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Observations of Upper Atmospheric Weather During Solar Minimum Winter

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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_∞) derived from incoherent scatter radar measurements made during January 14-17, 1986, in the American sector. Specifically, they found a suppression in T_∞ at low latitudes (near 18°N) with respect to middle latitude T_∞ 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_∞.

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_∞ 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_∞ 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

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TABLE 1. Geophysical Conditions

Date	$F_{10.7}$	*Ap*	*Kp*							
Jan. 14, 1985	75.1	9	1^+	3^-	2^-	2^+	3^-	3^+	1^+	1^+
Jan. 15, 1985	74.8	9	1^+	1^+	2	2^+	2	3^+	3	2
Jan. 16, 1985	74.9	8	2^+	3	2^+	2^+	2^+	2	1	1^-
Jan. 17, 1985	77.2	9	0	0^+	1	3^+	2^+	3^+	3^-	2
Jan. 14, 1986	76.8	4	1	1^-	1^-	1^+	1	1	1	1^-
Jan. 15, 1986	79.0	5	0^+	1^-	1^+	2	1^+	2^+	2^-	0^+
Jan. 16, 1986	77.7	3	0^+	1^-	1	1^-	0^+	1^-	1^-	0^+
Jan. 17, 1986	78.0	6	0	1^-	1	1^+	1^+	2^-	2^+	3
Jan. 27, 1987	72.1	7	1	3^-	1^+	3	3^-	1^-	1^-	1
Jan. 28, 1987	73.0	11	2^+	2^+	2^+	2^-	2^-	3^+	3	3^+
Jan. 29, 1987	72.8	10	5^-	3^+	2	1	1^+	1^-	1^-	1^+
Jan. 30, 1987	72.0	4	2^-	0^+	0	0^+	1^-	2^-	1^+	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_∞ in the American sector, since the initial evidence of winter thermospheric weather due to other than geomagnetic forcing was seen in this parameter. T_∞ 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_∞ 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_∞ 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_∞ determinations at 18°N and 43°N for each of the three January periods are illustrated in Figures 1*a* and 1*b*, respectively. Results of harmonic analyses at these latitudes highlight the differences in T_∞ 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_∞ at the lower latitude (Figure 1*a*). Nighttime (daytime) T_∞ 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_∞ at 43°N are virtually identical for the 1985 and 1987 experiment periods (Figure 1*b*). 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_∞ with respect to middle-latitude T_∞ 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_∞ 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_∞ 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 in the higher order harmonics as seen in Figure 1*a* and Table 2. We return in section 4 to a discussion of uncertainties in ISR T_∞ determinations in order to further justify the apparent low-latitude T_∞ 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-

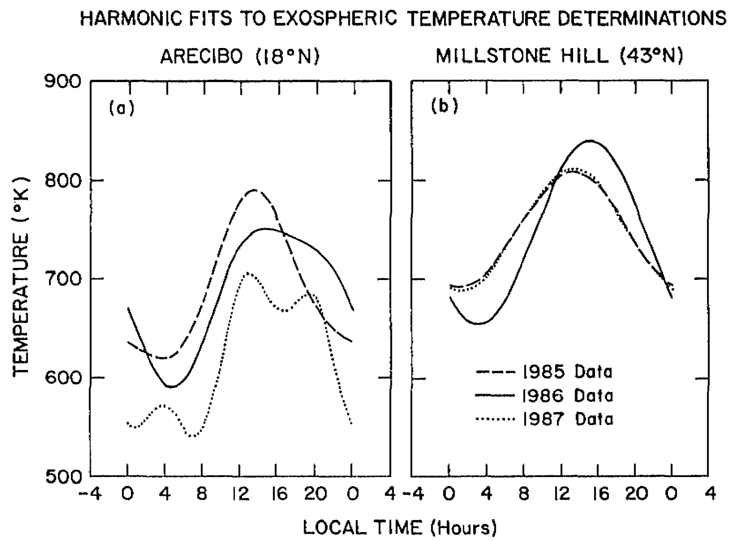

Fig. 1. Harmonic fits to ISR T_∞ determinations over (*a*) Arecibo (18°N) and (*b*) Millstone Hill (43°N) during January 14-17, 1985 (dashes), January 14-17, 1986 (solid), and January 27-30, 1987 (dots).

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_∞ 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_∞ 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_∞ 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_∞ 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 magnetic meridian over Millstone Hill for the three January periods. The anomalous behavior of diurnal T_∞ 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_∞ at

18°N (Figure 1*a* 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 unknown 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.

