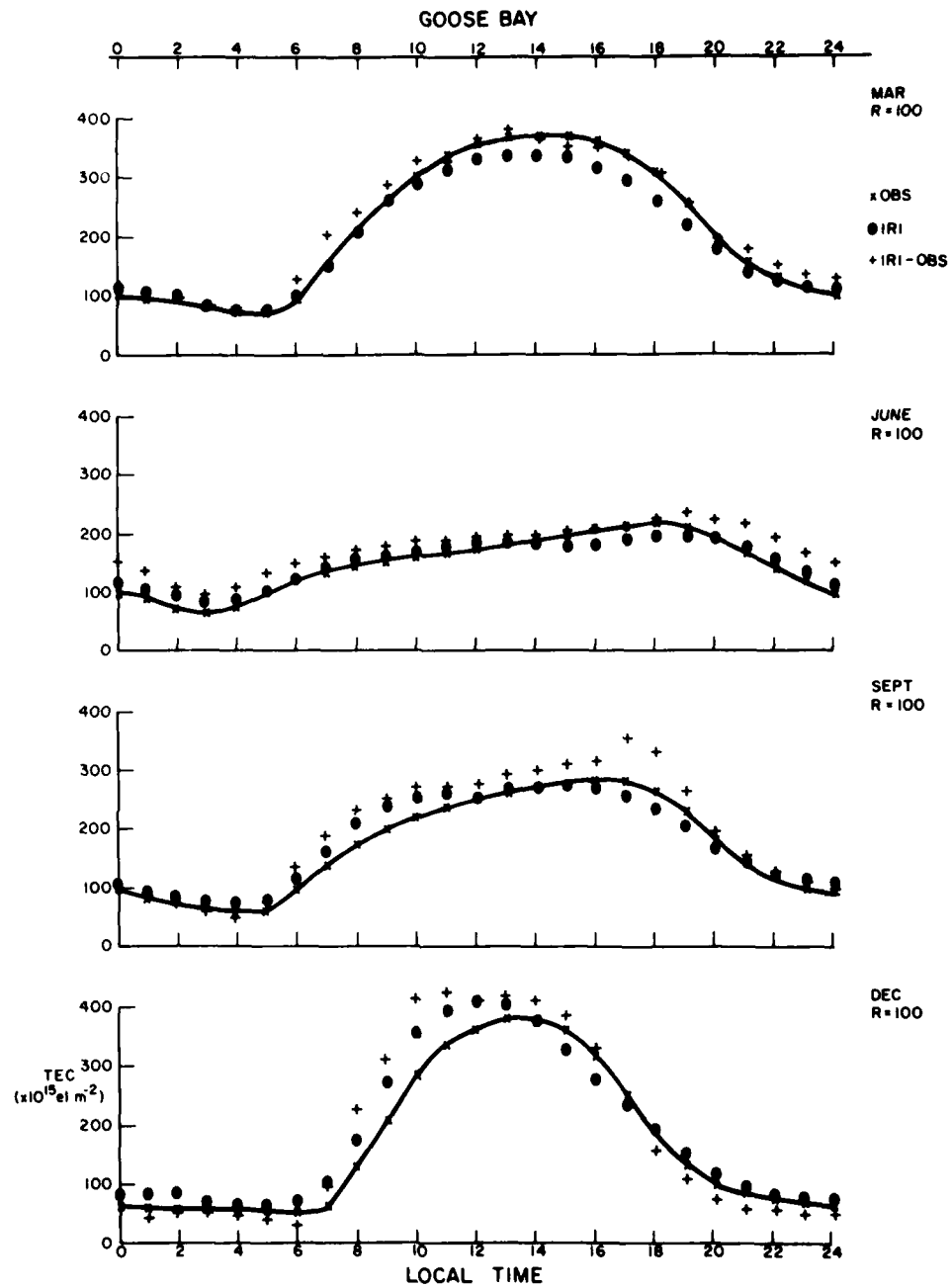


Figure 5. Predicted and Observed Values of TEC at Goose Bay for Four Months With High Solar Activity ($R = 100$)

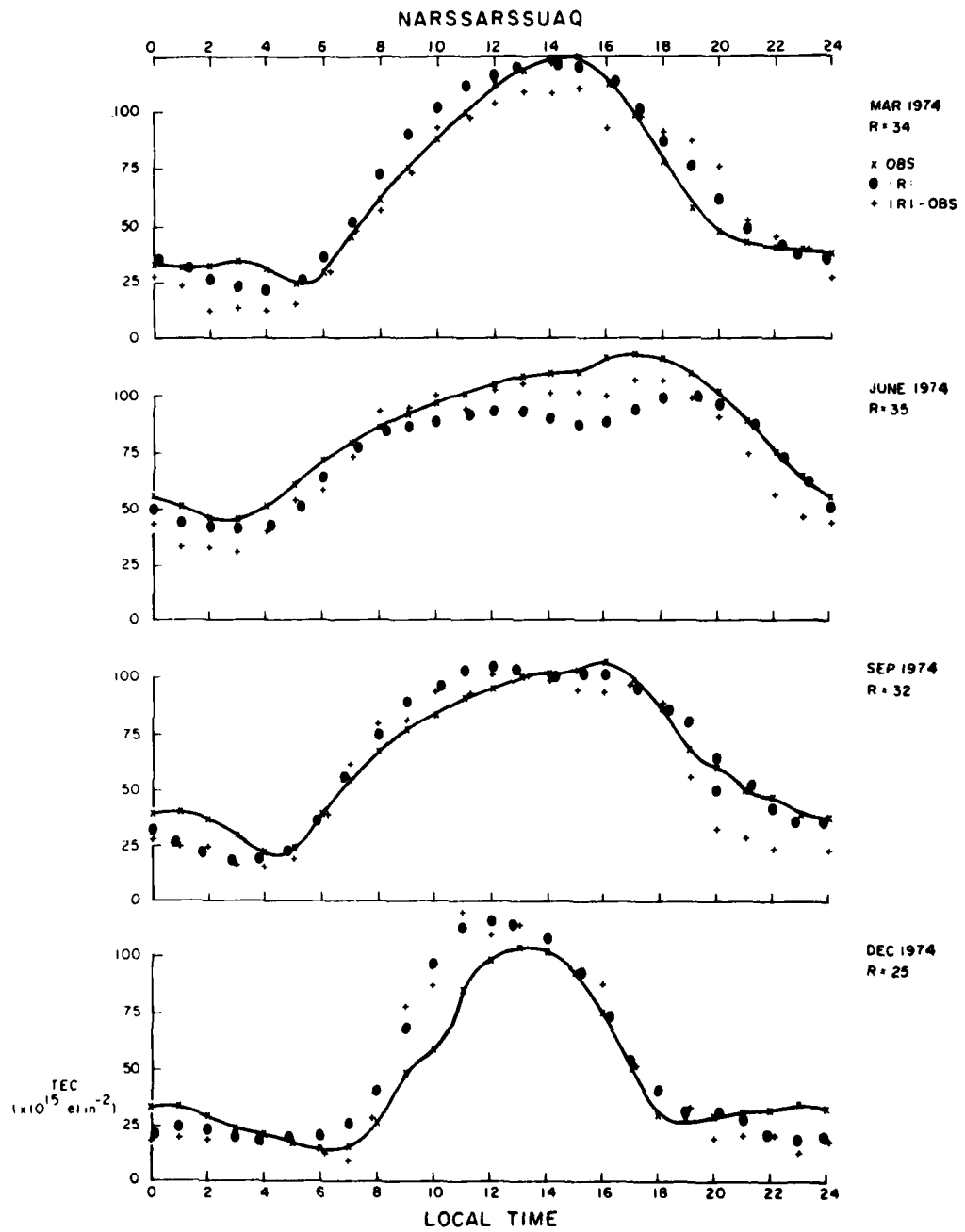


Figure 6. Predicted and Observed Values of TEC at Narssarssuaq for Four Months With Low Solar Activity (1974)

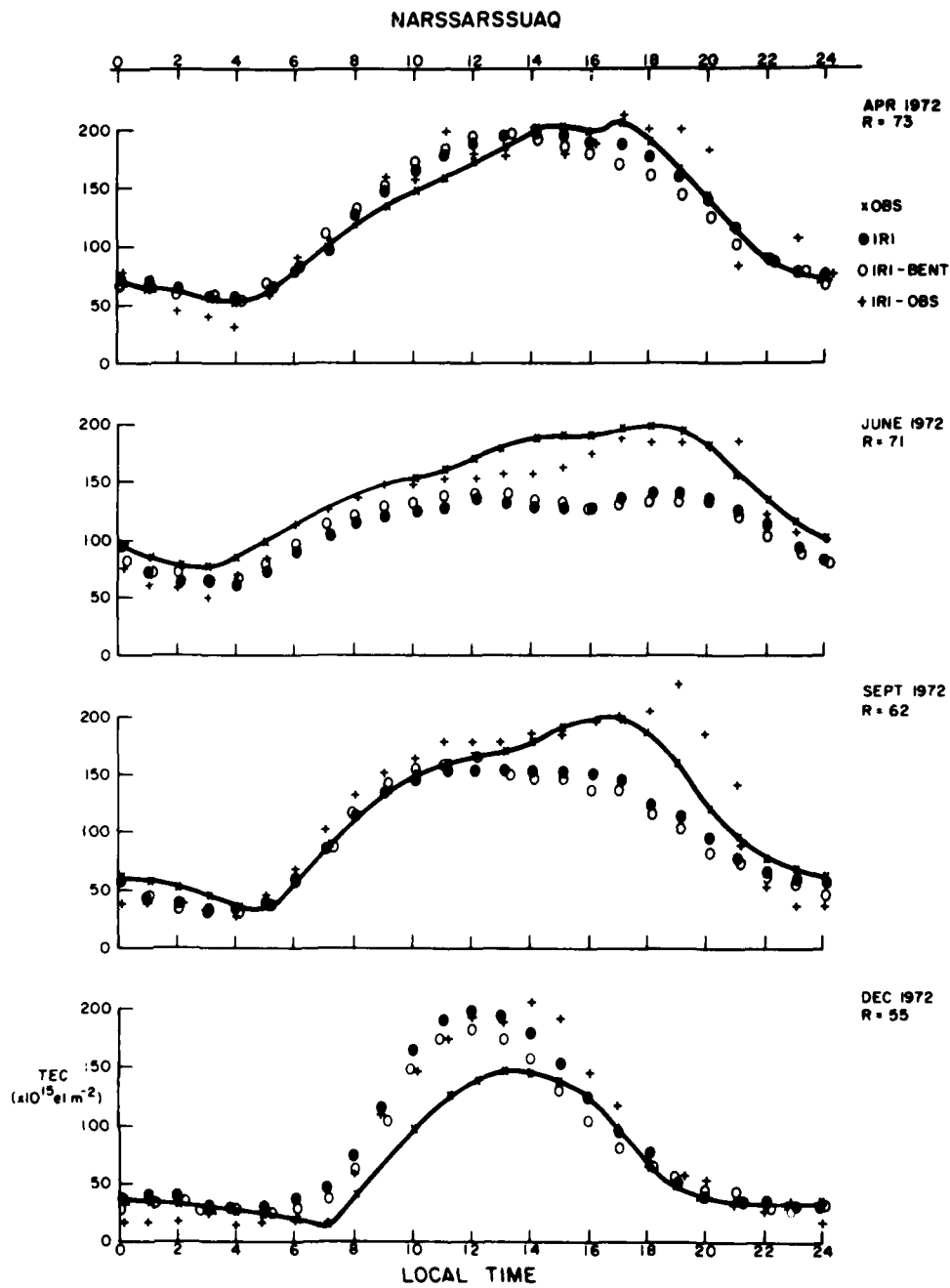


Figure 7. Predicted and Observed Values of TEC at Narssarssuaq for Four Months With Medium Solar Activity (1972)

