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A Study of the Undisturbed Mid-Latitude Ionosphere Using Simultaneous Multiple Site Ionosonde Measurements During the Sundial–86 Campaign

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The Sundial–86 campaign obtained simultaneous ionosonde measurements of N_mF2 from 41 mid-latitude sites geographically dispersed around the world from September 21 to October 5, 1986. A three-dimensional, time-dependent model of Earth's ionosphere has been used to fit the variations in N_mF2 obtained from these sites. The model successfully reproduced the measurements in both the northern and southern hemispheres using the vertical plasma drift as a free parameter. During geomagnetically quiet conditions this drift is primarily due to the meridional neutral wind. The vertical plasma drift required to fit the data is consistent from location to location and the deduced meridional neutral wind is also consistent with previous neutral wind measurements and models. However, it is shown that a lack of knowledge of the variation of the O^+ flux at the top of the atmosphere introduces a large uncertainty in the deduced thermospheric winds.

1. INTRODUCTION

The goal of the Sundial program is to further our understanding of Earth's ionosphere and its interaction with the neutral atmosphere and the magnetosphere [*Szuszczewicz et al.*, 1988]. The Sundial program is centered around global ionosonde measurements obtained during campaigns spaced 9 months apart. In addition to ionosonde measurements, satellite and ground-based measurements of solar and geomagnetic parameters, incoherent scatter measurements of the ionosphere and optical measurements of thermospheric dynamics are obtained.

One goal of the program is to infer the dynamic behavior of the neutral atmosphere via a detailed understanding of the ionosphere. Since ionosondes are inexpensive, easily maintained, geographically dispersed, and able to operate regardless of tropospheric weather conditions, there have been attempts in the past to infer thermospheric dynamics from them. *Rüster and Dudeney* [1972], *Rishbeth* [1972], and *Rishbeth et al.* [1978] attempted to estimate neutral winds using measurements of N_mF2 and h_mF2 at single sites. In the latter study the authors showed that the variation in h_mF2 with changes in the meridional wind was approximately linear for "small" winds under "steady state" conditions.

Recently, this linear relationship has been used by *Miller et al.* [1986] to deduce the horizontal component of the neutral wind along a magnetic meridian from measurements of h_mF2. Specifically, the meridional wind component is obtained from the relation $u = (h_{max} - h_0)/\alpha$, where u is the meridional wind, h_{max} is the measured value of h_mF2, h_0 is h_mF2 for $u = 0$, and α is a constant. The quantities α and h_0 are calculated using an interhemispheric ionospheric model as follows. For a specified location and time, three model runs are conducted with "constant" wind speeds of 50, 0, and −50 m/s. This provides calculated values of h_mF2 at each of the three wind speeds, from which h_0 and α can be determined by a linear regression. Once h_0 and α are calculated, the measurement of h_{max} yields the meridional wind via the above simple formula that relates these two parameters. This relatively simple method for obtaining meridional winds was tested against winds calculated from Millstone Hill and Arecibo incoherent scatter measurements of electron density profiles for several quiet days. The simple method appeared to be more reliable during the day than at night, where the uncertainty approached a factor of 2. More recently, the simple method has been used to obtain "average" meridional winds from averaged ionosonde data as well as from the International Reference Ionosphere and during the Equinox Transition Study [*Miller et al.*, 1988; *Crowley et al.*, 1989]. Recently, the linear method has been favorably compared to the nonlinear method of *Rishbeth et al.* [1978] using equinox measurements from Millstone Hill [*Buonsanto et al.*, 1989].

In general, the calculation of mid-latitude winds from ground-based measurements of ionospheric parameters is not straightforward. During magnetic storms and substorms, magnetospheric electric fields can penetrate to mid-latitudes and the zonal component of these fields can affect h_mF2, which is why *Miller et al.* [1986] restricted their model tests to quiet days, although with concurrent incoherent scatter radar measurements of the electric field the winds derived from h_mF2 can be corrected [*Miller et al.*, 1987]. Also, near sunrise and sunset the F layer grows and decays, respec-