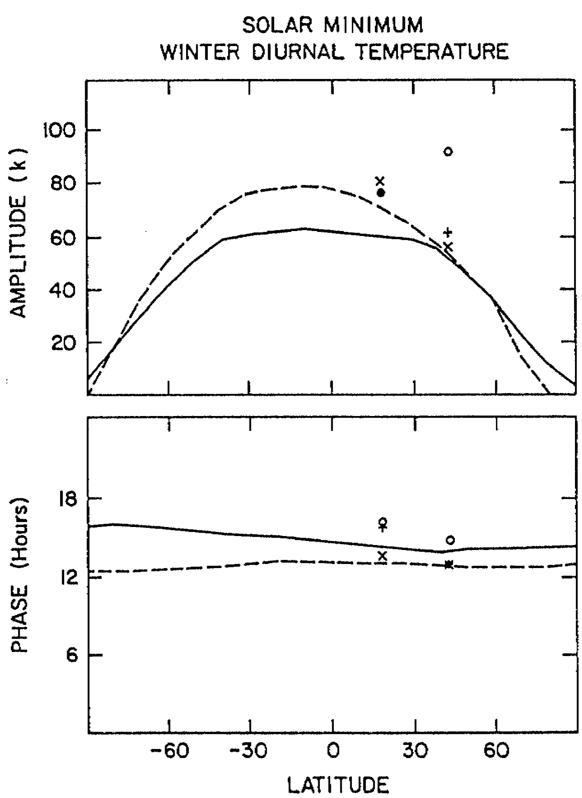

Fig. 2. Diurnal temperature (top) amplitude and (bottom) phase versus latitude during January 14-17, 1985 (crosses), January 14-17, 1986 (circles), and January 27-30, 1987 (pluses), with the model predictions of Roble (private communication, 1990) (solid curve) and *Forbes and Garrett* [1978] (dashed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

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 (≈ 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 (≈ 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

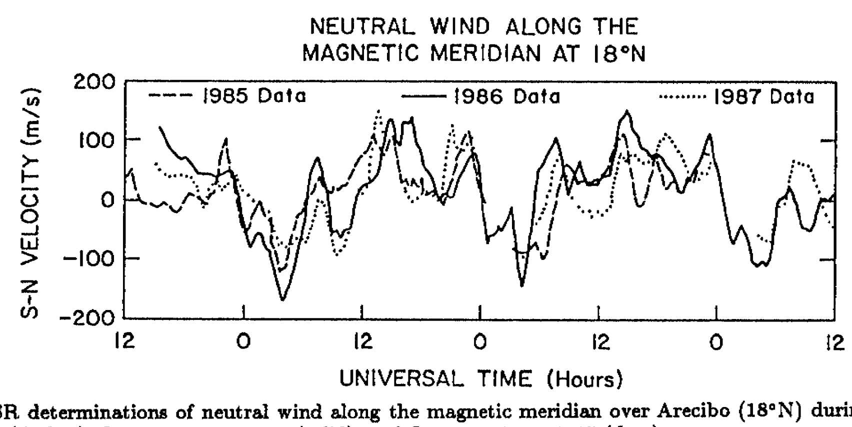

Fig. 3. ISR determinations of neutral wind along the magnetic meridian over Arecibo (18°N) during January 14-17, 1985 (dashes), January 14-17, 1986 (solid), and January 27-30, 1987 (dots).

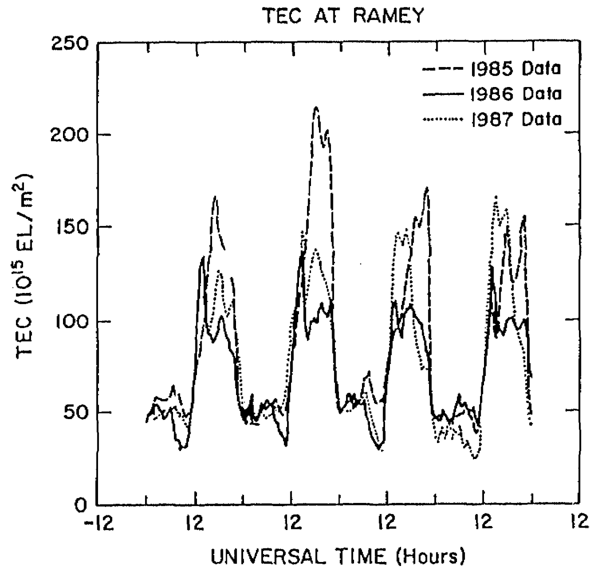

Fig. 4. Total electron content (TEC) measurements over Ramey Air Force Base (18°N) during January 14-17, 1985 (dashes), January 14-17, 1986 (solid), and January 27-30, 1987 (dots).

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°N in January 1986 as compared with 1987 and 1985, respectively. This behavior suggests that UV and EUV irradiance may have been in decline during 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 α (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 α. *Specifically, they reported that solar Lyman* α 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 α 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 α 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_∞ (Figure 1*b*) 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 1*a* 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_mF_2) over Wallops Island, Virginia (38°N), with the corresponding altitudes (H_mF_2) at which