4.2 Manila/Manila

It is in the calculation of the Manila TEC that we encounter the first major discrepancies between the calculated and observed values of TEC. Manila TEC data were available for 1980-1982, apart from missing months. Figure 8 shows the observed and predicted values of TEC for April 1982 ($R = 124$), June 1981 ($R = 155$), October 1981 ($R = 142$), and December 1981 ($R = 138$). (March and September data were not available.)

In general, the IRI predicts daytime values of TEC which are only about one-half of the observed values, in all months. The errors at night are somewhat smaller. The source of the error does not lie in the prediction of foF2, since as Figure 9 shows, the error in the predicted foF2 is typically only about 10%. Use of the original Bent profiles⁹ improves the situation but still leads to prediction errors reaching $300 \times 10^{15} \text{ el m}^{-2}$ and incorrect diurnal variations.

4.3 Luning/Chung Li

The Luning TEC data were available for 1980-March 1983, with some missing months. We have compared the predicted and observed values of TEC for March 1980 ($R = 80$), June 1981 ($R = 142$), September 1982 ($R = 109$), and December 1981 ($R = 138$).

Figure 10 shows that, as with Manila, the IRI greatly underestimates the TEC in some months, that the prediction of foF2 is not the problem, and that the use of the Bent topside profile leads to more accurate results. However, the discrepancy between the predicted and observed TEC values still exceeds $300 \times 10^{15} \text{ el m}^{-2}$ during the day in September and December.

4.4 Palehua/Maui

The Palehua TEC data were available for 1980-1982 and we have compared the predicted and observed TEC values for March, June, September, and December ($R = 140$). Figure 11 shows that Palehua follows Luning and Manila in the way the IRI greatly underestimates the TEC during the day during some months. The discrepancy is least for June, when it is of the order of $80 \times 10^{15} \text{ el m}^{-2}$ or about 15%. The daytime discrepancies remain essentially unchanged when Maui observations of foF2 are used. However, the discrepancies at night tend to decrease.

Use of the original Bent profiles above the peak of the layer yields values in better agreement with the observations, but large discrepancies still remain in December. The calculated diurnal variation agrees well with the observations in September, but not in the other months.

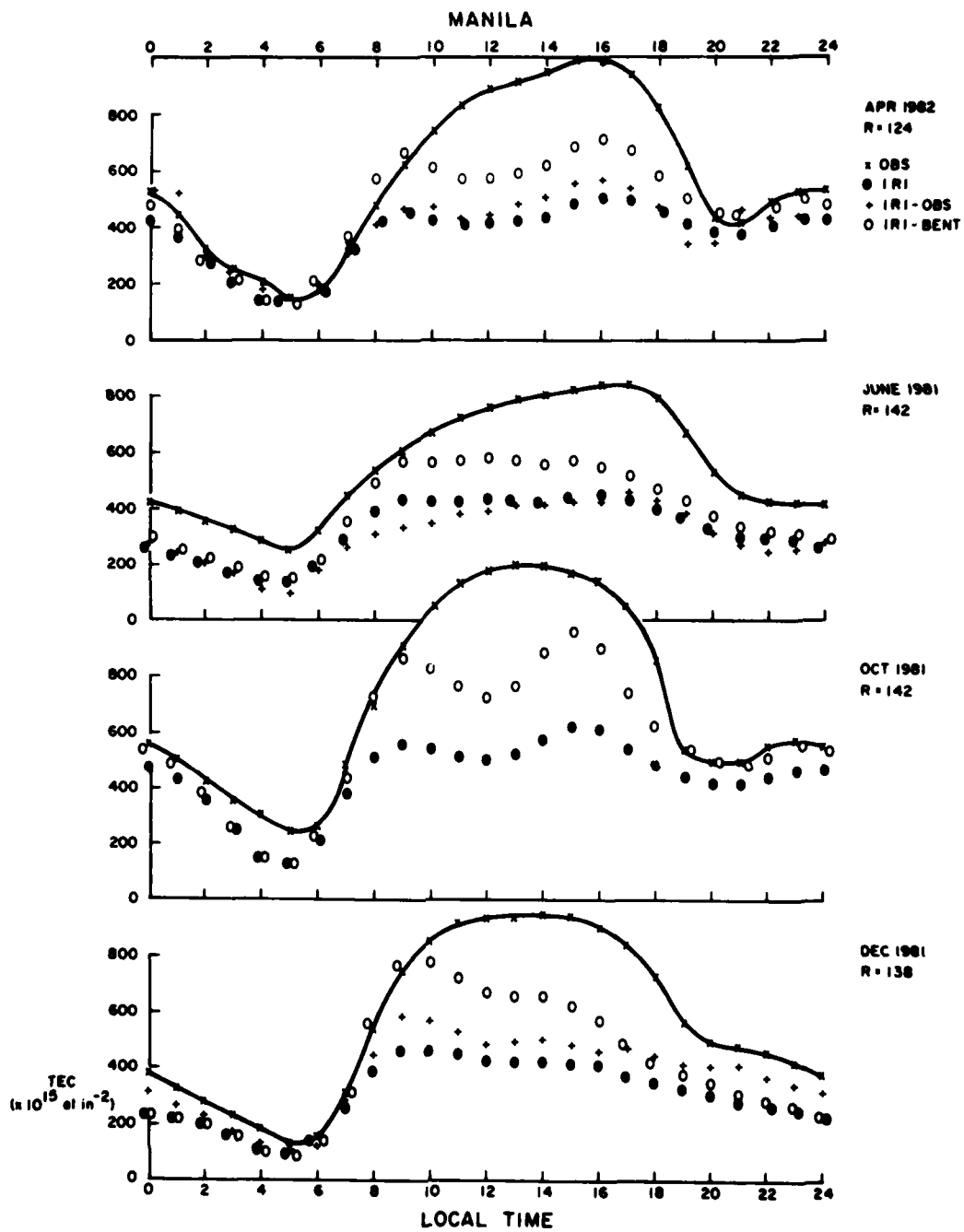


Figure 8. Predicted and Observed Values of TEC at Manila for Four Months With High Solar Activity (1981, 1982)

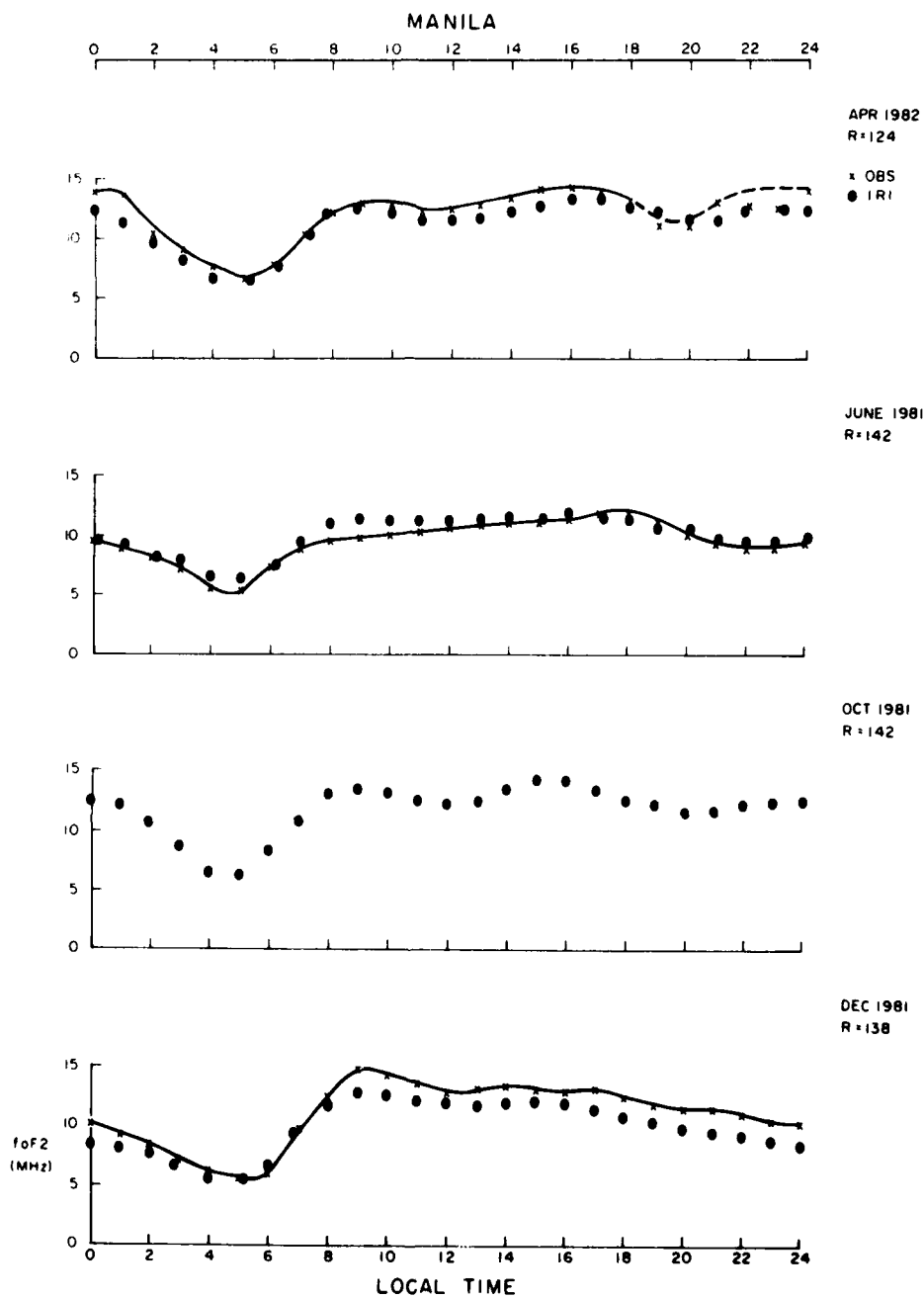


Figure 9. Predicted and Observed Values of foF2 at Manila for Four Months With High Solar Activity (1981, 1982). No observations were available for October 1981

