

## Observations of Upper Atmospheric Weather During Solar Minimum Winter

M. E. HAGAN,<sup>1,2</sup> C. A. BARTH,<sup>3</sup> W. K. TOBISKA,<sup>4</sup> A. H. MANSON,<sup>5</sup> R. A. VINCENT,<sup>6</sup>

M. J. BUONSANTO,<sup>1</sup> R. G. BURNSIDE,<sup>7</sup> AND V. B. WICKWAR<sup>8</sup>

We report on a wide variety of thermospheric and ionospheric observations from three consecutive January World Day campaign periods. Despite remarkably similar geophysical conditions characterizing the in situ forcing of the upper atmosphere during these solar minimum campaigns, we find significant variability in the observations of the ionosphere and thermosphere particularly at low latitudes in the American sector. In addition, we present further observational evidence of the unexpected exospheric temperature suppression at low latitudes initially reported by Hagan and Salah (1988). We discuss the lower and upper atmospheric coupling mechanisms of plausible importance to the interpretation of the observed thermospheric weather patterns. We report evidence that lower thermospheric [NO] (nitric oxide number density) and upward propagating atmospheric tides affected the thermospheric energy and momentum budgets during the campaign periods.

### 1. INTRODUCTION

*Hagan and Salah* [1988] reported on an unexpected latitudinal variation in exospheric temperature ( $T_{\infty}$ ) derived from incoherent scatter radar measurements made during January 14-17, 1986, in the American sector. Specifically, they found a suppression in  $T_{\infty}$  at low latitudes (near 18°N) with respect to middle latitude  $T_{\infty}$  measurements as well as to numerical [*Roble and Ridley*, 1987; *Roble et al.*, 1982; *Forbes and Garrett*, 1978] and empirical model predictions [*Hedin*, 1983, 1987]. *Hagan and Salah* [1988] suggested that upward propagating semidiurnal tides could be responsible for the observed latitudinal variation in  $T_{\infty}$ .

The observations reported by Hagan and Salah provide evidence that the expected climatological pattern of the magnetically undisturbed northern hemisphere winter thermosphere during solar minimum conditions may not be representative of observed weather patterns. In this report we examine additional evidence of weather variability during solar minimum winter. We propose that coupling between the lower and upper atmosphere is responsible for the observed weather patterns. Further, we suggest a series of numerical experiments aimed at testing the role of the physical

processes that may be responsible for winter thermospheric weather.

In order to determine whether the unexpected  $T_{\infty}$  behavior reported by Hagan and Salah was typical of other upper atmospheric fields during that time, we describe a number of previously unreported data sets from the January 1986 campaign period. In addition, we compare and contrast the January 1986 measurements with data from two additional campaign periods in order to investigate whether the 1986 data sets are anomalous or characteristic of the upper atmosphere during recent solar minimum and geomagnetically undisturbed winter conditions. As seen in Table 1, the geophysical conditions which characterized January 14-17, 1986, were also typical of two additional World Day campaign periods, specifically, January 14-17, 1985, and January 27-30, 1987. The combination of measurements from these three northern hemisphere winter solar minimum periods forms the basis of our investigation. In the remainder of this report we describe the thermospheric and ionospheric weather observed at low and middle latitudes during the three January periods. Further, we interpret the observed variability in light of complementary mesospheric and lower thermospheric measurements.

Section 2 contains the description of a series of upper atmospheric measurements from the three January periods. We report on ionospheric variability as seen in measurements using incoherent scatter radars (ISR), satellite beacon transmissions, and ionosondes. We also present evidence of thermospheric variability in  $T_{\infty}$  as well as neutral wind determinations from ISR measurements.

In section 3, we identify mechanisms which couple the middle and upper atmosphere and which may play a role in the observed thermospheric weather. We also discuss complementary mesospheric and lower thermospheric measurements. We present nitric oxide density ([NO]) measurements from the Solar Mesospheric Explorer (SME) satellite [*Barth et al.*, 1988]. In addition, we present neutral wind measurements from partial reflection drift radars during the three January periods.

In section 4 we discuss the role of lower thermospheric [NO] and upward propagating atmospheric tides in thermospheric weather variability. Finally, we outline a plan for a

<sup>1</sup> Massachusetts Institute of Technology, Haystack Observatory, Westford, Massachusetts.

<sup>2</sup> Also at High Altitude Observatory, National Center for Atmospheric Research, Boulder, Colorado.

<sup>3</sup> Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder.

<sup>4</sup> Space Sciences Laboratory, University of California, Berkeley.

<sup>5</sup> Institute of Space and Atmospheric Studies, University of Saskatchewan, Saskatoon, Canada.

<sup>6</sup> Department of Physics, University of Adelaide, Adelaide, South Australia.

<sup>7</sup> Arecibo Observatory, Cornell University, Arecibo, Puerto Rico.

<sup>8</sup> Center for Atmospheric and Space Science, Utah State University, Logan.

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TABLE 1. Geophysical Conditions

Date	$F_{10.7}$	$A_p$	$K_p$							
Jan. 14, 1985	75.1	9	1 <sup>+</sup>	3 <sup>-</sup>	2 <sup>-</sup>	2 <sup>+</sup>	3 <sup>-</sup>	3 <sup>+</sup>	1 <sup>+</sup>	1 <sup>+</sup>
Jan. 15, 1985	74.8	9	1 <sup>+</sup>	1 <sup>+</sup>	2	2 <sup>+</sup>	2	3 <sup>+</sup>	3	2
Jan. 16, 1985	74.9	8	2 <sup>+</sup>	3	2 <sup>+</sup>	2 <sup>+</sup>	2 <sup>+</sup>	2	1	1 <sup>-</sup>
Jan. 17, 1985	77.2	9	0	0 <sup>+</sup>	1	3 <sup>+</sup>	2 <sup>+</sup>	3 <sup>+</sup>	3 <sup>-</sup>	2
Jan. 14, 1986	76.8	4	1	1 <sup>-</sup>	1 <sup>-</sup>	1 <sup>+</sup>	1	1	1	1 <sup>-</sup>
Jan. 15, 1986	79.0	5	0 <sup>+</sup>	1 <sup>-</sup>	1 <sup>+</sup>	2	1 <sup>+</sup>	2 <sup>+</sup>	2 <sup>-</sup>	0 <sup>+</sup>
Jan. 16, 1986	77.7	3	0 <sup>+</sup>	1 <sup>-</sup>	1	1 <sup>-</sup>	0 <sup>+</sup>	1 <sup>-</sup>	1 <sup>-</sup>	0 <sup>+</sup>
Jan. 17, 1986	78.0	6	0	1 <sup>-</sup>	1	1 <sup>+</sup>	1 <sup>+</sup>	2 <sup>-</sup>	2 <sup>+</sup>	3
Jan. 27, 1987	72.1	7	1	3 <sup>-</sup>	1 <sup>+</sup>	3	3 <sup>-</sup>	1 <sup>-</sup>	1 <sup>-</sup>	1
Jan. 28, 1987	73.0	11	2 <sup>+</sup>	2 <sup>+</sup>	2 <sup>+</sup>	2 <sup>-</sup>	2 <sup>-</sup>	3 <sup>+</sup>	3	3 <sup>+</sup>
Jan. 29, 1987	72.8	10	5 <sup>-</sup>	3 <sup>+</sup>	2	1	1 <sup>+</sup>	1 <sup>-</sup>	1 <sup>-</sup>	1 <sup>+</sup>
Jan. 30, 1987	72.0	4	2 <sup>-</sup>	0 <sup>+</sup>	0	0 <sup>+</sup>	1 <sup>-</sup>	2 <sup>-</sup>	1 <sup>+</sup>	1