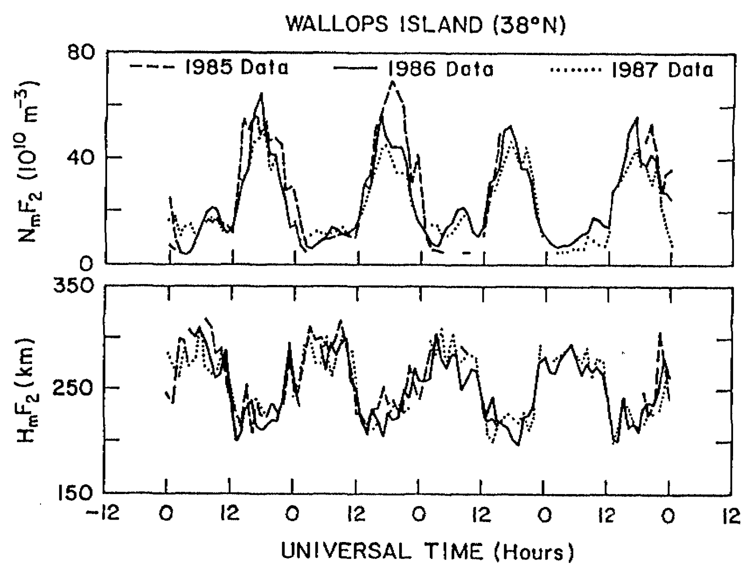

Fig. 5. Ionosonde measurements of (top) N_mF_2 and (bottom) H_mF_2 over Wallops Island (38°N) during January 14-17, 1985 (dashes), January 14-17, 1986 (solid), and January 27-30, 1987 (dots).

N_mF_2 occurred during the three January periods. On average, N_mF_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°N), and Okinawa, Japan (26°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_mF_2 from low-latitude stations at Maui, Hawaii (20°N), Dakar, Senegal (15°N), and Manila, Philippines (15°N), are illustrated in Figures 6*a*, 6*b*, and 6*c*, 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 6*c*), the African data (Figure 6*b*) indicate largely comparable ionospheric conditions during the three periods. Further, the Pacific data (Figure 6*a*) 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 6*a*-6*c*) suggests further that the low-latitude suppression in T_∞ (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

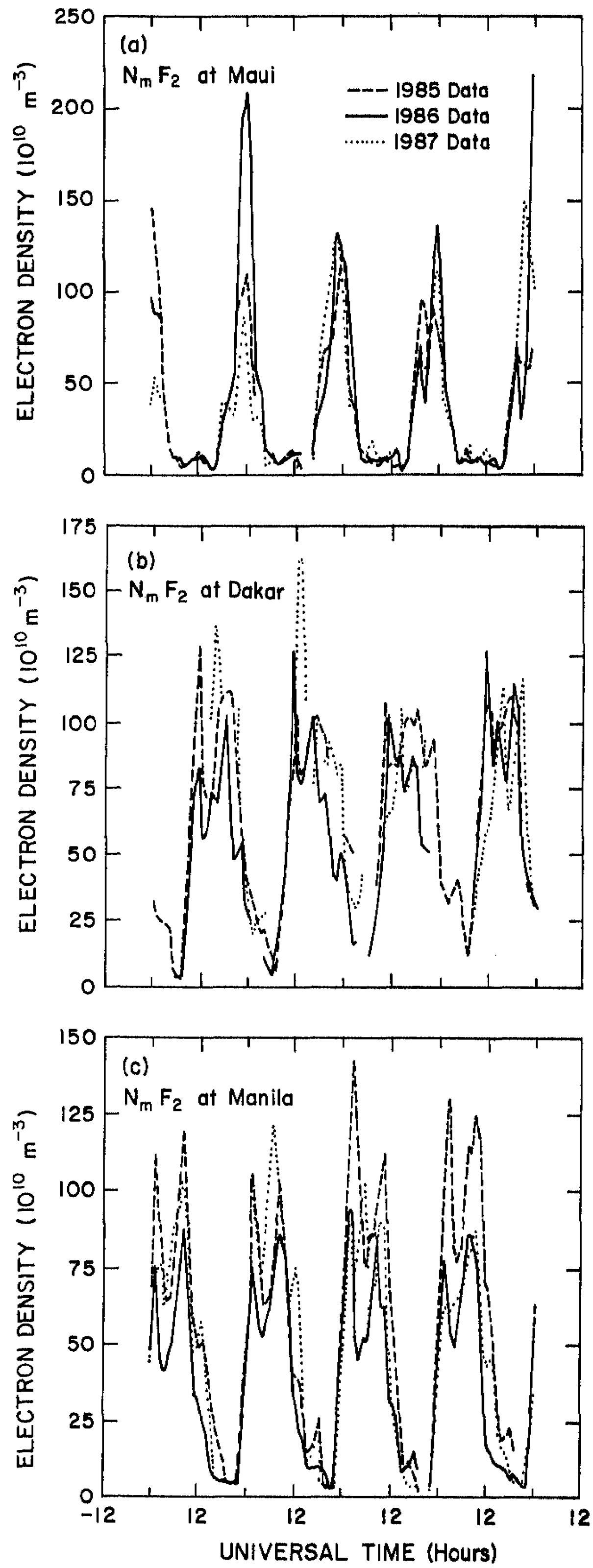

Fig. 6. Ionosonde measurements of N_mF_2 over (*a*) Maui (20°N), (*b*) Dakar (15°N), and (*c*) Manila (15°N) during January 14-17, 1985 (dashes), January 14-17, 1986 (solid), and January 27-30, 1987 (dots).