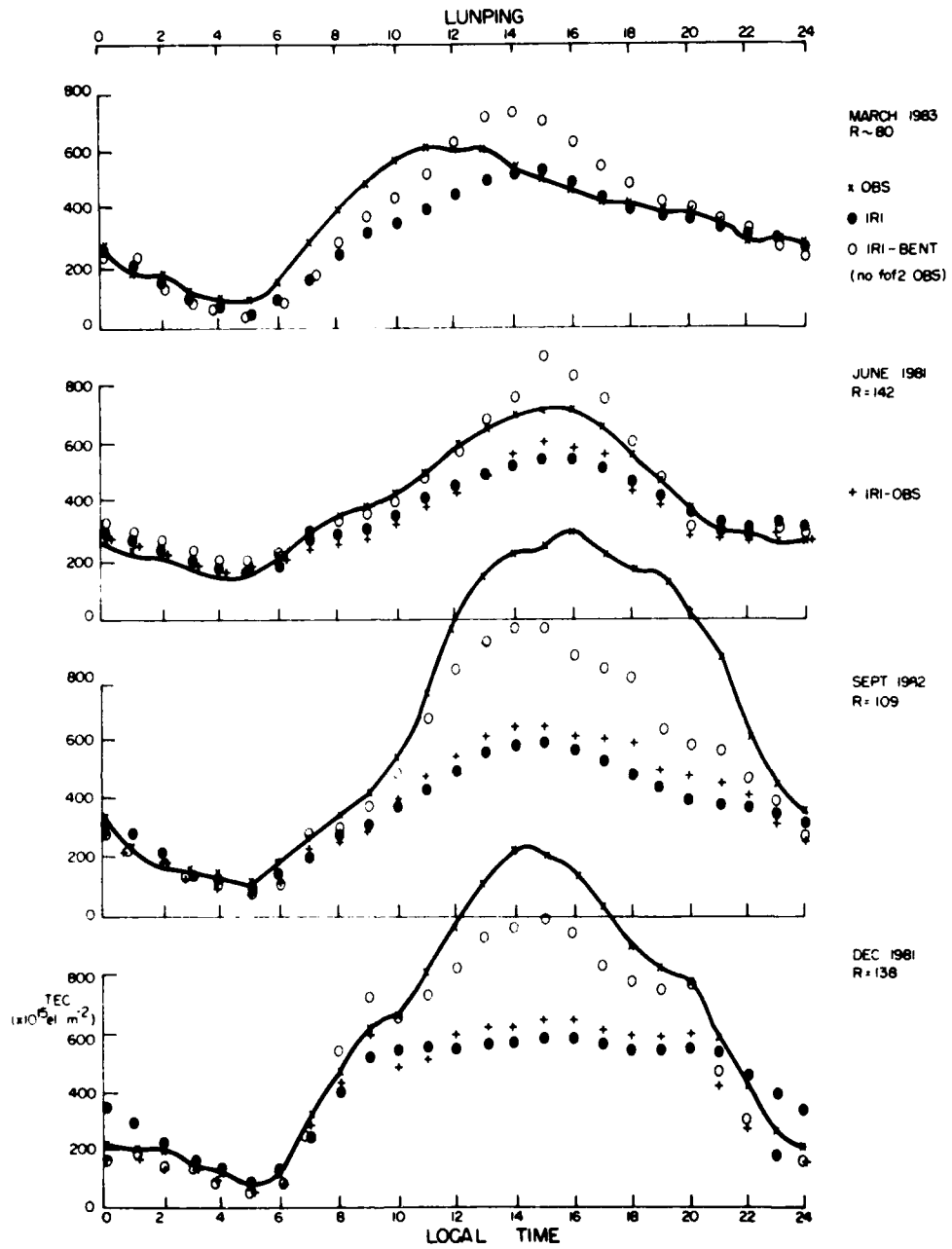


Figure 10. Predicted and Observed Values of TEC at Lunping (Taiwan) for Four Months With High Solar Activity (1981, 1982, 1983)

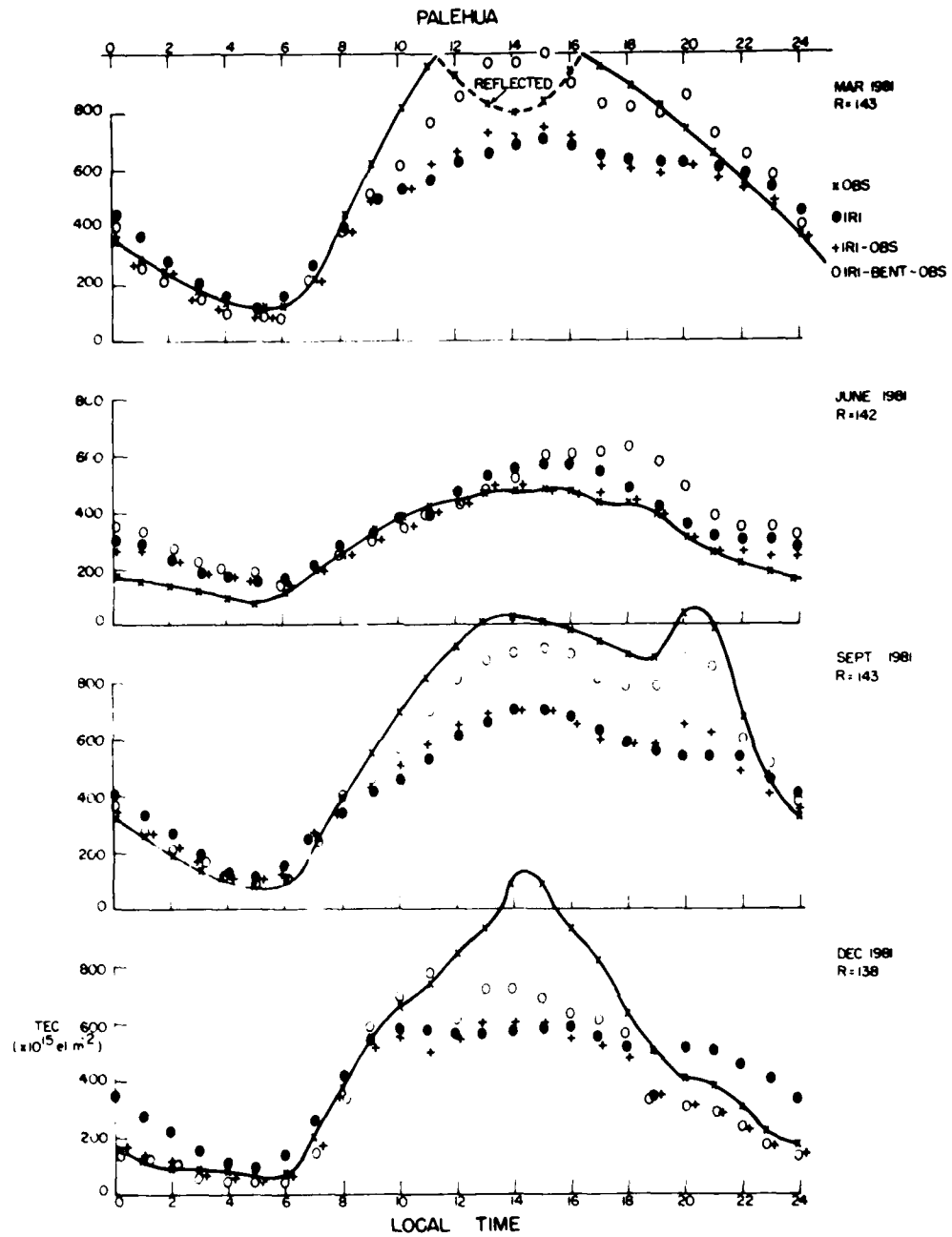


Figure 11. Predicted and Observed Values of TEC at Palehua (Hawaii) for Four Months With High Solar Activity (1981)

5. "C" STATIONS

These are the stations for which the calculation of foF2 relies on the CCIR method, with no real means of checking the calculated values. However, the results for the "A" and "B" stations suggests that the major source of any discrepancies will lie in the topside N(h) profile. We consider the "C" stations in order of increasing dip latitude.

5.1 Ascension Island

For Ascension Island we have considered the months March 1981 ($R = 143$), June 1980 ($R = 153$), September 1980 ($R = 150$), and December 1980 ($R = 143$). In general, the daytime TEC values predicted by the IRI are too low by at least $200 \times 10^{15} \text{ el m}^{-2}$, the discrepancy reaching $600 \times 10^{15} \text{ el m}^{-2}$, or $\sim 50\%$, in March 1981 (see Figure 12). The original Bent topside profile yields somewhat more accurate results, but for June 1980, retains the peculiar diurnal variation given by the IRI.

The post-sunset peak in the observed values of TEC is missing from both sets of predicted values, although there is a plateau from 1800-2400 LT in December 1980.

5.2 Osan, Korea

TEC data for Osan were available for 1980-1982, with some missing months, noticeably the equinoxes. We have considered the data for April, June, October and December 1981 ($R \sim 140$) and the results are shown in Figure 13.

The daytime values of TEC calculated using the IRI are generally quite good, although the errors reach $\sim 140 \times 10^{15} \text{ el m}^{-2}$ for October 1981. The nighttime values given by the IRI, on the other hand, tend to be too high by a factor of ~ 2 , with a typical absolute error of $\sim 100 \times 10^{15} \text{ el m}^{-2}$.

5.3 Ramey

Ramey TEC observations were available for 1980-1982 and we have considered the data for March, June, September, and December 1981 ($R \sim 140$). The predicted values, shown in Figure 14, tend to underestimate the observed TEC by up to $\sim 200 \times 10^{15} \text{ el m}^{-2}$ ($\sim 25\%$) during the day, except in June. There is no consistent discrepancy at night, with only a small discrepancy in June and December, but an underestimate by $\sim 80 \times 10^{15} \text{ el m}^{-2}$ ($\sim 30\%$) during March and September.