follow-on study in section 5. Therein, we suggest a series of numerical experiments using the National Center for Atmospheric Research (NCAR) thermosphere/ionosphere general circulation model (TIGCM). In addition, we describe an ongoing numerical investigation of variability in upward propagating semidiurnal tides using an extension of the model described by *Forbes and Vial* [1989].

## 2. UPPER ATMOSPHERIC MEASUREMENTS

In conducting our investigation of variability in the upper atmosphere during solar minimum winter, we examined all available thermospheric and ionospheric data from measurements made during the three January periods described in Table 1. While we found interesting aspects of thermospheric weather in each of these data sets, it is impossible to include detailed discussions of our entire data base in this report. However, in this section, we discuss the subset of upper atmospheric measurements that best highlights the important and large-scale features found in our data base. We refer the reader to complementary reports by *Buonsanto* [1991] and *Burnside et al.* [1991] for more detailed discussions of measurements made at Boulder and Arecibo, respectively, during these and additional periods.

### 2.1. ISR Measurements

First, we examine the behavior of  $T_{\infty}$  in the American sector, since the initial evidence of winter thermospheric weather due to other than geomagnetic forcing was seen in this parameter.  $T_{\infty}$  determinations were calculated from ISR measurements made over Arecibo (18°N) and Millstone Hill during each January period using the standard determination techniques [*Bauer et al.*, 1970]. Measurements made with the steerable dish over Millstone Hill were binned [*Oliver*, 1984] prior to this analysis, resulting in local time/latitude  $T_{\infty}$  maps with 1° latitude increments between 30° and 55°N [e.g., *Hagan and Salah*, 1988]. We found no significant day-to-day variability in  $T_{\infty}$  at any latitude during the three periods, so we were able to harmonically decompose [*Hagan and Oliver*, 1985] the data from each period with enough accuracy (multiple correlation coefficients > 0.72) in order to better illustrate the latitudinal and interannual variability that we observed. The harmonic fits to

$T_{\infty}$  determinations at 18°N and 43°N for each of the three January periods are illustrated in Figures 1a and 1b, respectively. Results of harmonic analyses at these latitudes highlight the differences in  $T_{\infty}$  at low and middle latitudes during the periods that we analyzed. Diurnal mean exospheric temperatures as well as diurnal and semidiurnal amplitudes and phases corresponding to each of the fits at these latitudes are listed in Table 2. Interannual differences of up to 100°K throughout the day and night are found in  $T_{\infty}$  at the lower latitude (Figure 1a). Nighttime (daytime)  $T_{\infty}$  were largest during 1986 (1985). The thermosphere over Arecibo was cooler during 1987 throughout the day and night in comparison with the other years, however. Harmonic fits to  $T_{\infty}$  at 43°N are virtually identical for the 1985 and 1987 experiment periods (Figure 1b). However, despite remarkably similar diurnal mean temperatures during each January at this latitude (Table 2), the diurnal temperature amplitude was 30°K larger in 1986 than it was during the other years, pointing to a warmer (cooler) daytime (nighttime) thermosphere at middle latitudes during 1986 as compared with the other years.

The low-latitude suppression in  $T_{\infty}$  with respect to middle-latitude  $T_{\infty}$  initially reported by *Hagan and Salah* [1988] is seen in the diurnal mean temperatures in each of the January periods in progressively larger amounts (Table 2 and Figure 1). During the 1985 period, however, this feature is barely discernible since the temperature suppression is of the order of the 50°K error estimate applicable to ISR  $T_{\infty}$  determinations from measurements made during geomagnetically undisturbed conditions. As a result, *Oliver and Salah* [1988] reported no deviation from the climatological expectation in the observed latitudinal behavior of  $T_{\infty}$  in their initial report on these data. It is also interesting to note that the suppression in the diurnal mean temperature at the lower latitude is accompanied by significant variability in the higher order harmonics as seen in Figure 1a and Table 2. We return in section 4 to a discussion of uncertainties in ISR  $T_{\infty}$  determinations in order to further justify the apparent low-latitude  $T_{\infty}$  suppression.

We illustrate the latitudinal variation of diurnal temperature amplitudes and phases resulting from our harmonic fits together with the numerical model results of an NCAR TIGCM [*Roble et al.*, 1988] simulation (R. G. Roble, pri-

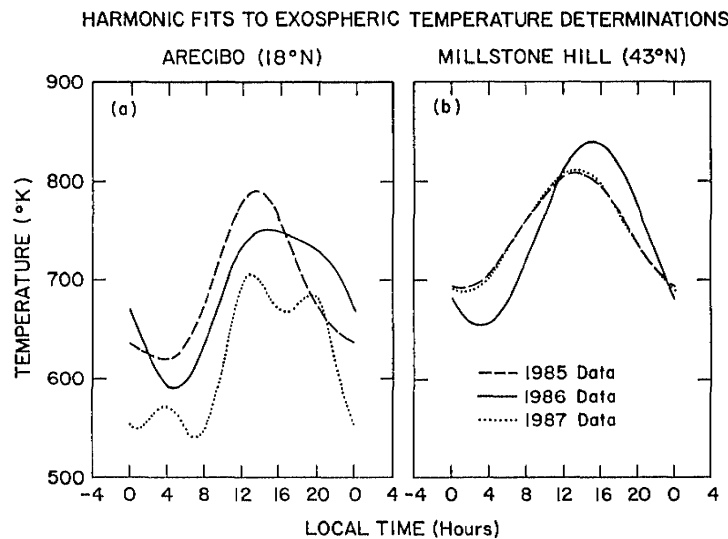


Fig. 1. Harmonic fits to ISR  $T_{\infty}$  determinations over (a) Arecibo (18°N) and (b) Millstone Hill (43°N) during January 14-17, 1985 (dashes), January 14-17, 1986 (solid), and January 27-30, 1987 (dots).