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 7*a* (Figure 7*b*) 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 7*a* 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 7*a* 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 7*a*. 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

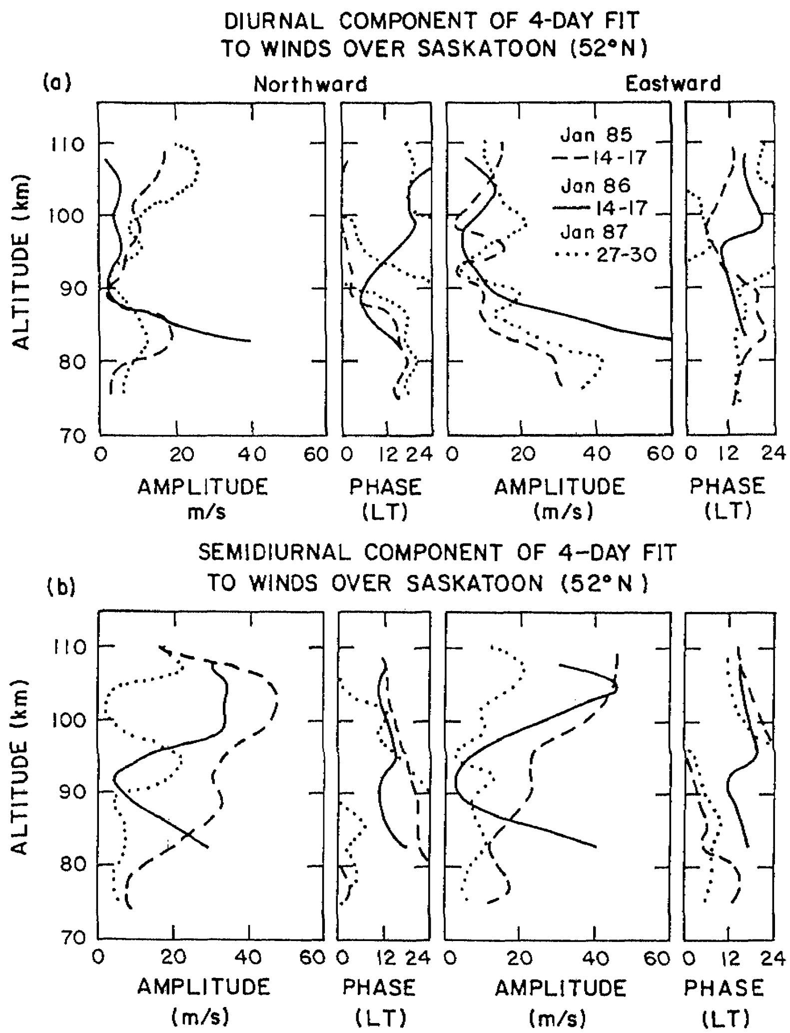

Fig. 7. (*a*) Diurnal and (*b*) semidiurnal amplitudes and phases of (left) northward and (right) eastward winds in the mesosphere and lower thermosphere over Saskatoon (52°N) during January 14-17, 1985 (dashes), January 14-17, 1986 (solid), and January 27-30, 1987 (dots).

these three periods as shown in Figure 7*b*. 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 7*a* and 7*b*). 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°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 8*a*, 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 8*a*), 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