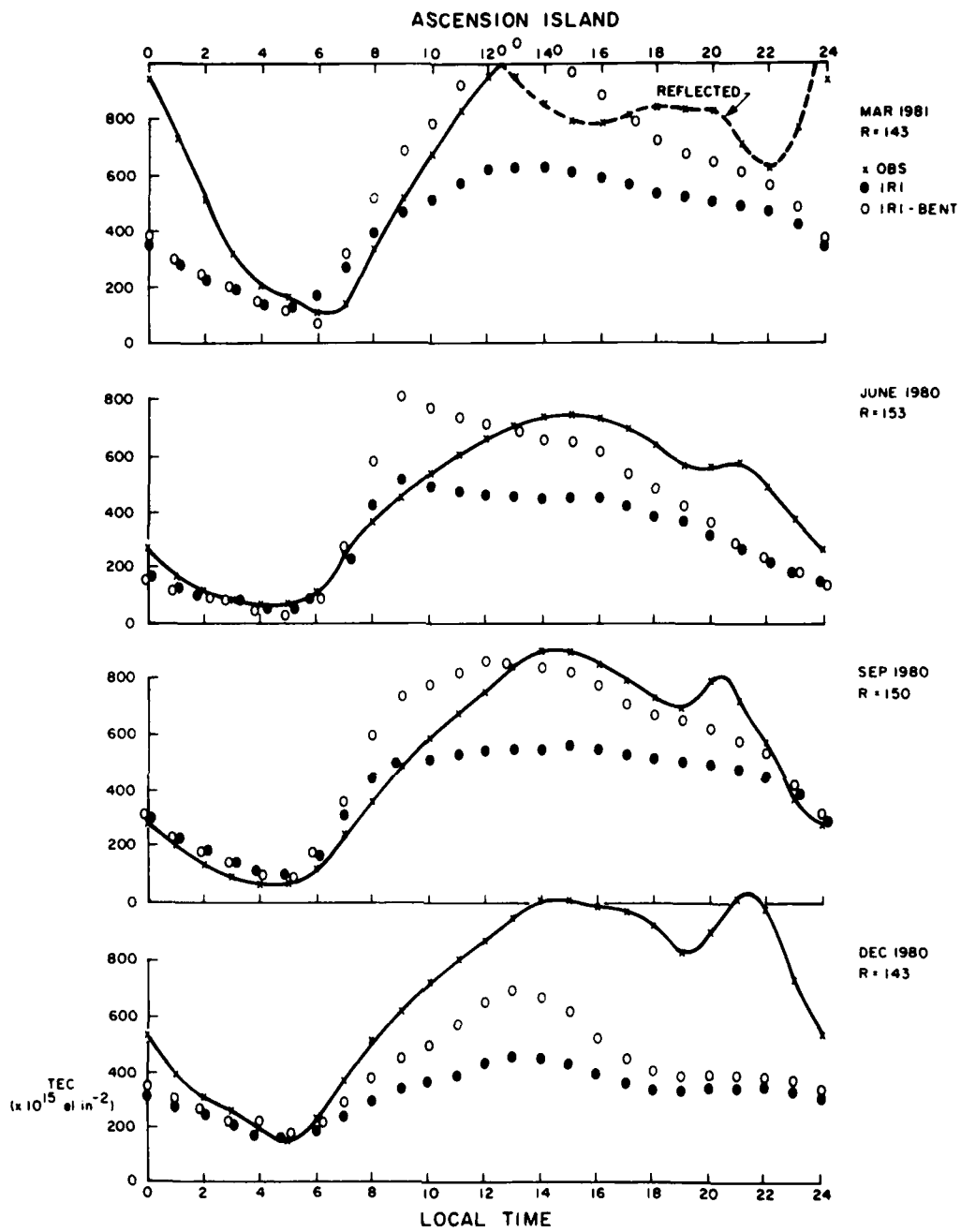


Figure 12. Predicted and Observed Values of TEC at Ascension Island for Four Months With High Solar Activity (1980, 1981)

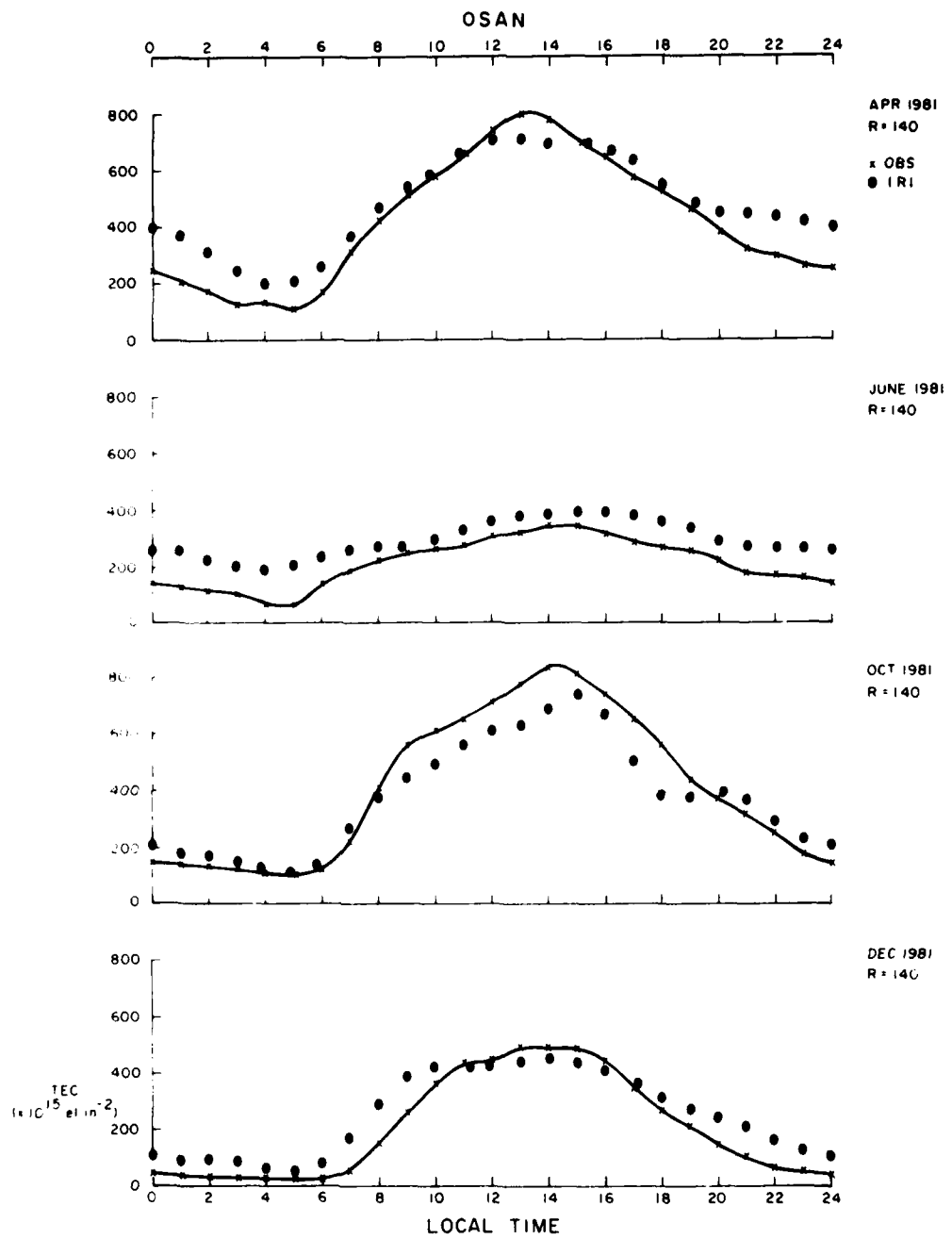


Figure 13. Predicted and Observed Values of TEC at Osan (Korea) for Four Months With High Solar Activity (1981)

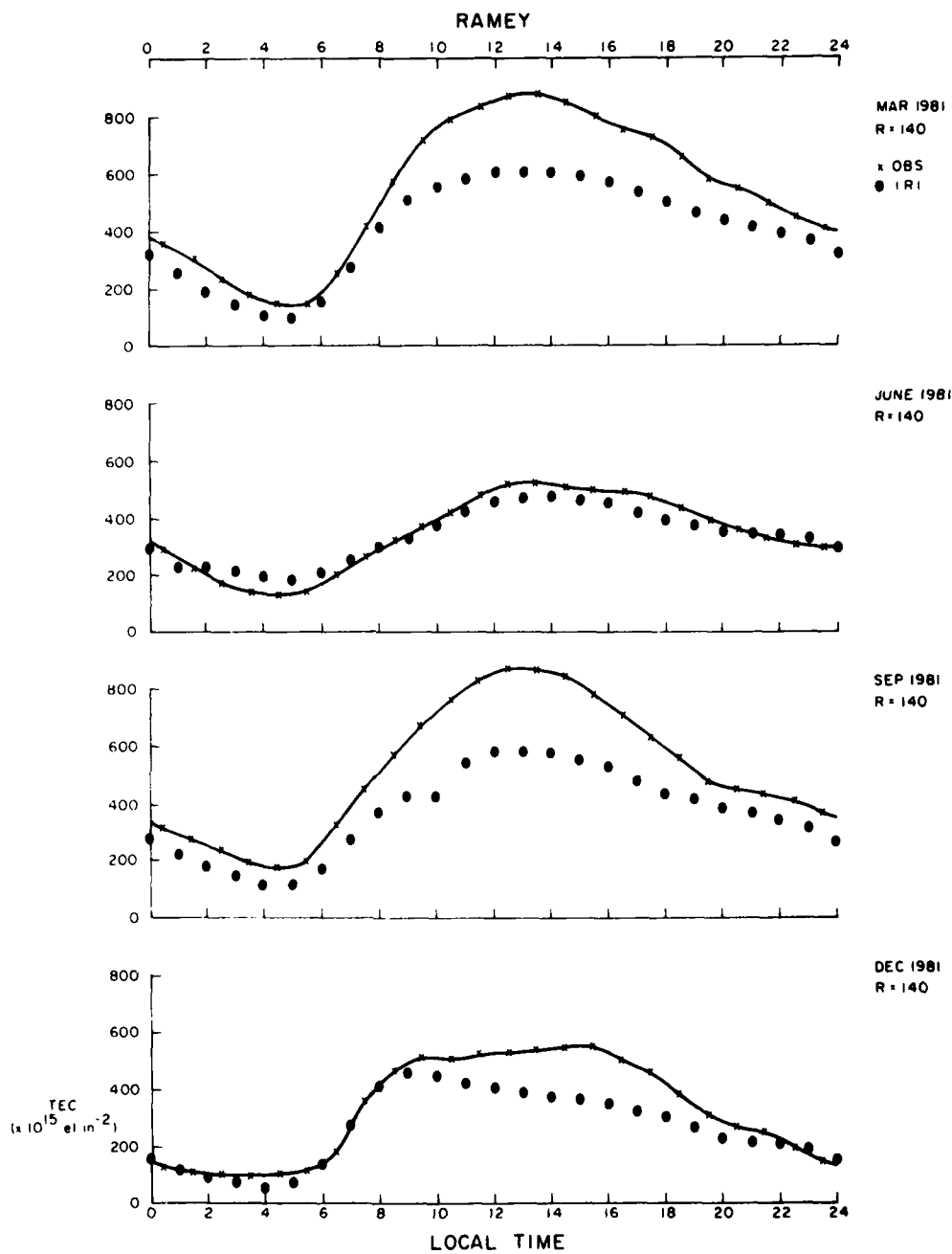


Figure 14. Predicted and Observed Values of TEC at Ramey (Puerto Rico) for Four Months With High Solar Activity (1981)

5.4 Athens

Athens TEC data were available for 1980-1982, with some missing months. We have considered the data for March 1982 (R = 129), June 1981 (R = 142), September 1982 (R = 117), and December 1982 (R = 138). The results are shown in Figure 15.