TABLE 2. Results of Harmonic Analyses

Year	Latitude, °N	Mean, °K	Diurnal Amplitude/Phase	Semidiurnal Amplitude/Phase	Terdiurnal Amplitude/Phase
1985	18	692	81.8/14.2	-	-
1986	18	686	78.2/16.4	18.0/11.2	-
1987	18	621	77.6/15.8	6.8/12.4	31.6/12.5
1985	43	749	56.7/13.0	-	-
1986	43	747	92.4/15.4	-	-
1987	43	750	62.0/13.1	-	-

vate communication, 1990) and the predictions of *Forbes and Garrett* [1978] in Figure 2. This figure illustrates the interannual variability of the diurnal exospheric temperature observed over Millstone. During the 1986 period, the diurnal temperature amplitude was found to be about 30°K warmer than the observed amplitudes during the other January periods. Interestingly enough, this is the only feature of significant variability in  $T_{\infty}$  over Millstone (Table 2) and marks the sole departure from climatological expectations for the period, since the diurnal amplitudes and phases associated with middle-latitude  $T_{\infty}$  observations during 1985 and 1987 are largely consistent with the numerical modeling results of both *Forbes and Garrett* and the NCAR TIGCM, which represent average conditions. In contrast, while  $T_{\infty}$  measurements over Arecibo exhibited significant interannual variability in both the means and higher-order harmonics (Figure 1 and Table 2), the diurnal temperatures were the only consistent feature of  $T_{\infty}$  over Arecibo during the three periods. Further, the observed diurnal temperatures over Arecibo were in reasonable agreement with numerical model predictions (Figure 2).

We found no evidence of interannual variability in middle-latitude thermospheric circulation in our examination of ISR determinations of neutral wind along the mag-

netic meridian over Millstone Hill for the three January periods. The anomalous behavior of diurnal  $T_{\infty}$  at 43°N during 1986 that we previously discussed was not evident in the wind determinations. The middle-latitude circulation during recent solar minimum and geomagnetically undisturbed winter periods was in good agreement with climatological predictions and characterized by mean southward winds of 80 m/s with diurnal amplitudes of about 150 m/s peaking near noon (local time). However, we did find notable variability in the circulation over Arecibo illustrated in Figure 3. These data were determined from ISR measurements using standard determination techniques and are characterized by uncertainties of less than 50 m/s (typical of geomagnetically undisturbed conditions) [e.g., *Salah and Holt*, 1974; *Oliver and Salah*, 1988]. We found interannual differences of up to 100 m/s in both daytime and nighttime wind determinations. We were not able to characterize the observed interannual variability with tidal harmonics, however, since there was significant day-to-day variability within the experimental periods (Figure 3). Figure 3 illustrates some evidence of slightly stronger ( $\approx 50$  m/s) southward winds near midnight ( $\approx 4$  UT) during 1986 which turn northward more rapidly as compared with the observations of 1985 and 1987. However, in contrast with the signatures of the diurnal mean  $T_{\infty}$  at

18°N (Figure 1a and Table 2), there was no pronounced interannual variability in the diurnal mean wind over Arecibo during the three January periods.

Thus far, we have characterized the thermospheric variability in the American sector during recent solar minimum winter with determinations from ISR measurements. In the following sections we describe the signatures of ionospheric variability that were observed. We present ionospheric data which complement the ISR measurements. In doing so, we confirm the reliability of the ISR measurements and ensure that we are not ascribing geophysical variability to any un-

known instrumental error in the ISR data. The characteristics of the ISR electron density measurements for the three January periods are also evident in the ionosonde and total electron content (TEC) data that we present in the following sections.

## 2.2. Satellite Beacon Total Electron Content Data

Total electron content measurements from Faraday rotation of satellite radio beacon transmissions over Ramey Air Force Base, Puerto Rico (18°N), are illustrated in Figure 4. There was more pronounced day-to-day variability in TEC during the 1985, and 1987 periods as compared with 1986. Average daytime density during January 15, 1985, was significantly ( $\approx 30\%$ ) larger than it was during the other 1985 daytime periods. These daytime densities were higher than those measured throughout the 1986 and 1987 periods as well. Both day-to-day and interannual variability was less pronounced at night with the exception of a postmidnight ( $\approx 4$  UT), predawn depletion of the ionosphere. This feature was found during three of the four January 1986 nights illustrated in Figure 4. It was intermittently evident in the 1987 data and barely discernible during the 1985 period.

X. Pi and M. Fox (private communication, 1991) suggest that the day-to-day and interannual variabilities that we report are typical of TEC measurements in the low-latitude ionosphere during recent solar minimum northern hemisphere winter conditions. In analyses of TEC measurements from Ramey, Kennedy Air Force Base Florida (28°N), and Hamilton, Massachusetts (43°N), spanning the 11-year period 1977-1987, Pi and Fox found, in general, more variability in TEC during solstice as compared with equinox. Further, their analyses reveal that the variability observed at all three stations during January of 1985-1987 was typical qualitatively and, if anything, below average quantitatively. Johanson *et al.* [1978] also investigated solar cycle and seasonal variability in TEC. They reported significant daytime variability about monthly mean conditions during January 1969 and January 1974 at six separate low- and middle-latitude locations in the Pacific, American, and European sectors. However, results of their analyses suggested that daytime variability tended to peak at the equinoxes during both solar minimum and solar maximum conditions. In light of the aforementioned analyses, we conclude that there was nothing particularly anomalous about the ionospheric variability observed at low latitudes in the American sector during the January 1985-1987 periods. Nevertheless, we