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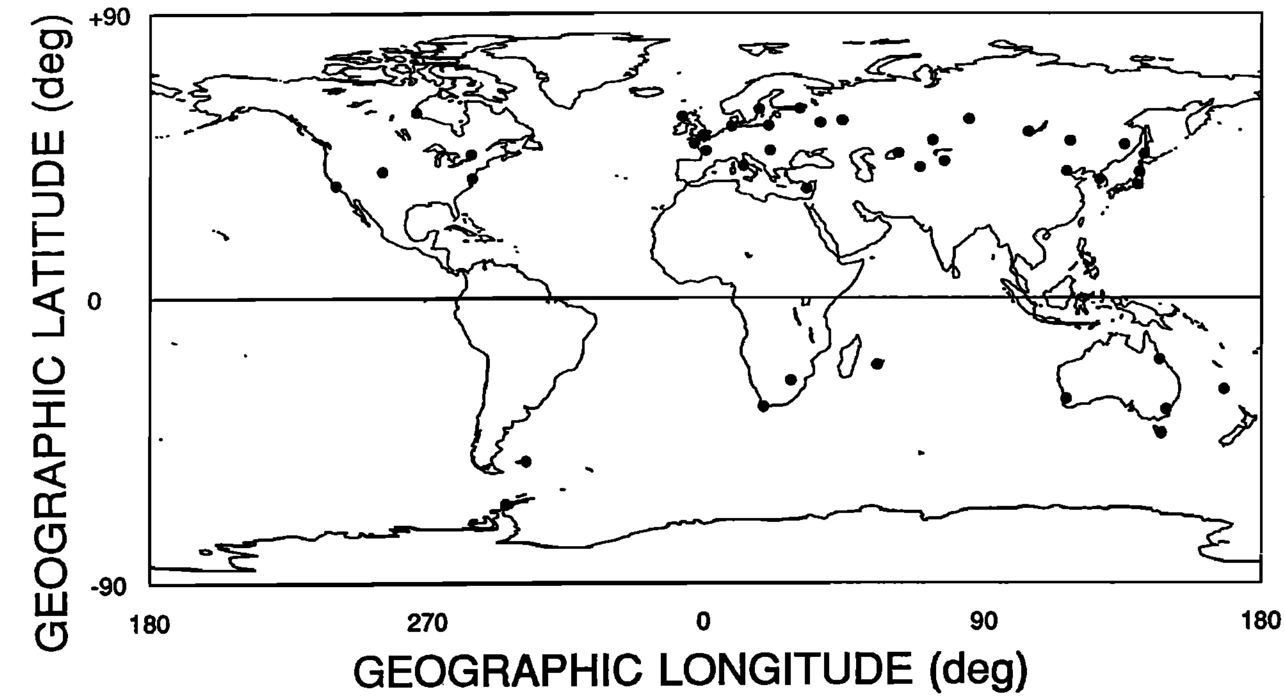

Fig. 1. Sundial stations contributing measurements used in this study. The station names and locations are listed in Table 1.

tively, and there are corresponding h_mF2 variations at these times. Another process that affects both h_mF2 and N_mF2 is a flow of plasma between the ionosphere and the overlying plasmasphere. Finally, on a shorter time scale, upward propagating gravity waves affect h_mF2.

In this study, we used a three-dimensional time-dependent ionospheric model, coupled with a geographically dispersed, simultaneous set of "typical" ionosonde measurements, in order to determine whether the data can be uniquely interpreted. The adjustable input parameters in the model were the vertical plasma drift and the ionosphere-plasmasphere exchange flux.

2. Sundial-86 Ionosonde Measurements

The Sundial-86 campaign took place from September 21 (day 264) to October 5 (day 278) in 1986. During this period, geomagnetic activity varied from low ($Ap = 4$) to moderate ($Ap = 43$) conditions. Figure 1 shows the geographic distribution of the 41 mid-latitude ionosonde stations that participated in the campaign. The most reliable ionospheric parameter obtained from the stations was N_mF2, and this parameter was typically recorded on an hourly basis. Unfortunately, measurements of h_mF2 were not available from this campaign.

Figure 2 shows N_mF2 values for the entire Sundial-86 period, as recorded by the ionosonde in Canberra, Australia. A very marked diurnal cycle is evident, but the variation from day to day can be very large. Typically, when data of this nature are used in the international reference ionosphere, the different diurnal cycles are averaged. Likewise, in deducing meridional winds from ionosonde h_mF2 values, *Miller et al.* [1988] averaged the data to obtain "average" diurnally varying winds for several individual stations. However, even during quiet periods, the difference between the average and actual diurnal variations can be large. Figure 3*a* shows the difference between the average diurnal variation of N_mF2 at Canberra for the Sundial-86 period and the actual variation for day 271. On this quiet day the difference approaches a factor of 2. The empirical formula of *Dudeney* [1983] was used to estimate h_mF2 from M(3000)F2. The difference between the average of the Sundial-86 period and actual h_mF2 values obtained can also be large, as shown in Figure 3*b* for Canberra.

Our interest was in the actual diurnal variation at the various ionosonde stations, and our goal was to determine whether the data, as currently processed, can be unambiguously interpreted in terms of a meridional wind or a

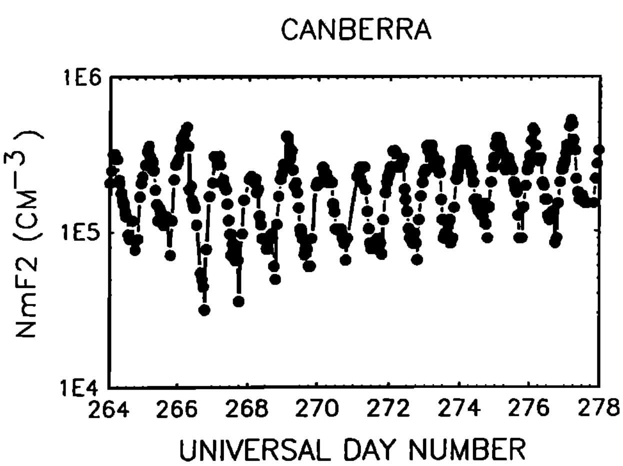

Fig. 2. Hourly N_mF2 values from Canberra, Australia, for the 14-day Sundial-86 period (September 21 to October 5, 1986).