The IRI TEC values during the day tend to be too low by up to $\sim 200 \times 10^{15} \text{ el m}^{-2}$ in March and December, while the values during the night tend to be too high by up to $\sim 100 \times 10^{15} \text{ el m}^{-2}$ in September and December.

5.5 La Posta

La Posta TEC data were available from 1980 to 1983 and we have considered the four months March, June, September, and December 1981 (R \sim 140) (see Figure 16). During the day, the discrepancies between observed and predicted values reach $\sim 150 \times 10^{15} \text{ el m}^{-2}$ in March and December, with the IRI values being too low. At night, the predicted TEC values tend to be too high by a factor \sim 2. Figure 16 also shows the TEC values calculated using the original Bent topside profiles. In this case, the results are very similar to the IRI results.

5.6 Patrick

TEC data for Patrick were available for 1980-1983 and we have considered March, June, September, and December 1981 (R \sim 140) (see Figure 17). In general, the IRI underestimates the TEC during the day by up to $\sim 200 \times 10^{15} \text{ el m}^{-2}$ except in June when the discrepancies are very low. The discrepancies at night do not yield a consistent picture.

5.7 Shemya

For Shemya, TEC data were available for September 1977 to April 1979, and for 1980-1982. We have considered the months March 1979 (R = 137), June 1978 (R = 89), September 1978 (R = 108), and December 1978 (R = 118) (see Figure 18). In general, the discrepancies are reasonably small, except in June 1978, when the calculated and observed diurnal variations of TEC do not follow each other very closely.

5.8 Boulder

Boulder TEC data were available for 1980-1982 and we have considered the months March, June, September, and December 1981 (R \sim 140). In general, the agreement between the observed and predicted values of TEC is quite good during the day, but the predicted nighttime values are a factor of \sim 2 too high (see Figure 19).

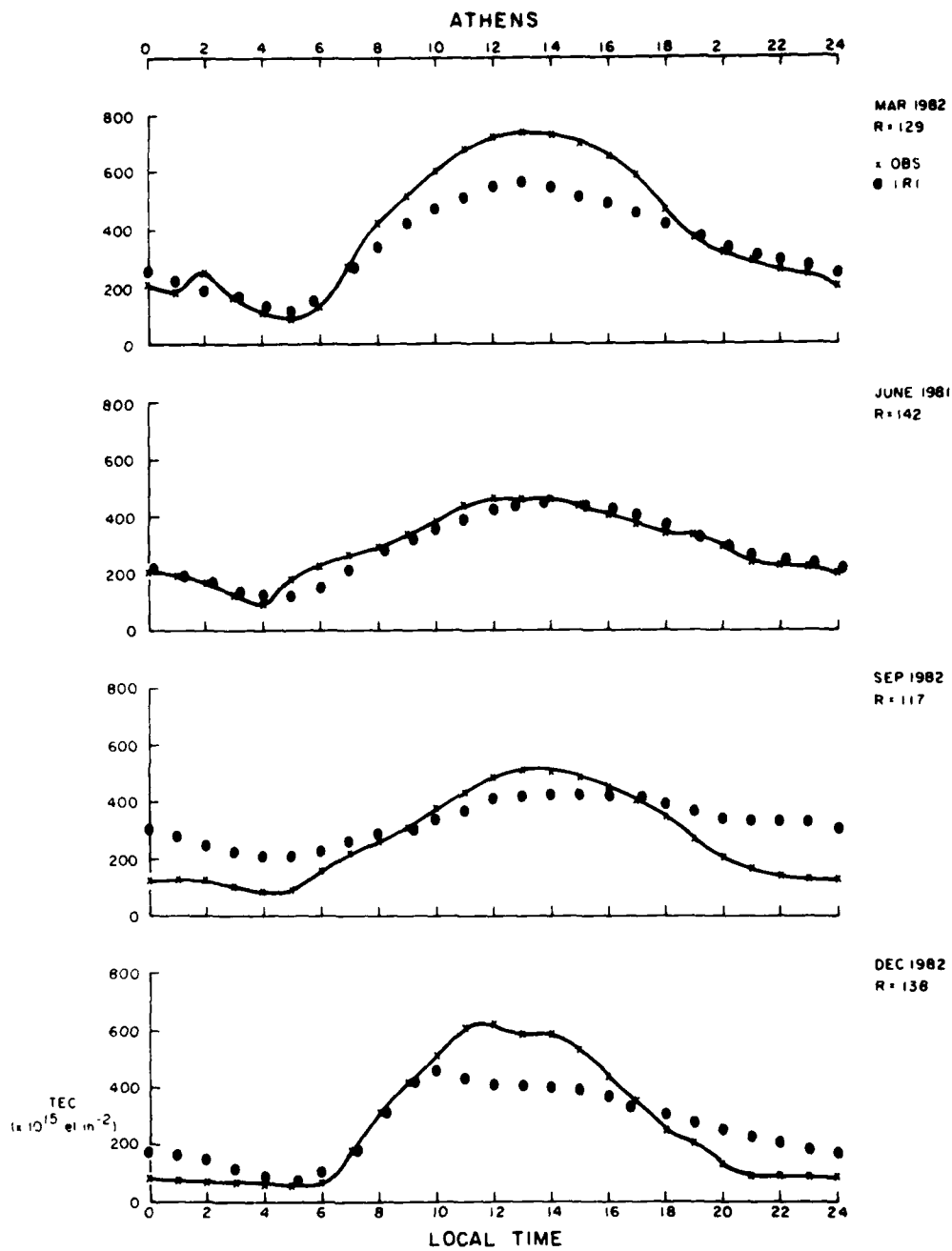


Figure 15. Predicted and Observed Values of TEC at Athens for Four Months With High Solar Activity (1981, 1982)

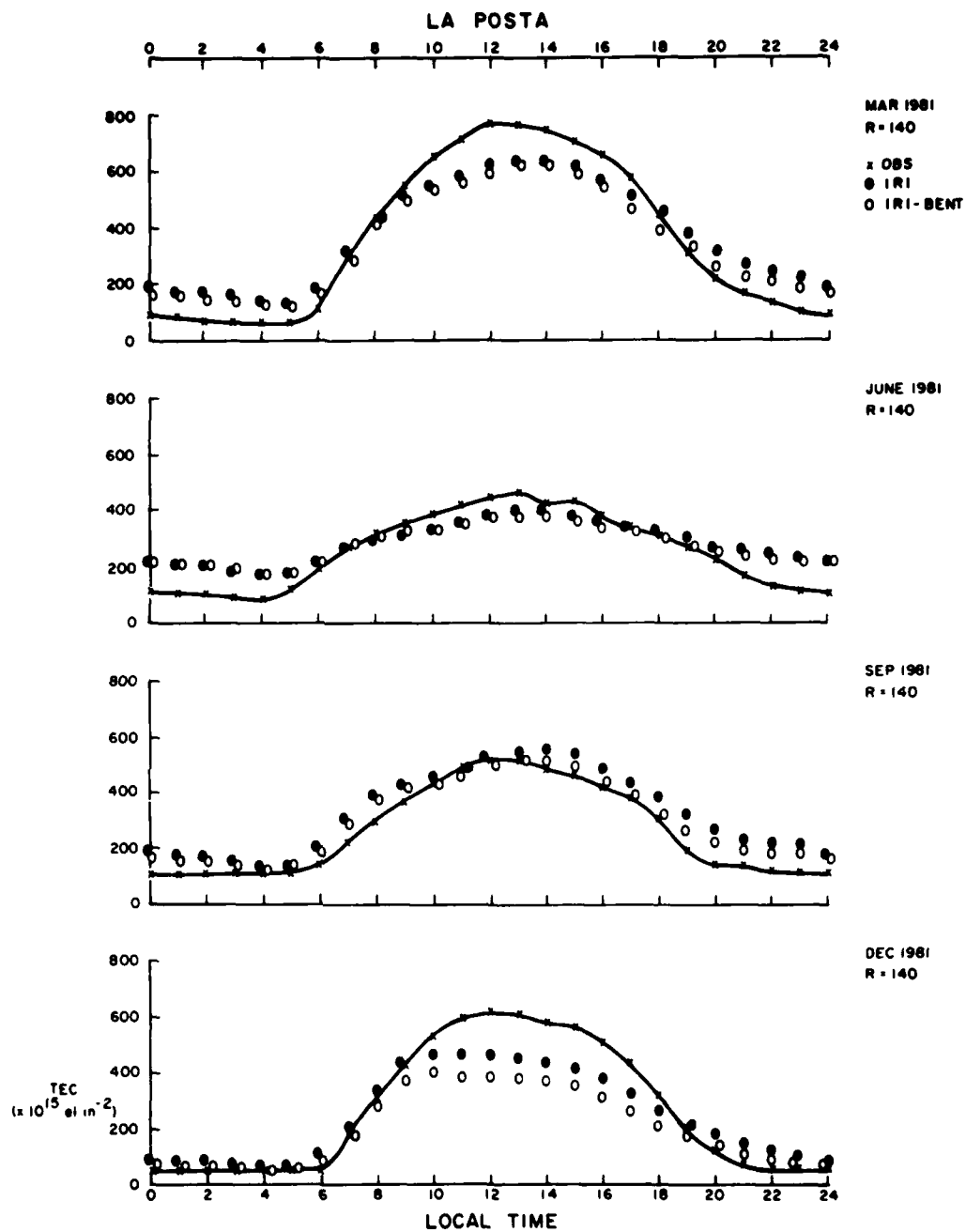


Figure 16. Predicted and Observed Values of TEC at La Posta (California) for Four Months With High Solar Activity (1981)