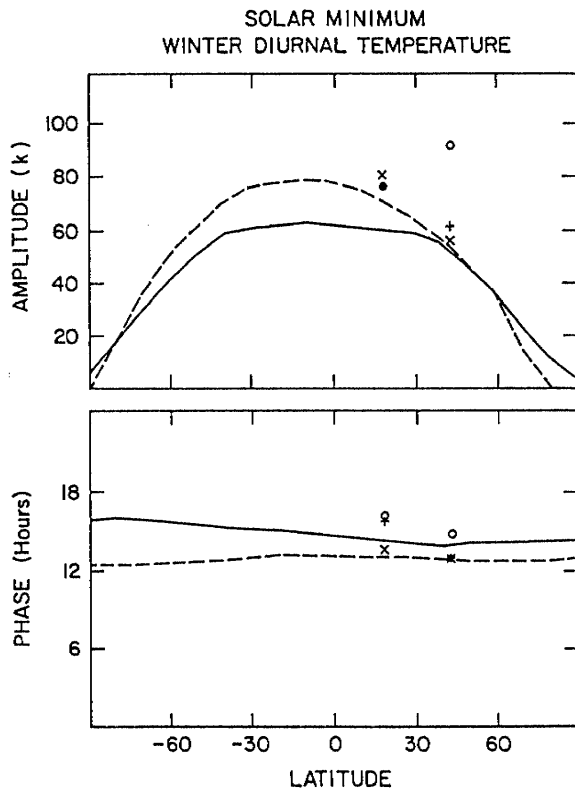


Fig. 2. Diurnal temperature (top) amplitude and (bottom) phase versus latitude during January 14-17, 1985 (crosses), January 14-17, 1986 (circles), and January 27-30, 1987 (pluses), with the model predictions of Roble (private communication, 1990) (solid curve) and Forbes and Garrett [1978] (dashed curve).

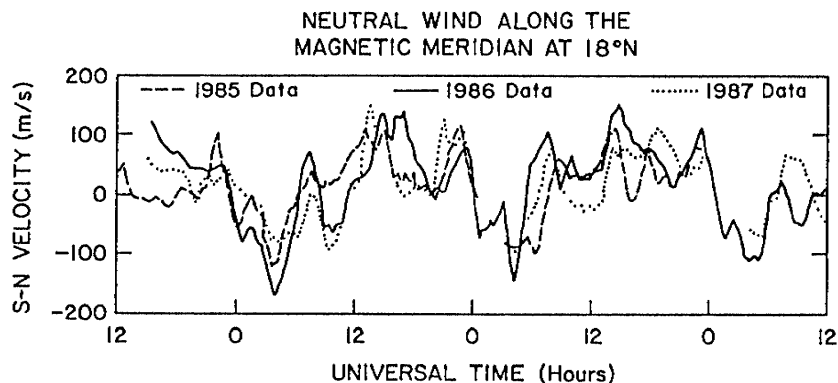


Fig. 3. ISR determinations of neutral wind along the magnetic meridian over Arecibo (18°N) during January 14-17, 1985 (dashes), January 14-17, 1986 (solid), and January 27-30, 1987 (dots).

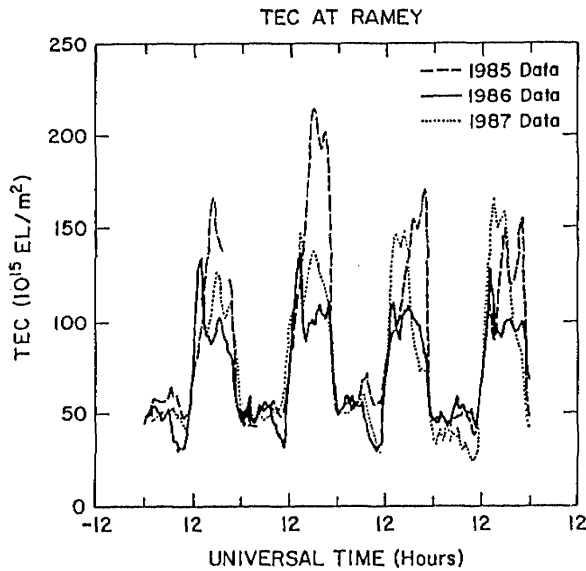


Fig. 4. Total electron content (TEC) measurements over Ramey Air Force Base ( $18^{\circ}\text{N}$ ) during January 14-17, 1985 (dashes), January 14-17, 1986 (solid), and January 27-30, 1987 (dots).

did pursue one aspect of the interannual variability observed over Puerto Rico, and we report it below.

The most interesting feature of the TEC data over Ramey (Figure 4) was the apparent decrease in daytime values of TEC during January 14-17, 1986, as compared with the other periods. The same decrease was measured with the ISR at Arecibo. During January 1986, ISR densities over Arecibo (not shown) were suppressed at all altitudes throughout the  $F$  region in comparison to the densities during the other January periods. Figure 4 illustrates that, on average, ionospheric density was suppressed by 25% and 30% during the day at  $18^{\circ}\text{N}$  in January 1986 as compared with 1987 and 1985, respectively. This behavior suggests that UV and EUV irradiance may have been in decline dur-

ing 1985 and 1986 despite nearly constant 10.7-cm solar radio flux values (Table 1).

Barth *et al.* [1990] found that the correlation between solar irradiance at Lyman  $\alpha$  (121.6 nm) and the 10.7-cm solar radio flux changed during different periods in the solar cycle in an analysis of SME measurements made between October 1981 and April 1989. Their analysis of the solar minimum period (July 1984 to April 1987) in particular revealed that the 10.7-cm flux was not a reliable indicator of solar Lyman  $\alpha$ . Specifically, they reported that solar Lyman  $\alpha$  was variable throughout the 1985-1987 solar minimum period when the 10.7-cm flux appeared to remain at a minimum value. We have no evidence to suggest that ionizing fluxes are correlated with Lyman  $\alpha$  during solar minimum because there are no available measurements at EUV wavelengths during 1985-1987. However, Tobiska and Barth [1990] found relatively high correlations (correlation coefficients of 0.77-0.91) between chromospheric solar ionizing EUV fluxes and Lyman  $\alpha$  during the rise of solar cycle 21 (July 1977 to December 1978). In order to investigate whether solar cycle variability within the 1985-1987 period was responsible for observed thermospheric and ionospheric variability, we looked for consistency in interannual variability in our examination of additional data sets. The behavior of middle-latitude  $T_{\infty}$  (Figure 1b) described above suggests that there was no apparent variability in the in situ forcing of thermospheric temperature. However, we examined additional evidence before precluding the notion that the variability seen over Puerto Rico (Figures 1a and 4) was perhaps partially attributable to differences in solar irradiance. We report on some of the additional data sets that we examined in section 2.3.