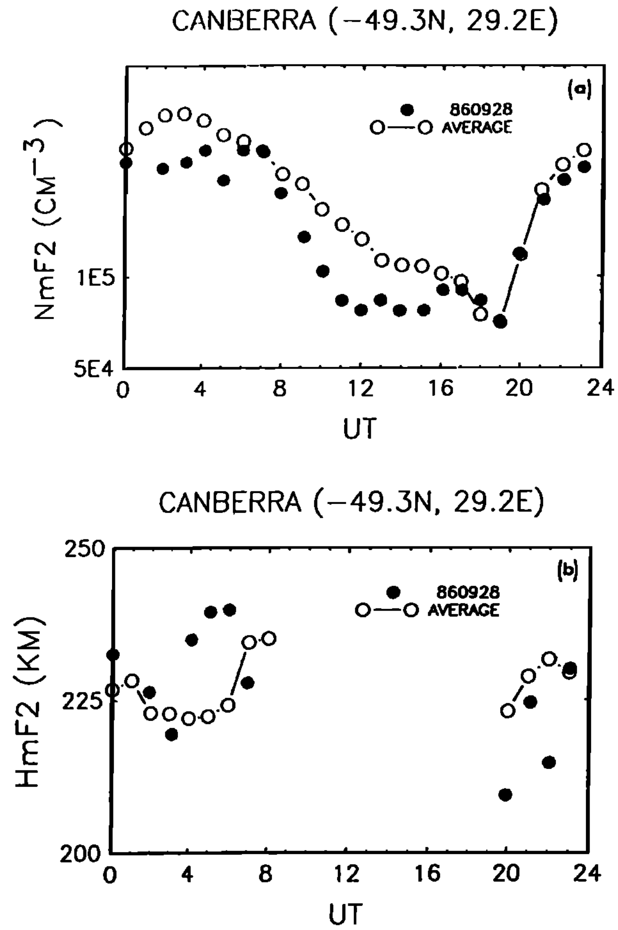

Fig. 3. The diurnal variation of average and actual (*a*) N_mF2 and (*b*) h_mF2 values for day 271 at Canberra. The average is computed for the entire Sundial–86 campaign. The h_mF2 values are calculated using the formula given by *Dudeney* [1983].

plasmasphere-ionosphere coupling flux. The relatively quiet days 271 and 272 were chosen for the study in order to minimize the possible effects of magnetospheric or dynamo electric fields. In addition to being halfway between the disturbed periods of days 267 and 275, days 271 and 272 also contained data from the largest number of stations.

It was not practical to make 41 separate computer simulations for the 41 stations, and furthermore, it was unlikely that sufficient new information would be obtained for this number of simulations to be warranted. Hence the data were consolidated into groups that best reflected regions where the model was most sensitive. Experience has shown that the ionospheric model is more sensitive during quiet times to latitudinal rather than longitudinal effects, hence groupings were chosen to emphasize latitudinal differences (such as groups 1 and 2 in Europe). To facilitate assimilation of a large number of measurements from the 41 sites, nearby locations with similar diurnal variations of N_mF2 were grouped together by geographic latitude and longitude. The average position of each group, shown in Table 1, was used for the model calculations. The selection criteria used in the northern hemisphere was, in the European sector (350° to 60° longitude), 50° to 60° latitude (group 1), and 30° to 50° (group 2). The next groups were in the Asian sector (60° to 180° longitude) and were at latitudes of 50° to 60° (group 3), 40° to 50° (group 4), and 30° to 40° latitude (group 5). The final northern hemisphere sites from 250° to 300° longitude in North America were 40° to 60° (group 6) and 30° to 40° latitude (group 7). Groups 8 to 11 were in the southern hemisphere (see Table 1).

The measurements from each group were averaged and weighted by the variance of the individual measurements. The deviations between measurements from the individual stations, relative to the mean, were expressed as the root-mean-square (rms) deviation [*Bevington*, 1969]. When the stations contributing to the average at a given time had approximately the same value of N_mF2, the rms deviations were small, and vice versa. Measurements flagged with a URSI descriptive letter *D* or *E* (corresponding to measurements exceeding the frequency limits of the ionosonde) were not included in the averages.

3. Model Studies

3.1. *The Ionospheric Model*

The ionospheric model was initially developed as a mid-latitude, multi-ion (NO^+, O_2^+, N_2^+, and O^+) model by *Schunk and Walker* [1973]. The time-dependent ion continuity and momentum equations were solved as a function of altitude for a corotating plasma flux tube including diurnal variations and all relevant *E* and *F* region processes. This model was extended to include high-latitude effects due to convection electric fields and particle precipitation by *Schunk et al.* [1975, 1976]. A simplified ion energy equation was also added, which was based on the assumption that local heating and cooling processes dominate (valid below 500 km). Flux tubes of plasma were followed as they moved in response to convection electric fields. A further extension of the model to include the minor ions N^+ and He^+, an updated photochemical scheme, and the mass spectrometer/incoherent scatter (MSIS) atmospheric model [*Hedin et al.*, 1977] is described by *Schunk and Raitt* [1980].

The addition of plasma convection and particle precipitation models is described by *Sojka et al.* [1981*a*, *b*]. The ionospheric model has been extended by *Schunk and Sojka* [1982] to include ion thermal conduction and diffusion-thermal heat flow, so that the ion temperature is now rigorously calculated at all altitudes between 120 and 1000 km. The adopted ion energy equation and conductivities are those given by *Conrad and Schunk* [1979]. Also, the electron energy equation has been included recently by *Schunk et al.* [1986], and consequently, the electron temperature is now rigorously calculated at all altitudes. The electron energy equation and the heating and cooling rates were taken from *Schunk and Nagy* [1978], and the conductivities were taken from *Schunk and Walker* [1970]. The incorporation of the *Sterling et al.* [1969] equatorial ionospheric model and the various improvements to this model are described by *Sojka and Schunk* [1985].