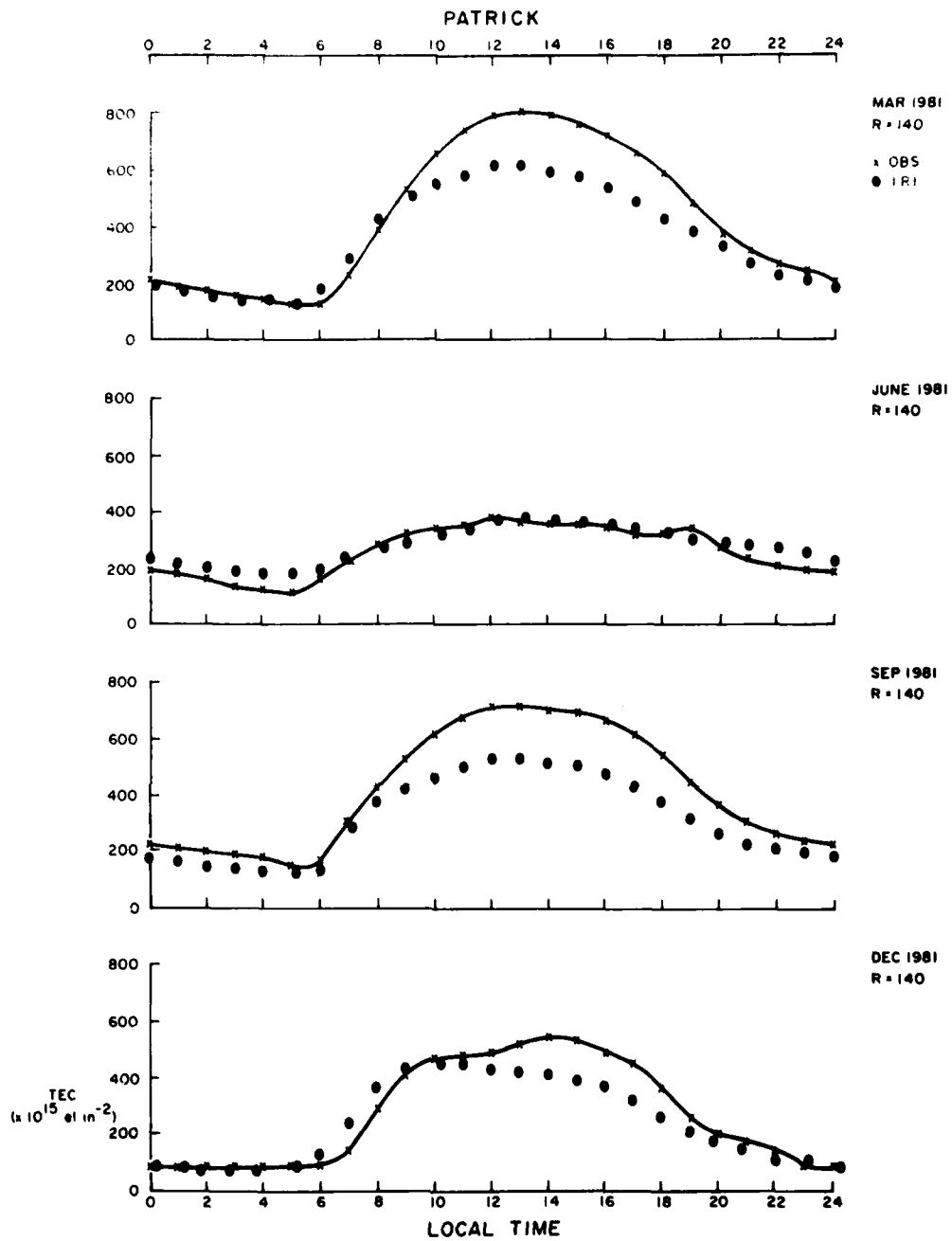


Figure 17. Predicted and Observed Values of TEC at Patrick AFB (Florida) for Four Months With High Solar Activity (1981)

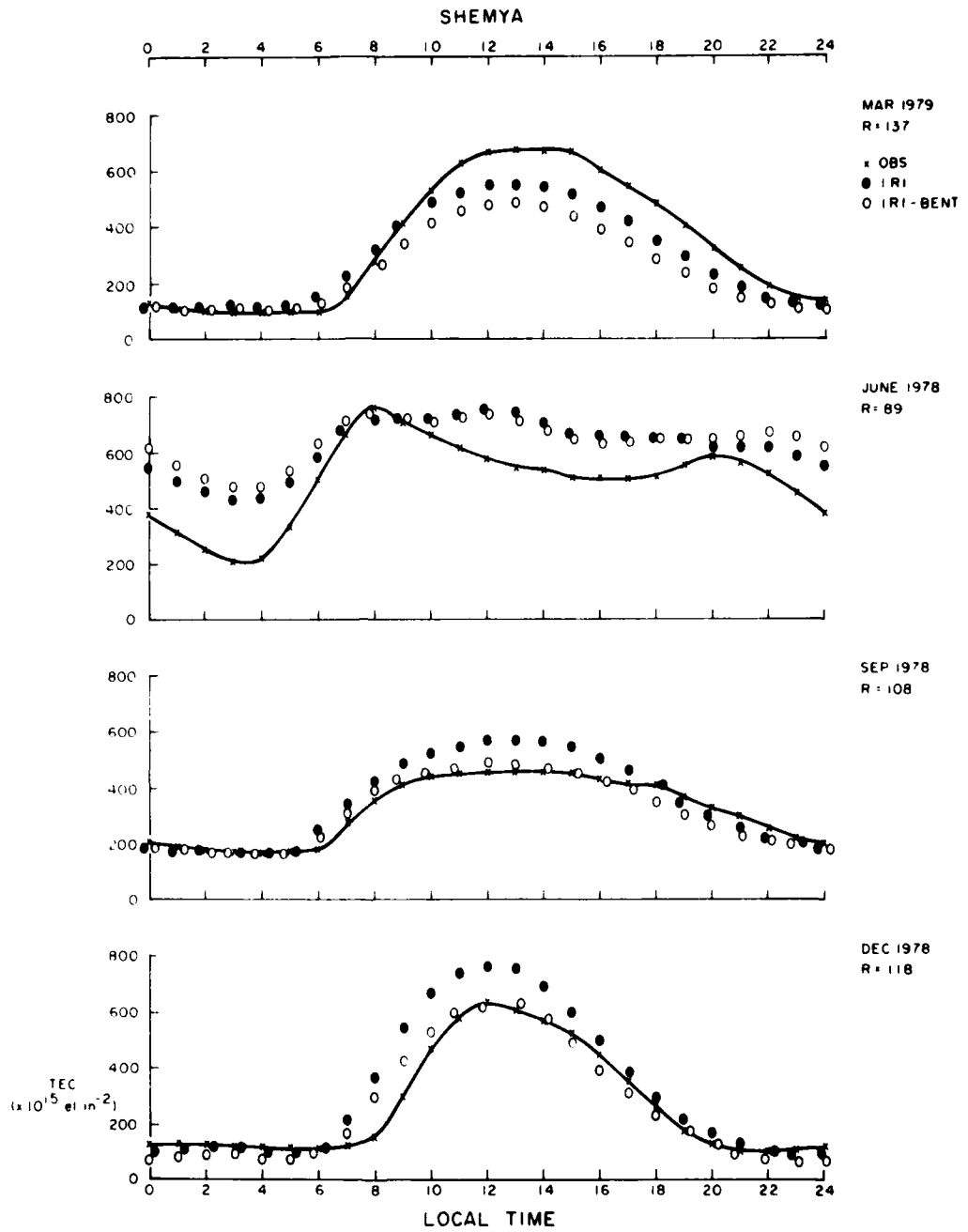


Figure 18. Predicted and Observed Values of TEC at Shemya (Alaska) for Four Months With High Solar Activity (1978, 1979)

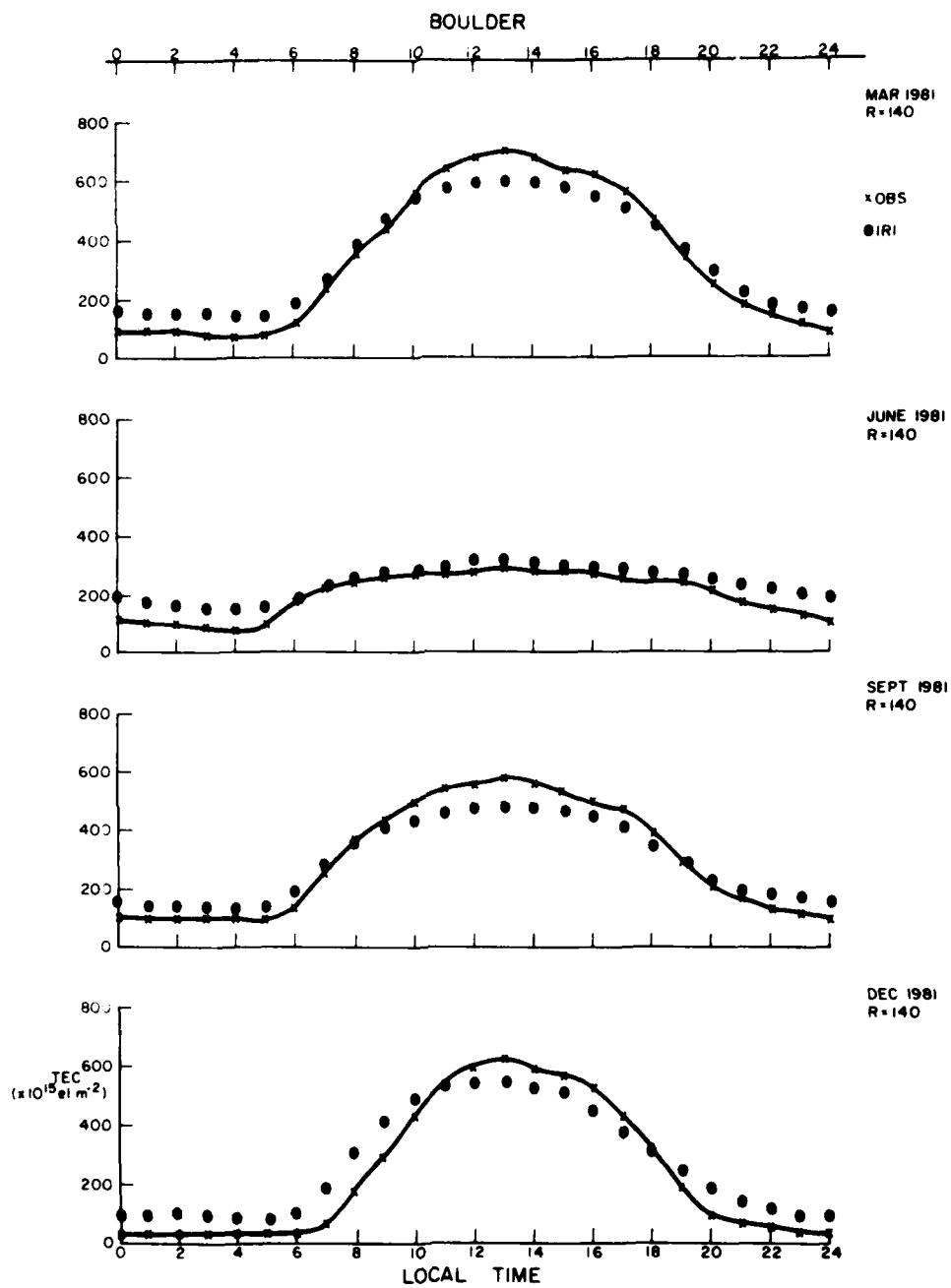


Figure 19. Predicted and Observed Values of TEC at Boulder for Four Months With High Solar Activity (1981)