### 2.3. Ionosonde Electron Densities

We found that the salient features of the middle latitude ionosphere were largely consistent from year to year during the three January periods. Figure 5 illustrates  $F$  region peak densities ( $N_m F_2$ ) over Wallops Island, Virginia ( $38^{\circ}\text{N}$ ), with the corresponding altitudes ( $H_m F_2$ ) at which

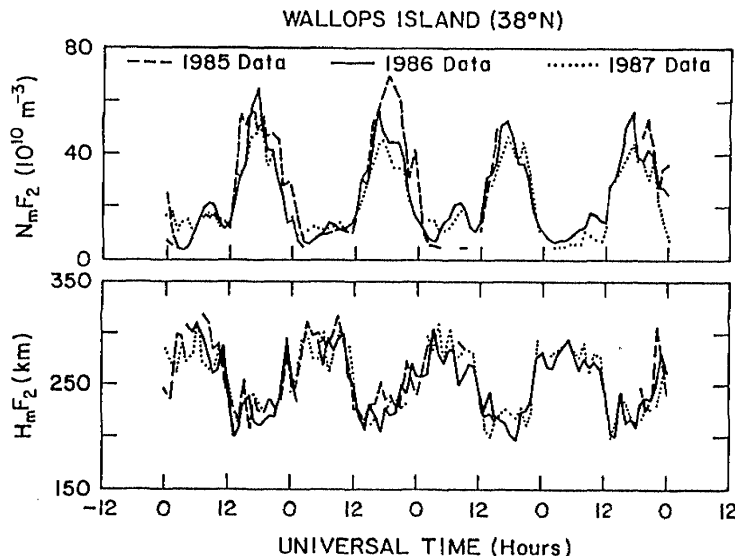


Fig. 5. Ionosonde measurements of (top)  $N_m F_2$  and (bottom)  $H_m F_2$  over Wallops Island ( $38^{\circ}\text{N}$ ) during January 14-17, 1985 (dashes), January 14-17, 1986 (solid), and January 27-30, 1987 (dots).

$N_m F_2$  occurred during the three January periods. On average,  $N_m F_2$  over Wallops did not vary interannually, nor did the height of the  $F$  region peak density change from year to year. The same consistency was also evident in Millstone Hill ISR electron densities throughout the  $F$  region over Millstone Hill (not shown). We examined ionosonde data from other middle-latitude stations as well. While measurements made at Boulder, Colorado ( $40^\circ\text{N}$ ), and Okinawa, Japan ( $26^\circ\text{N}$ ), did reveal some signatures of interannual variability (not shown), they were comparatively weaker than the lower-latitude effects that we describe below. Further, middle-latitude data during the observational periods provided no evidence of the decrease in ion densities during 1986 that was observed at low latitudes in the American sector (Figure 4).

$N_m F_2$  from low-latitude stations at Maui, Hawaii ( $20^\circ\text{N}$ ), Dakar, Senegal ( $15^\circ\text{N}$ ), and Manila, Philippines ( $15^\circ\text{N}$ ), are illustrated in Figures 6a, 6b, and 6c, respectively. While the suppression in low-latitude density during January 14-17, 1986, seen in the American sector (Figure 4) was present to a smaller extent over Asia (Figure 6c), the African data (Figure 6b) indicate largely comparable ionospheric conditions during the three periods. Further, the Pacific data (Figure 6a) point to a relative enhancement in ionospheric density during 1986 as compared with the other periods.

On the basis of the latitudinal and longitudinal interannual variability of the ionospheric data that we examined, we conclude that the observed thermospheric and ionospheric weather cannot be attributed to variability in solar irradiance at UV or EUV wavelengths. We suggest that coupling between the middle and upper atmosphere during recent solar minimum winter was responsible for the weather variability. The longitudinal variability which characterized the low-latitude ionosphere (Figures 6a-6c) suggests further that the low-latitude suppression in  $T_\infty$  (Figure 1) cannot be solely attributable to upward propagating semidiurnal tides [Hagan and Salah, 1988]. We examined a series of upper mesospheric and lower thermospheric measurements in order to identify additional physical processes which may have played an important role in coupling the middle and upper atmosphere during recent solar minimum winter. In section 3, we report on this portion of our investigation.

### 3. MESOSPHERIC AND LOWER THERMOSPHERIC MEASUREMENTS

#### 3.1. Atmospheric Tides

Atmospheric tides have been shown to play an important role in the propagation of energy and momentum from the lower and middle atmosphere into the thermosphere. Forbes [1991] recently reviewed the important mechanisms involved in tidal coupling between atmospheric regions. In this section we report on observations of mesospheric and lower thermospheric tides during January 14-17, 1985, January 14-17, 1986, and January 27-30, 1987, in order to investigate the nature of the variability in these fields during the periods of interest to our thermospheric weather study.

Medium-frequency radars (MFR) have been used to monitor atmospheric tides in the mesosphere and lower thermosphere since the mid-1970s. During the past decade, improved height resolution and more continuous measurements