3.2. *Physical Processes Which Affect N_mF2 and h_mF2*

The drift velocity of the ionospheric plasma can change the peak of the *F* region electron density (N_mF2) and the height of the peak (h_mF2). The drift velocity of the plasma is related to the time derivative of the density through the continuity equation

TABLE 1. Ionosonde Stations

	Geographic		Centered Dipole	
	Latitude	Longitude	Latitude	Longitude
Group 1				
Leningrad	60.0	30.7	56.2	118.0
Uppsala	59.8	17.6	58.4	106.5
South Uist	57.4	352.7	61.0	80.6
Gorky	56.2	44.3	50.3	127.3
Moscow	55.5	37.3	50.8	121.1
Kalingrad	54.6	20.6	53.1	106.0
St. Peter-Ording	54.3	8.6	55.0	94.6
Slough	51.5	359.4	52.2	83.9
Average	56.2	18.9	54.8	105.3
Average I	69.8			
Group 2				
Lannion	48.8	356.6	52.2	79.7
Bekescsaba	46.7	21.2	45.3	102.8
Poiters	46.6	0.3	49.3	82.4
Rome	41.8	12.5	42.3	92.6
Cape Zevgari	34.6	33.0	31.4	110.0
Average	43.7	12.7	44.1	93.5
Average I	59.3			
Group 3				
Tomsk	56.5	84.9	45.9	160.2
Irkutsk	52.5	104.0	41.1	175.0
Karaganda	49.8	73.1	40.3	149.3
Manchouli	49.6	117.4	38.2	185.9
Average	52.1	94.9	41.0	167.6
Average I	70.4			
Group 4				
Novo Kazulinsk	45.8	62.1	37.6	139.0
Alma Alta	43.2	76.9	33.4	151.3
Tashkent	41.3	69.0	32.3	144.1
Peiping	40.0	116.3	28.6	185.3
Average	42.6	81.1	32.4	154.9
Average I	60.8			
Group 5				
Khabarousk	48.5	135.2	38.0	200.8
Wakkanai	45.4	141.7	35.4	206.7
Akita	39.7	140.1	29.6	206.1
Seoul	37.4	127.0	26.4	194.9
Tokyo	35.7	139.5	25.6	206.1
Average	41.3	136.7	30.9	203.0
Average I	55.6			
Group 6				
Churchill	58.7	265.8	68.6	324.0
Ottawa	45.4	284.1	56.7	352.2
Boulder	40.0	254.7	48.9	317.4
Average	48.0	268.2	58.3	331.5
Average I	75.8			
Group 7				
Wallops Island	37.8	284.5	49.2	353.1
Point Arguello	35.6	239.4	42.2	301.6
Average	36.7	262.0	46.5	326.6
Average I	65.8			
Group 8				
Townsville	-19.6	146.8	-34.0	23.8
Norfolk Island	-29.0	168.0	-39.9	49.7
Average	-24.3	157.4	-37.2	36.6
Average I	-52.8			
Group 9				
La Reunion	-21.2	55.6	-25.6	283.1
Johannesburg	-26.1	28.1	-23.0	255.1
Cape Town	-34.4	19.2	-28.7	244.3
Average	-27.3	34.3	-25.8	260.5
Average I	-61.2			
Group 10				
Mundaring	-32.0	116.2	-47.2	347.7
Canberra	-35.3	149.0	-49.3	29.2
Hobart	-42.9	147.3	-57.0	29.2
Average	-36.7	137.5	-51.8	15.0
Average I	-68.4			
Group 11				
Falkland Island	-51.7	302.2	-36.2	177.1
Argentine Island	-65.2	295.7	-49.9	173.3
Average	-58.4	299.0	-43.0	175.0
Average I	-53.2			

$$\frac{\partial N}{\partial t} = q - L(N) - \nabla \cdot (N\mathbf{V}) \qquad (1)$$

where q (L) is the rate of production (loss) of electrons, and $\mathbf{V}$ is the plasma drift velocity. An excellent review of the physical meaning of this equation in the F region has recently been presented by *Rishbeth* [1986].

Rishbeth [1986] lists the major physical processes that contribute to the drift velocity at mid-latitude. When the contribution of these processes to the $\nabla \cdot (N\mathbf{V})$ term of the continuity equation is a significant fraction of the chemical losses due to recombination, N_mF2 can be significantly altered. The important processes are, first, thermal expansion and contraction of the atmosphere, which does not affect the pressure level of a parcel of air but will change its height. Second are neutral winds, which can move the plasma up and down the magnetic field, which changes both N_mF2 and h_mF2. Third, zonal electric fields can cause $\mathbf{E} \times \mathbf{B}/B^2$ vertical drifts of the plasma (where $\mathbf{E}$ and $\mathbf{B}$ are the ionospheric electric and magnetic field vectors). At mid-latitudes this effect can be particularly important at sunrise and sunset. Fourth, plasma diffusion acts to smooth out inhomogeneities caused by other processes, such as plasma instabilities. Fifth, flux into and out of the plasmasphere can increase or decrease N_mF2 and slightly alter h_mF2. For filled flux tubes at night, the downward flow of H^+, which then undergoes charge exchange to become O^+, is deposited in the ionosphere to help maintain the nighttime F region densities.