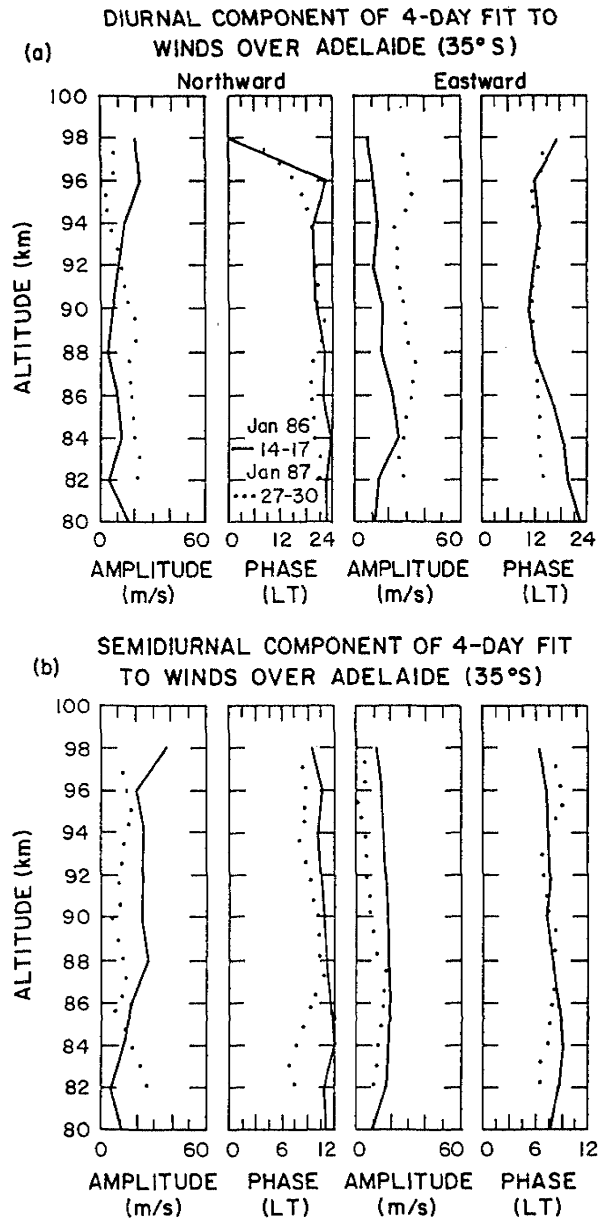

Fig. 8. (*a*) Diurnal and (*b*) semidiurnal amplitudes and phases of (left) northward and (right) eastward winds in the mesosphere and lower thermosphere over Adelaide (35°N) during January 14-17, 1986 (solid), and January 27-30, 1987 (dots).

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 amplitudes 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.*, 1989*a*,*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 9*a* and 9*b*, 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 ($\pm 30°$) [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 1.5-2×10^7 molecules/cm^3 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°-55°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°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°. As a result of the orbit changes, the northern limit of [NO] measurements shifted from about 55°N during January 1985 to near 45°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_∞ data, we assume further that longitudinal variations in [NO] were not strong during these periods.

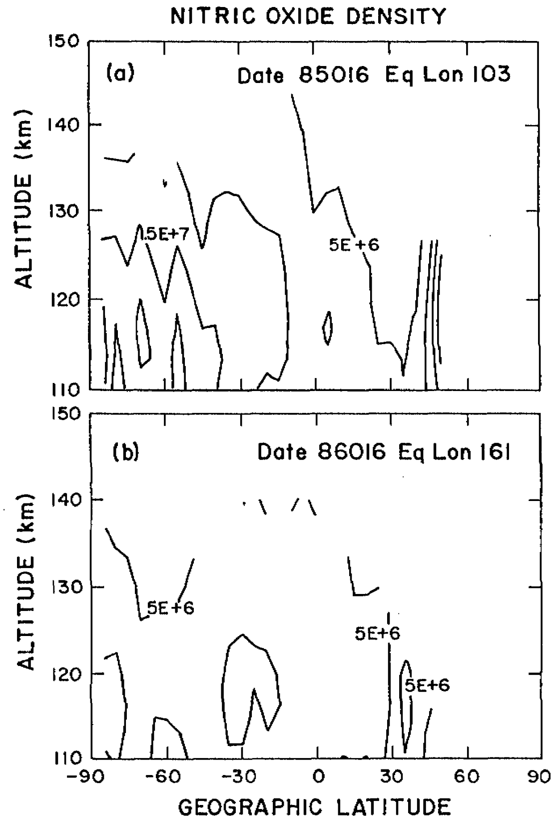

Fig. 9. (*a*) Contours of [NO] (molecules/cm^3) versus altitude and geographic latitude during January 16, 1985. Minimum contour level is 5×10^6. Contour interval is 5×10^6. (*b*) Same as Figure 9*a* except for January 16, 1986.

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°S between 105 and 120 km. However, only the measurements from the 1985 campaign period (Figure 9*a*) 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 solar Lyman α radiation had declined relative to January 1985 average solar Lyman α flux [*Barth et al.*, 1990]. In contrast, between January 1985 and January 1986 the long-term average of 10.7-cm solar radio flux remained nearly constant (e.g., Table 1). *Barth et al.* [1988] reported high correlations between [NO] and solar Lyman α irradiance in their analysis of SME data from January 1982 through April 1985. Our data (Figure 9) provide further evidence of this correlation. There may also be a signature of longitudinal variability of NO embedded in our interannual comparison due to the change in the SME orbit between the January 1985 and 1986 periods. We were not able to quantify the effect of the 60° longitudinal shift for these particular periods.

We found significant interannual variability in the [NO] measurements made during January 14-17, 1985 and 1986. We highlighted this characteristic in the illustration of the [NO] measurements from an individual day during each campaign period (Figure 9). However, we also found significant day-to-day variability in [NO], particularly at middle and high latitudes, within each of the campaign periods. Previously, *Fesen et al.* [1990] reported that significant day-to-day variability in [NO] was a persistent feature of the lower thermosphere, even during geomagnetically undisturbed conditions. Figures 10*a* and 10*b* illustrate [NO] profiles from measurements made at 18°N and 43°N during January 15 and 16, 1985, respectively. These measurements typify the day-to-day variability that we found. While the low-latitude [NO] remained nearly constant over the course of the 2 days, the corresponding middle-latitude densities were significantly larger ($\approx 6.8 \times 10^6$ molecules/cm^3 near 120 km) on January 16, 1985, than they were on the previous day. Assuming this [NO] enhancement was probably due to increased particle precipitation, there may have been an associated enhancement in aurorally driven thermospheric circulation. We discuss the implications of variability in lower thermospheric NO in more detail in section 4.