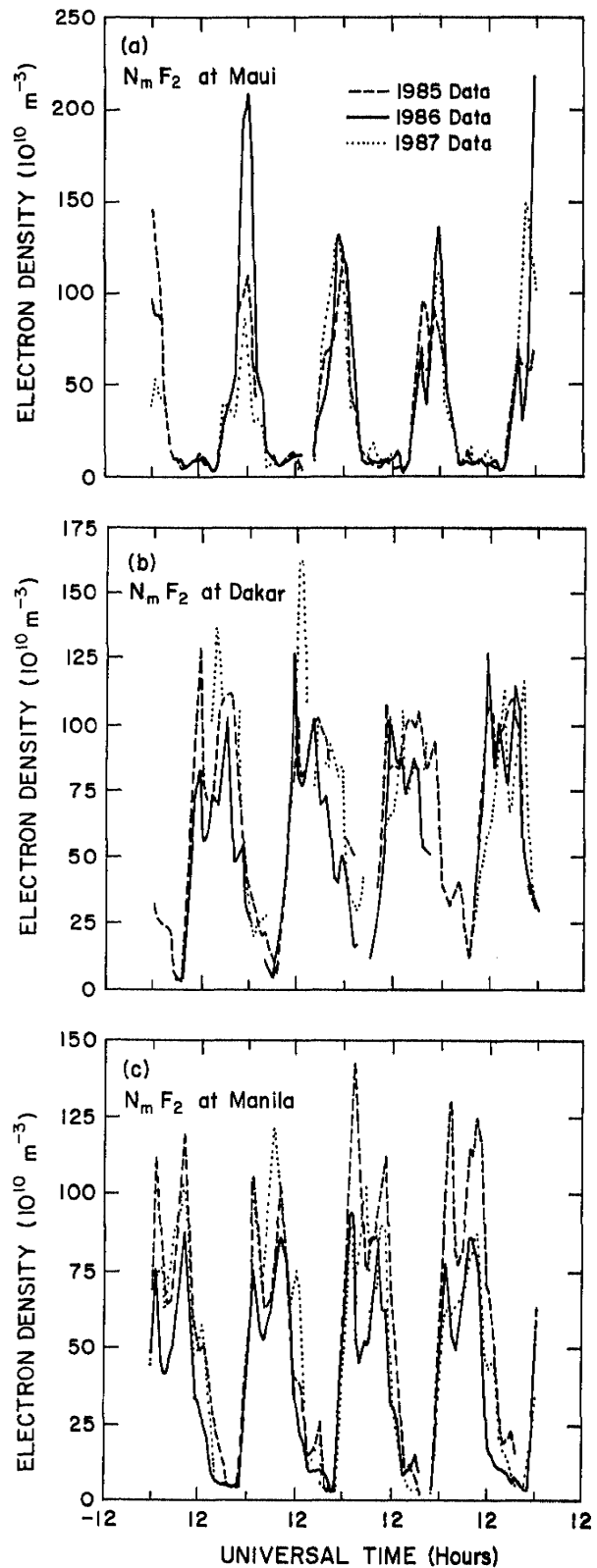


Fig. 6. Ionosonde measurements of  $N_m F_2$  over (a) Maui ( $20^\circ\text{N}$ ), (b) Dakar ( $15^\circ\text{N}$ ), and (c) Manila ( $15^\circ\text{N}$ ) during January 14-17, 1985 (dashes), January 14-17, 1986 (solid), and January 27-30, 1987 (dots).

made it possible to develop monthly climatological maps of middle atmosphere tides in both middle- and high-latitude regions [e.g., *Manson et al.*, 1989; *Avery et al.*, 1989; *Vincent et al.*, 1989]. MFR measurements were made at Adelaide, South Australia (35°S), and Saskatoon, Saskatchewan (52°N), during the January periods that we investigated (Table 1). In the remainder of this section, we report on the interannual variability of diurnal and semidiurnal tides determined from these measurements and characterize them in light of the January climatologies described above.

Figure 7a (Figure 7b) illustrates the diurnal (semidiurnal) component of northward and eastward velocity from 4-day fits to the winds between 75 and  $\approx 102$  km over Saskatoon during the three January periods. Figure 7a suggests that the diurnal amplitudes of the winds in this region of the middle atmosphere were largely consistent during the three periods that we investigated. The corresponding phases were similar only below about 85 km. There was something slightly anomalous about the 1986 data, however. Specifically, diurnal wind amplitudes between 80 and 85 km appear

to have been larger during 1986 than they were during the other years. Corresponding phases between 95 and 100 km were also anomalous during the 1986 period. In general, the diurnal tide at this location is comparatively weaker than the semidiurnal component; it is highly variable interannually and is characterized by a lack of phase coherence. For example, in their analysis of monthly phase averages during January 1985, *Manson et al.* [1989] reported significant variability in diurnal phases. In particular, they were unable to define 30-day eastward diurnal phase averages between 85 and 100 km because of this variability. Further, the diurnal wind amplitudes illustrated in Figure 7a were larger than both the 10-day and 30-day climatologies ( $\approx 3 - 6$  m/s) described by *Manson et al.* [1989]. As a result, we drew no significant conclusions from the apparent interannual variability of the diurnal phases illustrated in Figure 7a. However, we return to a discussion of the 1986 measurements after describing the features of the semidiurnal tides below.

The northward and eastward semidiurnal wind amplitudes exhibited pronounced variability above 80 km during

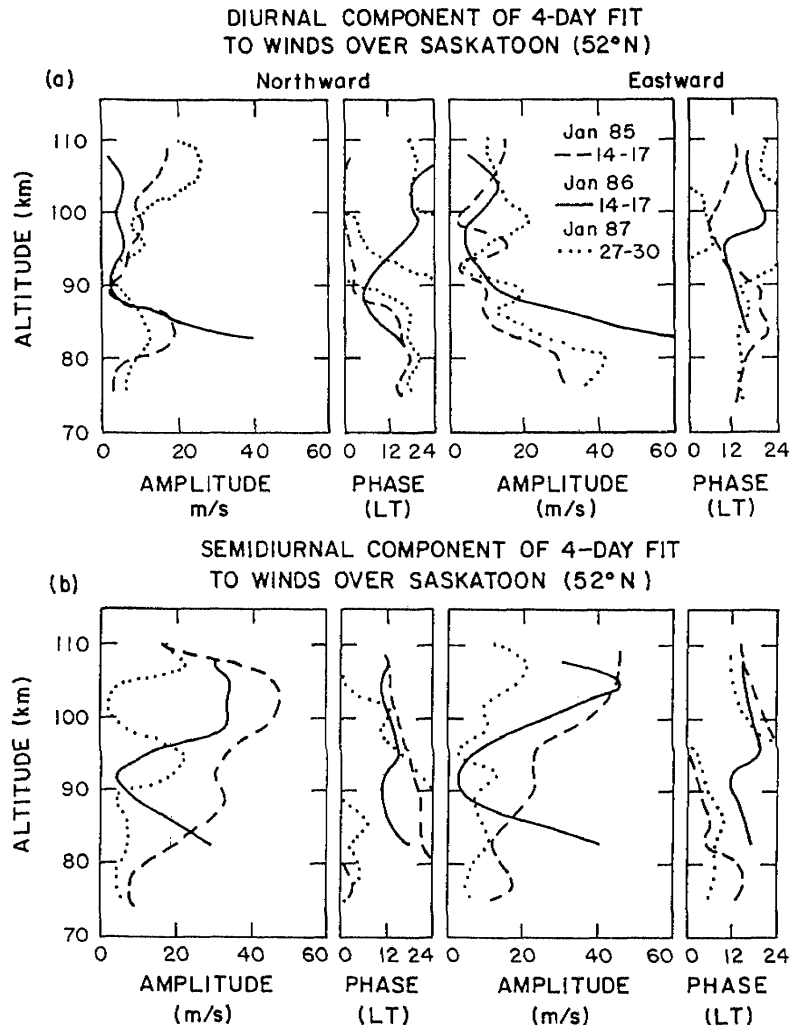


Fig. 7. (a) Diurnal and (b) semidiurnal amplitudes and phases of (left) northward and (right) eastward winds in the mesosphere and lower thermosphere over Saskatoon (52°N) during January 14-17, 1985 (dashes), January 14-17, 1986 (solid), and January 27-30, 1987 (dots).

these three periods as shown in Figure 7b. On average the 12-hour components were characterized by relatively short wavelengths typical of the winter climatology at this location ( $\approx 30 - 40$  km) [e.g., *Manson et al.*, 1989]. Semidiurnal wind amplitudes were comparable (approaching 40 m/s) between 95 and  $\approx 102$  km during the 1985 and 1986 periods, while the semidiurnal winds were less than 10 m/s in the same altitude region during January 27-30, 1987.