3.3. *Comparisons With Measurements, Neutral Wind Effects*

The ionospheric model was run for each of the 11 groups using the geophysical parameters listed in Table 2. As this was a period of low geomagnetic activity and the site selection was limited to mid-latitudes, substorm effects due to convection electric fields and auroral particle precipitation

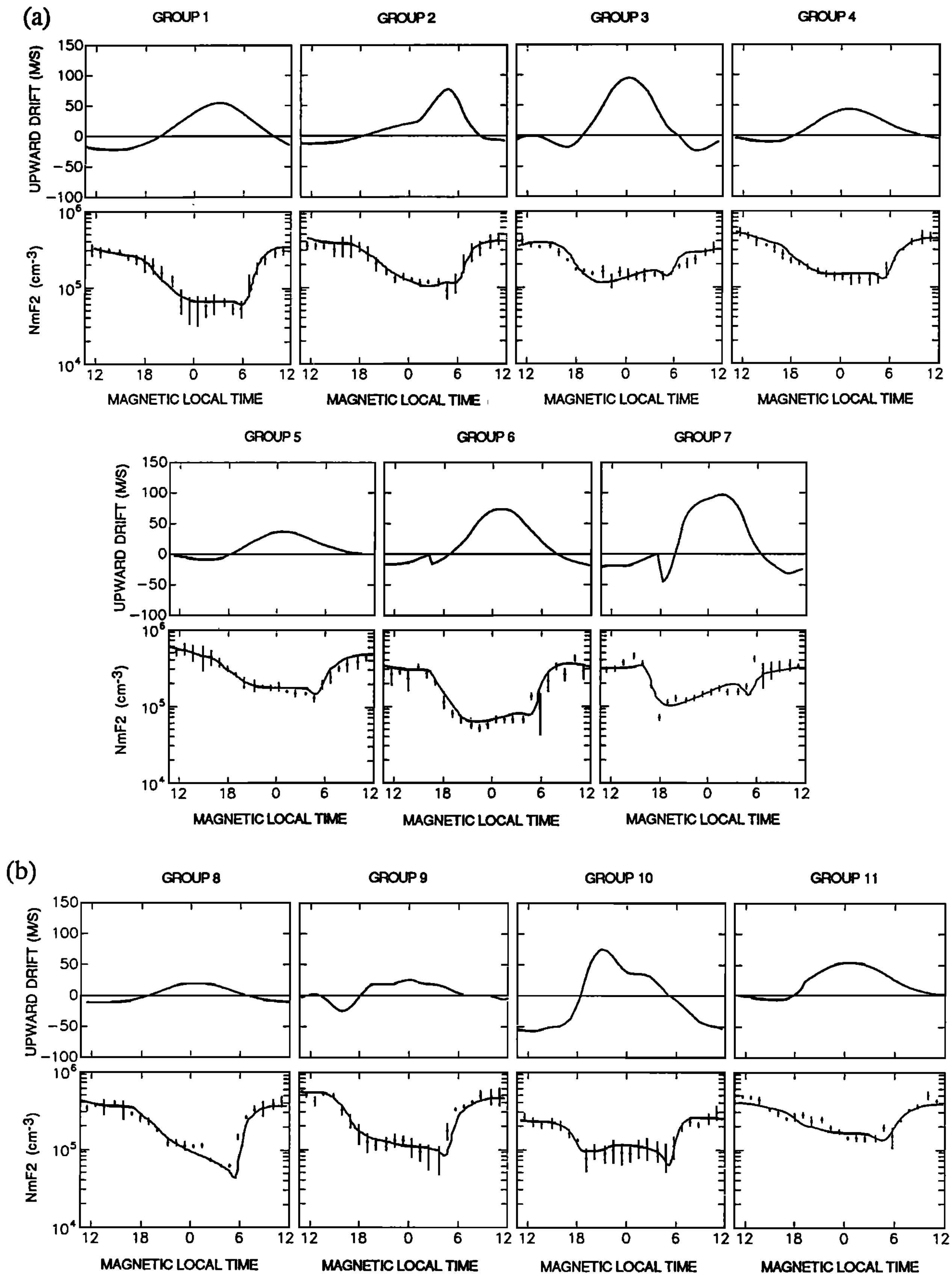

Fig. 4. The diurnal variation of hourly N_mF2 values for the 11 groups of stations (solid circles in lower panel). The line through each point is 2 root-mean-square deviations in length. The calculated N_mF2 values are shown by the solid lines in the lower panels, and the vertical plasma drift used in the calculations is shown in the upper panels. (*a*) northern hemisphere stations and (*b*) southern hemisphere stations.

TABLE 2. Geophysical Parameters for September 28 and 29, 1986

Parameter	Value
Previous day's 10.7 cm flux	69.6×10^{-22} W m^{-2} Hz^{-1}
3-month mean 10.7 cm flux	74.0×10^{-22} W m^{-2} Hz^{-1}
Ap	13

are negligible. In addition to assuming a model atmosphere, a meridional neutral wind is required, which acts to raise or lower the ionosphere [*Rishbeth and Garriott*, 1969]. For this study, the induced vertical plasma drift was varied as a function of time and model calculations were performed until the calculated N_mF2 variations agreed with the measured diurnal variation for each of the 11 groups of sites. For these simulations the ionosphere was allowed to "breathe," i.e., the O^+ flux through the upper boundary (1000 km) varied during expansion and contraction of the *F* layer. This boundary condition is appropriate for full flux tubes. However, for the usual case of partially depleted flux tubes, the O^+ flux to or from the plasmasphere can be appreciably different than that which occurs for full flux tubes. This problem will be discussed in more detail in the next subsection.