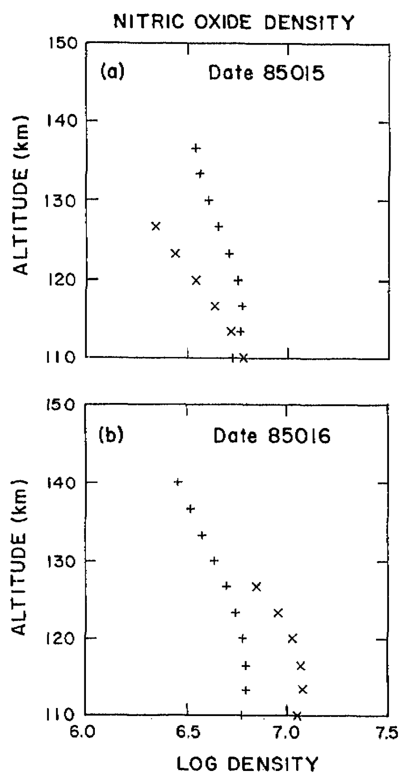

Fig. 10. (*a*) log [NO] (molecules/cm^3) versus altitude at 18°N (+) and 43°N (x) during January 15, 1985. (*b*) Same as Figure 10*a* except for January 16, 1985.

4. Discussion

We have presented evidence of variability of winds and [NO] in the lower thermosphere (section 3) which may be important to interpreting the thermospheric weather that we reported in section 2. We begin our discussion with a brief description of the inherent uncertainties in the ISR T_∞ determination technique in order to ensure the credibility of the low-latitude T_∞ suppression that we reported. In the remainder of this section, we discuss plausible mechanisms that couple the lower and upper thermosphere in light of our data sets.

4.1. *Uncertainties in ISR T_∞ Determination Technique*

Since the T_∞ that we report (Figure 1) are not direct measurements and we find an unexpected feature in these data, we need to address the uncertainties in the ISR T_∞ determination technique, so as to ensure that we are not ascribing a geophysical effect to a bias error in our data. The specifics of the ISR T_∞ determination technique have been sufficiently reported in the literature [e.g., *Nisbet*, 1967; *Bauer et al.*, 1970; *Oliver et al.*, 1984; *Burnside et al.*, 1988]. We confine our present discussion to T_∞ uncertainties inherent in the technique. Further, the uncertainties that we discuss are only applicable to T_∞ data determined from ISR measurements made during geomagnetically undisturbed times.

ISR T_∞ are determined from measurements of ion temperature, electron temperature, and electron density, assuming thermodynamic heat balance in the upper atmosphere, wherein heat gained by the warmer electron gas is balanced by the heat that the ions transfer to the cooler neutral atmosphere. The T_∞ data reported in section 2 were calculated from measurements made between 260 and 400 km, assuming an O^+ ionosphere, and neutral oxygen densities ([O]) from MSIS-86 [*Hedin*, 1987]. In assuming a model [O], we introduce a bias error in our temperatures, thereby increasing the uncertainty in our temperature determination. While statistical uncertainties which result from such calculations are of the order of 10°K, we ascribe a 50°K uncertainty to our determinations to account for such bias. We also determined additional T_∞ which did not include this bias error, and we discuss the technique and these results below.

A dual [O] and temperature search in T_∞ calculations removes the bias error from the determinations. Further, questions surrounding the O^+-O collision cross section [e.g., *Burnside et al.*, 1987; *Sipler et al.*, 1991] are removed from the calculation, since it is the product of the collision cross section and [O], the collision frequency, which may be determined during daytime conditions from ISR measurements. Effects of uncertainty in [O] are equivalent to effects of uncertainty in O^+-O collision cross section. An [O] search in T_∞ calculations allows the neutral temperature profiles to adjust themselves correctly to their asymptotic shapes regardless of the collision cross section assumed, since the product of these terms is the free parameter. In removing the bias error by searching for [O], statistical T_∞ errors then rise to about 30°K during the day. We are unable to calculate nighttime T_∞ using this approach, however. We chose to report T_∞ determinations assuming MSIS-86 [O] densities in order to include both the daytime and nighttime data in our analyses. We did, however, calculate complementary daytime T_∞ allowing [O] to be searched. *Burnside et al.* [1991] report on Arecibo T_∞ and [O] determinations using this technique for the January 1986 and 1987 periods. These results reveal that MSIS-86 systematically overestimates [O] determinations over Arecibo during these times. However, complementary T_∞ determinations are within the 50°K uncertainties ascribed to the determinations that we reported (Figure 1*a*). Further, no such systematic inaccuracy in [O] is found in similar Millstone Hill calculations. Therefore, we conclude that the T_∞ suppression discussed in section 2 is not an artifact of the MSIS-86 [O] assumed in the determination of these data.