5.9 Anchorage

Anchorage TEC data were available for 1980-1983, with some missing months, and we have considered March 1981 ($R = 143$), June 1982 ($R = 117$), September 1981 ($R = 143$), and December 1980 ($R = 143$) (see Figure 20). The discrepancies between calculated and observed values of TEC during the day show no consistent trend, the IRI values being too low in March, too high in December and fairly minor in June and September. The discrepancies at night are also fairly minor. In this case, the IRI values match the observations better than do the values calculated using the original Bent topside profile.

6. DISCUSSION OF RESULTS

Since we have found that errors in the calculated values of foF2 are not the major cause of the discrepancies between calculated and observed values of TEC, and that the discrepancies are significantly greater at low latitudes, we shall discuss the results under three latitude headings—mid, high, and low.

6.1 Mid-Latitude Stations

We consider here Osan, Ramey, Athens, La Posta, Patrick, Shemya, Boulder, and Hamilton. The low latitude limit was set by the fact that Palehua TEC is affected by the equatorial anomaly, while the upper latitude limit was set to $L = 4$.

The Boulder, Hamilton, and Osan results show no major discrepancies between the observed and calculated values of TEC during the day, but the IRI values tend to be too high at night by a factor ~ 2 . The IRI results for Athens, La Posta, Patrick, and Ramey are too low during the day in March, September, and December, but have only minor errors in June (summer). There is no consistent discrepancy at night. The discrepancies at Shemya are similar, except for June, when the calculated values of TEC vary substantially both in absolute value and diurnal variation from the observed values. The cause of these discrepancies is not known, but the double-peaked diurnal variation of the TEC (which is also found for June 1981) indicates that in June the ionosphere at Shemya differs from the normal mid-latitude ionosphere. The discrepancies at the other stations in the other seasons may in fact be partly due to errors in the predicted values of foF2, but the consistency of the errors over a wide range of longitudes also suggests that the profile shape may be at fault as well.

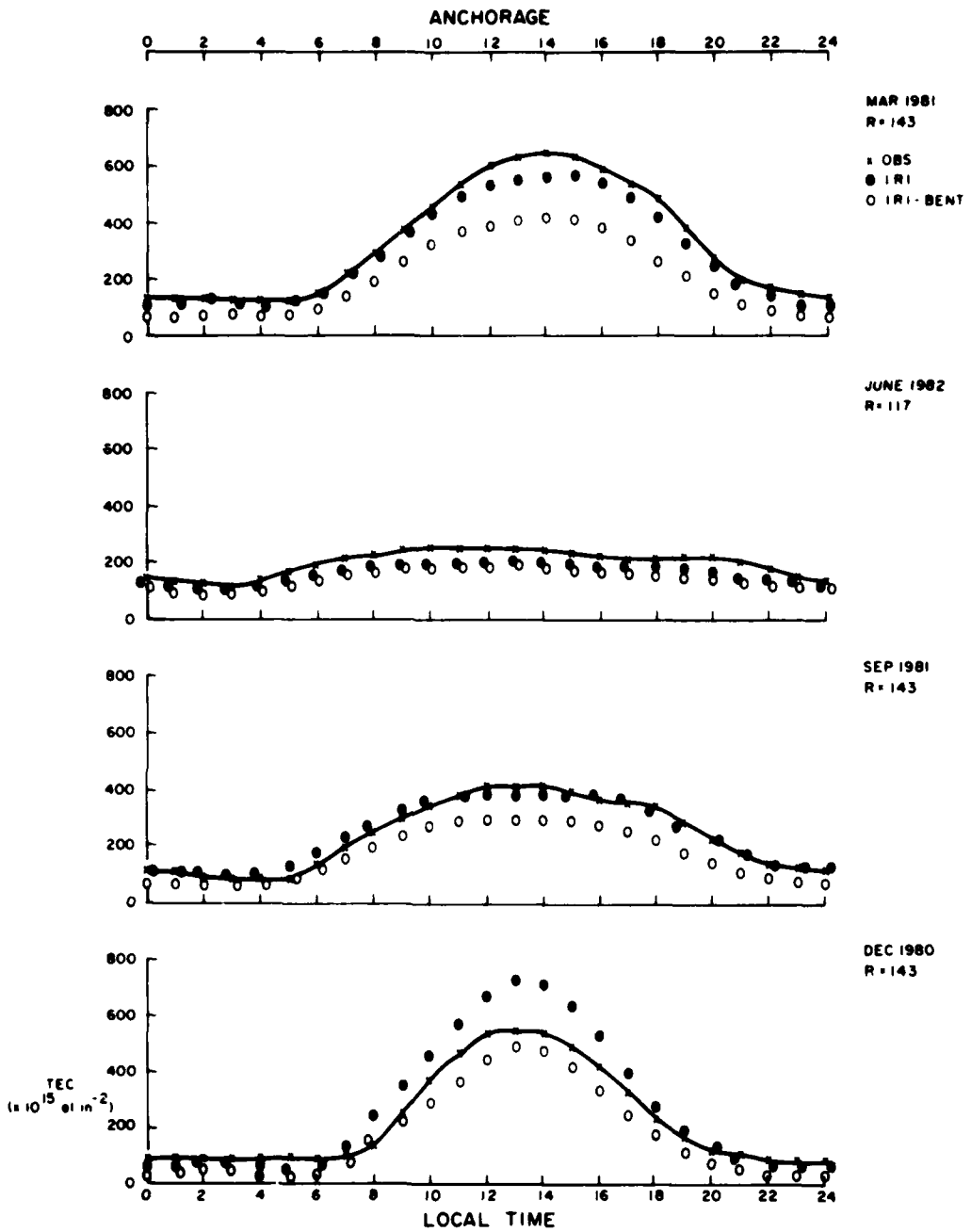


Figure 20. Predicted and Observed Values of TEC at Anchorage for Four Months With High Solar Activity (1980, 1981, 1982)

6.2 High-Latitude Stations

The results for Anchorage, Goose Bay, and Narssarssuaq are similar to those for the mid-latitude stations, with no major discrepancies, especially when observed values of foF2 are available. The largest discrepancy occurs for about 08-14 LT in December when the IRI values are too high.

6.3 Low-Latitude Stations

The four low latitude stations, Manila, Ascension Island, Luning, and Palehua all yield considerable discrepancies between the observed and calculated values of TEC. During the day, the calculated values can be a factor of 2 too low (absolute error $\lesssim 500 \times 10^{15} \text{ el m}^{-2}$), with an incorrect diurnal variation. The IRI also does not reproduce the observed post-sunset increase of TEC at Ascension Island.

As indicated by the results for Manila, Luning, and Palehua, the discrepancies are not due to errors in the predicted values of foF2 and must therefore be due to the N(h) profile shape. Larger daytime values of TEC, which agree better with the observed values, are obtained by replacing the IRI topside profiles by the original Bent profile. While this procedure was not found necessary at mid- and high-latitude stations, it is at least a step in the right direction for low latitude stations. In some months, the modified IRI profiles yield good agreement with the observations. Even so, the calculated diurnal variations of TEC often do not match the observed daytime variations, nor the post-sunset increases at Ascension Island.

The IRI-BENT (that is, with the original Bent topside profile) results for Manila indicate a "crisis of confidence" which occurs at around 08 LT—the calculated TEC flattens out rather than continuing the post-sunrise increase. Consideration of the diurnal variation of foF2 at Manila, with foF2 going through 10 MHz at around 07 LT, led us to consider a possible modification of the Bent topside profile, in particular the semi-thickness of the topside parabolic YT. The coding for PROF2 (Llewellyn and Bent,⁹ especially page 181) shows that if foF2 exceeds 10.5 MHz, YT is given by the formula:

$$YT = YM \times \{0.133 \times (\text{foF2} - 10.5) + 1\} ,$$

where YM is the half thickness of the bottomside parabola. Since the TEC increases when YT is increased, the value of TEC given by the IRI-BENT model can be increased when foF2 > 10.5 MHz simply by increasing the factor 0.133. Increasing it to 0.5 yields TEC values more in agreement with the observed daytime values.

The predicted daytime TEC values for the IRI-BENT model can also be increased (by a lesser amount) by relaxing the upper limit on the 10.7 cm flux set by Llewellyn and Bent.⁹ Subroutine REFRAC (Report page 172) limits the flux to 130.

Removing this limit allows the exponent of the lower topside exponential to achieve lower values, yielding a more slowly decaying profile. (See Figure 4 of Llewellyn and Bent.¹¹) The exponents must, however, be constrained to stay positive, which was the original reason for the limit on the flux value.

Better agreement with the observed daytime TEC values at low latitude stations may thus be obtained by judicious manipulation of the parameters of the Bent top-side profile. We have not pursued this point. All results given in this report were obtained using the unmodified Bent profiles.