The most pronounced feature of the variability observed over Saskatoon is evident in the amplitudes of the tides below 90 km during January 14-17, 1986. Both the diurnal and semidiurnal components of the winds approach 0 m/s near 90 km and rapidly increase as altitude decreases to 80 km (Figures 7a and 7b). Unfortunately, there were insufficient measurements (less than 16 different local time hours) to obtain reliable diurnal harmonics from the 4-day fits below 80 km during the 1986 period. However, there are sufficient data to suggest that interference between waves or modes [Forbes, 1982; Teitelbaum *et al.*, 1989] may play an important role in the interpretation of the tides near 90 km during 1986.

It is also interesting to note the relatively large amplitudes in both the diurnal and semidiurnal wind components between 80 and 85 km over Saskatoon during 1986. We believe that these features may be evidence of a significant in situ heat source in the upper mesosphere. Recently, *Mlynczak and Solomon* [1991] identified a new heat source which is important to this region of the middle atmosphere and comparable to heating attributable to direct solar forcing as well as well-known exothermic reactions involving odd-oxygen reactions [e.g., *Garcia and Solomon*, 1983]. In particular, they reported on an additional class of exothermic reactions involving members of the odd-hydrogen family. *Mlynczak and Solomon* calculated associated mesospheric heating rates which peak just below 90 km.

Further evidence of middle atmosphere heating is found in the Adelaide, South Australia ( $35^{\circ}\text{S}$ ), MFR wind measurements made during January 14-17, 1986, and January 27-30, 1987. The diurnal harmonic components of 4-day fits to the Adelaide wind data, illustrated in Figure 8a, were characterized by large amplitudes when compared with climatological averages [Vincent *et al.*, 1989]. More importantly, the diurnal wind phases exhibited largely evanescent behavior. The exception to this characterization is evident in the eastward component of the diurnal wind during the 1986 period. Specifically, the eastward phases were characterized by a strong tilt below 90 km (Figure 8a), suggesting that there was some contribution from the so-called (1,1) propagating mode in that set of data. We conclude that while there may have been important energy and momentum forcing of the diurnal tide in the middle atmosphere producing large diurnal wind amplitudes during both January periods, there was, in general, relatively little evidence of a significant upward propagating diurnal tide in the Adelaide data. Since the Adelaide location is favorable for experimental evidence of a significant propagating diurnal tide [e.g., *Forbes and Hagan*, 1988; *Forbes and Vincent*, 1989], our results suggest that the middle atmosphere diurnal heat sources were primarily exciting trapped modes (e.g., the so-called (1,-2) mode) during the periods of interest to this report. Our results could also be evidence, however, that the (1,1) mode was excited in the lower atmosphere and

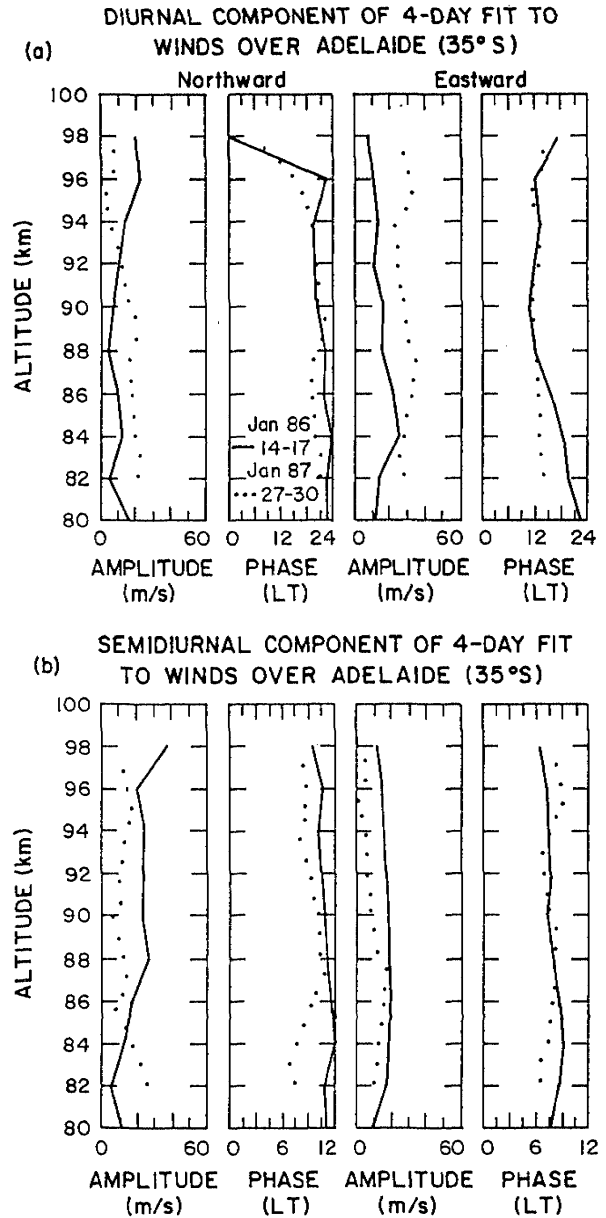


Fig. 8. (a) Diurnal and (b) semidiurnal amplitudes and phases of (left) northward and (right) eastward winds in the mesosphere and lower thermosphere over Adelaide ( $35^{\circ}\text{N}$ ) during January 14-17, 1986 (solid), and January 27-30, 1987 (dots).

damped by eddy diffusivity as it propagated upward [Forbes and Hagan, 1988].