The results of this study for the 11 groups are shown in Figures 4*a* (northern hemisphere) and 4*b* (southern hemisphere). The ionosonde measurements of N_mF2 are plotted as points in the lower row, with the vertical line through the points 2-rms deviations in length, as discussed in the previous section. The model calculation is the solid line. Above each of these plots is the vertical plasma drift required to reproduce the measurements. The vertical plasma drift is shown in a coordinate system with upward positive. For these mid-latitude sites, MLT and solar local time are within an hour of each other.

If the vertical plasma drift (v) is due only to the meridional neutral wind (u), then $u = -v/(\sin I \cos I)$, where I is the dip angle. The meridional wind obtained in this way for each site seems reasonable, with daytime poleward winds generally less than 100 m/s and nighttime equatorward winds of less than 300 m/s. The direction and magnitude of the wind is consistent with measurements and models of the *F* region [e.g., *Hernandez and Killeen*, 1989]. To better judge whether the winds from the individual locations form a consistent wind pattern when viewed simultaneously, Figure 5 shows the meridional wind as vectors at four universal times (0300, 0900, 1500, and 2100 UT) on a magnetic dial plot. The number at the head of each vector indicates the group number. Both the northern and southern hemisphere winds are consistent with current global models of the upper thermosphere (see, for instance, *Roble* [1983]) but with some variability from location to location. The nighttime meridional wind blows equatorward, and in the northern hemisphere it is stronger in the morning. The daytime winds are typically small and poleward. This diurnal wind pattern is necessary to balance production in the daytime ionosphere and prevent the nighttime *F* region from disappearing. As discussed previously, the wind is interpreted as only blowing in the meridional direction. This assumption is likely incorrect, particularly at dawn and dusk, but does not affect the model results which only use the wind to raise or lower the layer.

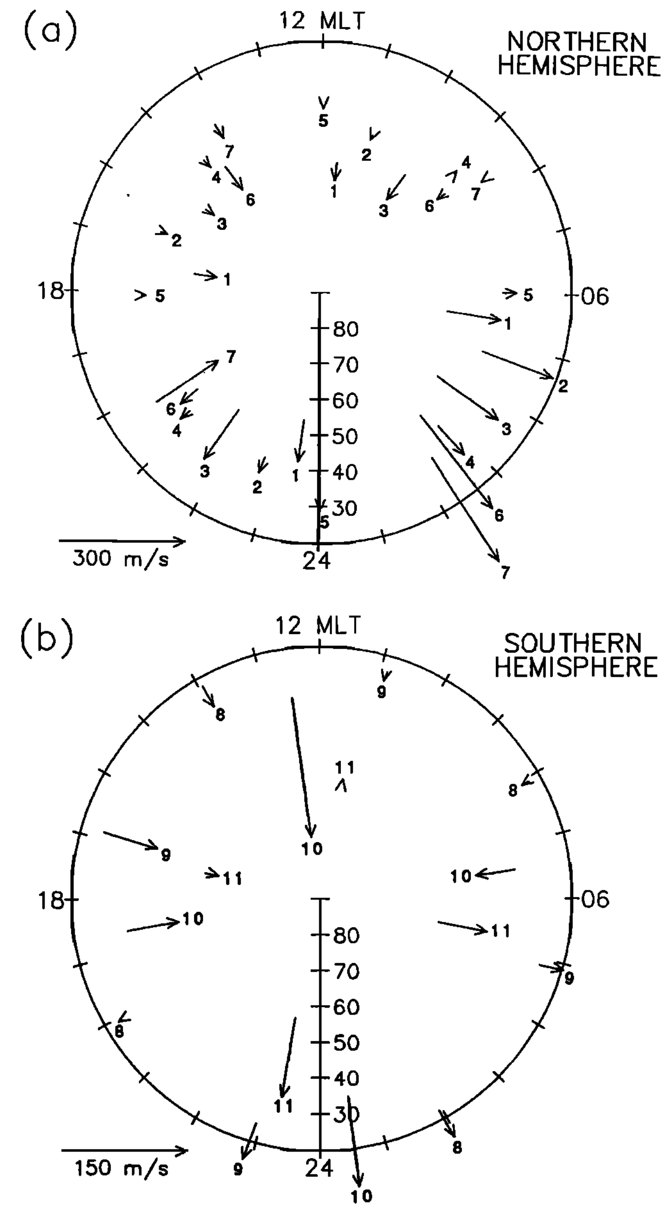

Fig. 5. Wind vectors at 0300, 0900, 1500, and 2100 UT for the (*a*) northern and (*b*) southern hemispheres as determined from the vertical plasma drifts used to reproduce the N_mF2 measurements.

3.4. *Comparisons with Measurements, O^+ Flux Effects*

It is tempting at this point to conclude that this comprehensive mid-latitude data set has allowed a large-scale picture of the neutral dynamics of the upper thermosphere to be obtained. Unfortunately, the neutral wind is not the only process that controls the variation of N_mF2. Plasma flows to and from the plasmasphere are known to have a marked effect on N_mF2 and a smaller effect on h_mF2 [see *Schunk and Walker*, 1972; *Schunk and Nagy*, 1980; and references therein]. During equinox and under full flux tube conditions, O^+ flows up from the ionosphere during the day, charge exchanges with neutral hydrogen to produce H^+, and H^+ is then stored in the outer plasmasphere. At night the reverse process occurs, and therefore the diurnal variation consists of an ebb and flow of plasma between the ionosphere and plasmasphere. During the summer months, on the other hand, the full flux tube situation may produce a flow that is upward in the northern hemisphere and downward in the southern hemisphere both during the day and at night.