4.2. *The Role of Lower Thermospheric Nitric Oxide*

NO primarily acts as a thermospheric heat sink, emitting at 5.3 μm in the infrared [e.g., *Ogawa*, 1976; *Gordiets et al.*, 1978]. NO cooling efficiencies increase with solar activity as both [NO] and temperature increase [e.g., *Stair et al.*, 1975; *Roble and Emery*, 1983]. *Gérard and Roble* [1986, 1988] developed a two-dimensional chemical-dynamical model of the upper mesosphere and thermosphere in order to investigate the role of nitric oxide [NO] during variable solar cycle conditions. They reported on a series of numerical experiments wherein they calculated the latitudinal and altitudinal variations in zonally averaged temperature and winds both with and without effects of NO. *Gérard and Roble* [1986] provided further insight into the effects of NO during solar minimum December solstice conditions. Their results indicated that NO cooling maximizes in the warmest regions of the thermosphere, resulting in temperature decreases throughout the thermosphere in the southern hemisphere [*Gérard and Roble*, 1986]. However, they calculated small temperature enhancements (5°-15°K) in thermospheric temperature between 130 and 400 km in the northern hemisphere when they included the effects of NO in their model. They also found that NO affects the dynamics of the thermosphere. Specifically, NO produces decreases in latitudinal temperature gradients which tended to slow down the circulation. In turn, the NO effects on thermospheric temperature and dynamics result in composition changes. *Gérard and Roble* [1986] calculated variations in [O_2] (20%), [N_2] (5%), and [O] (15%) due to [NO].

In interpreting our thermospheric weather, it is particularly important to note that the Gérard and Roble results suggest that the minimum [NO] occurs at low-middle latitudes in the northern hemisphere and is associated with downward motion as the summer-to-winter circulation cell and the high-latitude aurorally driven cell converge. This downwelling results in adiabatic heating and the northern hemisphere thermospheric temperature enhancements discussed previously. It is, at the very least, improbable that the large-scale thermospheric circulation during January of 1985-1987 differed appreciably from the simulation results of Gérard and Roble. While the exospheric temperature suppressions over Arecibo that we report could be due to adiabatic cooling, we cannot identify a plausible source of upwelling at low latitudes in the northern hemisphere during these periods in order to justify such a scenario. We can envision a relatively weaker, aurorally driven circulation cell during the experimental periods, resulting in an effective poleward shift of the two-cell convergence zone, however. The resultant adiabatic heating effects would be largely confined to middle and high-middle latitudes in the northern hemisphere. However, the associated low- and middle-latitude heating differentials could not fully account for the observed T_∞ differences (Figure 1) during recent solar minimum winter conditions.

Barth [1990] developed a series of reference models of thermospheric [NO] from SME satellite measurements made between 1982 and 1985. His results reveal significant solar cycle variability in lower thermospheric [NO] at all latitudes and seasons. Further, SME [NO] reference models are characterized by a latitudinal minimum near 15°-30°N (geomagnetic latitude) during December solstice with sharp increases toward the winter pole (e.g., Figure 9). These characteristics largely complement the features of AE-C satellite [NO] data previously reported by *Cravens and Stewart* [1978] and *Cravens et al.* [1979]. However, in the southern hemisphere and equatorward of about 40°N (geomagnetic) in the northern hemisphere during winter, NO densities from AE measurements made as solar cycle 20 approached minimum were 2 to 3 times larger than [NO] from SME measurements made in the declining phase of solar cycle 21 [*Fesen et al.*, 1990]. The *Gérard and Roble* [1986] numerical experiments (described above) investigated the effects of [NO] during solar minimum winter for densities largely consistent with the AE observations.

While *Gérard and Roble* [1986] provide the best available simulation results for understanding the effects of NO on thermospheric temperature and dynamics for geophysical conditions characteristic of the periods of interest to our weather study, experimental evidence (Figures 9 and 10; *Fesen et al.* [1990]) suggests that neither the magnitudes nor the latitudinal gradients of lower thermospheric [NO] associated with recent solar cycle minimum conditions were accurately modeled in their study. While it is improbable that such differences in [NO] could produce large-scale changes in thermospheric circulation, we believe that the persistent suppression in the low-latitude diurnal mean T_∞ ($\approx 50° - 70°$K) during the recent solar minimum northern hemisphere winters could still be explained in light of the observed SME [NO] data. Specifically, exothermic chemical reactions involving $N(^2D)$, $N(^4S)$, and NO are an important source of heat in the lower thermosphere. SME [NO] suggest that in the northern hemisphere during the declining phase of solar cycle 21, low-latitude [NO] were overestimated in the simulations of Gérard and Roble, while their middle- and high-latitude [NO] accurately modeled recent observations. The implications of these differences for their thermospheric temperature results could be the overestimation of the effects of exothermic heating due to NO in the lower thermosphere at low latitudes in the northern hemisphere, while the same effects at middle and high latitudes would not be overestimated. Because thermal conduction is efficient throughout the thermosphere, latitudinal variations in lower thermospheric heating could affect the latitudinal structure of T_∞. However, follow-on numerical experiments with the TIGCM are needed to investigate the relative importance of exothermic reactions in the low-latitude lower thermosphere during solar cycle minimum.

Finally, we found significant day-to-day variability in low-latitude lower thermospheric [NO] during the January periods that we investigated (Figure 10). These results suggest that both interannual and day-to-day variability of [NO] may be of further importance to the interpretation of observed variability over Arecibo during January of 1985-1987. A new series of chemical-dynamical modeling experiments is needed to resolve the questions surrounding the effects of NO on thermospheric temperature, composition, and dynamics during recent solar minimum winter conditions.