While diurnal wind amplitudes over Adelaide during the 1987 period were larger than they were during the 1986 period (Figure 8a), the reverse was true for the semidiurnal wind components (Figure 8b). The phases, however, were largely consistent during both periods and reflect the climatological behavior described by *Vincent et al.* [1989]. *Fraser et al.* [1989] discussed interannual variability in mesospheric and lower thermospheric tides over Adelaide. In particular, they reported that interannual variability (up to 20 m/s) was a persistent feature of the semidiurnal zonal wind ampli-



tudes during the month of January between 1980 and 1986. They found no significant variability in either the meridional semidiurnal wind amplitudes or the semidiurnal phases during the same periods, however.

We have illustrated significant interannual variability in observed mesospheric and lower thermospheric tides at two locations during three January periods when the thermosphere exhibited interesting weather. However, on the basis of the limited geographical availability of these measurements, we are unable to infer additional global information from the data. Specifically, we are unable to determine whether the upward propagating (global) diurnal and semidiurnal tides were significantly variable during these periods or whether the observed variability could be attributable to a 5- to 10-day wave which was at different phases during the three experimental periods. As a result, we are also unable to evaluate whether the climatological lower boundary specifications for NCAR TIGCM simulations [Forbes and Vial, 1989] are well suited for simulations of the specific periods that we have investigated. On the basis of the observational information that we have, however, we cannot preclude the role of upward propagating semidiurnal tides in the plausible interpretations of the upper atmospheric variability observed during recent solar minimum winter.

### 3.2. Nitric Oxide

The latitudinal, altitudinal, and absolute density distribution of nitric oxide [NO] in the thermosphere exerts an important influence on the temperature, composition and dynamics throughout the region [e.g., Kockarts, 1980; Roble and Emery, 1983; Gérard and Roble, 1986; Siskind et al., 1989a,b; Fuller-Rowell and Rees, 1991]. In the following paragraphs, we describe [NO] data from SME satellite observations made during the specific January periods of interest (Table 1). Further, we characterize these measurements in the light of the reference models developed from the SME [NO] data base [Barth, 1990].

Lower thermospheric [NO] from measurements made with an ultraviolet spectrometer on board the polar-orbiting SME satellite [Barth et al., 1988] during January 16, 1985 and 1986, are illustrated in Figures 9a and 9b, respectively. SME [NO] measurements were not available during January 1987. Figure 9 illustrates the interannual variability that typified the [NO] data we examined for the January 14-17, 1985, and January 14-17, 1986, periods. While low-latitude ( $\pm 30^\circ$ ) [NO] data were largely comparable during these times, [NO] measurements made over the southern hemisphere were significantly different at both middle and high latitudes. Specifically, [NO] measurements in these regions were of the order of  $1.5\text{--}2 \times 10^7$  molecules/cm<sup>3</sup> between 100 and 130 km during the January 1985 period and about half as large during January 14-17, 1986. There were no direct [NO] measurements available poleward of  $45^\circ\text{--}55^\circ\text{N}$  in the northern hemisphere during either January campaign period. The observational limits, in both cases, were associated with the location of the solar terminator. During January 1985, SME flew one orbit per day and crossed the equator near  $100^\circ\text{W}$  longitude over the Pacific Ocean. During January 1986, the flight pattern was similar, but the equatorial crossing longitude was shifted west by some  $60^\circ$ . As a result of the orbit changes, the northern limit of [NO] measurements shifted from about  $55^\circ\text{N}$  during January 1985

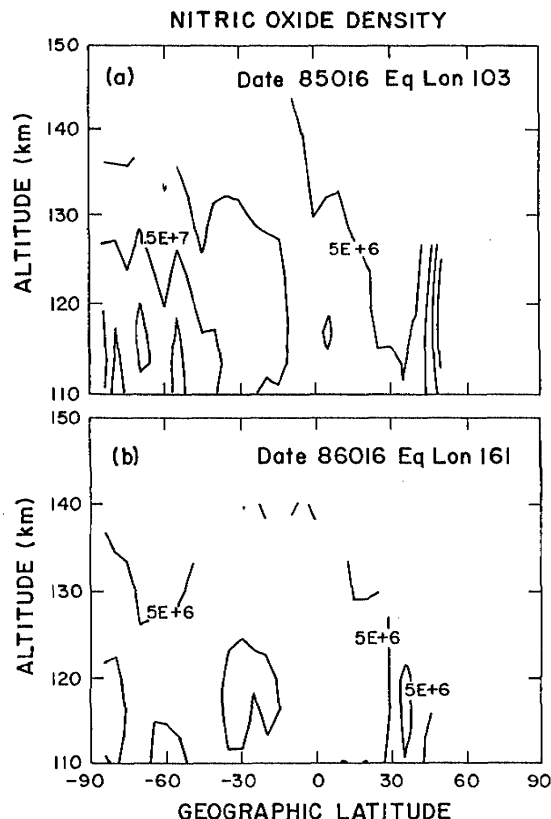


Fig. 9. (a) Contours of [NO] (molecules/cm<sup>3</sup>) versus altitude and geographic latitude during January 16, 1985. Minimum contour level is  $5 \times 10^6$ . Contour interval is  $5 \times 10^6$ . (b) Same as Figure 9a except for January 16, 1986.

to near  $45^\circ\text{N}$  latitude during January 1986. Even though there are no data at higher latitudes in the northern hemisphere, it is still reasonable to assume that NO densities were relatively depleted in these regions during January 1986 as compared with January 1985. Energetic particle precipitation plays a dominant role in the production of NO at high latitudes. It is reasonable to infer the qualitative features of the interannual variability in the high-middle- and high-latitude northern hemisphere from the southern hemisphere [NO] observations, assuming particle precipitation is symmetric in the two hemispheres. In order to utilize the SME NO data in our interpretation of the Arecibo  $T_\infty$  data, we assume further that longitudinal variations in [NO] were not strong during these periods.

The salient features of empirical [NO] model predictions for solar minimum and northern hemisphere winter conditions [Barth, 1990] are contained in the measurements illustrated in Figure 9. For example, maximum NO densities are found near  $60^\circ\text{S}$  between 105 and 120 km. However, only the measurements from the 1985 campaign period (Figure 9a) are comparable in magnitude to the absolute NO density predictions of the reference model. This discrepancy is not surprising, however, since the reference model was developed from all available SME [NO] data collected between December 9, 1984, and January 4, 1985. The smaller densities characterizing the January 1986 data are also associated with a period when the long-term average flux of