If the real ionosphere-plasmasphere system always behaved in the simple manner described above, it would be relatively easy to include ionosphere-plasmasphere coupling in the routine modeling of ionosonde data. Unfortunately, the frequent occurrence of magnetic storms precludes this. During magnetic storms the plasma in the outer plasmasphere is stripped away by convection electric fields, and left behind are partially depleted or empty plasma flux tubes. Since the refilling time is longer than the time between magnetic storms, most mid-latitude flux tubes are always in a partially depleted state. Unfortunately, the plasma flux coupling between the ionosphere and the outer plasmasphere depends on the state of the refilling. Furthermore, a lack of knowledge of the state of the refilling precludes any simple description of the behavior of the flux at conjugate sites, particularly at equinox when solar production on both ends of the tubes is approximately equal.

From the modeling point of view, a rigorous inclusion of ionosphere-plasmasphere coupling would require modeling each station for at least the 11-day refilling period taking into account magnetic storm effects. Since information on storm electric fields is not routinely available, rigorous ionosphere-plasmasphere modeling is not possible at the present time. Therefore it is important to determine the extent to which ionosphere-plasmasphere flows can affect N_mF2 and hence the earlier determination of the meridional winds.

The calculation of N_mF2 for group 1 shown in Figure 4*a* is shown again in Figure 6*a*. To highlight the importance of the neutral wind in maintaining the nighttime *F* region, Figure 6*b* shows a similar calculation with no vertical plasma drift at night. With no neutral wind to drive plasma up the field line, where it has a longer lifetime against recombination, the densities decrease to 5.3×10^3 cm^{-3}, an order of magnitude lower than in Figure 4*a*. In contrast, how important is the contribution of O^+ flux from the plasmasphere?

Figure 6*c* shows a computation of N_mF2 for group 1 using a crude approximation to a reasonable mid-latitude O^+ flux between the ionosphere and plasmasphere and no vertical plasma drift. The O^+ flux was chosen to be 3×10^8 cm^{-2} s^{-1} when the Sun was above the horizon, and -1×10^8 cm^{-2} s^{-1} when the Sun was below the horizon [e.g., *Evans and Holt*, 1978]. No attempt was made to include a smooth transition between the two extremes. Even using this crude diurnal dependence for the O^+ flux at the top of the atmosphere, reasonable agreement with the measurements is obtained (for comparison, the computation with a vertical plasma drift and no O^+ flux at the top is replotted in Figure 6*a*).

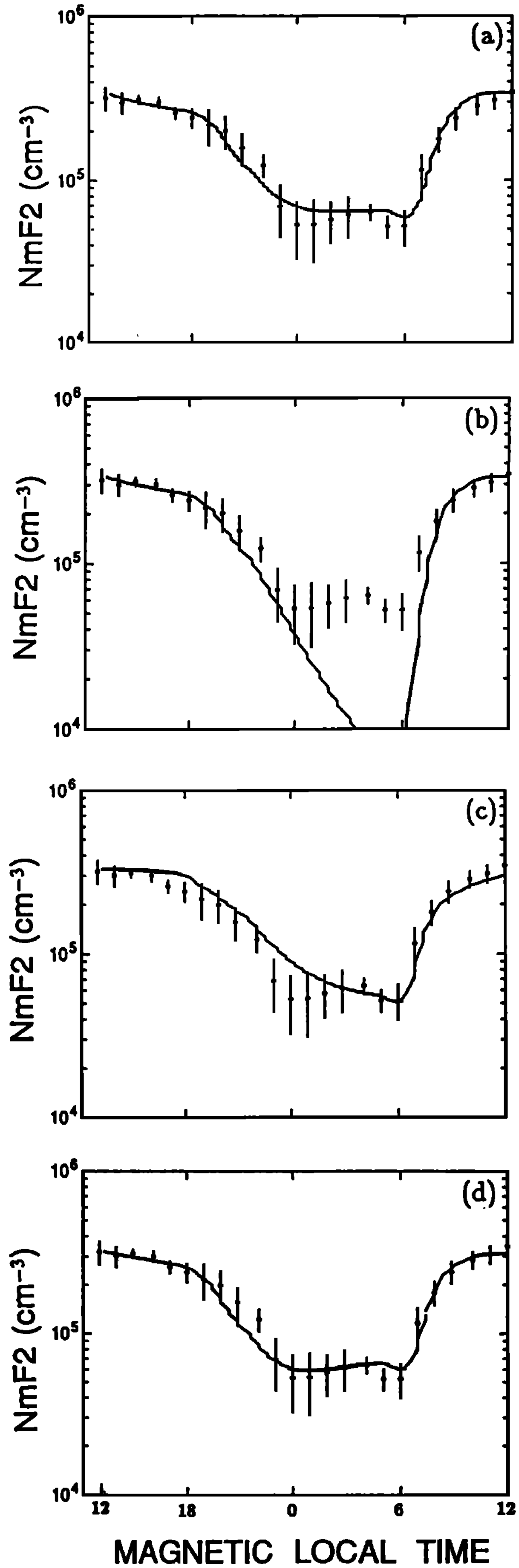

Fig. 6. Calculated versus measured N_mF2 values for group 1 using (*a*) vertical plasma drift and no O^+ flux at the top of the atmosphere, (*b*) no vertical plasma drift and no O^+ flux, (*c*) no vertical plasma drift and an O^+ flux of 3×10^8 cm^{-2} s^{-1} during the day and -1×10^8 cm^{-2} s^{-1} at night, and (*d*) vertical plasma drift as in Figure 6*a* but at half the speed at night supplemented with an O^+ flux of -5×10^7 cm^{-2} s^{-1}.