The TEC at Ascension Island has been modeled theoretically by Anderson and Klobuchar,¹² who were able to reproduce the observed TEC variations including the late afternoon decrease and post-sunset enhancements. In an (as yet) incomplete study of the effects of $\underline{E} \times \underline{B}$ drifts at equatorial stations, Anderson and McNamara calculated the N(h) profiles and TEC for Palmyra (5.9 N, 197.8 E, 13° dip) for January 1949 (R = 137). The calculated TEC values are shown in Figure 21, which also shows the observed TEC for Manila for January 1982 (R = 137), the IRI TEC values and the daytime IRI-BENT TEC values. The theoretical values (A) are clearly the best match to the observed data, although some discrepancies still remain at about 18-22 L.T. These may in fact be due to different $\underline{E} \times \underline{B}$ drifts existing at Manila and Palmyra, and are not our present concern. We are concerned rather with the considerably different N(h) profiles given by the IRI-BENT program and by the theoretical model. Figure 22 shows that the two profiles for 12 L.T, January, R = 137, bear little resemblance to each other, the theoretical profile being much broader than the IRI-BENT profile (and consequently yielding a greater TEC). This discrepancy points up the need for further studies of the profile shape at low latitudes. The fact that at least half of the "missing" TEC would appear to come from below the peak of the layer suggests caution in trying to match the observed values of TEC simply by adjusting parameters of the topside profile.

6.4 Nighttime Discrepancies

We have tended so far to discuss mainly the discrepancies which occur during the day, since these have been found to have the largest absolute values. However, the discrepancies might tend to reach higher relative values, which may be of more concern in some applications than the absolute discrepancies. There seems to be no general trend in the discrepancies, overestimates and underestimates being about equally likely. Some of the "A" and "B" stations, (for example, Hamilton and

12. Anderson, D.N., and Klobuchar, J.A. (1983) Modeling the total electron electron content observations above Ascension Island, J. Geophys. Res., 88:8020.

Goose Bay) shows very small discrepancies when observed values of foF2 are used. For Manila and Narssarssuaq, on the other hand, the IRI systematically underestimates the TEC, even when the observed foF2 values are used.

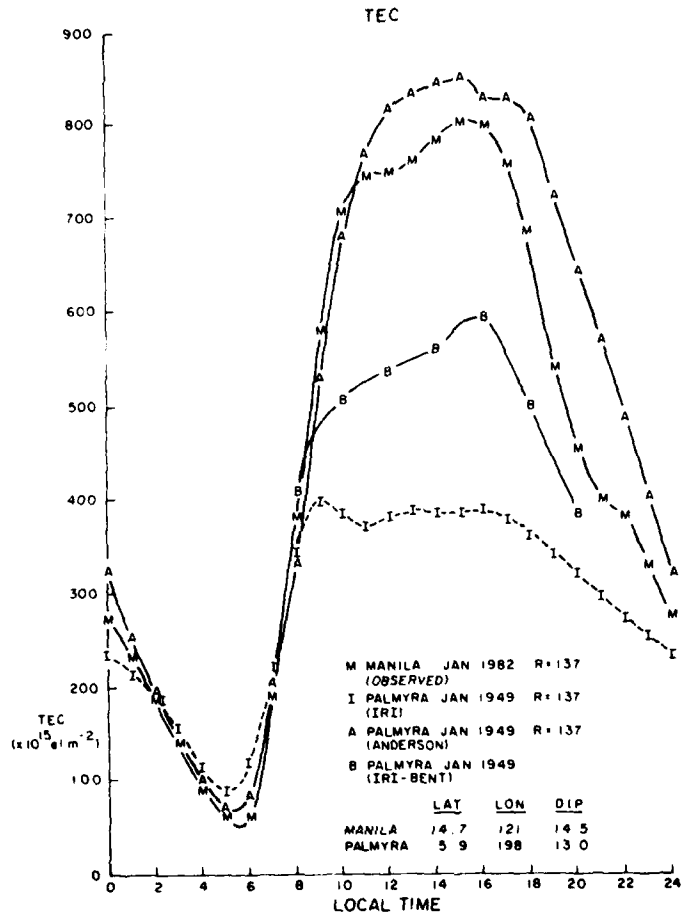


Figure 21. Calculated and Observed Values of TEC for January at a Station at 13° Dip, for $R = 137$. The observed values are for Manila, while calculated values are given for the IRI, the modified IRI-BENT and the Anderson theoretical models. The Anderson values were calculated for Palmyra

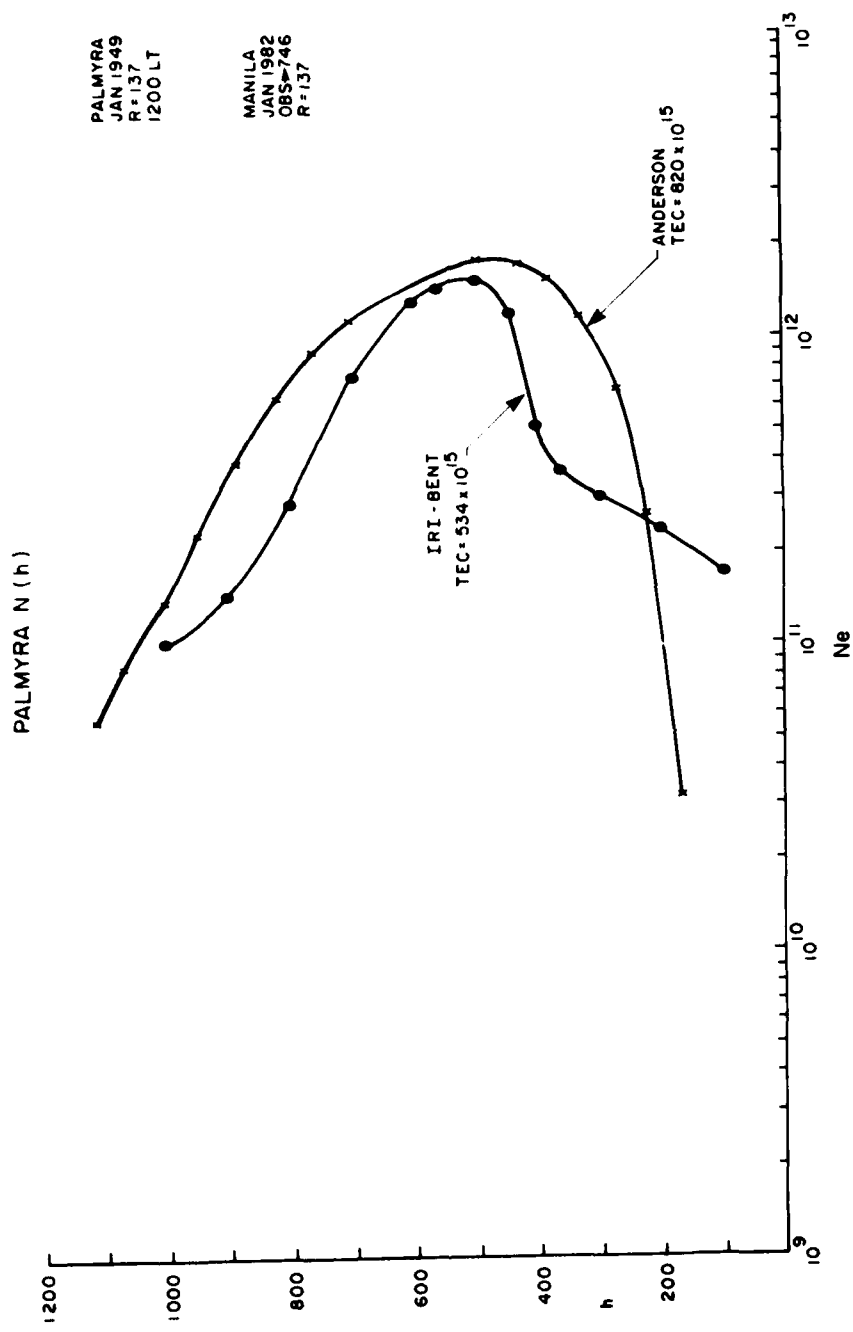


Figure 22. Electron Density Profiles at Noon in January, R = 137, for a Station at 13° Dip as Given by the Anderson and IRI-BENT Programs

7. CONCLUSIONS

We have found that, in general, the IRI yields reasonable, and often quite accurate, values of TEC at mid- and high-latitude stations, but that it tends to underestimate severely the daytime values of TEC at low latitude stations. Better agreement with the observed daytime values of TEC at low latitudes can be obtained by replacing the IRI topside profile by the original Bent profile, but theoretical model studies indicate that a substantial revision of both the IRI and IRI-BENT profiles is required at low latitudes. In those areas for which agreement has been found between observed and predicted values of TEC, the IRI electron density profiles are presumably good representations of the actual profiles. From an operational point of view, this means that the IRI may be used to calculate reliable values of TEC in those same areas.

References

1. Rawer, K. (1978) Goals and status of the International Reference Ionosphere, Res. Geophys. Space Phys. 16:177.
2. Rawer, K. (1981) Introduction to IRI 1979, In "International Reference Ionosphere - IRI 79", J.V. Lincoln and R.O. Conkright (Eds.) Report UAG-82, World Data Center A for Solar Terrestrial Physics, Boulder, Colorado.
3. CCIR (1974) Atlas of Ionospheric Characteristics, CCIR Report 340-2, International Union for Telecommunications, Geneva.
4. Bilitza, D. (1977) Modell zur Darstellung der Höhe des F2 - Maximums mit Hilfe des M-3000 - Wertes des CCIR, Kleinheubacher Ber. 20:4.
5. Bent, R.B., and Llewellyn, S.K. (1970) Description of the 1965-71 Ionospheric Model Used in the Definitive System (DODS), DBA-Systems, Melbourne, FL.
6. McNamara, L.F., and Wilkinson, P.J. (1983) Prediction of total electron content using the International Reference Ionosphere, J. Atmos. Terr. Phys. 45:169.
7. Lincoln, J.V., and Conkright, R.O. (1981) International Reference Ionosphere - IRI-79, Report UAG-82, World Data Center A for Solar Terrestrial Physics, Boulder, CO.
8. Chiu, Y.T. (1975) An improved phenomenological model of ionospheric density, J. Atmos. Terr. Phys. 37:1563.
9. Llewellyn, S.K., and Bent, R.B. (1973) Documentation and description of the Bent Ionospheric Model, AFCRL-TR-73-0657, AD 772733.
10. McNamara, L.F. (1983) The Conversion of Off-vertical Observations of Total Electron Content into Equivalent Vertical Incidence Values, AFGL-TR-83-0092.
11. Titheridge, J.E. (1972) Determination of ionospheric electron content from the Faraday rotation of geostationary satellite signals, Planetary and Space Science, 20:353.
12. Anderson, D.N., and Klobuchar, J.A. (1983) Modeling the total electron content observations above Ascension Island, J. Geophys. Res., 88:8020.

FILM
31