4.3. *The Role of Upward Propagating Tides*

During the past decade, a significant effort to improve numerical tidal models has contributed to increased understanding of processes important to the coupling between atmospheric regions [e.g., *Akmaev and Shved*, 1980; *Walterscheid*, 1981; *Vial*, 1986; *Forbes and Hagan*, 1988; *Miyahara and Wu*, 1989]. As a result of these and other efforts, we understand that the lower thermosphere is driven primarily by energy and momentum dissipation resulting from interactions between (and among) upward propagating waves and the mean flow. Atmospheric tides, in particular, are known to play an important role in propagating energy and momentum into the lower thermosphere. *Lindzen and Hong* [1974] initially identified the importance of the effects of mean winds on upward propagating semidiurnal tides in the atmosphere. Recently, *Forbes and Vial* [1989] have produced monthly simulations of mesospheric and lower thermospheric semidiurnal tides which account for seasonal variations in mean winds and tidal forcing. *Fesen et al.* [1991] used their results to specify improved lower boundary conditions for the NCAR TIGCM and better account for the role of upward propagating semidiurnal tides in coupling the lower and upper thermosphere. More recently, Forbes et al. (*Acceleration, heating, and compositional mixing of the thermosphere due to upward propagating tides*, submitted to *Journal of Geophysical Research*, 1991) also accounted for the upward propagating diurnal tide in NCAR TIGCM simulations. The results of both TIGCM numerical investigations suggest that upward propagating diurnal and semidiurnal tides significantly affect upper thermospheric temperature and dynamics particularly during solar cycle minimum conditions.

As discussed in section 3.1, significant interannual as well as day-to-day variability is a persistent feature of upward propagating atmospheric tides. *Forbes* [1991] discussed many of the mechanisms which may produce such variability. While any number of these processes could account for the tidal variability that we report, we found insufficient experimental evidence to identify any particular processes. We can report, however, that observed differences in lower atmospheric mean winds have been shown to produce variations in semidiurnal wind amplitudes approaching those observed over Saskatoon (Figure 7b). *Hagan et al.* [1990] reported on the results of a numerical experiment to investigate the effects of the quasi-biennial oscillation (QBO) in stratospheric winds and temperatures on upward propagating semidiurnal tides during northern hemisphere winter. In conducting their numerical experiments, Hagan et al. employed an extension of the *Forbes and Vial* [1989] semidiurnal tidal model. Briefly, they modified the zonal mean temperature and wind profiles for the month of January [*Forbes and Vial*, 1989] to include QBO variations (up to 30 m/s) in the lower atmosphere [after *Justus et al.*, 1980] calibrated to observed equatorial means during January of 1985-1987 (extension of *Najoukat*, [1986]). They subsequently calculated semidiurnal wind amplitudes which deviated from the climatological results [*Forbes and Vial*, 1989] by 5-20 m/s at middle and high latitudes near 100 km. Their results suggest one plausible source of the interannual variability characterizing the semidiurnal observations over Saskatoon during January of 1985-1987 (Figure 7b). *Hagan et al.* [1990] suggest a series of follow-on TIGCM simulations which could be performed to investigate whether these QBO effects can propagate into the thermosphere and produce thermospheric weather of the type that we describe (section 2.1). They recommend a numerical experiment for solar minimum conditions which includes variable lower boundary conditions resulting from their calculations with solar and auroral TIGCM forcing held constant, to resolve whether QBO effects found in semidiurnal tidal signatures could propagate into the upper thermosphere.

5. SUMMARY

We present evidence that the well-known climatological pattern of the magnetically undisturbed northern hemisphere winter thermosphere and ionosphere during solar minimum conditions may not be representative of observed weather patterns. We find that the suppression in T_∞ at low latitudes initially reported by *Hagan and Salah* [1988] persisted to varying degrees for at least the three periods that we considered. We suggest that the seasonal-latitudinal behavior of lower thermospheric [NO] during the declining phase of solar cycle 21 [*Fesen et al.*, 1990] affected thermospheric temperature, composition, and circulation so as to cause the suppression in low-latitude T_∞.

In addition, we report significant interannual variability in the upper thermospheric data sets ($z > 200$ km) which is most pronounced at low latitudes. We find, however, that the signatures characterizing the observed variability cannot be attributed to in situ forcing. We suggest that some of the observed interannual variability may be attributable to upward propagating atmospheric tides.

Finally, we suggest that a series of follow-on numerical experiments using the TIGCM be conducted to test our interpretation of the middle and upper atmospheric data sets. Specifically, the introduction of latitudinal variations in eddy diffusion parameterization in the TIGCM will affect [NO] and subsequently T_∞, thermospheric circulation, and composition [e.g., *Fuller-Rowell and Rees*, 1991]. If the observed low-latitude suppression in thermospheric temperature is indeed attributable to lower thermospheric [NO] as we suggest it is, the TIGCM should be able to model both the latitudinal gradients of [NO] and T_∞ given some adjustment of the eddy diffusion parameterization. Subsequently, we suggest that additional TIGCM simulations be performed to investigate whether variations in the upward propagating tides [e.g., *Hagan et al.*, 1990] could produce interannual variability similar to that which we report.

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