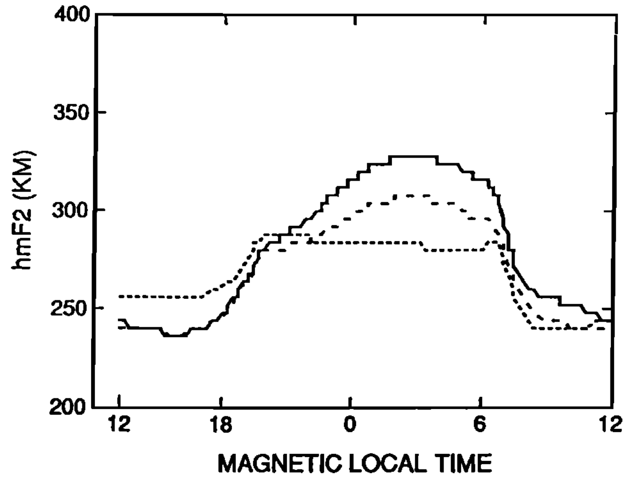

Fig. 7. Model calculations of h_mF2 for the cases in Figure 6*a* (solid line), Figure 6*c* (short-dashed line), and Figure 6*d* (long-dashed line).

Although the N_mF2 computations for the two cases are similar, some differences can be seen in h_mF2 (Figure 7). Here, h_mF2 as a function of time is shown for the vertical drift case (solid line) and the O^+ flux case (short-dashed line). During the daytime the difference between the two curves is smaller than the typical 25-km uncertainty in retrieving h_mF2 from ionograms [*Rishbeth and Garriott*, 1969]. In the postmidnight region the difference between the two curves is about 45 km for a few hours.

The real thermosphere is, of course, likely to have a neutral wind and O^+ flux present simultaneously. The meridional wind driving the vertical plasma drift in Figure 6*a* for group 1 peaked 2 hours after midnight at about −150 m/s. If the same wind variation is used, but halved at night, and an O^+ flux of -5×10^7 cm^{-2} s^{-1} is imposed at night, N_mF2 varies as shown in Figure 6*d*. There exists very little difference between the calculation assuming a maximum wind of −150 m/s at night and that assuming −75 m/s coupled with a reasonable (and, in fact, small) value for the O^+ flux at the top of the atmosphere.

Unfortunately, having h_mF2 estimates from the ionosondes would not likely alleviate this situation. Figure 7 shows the additional h_mF2 curve from the composite run (long-dashed line). These values of h_mF2 fall between the two extreme cases in the postmidnight sector. With the geophysical and instrumental variations inherent in real ionosonde measurements, it would be difficult to differentiate between the three curves. Hence the estimates of the neutral wind obtained in section 3.3 from measurements of N_mF2 could be in error by a factor of 2 (or more).

4. Summary and Conclusion

A global ionospheric model has been used to calculate the diurnal variations of N_mF2 for 41 mid-latitude ionosonde stations during a geomagnetically quiet period. By assuming reasonable variations of the vertical plasma drift and the MSIS atmosphere for the appropriate geophysical conditions, the measured diurnal variations of N_mF2 have been successfully reproduced in both the northern and southern hemispheres.

Although the neutral winds deduced from the vertical plasma drifts used to reproduce the N_mF2 values are qualitatively consistent with currently available measurements and model computations, the assumption that N_mF2 is controlled primarily by the neutral wind is probably not valid. Moderate values of the O^+ flux at the top of the atmosphere can also successfully reproduce the measurements, while assuming no vertical plasma drift. In addition, a model study using half the vertical plasma drift at night as that used to successfully reproduce the group 1 measurements, combined with a small O^+ flux at the top of the atmosphere, was also able to reasonably fit the measurements. Furthermore, the change in h_mF2 between this simulation and the drift-only case was less than 20 km and in the evening and at sunrise less than 5 km. Typically, a routine derivation of h_mF2 from scaling ionograms or the *Dudeney* [1983] empirical formula have errors of about ±20 km and hence would be inadequate in this case for distinguishing whether or not a plasmaspheric flux was present.

To improve the situation, better techniques are needed to extract h_mF2 values from ionograms in order to reduce the uncertainty in this parameter to less than ±5 km for individual observations. To determine neutral winds, it is important to have satellite or incoherent scatter radar determinations of the O^+ flux at the top of the atmosphere (≈ 1000 km). Conversely, to obtain ground-based estimates of O^+ flux from the plasmasphere requires accurate measurements of meridional neutral winds (in addition to electric fields). Finally, to better determine the accuracy of ionosonde-deduced meridional winds, simultaneous measurements of the winds by techniques such as high-resolution ground-based optical interferometry are necessary.

The Sundial program will eventually obtain measurements from over 70 ionosonde sites for campaigns of 1 month duration. If routine modeling of these measurements to provide neutral wind or plasmaspheric flux is envisioned, improvements in the data acquisition and analysis are necessary to provide sufficiently more accurate evaluations of h_mF2, in addition to high-quality measurements of N_mF2.

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